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WORKSHOP ON ARCTIC CONTAMINATION

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INTERAGENCY ARCTIC RESEARCH POLICY COMMITTEE

About the Journal

The journal *Arctic Research of the United States* is for people and organizations interested in learning about U.S. Government-financed Arctic research activities. It is published semi-annually (spring and fall) by the National Science Foundation on behalf of the Interagency Arctic Research Policy Committee and the Arctic Research Commission. Both the Interagency Committee and the Commission were authorized under the Arctic Research and Policy Act of 1984 (PL 98-373) and established by Executive Order 12501 (January 28, 1985). Publication of the journal has been approved by the Office of Management and Budget.

Arctic Research contains

- Reports on current and planned U.S. Government-sponsored research in the Arctic;
- Reports of ARC and IARPC meetings;
- Summaries of other current and planned Arctic research, including that of the State of Alaska, local governments, the private sector and other nations; and
- A calendar of forthcoming local, national and international meetings.

Arctic Research is aimed at national and international audiences of government officials, scientists, engineers, educators, private and public groups, and residents of the Arctic. The emphasis is on summary and survey articles covering U.S. Government-sponsored or -funded research rather than on technical reports, and the articles are intended to be comprehensible to a nontechnical

audience. Although the articles go through the normal editorial process, manuscripts are not refereed for scientific content or merit since the journal is not intended as a means of reporting scientific research. Articles are generally invited and are reviewed by agency staffs and others as appropriate.

As indicated in the U.S. Arctic Research Plan, research is defined differently by different agencies. It may include basic and applied research, monitoring efforts, and other information-gathering activities. The definition of Arctic according to the ARPA is "all United States and foreign territory north of the Arctic Circle and all United States territory north and west of the boundary formed by the Porcupine, Yukon, and Kuskokwim Rivers; all contiguous seas, including the Arctic Ocean and the Beaufort, Bering, and Chukchi Seas; and the Aleutian chain." Areas outside of the boundary are discussed in the journal when considered relevant to the broader scope of Arctic research.

Issues of the journal will report on Arctic topics and activities. Included will be reports of conferences and workshops, university-based research and activities of state and local governments and public, private and resident organizations. Unsolicited nontechnical reports on research and related activities are welcome.

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Proceedings of the
 Interagency Arctic Research Policy Committee
Workshop on Arctic Contamination
 May 2–7, 1993, Anchorage, Alaska

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Introduction

BRUCE F. MOLNIA

From May 2 to 7, 1993, the Interagency Arctic Research Policy Committee conducted a Workshop on Arctic Contamination. The Workshop, which was held in Anchorage, Alaska, addressed the Arctic contamination in its broadest sense, dealing with contamination from trace metals, persistent organic compounds, hydrocarbons, and radionuclides. The Workshop was attended by more than 200 participants, with non-U.S. participants representing Canada, the Russian Federation, Norway, Ireland (representing the European Economic Community), Finland, Great Britain, and Monaco (representing the International Atomic Energy Agency).

More than 50 members of the international scientific community made formal presentations describing significant aspects of the issue of Arctic contamination or describing unique characteristics of the Arctic environment that could impact contaminant dispersal or accumulation. These presentations form the basis for this special issue of *Arctic Research of the United States*. Twelve additional reports and 10 abstracts, prepared by invited Russian scientists, some of whom were unable to attend the Workshop, also appear in this special issue.

One topic that received a significant amount of attention was Native Peoples' concerns about Arctic contamination. Concerns ranged from the impact of contaminants on subsistence life styles, to health risks, to involvement of Native Peoples in the research process, from planning to implementation, to distribution of results. A recommendation was made to develop a clearinghouse for information distributed to the Native community.

One focus of the Workshop was to understand the disposal of radionuclide wastes by the former Soviet Union (FSU). This was done with the full cooperation of the government of the Russian Federation. Included in these Proceedings is a letter of welcome and cooperation from Russian Federation Ambassador Lukin to the Workshop participants. An English-language trans-

lation of the Yablokov Commission report, *Facts and Problems Related to Radioactive Waste Disposal in Seas Adjacent to the Territory of the Russian Federation*, prepared for Russian Federation President Boris Yeltsin, was distributed to all Workshop participants. Although the report is not reproduced here, a paper by Vitaliy Lystsov, presenting additional comments on that report, is included in this volume.

Not all Arctic contamination is the result of the activities of the FSU. U.S. Senator Frank Murkowski presented a summary of the environmental legacy of the Cold War, in which he identified more than 600 waste disposal sites in Alaska, many of which require remediation.

An analysis of the information presented at the Workshop suggests that more credible scientific information is needed before a comprehensive risk assessment to determine the effects of Arctic contamination of ecosystems and human health can be completed. Surprisingly there is a general absence of systematically collected scientific information about contaminant type, distribution, transportation, and fate throughout the Arctic.

At some locations, adequate data do exist, but generally this is not the case. As an example, at the time of the Workshop, virtually no information existed about the status of radionuclide waste materials dumped at any of the FSU's marine dump sites in the Kara Sea, Barents Sea, or Pacific Ocean. The Kara Sea sites had not been investigated in more than 25 years. Oceanographic studies conducted elsewhere in the Kara and Barents seas do not show elevated levels of radioactivity, suggesting that no significant leakage has occurred from the FSU dump sites to date. In fact, the only long-term sources of detectable radioactivity entering the Barents Sea are nuclear plants in France and the United Kingdom.

One report of a highly radioactive piece of metal found on a Novaya Zemlya beach suggests that sea ice

may be interacting with dumped materials and may be redistributing and transporting pieces of these dumped materials from their initial disposal sites. Materials, including contaminants, entrained in sea ice can be transported throughout the entire Arctic.

Other presentations described radioactive waste from several nuclear facilities of the FSU having been dumped into adjacent river systems. Chronic problems were described at some of these facilities, including the present leakage of waste. Observed concentrations of both trace metals and organic contaminants in Siberian rivers, especially the Ob and Yenisey, exceed the maximum limits of Russian Federation law by up to half an order of magnitude.

Not all radioactive contamination results from human activities. In some Siberian oil and gas production areas, permafrost processes concentrate natural radioactivity in brines, resulting in radiation levels up to an order of magnitude above maximum acceptable levels.

The Workshop also addressed persistent organic compounds (such as PCBs). These compounds are transported over long distances by both air and water and are distributed throughout the Arctic. Many of these compounds are biomagnified in the Arctic where they

degrade slowly. A circum-Arctic compilation of data on levels of these contaminants would be most useful in assessing their status. Similarly, systematic information about their levels in Arctic inhabitants is needed. Based on a limited sampling, no evidence has been found of high levels of trace metal contamination in tissue samples collected in Alaska.

Presentations described a series of 1993 cooperative cruises that will attempt to sample contaminants at selected locations in the Barents, Kara, Laptev, East Siberian, Bering, Chukchi, and Beaufort seas. In spite of the flurry of activity, it was concluded that no systematic program exists to monitor U.S. Alaskan waters.

The papers presented here follow the order of presentation at the Workshop. Papers in this volume are organized along the following six themes:

- I. Introduction
- II. Characterization of the Arctic Environment
- III. An Introduction to Arctic Contamination
- IV. Characterization of Arctic Contamination
- V. Ecological and Human Health Impacts of Arctic Contamination
- VI. Russian Concerns and Perspectives on Arctic Contamination.

May 1, 1993

WELCOME

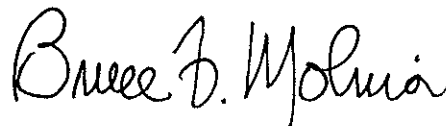
On behalf of the Interagency Arctic Research Policy Committee (IARPC), welcome to the Workshop on Arctic Contamination!

The IARPC is composed of the fourteen United States Federal agencies that conduct or manage research in the Arctic. Its existence was mandated by the Arctic Research and Policy Act of 1984 (ARPA), which directed the IARPC to coordinate Federal agency Arctic research programs and to cooperate in the planning and conduct of Arctic research. The IARPC also strives to maximize the return on the United States investment in Arctic research by attempting to eliminate duplication of effort and by attempting to coordinate research on topics of mutual interest to IARPC member agencies. Presently, the number one issue of concern to IARPC member agencies is contamination in the Arctic. Included in the introductory materials, which follow, are the IARPC's *Policy Statement on Arctic Contamination* and the IARPC's *Agenda for Action to Implement the Policy Statement on Arctic Contamination*. The Policy Statement was adopted on August 27, 1992. The Agenda for Action was adopted on November 25, 1992.

The purposes of this IARPC-convened **Workshop on Arctic Contamination** are:

- 1) to identify sources of existing data and information about Arctic contamination;
- 2) to identify the breadth of existing data and information about Arctic contamination;
- 3) to identify major data gaps that need to be filled to complete a thorough analysis of the Arctic contamination question; and
- 4) to begin the process of determining whether specific Arctic contaminants present a risk to the environment, ecosystems, or human health in: a) Alaska, b) the entire Arctic, or c) the global environment.

In the weeks following the Workshop, information collected by the IARPC will be carefully evaluated and analyzed by the IARPC staff and the IARPC Environmental Monitoring and Assessment Task Force. The goal of the IARPC, and the ultimate purpose of this Workshop, is to provide United States Government decision-makers with a factual basis for formulating United States policy on Arctic contamination.



Bruce F. Molnia
for the IARPC Technical Committee

Greetings from the Interagency Arctic Research Policy Committee (IARPC)

Cornelius W. Sullivan
National Science Foundation

Like so many things in Washington today, I too am in transition between being a Professor at the University of Southern California, in Los Angeles, and taking on a new position as Director of the Office of Polar Programs, at the National Science Foundation. In that role, on behalf of the Interagency Arctic Research Policy Committee (IARPC), I am delighted to welcome you to the Committee's Workshop on Arctic Contamination.

The United States and other Arctic nations are concerned about the reported contamination of the Arctic by radioactive materials and other hazardous substances. We are concerned because of the potential for distribution of radioactive and toxic contamination in the terrestrial, aquatic, and marine ecosystems and environments, the ecological risk of contamination to those Arctic ecosystems, the health risks to human populations, and the economic impacts associated with contaminant transport throughout Arctic and adjacent seas, and including the effects on fisheries, food stuffs, and other resources.

With the caveat that most people give these days, subject to the availability of funding from the U.S. Congress, the Interagency Arctic Research Policy Committee plans a coordinated U.S. program to evaluate the ecological health, and health risks, of Arctic contamination. Further we propose to coordinate in an international

effort under the umbrella of international organizations to evaluate the scope of this problem, to rescue data from world archives, and to promote international scientific cooperation. In this program we hope to assess the rates of movement of toxic materials and contaminated organisms into and out of Arctic territorial waters. We want to assess the probable long-term effects on food webs, on peoples of the North, and on peoples of lower latitudes, through export of fishery products. This Workshop to evaluate and assess the compilation of existing data and analyses, and to recommend future actions toward an assessment of Arctic contamination, is the first step in our effort. We have here today over 200 representatives of a number of groups involved in Arctic research, and who are concerned by the widespread reports of Arctic contamination. We are here to learn from each other. The Interagency Arctic Research Policy Committee seeks your collective advice on the content of the United States plan to examine the issues of Arctic contamination. The next five days offer you the opportunity to share your information and your views on this issue. We hope those views will converge on some points of broad agreement. We seek your advice, and I am pleased to welcome your participation. Thank you for coming, and I know you join me in looking forward to a very successful Workshop.

To the Participants of the International Workshop on Arctic Contamination (Anchorage, Alaska)

The problem of the radioactive contamination of the seas within the Arctic Ocean and other parts of the world's oceans has been receiving increased attention by the public in many countries, including the Russian Federation.

During the Cold War, there was no priority in dealing with this problem in the former USSR. The nuclear arms race, the nuclear energy development, and the construction of both nuclear-powered icebreakers and the nuclear submarines, raised an urgent demand to establish sites for the storage of the produced radioactive waste (RAW). The simple choice was to dump the solid radwaste (SAW) and liquid radwaste (LAW) at sea, as was the practice of most countries with developed nuclear industries at that time. Available data indicate that the USSR had been dumping and releasing RAW, including parts of nuclear reactors with unloaded fuel, in the Barents and Kara seas, as well as in the far-eastern seas, since 1960.

A complete assessment of the situation regarding radioactive contamination of northern seas cannot be made without considering the amount of radioactive substances coming from outside the region through the atmosphere, rivers, and particularly the liquid radwaste released by nuclear reprocessing plants at Sellafield, UK, and La Hague, France, and brought to the Arctic by the Gulf Stream.

The scale of radioactive contamination of the world's oceans will not be completely assessed without taking into consideration all other radwaste dumped in the seas by the eleven other countries since 1946, as well as sunk nuclear submarines and lost nuclear weapons.

Most governments of the world are calling for a ban on dumping any type of RAW at seas because of the growing concerns over the radioactive contamination of the marine environment. This was the purpose of Denmark's initiative calling for a total ban on RAW dumping at seas. The idea of a moratorium on RAW dumping at seas was raised for the first time in 1983, under the auspices of the London Convention. It called for refraining from dumping of intermediate- and low-level radioactive waste until recommendations are set up and submitted to the 16th Consultative Meeting, held in November 1993.

The 1992 United Nations Conference on Environment and Development supported an initiative proposed by Denmark, Iceland, and Norway, which called for a ban on the dumping of all kinds of radioactive waste at sea. This general agreement, between more than 150 countries, was adopted by consensus (including Russia). It will result in some policy changes within many of those nations. At present, a number of nations have some reservations on this matter and insist on having some transition period, in order to solve all problems related to the preparation for the disposal of RAW (LAW and SAW) on land. The 1992 Convention on the Protection of the Marine Environment of the Northeastern Atlantic (which the Russian Federation has not yet signed) grants, for example, Great Britain and France the opportunity for a gradual reduction of radioactive releases into seas until 2018. That offer corresponds to the interest and capabilities of Russia.

In the process of obtaining the actual information needed to bring Russia into compliance with international treaties, which Russia joined as a successor to the USSR, the President of the Russian Federation created the governmental commission on the matter of RAW disposal at sea in October 1992. In February 1993 the Commission submitted to the President of the Russian Federation a report with current information on dumping of radwaste at sea, as well as its recommendations. On the basis of this report, the Commission released the White Book, which is available, as far as I know, at the Workshop.

In addition, the Government of the Russian Federation has been reviewing the Governmental Program on Recycling and Disposal of Radioactive Waste and Spent Nuclear Materials in 1993-1995 through 2005. This program, particularly, envisions an assessment of radioecological consequences of both dumped radwaste at sea and sunk nuclear submarines. Within the framework of the program, pilot repositories will be sited for the disposal of solid low- and intermediate-level RAW.

In conclusion, let me point out that despite the existence of the complicated political and economic situation in our country, Russia has been taking and will take the necessary measures in the interest of monitoring and stabilizing the ecological situation in the northern and far-eastern seas. You see there is a strong understanding in Russia that global recognition of this problem is a natural basis for expanding the mutually beneficial cooperation in this field with all concerned countries.

Please, take my best wishes in your extremely difficult and responsible effort for the protection of our beautiful environment.

V. LUKIN
Ambassador of the Russian Federation
to the U.S.A.
April 29, 1993

Workshop on Arctic Contamination Background and Objectives

Bruce F. Molnia
U.S. Geological Survey
Workshop Technical Committee Chairman

I would like to welcome you on behalf of the Inter-agency Arctic Research Policy Committee (IARPC). The IARPC is composed of the 14 United States federal agencies that conduct or manage research in the Arctic, and it is the product of the Arctic Research and Policy Act of 1984. This Act directed the agencies to coordinate their activities, to cooperate in planning, and to conduct Arctic research in concert. The IARPC strives to maximize the return on the United States investment in the Arctic, and on Arctic research, by attempting to eliminate duplication of effort, and by attempting to coordinate research on topics of mutual interest to the IARPC member agencies. Presently the number one issue of concern to the IARPC member agencies is contamination in the Arctic.

For this Workshop we tried to present you with as much information as we could, and I have had a number of comments and complaints that the notebook is just too heavy to carry home. Included in the notebook's introductory material are both a policy statement and an agenda for action from the IARPC. The agenda for action calls for, among other things, holding a Workshop to gather data and to identify major data gaps. That is why we are here today. The purposes of this IARPC-convened Workshop on Arctic Contamination are:

- (1) To identify sources of existing data and information about Arctic contamination.
- (2) To identify the breadth of this existing data.
 - How much is there?
 - Where does it reside?
 - How accurate is it?
 - What can we do with it?
 - Is there more that we need to know?
- (3) To identify the major data gaps that need to be filled to complete a thorough analysis of the Arctic contamination question.

- (4) To begin the process of determining whether specific Arctic contaminants present a risk to the environment, to ecosystems, to human health in Alaska, in the entire Arctic, and to the global environment.

Following this Workshop, the members of the IARPC staff will synthesize the information that we gathered here. We will identify the data gaps that we feel need to be filled in order to have a comprehensive and usable data set in order to make intelligent policy decisions on Arctic contamination. We will provide the results of our data synthesis to members of Congress, to the heads of federal agencies and other bureaus, hoping that they will be able to take this factual and credible scientific information, and use it to provide a basis for continued Arctic scientific research and monitoring, especially in the area of Arctic contamination.

The next five days are going to be filled with information. I apologize to you ahead of time, if you look at the Agenda, you will notice there is not much free time. We have presentations scheduled that start at 8:30 and run until almost 6:00 p.m. During two evenings, we will have poster sessions. Friday afternoon we are going to conduct a panel on risk assessment, trying to identify from what we have heard over the course of the first four and a half days, what problems are there, and do they present a risk to the environment, to human health, to ecosystems?

Your notebook contains a variety of different kinds of information. It has the policy statement and the agenda for action, as I mentioned. It also contains a copy of the English language translation of the Yablokov Commission Report on the dumping of radionuclide waste in the territories around the Russian Federation. Further, you will find a preliminary bibliography on Arctic contamination that was compiled for this meet-

ing. Rather than giving you 215 pages of additional text to carry, the complete text is an ASCII file on an MS DOS 3¹/₂" floppy disk. Ann Brennan compiled this for us and we hope to publish a final version of the bibliography at the end of the summer.

The Workshop notebook also contains either summaries or executive summaries of each of the presentations that will be made in Monday and Tuesday's Plenary Sessions. It includes a number of abstracts from presentations in the Wednesday and Thursday Technical Sessions, including about 30 abstracts and short summaries, from members of the Russian scientific community and Russian government. We have with us today about a dozen Russians. One or two more will be coming. Unfortunately another 13 who we had invited, who we provided tickets for, are unable to make it because of either passport or visa problems, which have prevented them from exiting St. Petersburg and Moscow. We have information in the notebook, and we will have a very interesting session on Wednesday, listening to presentations by members of the Russian scientific community, on both environmental policy and environmental issues, and some scientific information about contamination, the biota, and other physical aspects of the Russian environment.

At the end of the Workshop notebook are 28 abstracts that pertain to the poster sessions that will be seen on Tuesday and Thursday evenings.

The Technical Sessions on Wednesday and Thursday are structured to maximize participation by everyone in the audience. If you would like to make a presentation, we will put you on the agenda. If you take the time to look at the Workshop agenda, you will see that there are three sessions Wednesday morning, and four sessions on Wednesday afternoon, Thursday morning, and Thursday afternoon. Each of the sessions is structured, as I said, to maximize participation. We want to learn whatever information you have to present to us. We want to maximize everyone's participation to make this not only a Workshop where we walk away with something, but where you walk away with also a much broader base of information about the issue of Arctic contamination.

The IARPC is not only concerned about radionuclide contamination. This Workshop is structured so that we deal also with contamination from persistent organic compounds, trace metals, and chronic hydrocarbons. You will hear presentations on each of those in today and tomorrow's Plenary Sessions.

The Environmental Legacy of the Cold War

U.S. Senator Frank H. Murkowski

I wish to thank the Interagency Committee, the National Science Foundation, and the community of Arctic scientists for convening this workshop on Arctic contamination.

Back when we wrote the Arctic Research and Policy Act—the Act that chartered the Interagency Committee and created the Arctic Research Commission—nobody envisioned that you'd have to deal with widespread Arctic environmental contamination. But I commend you and the Commission for taking the subject very seriously.

On behalf of all Alaskans, I also want to thank you for convening this workshop here in Alaska, in view of those with a great stake in the issue.

Arctic contamination is one environmental legacy of the Cold War. If the Cold War can be likened to a wild party—then we've reached the morning after. It's time to wake up, look around, survey the damage, and clean up the mess.

Some of the mess is in our own backyard—but the situation looks far worse when we look next door to our Russian neighbors.

Last August, we convened a hearing of the Senate Intelligence Committee in Fairbanks highlighting environmental problems in the Former Soviet Union. It was the first and only time that this Committee ever held a field hearing, and one of the very few times it has convened hearings fully open to the public.

At the hearing we heard Robert Gates, then the Director of Central Intelligence, paint a picture of Russia's deteriorating environmental situation.

We also heard Assistant Secretary of State Buff Bohlen stress the importance of the Arctic and the need for an international long-term environmental monitoring program in the Arctic.

Finally, we heard an international panel of scientists agree that we may face serious environmental problems

in the Arctic, and that we need more information to assess risks and determine a course of action.

Since that time we have indeed learned a little more. Some of our fears have been confirmed.

Let's focus for a moment on just one aspect of Arctic contamination—Soviet and Russian ocean dumping of radioactive waste. A "White Paper" commissioned by President Yeltsin released on March 23rd revealed:

- Solid radioactive wastes were dumped at 12 sites—including 4 sites in the Russian Far East.
- Liquid radioactive wastes were dumped at 5 sites in the Barents Sea and 9 sites in the Sea of Okhotsk, the Sea of Japan, and in the Pacific high seas.
- The solid waste includes 18 reactors—6 with nuclear fuel.
- The radioactivity associated with this dumping is estimated at 2.4 million curies. (For the sake of comparison, the accident at Three Mile Island released 15 curies. The Chernobyl disaster released an estimated 65 million curies.)

The 2.4 million curies reported to be dumped is *twice* the radioactivity that the International Atomic Energy Agency had estimated was dumped by *all nations* during the entire nuclear age.

But that 2.4 million curies is just *part* of the radioactive contamination threatening the Arctic.

- It doesn't include radioactive materials from nuclear activities at Chelybinsk and Tomsk that move into the Arctic through the great northward-flowing Russian rivers.
- It doesn't include radioactivity released from nuclear testing and accidental releases;
- It doesn't include potential releases from *future* accidents, reactor decommissioning, and nuclear weapons disposal.

Russian scientists have quietly told me that as much as *two billion curies* of radioactive waste might reach the

environment as a result of past practices in the Former Soviet Union—so there may be distressing nuclear revelations in our future if this contamination is released into the environment, enters the food chain, and affects our health.

And of course, as the organizers of this workshop have aptly recognized, radioactivity is *only one* of the potential contaminants that threaten the Arctic. We need to be concerned about industrial pollution, heavy metals and persistent organic chemicals as well.

The impacts of environmental practices in the Former Soviet Union are already apparent

- The air is unfit to breathe in 103 cities—home to 70 million people. In the Siberian city of Norilsk, the air is so polluted that children must be kept indoors 90 days per year.
- Seventy-five percent of their surface water is polluted. Several of the large Russian rivers that flow into the Arctic—the Ob, Lena, Yenisey—are highly polluted.
- A major inland sea—the Aral—is turning to desert. Once larger than Lake Huron, the Aral has shrunk by two-thirds. It is the site of so much contamination that mothers in the area cannot breast-feed their children without the risk of poisoning them.
- Life expectancy is falling. Average life expectancy among men in the Soviet Union fell from 66.1 years in 1965 to 62.3 years in 1981. In Anchorage's sister city of Magadan, the rate of death caused by cancer has increased by 73% over the past 10 years. Air pollution in Magadan over that same period has more than doubled—there may be a relationship.
- Infant mortality is rising—estimated by some to be 33 per thousand or higher—a rate comparable to some third-world countries. Even for the children who make it past their first year, good health is difficult to attain. Delegates to the 19th Part Conference in Moscow were told that 53% of all Soviet schoolchildren were in poor health. In 1988, two out of every five young men who reported for compulsory military duty in Russia were unfit to serve for health reasons.

Will we see a decline in public health in the broader Arctic from environmental contamination? Unfortunately, we don't yet know. We are still just scratching the surface. *We must undertake the sustained scientific program* that will answer our questions and address our fears about Arctic contamination.

As we move ahead, there are several guiding responsibilities to keep in mind:

First, we have an obligation to be open and honest with the public at all times. This includes establishing a standard of honesty about the sources of Arctic contamination that may exist in our own backyard.

If this requires opening up old U.S. Department of Defense or other government files to public and scientific scrutiny, then we must do it. We are asking the Russians to open many of their files to the world, and we must be willing to do the same.

Second, environmental contamination, particularly the nuclear variety, provokes great emotion. We must base our decisions on sound science rather than emotion.

Finally, we have an obligation to take advantage of unique opportunities that have come with the end of the Cold War—particularly those that will allow us to work alongside our new Russian friends and Arctic neighbors.

I'd like to talk about each of these responsibilities and obligations in some detail.

The Need for Openness

This workshop is a continuation of the process we began with the Intelligence hearing in Fairbanks last year. It is a process of honest inquiry, conducted in public.

Traveling in rural Alaska, and listening to those who subsist from the living resources of the land and sea, I've found great concern and fear that subsistence resources are or will become contaminated from radioactivity or other pollutants.

These fears are not solely focused on what may lie across the Bering Strait in Russia—fears also exist where there are DEW-line sites, old "White Alice" sites, and other formerly used U.S. defense sites here in Alaska.

According to the Department of Defense, there are 648 *Alaskan* sites in the Defense Environmental Restoration Program. *More than 150* are judged to require some level of cleanup. This cleanup will take *50 years* at the current rate.

More recently the Department of Defense issued an interim report listing sites at Fort Greely, Fort Wainwright, Adak, Dutch Harbor and Attu where chemical weapons were or may have been tested, stored or discarded.

Alaskans rightfully demand to know what effects, if any, these past activities have had or may yet have on the environment and resources on which we depend. Where cleanup is required, it should be undertaken without undue delay.

I have asked the Department of Defense for a comprehensive evaluation of its past activities with past or potential environmental impacts on Alaska, adjacent seas, and the Arctic as a whole. I will continue these efforts to bring information from the Department of Defense into the public arena—for a full evaluation by the scientific community and the public.

Project Chariot

Let me turn to Project Chariot, because it has been widely cited as an example of Arctic contamination in our own backyard.

By now most are aware of Project Chariot, a project dating from the 1950s that envisioned the use of nuclear detonations to build a harbor at Cape Thompson, Alaska. This was part of the old Plowshare or "Atoms for Peace" program.

Although the nuclear detonations were never carried out, 26 millicuries of radioactive tracers left over from ecological experiments were disposed of at the site.

When news of these disposed radioactive tracers broke, the headlines told of a nuclear waste "dump." The worst fears of the local people living near Cape Thompson were awakened.

I went to Point Hope, a nearby village, and listened to people express their fears. They are absolutely certain that there is a link between the contaminated soil and the cancer experienced by some residents—even though all available medical and scientific evidence suggests otherwise.

A cleanup effort to remove the contaminated soil is now underway, in the hope that cleanup will occur this summer. Admittedly the cleanup is not occurring because of the risk posed by the contamination—it is occurring because the local people demand it.

In this case their demand can be justified because they were not told about the tracer experiments at the time of the tests. It is easy to understand why they are skeptical of government assurances that they face no threat.

So this case is one involving public trust—not environmental risk. Last year the Secretary of Energy promised that the contamination would be removed if that's what the local people wanted. So I will see that this promise is kept—it's what we must do to try and regain public trust.

The Project Chariot episode, while apparently not a serious human or environmental threat, is a case study that we can learn from:

- It demonstrates the need to be completely truthful with the public.
- It provides a preview of the public reaction we may face as new sources of Arctic contamination are uncovered.

Other Cold War Leftovers

Let me give you another example of past Cold War activities we recently came across that may evoke a great deal of public concern.

Last week my staff, digging through old Project Chariot documents, came across a report stating that more than 7000 pounds of nitromethane—a liquid chem-

ical explosive—were dumped on the tundra when the Project Chariot site was closed down.

I'm no scientist—I don't know the environmental consequences of this dumping. Perhaps it all evaporated and poses no risk. But we are determined to find out and provide the truth to the people who live nearby.

There was another perplexing rumor we encountered in following up on Project Chariot: The allegation that Alaska Natives were used in "nuclear experiments" during the 1950s. These stories were repeated to me and my staff on several occasions.

Many of us recall the general climate of the Cold War in the late 1940s and 1950s. As Project Chariot illustrates, it was a time when we actually considered using nuclear detonations to build harbors. It was also a time when military scientists performed medical experiments on human subjects, the worst of which studied the effects of radiation and chemical weapons on humans.

Significant numbers of Americans participated—some thought it was their patriotic duty, and others were just following orders.

Given the nature of those times, it seemed entirely possible that similar experiments might have occurred in Alaska. So when confronted with these rumors of medical experiments on human subjects, we took them seriously.

Recently we obtained a document from 1957 that outlined how the Air Force's Arctic Aeromedical Lab at Ladd Air Force Base had a complete mobile isotopic lab used in remote areas of Alaska. In one study the Air Force apparently gave doses of iodine-131 to Eskimos and Athabascan Indians, as part of its research to see if soldiers and airmen could be better conditioned to adapt and fight in cold conditions.

Of course, this revelation raises all kinds of questions:

- How were the participants recruited?
- Did the research pose a risk to the participants?
- Were the human participants in this research told of the risks, if any existed?
- Was there any followup done to determine if there were long-term effects?
- Was the mobile isotopic lab used for other studies?

It may turn out that this is a case where there were no human risks—but the burden of proof is with those responsible for the experiments.

In keeping with the responsibilities of openness I outlined earlier, we need to find the truth. As a first step I have asked independent experts at the National Academy of Sciences to provide an evaluation.

What Do We Do Now?

So what do we do now about the broader problems of Arctic contamination?

This workshop is a start. Your job is to assess the ex-

tent and magnitude of Arctic contamination and the risks it poses.

Granted, there are limits to how well you can do this from an auditorium in Anchorage rather than a research ship or station in the field. But this step will be worth it—*if we follow up with the required field research to answer questions we can't answer today.*

We need a sustained, comprehensive long-term environmental monitoring program that samples key marine organisms, including species used for human subsistence. The results of this research should be made available to the public in a form they can understand. This will help inform them and allay unwarranted fears.

We do not yet have an Arctic Monitoring and Assessment Program in place, and the President's FY 1994 budget has insufficient resources to do the job. That is unfortunate. I hope the agencies aren't engaged in the old Washington game of low-balling the budget request with the expectation that a sympathetic Congress will add money during the appropriations cycle.

While we were able to find \$10 million last year to enhance scientific understanding of the nuclear contamination issue—that was something of a lucky break in this budget environment.

I am encouraged, however, by what I hear coming out of an interagency review of U.S. Arctic Policy, and hope that the commitment to a sustained Arctic Moni-

toring and Assessment Program (AMAP) carries the day.

After the Clinton Administration has unveiled its new Arctic policy, I will press for hearings in the Senate Foreign Relations Committee. International Arctic environmental contamination will be a key subject of that hearing—perhaps we can build on what you're able to accomplish this week.

To summarize... nuclear waste dumps, contaminated defense sites, improperly disposed chemical weapons and other contaminants are dark legacies of the Cold War. Like any war, the Cold War exacted a price.

In saying that, I don't diminish the Cold War's tremendously positive outcomes—the greater democracy and freedom made possible around the world by the sacrifices made during that conflict.

But if the *old* Cold Warriors were generals and diplomats brandishing swords, then perhaps the new *Post Cold Warriors* are scientists equipped with the tools of Arctic research.

We committed talent, treasure and technical innovation to fight the Cold War. We must now employ the same to assess the damage and undertake the cleanup where it's warranted.

I appreciate your willingness to rise to this challenge. We are counting on you, and I will look forward to hearing the conclusions you reach this week and beyond.

Characterization of the Arctic Environment

Introductory Comments

Donald D. O'Dowd, Chairperson
Arctic Research Commission
Washington, D.C.

I am pleased to add my welcome on behalf of the Arctic Research Commission (ARC) to this important conference. The Commission issued a Resolution in August 1992 which urged the Interagency Arctic Research Policy Committee (IARPC) of our government to undertake a scientific assessment of circumarctic contamination by toxic materials. We are pleased that IARPC has brought us together to begin the assessment process.

For the most part these industrial materials, some of them radioactive, are produced outside the Arctic, but transported into the arctic environment with uncertain fate and effects. Their sources and chemical composition are key to analysis of the longevity and transport processes as well as ultimate effect on human health. Understanding the processes and rates of chemical transformations and transport by air, on land or in the sea very much depend on our understandings of the arctic environment. It is time to determine what we collectively know and to define what we need to know.

The Arctic presents very special problems that distinguish it from all other regions. They are related to the unique aspects of the environment such as permafrost, sea ice, a large-amplitude photocycle, short and intensive growing seasons, the small number of species in arctic ecosystems, and a slow recovery from environmental insult. There is a serious lack of data and information concerning long-term changes, and a relatively small number of qualified and experienced arctic investigators.

To provide a characterization of our knowledge of the environment in the Arctic, seven experts will provide their considered views of the state of arctic science during this first morning of the Workshop. I hope that you will note those areas of uncertainty in our knowledge because in addition to the new global concern to safeguard the arctic environment, we also have an opportunity to better learn about a critical area of the global earth system that sustains us.

Introductory Summary

Loren Setlow
Polar Research Board
National Research Council
Washington, DC

I think there are a number of take-home messages from both the morning and afternoon sessions. Your impressions and expectations may be different than mine, but I hope we will see some common themes as the Workshop progresses.

First of all, I think one of the important points to remember is that Arctic processes are not similar to the ones we find in the mid-latitudes. Second, the wildcards of ice, permafrost, and tundra vegetation introduce new factors into understanding what is going on in the Arctic. Third, the international aspects of the movement and migration of physical and biological agents are not dealt with on such a scale or diversity anywhere else in the world, except for perhaps the Antarctic. Fourth was the message that was delivered by Senator Murkowski this morning, that there is not a lot of money out there to study the impact of pollution on the ecosystem.

The point I feel should be made in the periphery of all the discussions at the Workshop, but may not have been demonstratively stated, is the logistical and the political aspects in superimposed restrictions on the timing and the availability of scientific data in understanding what is going on in the Arctic. Several speakers will describe their programs to address the measurement and collection of data on pollution in the Arctic. They will also talk about the international spirit of cooperation.

The important point is, first of all, that the data sets on contaminants and even basic scientific data are in a very elementary state, or even missing. There is a lot of information that is not in this country that we need access to. Second, there is a significant level of scien-

tific endeavor now taking place nationally and internationally in the Arctic. Third, the initial cruise results indicate that radioactive levels in the Kara and Barents seas are not currently spiking as high as for recorded periods of open-air nuclear testing. Fourth, that certain species tend to accumulate and move nuclides beyond the area of contamination and are an important source of movement of these contaminants. Lastly, the selection of contaminants to study, measure, and raise hell over, must be carefully made. Risk assessment should consider the potential for leakage, or major destructive events that affect the canisters or sunken reactor cores.

We must also remember that we are not just looking at radionuclides in this Workshop. Contamination by organic waste, untreated sewage, heavy metals, hazardous waste, pesticides, hydrocarbons, airborne contaminants, and radionuclides are all significant, and it is not limited just to Russia. We have to look at northern Europe, Alaska, as well as Russia.

I remind you to take a look at the purposes of this Workshop, to see where we stand in the progress of this program, to see what the IARPC can accomplish as we go through the process, and to see how we are moving in trying to answer the questions that the IARPC is asking in this Workshop. We have 14 mission-oriented agencies that are working here to try to pull all this together. We also have the scientific endeavor that tends to be focused by scientific discipline. I ask you here to try and go beyond these restrictions in defining what the problems are. Then work within the framework of the agencies, and their particular missions, to help them go about solving those problems.

Characterization of the Arctic Environment

The Arctic Atmosphere as a Stagnant Catchment for Pollution

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Summary

Cold, dense air settles down over the Arctic Basin during the polar night. It is surprisingly polluted. Of course this goes in direct counterdistinction with the romantic notion of a "pristine Arctic." Such a misconception arose a hundred years ago during the heroic days of polar exploration. The reality is quite different.

The so-called Arctic Haze pollution is the most massive aerosol air pollution on Earth, especially when measured by the size of the area it affects. This area is roughly that of the African continent!

Material released into the Arctic atmosphere has a long lifetime, much longer than at temperate latitudes. This allows the pollutants to travel for great distances. Of special concern is that North America, which lies downwind from the Former Soviet Union (FSU), is vulnerable to pollution accidents in Russia.

Introduction

The polluted Arctic air mass is not circular, neither is it centered on the North Pole; it is strongly asymmetrical, lobbing down over the Canadian Shield to the region of the Great Lakes and covering the upper half of Russia. Figure 1, taken from Barry (1967), shows the geographic extent of this polar air mass. The extensions over continents are associated with anomalies in the atmospheric heat balance, and reflect the small heat capacity of land in comparison to oceans.

The major reason that the polar air mass becomes polluted is that the rates of particle and gas *removal* in this stable atmospheric system are greatly retarded. Presumably, also, the larger-than-world-average per capita injection of pollutants into the air from the FSU and in East Europe contribute to the large magnitude of

the Arctic Haze pollution. Because of the slow rate of atmospheric cleansing, the Arctic constitutes a region of more sensitivity to pollution perturbation than any other latitude zone.

North America is especially hard hit with the FSU's atmospheric pollution because it lies downwind in the general circulation of the atmosphere (the westerlies). It was only because of fortunate anomalous synoptic-scale circulation patterns that prevented the Chernobyl explosion from having a major impact on North America. In the more usual case, a release of toxic substance, such as from a reactor accident in the FSU, would be expected to place some of the population of North America in jeopardy.

The Arctic Haze is ephemeral to the extent that it lasts only for some months, not years. It is not like carbon dioxide or other long-lived greenhouse gases that go on to build up slowly throughout the planet's atmosphere, so at least if an accident occurred, the effects would not last for years. Still, it needs to be recognized that North America lies downwind from major areas of northern Eurasia, and that the travel time is less than the residence time of pollutants.

In the following section of this paper, we will explain some of the major properties and features of the Arctic Haze phenomenon.

A Simple Pillbox Model of the Polar Air Pollution

A great deal of the physics and chemistry going on in the polluted Arctic air mass shown in Figure 1 can be comprehended by thinking about a very simple model for the polluted Arctic atmosphere. We consider the polar air mass to be a cylindrically shaped, flat, pillbox-

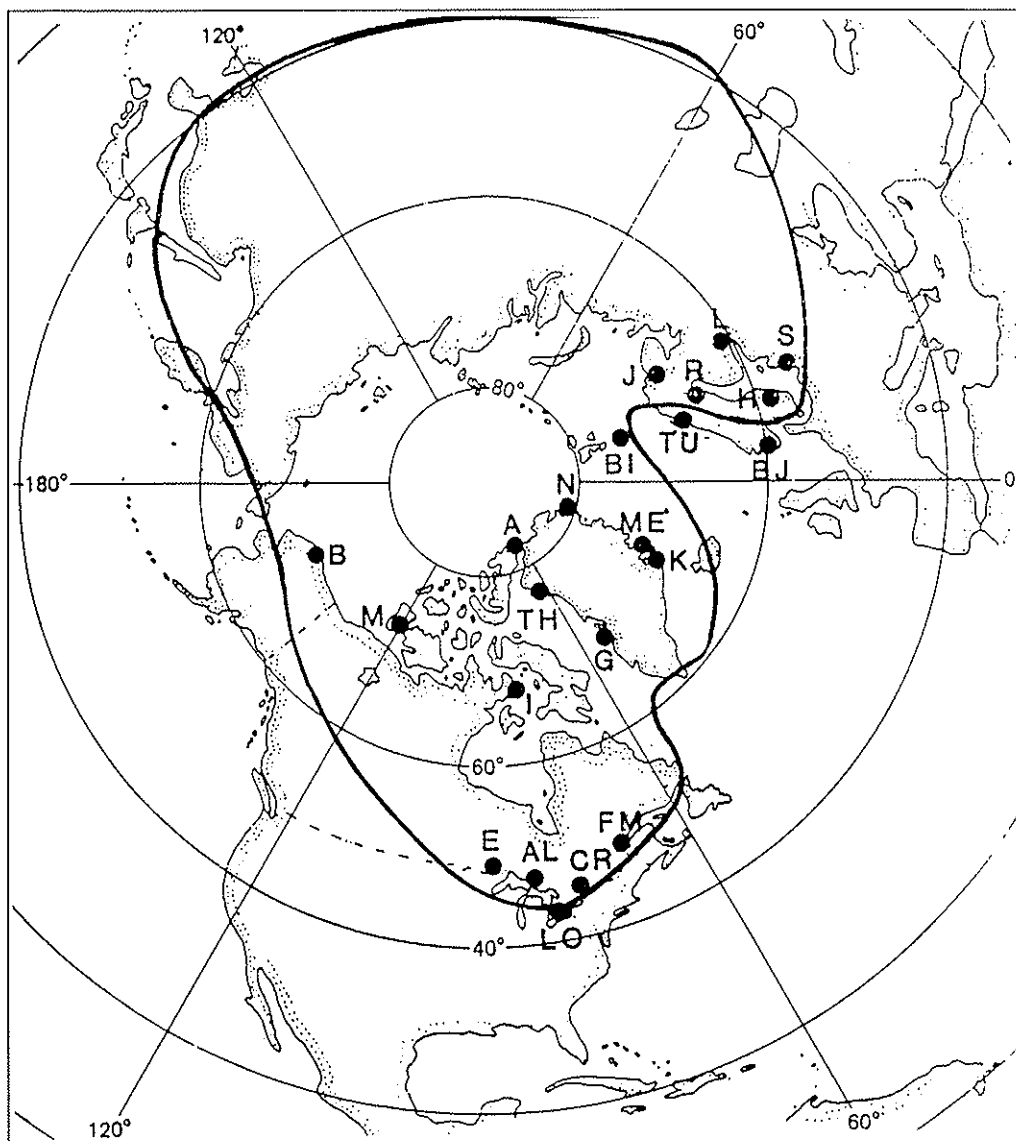


Figure 1. The Arctic Front boundary in winter. The region within the Front is strongly polluted in winter from industrial sources in Eurasia. (From Barry, R.G., Seasonal location of the Arctic Front over North America, *Geographical Bulletin*, 9, 79-95, 1967.)

shaped system. Obviously this is a great simplification, since the real airmass has two major lobes, but we think of the average position of an "equivalent" pillbox.

The pillbox changes in size throughout the year, growing quite small and perhaps even disappearing in the summer months and expanding to the limits shown in Figure 1 during the late winter months. Certain aspects of the pillbox and its pollution are diagrammed in Figure 2, which was constructed from average monthly values of the parameters.

At the top is shown the seasonal pulsation of the average radius of the Arctic airmass. The average radius is expressed in thousands of kilometers.

The next curve shows that the height of the pillbox

also alters during the year, possessing greater thickness in summer because of the mixing due to heating of the surface from the sun, and thinning during the winter polar night.

From the top two curves just described, we see that they go somewhat in opposite directions, acting to smooth out the seasonal variation in the pillbox-shaped airmass (see the third graph). An important deduction comes at this point: the seasonal variation as observed in many indicators of the Arctic Haze must not be due to simply the expansion and contraction of the airmass's volume over the course of a year: we have to evoke another cause for the seasonal variation!

Our model has provided somewhat disappointing

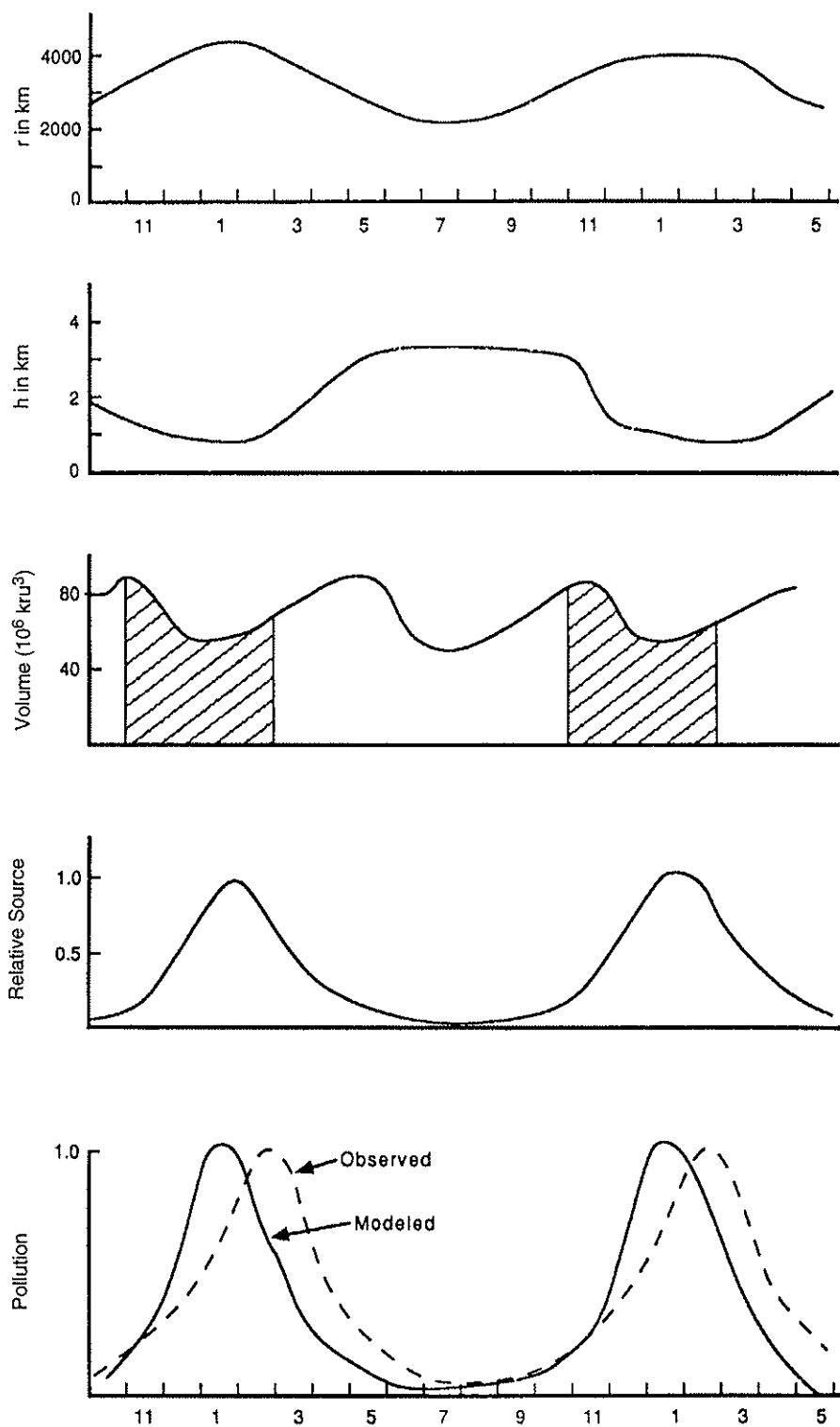


Figure 2. Pillbox model of the arctic air mass. The figure shows the seasonal variation of the mean pillbox radius, its height, its volume, the source strength of pollutants injected into it (normalized units) and the modeled arctic haze pollution. The dashed curve is measurement of sulfur dioxide from an arctic Canadian station at Alert (data from Len Barrie). Note that by incorporating a transport diffusion lag time to the air concentrations, better agreement is found with the measurements.

results because the Arctic Haze pollution undergoes a very strong and repeatable variation with the seasons, being absent in summer and strongest in late winter. A piston-like expansion and contraction of the Arctic Haze by the polar air mass, as discussed and displayed in the first three graphs in Figure 2 show that this is inconsistent with the observed seasonal variation.

The fourth graph in Figure 2 conveys a conceptually important idea: it is the estimated human pollution injected into the stable Arctic air mass that we are discussing. This graph displays a strong seasonal variation basically because our industrial emissions tend to go along with population density, and population density drops off rapidly toward the polar regions (few people live in northern Alaska, Canada and Siberia). This graph was constructed by looking up estimated industrial emissions as a function of latitude (zonally averaged) and weighting the monthly-averaged shape of the polar air mass with these emissions.

The bottom graph in Figure 2 shows the pollution estimated with this simple pillbox model. Our approach is sometimes called a "bathtub model"; it assumes that concentration of pollutants is balanced by removal, or cleansing, machinery of the atmosphere, rain washout for instance.

In our extremely simple model, what is to be noted is that the simple assumption of "pollution equals sources of pollution" is to a surprising degree achieved across an area equal in size to the African continent.

Note that this model gives even better results if we delay the "effect" from the "cause" (dotted line in the bottom graph), implying that the time the material spends in the atmosphere is about a month.

One concludes from these sorts of arguments that the Arctic atmosphere is to an important extent much like a stagnant pond, with mixing throughout the pond being rapid in comparison to residence time between input and output. The situation is illustrated in Figure 3, where the Arctic condition corresponds to the left hand cartoon in the figure: the "output tap is nearly closed off." The implication is that pollution injected into the atmosphere as a "cause" provokes a greater level of atmospheric concentration as an "effect": the Arctic atmosphere is vulnerable to pollution!

Accidental Releases of Radioactive Material from FSU

When the 1000-megawatt nuclear power plant at Chernobyl village, 80 miles north of Kiev in the Ukraine, lost coolant to the reactor's core in April 1986, the fission continued within the nuclear fuel rods; without water to cool them off, heat built up rapidly. As the temperature rose, the remaining water turned to steam and gases exploded, shattering the building, igniting the graphite and blowing out the core. The radioactive material injected into the atmosphere split into two paths, one passing over and affecting Scandinavia, the other traveling across southern Siberia and the north Pacific.

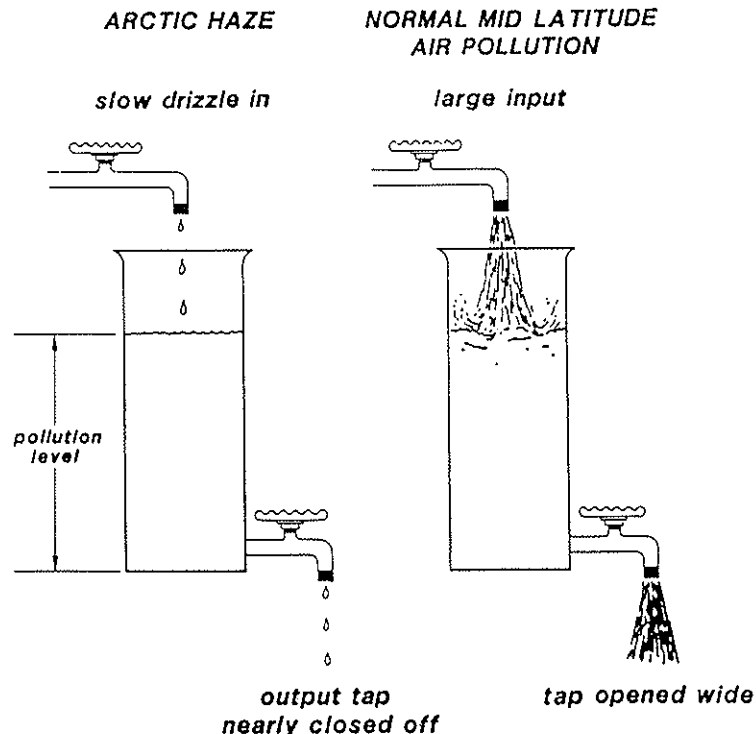


Figure 3. Arctic contamination situation.

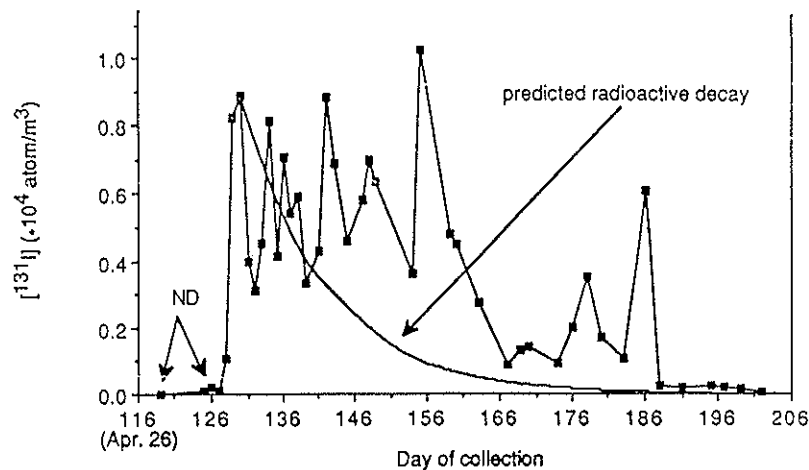


Figure 4. Radioactive fallout measured at the Geophysical Institute at the University of Alaska Fairbanks following the Chernobyl nuclear accident.

Strong storm systems near the Aleutian Islands helped scrub the radioactivity out of the atmosphere, resulting in only modest amounts of debris falling out on western North America, including Alaska. Figure 4 shows the rise, then decline of radioactive material measured by the Geophysical Institute at the University of Alaska after the Chernobyl explosion.

The explosion of the Chernobyl reactor in 1986, the recent accidental release of plutonium at Tomsk, and detection of large quantities of Cs in the Arctic during the bomb test years, all suggest that radioactive contamination events of the Arctic atmosphere are likely to continue.

Fortunately the weather patterns were anomalous in April 1986, when Chernobyl happened, so only small quantities of fallout occurred in the Arctic Basin. It is quite common to have injection pathways of pollutants traveling from the central and western regions of the USSR into the Arctic during this time of year when Arctic Haze is at its maximum. The recent release of plutonium from the Tomsk reprocessing facility also occurred at a time when the stagnant conditions in the Arctic had broken down.

Given the frequency of occurrence of major accidents, apparently on the order of one or two per decade, and that the Arctic air mass is stagnated about half the year, one would "forecast" (very roughly) that accidental releases of radioactivity may affect the Arctic once per one or two decades.

Concluding Remarks

The peoples of the Arctic regions are under possible threat from future accidental releases of radionuclides

and, possibly, from continued releases of heavy metal and organic compounds from the former Soviet Union.

Above all, it needs to be recognized that the Arctic atmospheric environment is a very different environment than most people are familiar with. Residence times of materials, in marine and terrestrial ecosystems and in the atmosphere itself, are generally much longer due to the lack of moisture passing through the system and because of the dynamical stability associated with strong temperature inversion during the polar night. Paradigms borrowed from experiences of radioactive waste treatment at mid-latitude locales are inappropriate for the Arctic. Atmospheric dispersion models developed to accommodate air pollution abatement in the mid-latitudes are largely irrelevant for the stable conditions found in polar air masses.

There is a need to develop a strategic air dispersion model, meeting the need to accommodate data entering in nearly real time to develop emergency response to episodic releases of radioactive material into the polar air mass system. We need to develop an extensive early warning system to protect human health in the event of an emergency.

There is also the need to extend the measuring network to toxic materials, such as pesticides and heavy metal pollutants. Such compounds already are affecting the Arctic. The major injection pathways involve northward-flowing currents of air flowing over central Eurasia into the polar air mass system.

Above all, the stagnant pond analogy for the Arctic atmosphere must be borne in mind. The Arctic pollution is the largest documented pollution on the planet.

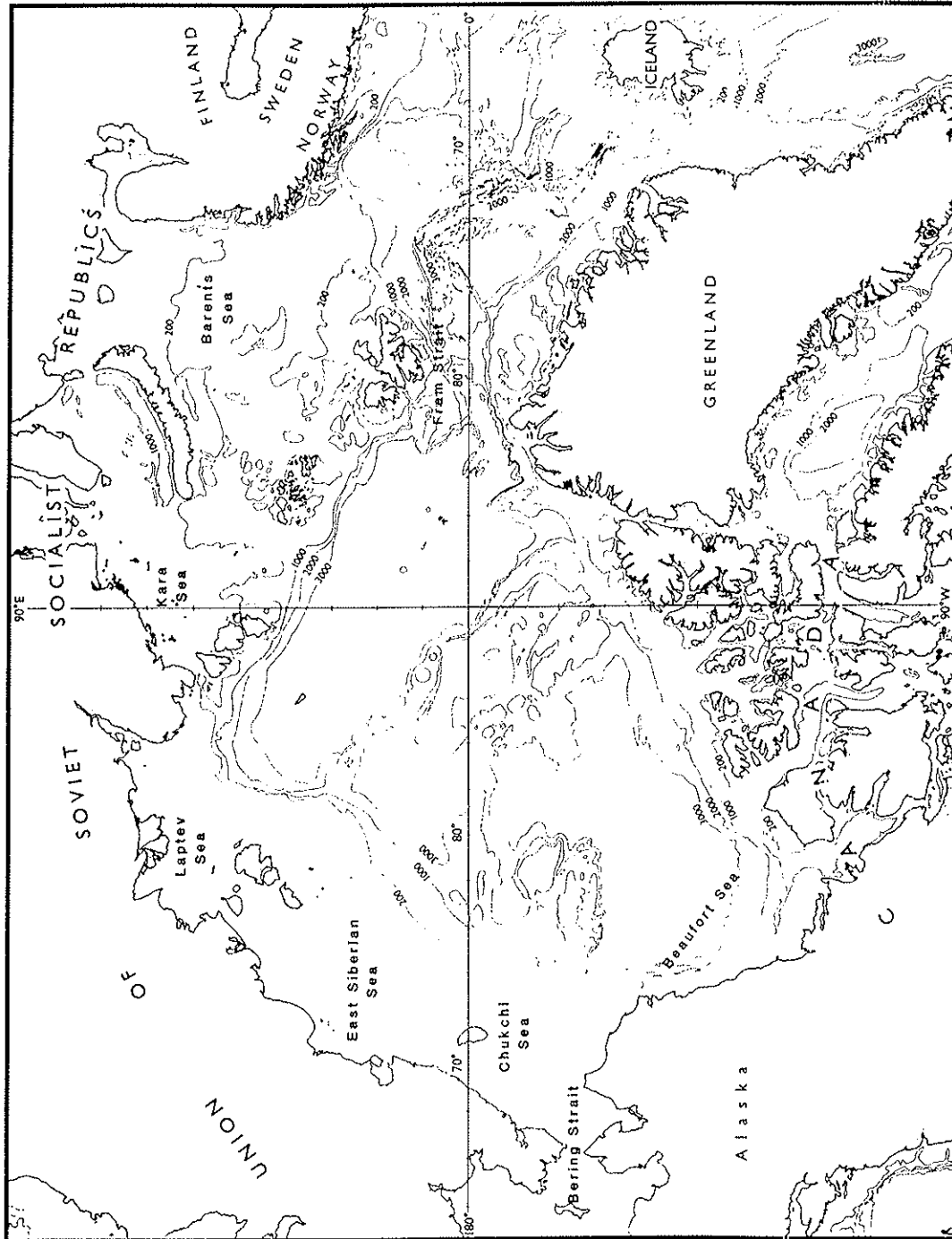


Figure 1. The Arctic Ocean and portions of the adjoining seas. Depths are in meters. (Adapted from Aagaard, 1989.)

Contamination of the Arctic Ocean Processes

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My underlying concern in this discussion is to evaluate the efficacy of contaminant dispersal in the Arctic Ocean. In particular, I want to point toward the means by which contaminants, whether solutes or particles, are likely to be transported, and also to consider some barriers to such transport. The Arctic Ocean is in certain respects a rather peculiar place, and lessons we have learned in other parts of the World Ocean are not necessarily transferable to the Arctic in a straightforward way.

To begin with, the Arctic Ocean (Figure 1) is a nearly land-locked deep ocean basin, subdivided by a series of undersea ridges, and with only one deep connection with the rest of the World Ocean, viz., through Fram Strait between Greenland and Spitsbergen. The chief division of the deep basin is effected by the Lomonosov Ridge, which separates the Canadian and Eurasian basins. Surrounding these basins are the world's most extensive continental shelves, in some cases very shallow and flat (the Chukchi, East Siberian, and Laptev Seas particularly), but in other cases relatively deep and cut by large undersea valleys and troughs (e.g., the Kara and Barents seas). In area the arctic shelves represent about 25% of the world total, and, as we shall see, an appreciation of the interactions between the shelves and the deep basins must be at the core of any physical and biogeochemical understanding of the Arctic Ocean.

Furthermore, since the Arctic Ocean is nearly land-locked, we should expect it to receive a great variety of materials from the surrounding land areas, including both anthropogenic and naturally occurring contaminants. While such would be the case for most mediterranean areas, in the Arctic Ocean this expectation is enhanced because about 10% of the world's rivers discharge into it, despite it representing only

1.5% of the world's ocean volume. The total river discharge into the Arctic Ocean is in fact about $3300 \text{ km}^3 \text{ yr}^{-1}$ (Aagaard and Carmack, 1989), i.e., six times that of the Mississippi; the runoff into the Kara and Laptev seas is particularly great (Figure 2). Combined with the freshwater separation caused by the freezing and melting cycle and the inflow through Bering Strait of low-salinity water from the Pacific, the effect of the runoff has been to create a great reservoir of low-salinity water at the surface of the Arctic Ocean (Figure 3), with profound consequences for arctic climatology. In particular, it is this stratification (the halocline) which allows the permanent ice cover of the central Arctic to persist (Aagaard and Coachman, 1975).

An extraordinary feature of the Arctic Ocean and its surrounding shelf seas is that despite the freshwater discharge onto the shelves, it is the deep basins which are permanently stratified by a cap of low-salinity water. (Curiously also, the Eurasian Basin is much less stratified than is the Canadian Basin, despite the proximity of the former to the massive runoff from the Eurasian land mass.) In contrast, the shelf waters, although stratified in summer, are relatively well mixed during the winter, and are in fact in many places homogeneous then. In effect, the central basins of the Arctic Ocean below about 50 m, which is near the maximum thickness of the surface mixed layer, are permanently insulated from local surface processes (except for the sinking of particulate matter), while around the periphery of the Arctic Ocean vast shelf areas are thoroughly mixed on a seasonal basis, primarily by the surface density flux associated with freezing. (Note also that runoff is generally very small in winter, so that the surface buoyancy flux due to the addition of fresh water over the shelves is small then and not available to offset the effect of

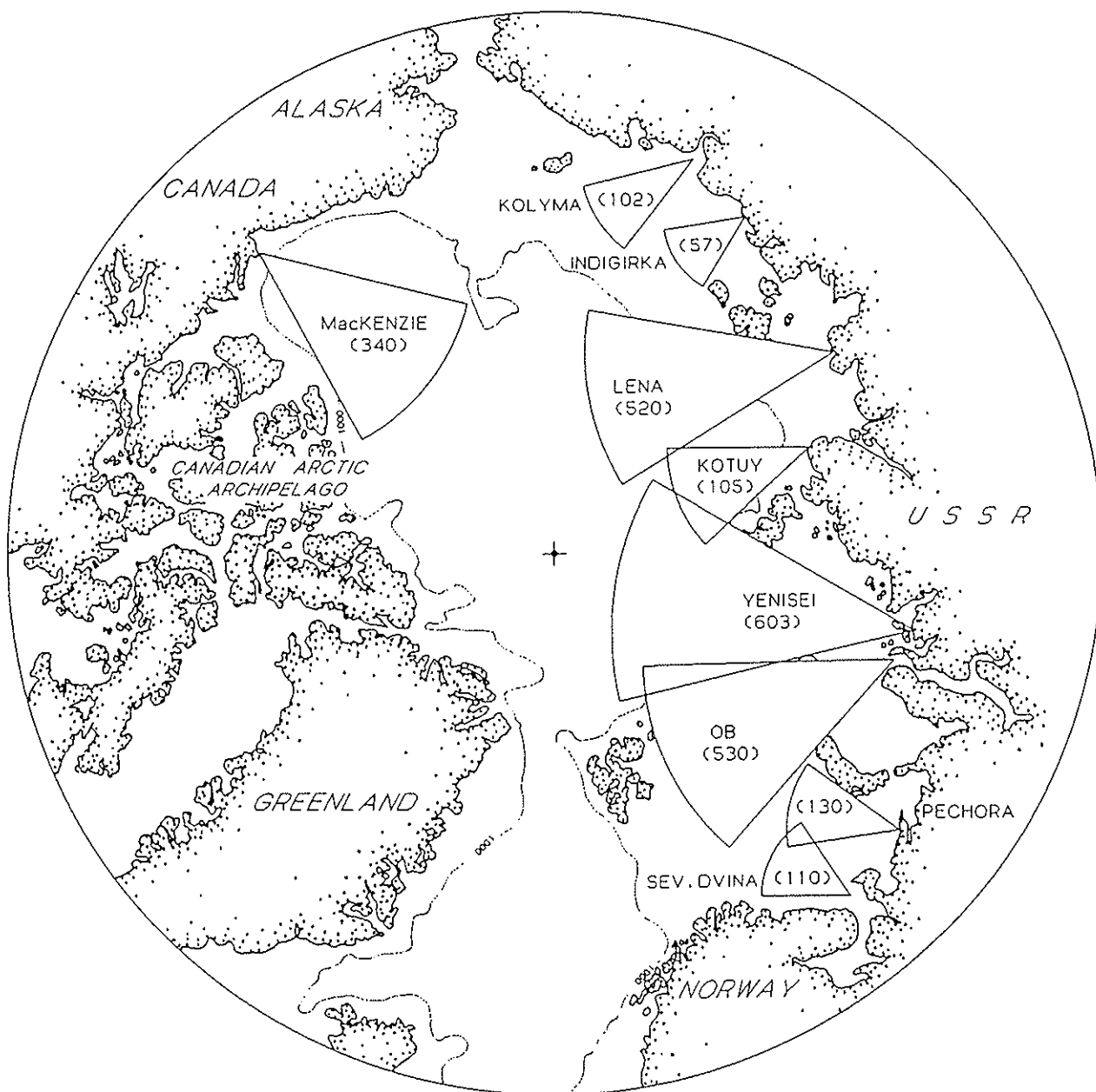


Figure 2. Mean annual runoff to the Arctic Ocean in km^3/yr . Only the nine largest rivers are shown. (From Aagaard and Carmack, 1989.)

freezing in increasing the surface density.) The importance of the ocean density structure to arctic contamination issues is that below the shallow surface mixed layer of the Arctic Ocean, local communication between the surface and the deep basins is effectively restricted to the sinking of particles. Instead, the Arctic Ocean is ventilated laterally from its shelves, which receive the runoff and sediments from the vast continental land areas to the south. In summer, these shelf seas also support significant biological production, and a portion of the resultant organic material and its decomposition

products (together with biologically incorporated contaminants) is then available for transfer off the shelf and into the interior ocean (Wallace et al., 1987). The residence time of waters on the shelf, and of their dissolved materials, varies considerable, depending on the geometry of the shelf and on its circulation: from as little as a few months, e.g., in parts of the Chukchi Sea with a strong throughflow from the Pacific, to 2-4 years in the Barents and Kara seas (Hanzlick and Aagaard, 1980; Schlosser et al., submitted).

While we do not have a detailed understanding of the

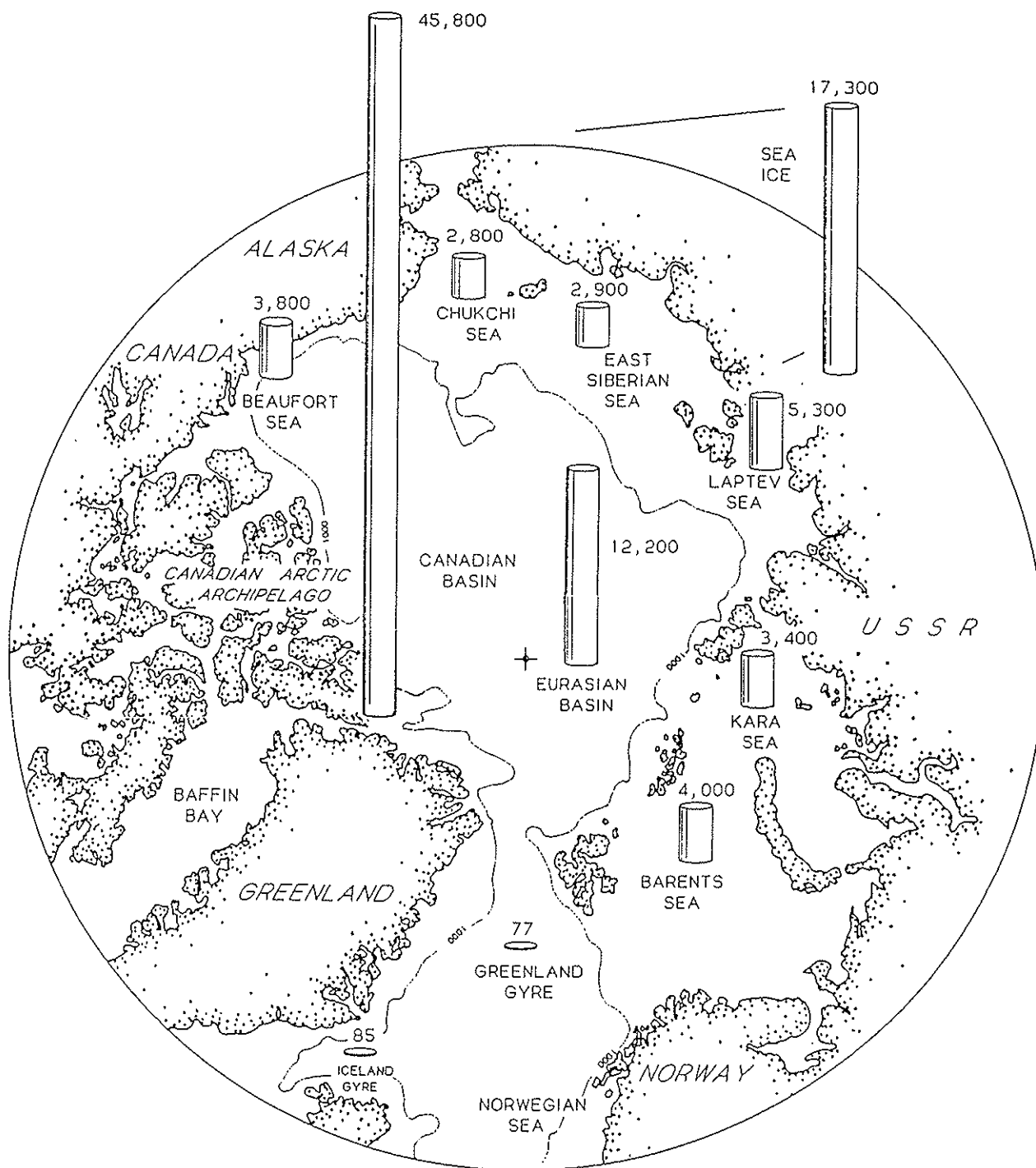


Figure 3. The distribution of freshwater storage in the Arctic Ocean and portions of the adjoining seas. Values are in km^3 . The placement of each bar indicates the region to which it is applicable. (From Aagaard and Carmack, 1989.)

mechanisms responsible for the transfer of shelf water properties into the interior ocean, the signatures of this transfer are unmistakable throughout the Arctic Ocean. For example, the temperature-salinity structure of the halocline (Aagaard et al., 1981), its dissolved oxygen distribution (Wallace et al., 1987), its nutrient concentration (Nikiforev et al., 1966), and its natural radionu-

clide content (Moore and Smith, 1986) all point toward large lateral influxes of shelf waters to the central basins of the Arctic Ocean. These influxes originate in the formation of dense waters on the shelves during winter, through cooling and through the brine rejection associated with freezing (Aagaard et al., 1981). The process is shown schematically in Figure 4, together with its effect

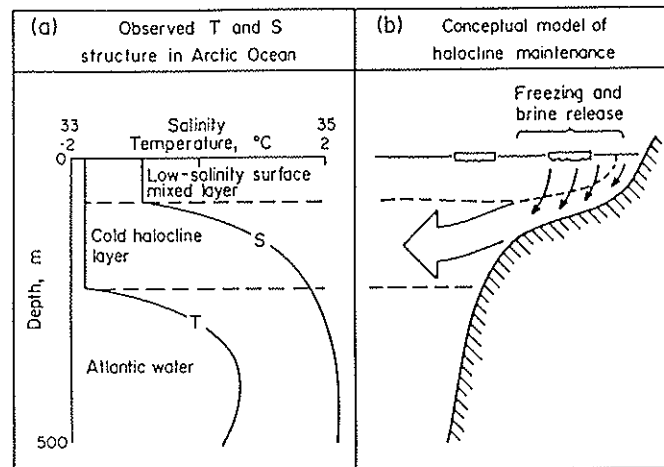


Figure 4. Schematic representation of the temperature and salinity structure in the upper Arctic Ocean and its maintenance. (From Aagaard et al., 1981.)

on the upper ocean temperature and salinity distribution.

Even with the very sparse set of available observations from the Arctic Ocean, we can discern several different major sources of these shelf waters for the interior ocean (refer to Figure 5 for locations). In particular, both the physical (Aagaard and Carmack, 1989) and chemical (Jones and Anderson, 1986) properties of the upper halocline suggest a principal origin in the Chukchi Sea, while the waters of the lower halocline probably originate in the Barents and Kara seas. The Canadian Basin source represents low-salinity Pacific waters which have entered the Arctic Ocean through Bering Strait and have been cooled and had their salinity increased somewhat on the shelf, while the Eurasian Basin source represents much more saline waters from the North Atlantic which have been cooled and mixed on the western Eurasian shelves. There also appear to be differences in the manner in which carbon is cycled in these source areas (Jones and Anderson, 1986). Note that waters from the Canadian and Eurasian shelf sources are not restricted to their respective adjacent basins, but are in fact also in each instance found in the other major basin. For example, the upper halocline water from the Chukchi Sea, with a salinity mode near 33.1 and marked by a pronounced nutrient maximum, can be seen to exit the Eurasian Basin through western Fram Strait (Jones et al., 1991). We can be quite certain, therefore, that the dissolved phase of contaminants introduced onto these various shelves will spread throughout the Arctic Ocean, with much of the shelf material being injected into the halocline. Tritium and helium distributions suggest that the spreading of the shelf waters within the upper Arctic Ocean is completed

within about ten years of their injection (Östlund, 1982, Schlosser et al., 1990).

The general mechanism which has been proposed to move waters off the shelves is the sinking of dense plumes along the continental slope (Melling and Lewis, 1982), which eventually detach from the bottom and may then move into the interior at a level appropriate to their density (Aagaard et al., 1985). Such sinking from the shelf is likely to be both localized and intermittent. For example, bathymetry probably is important in channeling the flow, and submarine canyons and sea valleys are particularly likely to provide such channeling. Indeed, the first brine-enriched dense outflows observed in the Arctic were found in Barrow Canyon, off the coast of northwestern Alaska. Figure 6 shows the concentration of the brines adjacent to the Alaska coast in early March 1982, and Figure 7 the daily mean temperature and salinity in Barrow Canyon during a 50-day period the same winter. The very high salinities in the canyon, almost 3.5 per mille above ambient values and with an associated temperature closely following the freezing point, represent cold brine drainage from the eastern Chukchi Sea. In this instance the outflow was very rapid, with a mean velocity the last week of February of 45 cm s^{-1} . These dense outflows from the shelf appear to be episodic, and it quite clear at this point that they do not occur every winter (Aagaard and Roach, 1990). For example, in the Canadian Beaufort Sea, recent work suggests that a preconditioning of the shelf by prolonged wind-driven flushing the previous fall is required for dense outflow to occur (Melling, in press). Such wind-driven flushing, then, represents an alternative means of transferring contaminants from the shelf into the offshore regime.

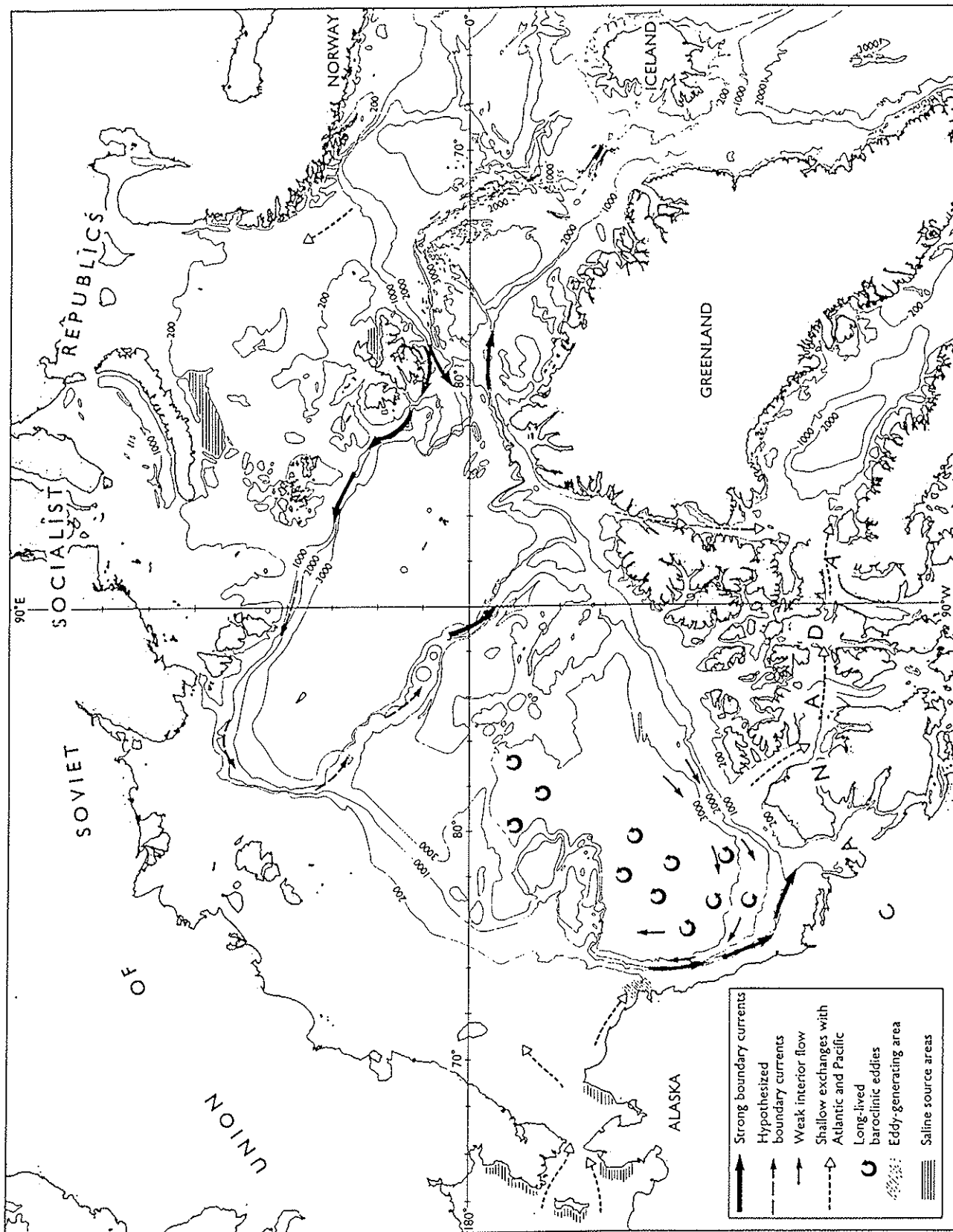


Figure 5. Schematic sub-surface circulation in the Arctic Ocean. Exchanges with the seas to the south generally extend to the sea surface. Known formation areas for saline shelf water and a probable eddy-generating area are also shown. (From Agaard, 1989.)

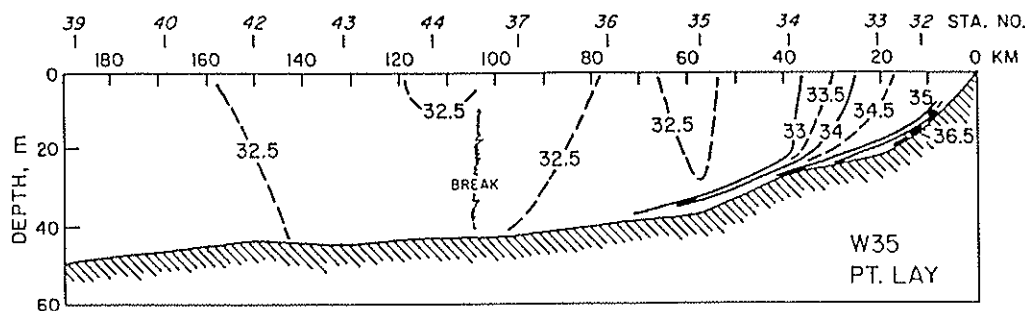


Figure 6. Salinity section across the northeastern Chukchi Sea during 3-4 March 1982. The water was everywhere at the freezing temperature. (From Aagaard et al., 1985.)

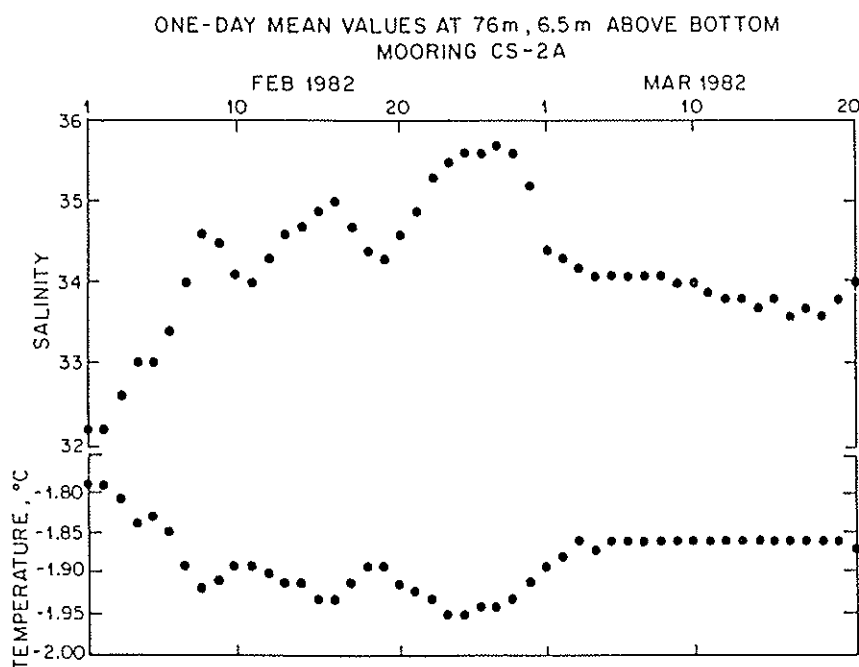


Figure 7. Daily mean salinity and temperature in Barrow Canyon during February–March 1982. (From Aagaard et al., 1985.)

Dissolved materials can also be transferred onto the shelf from the adjacent basins, and certainly in years when the shelf drainage is strong, there must be a compensating movement of water onto the shelf. On-shelf movement has also been proposed to take the form of wind-driven upwelling across the shelf break (Hufford, 1974), but recent work in Barrow Canyon suggests that an onshore flux through upwelling is most likely to occur through submarine canyons and that much of it is not locally wind-driven, but rather represents the interaction of remotely forced motions with the local bathymetry (Aagaard and Roach, 1990). Figure 8 shows a portion of the velocity, temperature, and salinity record during the winter of 1986-1987, again at a site in Barrow Canyon, together with the computed salt and heat fluxes. The hatched fluxes represent the upwelling onto the shelf of warm and saline water from the Atlantic layer

at intermediate depths offshore. We should therefore consider the canyons and sea valleys which cut across the shelves of the Arctic Ocean to be particularly likely avenues of exchange for waterborne contaminants moving both onto and off the shelf.

A striking feature of the Arctic Ocean is its permanent ice cover, which thins each summer, but actually disappears only over portions of the continental shelves. The following fall and winter, new ice forms, and the ice cover returns to its winter state. When seawater freezes, much of its dissolved burden is separated out and ejected into the underlying water. This is the origin of the dense brines discussed above. (Note, however, that not all the dissolved material is ejected into the underlying water, either during the initial freezing or as the ice thickens through the winter, but that some remains trapped in brine pockets within the ice throughout the

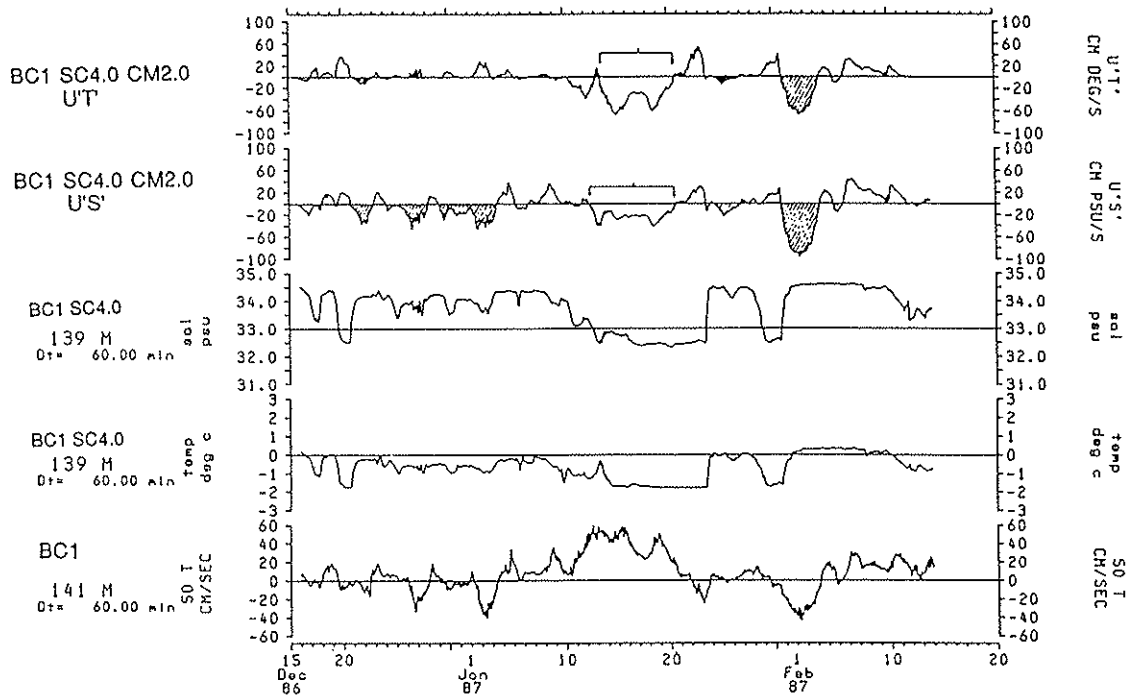


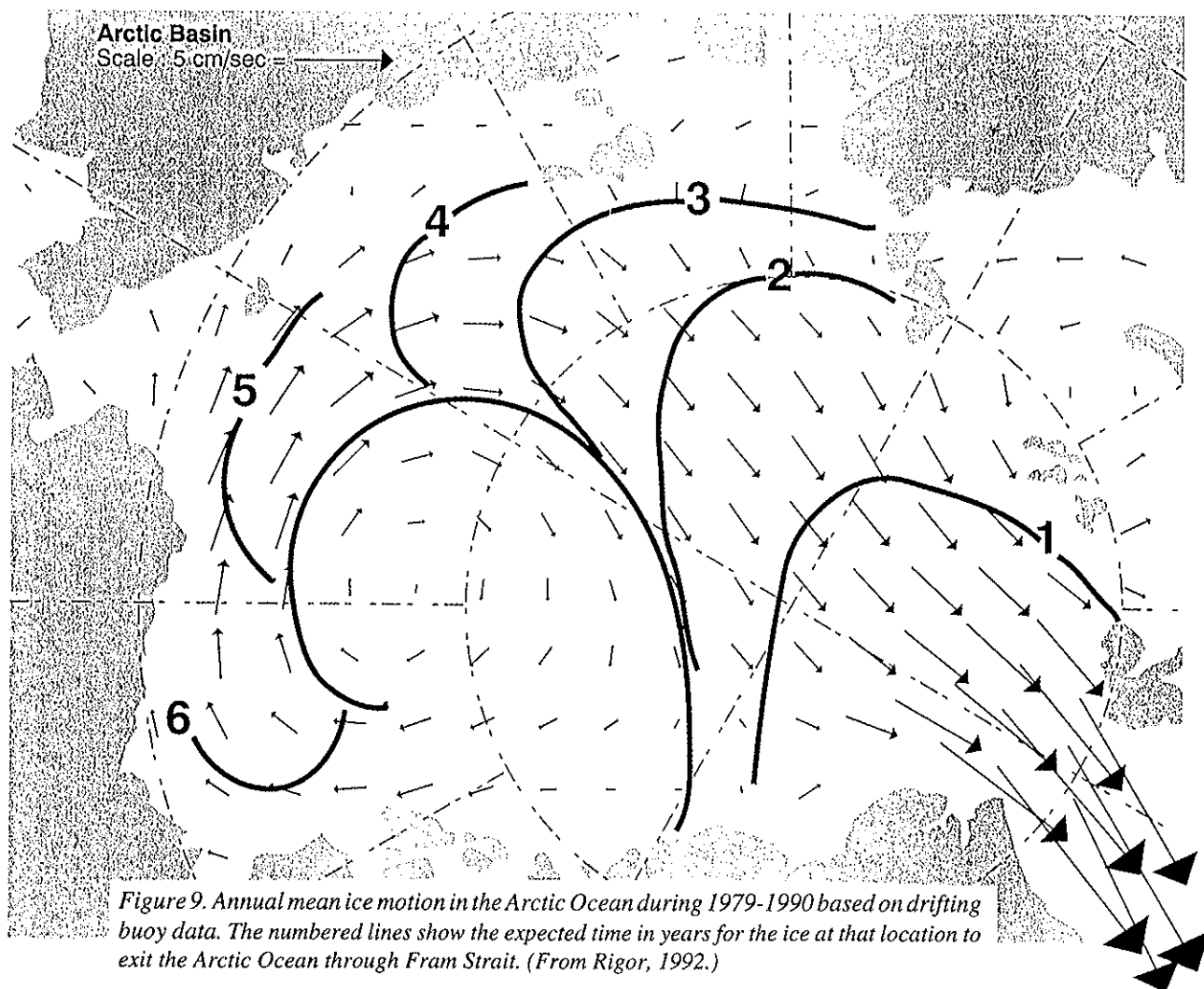
Figure 8. Heat flux, salt flux, salinity, temperature, and velocity in Barrow Canyon during the winter of 1986-87. The negative fluxes marked by hatching represent the upwelling of warm saline water from offshore Atlantic layer onto the shelf. (From Aagaard and Roach, 1990.)

first year and will be transported in that form with the ice, not to be added to the water column until the following summer, when brine channels drain and ice melts.) This distillation process associated with freezing will of course concentrate in the underlying water not only sea salts, but also the dissolved contaminant burden of the surface water which freezes. In shallow water on the shelf, this enrichment might be substantial, and the concentrated contaminants can then be temporarily impounded in depressions in the bottom and behind the extensive barriers of grounded ice common on the inner shelf (Macdonald and Carmack, 1991b). Freezing thus provides an effective means of transferring contaminants from the surface water, where it may have been brought by runoff, precipitation, summer ice melt, or airborne deposition, to the sea floor, where it can be incorporated into the often rich benthic biota and into the sediments. Sea ice can also incorporate contaminants in another form, viz., as suspended material. Through several different distinctive mechanisms associated with freezing, large amounts of shelf sediments can be locked into the ice, particularly during the early period of freezeup in the fall (Reimnitz et al., 1992). This material will then move with the ice, perhaps very long distances, and a portion of the ice-borne sediments can be deposited elsewhere during the melt season the following summer.

Ice movement throughout the Arctic Ocean has been

monitored in considerable detail since 1979 with the aid of satellite-tracked drifting buoys (Rigor, 1992), and before that by drifting stations (Colony and Thorndike, 1984). A great deal of information on the rates, patterns, and variability of the motion is therefore now available. Figure 9 shows the mean drift during 1979-1990; the solid lines denote the expected number of years for ice at that location to exit the Arctic Ocean. (Note, however, that on a variety of shorter time scales the ice drift will deviate significantly from this multi-year mean state. For example, the mean seasonal drifts over the same 12-year period are shown in Figure 10.) The principal features of the long-term mean ice drift are the large clockwise gyre covering the Canadian Basin, the so-called Beaufort Gyre, and the generally westward movement across the Eurasian Basin, the Transpolar Drift. It is clear, therefore, that we should expect efficient long-range transport of contaminants carried with the ice along preferred and well-established routes, e.g., from the Laptev Sea across to northern Greenland, with Figure 9 showing that the latter transfer will on the average require somewhat over three years.

The circulation of the shallow surface mixed layer of the ocean, normally less than 50 m thick, is likely very similar to that of the ice (Thorndike and Colony, 1982). However, below the mixed layer the ocean circulation is in many areas directed opposite to the ice motion and that of the uppermost layer of the ocean. Perhaps most



important among these counterflows for purposes of contaminant dispersion are the subsurface boundary currents, the first of which was discovered in the Beaufort Sea north of Alaska (Aagaard, 1984). These boundary flows are among the strongest currents in the otherwise generally low-velocity Arctic Ocean. They are a few tens of kilometers wide, and they are trapped over the steep topography which borders each of the major basins, including the flanks of the Lomonosov Ridge (Aagaard, 1981). The current speed has a maximum at some intermediate depth, and the flow does not in general have a surface manifestation, as shown in Figure 11, which is a composite representation of current measurements over the Eurasian continental margin between Spitsbergen and Franz Josef Land. Note that the undercurrent is directed counterclockwise in each basin (cf., Figure 5) and is therefore opposite in direction to the motion of the ice and the surface mixed layer along almost all of the continental margin surrounding

the Arctic Ocean (Aagaard, 1989). Recent tracer measurements in the Eurasian Basin suggest that a similarly enhanced flow may also be trapped over the Nansen-Gakkel Ridge, which runs parallel with the Lomonosov Ridge and divides the Eurasian Basin in two (Anderson et al., 1989; Jones et al., 1991). The importance of these boundary currents to contaminant dispersion is that they appear to be the most energetic component of the large-scale circulation and that they border all the shelf seas. We can therefore expect that a significant portion of the dissolved materials moved off the shelf, for instance with the dense brine-enriched waters generated during winter, will be entrained in this strong and narrow flow and transported around the basin peripheries. For example, the very few current measurements to date suggest that the distance around the periphery of the Eurasian Basin from Fram Strait to the Pole could easily be accomplished in less than three years (Aagaard, 1989), and this estimate is consistent

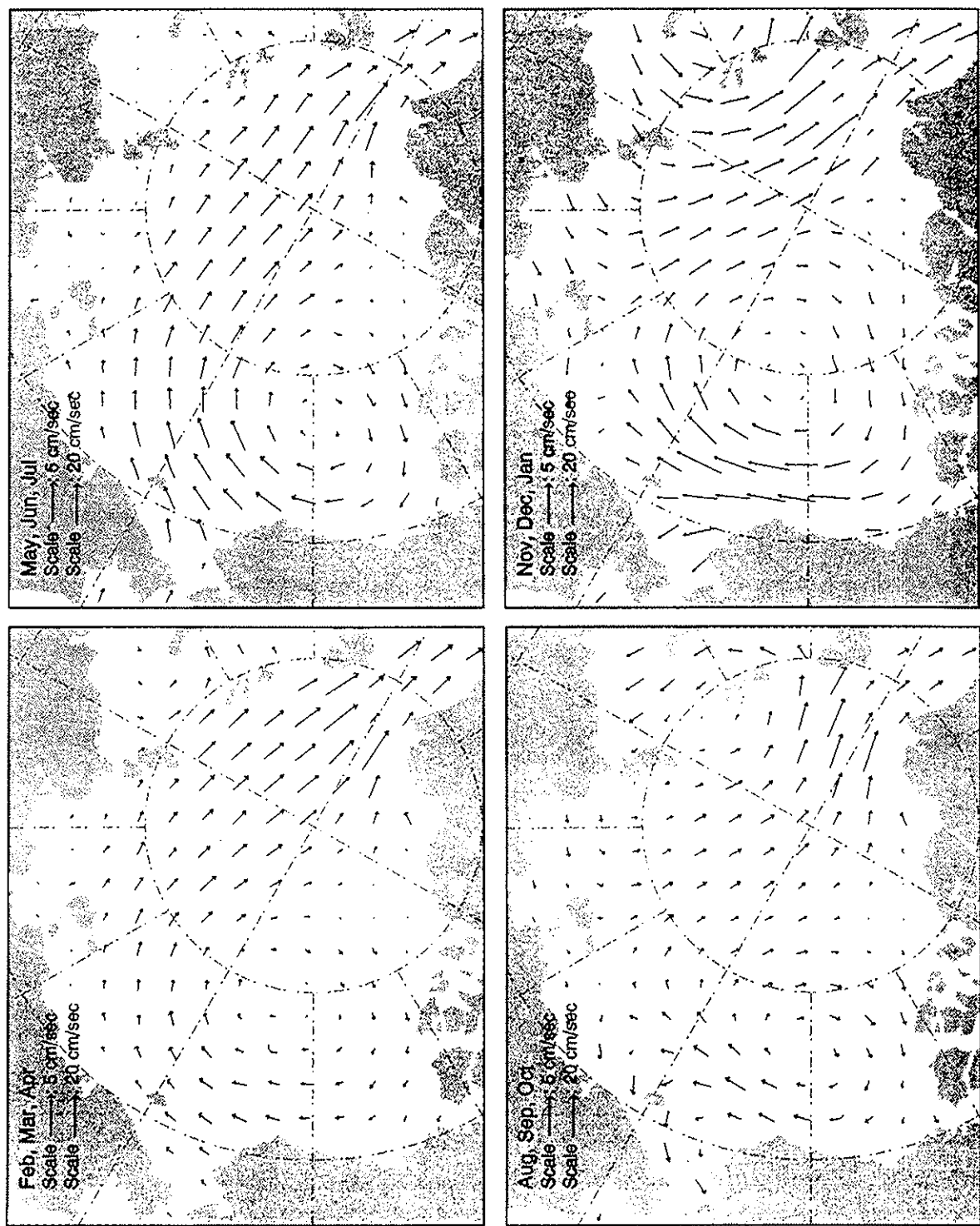


Figure 10. Seasonal mean ice motion in the Arctic Ocean during 1979–1990 based on drifting buoy data. (From Rigor, 1992.)

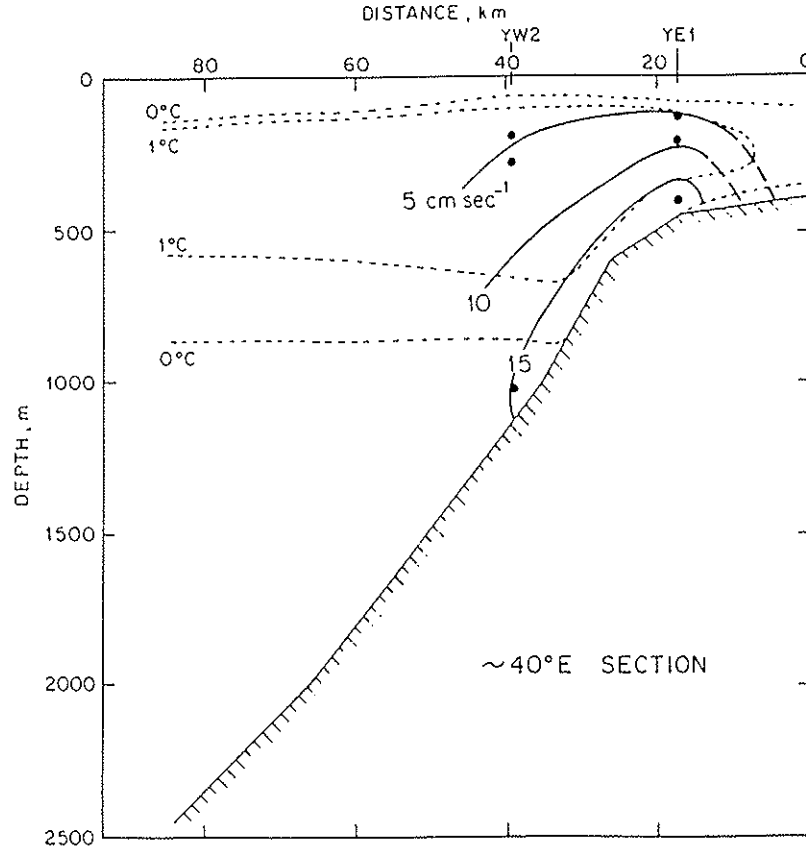


Figure 11. Composite mean velocity section across the southern Eurasian Basin slope near 40°E from July-September 1980. The current is directed into the figure. (From Aagaard, 1989.)

with the independent conclusion from the radionuclide measurements of Livingston et al. (1984).

Although tracer data from the Canadian Basin are almost nonexistent, there have now been a sufficient number of stations worked in the Eurasian Basin to give some idea of ventilation rates in the interior of the ocean away from the boundary current (Schlosser et al., 1990; Schlosser et al., submitted). These suggest that the upper ocean above the Atlantic layer has, as we have already noted, a residence time of about a decade (7-14 years), with the apparent age increasing downward. From the lower part of the halocline to about 1000 m depth, the age of the waters in the central Eurasian Basin increases to approximately twice this. The renewal rates in the deep water are very much slower, corresponding to a residence time in the neighborhood of 200 years or more. The deep waters of the Canadian Basin are the oldest of all, probably about 500 years (Östlund et al., 1987; Macdonald and Carmack, 1991a; Macdonald et al., 1993). Materials deposited into the deep Canadian Basin in particular, will therefore remain there for a very long time, unless the present ocean climatology changes and the ventilation rate is increased.

Below the surface mixed layer, the mean flow field in the interior Arctic Ocean appears to be extremely weak (Melling et al., 1984; Aagaard, 1989), and the internal wave energy is far less than the canonical value for the World Ocean (Levine et al., 1987; Padman and Dillon, 1989). How is the interior Arctic Ocean then stirred and mixed? Part of the answer may lie with intense small, but long-lived, eddies which appear to be ubiquitous in at least the Canadian Basin (Manley and Hunkins, 1985). An example is shown in Figure 12, taken from Newton et al. (1974). Typical eddy diameters are in the range 10-20 km, and their tangential speeds can exceed 30 cm s^{-1} . The eddies are generally embedded in the pycnocline or within the Atlantic layer, and their thickness does not usually exceed 400-500 m (D'Asaro, 1988). Note that the eddies have little or no surface manifestation. Particularly pertinent to our present discussion, however, is 1) that the water properties within the eddies are generally anomalous, suggesting that the eddies have a distant origin, 2) that the eddies are most probably formed near the margins of the Arctic Ocean, and 3) that the eddies have extremely long lives, probably several years (D'Asaro, 1988).

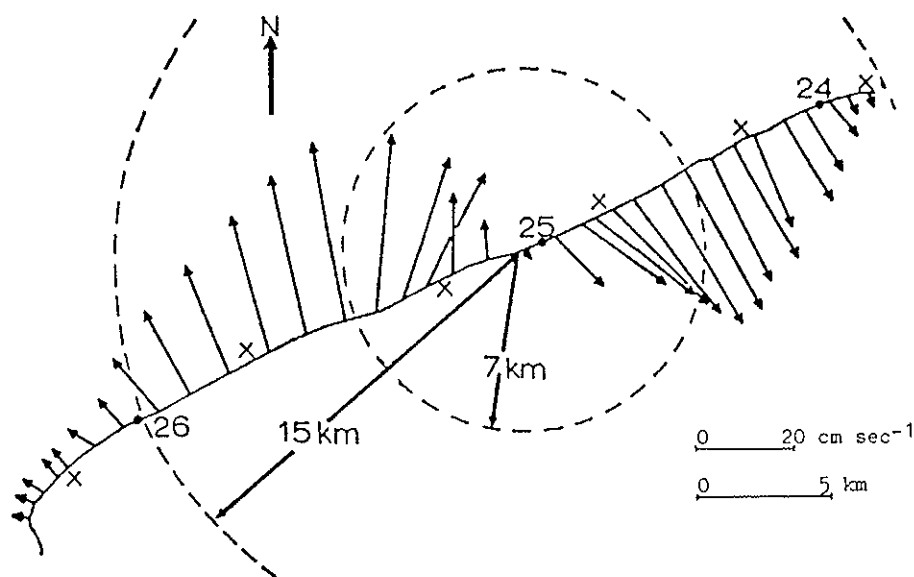


Figure 12. Two-hour mean currents at 150 m during 24-26 March 1972 near 76°N, 149°W in the Canadian Basin. The dashed circles show the radius of maximum velocity and the extent of the eddy's influence. (From Newton et al., 1974.)

These energetic rotating lenses of water may therefore be a primary transport mechanism in the interior Arctic Ocean, carrying dissolved materials with them as they drift over long distances before slowly dissipating within the Arctic Ocean and releasing their contents to the surrounding ocean.

In addition to processes native to the deep basins and their adjacent shelf seas, the Arctic Ocean is significantly influenced by exchanges with the Pacific and the Atlantic oceans (Figure 5). Low-salinity waters enter from the Pacific through Bering Strait, while a range of more saline waters enter from the Atlantic through Fram Strait and also through the Barents Sea. All these inputs place their distinctive marks on the Arctic Ocean, e.g., on its temperature, salinity, and nutrient structure, and it is likely that a great variety of anthropogenic contaminants carried with these inflows also imprint the Arctic Ocean, although we know very little about the contaminant burden of the inflows. However, a documented example of contaminant import is that of low-level radionuclides from the nuclear fuel reprocessing plants in western Europe which entered the Polar Basin near Spitsbergen in about 1976 and were observed at mid-depth near the Pole three years later, marked by a high $^{137}\text{Cs}/^{90}\text{Sr}$ ratio (Livingston et al., 1984). Livingston (1988) has argued that this signal was initially transmitted into the Arctic Ocean by dense drainage from the Barents Sea, such as we have discussed earlier. The water would subsequently have been carried counterclockwise around the Eurasian Basin to the Pole, very likely by the subsurface boundary current trapped over the basin margin.

Export of water from the Arctic Ocean is most importantly directed through Fram Strait, thence southward along the east coast of Greenland into the North Atlantic. This outflow also on the average carries in excess of 100,000 tons of sea ice per second out of the Polar Basin. Additional significant export of water occurs through the passages of the Canadian Arctic Archipelago; this water is drawn from the Canadian Basin.

Despite the relatively quiet, low-energy ocean beneath the permanent ice cover of the central Polar Basin, we thus see ample evidence of efficient transport mechanisms within the Arctic Ocean. Contaminants entering the Arctic, whether with the rivers great and small which drain the surrounding continental land masses, or from atmospheric deposition, or from import through the various oceanic straits and passages, can relatively rapidly be transported long distances, either with the sea ice or in the boundary currents. Both sea ice and dense drainage flows generated on the shelves during freezing can move materials off the shelves into the deep basins, and waters can apparently also upwell onto the shelves from deeper levels offshore. The large density stratification of the Arctic Ocean will therefore not prevent the downward movement of contaminants, whether through the seasonal development of drainage flows from the shelves, or from sinking of particulate matter carried by the ice and which has been incorporated into the ice over the shelves. A portion of the particulates transported with the ice should be expected annually during the melt season to sink from the surface throughout the Arctic Ocean. Based on physical processes alone, therefore,

contaminants in the Arctic Ocean should be expected to have considerable mobility both vertically and laterally. It is also likely that for the foreseeable future, the concentration of a variety of contaminants within the deep Arctic Ocean and its sediments will increase, since the replacement time scale for its deeper waters is rather long and will not offset the introduction of materials which almost certainly is occurring at present.

Finally, I note that the circulation of the Arctic Ocean has in the past been argued to resemble that of an estuary, with a surface outflow of low-salinity waters due to excess runoff and a subsurface inflow of denser waters from the south. While this physical analogy has limitations and is not altogether accurate, there may be some merit in extending the estuarine analogy to contaminants, for which estuarine processes can provide a means of concentrating materials inside the estuary. For example, nutrient trapping in estuaries is well known.

The Arctic Ocean is rapidly becoming a focus for issues of global climate change. The World Climate Research Programme has recently begun planning an international program on the Arctic (the Arctic Climate System Study: ACSYS), and component investigations are already being undertaken. It is likely that this study will provide an important framework for investigations during the next decade. In examining both climate and contaminant issues in the Arctic, I am struck by the overlapping interests of both problem areas in determining the controlling physical and biogeochemical processes and their time scales, and in acquiring a quantitative prognostic capability. I therefore suggest that an extremely important step is to ensure that global change and contaminant studies in the Arctic find suitable mechanisms for working together to the substantial benefit of both endeavors. Indeed, the joint Canadian/American TransArctic Section, which will cross the Polar Basin from the Chukchi Sea to Fram Strait in 1994, will carry a wide variety of global change programs spanning both climate and contaminant research. Perhaps it can serve as a model, or even be catalytic, in creating the desired synthesis of approaches and solutions to the related research needs and opportunities of understanding both contamination and global change in the Arctic.

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Possible Roles of Sea Ice in the Transport of Hazardous Material

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Introduction

The purpose of this paper is to provide the non-specialist with an assessment of the possible roles that sea ice can play in the transport of hazardous material within the Arctic Basin. Although some of the following material is speculative, there are a number of general statements that can be made about possible transportation mechanisms and their presumed effectiveness. It should be noted, however, that essentially none of the following material is based on actual observations of the transport of real hazardous material. Instead sediment, usually derived from the sea floor, is used as a proxy to discuss probable fates of far less desirable materials such as nuclear waste.

Indeed, one might well ask, "Why discuss sea ice at all in that everyone knows that sea ice contains less impurities than the water from which it forms?" This statement is, in fact, true for every soluble salt found in seawater and for every sea ice type (Weeks and Ackley, 1986). The reasons for this are related to the very restrictive chemical bonding and atomic radius requirements for atomic substitution in ice. The only substances that are known to substitute in the ice lattice in measurable amounts are the compounds NH_4F , NH_4OH , HF and NH_3 (Hobbs, 1974), compounds that, fortunately for the human race, are not abundant naturally and whose concentrations in sea ice are negligible.

Besides, the incorporation of sea salts into sea ice occurs not as atomic substitution but as entrapment of a portion of the growth liquid in the form of liquid inclusions. The amount of liquid included, which determines the salinity of the sea ice, depends on the salinity of the seawater at the growth interface and the growth velocity. For natural sea ice forming from seawater of a

salinity of $\sim 34\text{‰}$, typical initial salinities are in the range of 10 to 15‰, values that will, as the ice ages, gradually decrease to 4 to 6‰ by the start of the spring melt season. A discussion of the different mechanisms involved in controlling the salinity profile of sea ice, as well as of current attempts to model these processes, can be found in Cox and Weeks (1988). If the ice has survived a summer, becoming what is loosely referred to as multiyear (MY) ice, the salinity of the portions of the ice above sea level drops to nearly zero while the ice below sea level shows salinities varying between 3 to 5‰ (Malmgren, 1927; Schwarzscher, 1959). In a sense, the formation of sea ice acts as a purification process that results in the rejection of much of the soluble material that was initially in the portion of the water column that has been frozen and that transfers it to lower levels of the ocean. The fate of this material will be discussed by other presenters at this meeting.

In summary, any chemical pollutant that is introduced into the Arctic Ocean in a dissolved state will be less concentrated in the sea ice than in the underlying seawater. The only interest in the ice in such a situation is as a visible "tracer" indicating the general motion of the upper layer of the ocean. The various techniques useful in tracking the drift of the ice will be discussed later. It should also be noted here that in the Arctic Ocean the motion of the ice and of the upper portion of the water column (to depths of approximately 50 m) are essentially completely decoupled from the motion of the lower and predominant portion of the water column. For instance, the upper portion of the Arctic Ocean moves in a generally clockwise pattern while at greater depths the circulation is counterclockwise (Aagaard, 1979).

Mechanisms for incorporating solid materials into sea ice

Overview

It is in the transport of solids that sea ice comes into its own as a potentially important transporter of solid hazardous material. As will be seen, the processes involved are somewhat unusual and only occur in the polar oceans. The more important of these processes are capable of concentrating solid material in the ice cover in amounts far in excess of that found in the underlying sea water. Processes that are believed to contribute to the entrainment of solid material on and into sea ice include (1) bottom adfreezing in extensive shallows covered by bottom-fast ice, (2) bluff slumping onto fast ice, (3) flooding of fast ice by sediment-laden river water, (4) the wind-borne transport of material onto the ice surface, (5) transfer of material suspended within the water column and on the sea floor to the ice by suspension freezing, and finally, (6) the incorporation of material into the ice during the gouging of the sea floor by pressure ridges (Kindle, 1924; Osterkamp and Gosink, 1984; Reimnitz et al., 1992).

The following sections will review studies of what are currently believed to be the two most important of these processes: suspension freezing and ice-induced gouging of the sea floor. Although the other processes are undoubtedly locally important, they are not believed to transfer amounts of sediment either into or onto the ice that are volumetrically significant on a regional basis. For a transfer mechanism to be effective, it must be able both to transfer reasonable amounts of material to the ice and to operate over an appreciable area. Even along the edge of the Arctic Ocean, bottom freezing by undeformed fast ice only occurs in water shallower than 2 m, a value that is limited by the local winter climate which controls the maximum possible ice thickness. Bluff slumping is strictly limited to coastlines although near-shore water depth is no longer a restriction. River flooding is also very localized and, as it primarily occurs in the spring, the affected near-coastal ice commonly melts resulting in the transfer of the river sediment load from the ice to the sea floor. Aeolian deposition of significant amounts of material also appears to be only locally important. Recent work in the Canadian Archipelago, where aeolian transfer might be expected to be particularly effective because of the invariable nearness of land, suggests that this process is relatively unimportant (Reimnitz et al., 1992). Also, sea ice sampled in the nearshore 2 km north of Barrow contained only insignificant amounts of dust in the snow cover upon the ice (Darby et al., 1974). In addition, ice sampled (Pfirman et al., 1989a; 1989b; 1990) in the Eurasian Basin carried fine sediment suggestive of an aeolian origin, the total amount of such sediment was small.

Suspension Freezing

Suspension freezing is the descriptive term first used by Campbell and Collin (1958) to describe a process that is now known to be caused by the formation of frazil ice (ice crystals that form within the water column). This process is quite effective in transferring to the ice both sediment suspended in the water column and sediment residing on the seafloor. The conditions necessary for suspension freezing to occur have recently been summarized by Reimnitz et al. (1992) as including strong winds, intense turbulence in the open water of a shallow sea and extreme sub-freezing temperatures. When these conditions occur, the water column can become supercooled a fraction of a degree allowing large quantities of frazil ice to form and to be swept by the turbulence throughout the water column. In saltwater frazil crystals are characteristically 1 to 3 mm in diameter and initially occur in the form of thin discs. These crystals not only nucleate on particles in the water column but during their growth stage they are sticky and are extremely effective in scavenging particles from the water column. During periods of sustained turbulence, current evidence suggests that marine frazil can remain suspended for significant periods of time (hours to even days). When the turbulence abates, the frazil crystals characteristically form into flocs that float to the surface where they form a slush layer either on the surface of the sea or at the base of an existing ice cover. During the floc stage, additional suspended material can also become entrapped in the interstices of the agglomerated crystals. One surprising fact is that, at least in the case of diatoms studied in the Southern Ocean, and presumably true also for fine sediment, the amount of material observed in the ice greatly exceeds the amount that could be explained as being present in the water column at any given time (Ackley et al., 1979). This anomaly has now been reasonably explained by noting that, after the frazil has accumulated into a layer of slush forming what is commonly referred to as grease ice, it is a very common occurrence that a swell will continue for some period of time after the frazil layer has formed. This process cycles water containing additional suspended material, through the ice which acts like a sieve systematically trapping the particles within the porous ice matrix. A theoretical treatment of this process has recently been developed (Shen and Ackermann, 1990).

The other important aspect of suspension freezing process is that it is also capable of picking up coarse material off the bottom and of transporting it upward to where it can be incorporated in a developing ice sheet. A general description of this process is as follows. As the frazil crystals resulting from suspension freezing are swept downward by the vertical turbulence, they can also come into contact with, and adhere to, material on

the seafloor. Such, so-called, anchor ice appears to form selectively on coarser material. There appear to be several reasons for this. As the coarser clasts project into the flow, they cool quickly to the subfreezing temperatures necessary for anchor ice formation. Also clasts projecting into the flow will clearly encounter and collect more frazil crystals. The spongy masses of ice that can form on such clasts can be quite large. Once the vertical turbulence subsides, these ice masses, which are buoyant, can many times leave the bottom containing significant quantities of attached sediment. In rivers, rocks as heavy as 30 kg have been observed to be incorporated into an ice cover via this mechanism (Martin, 1981). However, most material is significantly smaller and therefore requires less attached ice for flotation. During the transfer up to the ice cover, these ice masses also are presumably effective in sweeping particulate matter from the water column. At present, field observations in the Arctic suggest that anchor ice formation only occurs under turbulent open water conditions with strong wind-driven currents and when the immediate heat sink is the atmosphere (Reimnitz et al., 1987).

An example of the overall efficiency of the suspension freezing process can be gained from the field observation that, in 1979, the sea ice between the Colville and the Sagavanirktok rivers on the Beaufort coast contained 16 times more sediment than the annual supply to the same region (Reimnitz and Kempema, 1987; Kempema et al., 1989). In this particular event sediment loads in the ice were estimated to be $1000 \text{ m}^3/\text{km}^2$ and to extend out to water depths of at least 20 m. Field observations and laboratory experiments relating to the general process of suspension freezing and of anchor ice formation can also be found in Barnes et al. (1982), Clayton et al. (1990), Kempema et al. (1986, 1990), Osterkamp and Gosink (1984), and Reimnitz et al. (1987, 1990, 1993).

Now that we are confident that suspension freezing is capable of entraining significant amounts of sedimentary material into the ice, we must answer two further questions: "What is the maximum water depth at which this process is effective and during what portion or portions of the year does such entrainment occur?" There is a variety of evidence relating to the question of the maximum effective water depth. For instance in the Arctic, Reimnitz et al. (1992) have found mollusk species that characteristically live at water depths of 25 to 30 m that have been incorporated in the ice via the process of anchor ice transport. A similar depth range is suggested by the types of ostracodes found in the ice. In addition, mixing and supercooling characteristically associated with anchor ice formation have been observed to depths of 20 m on the Beaufort Shelf and to 22

m in the Laptev Sea (Zakharov, 1966a). Similar depths for convection of supercooled water on the arctic shelves of Alaska have reportedly been observed by Hufford (Reimnitz et al., 1987). Particularly important are recent observations (Reimnitz et al., 1993) on the incorporation of benthic microfossils in sea ice during a particularly intense suspension freezing event along the Beaufort coast that suggest that the affected water depth may extend to 50 m. The details of this event will be discussed later.

In the Antarctic there is appreciable evidence that anchor ice forms at significantly greater depths. In McMurdo Sound, its occurrence has been documented at depths up to 33 m (Dayton et al., 1969) and, at nearby White Island, ice buildup on fishtraps has been noted at depths of over 70 m (Reimnitz et al., 1987). In fact, evidence has been presented (Dieckmann et al., 1986) that indicates that, in the vicinity of the Filchner Ice Shelf, organisms have been raised from the bottom in water up to 250 m deep. Whether these latter extreme depths are applicable to the Arctic is doubtful in that, at least at sites near to the Antarctic ice shelves, the mechanism for producing the supercooling appears to be appreciably different and not directly associated with surface meteorological conditions. In these cases, the postulated mechanism is as follows. Near the outer edges of the extensive Antarctic ice shelves, the seawater layer in direct contact with the bottom of the ablating shelf is both less saline than the underlying water, as the result of the production of meltwater, and also is exactly at its freezing point because of its contact with the ice. Once this water flows beyond the edge of the shelf, it rises because of its lower density and supercools during the rise as the result of adiabatic decompression. Considering that these ice shelves can have drafts in excess of 200 m, they provide a quite plausible mechanism for generating supercooled water at appreciable depths. Further discussion of this explanation, which was initially proposed by Foldvik and Kvinge, as well as related field observations bearing on its occurrence, can be found in the following references (Foldvik and Kvinge, 1974; Foldvik and Kvinge, 1977; Gow et al., 1982; Lewis and Perkin, 1985; Jacobs and Comiso, 1989; Jeffries and Weeks, 1992).

The above discussion can be summarized as follows: Current observations indicate that in the Arctic the process of suspension freezing is commonly capable of transporting material from the sea floor to the overlying ice in water depths of 20 to 25 m and occasionally capable of transport at depths to 50 m. Occurrences in deeper water, that have been documented in the Antarctic, do not appear to be common in the Arctic, and if present will probably be found at sites where ice shelves or glacier tongues extend into the sea.

Now that we have considered where suspension freezing can occur, we need to examine when it can occur. A reconsideration of the requirements is useful here: strong winds, extreme sub-freezing temperatures, open water, intense turbulence. Strong winds can occur any time although they are generally more intense in the fall and winter. Extreme sub-freezing temperatures limit the times to late September through April at most arctic locations. It is the combined requirements of intense turbulence and open water that are the most interesting. To produce intense turbulence one must have, not just strong winds and open water, but an appreciable fetch. Such conditions are clearly present in the fall during the initial stages of ice cover formation when large stretches of open water are present. In fact most field descriptions of suspension freezing events are from just this season.

The question is "Are there locations over the arctic continental shelves with water depths of 50 m or less where pronounced turbulence is to be expected at other times of the winter?" At first glance one might think that the answer would be no, because after the initial general freeze-over occurred, the fetch would invariably be limited by the presence of sea ice. Indeed, this statement probably applies to most of the Arctic Ocean where the presence of ice effectively eliminates the short-period wave field and lead widths are commonly less than a few kilometers.

However, there are a number of places where pronounced turbulence is to be expected: the polynyas that occur around the margins of the Arctic Basin. The term *polynya*, a Russian term that is in general use by the international sea ice community, refers to an open water or thin ice area of some considerable extent (tens to hundreds of kilometers) that exists in a region that is surrounded by heavy ice and where climatologically heavy ice is to be expected. In the following we will also restrict the use of the term to cases where such a situation repeatedly occurs in roughly the same location.

There are generally considered to be two types of polynyas (Smith et al., 1990): sensible heat polynyas and latent heat polynyas. The sensible heat variety is believed to be the result of the introduction of warm water, probably from below, that prevents ice from forming. If there is sufficient warm water being introduced into a region to result in the effective removal of ice, the introduced heat is certainly capable of preventing the formation of the supercooled water required for frazil ice generation and anchor ice formation. Therefore this type of polynya is not of interest to us.

Latent heat polynyas, on the other hand, are invariably the combined result of the local topography and meteorology with the topography blocking the flow of ice into a region and the meteorology moving the ice

already in the region away to some downwind location. No ice in (because of a land barrier or ice arching across a strait) + an offshore or off ice edge wind which moves any ice in the region away = 1 ea. polynya. In such a case, warm water is not keeping the polynya open, and the combination of a strong wind, very cold air temperatures (many times coming off large land masses such as Alaska or Siberia) and an appreciable fetch is invariably present. There is another important aspect of this process, it produces its own fetch and, therefore, can in principle occur any time during the winter. If the geometry of the geography is "right," all that is needed is a frigid and strong offshore wind. This is a requirement that is not in short supply in many areas of the Arctic. Do such latent heat polynyas exist? They definitely do and they are not rare. Also, in that their up-wind boundary commonly starts either at the shoreline or at the fast ice edge, their locations, almost by definition, include some, or all of the bathymetry between 0 and 50 m. In fact, this type of polynya would appear to be a well-designed machine for incorporating material both from the sea floor and from within the water column into the sea ice cover.

One might well ask next, "How effective are these polynyas as initiators of solid material transport, via the sea ice cover, across the Arctic Ocean?" The amount of real observational data bearing on this question is limited. The reasons for this are several. Operations on the edges of large polynyas can be quite dangerous unless the party has significant logistic support as the possibility always exists that the nearshore ice will break off and drift into the polynya. Operations in a polynya commonly require specialized ship support. Needless to say, such operations are invariably expensive, and in the past have received little support. Although this is gradually changing as obvious reasons for studying such areas have increased, the number of in-situ studies of sediment transport in such areas is still very limited. Discussions of a variety of subjects relating to the polynya problem can be found in the following references: (Arikainen, 1977a, 1977b, 1981; den Hartog et al., 1983; Dey and Feldman, 1989; Knapp, 1972; Kozo et al., 1990; Kupetskii, 1958; Martin and Cavalieri, 1989; Pease, 1987; Reimnitz et al., 1993; Schumacher et al., 1983; Smith et al., 1983, 1990; Steffen, 1985; Topham et al., 1983; Ushio and Wakatsuchi, 1990).

What actual observational data exist concerning the role of these polynyas in the incorporation of sediment into the sea ice? Only recently has this problem started to receive the attention it deserves. An excellent description of how effective a polynya can be in introducing sediment into the sea ice cover has recently been prepared by Reimnitz et al. (1993). During this particular ice-growth year (1988-1989) the usual freezeup

storms did not appear to introduce significant amounts of sediment into the ice. However in January strong offshore winds opened a shore polynya that extended along the entire north coast of Alaska and east beyond the mouth of the MacKenzie River. Satellite imagery also indicated that large polynyas had formed along the Chukchi and Eastern Siberian coasts at the same time. Unfortunately no detailed observations were made concerning the incorporation of material into the ice covers of these regions. The Beaufort polynya remained open through February and into March. In fact aircraft flights on 3 March 1989 showed that the polynya extended from the shore to 30 km offshore. During this period, the offshore winds were so strong that the stamukhi zone (a

band of pressure ridges that usually forms as the result of the grounding of deformed ice in water of approximately 20-m depth and that serves to stabilize the near-shore ice) was either not able to form or, if formed, was destroyed. In fact the present author lost several sampling sites during these storms when the fast ice being systematically sampled on the Chukchi coast near Barrow suddenly became pack ice never to be seen again.

The sediment load in the ice resulting from this polynya has been conservatively estimated at over 289 t/km² and benthic fossils entrapped in the ice suggested that sediment was uplifted off the bottom at depths of up to 50 m. Although a polynya event of this magnitude is atypical, at least for the Beaufort Coast, it clearly

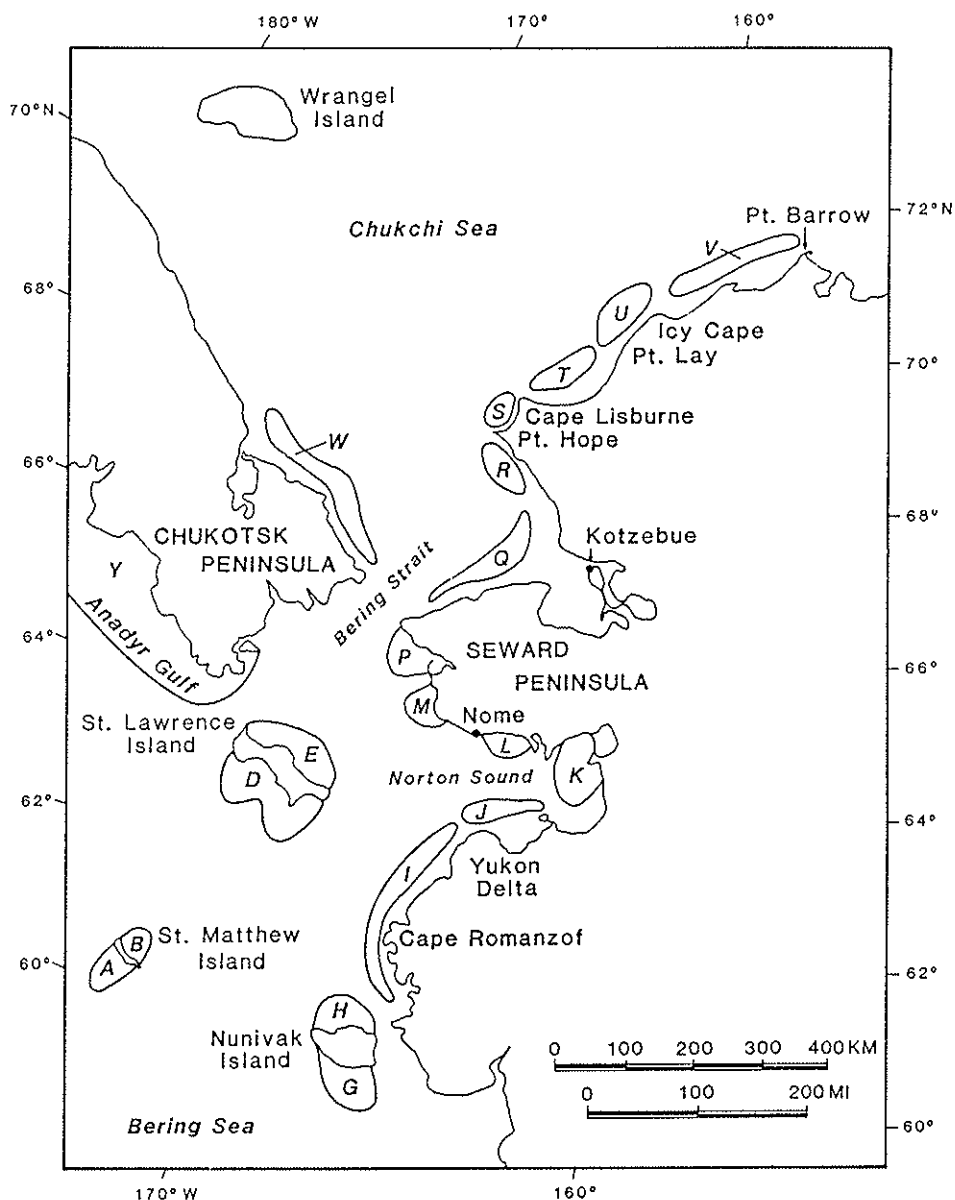


Figure 1. Polynya locations in the southern Chukchi and Bering seas (Groves and Stringer, 1991).

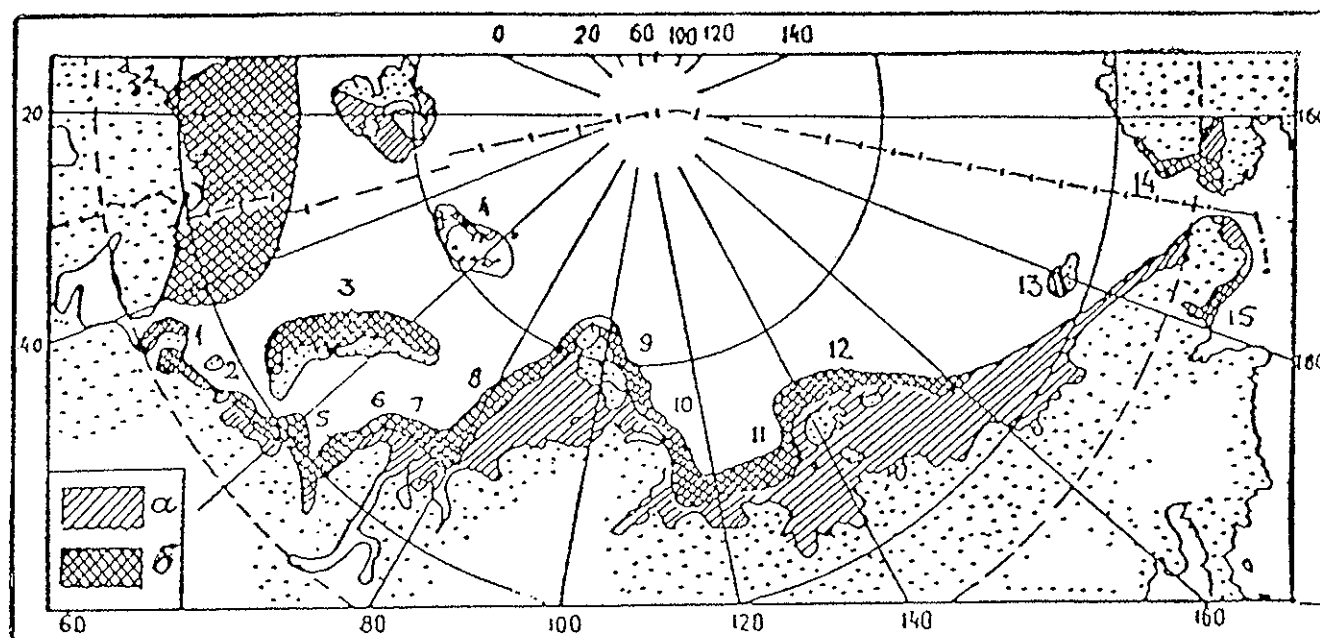


Figure 2. The distribution of (a) fast ice and (b) polynyas 1, 2, 3,... over the Russian Shelf during winter based on Russian observations.

demonstrates the effectiveness of the suspension freezing mechanism. In addition, it has been estimated based on these field observations that, if one assumes a steady ice drift to the west of 3 cm/s, the sediment transport through a 1-km north-south segment of the Beaufort Shelf via the ice would be 67,420 t during a 3 month period (Reimnitz et al., 1993).

Years with major sediment entrainment events may, of course, be followed by a year, or years, when only comparatively clean ice is produced. The largest such entrainment event studied to date occurred during the fall of 1978 and resulted in an ice cover that contained 16 times more sediment than the local rivers supply annually to the affected shelf region (Reimnitz and Kempema, 1987). If this ice were all to move off the shelf before depositing its load, a net sediment loss or shelf erosion would occur.

The fact that advection polynyas are both common and generally occur where one might expect them to occur off the coast of Alaska and around the margins of the Arctic Ocean can clearly be seen in Figures 1 and 2. Figure 1 shows the locations of known polynyas occurring in the Chukchi, Bering and Eastern Siberian seas (Stringer and Groves, 1991). Figure 2, which is based on Russian sources (Proshutinsky, personal communication), provides similar information on polynya sites along the Siberian coast and offshore of the islands on the Russian Shelf. Invariably all these features will not be active during a given year. However on the time scales of the lifetimes of many types of hazardous materials, the incorporation of solid material into near-

coastal sea ice via polynya formation and suspension freezing can be considered to be an essentially continuous process. Note in Figure 2 that major polynya areas occur along most of the Russian coast and are particularly prominent where islands block the generally offshore motion of the ice. In a recent study using satellite imagery (Martin and Cavalieri, 1989), the entire circumference of Franz Josef Land, the west side of Novaya Zemlya and the north and east sides of Severnaya Zemlya appeared to be active polynyas. All these polynyas started in shallow water. In addition, Reimnitz and co-workers (Reimnitz et al., 1992) have recently studied ice that formed in the vicinity of a large, recurring polynya located along the coast of the Laptev Sea. Its width was typically 15 km and it extended for 1800 km along the coast. Initially its inshore boundary was located at a water depth of 10 m but by January this boundary had moved to depths of 20 to 30 m and was located at a distance of 200 km from the shore. The one time it was possible to directly examine ice from this region, it proved to be relatively free of sediment. This may be the result of the fact that the discharges of the Lena and other large rivers located in this area result in a water column that is sufficiently stable to prevent suspension freezing from reaching the sea floor. However Russian oceanographic studies (Zakharov, 1966b) indicate that convection is commonly sufficiently intense to reach to the bottom in this area. Clearly additional field studies will be required to document the effectiveness of the Russian polynyas in the sediment entrainment process.

Ice-Induced Disturbances of the Sea Floor (Gouging)

Suspension freezing is capable of transferring material, both suspended within the water column and resident on the surface of the sea floor, into the overlying layer of sea ice. Is there an additional mechanism capable of transferring material, buried to depths of several meters beneath the sea floor, either back to the surface of the sea floor, into suspension, or directly into the ice cover itself? There definitely is. The fact that, as the ice pack moves over the shallower waters of the continental shelf, the keels of pressure ridges and the lower surfaces of ice islands and icebergs plow up the sea floor has been a known scientific curiosity since the 1920s. Once offshore oil development on the margins of the Arctic Ocean became a possibility, a thorough understanding of this process became of considerable importance in that it presented an obvious hazard that would have to be considered in the design of offshore pipelines. In fact, during the last 20 years gouging, or scouring as some people prefer to call it, has received considerable attention. For instance, a recent bibliography of the ice scour literature (Goodwin et al., 1985) lists a total of 379 publications with some 101 papers dealing with the Beaufort Sea, 23 discussing the Chukchi/Bering Seas, 15

dealing with theory and modeling, and 29 dealing with protection. There is also a large literature bearing on the subject of gouges off the east coast of Canada that are produced by true icebergs.

What is currently known about gouging? It is now well established that gouge depths, as observed at a given time, are well described by a simple negative exponential distribution (Figure 3). Small gouges are frequent and deep gouges are rare. Curves that summarize current data on the distribution of gouge depths along the Beaufort Coast as a function of water depth are presented in Figure 4. The spacing between gouges also shows a similar exponential dropoff suggesting that gouging can be approximated as a Poisson process. Both the frequency and the intensity of gouging are clearly related to water depth. In the United States portion of the Beaufort Sea, most deep gouges occur in water depths of 30 to 40 m. To date, the largest gouges observed on the U.S. portion of the Beaufort Shelf have depths of approximately 5.5 m (Barnes et al., 1984). Larger gouges up to 6 m deep have been observed in the Canadian portion of the Beaufort Sea, an increase that is probably related to changes in the characteristics of the subsea sediments as one moves closer to the Mac-

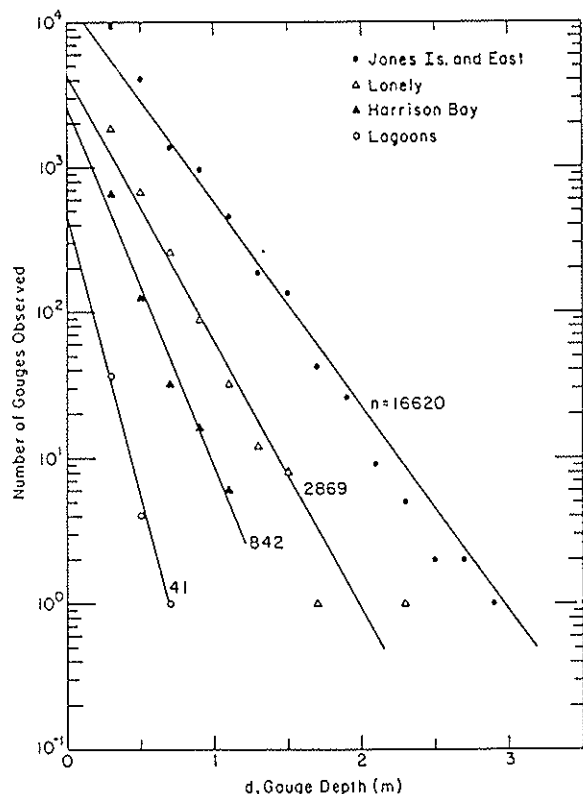


Figure 3. Semilog plot of the number of gouges observed vs. gouge depth for four regions along the Alaskan coast of the Beaufort Sea (Weeks et al., 1984).

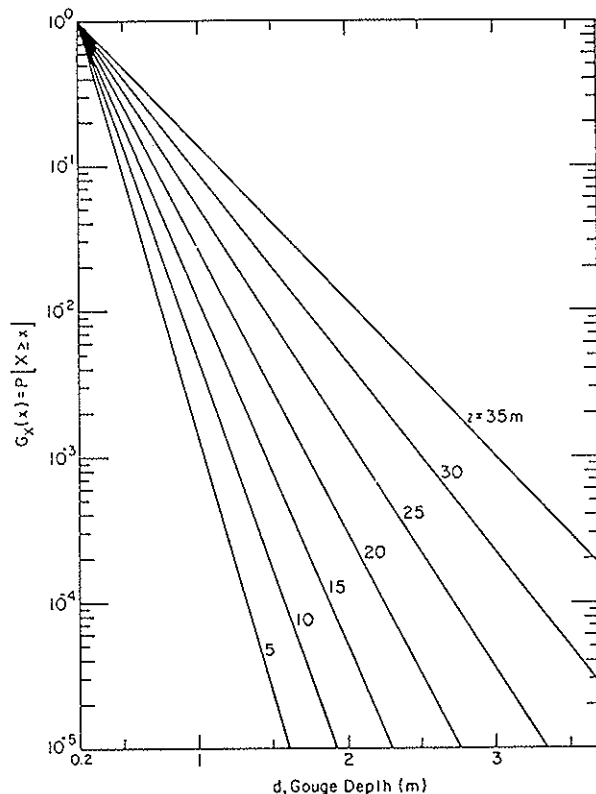


Figure 4. Plot of the exceedance probability $[G_X(x)]$ vs. gouge depth for different mean water depths (z) in the offshore region of the Beaufort Sea unprotected by barrier islands (Weeks et al., 1984).

Kenzie Delta. Gouge densities are extremely variable reaching values as large as 500 gouges per square kilometer. Track samples indicating in excess of 100 gouges per kilometer are not rare. In the Chukchi Sea, the deepest gouges occur at water depths of 35 to 50 m and are as much as 4.5 m deep. Most gouges are oriented roughly parallel to the coast running generally east-west in the Beaufort Sea and northeast-southwest in the Chukchi Sea. In both the Beaufort and Chukchi Seas, the presence of offshore shoals has a major effect on gouge occurrence with the largest numbers of gouges occurring on the seaward flanks of shoals (Reimnitz and Kempema, 1984). In general, currently active gouging is rare in water deeper than 50 m and does not appear to occur in water deeper than 60 m. Unfortunately, the amount of data bearing on these limiting values is small.

What aspects of existing data sets need improving? First, it would be highly desirable to have a better estimation of the water depth at which gouging ceases to be a problem. To understand this concern, one must realize that in the geologically recent past, sea level was roughly 100 m lower than now. Therefore gouges occurring in deeper waters may be relic and not indicative of current activity. This is particularly true if gouges formed in deeper water survive for long periods of time. Considering the shallow nature of the Arctic shelves, small changes in the maximum water depth where active gouging occurs make large changes in the areas where gouging must be considered as a problem.

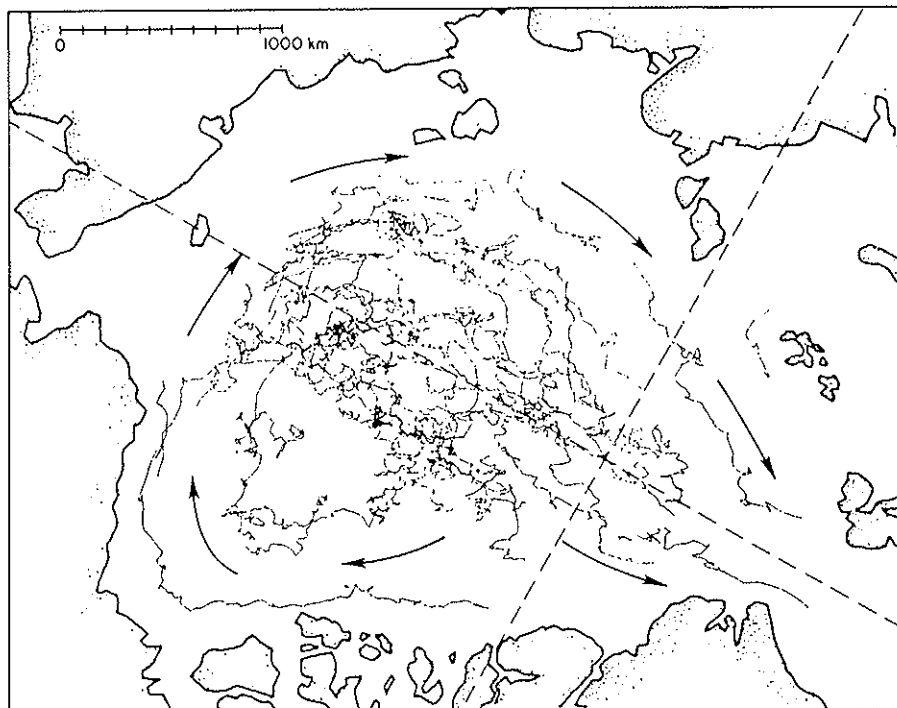
Even more important is the small amount of data that provide direct determination of gouging rates as a function of water depth and location. When one examines a region and determines there are 100 gouges per kilometer, does this mean that they formed during the last year, during the last 10 years, or during the last 1000 years? As there is, as yet, no absolute way to date individual gouges, this question is currently unresolved and of great importance in estimating safe burial depths (Weeks et al., 1984; Wang, 1990). Current simulations of the gouge infilling process (Weeks et al., 1985) suggest that most gouges are infilled within a few years. However these models are very crude. This conclusion is also supported by field observations suggesting significant sediment movement along the arctic shelves (Barnes and Reimnitz, 1974, 1979). Whether these conclusions apply to water depths greater than 45 m is not known. In addition, the detailed oceanographic data necessary to drive even crude sediment transport models is almost nonexistent even for regions such as the Beaufort Shelf where interest in offshore oil and the associated subsea pipelines has generated considerable interest in both gouging as a pipeline hazard and the associated oceanographic environment. The published data base for the Siberian Shelf is, to the best of my knowledge, virtually non-existent.

The development of a good data base on gouging rates requires yearly replicate measurements of the gouging patterns on selected representative regions of the shelf of interest. Some such data exist for the Beaufort Sea (Barnes et al., 1978; Rearic et al., 1981), the expansion of this data base would be highly desirable. We stress that this type of information cannot be obtained in a short time even if major financial resources are devoted to the problem. On the other hand, by carrying on a low-level, continuing program, excellent data sets can be obtained for reasonable costs. The longer the time series, the more confident will be the estimates of the gouging rates and initial gouge depths. The existing repetitive record of gouge tracks along the Beaufort Shelf indicates that the average volume of sediment excavated and mobilized by ice keels in the water depth range between 7 and 18 m was 3000 to 6000 m³/km²/yr (Rearic, 1986). These values increased with depth to the seaward limit of the surveys and, based on studies of gouging frequency and intensity would be expected to peak at water depths of 30 to 40 m. In short, on the shelves of the Arctic Ocean at water depths of 50 m or less, even objects buried in the sediments to depths of 5 m are not safe from the gouging process. This process is also presumably capable of disrupting containers containing hazardous material causing the material to be released on the sea floor where it would be exposed to suspension freezing and to other more conventional sediment transport mechanisms.

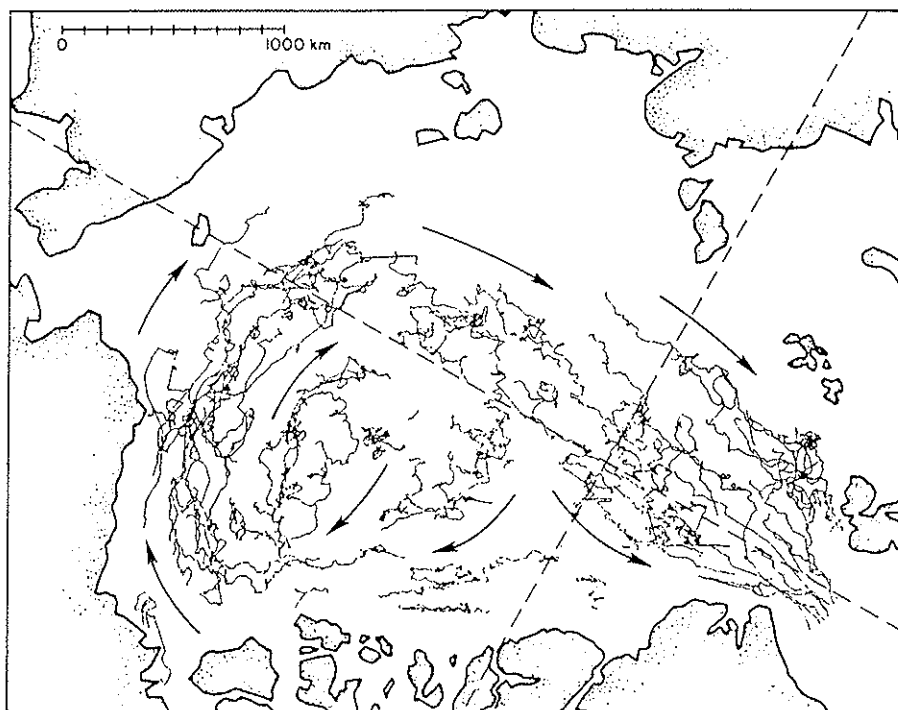
Unfortunately, the literature on sediment transport by gouging is, to date, quite limited (Barnes et al., 1990). Quantitative data on the direct transfer of sediment via gouging to the ice cover for further transport are essentially non-existent. However there is no doubt that this is an active process. I am not aware of any quantitative published data on the gouging phenomena on the Russian shelves. Again there is no doubt that this is an active process. The simple fact that *stamukhi* is a Russian word is informative here. It should also be noted that there is a significant tide at many locations on the Russian shelf. When such tides are coupled with the geometric restrictions that occur in regions where extensive ice grounding and gouging are found, opportunities for local scouring and redistribution of sediments invariably occur. Finally, one should recall that icebergs are formed at locations in the western Russian arctic islands. Such features can ground in deeper water resulting in both deep wallow holes and linear gouges.

Patterns of ice movement

Once solid material of any kind, hazardous or non-hazardous, hitches a ride either within the sea ice cover or on its upper surface, where does it go? In that the introduced matter is a passive hitchhiker, it goes where



a. Trajectories of various research stations (1893-1972). The bold arrows provide a sense of direction.



b. Trajectories of automatic data buoys (1979-1982). (Colony and Thorndike, 1985.)

Figure 5.

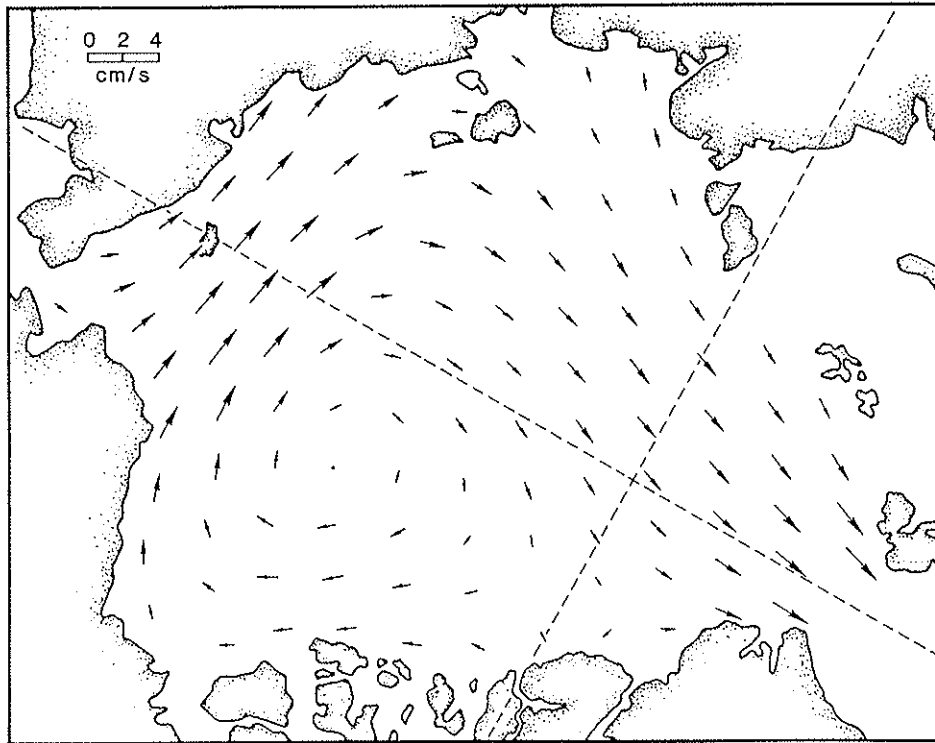


Figure 6. The field of interpolated mean ice motion for the Arctic Basin. The vectors originate at the centers of the boxes. The interpolated motion in data sparse regions should be regarded with caution. (Colony and Thorndike, 1985.)

the ice goes and gets off where the ice melts. Just where is this? Data relating to the large-scale motion of the Arctic pack, initially based on the drift of beset ships, has been collected since the drift of the Fram (1894-1896). Through time our insights into this phenomenon have consistently improved as more and more data became available including the tracks of the Soviet "North Pole" stations, the U.S. ARLIS stations, the ice island T-3, and finally the data buoys using satellite relays (Munoz, 1986; Untersteiner, 1988). A plot of all this information collected between the time of the Fram and 1982 has been assembled by Colony and Thorndike (1984) and is shown in Figure 5. It has been suspected since the time of Nansen and recently explicitly documented by Thorndike and Colony (1982) that, in the short term, the ice goes where the wind takes it. In fact 70% of the short-term variance of the ice motion can be explained by the local geostrophic wind. In that the wind field over the Polar Basin is dominated by anticyclonic activity, the drift of the pack would be expected to mirror this, and it does. Figure 6 shows the mean field of the ice drift as calculated from the observational data (Thorndike and Colony, 1982). This motion field is usually described in terms of two main features. The first of these is the Trans-Polar Drift Stream which moves ice from the Siberian Shelf, over the Pole and out

of the Basin through Fram Strait; a trip that commonly takes 3 years. The second feature is the Beaufort Gyre, a large anticyclonic circulation centered about halfway between Barrow and the Pole. A typical trip around the gyre takes 5 years (Thorndike, 1986). In fact, in the mean representation of the motion field shown in Figure 6, the Trans Polar Drift Stream and the Beaufort Gyre appear to blend into one gigantic clockwise circulation.

It should be noted that the mean representation is, in one sense, a bit deceptive in that it lures the non-specialist into thinking that the ice motions are always as represented. As an example of the possible magnitude of the short-term variations, it is now known that the Beaufort Gyre can rotate counterclockwise for periods lasting up to 30 days (Serreze et al., 1989). These events characteristically occur in the late summer to early autumn and are a wind-driven response to a persistent cyclonic pattern that occasionally develops at that time of the year. An example of this drift pattern as demonstrated by the buoy motions and the estimated ice drift vectors as calculated by a numerical model utilized by Proshutinsky (personal communication) is shown in Figure 7. This figure is particularly interesting in that it clearly demonstrates that even the exceptions to the mean drift pattern can now be reasonably well predicted by current modeling efforts.

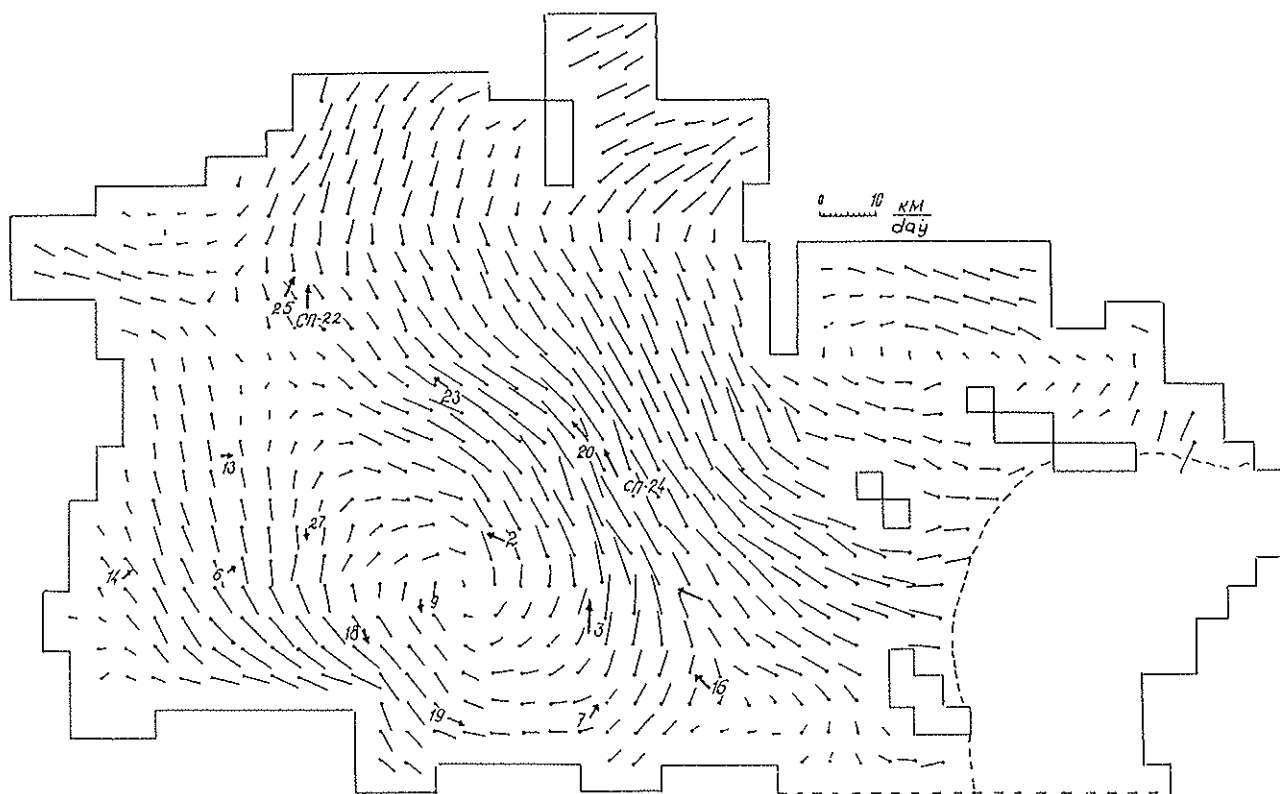


Figure 7. The observed drift vectors obtained from automated buoys (numbered) and the calculated drift field for June 1979 (Proshutinsky, 1993).

However, it is important to note two things. First, existing models have the most difficulty in forecasting ice behavior in the nearshore region (Overland and Pease, 1988). This is hardly surprising, in that in such regions the geometric variations of the coastline as well as the topography of both the land and the seafloor exert complex influences on the wind field above the ice, the currents beneath the ice, and the lateral transmission of stresses through the ice. As a result ice motions near the coast can be quite complex. Second, the observational data base on ice drift near the coast is surprisingly sparse. Note that, with the exception of the Beaufort and Chukchi shelves, mean drift vectors are largely missing at near-coastal locations in Figure 6. There are two reasons for this data gap. First manned stations are usually sited at locations greater than 200 km from a coast because experience has shown that ice floes at sites closer to the coast commonly encounter episodes of lead formation and ridging. Second, the Cold War limited the installation of data buoys at sites on the Russian Shelf. Fortunately this restriction has now disappeared and cooperative projects are now underway. There is also a large Russian data set of the drift of near-shore radio drift buoys (Figure 8) that, as yet, has not been incorporated into an overall analysis because the basic data set has not been published. Unfortunately, it is at these nearshore shelf sites, particularly those on

the Russian Shelf, where there is the most concern regarding the introduction of hazardous material into the Arctic Ocean. Figures 9 and 10 show two additional representations of the drift patterns in the Basin. The first is by Gordienko (1958) and is of interest in that it shows a more clearly delineated Trans-Polar Drift Stream and also summarizes the Soviet experience concerning ice movements near their coast. The second figure is by Proshutinsky (1993) and summarizes more recent Russian views on this subject based on observations collected by the Arctic and Antarctic Research Institute in St. Petersburg.

Let us now examine the ice drift patterns for several sites where hazardous material of one type or another is presumed to be present. We will assume that this material has become entrained in the ice by some mechanism and ask ourselves the question, "Where is it most likely that the undesirable material will be deposited?" Field observations support the assumption that the great majority of any foreign material that is incorporated either in or on the ice remains in the ice and is gradually moved toward the upper ice surface where it is concentrated as a lag deposit. When the ice melts, this material is again released back into the water column. A representation of this transportation scenario for ice initially formed on the Russian Shelf, as well as in the Arctic Basin in general, is shown in Figure 11 (Pfirman et al., 1990).

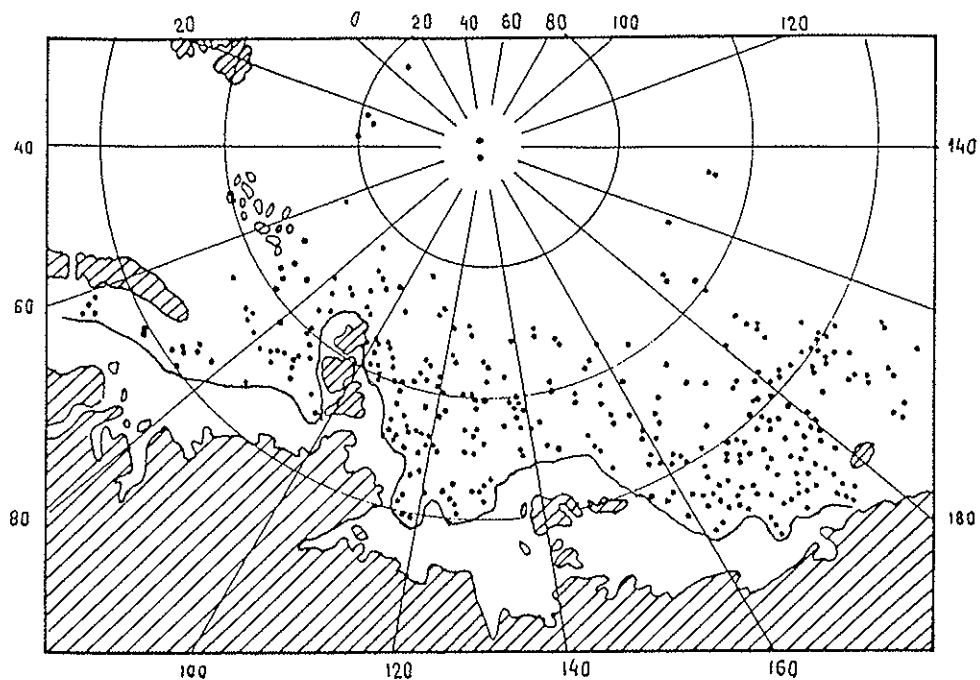


Figure 8. The initial locations of Soviet radio data buoys during 1953-1969.

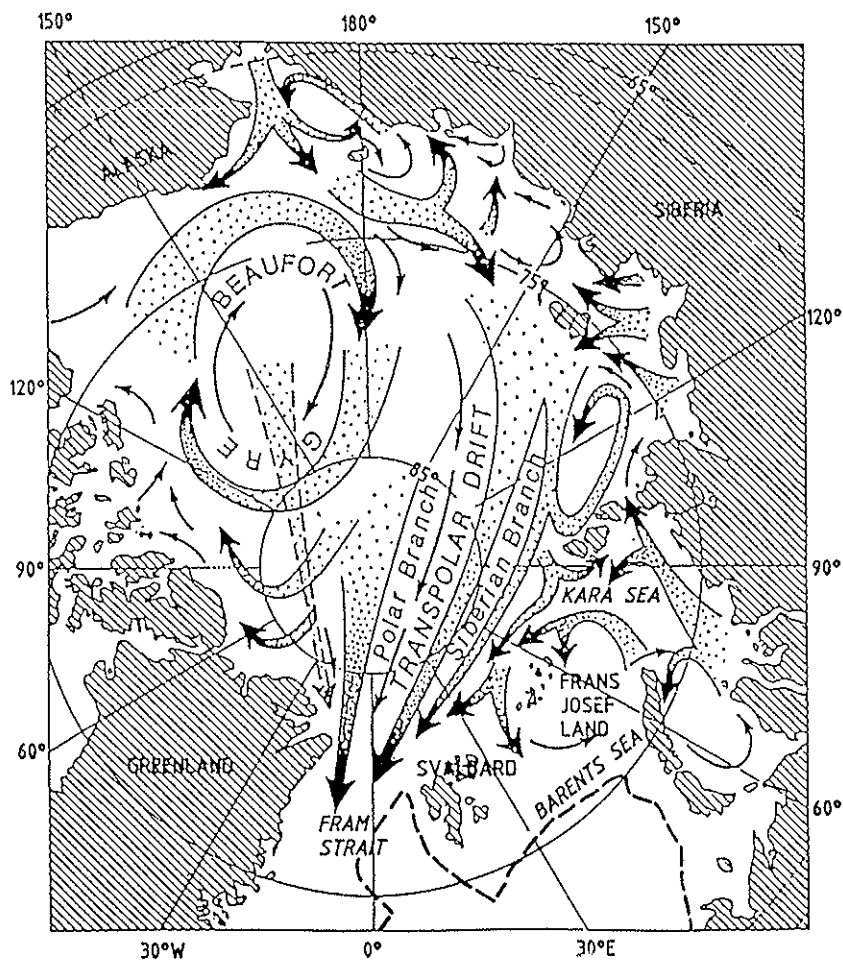


Figure 9. Arrows show an early estimate of the mean ice drift adapted from Soviet sources (Gordienko, 1958; Gordienko and Laktionov, 1969) and the average maximum extent of sea ice during the time period 1973-1976, based on the 15% concentration level (Parkinson et al., 1987). The figure is from Pfirman et al. (1989).

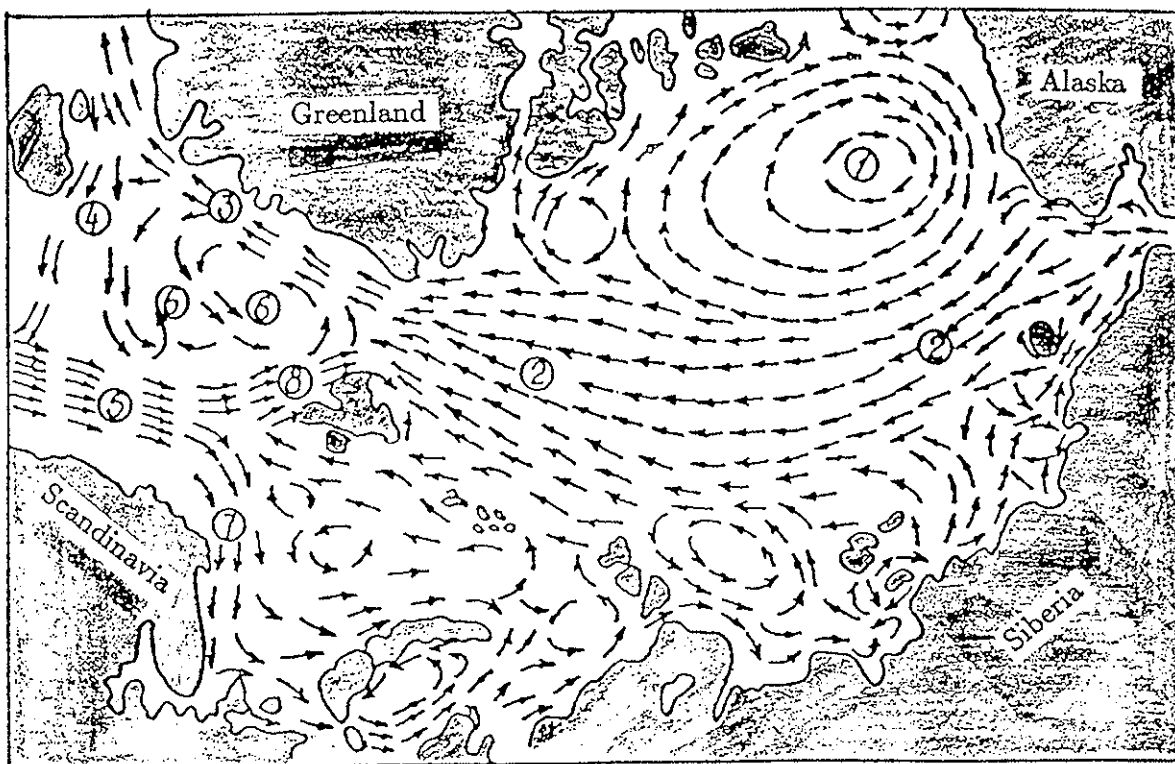


Figure 10. Schematic of the ice drift and surface currents in the Arctic Basin based on Russian sources (Proshutinsky, personal communication).

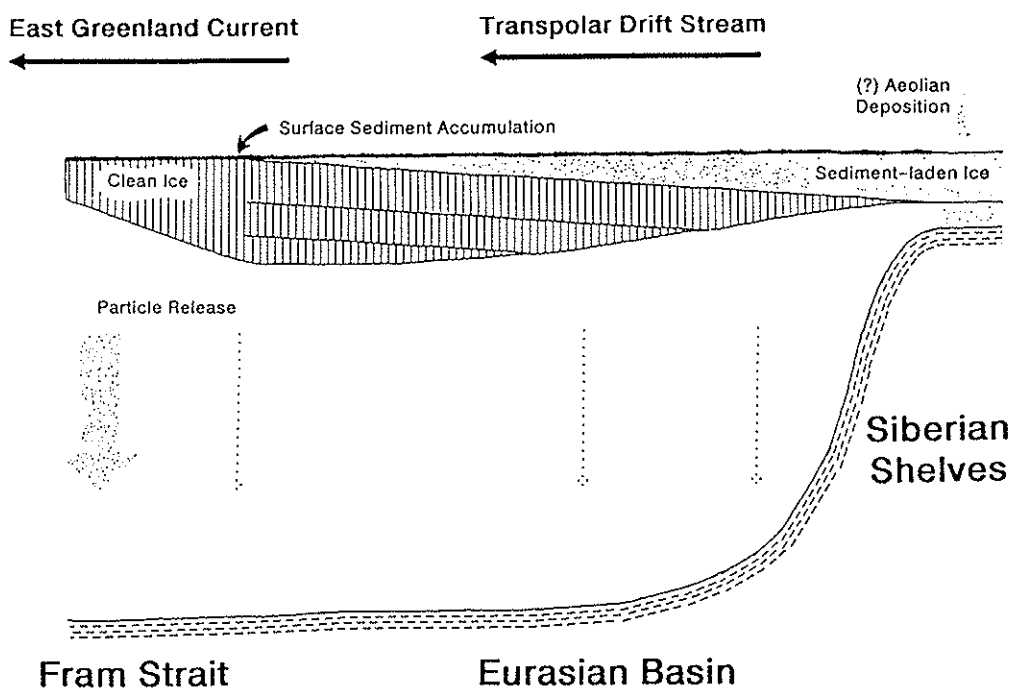


Figure 11. A schematic representation of ice growth, surface melting, and surface sediment accumulation during the drift of a hypothetical ice floe from the Siberian Shelf to the Fram Strait region. Note that variations in thickness due to ice melt and freeze-on and ice rafting are not represented (Pfirman et al., 1990).

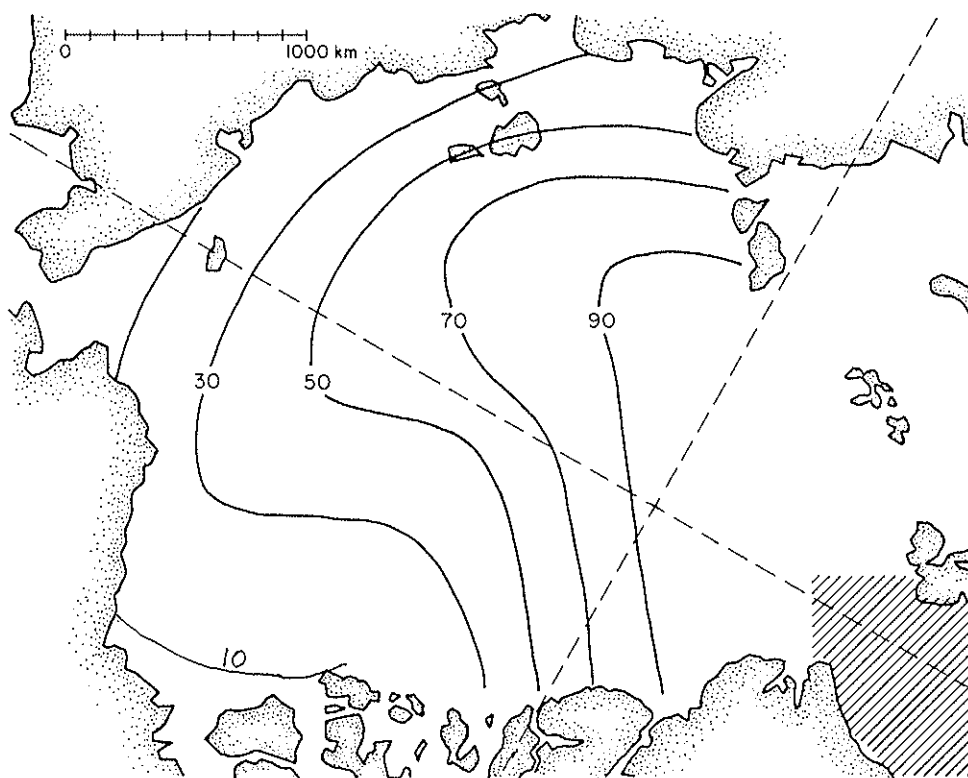


Figure 12. Contours of the asymptotic probability of ice, from different regions in the Arctic Basin, exiting the Basin via Fram Strait (the shaded area) (Colony and Thorndike, 1985).

If the above holds, a sense of the probable deposition (out of the ice) sites can be obtained by utilizing the results of Colony and Thorndike (1985) who have utilized observed drift data to calculate probabilities that ice that formed in a particular site would melt in some specified place. Figure 12 shows contours of the asymptotic probability of exiting the Arctic Basin via Fram Straits (the hatched area). These results clearly indicate that the majority of the ice formed over the Russian Shelf in general, and the western portions of this shelf in particular, exit the Arctic and melt in either the Greenland Sea or the North Atlantic. Figure 13 shows the contours of the asymptotic probability for ice moving into the shaded regions and melting, thereby presumably depositing their sediment load, in the (a) Beaufort Sea, (b) Chukchi Sea, (c) East Siberian Sea, and (d) Laptev Sea. The only problem with these results is that, as mentioned earlier, the data on which the Colony and Thorndike analysis was based did not include drift data from near-coastal regions on the Russian Shelf.

It is worth noting that if it is deemed important to establish the trajectories that ice floes initially located at specific near-coastal dumping locations along the northern coast of Russia will take enroute to their final demise (melting), this is fairly easy to accomplish via at least two different methods. The first approach, which would

require Russian cooperation, would be to place data buoys at sites of interest and then track the motions of the buoys with time. The second approach would be to use sequential SAR data to track ice floes that pass over the sites of interest. Automated floe tracking procedures that are currently being implemented via a Geophysical Processor System at the Alaska SAR Facility would prove very useful in such a study (Kwok et al., 1990; Weeks et al., 1991). Although such investigations are possible now through the use of data from ESA's ERS-1 satellite, they will become significantly easier when the 500-km-wide swath width imagery of the Canadian Radarsat becomes available in 1995 or 1996.

Conclusions

On the shelf regions of the Arctic Ocean, if water depths are 50 to 60 m or less, there are clearly effective mechanisms involving ice for plowing up material buried at depths of up to 6 m, for rupturing containers, and for spreading the encapsulated material over the sea floor. Mechanisms are also active that can transfer large amounts of material from the seafloor and from within the water column upward and into the ice. Although these mechanisms are episodic, when one considers the half-life of certain hazardous materials, their activity can essentially be considered as continuous. Once con-

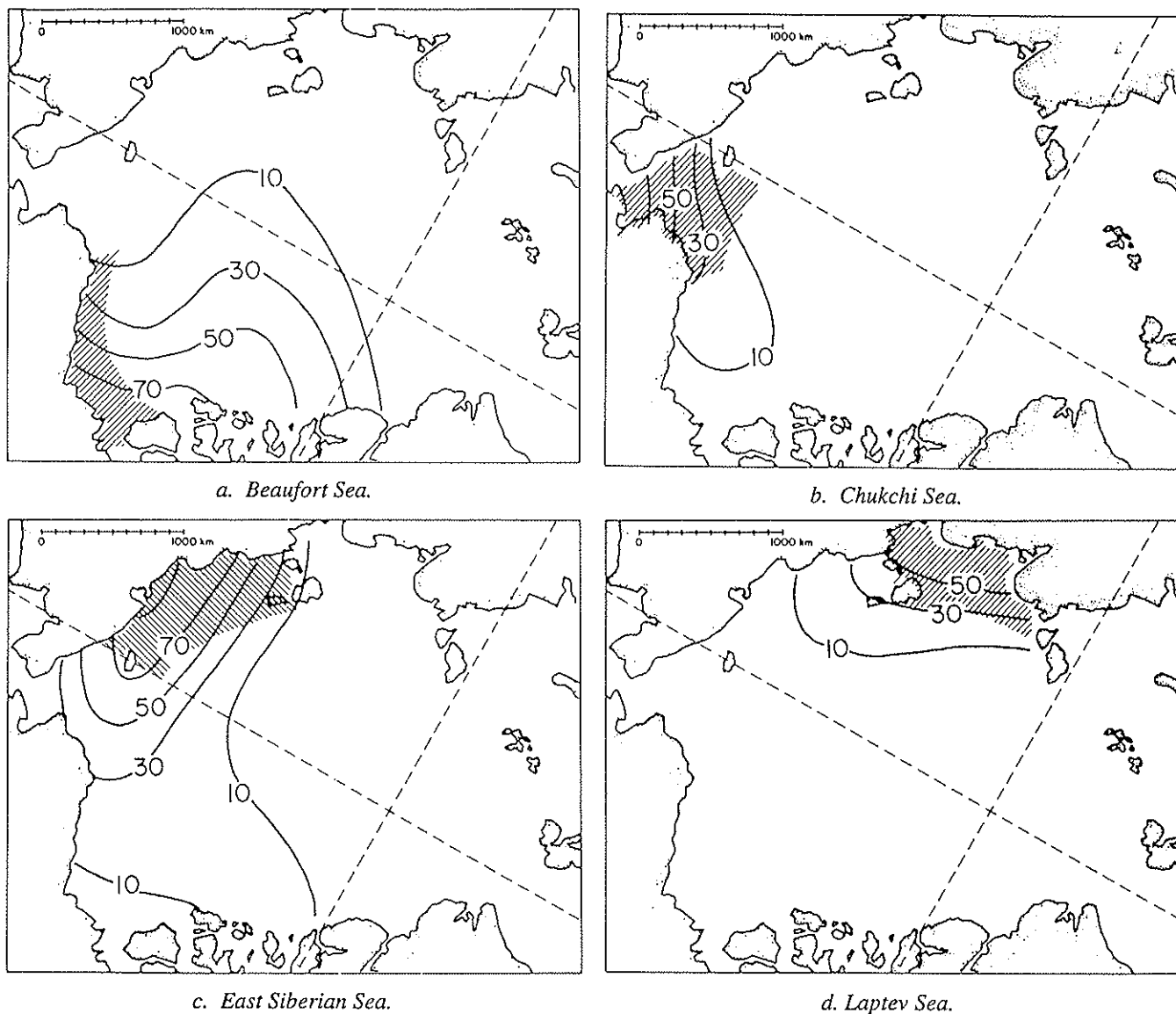


Figure 13. Contours of the asymptotic probability of ice moving into the shaded region and melting (Colony and Thorndike, 1985).

can essentially be considered as continuous. Once contained in the ice, the undesirable material will move with the ice and will not be deposited until the ice melts. This latter event could take place thousands of kilometers and tens of years removed from the time and place of the transfer to the ice. The processes involved here only occur in areas that possess heavy sea ice covers and in the past they have received little attention. This is a situation that will clearly have to change if we are to understand the role of sea ice in the transport of hazardous material in the Polar Regions. I cannot overstate the conclusion that we are not dealing with "normal" well-studied oceanographic processes that we understand. The Arctic offers a truly different situation.

Considering that hazardous waste disposal sites in

the western Russian Arctic are currently of the most interest, I believe that it can be concluded that the chances are slight that hazardous material will be transported via the ice cover from these regions to the coasts of Alaska or into the Bering Sea. Although chances are higher that material deposited on the shelf of the East Siberian Sea could be transported to Alaska (note the eastward ice drift vectors located near the Siberian Coast in Figure 10), I nevertheless believe these chances to also be very small. The quantification of these probabilities will require data on near-shore ice movements over the appropriate shelves. Although ice does move from the Chukchi Sea into the Bering Sea during some periods of the winter, the ice involved invariably forms in the southern portions of the Chukchi. Fortu-

sites in this region. Clearly the areas most at risk from ice related transport of hazardous material deposited on the Russian Shelves are the Barents Sea, the Greenland Sea, the North Atlantic and even Baffin Bay. The fact that these are regions of extensive commercial fishing makes these conclusions appear to be of particular concern.

Clearly we need more detailed information so that we can discuss both the processes that incorporate foreign material into ice and the resulting transportation routes taken by the ice in a more rigorous manner. We know how to collect this data and a small but knowledgeable body of specialists exists that have experience with these matters. Unfortunately such programs are never inexpensive because of the appreciable logistics costs involved. The biggest data void is, of course, the environmental conditions near specific locations on the Russian Shelf. The present political situation offers a unique opportunity to develop cooperative programs with the appropriate portions of the Russian science community. Here I refer not only to the Russian Academy of Sciences but also to groups such as the technical staff of the Arctic and Antarctic Research Institute in St. Petersburg. This organization has extensive data holdings concerning ice conditions on the Russian Shelf as well as vast experience in operating in such regions. There is no laboratory in the west with equivalent expertise. If ever a problem called for building cooperative research programs with appropriate Russian research groups such as AARI, it is the one we are discussing now.

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Sediment and Sediment Processes in the Arctic

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The sediment types, distribution, and processes that deposit or modify the seafloor are poorly known for the Arctic region. The deep Arctic Ocean seafloor consists of fine-grained clastic sediment containing abundant microfossils. Sediment found within the shallow epicontinental seas is extremely variable in texture consisting of silt/clay, sand, and gravel or a mixture of these three textures (see Figure 1). The sources that contribute sediment to the Arctic are rivers, coastal erosion, aeolian, and biogenic (Figure 2).

Turbidite sedimentation is the major depositional processes (Figures 3 and 4) within the deep Arctic basins. In basins with restricted sediment sources turbidite deposition may only be active during glacial periods. On bathymetric highs (Figure 5) and in areas not dominated by turbidites biogenic and ice-rafted clastic sediment is deposited. Sedimentation rates range from 1 to 2 mm/1000 years in ice-rafted areas up to 1 m/1000 years in areas containing turbidite deposition. Processes that transport or modify the deep basin regions include currents which erode sediment, expose bedrock on bathymetric highs, or produce mudwaves on bathymetric highs and basins; ice-rafting in all areas; and bioturbation which reworks the sediment to depths of up to 36 cm.

Sedimentation within the wide, shallow epicontinental seas (Figures 6 and 7) is complex and controlled by fluvial input or lack of and local internal drainage systems (canyons, sea valleys, and troughs) that incise the shelf regions (Figure 8). Processes that transport and modify the seafloor are oceanographic currents which erode sediment and produce surficial gravel lags or extensive sand wave fields; storms during open water season which rework the upper surficial sediment of the

epicontinental seas producing bedforms or gravel lags to over 100 m depth; active ice gouging which ploughs the sediment to at least 5 m depth beneath the sea floor and may occur to at least 70 m water depth; anchor ice-frazil ice formation which will remove sediment from the sea floor and occurs to water depths of at least 100 m; ice-rafting of sediment by nearshore fast ice formation, frazil ice, and ice gouging; bioturbation which completely mixes the shelf sediments; and benthic surficial feeding by walrus in all shelf areas to at least 85 m water depth and by gray whales in the Chukchi and East Siberian seas.

Previous investigations where sediment cores have been obtained consist of ice stations and ships (Figures 9, 10, 11 and 12). Ice-station T3 (1963–1974) obtained 580 cores. The T3 cores, which are in excellent condition, are archived at the University of Wisconsin (Dave Clark, personnel communication) and represent the most extensive set of Arctic cores. Over 400 cores obtained from the Laptev, East Siberian, and Chukchi seas, which are also in excellent condition are archived at Oregon State University (Peter Clark, personnel communication). Both the T3 and shelf areas cores were obtained by gravity and piston cores which during the coring operations the upper surficial part of the core is generally lost. The cores obtained in the Chukchi Sea since 1981, in Northwind Ridge in 1988 and 1992, and Beaufort Sea-Canada Basin are stored at the U.S. Geological Survey at Menlo Park, California. Excellent cores were obtained in the Greenland–Norwegian Sea, Nansen Basin, Amundsen Basin, Lomonosov Ridge, and Makarov Basins from 1986 to 1992 by the Germans and are stored at Alfred Wegener Institute for Polar and Marine Research, Bremerhaven.

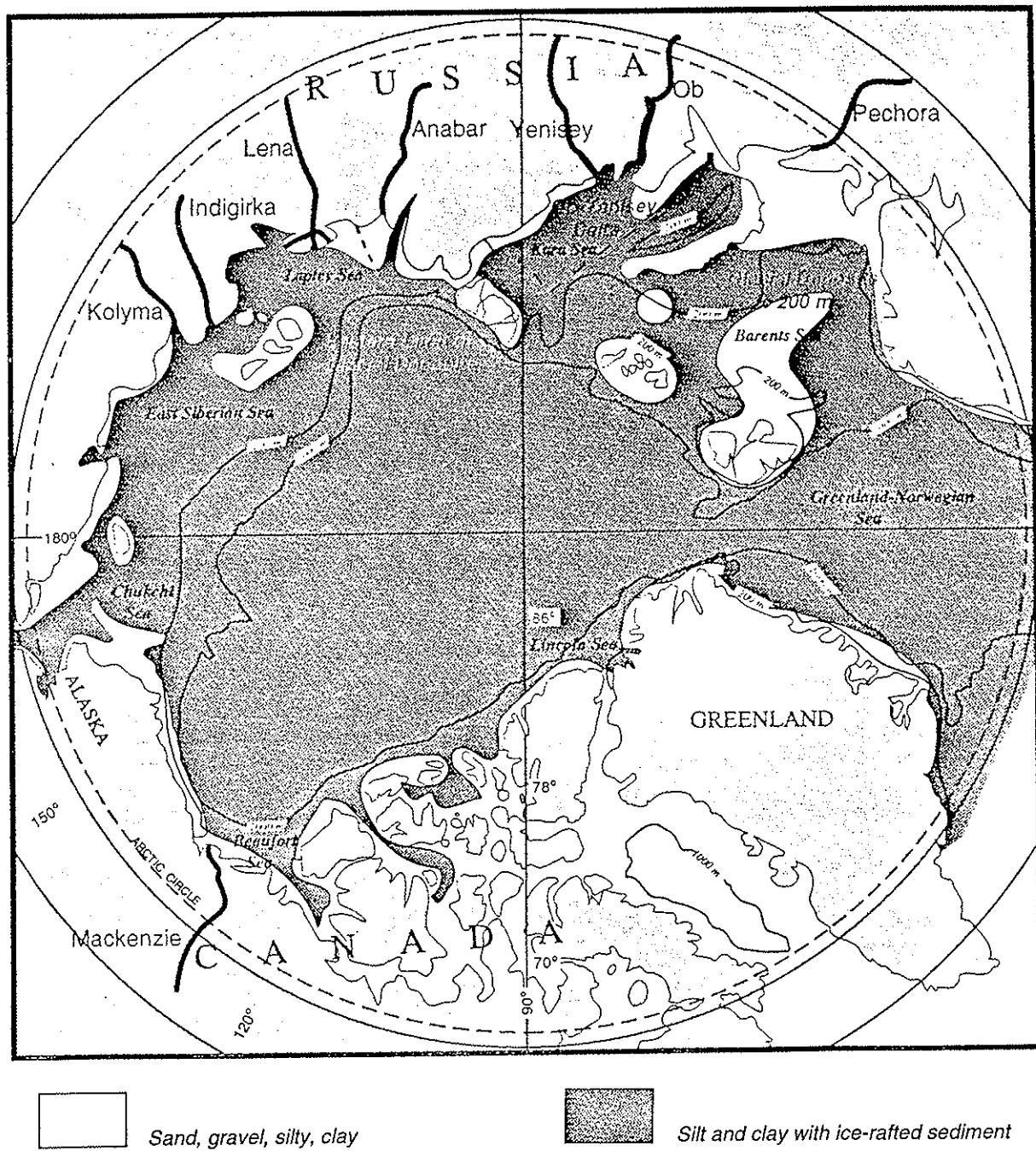


Figure 1. Surface textures of the Arctic Ocean. Brown mud, containing ice rafted clasts, covers most of the Arctic Ocean Basin and can be found as shallow as 60 m on the shallow seas. The epicontinental seas contain variable sediment textures consisting of mud, sand, and gravel but usually contain a mixture of the three textures.

AEOLIAN (<1%)

COASTAL EROSION (Up to 35 m/year)

RIVERS (Silt/clay, prograding deltas)

BIOGENIC (11-29%)

CHEMICAL (Fe/Mn nodules/coatings)

EROSION OF SHELF AREAS (Ice rafting by sea ice, glaciers)

Figure 2. Sediment sources in the Arctic Ocean.

MAJOR FEATURES OF ARCTIC BASINS

1. CONSISTS OF BASINS (some restrictive) SEPARATED BY BATHYMETRIC HIGHS.
2. RANGE IN DEPTHS FROM 4000 M (Nansen Basin) TO AS SHALLOW AS 279 M ON BATHYMETRIC HIGHS (Chukchi Borderland).
3. SEDIMENTATION--TURBIDITES IN BASINS (1 M/1000 years, Canada Basin); ICE-RAFTED SEDIMENT IN BASIN AREAS LACKING TURBIDITES (1 to 2 mm/1000 years); TO CYCLIC ICE-RAFTED/NON ICE-RAFTED SEDIMENT ON BATHYMETRIC HIGHS (up to 4 cm/1000 years).
4. BIOTURBATED DARK BROWN MUD, 10-20 CM THICK, CONTAINING ICE-RAFTED CLASTS BLANKETS ALL OF ARCTIC SEA FLOOR (to as shallow as 50 m depth on epicontinental seas).
5. CONTAINS ABUNDANT MICROFOSSILS.
6. Fe/Mn MICRONODULES AND COATINGS ON GRAINS COMMON TO RARE.

BASIN PROCESSES

1. ICE RAFTING.
2. CURRENTS (erode substrate, locally produce migrating bedform fields as mud waves).
3. BIOTURBATION (mixes sediment, vertical burrows range from 2 to 36 cm depth in sediment).
4. TURBIDITE SEDIMENTATION DOMINATES DEEP OCEAN BASINS, SAND/GRAVEL-RICH NEAR GLACIAL SOURCES, MUD-RICH IN DISTAL BASIN REGIONS (in restricted basins turbidite sedimentation only active during glacial periods).
5. BASINS SLOPES GENERALLY EROSIONAL WITH BEDROCK OR OVERCONSOLIDATED SEDIMENTS NEAR SEDIMENT/WATER INTERFACE.

Figure 3. Major features of the Arctic Basin and deep basin sedimentation processes.

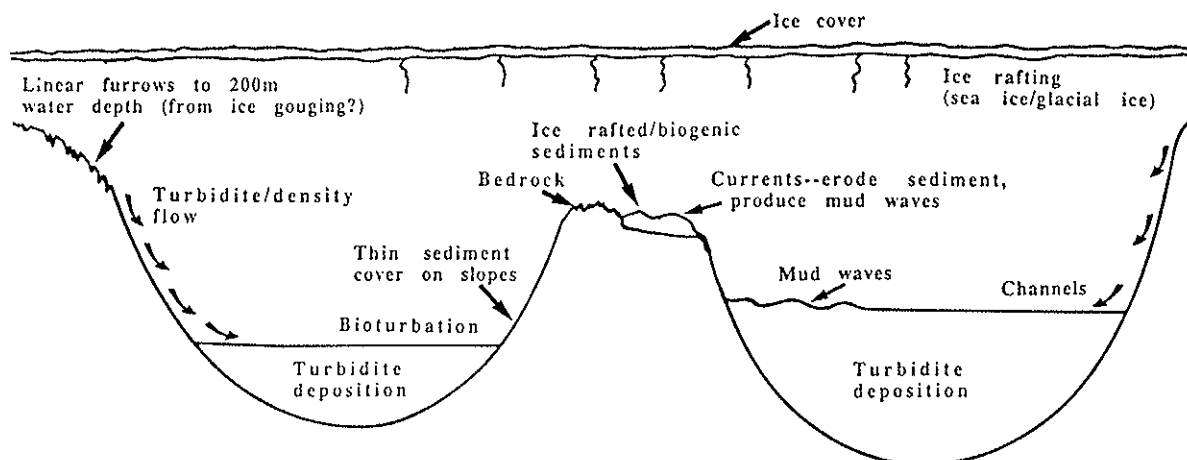


Figure 4. Sediment processes occurring with the Arctic basin. Turbidite deposition dominates most basin regions. Sediments on bathymetric highs and in areas lacking turbidites contain condensed sediment section resulting from ice rafting. Locally bedrock exposures and mud waves can be found on some bathymetric highs; mud waves may be found in some basins.

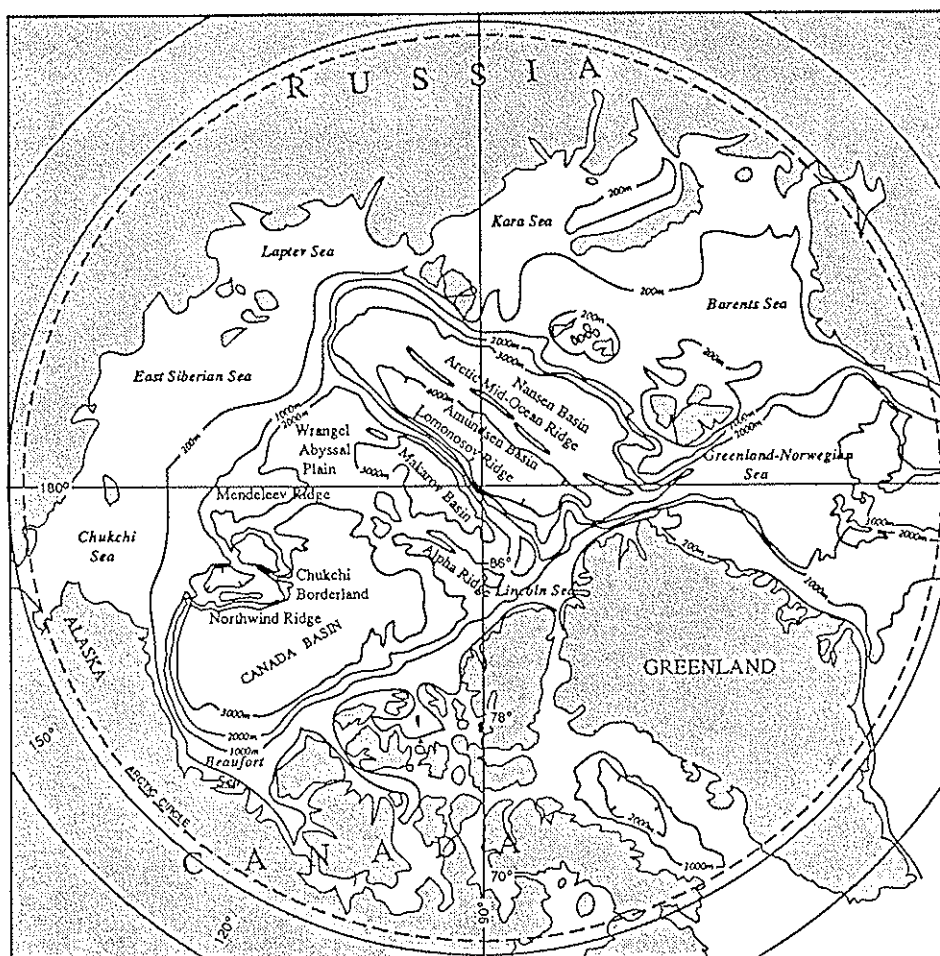


Figure 5. Major bathymetric features of the Arctic Ocean.

SEAS

1. RANGE IN WIDTHS FROM 50 KM (Beaufort Sea), 500-700 KM (Chukchi to Laptev Seas), TO 1500 KM (Barents Sea).
2. SHALLOW--50 TO 60 M DEEP (Barents Sea up to 300+ m deep).
3. MOST CONTAIN SEA VALLEYS/CANYONS/TROUGHS.
4. EROSIONAL.
5. VARIABLE TO PATCHY SEDIMENT DISTRIBUTION AND SEDIMENT TEXTURES CONSISTING OF GRAVEL-SAND-MUD OR MIXED TEXTURES.
6. MAY CONTAIN EXTENSIVE BENTHIC FAUNA.

SHELF PROCESSES

1. CURRENTS (migrating bedform fields).
2. STORMS (reinforce currents, erode sea bed to depths of 100 to 140+ m).
3. BIOTURBATION (mixes sediment, active vertical burrows found up to 1.5 m depth in sediment).
4. ICE GOUGING (to 5 m depth below sea floor, active ice gouging to 70 m water depth, relict glacial ice gouging to 200-500 m water depth).
5. ANCHOR ICE-FRAZIL ICE FORMATION (removes sediment-occurs in less than 100 m water depth?).
6. ICE RAFTING.
7. BENTHIC FEEDING (mixes/disrupts sea bed-walrus all regions, grey whales Chukchi Sea and East Siberian Sea).

Figure 6. Major features of the Arctic epicontinental seas and shelf sedimentation processes.

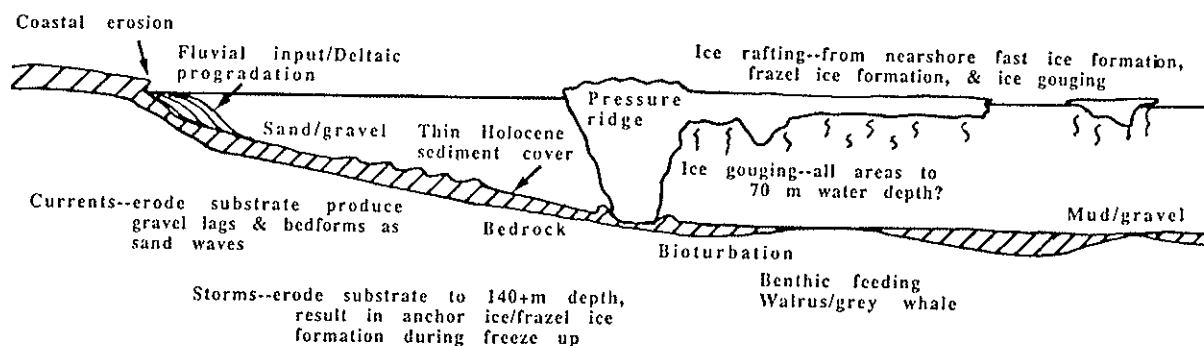


Figure 7. Sediment processes occurring within the epicontinental seas.



Figure 8. Main sea valleys, canyons, and troughs that cut the shallow epicontinental seas.



Figure 9. Areas of coring investigations conducted from ice stations within the Arctic Ocean.

Project	Dates	Number cores	Core Length	Area
Russian	1948-1960	500	1-4 m	Arctic Ocean
POLE-7	1957-1958	600	4.1 m	Makarov-Nansen Basins
ALPHA 1	1957-1958	14	2.5 m	Mendeleev Basin- Alpha Ridge
CHARLIE	1959-1960	22	2.5 m	Canada Basin- Chukchi Borderland
ARLIS II	1962-1965	6+?	<1m	Lomonosov Ridge- Mendeleev Basin
T-3	1964-1973	580	Ave 3m, to 5.5m	Canada Basin- Chukchi Rise- Alpha Ridge
LORAX	1979	42	0.2-1.7 m	Lomonosov Ridge
FRAM I-IV	1979-1982	9+	<1m	Fram-Nansen Basins
CESAR	1983	36	1.3-7.5 m	Alpha Ridge

Figure 10. Ice station sediment cores.



Figure 11. Areas of coring investigations conducted from ships within the shallow epicontinental seas and basins.

SHIPS Arctic Basin				
Project	Dates	Number cores	Core Length	Area
RUSSIAN	?	Numerous cores	?	Arctic Ocean
YMER-80	1980	33+	?	Nansen Basin- Norwegian- Greenland Sea
U.S.	1970-71	20	2.5-12m	Beaufort Sea- Canada Basin
U.S.	1988,92	60	0.5-7.8m	Northwind Ridge
U.S.	1989	26	1.6-6.4m	Beaufort Sea- Canada Basin
GERMAN	1986	?	0.3-6m	Greenland- Norwegian Sea
GERMAN	1988	28	0.3-4.5m	Nansen Basin- Yermak Plateau
GERMAN	1991	140	0.3-16.9m	Lomonosov Ridge, Admundsen-Nans Basin
SHIPS Shelf Areas				
Project	Dates	Number cores	Core Length	Area
RUSSIAN	1950-92	Numerous cores	<8m	Barents to Chukcl Seas
FINNISH	1957	41	1-7.2m	Barents Sea
CANADA	1960-90	300+	?	Beaufort Sea
U.S.	1965	65	<1.5m	Kara Sea
U.S.	1962-65	100	<1.5m	Laptev Sea
U.S.	1962-64	147	0.4-6m	East Siberian Sea
U.S.	1959-1992	400+	0.4-7m	Chukchi Sea
U.S.	1970-1985	130	To 6m	Beaufort Sea
GERMAN	1987	?	0.3-6m	Barents Sea
GERMAN	1992	31	0.8-0.9m	Kara-Barents Sea

Figure 12. Cores recovered from ships in the Arctic basin and shelf areas.

The Permafrost Environment

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Permafrost occurs throughout the Arctic, both on land and on the continental shelves. Unlike sea ice, snow cover and glaciers, permafrost is not visible to the human eye, and in fact, by strict definition it is simply a thermal condition of earth; that is earth material which remains below 0°C continuously for more than two years. By this definition, water may occur as an unfrozen liquid as is the case of saline sediments or occur as massive sheets of below ground ice. Permafrost can be “dry” or lacking moisture, but in most cases, permafrost is consolidated by interstitial ice. The term “permafrost” was coined in the English language by Simon Muller during World War II and was based on the extensive Russian literature on perennially frozen ground that dates back to its discovery in Yakutsk in the early 1800s.

Approximately 20% on the earth’s surface is underlain by permafrost (Figure 1). It develops where there is a negative heat balance at the ground surface; commonly associated with mean annual air temperature of –3°C. The oldest existing permafrost is thought to have formed 1.5-2.2 million years ago. During the glacial and interglacial periods, permafrost formed and thawed as climatic conditions oscillated. Evidence of these events are inferred from fossil mammal and other organic remains and casts of ice wedge that formed under colder conditions. The thickness of the perennially frozen ground is a function of surface climate, thermal conductivity of the sediments and rocks and time. In the colder, high latitudes, the thickness can exceed 700 m and reflects long periods colder than present. Changes in the geothermal gradients of permafrost reveal subtle changes in surface climate and environments and therefore provides permafrost with a memory of prior conditions.

Subsea or offshore permafrost developed when the continental shelves were exposed to cold subaerial periglacial environments. With inundation of the shelf and shoreline transgression, the cold subsea permafrost warmed, disappeared or is still preserved under the shallow, ice-covered waters of the shelf.

The distribution of land permafrost demonstrates a marked latitudinal zonation with the colder and more continuous zone in the north and the warmer and more discontinuous to sporadic occurrence to the south. Permafrost occurs in over half of Russia and Canada, 85% of Alaska, and 20% of China, as well as at higher elevations in most mountainous regions. Sections of older or “relict” permafrost are preserved at depth in some regions such as West Siberia. The upper layer above permafrost that freezes and thaws annually is termed the “active layer.” Its thickness varies based on climate, vegetation and material type from several decimeters in peats to several meters in well-drained materials. In the continuous zone, permafrost may be absent beneath rivers and deep lakes, thus providing connections with unfrozen zones below the permafrost (Figure 2).

Ground ice is perhaps the most important feature of permafrost terrain. Several forms are recognized ranging in size from microscopic to massive: pore ice, segregated ice, ice wedge ice, pingo ice and buried ice of various origins. Ice wedges develop over time and serve as important stratigraphic and environmental indicators. The distribution and quantity of ground ice are important in engineering design and environmental protection, since upon melting the ice-rich ground loses strength and volume and fails on slopes. Passive construction techniques require the preservation of the ground ice to avoid subsidence and erosion.

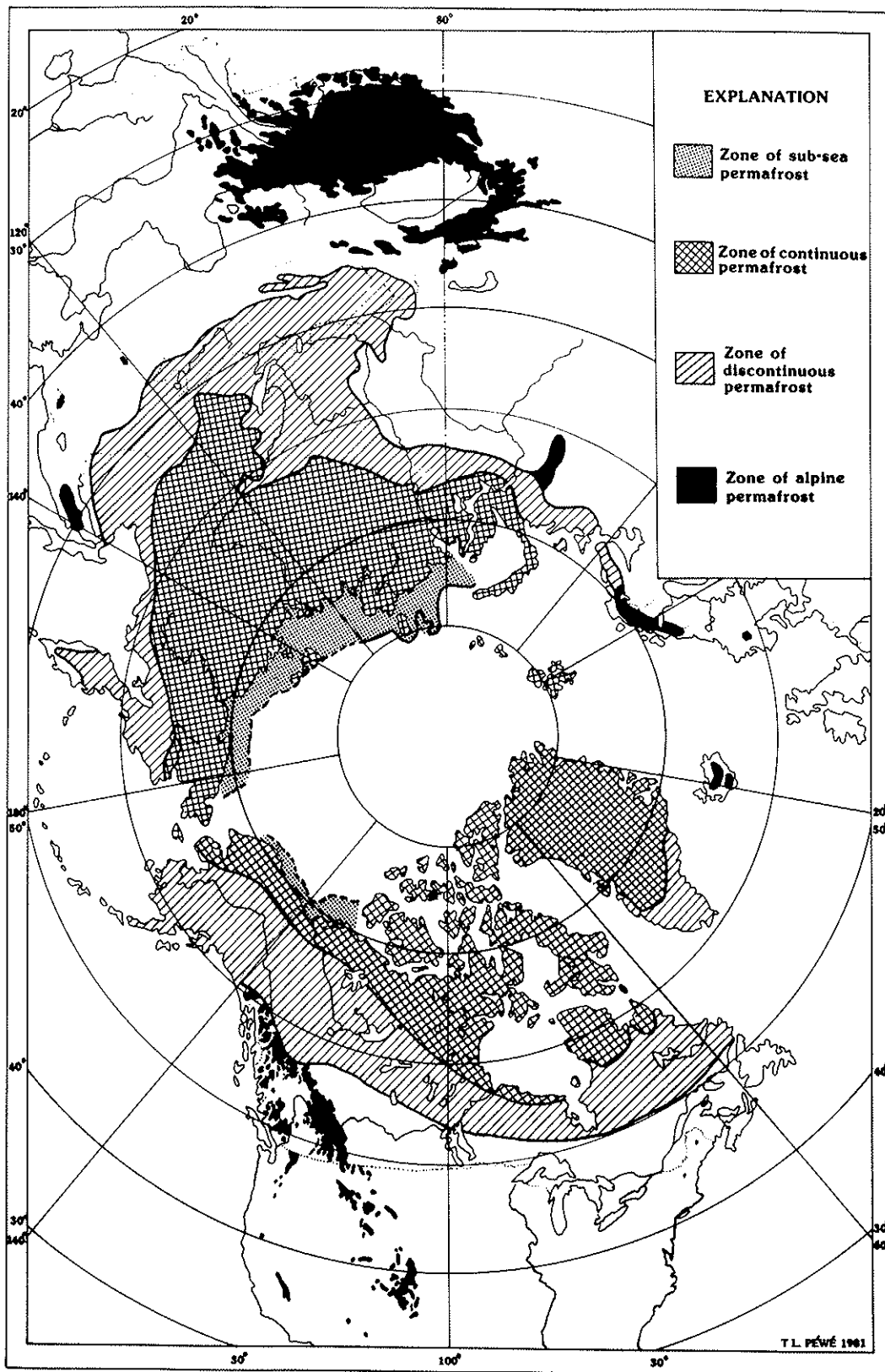


Figure 1. Distribution of permafrost in the Northern Hemisphere. Isolated areas of alpine permafrost not shown on the map exist in the high mountains and outside the map area in Mexico, Hawaii, Japan, and Europe. (From Péwé, 1991).

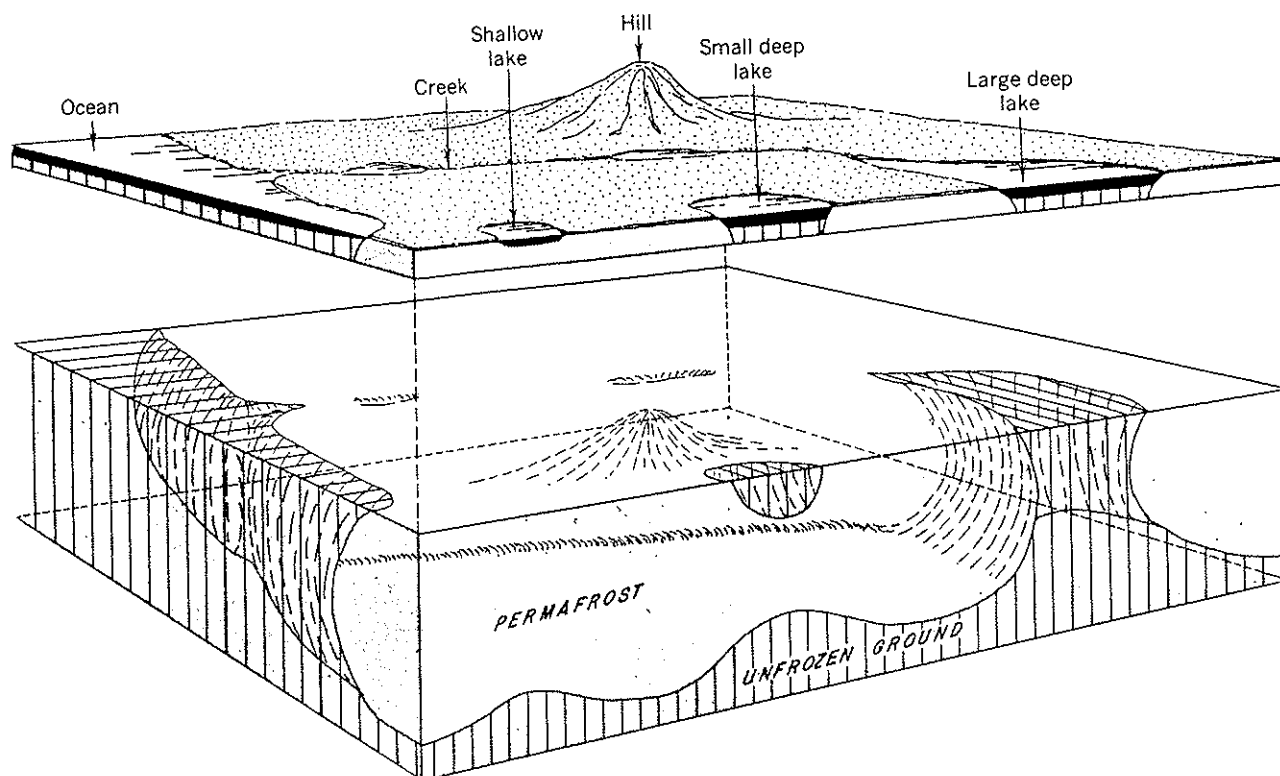


Figure 2. Cutaway block with surface lifted, showing the effect of surface features on the distribution of permafrost in the continuous permafrost zone. (From Péwé, 1991).

In order to provide a unified map of permafrost and ground ice conditions of the Northern Hemisphere and at a scale containing representative, comparative details, the International Permafrost Association undertook to prepare a circumarctic map of permafrost conditions at a scale of 1:10,000,000. The map is a cooperative effort of the geological surveys and ministries of the U.S., Canada and Russia and is scheduled to be printed by the USGS within the year (see draft poster display). Other regional geocryological maps at one million scale have recently been published for West Siberia and Northwestern Canada.

From this brief summary, it can be said that permafrost conditions serve both to contain and enhance the movement of contaminants. Contaminants contained in permafrost can be released as the ground thaws. Since cold, ice-cemented permafrost is essentially impervious, there have been attempts and suggestions to use it for liquid storage and disposal of wastes. On the other hand, since permafrost terrain has unfrozen conduits, these can serve as pathways for movement of contaminated surface and ground waters. The thin, active layer can absorb, contain and even concentrate contaminants, but when frozen can result in accelerated runoff of surface contaminants. The physical-chemical properties of frozen ground must be understood and considered when assessing and developing mitigation for Arctic contamination.

Finally, a great deal is known about permafrost; however, information is scattered through many engineering and scientific disciplines, publications and languages. Over half of the current world literature is in Russian. Fortunately, several readily available bibliographic sources are available and include the CRREL-sponsored Cold Regions Science and Technology Bibliography which is also available on a CD-ROM and on-line retrieval. In conjunction with the international permafrost conferences held every five years, a bibliography of world permafrost is prepared and published as part of the National Snow and Ice Data Center's series *Glaciological Data*. The most recent five-year compilation was prepared for the Sixth International Conference on Permafrost held in Beijing in July 1993 (Brennan, 1993).

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Characterization of the Arctic Environment

Marine Biological Resources

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Characteristics of the Arctic Marine Ecosystems

The Arctic Ocean with its permanent ice cap and seasonally fluctuating ice pack is the major dominating influence on the northern high latitude ecosystems. The "Arctic," as defined by the Arctic Research and Policy Act of 1984, includes all U.S. and foreign territory north of the Arctic Circle (Beaufort and Chukchi seas) plus the Bering Sea. This is reasonable since the ice pack may extend down into the southern Bering Sea during the winter, resulting in "Arctic" conditions far south of the Arctic Circle.

Arctic marine ecosystems are characterized by seasonally limited sunlight, ice cover that inhibits energy penetration (photic and mechanical), low mean temperatures, low species diversity (seasonally high numbers of individuals of a few species), low annual biological productivity (with short bursts of reproduction and growth during the summer), extreme seasonal differences in numbers of individual organisms, and long-lived organisms with high lipid levels.

In comparison with the Arctic Ocean, both biological diversity and production are relatively high in the Antarctic Ocean. Dunbar (1982) has suggested that the degree of specialization toward a polar environment (as indicated by typical Antarctic species) which is more advanced in the southern polar region, might be explained by the relative youth of the Arctic as compared to the Antarctic. The permanent ice cover in the Antarctic has persisted for over 14 million years, while in the Arctic it is relatively young, only about 3 million years old (Shackleton, 1982). Also on a time scale of decades to a few thousand years, general oceanographic conditions in high latitudes appear to have changed markedly and possibly repeatedly, thus preventing the evolution of a mature and fully developed ecosystem.

Some of the differences in the biological characteristics of the earth's polar marine systems may also be explained by the ice caps themselves and their relationship to rest of the world's oceans. The ice cap of the Antarctic covers a continent, while that of the Arctic provides a central cover for the ocean itself. The Antarctic ocean has free exchange with both the Atlantic and Pacific oceans; exchange between the Arctic Ocean and other bodies of water are much more limited.

The paucity of fauna and flora in the Arctic Ocean is well known. Dunbar (1982) attributes this to low primary production and extreme seasonality of the environment. The low primary production is directly related to the high water column density stratification and vertical stability due to the presence of an ice cover over the ocean. The ice cover also limits light penetration and primary production. In much of the Arctic, the ice front is near land and during much of year it is continuous with the land, while in the Antarctic the ice edge is associated with deep ocean upwelling areas and the normally associated high primary production.

Although published values vary widely within regions of the Arctic, it appears that primary production increases with decreasing latitude from the high Arctic ice pack (see Table 1). Arctic ecosystems generally have fewer species than ecosystems of lower latitudes; therefore, food webs are relatively simple, although food chains are not necessarily short. Mean production and biomass are low (nutrient limited), there are large seasonal fluctuations and systems tend to be unstable and subject to large fluctuations extending beyond the seasons (Baker and Angel, 1987). Faunal resources are characterized by large numbers of individuals of relatively few species, most of which are migratory and concentrate in large aggregations during the breeding

Table 1. Primary production estimates ($\text{g cm}^2 \text{yr}^{-1}$) for Arctic marine regions.

<i>Region</i>	<i>Production</i>	<i>Source</i>
Arctic:		
Arctic Ocean	0.6–5	Dunbar, 1986
Barents Sea	60	Roy et al., 1987
	25	Dunbar, 1986
	100–150	Falk-Petersen et al., 1990
Balsfjord (Norway)	115	Eilertsen & Tassen, 1984
Spitsbergen fjords	150	Eilertsen et al., 1989
Greenland	30–100	Dunbar, 1986
Godhaven	90	Anderson, 1977
Dumbell Bay (Ellesmere I.)	9–12	Dunbar, 1986
Davis Strait	50	Dunbar, 1986
Lancaster Sound	54	Welch et al., 1992
	74	Dunbar, 1986
Cornwallis I.	15–32	Dunbar, 1986
Beaufort Sea	9–18	Dunbar, 1986
	15–40	Schell, 1983
Chukchi Sea	18–28	Dunbar, 1986
including Kotzebue S.	75–100	Schell et al., 1988
Arctic Transitional:		
Bering Sea	20–150	McRoy & Goering 1976
	75–250	Dunbar, 1986
Subarctic:		
Gulf of Alaska	48	Dunbar, 1986
	50–300	Sambrotto & Lorenzen, 1986

season. Arctic fauna are usually long-lived, have high adult survival rates, exhibit deferred age of first reproduction in females, and have relatively low reproduction rates (Cooch et al., 1987).

Marine Biota of the United States **Arctic: Comparison of the** **Beaufort, Chukchi, and Bering Seas**

The narrow and relatively shallow Bering Strait, which separates the Chukchi and Bering seas, is an important geographical region in the U.S. Arctic. It is the point of nutrient exchange between the North Pacific (via the Bering Sea) and Arctic Ocean. Relatively high velocity current flows through the Bering Strait carrying particulate and dissolved material from the northern Bering Sea (inorganic nutrients and organic carbon, including input from the Yukon River) into the southeastern Chukchi Sea. It also acts as a funnel for the movement of seasonally migrating fish, birds, and marine mammals between these regions. Seasonal ice conditions here have a major bearing on the timing of migration between the Arctic Ocean and the Bering Sea.

Biologically, the southern portion of the Bering Sea, including the Pribilof Islands south to the Aleutian

Chain and Bristol Bay, can be considered as part of the North Pacific Ocean. Northward of this area, the Bering Sea is increasingly influenced by the Arctic. The Bering Sea, therefore, represents a region of transition between the subarctic North Pacific Ocean and the Arctic Ocean. In the Bering Sea, ice-frequenting marine mammal species (ringed seals, bearded seals, beluga whales, bowhead whales, walrus, etc.) overlap in distribution with those marine mammal species characteristic of the ice-free North Pacific (harbor seals, Steller sea lions, northern fur seals, killer whales, Dall's porpoise, etc.).

Although coastal lagoons, inland streams, and tundra lakes of the Beaufort Sea coast provide major habitat for very large numbers of shorebirds and waterfowl during the summer season (May–September), the seabird populations north of the Bering Strait are relatively small when compared to that of the Gulf of Alaska and southern Bering Sea. Although this is related to differences in primary production, the scarcity of suitable coastal cliffs for nesting is also an important factor in the case of colonial seabirds. The most northern major seabird colonies are located at Cape Lisburne in the eastern Chukchi Sea and extend from there southward through the northern Bering Sea to include Cape

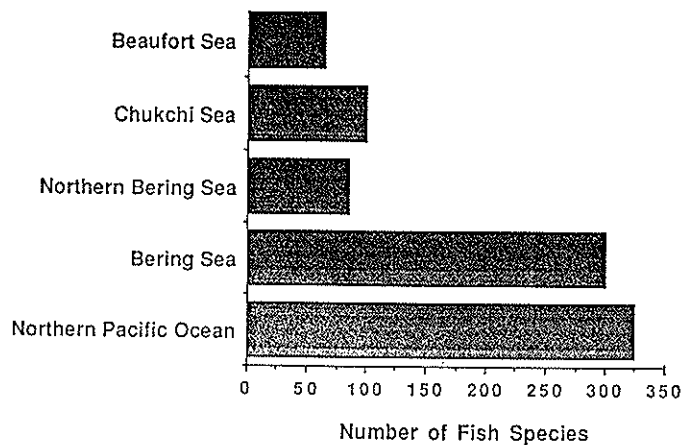


Figure 1. Comparison of number of fish species occurring in the Beaufort, Chukchi, and Bering seas, and North Pacific Ocean. From Truett and Craig (1985).

Lewis, Cape Thompson, Kotzebue Sound, Little Diomed Island, Bluff (Norton Sound), and St. Lawrence Island.

Dunbar (1982) has pointed out that, in contrast to what is the general pattern at lower latitudes, the top predator level in the arctic marine ecosystems is dominated by mammals rather than fish. Even in the peripheral northern seas, fish appear more important than in the Arctic. This pattern of decrease in the number of fish species from the Beaufort Sea to the North Pacific is reflected in Figure 1.

Information on invertebrate communities of the Beaufort, Chukchi, and Northern Bering seas suggests that the region of North Pacific/Arctic transition extends into the Chukchi Sea. Wolotira (1980) has pointed out that the offshore benthic community of the northern Bering/ eastern Chukchi seas is characteristic of the Pacific Boreal, and that this might be due to a restricted access to the Bering Sea via the Bering Strait and prevailing northward water currents impeding southerly dispersals of invertebrates. In the Eastern Chukchi Sea, the epibenthos is dominated by echinoderms, particular the starfish, *Asterias amurensis*. Although productivity and species diversity is relatively low, the standing biomass of the benthos is higher here than in the southern Bering Sea, which may be due to an associated scarcity of benthos feeding demersal fish (Feder and Jewett, 1988).

Ice as an Ecological Factor

The role of the polar pack ice in limiting primary production and the seasonal patterns in its growth and retreat have already been mentioned. The polar ice has a major role in the kind of marine food webs that occur here and the species that constitute these webs. In order to respond to the seasonal Arctic freeze-up, biota have two options: they have to adapt physically and physiologically to maintain themselves in the ice and take advantage of the limited resources, or they have to

migrate out of the Arctic during the winter. The latter appears to be the major choice of marine birds and waterfowl, most marine mammals (ringed seal and polar bear being exceptions), and fish. In the case of fish, certain anadromous species appear in Arctic marine waters only as transients between natal streams and subarctic oceanic rearing areas (salmon), others that have spent the summer feeding in the Arctic marine waters migrate back into Arctic coastal streams to overwinter (arctic char), while others (arctic cod) remain in the Arctic marine waters to feed under the ice on the limited food resources.

Adaptation of the invertebrate fauna to seasonal ice formation is quite important for maintaining the few vertebrate species that do overwinter in the Arctic. The benthos of lagoons and shallow nearshore areas, such as occurs in the Beaufort Sea, are dominated by epibenthic invertebrates (e.g., mysids, amphipods, and isopods). The infauna is limited to an impoverished community of chironomids and enchytraeid worms (oligochaetes). These shallow habitats (< 2 m) freeze to the bottom during the winter and salt exclusion leads to hypersaline waters in deeper areas. During freeze-up, most epibenthic invertebrates either move into deeper waters offshore or die in the hypersaline water. Mobile epifauna recolonize the denuded nearshore areas annually during break-up and increase in numbers and biomass during the summer (Carey et al., 1987).

The polar ice gives rise to an under-ice food web based on phytoplankton blooms in ice (diatoms) supporting under-ice dwelling invertebrates (copepods and amphipods: *Onisimus glacialis*; *Apherusa glacialis*; *Gammarus wilkitzkii*), an overwintering fish community (arctic cod and polar cod), and ringed seals. Although algae occurs on the underside and the lower portion of the ice itself from the beginning of freezeup, with the onset of lengthening of the daylight during the spring, the bloom within the ice actually begins (May-June in the Beaufort Sea) with an accompanying increase in the

numbers of the copepods and amphipods associated with this community. With breakup, the ice-associated algae is released into the water column to add to the primary production bloom originating in the water column itself.

During the winter, the pack ice coupled with the

shorefast ice restricts access to the water by birds and mammals and prevents movement through certain regions. During spring breakup and throughout the summer, the sea ice provides habitat for these animals and serves several functions. As shelter, ice provides cover from predators and moderates the effect of wind by

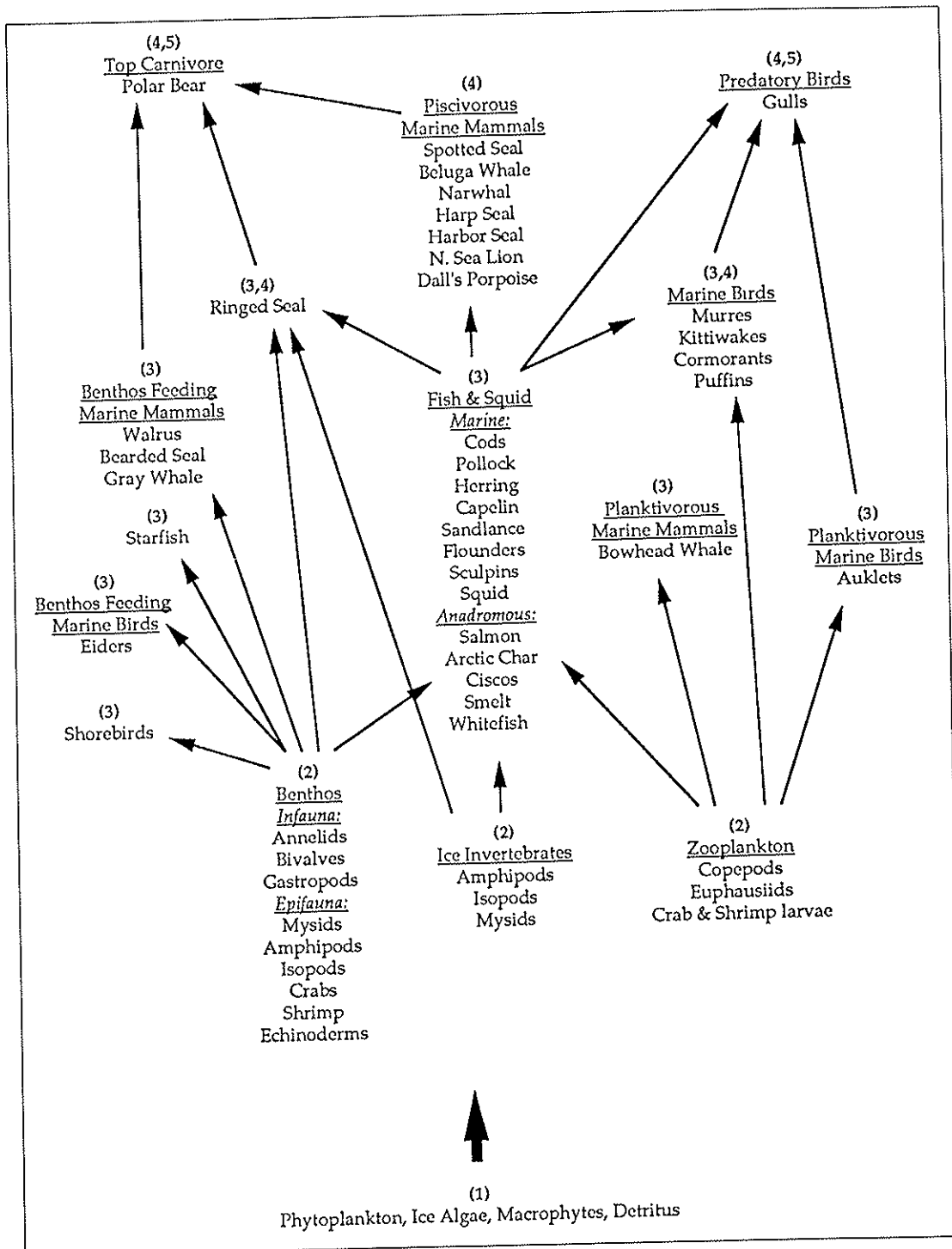


Figure 2. Generalized composite food web of the Arctic marine ecosystem. The number in parenthesis indicates trophic level in ascending order. Examples of each major category of biota are also listed.

creating areas of calm water. The sea ice also increases the area available to resting birds and to mammals for hauling out and bearing their young, therefore eliminating crowded conditions that are associated with island rookeries. The sea ice provides a platform for pinnipeds, such as walrus and bearded seals, to feed on the benthic foodbase found in the central basin of the relatively shallow Bering Sea. In the case of walrus, the retreating ice front also provides a means of transporting the resting animals northward into the Chukchi Sea while minimizing their expenditure of energy.

It appears that relatively high biological production occurs at the edge of the ice pack (ice front). As compared to the Antarctic, however, the Arctic has a poorly developed pagophilic avifauna. This may be due to the fact that in the Antarctic, the ice front is associated with the deep ocean where upwelling occurs, while in the Arctic Ocean most of the ice front is directly surrounded by land (Divoky 1981). Although the total biomass of Arctic pagophilic birds is small when compared with the remainder of the arctic seabirds or with the Antarctic pagophilic species, the Arctic ice front

appears to be important to pelagic birds where it abuts subarctic waters (Bering Sea in winter, or in certain areas of the eastern Arctic, such as Spitsbergen) or in areas where polynyas are maintained. The ice front is the only habitat utilized by wintering ivory gulls in the Western Arctic. Two arctic species of birds have major adaptations to the ice environment, ivory gulls and black guillemot, and Ross's gull is associated with ice for much of the nonbreeding season.

Trophic Level Components of Arctic Marine Food Webs

A scheme describing a generalized, composite food web for Arctic marine ecosystems is presented in Figure 2. This scheme combines nearshore coastal lagoon and offshore marine systems, and is based on published descriptions of food webs in selected regions of the Beaufort, Chukchi, and Bering seas, and Lancaster Sound (Carey et al., 1987; Truett, 1984; Truett and Craig, 1985a, 1985b; Welch et al., 1992). A more complete listing of major species that comprise each of these food webs is provided in Table 2.

Table 2. Selected Arctic Food Webs (from Carey et al., 1987; Truett, 1984; Truett and Craig, 1985a, 1985b; Welch et al. 1992). Number indicates trophic level in ascending order.

NORTHERN BERING SEA — Nearshore

- (1) **Energy Base:** phytoplankton, detritus, vascular plants
- (2) **Zooplankton:** copepods
- (2) **Infauna:** polychaetes, bivalves
- (2,3) **Epifaunal invertebrates:** mysids, amphipods, isopods
- (3,4) **Fish:** arctic cod, *Boreogadus saida*; saffron cod, *Eleginus gracilis*; chinook salmon, *Oncorhynchus tshawytscha*; coho salmon, *O. kisutch*; chum salmon, *O. keta*; pink salmon, *O. gorbuscha*; capelin, *Mallotus villosus*; pacific herring, *Clupea harengus pallasii*; sand lance, *Ammodytes hexapterus*; ciscoes, *Coregonus* spp.; whitefish, *Coregonus* spp.; Arctic char, *Salvelinus alpinus*
- (2,3,4) **Birds:** shorebirds; ducks; sandhill crane, *Grus canadensis*; black brant, *Branta bernicla*; tundra swan, *Cygnus columbianus*; gulls; terns; murre; kittiwakes; cormorants; horned puffin, *Fratercula corniculata*
- (3,4) **Mammals:** ringed seal, *Phoca hispida*; spotted seal, *Phoca largha*; beluga whale, *Delphinapterus leucas*.

NORTHERN BERING SEA — Offshore

- (1) **Energy Base:** detritus-based food webs, phytoplankton production
- (2) **Zooplankton:** copepods, decopod & barnacle larvae, euphausiids, (2) Infauna: polychaetes, bivalves
- (2,3) **Epifaunal invertebrates:** red king crab, *Paraligthodes*; blue king crab, *P. platypus*; Tanner crab, *Chionoecetes bairdi* and *C. opilio*; echinoderms (*Asterias amurensis*, *Gorgonocephalus caryi*, *Lethasterias namimensis*, *Evasterias chinosoma*, *Leptasterias polaris*, *Strongylocentrotus droebachiensis*); gastropods (*Neptunea heros*)
- (3,4) **Fish:** arctic cod, *Boreogadus saida*; saffron cod, *Eleginus gracilis*; chinook salmon, *Oncorhynchus tshawytscha*; coho salmon, *O. kisutch*; chum salmon, *O. keta*; pink salmon, *O. gorbuscha*; pacific herring, *Clupea harengus pallasii*; rainbow smelt, *Osmerus eperlanus*; starry flounder, *Platichthys stellatus*; shorthorn sculpin, Alaska plaice, *Pleuronectes quadrituberculatus*; yellowfin sole, *Limanda aspera*; walleye pollock, *Theragra chalcogramma*.
- (2,3,4) **Birds:** least auklet, *Aethia pusilla*; crested auklet, *A. cristatella*; parakeet auklet, *Cyclorhynchus psittacula*; short-tailed shearwater, *Puffinus tenuirostris*; blacklegged kittiwake, *Rissa tridactyla*; thick-billed murre, *Uria lomvia*; common murre, *U. aalge*; horned puffin, *Fratercula corniculata*; tufted puffin, *F. cirrhata*
- (3,4,5) **Mammals:** ringed seal, *Phoca hispida*; ribbon seal, *P. fasciata*; spotted seal, *P. largha*; polar bear, *Ursus maritimus*; walrus, *Odobenus rosmarus*; beluga whale, *Delphinapterus leucas*; gray whale, *Eschrichtius robustus*; bearded seal, *Erignathus barbatus*; bowhead whale, *Balaena mysticetus*.

Table 2 (cont'd). Selected Arctic Food Webs.

BEAUFORT AND CHUKCHI SEAS — Coastal Lagoons

- (1) **Energy Base:** old carbon detritus (peat), terrestrial carbon (river input + peat), marine primary production (60–70%).
- (2) **Infafauna (depauperate):** chironomids; oligochaetes.
- (2) **Epibenthic invertebrates:** mysids (*Mysis relicta*, *M. litoralis*, *Neomysis intermedia*, *N. rayii*); amphipods (*Apherusa glacialis*, *Gammaracanthus loricatus*, *Gammarus setosus*, *Pontoporeia affinis*, *Onisimus glacialis*); isopods (*Saduria entomon*)
- (3) **Fish:** anadromous (Arctic cisco, *Coregonus autumnalis*; least cisco, *C. Sardinella*; broad whitefish, *C. nasus*; humpback whitefish, *C. clupeaformis*; Arctic char, *Salvelinus alpinus*; chum salmon, *Oncorhynchus keta*; pink salmon, *O. gorbuscha*; boreal smelt, *Osmerus eperlanus*; in Chukchi Sea as far south as Peard Bay); marine (saffron cod, *Eleginus gracilis*; sand lance, *Ammodytes hexapterus*; capelin, *Mallotus villosus*; pacific herring, *Clupea harengus pallasii*; Fourhorn sculpin, *Myoxocephalus quadricornis*; Arctic cod, *Boreogadus saida*)
- (3,4) **Birds:** black guillemot, *Cephus grylle*; arctic tern, *Sterna paradisae*; Ross's gull, *Rhodostethia rosea*; Sabine's gull, *Xema sabini*; black-legged kittiwake, *Rissa tridactyla*; red phalarope, *Phalaropus fulicarius*; northern phalarope, *P. lobatus*; oldsquaw, *Clangula hyemalis*; black brant, *Branta bernicla*; glaucous gull, *Larus hyperboreus*; snow goose, *Chen caerulescens*
- (4) **Marine Mammals:** spotted seal, *Phoca largha*; beluga whale, *Delphinapterus leucas*

BEAUFORT AND CHUKCHI SEAS — Nearshore Pelagic (3 - 20 m)

- (1) **Energy Base:** phytoplankton (80%), ice algae, benthic algae, kelp (Peard Bay; offshore of Skull Cliff; boulder patch in Steffansson Sound; south of Belvedere Island; western Camden Bay; Beaufort Lagoon; Demarcation Bay).
- (2) **Infafauna:** annelids (*Scoloplos armiger*, *Scolecopelides arctius*, *Nephtys caeca*, *Prionospio cirrifer*, *Spio filicornis*, *Ampharete stroemi*, Tubificidae); bivalves (*Boreacola vadosa*, *Cyrtodaria kurriana*, *Portlandia arctica*, *P. intermedia*, *Loxycma fluctuosa*); priapulids (*Halicryptus spinulosus*, *Priapulius caudatus*)
- (2) **Epibenthic invertebrates:** mysids (*Mysis litoralis*); euphausiids (*Thysanoessa raschii*); amphipods (*Pontoporeia femorata*, *P. affinis*, *Onisimus litoralis*, *O. glacialis*); isopods (*Saduria entomon*, *S. sabini*)
- (2) **Zooplankton:** copepods
- (3) **Fish:** marine (arctic cod, *Boreogadus saida*)
- (3,4) **Birds:** black guillemot, *Cephus grylle*; arctic tern, *Sterna paradisae*; Ross's gull, *Rhodostethia rosea*; Sabine's gull, *Xema sabini*; red phalarope, *Phalaropus fulicarius*; oldsquaw, *Clangula hyemalis*; common eider, *Somateria mollissima*; glaucous gull, *Larus Hyperboreus*
- (3,4,5) **Marine mammals:** ringed seal, *Phoca hispida*; spotted seal, *P. largha*; bearded seal, *Erignathus barbatus*; polar bear, *Ursus maritimus*; walrus, *Odobenus rosmarus*; gray whale, *Eschrichtius robustus*

BEAUFORT AND CHUKCHI SEAS — Offshore

- (1) **Energy Base:** phytoplankton, ice algae, advection of particulate carbon and plankton from the Bering Sea
- (2) **Zooplankton:** copepods; decapod and barnacle larvae; euphausiids; mysids; Pelagic hyperiid and gammarid amphipods
- (2) **Infafauna:** polychaetes; bivalves
- (2) **Epibenthic invertebrates:** gastropods; echinoderms
- (3) **Fish:** arctic cod, *Boreogadus saida*
- (3,4) **Birds:** black-legged kittiwake, *Rissa tridactyla*; glaucous gull, *Larus hyperboreus*; short-tailed shearwater, *Puffinus tenuirostris*; ivory gull, *Pagophila eburnea*
- (3,4,5) **Marine mammals:** ringed seal, *Phoca hispida*; bearded seal, *Erignathus barbatus*; polar bear, *Ursus maritimus*; bowhead whale, *Balaena mysticetus*

LANCASTER SOUND

- (1) **Energy Base:** 90% phytoplankton, 10 % ice algae, 1% kelp
- (2) **Zooplankton:** copepods (*Pseudocalanus acuspes*, *Calanus hyperboreus*, *C. glacialis*, *Metridia longa*), ctenophores
- (2) **Infafauna:** *Mya truncata*, *Macoma calcarea*, *Hiatella arctica*, *Serripes groenlandicus*
- (2,3) **Epifaunal invertebrates:** pycnogonids, brittle stars, sea urchins, sea cucumbers, terebellid polychaetes, anemones
- (3,4) **Fish:** arctic cod, *Boreogadus saida*; halibut and squid
- (3,4) **Birds:** thick-billed murre, *Uria lomvia*; northern fulmar, *Fulmarus glacialis*; black-legged kittiwake, *Rissa tridactyla*, black guillemot, *Cephus grylle*; Glaucous Gull, *Larus hyperboreus*
- (3,4,5) **Mammals:** ringed seal, *Phoca hispida*; harp seal, *P. groenlandica*; polar bear, *Ursus maritimus*; walrus, *rosmarus*; beluga, *Delphinapterus leucas*; narwhal, *Monodon monoceros*; bearded seal, *Erignathus barbatus*.

The energy base for the Arctic marine food webs consists of production by marine phytoplankton, ice algae, and macrophytes, plus detritus derived from both marine and terrestrial sources. The relative contribution of each varies depending on the region and the specific system (coastal lagoon, offshore pelagic, etc.); however, it appears that in most if not all cases marine phytoplankton production contributes over half of the energy.

Three inter-linked food webs are based on a combination of phytoplankton production, ice algae, macrophyte production, and detritus: (1) benthic, (2) under-ice, and (3) planktonic. Major components of the under-ice fauna and benthic epifauna include amphipods, isopods, and mysids. These crustaceans play a major role as food organisms for a wide variety of dominant higher organisms, such as over-wintering Arctic and polar cod, marine birds, ringed seals (particular immature individuals), and seasonally migrating gray whales.

Important fish species include both marine species (arctic, polar and saffron cod, arctic flounder, pollock, capelin, herring, and sand lance) and anadromous species (arctic char, salmon, smelt and ciscos). The circumpolar Arctic cod is probably the most abundant fish in the Arctic Ocean. It provides a major food base for numerous marine mammals, including ringed seal, spotted seal, narwhal, and beluga whales, as well as marine birds. Various anadromous fish (salmon, char, cisco, and whitefish) appear to be particularly important in the diet of marine mammals that frequent river mouths on a seasonal basis and use the lagoonal systems of the Arctic (spotted seal and beluga whales). Smaller fish species, such as capelin and sandlance, appear to be important in the diet of marine birds, such as kittiwakes, cormorants, murres, and puffins. In the central and southern part of the Bering Sea, various demersal fish, such as pollock, along with squid are important links in the food web supporting such upper trophic level animals as northern fur seals, northern sea lions, Dall's porpoise, and murres.

In addition to being preyed on by many of the fish species, representatives of the zooplankton community (copepods and euphausiids) provide a food base for one species of Arctic marine mammal (bowhead whale) and three species of planktivorous marine birds (least, crested, and parakeet auklets). As compared to the toothed cetaceans (Dall's porpoise, beluga whale, and narwhal) and most pinnipeds, both the bowhead and gray whale feed at low trophic levels. Two additional marine mammal species that feed at a low trophic level are walrus and bearded seal. A major part of the walrus diet consists of infaunal bivalves, gastropods, and annelids, while the bearded seal preys on these organisms plus shrimp and crabs (epifauna).

The top trophic level in the Arctic is represented by

the polar bear (and humans). Although the major part of the polar bear diet consists of ringed seals, particularly during winter freeze-up, this carnivore also takes other seal species, beluga whale, and walrus when they are available.

Environmental Monitoring of Marine Biota: Items to Consider

Although use of biota to monitor levels and distribution of contaminants in marine systems is certainly not a new idea, most published examples of this approach have involved lower vertebrates (fish) and invertebrates (shellfish). Under the appropriate conditions and depending on the questions being asked some species of marine mammals and birds have also been considered as monitoring tools.

Geographic Distribution

Because of species-specific differences in response to environmental insult, species that have wide geographical distributions may be good candidates for monitoring. Information developed on the species in one region can be particularly valuable in interpreting results for the same species in another region. In some cases, a species from one location can act as a point of reference, as either representing the worst case or the best case example of contaminant body burdens for the same species in other locations. For example, the beluga whale is circumpolar in distribution. Very high levels of anthropogenic contaminants have been found in the Gulf of St. Lawrence population of this species. There are also indications of health and reproductive problems in these animals. The Gulf of St. Lawrence population might provide a measure of the worst case situation that can be used as a point of reference for determining how far other beluga populations are removed from this situation. (At this time however, no direct cause-effect relationship between contaminant loads and physiological problems have been established for these animals.) Other potential circumpolar indicators are: ringed seal, polar bear, bearded seal, arctic cod, and black guillemot.

One also has to consider the advantages and disadvantages of using animals that migrate over vast areas, as compared to those that are residents. For example, benthic organisms such as bivalves can be good candidates for monitoring contaminant loads in a particular bay or other geographically restricted marine system. Arctic cod might be appropriate for a major system, such as the Beaufort Sea, while beluga whales that migrate between the Beaufort Sea and the Northern Bering Sea would reflect the environment of this larger region of the U.S. Arctic. Biota that migrate seasonally out of the Arctic marine system would probably not be good candidates. For example, because of its seasonal

migrations, the contaminant loads in the northern fur seal reflect its exposure to sources ranging from the Bering Sea to the southern California coast (and probably also to the waters off Japan).

Loganathan and Kannan (1991) in their discussion of time perspectives of organochlorine contamination in the global environment point out that: From a spatial viewpoint, the more remote the receptor from the source of contamination, the more gradual the increase in concentration, and the more gradual the decline in concentration once the source is eliminated (e.g., river and coastal systems respond more quickly than open-ocean systems). Open-ocean biota, therefore, may reflect a more steady-state concentration and lesser year-to-year variation in the levels of bioaccumulative contaminants than other marine biota.

Life Span

Long-lived organisms have the potential for accumulating relatively high levels of anthropogenic contaminants; however, this also depends on the capability of the species to metabolize and excrete such compounds. Short-lived organisms (fish and shellfish) respond more quickly to contamination and elimination of the source of contamination than long-lived organisms (humans, marine mammals). Therefore, fish and shellfish are probably better short-term monitors and marine mammals are better long-term monitors.

Long-lived organisms with high metabolic capacity respond more rapidly to source of contamination than long-lived organisms with low metabolic capacity (Lo-

ganathan and Kannan, 1991). It follows that once sources are eliminated, the response (decrease in tissue concentrations) will be slower in the long-lived organisms with low metabolic capacity. Also, long-lived organisms with low metabolic capacity may be subject to greater toxic threat, particularly chronic effects. There is evidence to suggest that cetaceans have a low metabolic capacity to metabolize and excrete chlorinated hydrocarbons, such as PBCs (Tanabe et al., 1988) and therefore may be more sensitive to particularly non-labile chlorinated hydrocarbons, such as PCBs and chlorinated pesticides.

Food Web and Trophic Position

Generally speaking, the higher the trophic level the greater the potential for bioaccumulation. However, it should also be kept in mind that not all substances of environmental concern bioaccumulate and lower trophic level animals might be more sensitive. However, since lower trophic level animals are shorter lived, they may respond more positively to removal of the environmental insult.

Several examples in the literature, in which investigators have quantified the bioaccumulation and metabolism of chlorinated hydrocarbons in food chains, are pertinent to Arctic marine ecosystems. These include: (1) the fate of PCB congeners and chlordanes in the arctic cod-ringed seal-polar bear food chain in the Canadian Arctic (Muir et al., 1988), (2) the fate of PCB congeners in zooplankton-fish/squid-Dall's porpoise food chain in the North Pacific Ocean/ Bering Sea (Tan-

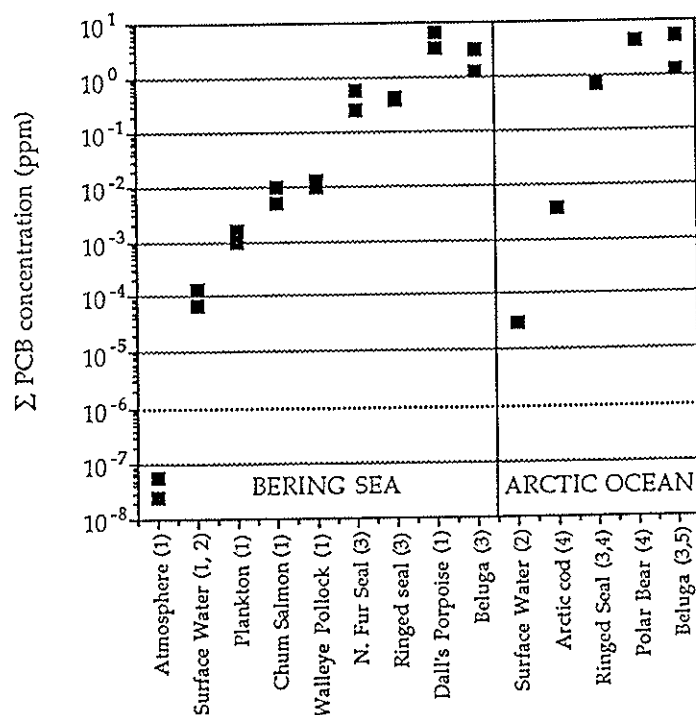


Figure 3. PCB concentration in the trophic components of the Bering Sea and Arctic Ocean. Data from (1) Tanabe and Tatsukawa (1986), (2) Bidleman (1989), (3) Becker et al. (1992), (4) Muir et al. (1988), and (5) Muir et al. (1990).

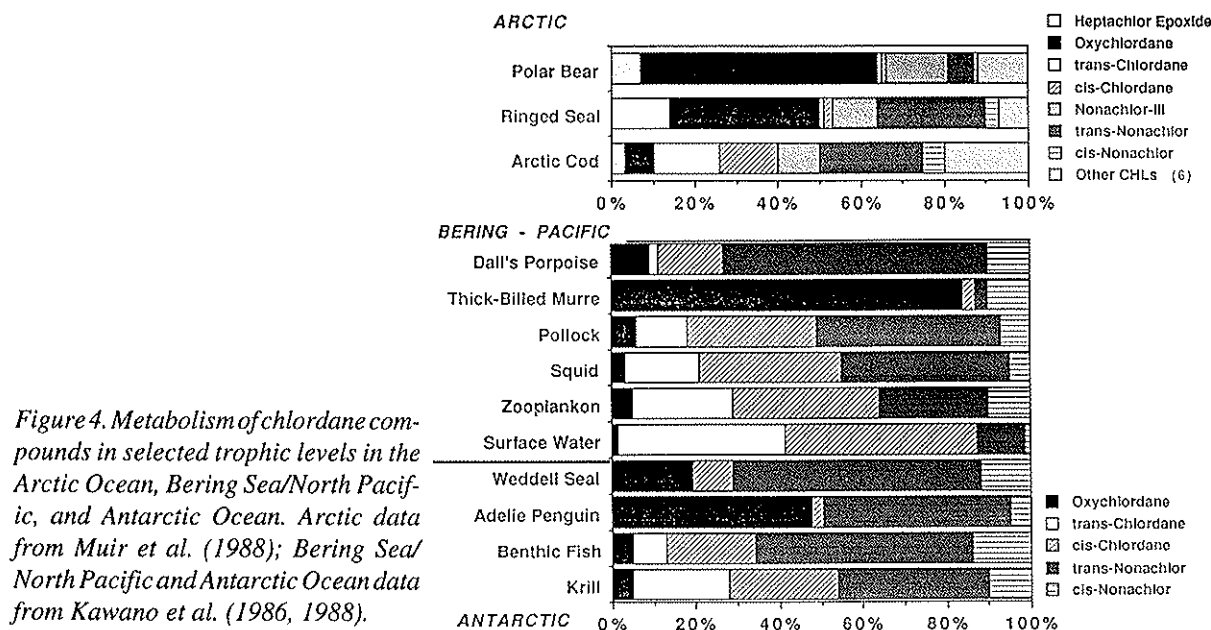


Figure 4. Metabolism of chlordane compounds in selected trophic levels in the Arctic Ocean, Bering Sea/North Pacific, and Antarctic Ocean. Arctic data from Muir et al. (1988); Bering Sea/North Pacific and Antarctic Ocean data from Kawano et al. (1986, 1988).

abe and Tatsukawa, 1986), (3) the selective bioaccumulation of chlordane, DDT, and HCH compounds in the zooplankton-fish/squid-Dall's porpoise/thick-billed murre food web of the North Pacific Ocean/ Bering Sea (Kawano et al., 1988), and (4) the selective bioaccumulation of chlordane residues in three trophic levels in the Antarctic: euphausiid, demersal fish, Weddell seal (Kawano et al., 1986). The results of these kinds of studies are particularly valuable in clarifying the ultimate fate of contaminants in question.

Figure 3 uses data from several sources to illustrate the bioaccumulation of PCBs in trophic levels of both the Bering Sea and Arctic Ocean. The trophic relationship between the polar bear, ringed seal, and Arctic cod provides a good mechanism for studying bioaccumulation in the food web and selective metabolism at each step of the substances of interest. The polar bear is "the" top predator in the Arctic and appears to be unique in its ability to metabolize recalcitrant aromatic compounds, such as DDE and PCBs (Norstrum et al., 1988). It is circumpolar in distribution and, although an opportunistic feeder, the ringed seal provides its most important food base in the form of skin and blubber, particularly during the winter. Arctic cod is an important food for adult ringed seals.

Physiological Characteristics

There are physiological differences between major taxa, between species of the same major taxa, between sexes of the same species, and between age groups of the same species that are reflected in different abilities to metabolize and excrete toxins and to differences in toxic response. The young and immature are more sensitive than the mature, have lesser capacity to metabolize and

excrete toxins, and show toxic response to much lower concentrations than mature individuals. Females have mechanisms for decreasing body burdens of bioaccumulative substances that males do not (e.g., lactation, parturition, egg laying, etc.); therefore, many anthropogenic contaminants accumulate in males to much higher levels than in females. Organism response can vary, depending on the season. During times of stress (molting, breeding, birth of young, egg laying, starvation periods, etc.), toxic response may be more extreme than during other periods.

Muir et al. (1988) showed a pattern of increased metabolism from cod to ringed seal to polar bear for chlordane compounds (CHLs). Concentration of CHLs increased with each successive step up the food chain; however, the chromatograms reflected predominately technical chlordane components in the fish muscle and mostly chlordane metabolites in the polar bear fat. Heptachlor epoxide and oxychlordane levels were enhanced at the upper trophic level, while *trans*-chlordane, *cis*-chlordane, *trans*-nonachlor and *cis*-nonachlor were reduced.

For comparison, Figure 4 presents the fraction of CHLs identified by Muir et al. (1988) in cod, ringed seal, and polar bear in the Arctic Ocean to the fraction of CHLs identified by Kawano et al. (1988) in trophic levels of the Bering Sea/North Pacific Ocean and Antarctic. Although this comparison is complicated by the fact that 12 chlordane isomers, plus heptachlor epoxide, were identified in the Arctic Ocean study, while only five were identified in the other, it is possible to point out some apparent similarities and differences between them. CHLs concentration increased from lower to upper trophic levels in all ecosystems. Although heptachlor epoxide data was not given for the Antarctic and Bering/Pacific regions,

metabolism of chlordane is reflected in both by the enhancement of oxychlordane and a substantial reduction in *cis*- and *trans*-chlordane. It appears oxychlordane is a particularly important metabolite in marine birds since this compound constituted a major fraction of CHLs in thick-billed murres and Adelie penguins. Unlike in the Arctic, *trans*-nonachlor appeared to be enhanced through the trophic levels in both the Antarctic and Bering/Pacific (the thick-billed murre appears to be an exception).

Relationship to Human Consumers

In selecting key organisms for monitoring, one must also remember that humans are part of Arctic marine ecosystems. Here, humans use many species of wildlife as food and are "top predators" in both the marine and terrestrial ecosystems. Selection of organisms and food webs for study should also consider those important for human consumers. The most important marine components in the diet of human consumers are finfish and marine mammals. Examples include Arctic cod, whitefish, Arctic char, salmon, beluga whale, narwhal, ringed and bearded seal, walrus, and bowhead whale.

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Terrestrial Biota of the Arctic

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Arctic terrestrial systems are, as a rule of thumb, much less complex than those at lower latitudes. Land surfaces in the Arctic that are not covered by snow and ice, and are available for growth of vegetation and animals, are subject to the extremes of the arctic climate and the local variations that occur. Numbers of vascular plant species, as well as animal species, decrease with increases in latitudes. Also, their densities and total biomass decrease with increases in latitude. For example, in northernmost Greenland and in Ellesmere Island, there are less than 100 vascular plant species present. By comparison, there are over a thousand vascular plant species in many areas of the Low Arctic. Heat, moisture, and available nutrients are the main factors limiting plant growth in the Arctic. Insularity, however, is also a factor that has accounted for the limitation in distribution of plant and animal species. For example, in Franz Josef Land, which is relatively isolated from continental land masses, there are less than 57 vascular plant species.

Although ecosystems tend to be less complex in the Arctic than they are at lower latitudes, they are also less well understood. They have been less well studied. This is probably because ecosystems at lower latitudes are closer to where scientists live and have their workplaces. There are both similarities and unique differences in flora and fauna throughout terrestrial areas of the arctic basin. For example, in northwestern Alaska, white spruce is the treeline species, whereas throughout much of Eurasia, larch is the treeline species that extends into the Arctic. The treeless tundra, however, is characteristically associated with arctic flora and fauna. Typically, arctic species are those that have evolved in tundra situations. There are, however, a diversity of shrubs present in the Arctic. *Salix arctica* is a prostrate

willow species that occurs at the northern limits of land in the Arctic (Fig. 1). Although timber volume in stands of arctic willow is too low to be of much interest to loggers, it is a primary forage species for all of the mammalian herbivores of the Arctic and for ptarmigan as well. The distribution of *Salix arctica* is circumpolar, with the exception of Svalbard and northern Scandinavia (Fig. 2). Whereas there is only one willow species in the extreme High Arctic, there may be over 20 species in the Low Arctic, which are equally important as forage for wildlife.

Another willow species shown in Figure 3 with reticulate leaves is *Salix reticulata*. It has a unique distribution (Fig. 4). It is a typical Beringian species that has spread in both directions following deglaciation, but it has not reached Greenland and some other areas of the Arctic, for example Iceland.

Some of the sedges (*Carex* spp. and *Eriophorum* spp.) are important plant species in the Arctic from the standpoint of their abundance, as well as their importance to animal herbivores. The tussock-forming sedge, *Eriophorum vaginatum*, is common on the North Slope of Alaska and is an important component of the calving grounds of caribou. It is well adapted to absorb solar input in early spring, even before snow melt-off. The floral buds are dark colored (Fig. 5); they absorb heat and are able to provide the first new growth of vegetation of high nutritive value for grazing herbivores. This is particularly important for caribou during and immediately after the calving period when female caribou have high energy and protein requirements in order to produce milk for their calves.

There are examples of local high biomass of animals in the Arctic (Fig. 6); however, concentrations of biomass, as in summer aggregations of caribou, are transi-



Figure 1. A stand of arctic willow, *Salix arctica*, in the polar desert of northern Greenland.

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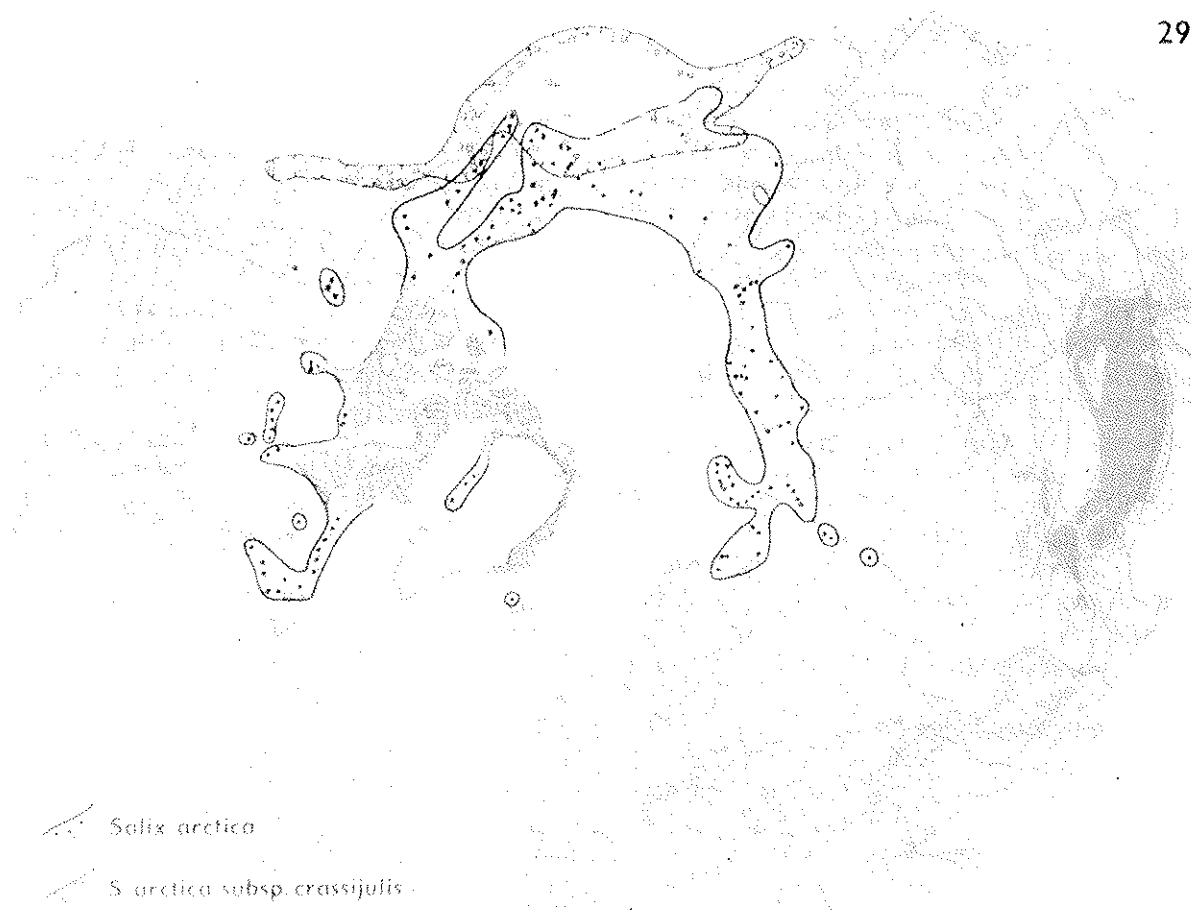


Figure 2. Circumpolar distribution of *Salix arctica* (from Hultén, E. 1962-71. *The circumpolar plants. I and II.* Almqvist and Wiksell, Stockholm).



Figure 3. The Beringian willow species, *Salix reticulata*.

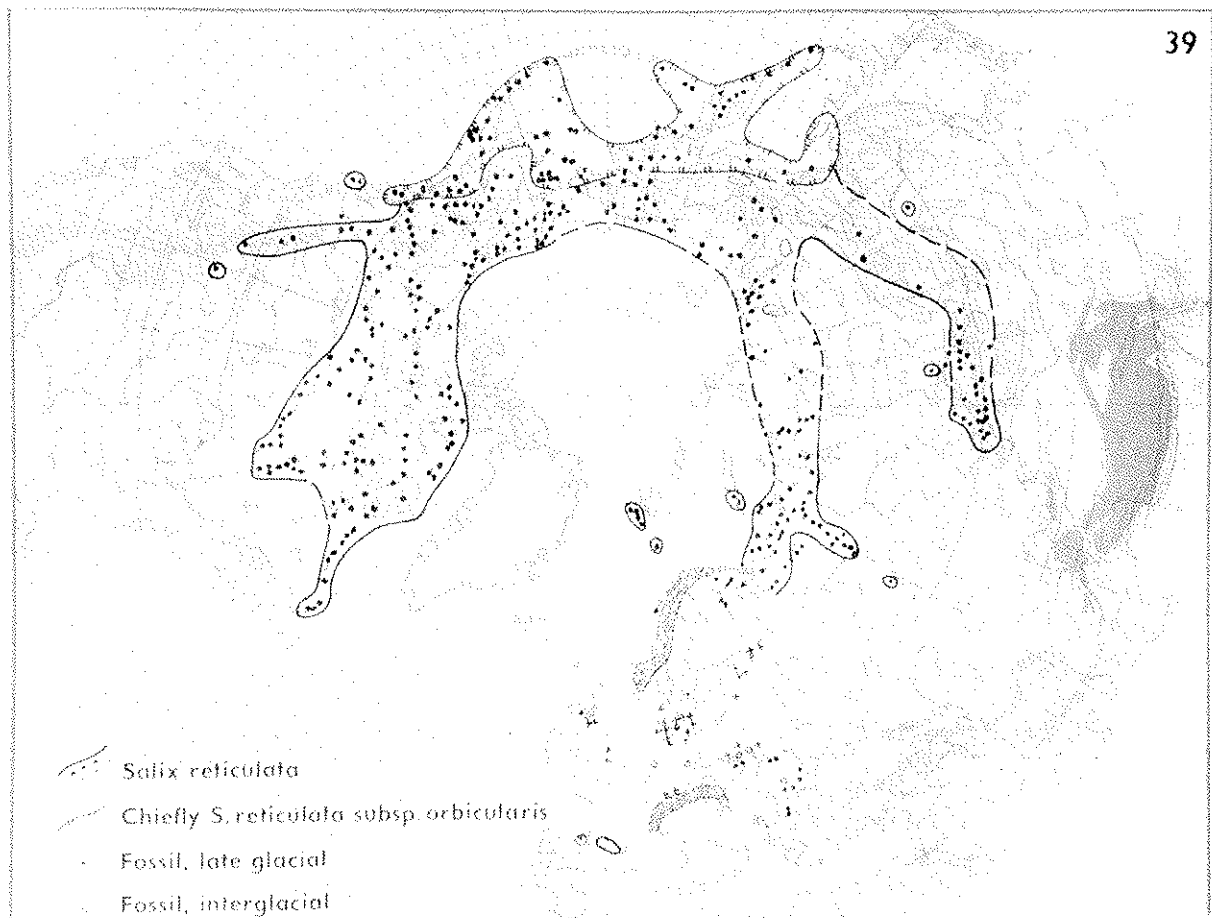


Figure 4. Distribution of *Salix reticulata*, showing its relationship to a likely Beringian origin (Hultén, loc. cit.).

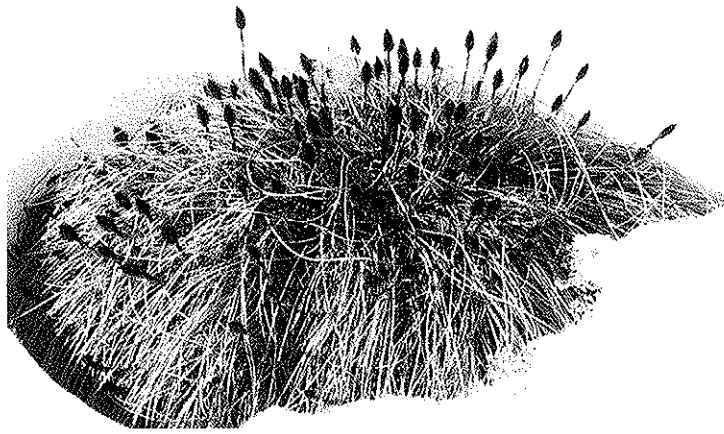


Figure 5. The tussock-forming sedge *Eriophorum vaginatum*, showing the dark floral buds that absorb the sun's heat to initiate growth before the ground is free of snow in spring.

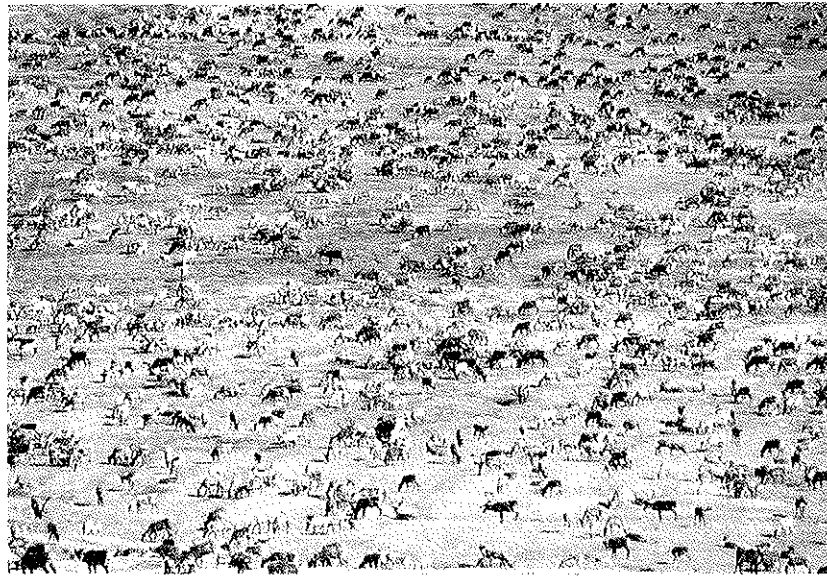


Figure 6. A dense post-calving aggregation of caribou of the Porcupine Caribou Herd that occupies range in northeastern Alaska and adjacent Canada.

tory in time and space. Caribou aggregate in summer to minimize insect harassment, but they also forage, and the high density of animals has substantial impact on the vegetation. They are present in summer aggregation areas for a matter of a few weeks before they move into other ecosystems to spend the winter.

In the extreme High Arctic of Peary Land in northern Greenland, there is little snow cover because it is a polar desert (Fig. 7). There is so little precipitation that permanent glacier ice cannot form. There is also very little vegetation in this environment. Animals live there and

are dependent, either directly or indirectly, on the limited plant growth that occurs in association with melting snow during the short summer. Muskoxen (*Ovibos moschatus*) in Figure 8 are feeding on the floral parts of *Saxifraga oppositifolia*, a forage of high quality, but which is quite ephemeral. As with many forage types of high quality, it is only available for a short time; thus, arctic herbivores have to be opportunistic to take advantage of its limited availability.

In the Low Arctic, low-lying coastal plain areas are underlain by permafrost, which limits drainage, and the



Figure 7. The polar desert landscape of Peary Land in northern Greenland.



Figure 8. Muskoxen on Bathurst Island in the Canadian Arctic foraging on the flowers of arctic saxifrage, *Saxifraga oppositifolia* (Kent Jingfors photo).

low evaporation rates and melt water account for extensive areas of standing water. There is abundant water for vegetative growth, so that where the land is not actually covered by water there is usually a fairly uniform cover of vegetation that is dominated by sedges.

In the High Arctic, similar growth of sedges occurs only where there is water from melting snow. The limited amount of winter snow accumulates in drifts, and as it melts in summer, it continues to provide moisture for plant growth. *Carex aquatilis* is the dominant forage species for muskoxen in the High Arctic (Fig. 9). *Carex aquatilis* is a good indicator of ecosystem productivity throughout the entire Arctic. It is

circumpolar in distribution (Fig. 10) and is an important food for a variety of herbivores, including not only caribou but also domestic reindeer.

Heat is important during the short summer growth period in the Arctic. Figure 11 shows an interior broad valley in eastern Greenland that is surrounded by relatively high mountains. It is protected from the colder influences of the Greenland icecap, as well as the adjacent ocean. Heat is also radiated from the sides of the mountains back into the valley, creating somewhat of an oasis, with high productivity of vegetation, and consequently, such areas are productive for herbivorous animals.

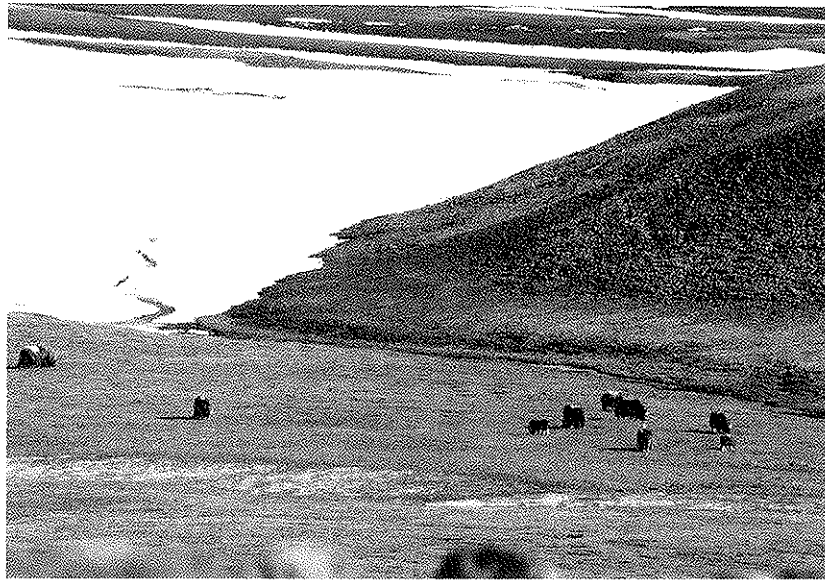


Figure 9. The sedge, *Carex aquatilis*, dominates in moist meadows watered by melting snow in the High Arctic. It is the primary food item in the diet of muskoxen

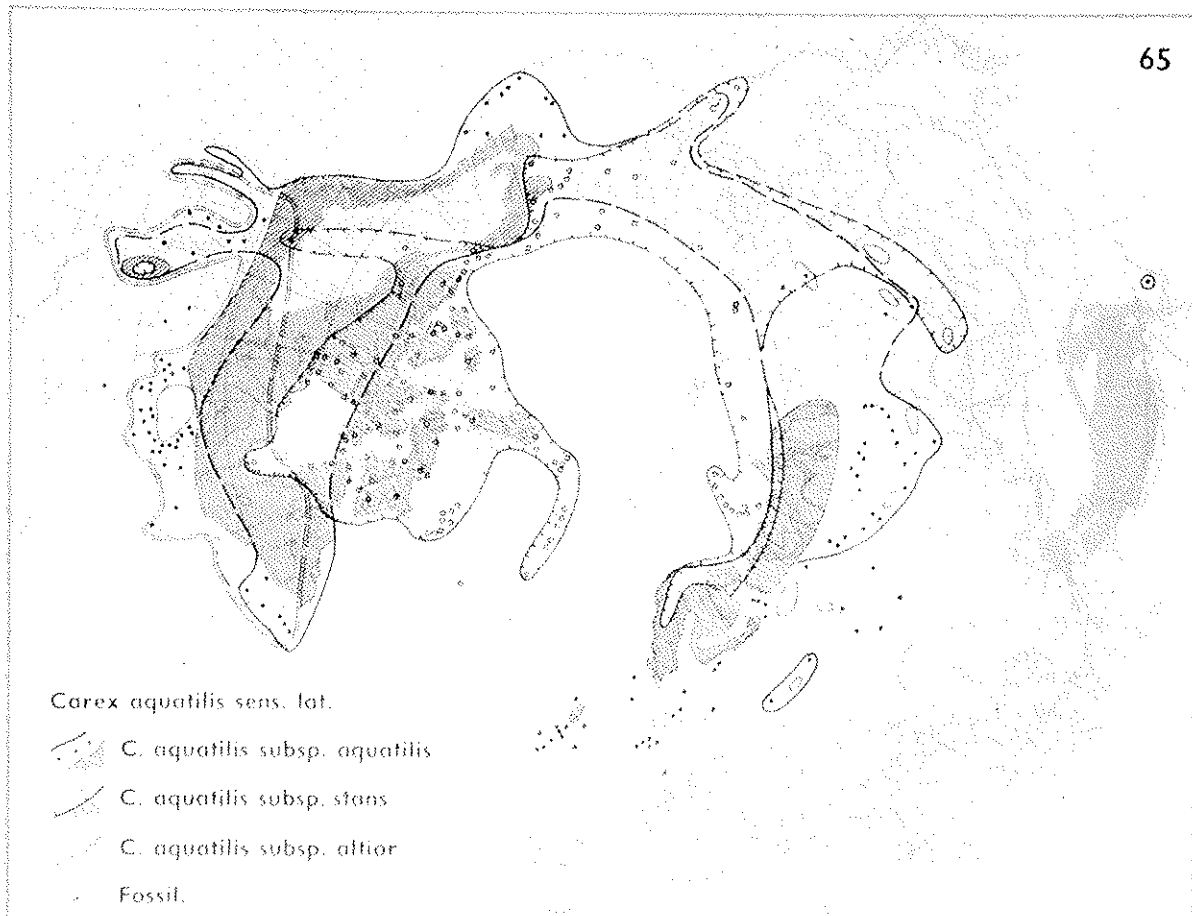


Figure 10. The circumpolar distribution of *Carex aquatilis* and its importance as a forage for arctic herbivores make it an appropriate indicator of the well-being of arctic ecosystems (Hultén, loc. cit.).



Figure 11. A broad interior valley in eastern Greenland with adjacent high mountains has a continental-like summer microclimate, creating an "oasis" for plant growth and herbivores.

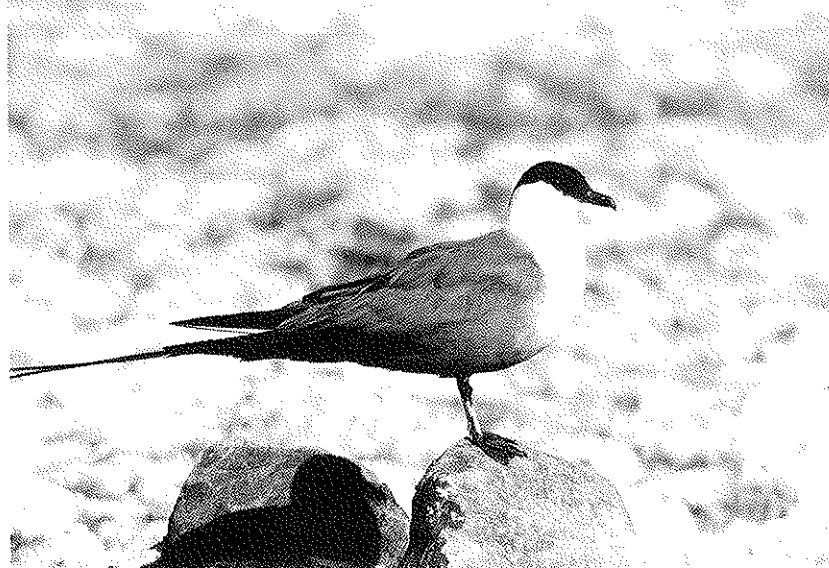


Figure 12. The long-tailed jaeger is largely terrestrial in summer in the Arctic, whereas in winter it occupies a pelagic marine habitat.

Migratory birds are also important in the Arctic. Some are terrestrial, some are marine-related, and some, such as the long-tailed jaeger (*Stercorarius longicaudus*) (Fig. 12), share a relationship with the marine and terrestrial environments. It is important when selecting indicator species, whether they be plants or animals, that they have wide circumpolar distributions so that they can be of use for comparisons between countries.

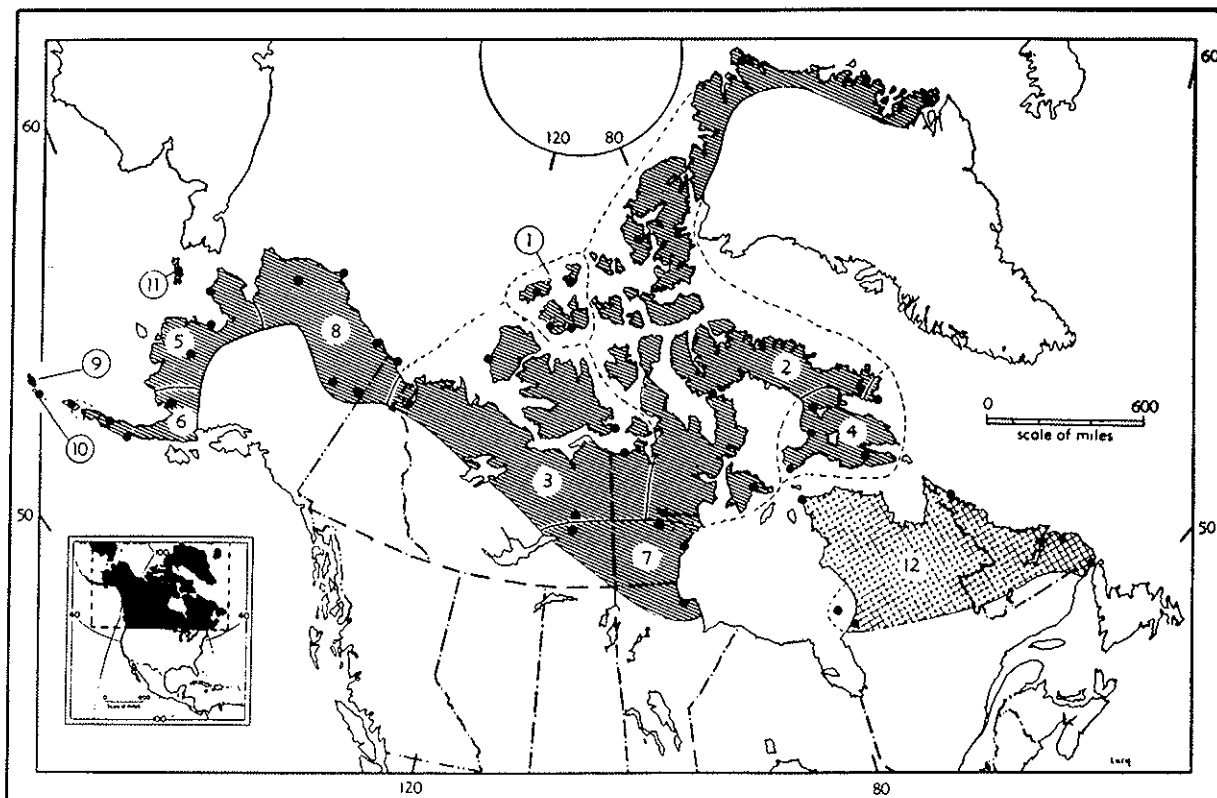
The arctic hare (Fig. 13) is present throughout the High Arctic, as well as in many areas in the Mid- and Low Arctic. Its distribution in Greenland and North America is somewhat unique. Alaska has a separate

species, which is not contiguous with the species occurring in Greenland and arctic Canada. The genetic work that has been done to date indicates that *Lepus othus* occurring in Alaska is a Beringian species with a closer relationship to the arctic hare in far eastern Siberia than to *Lepus arcticus* in Canada.

The collared lemming is also a High Arctic species. It is the only small rodent that occurs in the extreme High Arctic. Its distribution in North America and Greenland is shown in Fig. 14. It also occurs throughout Eurasia in the High Arctic and is potentially a good indicator species.



Figure 13. The arctic hare occurs as three species throughout the Arctic with disjunct distributions apparently related to its separation into different refugia during the late Pleistocene glaciation.



Map 427. American *Dicrostonyx*.

- | | | |
|--|--|--|
| 1. <i>D. groenlandicus clarus</i> | 5. <i>D. groenlandicus nelsoni</i> | 9. <i>D. groenlandicus stevensoni</i> |
| 2. <i>D. groenlandicus groenlandicus</i> | 6. <i>D. groenlandicus peninsulae</i> | 10. <i>D. groenlandicus unalascensis</i> |
| 3. <i>D. groenlandicus kilangmiutak</i> | 7. <i>D. groenlandicus richardsoni</i> | 11. <i>D. exsul</i> |
| 4. <i>D. groenlandicus lentus</i> | 8. <i>D. groenlandicus rubricatus</i> | 12. <i>D. hudsonius</i> |

Figure 14. Distribution of the collared lemming, *Dicrostonyx groenlandicus*, in North America and Greenland (from Hall and Kelson, 1959, *Mammals of North America*, Roland Press).

DISTRIBUTION OF OVIBOS MOSCATUS AND RANGIFER TARANDUS

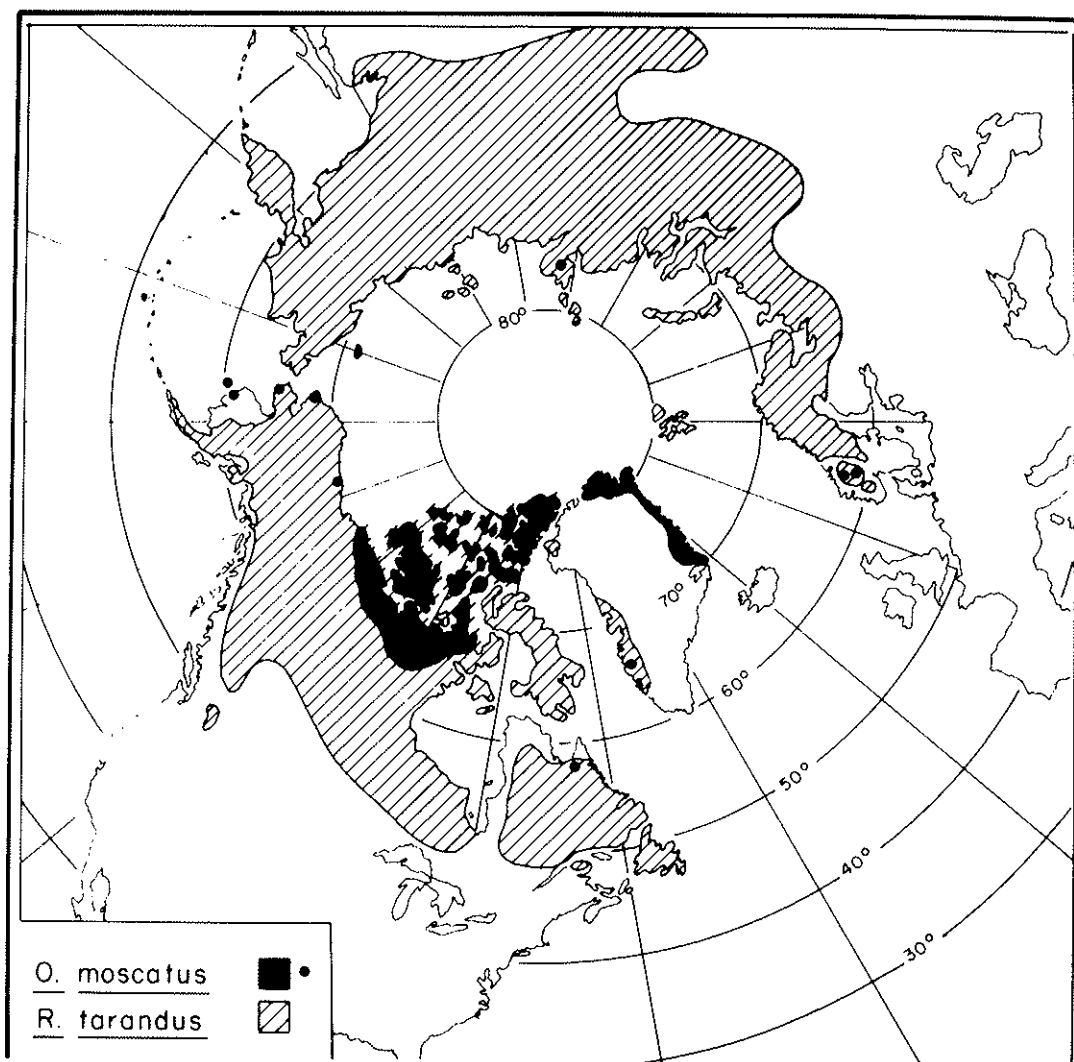


Figure 15. Distribution of caribou and reindeer, *Rangifer tarandus*, and muskoxen, *Ovibos moschatus*, throughout the circumpolar Arctic. Locations of introductions and reestablishment of muskoxen are indicated by black dots.

Caribou and reindeer, all of the same species (*Rangifer tarandus*), are circumpolar in distribution (Fig. 15). There are about three million caribou and wild reindeer, most of which are in North America, and another three million domestic reindeer, most of which are in Eurasia. Muskoxen historically were restricted in their distribution. They have now been reestablished in northern Alaska and the Taimyr Peninsula and Wrangell Island of Siberia. They have been introduced to northern Quebec, Labrador, western Greenland, and in Norway and adjacent Sweden.

Lichens are an important plant in the Low Arctic and Mid-Arctic, less so in the High Arctic where they grow less abundantly. They are an important forage species

for caribou and reindeer in winter. The structure of lichens is rather unique (Fig. 16). They are a symbiotic relationship between fungus and algae. Photosynthesizing algal cells live within the actual fungal structure of the lichens. Lichens have no roots. They derive what they require for growth, in the way of nutrients and moisture, from the atmosphere. They are uniquely designed to capture nutrients from the atmosphere; consequently, they are also very effective in capturing pollutants, which is not necessarily to their advantage.

Figure 17 is a winter shot of a portion of the metallurgical complex of Norilsk in northwestern Siberia. Some of our Russian colleagues have studied the effects of pollution, primarily sulphur components but also

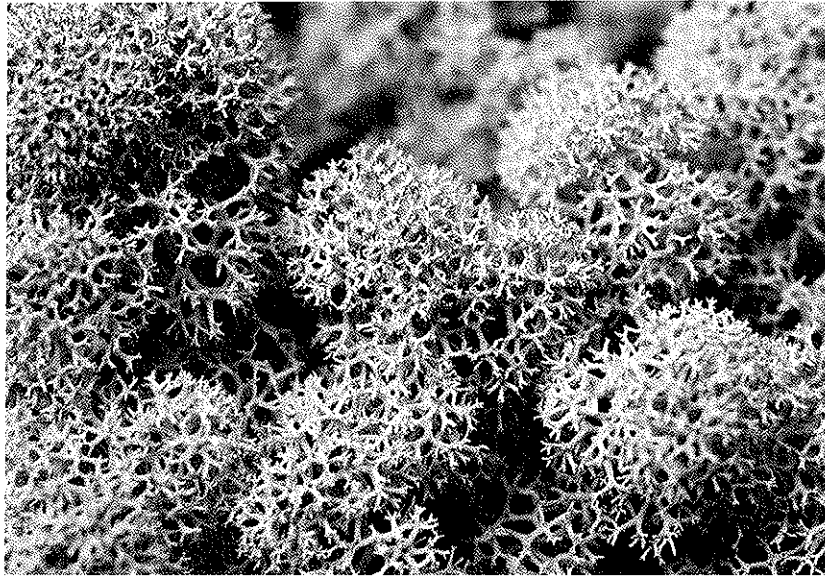


Figure 16. Lichens are a unique plant involving a symbiotic relationship between fungi as the structural component that houses algal cells. The algae, through photosynthesis, provide nourishment to both components of the plant. Lichens are an important winter food of caribou and reindeer.

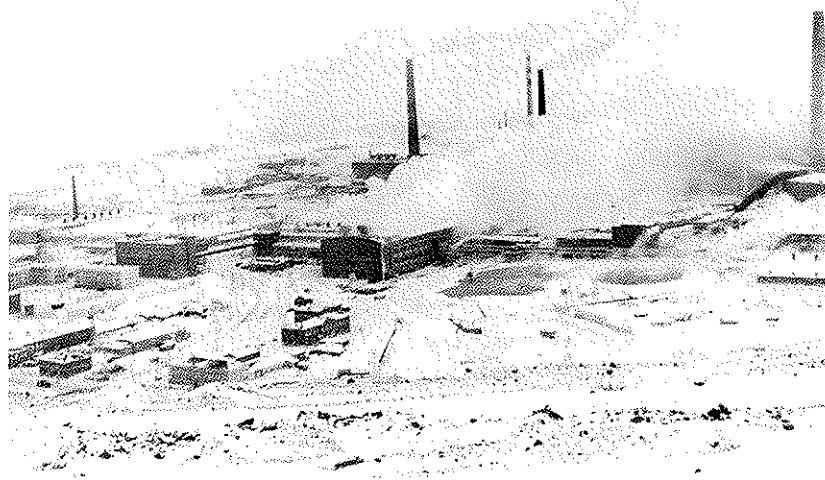


Figure 17. The mining and smelting of copper and other ores at Norilsk in northwestern Siberia had resulted in massive pollution of the surrounding environment.

heavy metals, from the Norilsk Metallurgical Complex on adjacent vegetation. In the black area in Figure 18, the degree of pollution is considered maximum, and lichens have been totally eliminated within that area. This had previously been an important grazing area for both domestic and wild reindeer. There has been significant damage to lichens, within a much larger area of over 300,000 square kilometers. The total area extends about 150 kilometers from Norilsk in several directions.

In addition to pollutants from industrial activities,

lichens also capture radioactive substances as a result of atmospheric testing of nuclear bombs, or accidents such as the Chernobyl disaster. Caribou are integrators of these pollutants, including radioactive substances. Radioactive cesium, for example, is passed up the food chain from lichens to caribou, wolves, and to people. Caribou and reindeer are an important food item for arctic residents. Figure 19 shows a native market in Nuuk, Greenland, where caribou meat is sold along with other native foods. Obviously, these people are

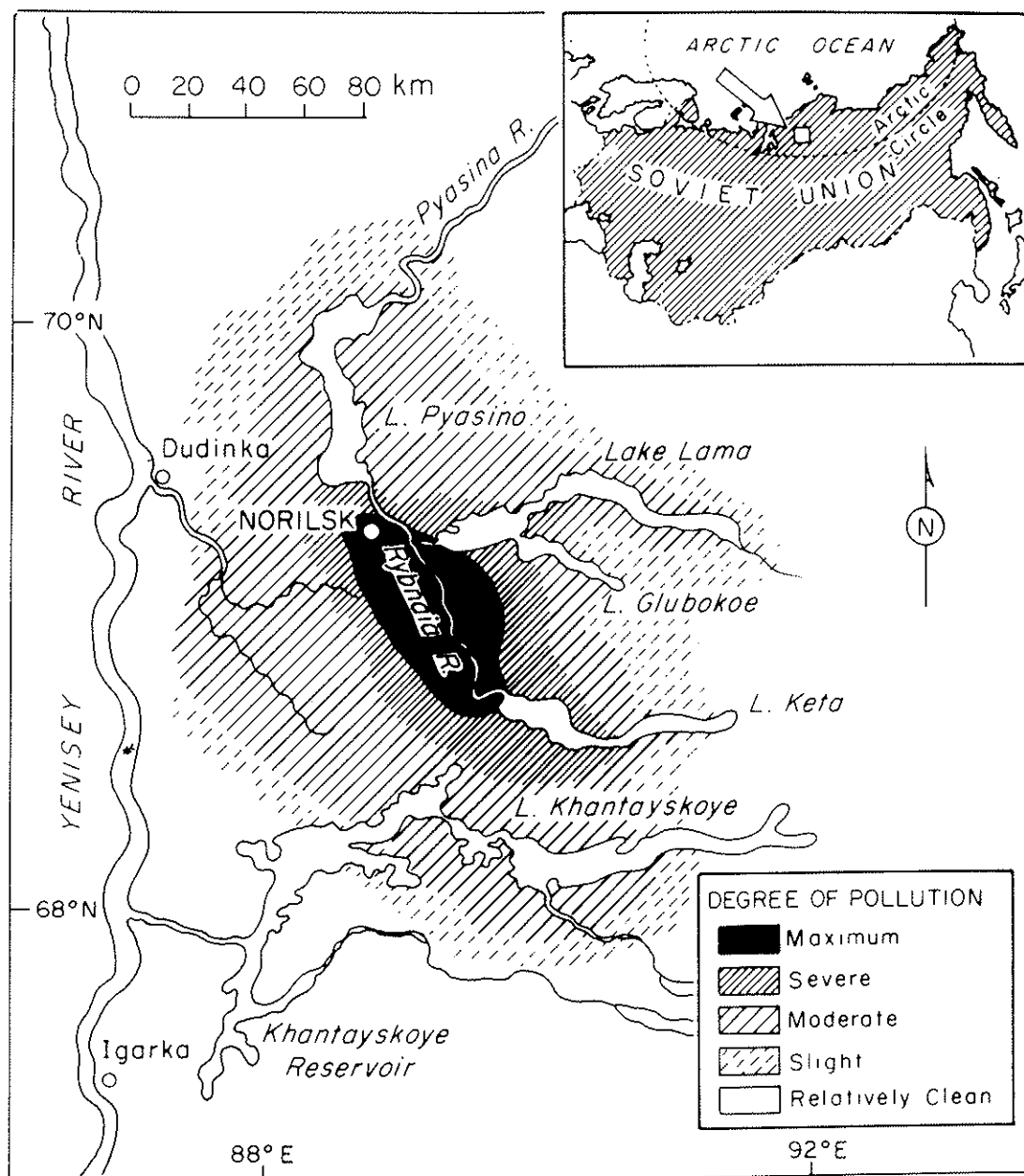


Figure 18. Studies by Russian scientists have documented the widespread effects on lichens and other vegetation of the atmospheric pollution generated by the Norilsk industrial complex (from Klein and Vlasova, 1991, *Rangifer* 12:21-27).

concerned about their relationship to their traditional foods and the accumulation of pollutants in their bodies. After the Chernobyl accident, the reindeer industry in Scandinavia suffered a pronounced economic decline because of concern about increased levels of radioisotopes in the meat of domestic reindeer. Not only were lichens an important factor in this transfer of radioisotopes to reindeer and caribou, but in subsequent years it was found that even though the levels of radioactive cesium were declining in lichens, they were apparently remaining high in mushrooms, which are used season-

ally by reindeer and caribou, as well as by humans in northern areas, especially in Eurasia.

Many other animal species offer potential as indicators of ecological change, but it is important to understand their ecological relationships. The arctic ground squirrel (*Spermophilus undulatus*), which is present in the Low Arctic and Mid-Arctic, is only active during the summer months. It is a hibernator. Its body tissues, therefore, reflect vegetation consumed during the summer period. Ptarmigan, which occur throughout the Arctic, are resident in many areas of the Low Arctic. In



Figure 19. A market selling native foods, including caribou, in Nuuk, the capital of Greenland.

the High Arctic, they are migratory, moving farther south to winter. Arctic foxes in winter are frequently associated with the marine environment, so their tissues may reflect consumption of marine organisms. In summer, when they are denning and breeding, they feed on small mammals to a large extent; however, they also include nesting seabirds in their diets.

Among top predators in arctic ecosystems are the humans who live in the Arctic and have traditionally made their home there. They are dependent upon both marine and terrestrial food resources. Understandably, they are concerned about how their health may be influenced by contaminants that pass up through arctic food chains to them. Their sled dogs are similarly at the top of arctic trophic levels and offer potential as indicator species. Both the human residents and their dogs should be recognized as components of the arctic biota.

In the freshwater environment of streams and lakes in the Arctic, there are also an abundance of macroinvertebrates that are potential indicators of pollution effects. They have been used at lower latitudes successfully in showing changes that have occurred as a result

of pollution. They may reflect the effects of pollution through changes in species composition within a community of organisms, changes in population levels and structure, as well as changes in overall function of ecosystems.

Attitudes about the Arctic have changed from what they have been in the past. The Arctic has been looked upon as a storehouse of resources to be exploited for the benefit of people living in more southern climes. Fortunately, that view is changing, and there is increasing concern for the well-being of arctic residents. Nevertheless, development is occurring in the Arctic and we need to be aware of the consequences of that development, on both a short-term and long-term basis. The pressures for development continue to come from lower latitudes, where there is little understanding of the complexity of arctic ecosystems. This workshop has the potential to direct emphasis on the Arctic, and as scientists we must play an active role in trying to protect the integrity and productivity of arctic systems and the well-being of the residents of the Arctic who are dependent upon these systems.

Arctic Contamination

An Introduction

Arctic Contamination International Coordination and Cooperation

Charles M. Newstead
U.S. Department of State
Washington, DC

It is a great pleasure to be here and see so many of you again. Also it is rewarding to meet some of the people that were just names on pieces of paper that passed across my desk as part of my activities in this field. I particularly would like to welcome our Russian colleagues on behalf of the U.S. Department of State. We are very pleased that you are here. You have an important role to play in helping all of us understand the Arctic contamination problem.

Earlier, we heard from Senator Murkowski, someone who really deserves a large measure of credit, for he was one of the first to realize the magnitude of this problem, and stimulate the U.S. Government to do something about it. In fact, about a year ago the Senator wrote to James Baker, who was then the Secretary of State, to outline this situation. In rather more polite terms than I use now, he asked Secretary Baker, "Why the hell haven't we gotten off our butt and done something about it?" About the same time, and concurrent with the letter, the matter was taken up by IARPC, the Interagency Arctic Research Policy Committee. There have been a number of meetings since that time. In fact, this Workshop came out of the discussions that we had at IARPC. Dr. Bruce Molnia, the Chairman of the IARPC Technical Committee, deserves a large measure of appreciation for organizing this Workshop and making it a reality. I think the Workshop will play an important role in pulling this issue together and helping us in the government decide what our next steps should be.

One must realize from the outset that international cooperation is essential if we are to get anywhere on this problem. It is just too big an issue for any one country to handle, and of course, much of the relevant data and expertise is in Russia and the other countries of the Arctic rim. Putting this cooperation together will not be easy. The situation is of course, much easier now that

the Cold War has ended, but even during that time, we did have scientific cooperation with the U.S.S.R. The nuclear research cooperation, particularly, was carried out under the "Peaceful Uses of Atomic Energy" (PUAE) Agreement, which was first signed by President Nixon and General Secretary Brezhnev in 1973, and later renewed and expanded by President Reagan and President Gorbachev in 1988. This Agreement included, actually, three major topics: fusion, high energy physics, and certain nuclear energy matters. These initiatives continued throughout the ups and downs of the Cold War, even during the time of Afghanistan, when a number of our other collaborative efforts were curtailed. Cooperation in nuclear energy never really got going in any major way. The fundamental research topics like high energy physics and fusion were more successful. Chernobyl, however, changed all that.

The U.S.S.R. provided little if any information in the first few days after Chernobyl. I was in the State Department Operations Center at the time trying to figure out what was going on. The President and the Secretary of State were on their way to Japan for an economic summit meeting, and of course, they were very concerned. There were reports of increases in the level of radioactivity in drinking water. I was given the unenviable task of explaining to them, by cable, what this all meant, and whether they had to be concerned about it. The cable had to be rewritten about ten times, because others at State kept telling me, they will not understand this, you have to make it simpler. No, this is still too complicated, you have to make it simpler. Imagine trying to explain what millicuries, roentgens, and becquerels are to a President. You can't. Finally you end up explaining more and more about less and less, until you have explained everything about nothing.

At that time we were in contact, of course, with the

Foreign Ministry in Moscow and the State Committee for the Utilization of Atomic Energy. We were asking them for information about these radiation readings we were getting from Sweden and Finland. The Soviets just would not tell us anything, which was the old style of doing things. It became obvious after a while that there had been a major reactor accident and we offered our help. Later the President himself, personally, in a letter to President Gorbachev, offered U.S. help. They just kept saying, "thank you very much, we don't need any help." Well, it turned out that was not quite the case. It was a more significant disaster than they realized. Moscow was not getting all the information from Chernobyl. The people at Chernobyl, I think, were probably just afraid to tell Moscow how bad it really was. It was only when members of a Special Commission went out to look at the site and realized things were really very serious, were evacuations ordered and important measures taken. I must say they did a generally good job of dealing with the follow-on.

We have learned a lot from Chernobyl; how to deal with nuclear emergencies, and how to cooperate better and more effectively. The Civilian Nuclear Reactor Safety Agreement and the Nuclear Waste Management and Environmental Restoration Agreement were then negotiated and placed under the umbrella PUAE Agreement. The PUAE Agreement was very helpful in dealing with conventional nuclear energy matters, but really does not have the infrastructure to deal with the present Arctic contamination problem. What we need is a new instrument, and we currently have under study what would be the best way to carry out the necessary bilateral and multilateral cooperation. There is a set of agreements which I think will be very useful, and that is the Arctic Environmental Protection Strategy (AEPS), and also the Arctic Monitoring and Assessment Program (AMAP). These seem best suited for multilateral cooperation in this matter.

The International Atomic Energy Agency (IAEA), which is a part of the United Nations, and is based in Vienna, played a very important role in the post Chernobyl discussions. They were instrumental in bringing all the concerned countries together, particularly Russia or the U.S.S.R., as it was then, into a forum where we could discuss the accident, begin to learn what had really happened, and assess the consequences. From this we have come to realize that the IAEA can play an important role, perhaps an essential role, in dealing with the radioactivity problems in the Arctic. In particular, IAEA has a laboratory called the Marine Environmental Laboratory (MEL), located in Monaco, that has a number of highly qualified people in this area.

The IAEA and Norway organized a meeting in Oslo in February, 1993, which I attended. There was good

participation from Russia, with, I think, ten Russian scientists. In addition, there was participation from the various European countries, and of course, from the United States and Canada. Following the Oslo meeting, the IAEA developed a four year program to deal with the Arctic radioactivity situation. Again, I think you will hear more about that from Dr. Fowler.

Another international organization that is considering dealing with this problem of Arctic contamination, is the Nuclear Energy Agency of the OECD in Paris. They discussed this matter at a special meeting of their Coordinated Research and Environmental Survey Program (CRESP). CRESP has been very active over the last fifteen years in making measurements and evaluations of the North Atlantic dumping site. I do not suppose that comes as a shock to you that there is a dumping site in the North Atlantic, where several Western European countries have in the past, quite legally at the time, carried out dumping under controlled conditions. To monitor the effects this dumping could have on the marine biology, a number of measurements have been carried out by these countries and the CRESP team. They have a lot of experience in this sort of monitoring. Generally our feeling is that they could play a useful role, in working with the IAEA in a coordinated way, to help with the program. This will probably require setting up an IAEA/NEA Coordinating Committee, so there would be no overlapping of efforts, which could be really counter-productive. This is essential for effective international cooperation. It is necessary to get the different organizations working together to decide who is going to do what, and to continue to coordinate and overview the whole thing. We are just at the beginning of this, really, for the Arctic contamination problem.

We also have a series of bilateral activities going on internationally. Perhaps the one that has received the most publicity is the initiative that Norway took with Russia, to conduct a research cruise last summer, and there are preliminary results and a report on that cruise. Unfortunately, they were not able to visit the dump sites in question, and their measurements were gathered rather far from the dump sites. We are hoping that this unfortunate situation can be remedied this summer, when another cruise will take place, and we have some assurances that, in fact, permission will be given to visit the dump sites. If there is a message I can ask you, our Russian colleagues, to take back home, that would be, please do what you can to see that there is a possibility for the 1993 Russian-Norwegian cruise to go to the proper places.

At present, the Office of Naval Research (ONR), in the Department of Defense, has a major program of work underway. As the Senator mentioned, ten million

dollars was appropriated for the Arctic radiation problems. Dr. Lou Codispoti, who is here at the meeting, will discuss this in more detail during his talk. ONR has planned what they call several "fast-track" activities. These activities will get underway very quickly, this summer. Others are more long-term activities which involve both the American laboratories and universities in collaborative efforts with many of the Russian institutes.

The Department of State also has a number of activities underway in the international arena. This includes support of the IAEA and for several U.S. universities and laboratories, that will be involved in making certain measurements with the IAEA. Concerning the non-radioactive pollutants, State's role is perhaps greater in this area than ONR, who are taking the lead in dealing with the nuclear pollutants, which was the way the legislation was written.

On another front, the Royal Norwegian Ministry of Foreign Affairs and the U.S. Department of State have agreed to hold a series of bilateral working group meetings to discuss Arctic contamination and nuclear safety. The first meeting is planned for June, 1993, in Washington. We are still in the process of setting this up and deciding the composition of the two U.S. delegations. Norway has played a very significant role in getting the ball rolling, and in making contact with Russian scientists and officials who are knowledgeable about these matters. This was particularly evident this past February in Oslo, when Norway was instrumental in arranging for ten Russian scientists to attend the meeting. We had some very good discussions in Oslo

and several of the participants are also attending this Workshop.

The message I want to deliver is that we all need to work together on this. The United States government is not interested in assessing blame. I am sure none of us are interested in doing that. Particularly I want to get the point across, that whatever happened before, happened. That was a different time and a different government. We now have a completely different political setup. New democracies have been established in Eastern Europe and the FSU. We appreciate the difficulty of undertaking major environmental projects during this period of severe inflation and other major economic problems that result from a change to democracy and the ultimate advantages of a market economy. We believe this will eventually all work out for the best. Meanwhile, we need to deal with the present contamination problem. It is important that we all understand what has happened, what the consequences of this could be, and what we need to do about it. Again, we are willing to work closely with you to try to solve it.

The results of this Workshop will be very helpful in determining what we should do next. There is however, another little problem. Once we decide what needs to be done, we need money to do it. That amount of money of course, is not available at this point, nor will it be available until the magnitude of the problem is fully understood. I am sure that the Arctic rim nations will give this very careful consideration. While it is going to be difficult with the current U.S. deficit, this is a very important problem and I believe that the U.S. will do its part of the research and other necessary activities.

International Radiological Assessment Programs Related to Radioactive Waste Dumping in the Arctic Seas IAEA-MEL's Role

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Abstract

In response to growing concern over the dumping of high level radioactive waste in the Kara and Barents Seas, an international effort to assess its consequences is currently underway. An oceanographically consistent, compartmental model featuring a finer spatial resolution in the areas containing the dumpsites has been developed to predict the long-term radiological impact of radioactive waste disposals in Arctic Seas on regional and global scales. Using a range of assumptions leading to conservative predictions, dose calculations were made for unit releases of cesium-137 (^{137}Cs) from dumped reactors in the Kara Sea and the sunken Komsomolets submarine in the Norwegian Sea. Preliminary modeling results based on the fish ingestion pathway give a maximum global collective dose commitment estimate on the order of 110 man Sv. The model also predicts a non-local maximum effective dose to the individual fish consumer of 15 Sv per year (Sv y^{-1}). These first modeling results suggest that the global radiological impact from the dumping will be comparable to or less than those resulting from other anthropogenic and natural sources of radioactivity.

The general lack of radiochemical and radioecological information for Arctic marine waters limits our ability to accurately predict the behavior and fate of radionuclides released from the dumpsites. Earlier and more recent measurements of ^{137}Cs in the Kara Sea support the hypothesis that no major leakage from the

dumpsites has yet occurred. However, specific sampling at the dumpsites themselves are urgently needed to confirm the previous observations. In the event of eventual release of radioactivity from these sites, based on available Arctic data, it is suggested that certain long-lived radionuclides like plutonium will become associated with the sediments and that very little of the plutonium inventory will be transferred to Kara Sea biota. For future assessments aimed at monitoring biological transfer from the dumpsites, benthic echinoderms and bivalve molluscs are proposed as the best bioindicator species of released radioactivity in this region.

IAEA-MEL is also participating in international assessments by providing assistance with direct radio-analytical measurements, intercalibration exercises and by preparing a synthesis of all existing radioactivity measurements from the Arctic Seas through the IAEA-MEL database.

Introduction

Wide-spread concern has been generated by the recent revelation that, between the early 1960's and the present, the former Soviet Union has dumped high-level radioactive waste in the vicinity of Novaya Zemlya in both the Kara and Barents Seas. According to the most recent information available (White Book 3, 1993), these dumping activities have added a total of up to 92 PBq to the marginal Arctic Seas primarily as nuclear

reactor assemblies and entire vessels, but also as liquid and packaged solid radioactive wastes. This figure surpasses by more than double the combined amount of radioactivity that 12 other nuclear nations have reported dumping in the sea over the last 45 years (IAEA, 1991). Because of the high levels of radioactivity involved and the potential for release in and transfer through the relatively shallow Arctic coastal waters, several interested countries and international and non-governmental bodies have responded to the urgent need for an in-depth assessment of the current situation.

This brief review summarizes IAEA-MEL's present activities within the framework of an international Arctic Seas assessment program, and presents preliminary results from a global dose assessment model based on present inventories of waste dumped in the Kara and Barents Seas. In addition, an evaluation of possible radioecological consequences is made and some suggestions are given on strategies for future monitoring of the dumpsites.

International Assessment Program

The International Atomic Energy Agency (IAEA) is the responsible advisory authority on radioactive matters under the London Convention 1972 (formerly the London Dumping Convention). Following notification of the dumping activities, the IAEA formulated a plan to carry out a long term assessment program related to Arctic Seas dumping which was endorsed by the Contracting Parties to the Convention at their last meeting in November 1992.

As part of the plan, in February 1993 the IAEA initiated the International Arctic Seas Assessment Project (IASAP) which is envisaged to last four years and will be run by the IAEA in co-operation with the Norwegian and Russian governments. The main objectives of this project are the following:

- Assemble all available information on the dumping locations, the nature and forms of the dumped radioactive waste, the relevant oceanography of the region, and potential radionuclide pathways to man;
- Review past and current knowledge on radioactivity levels in the area;
- Model transport processes in the marine environment leading ultimately to the prediction of radionuclide concentrations in the environment and in potential pathways of exposure of humans and the environment;
- Assess present and future health effects and the environmental impacts of dumping in the Kara and Barents Seas;
- Evaluate the feasibility of possible remedial actions, including recovery of the wastes, to reduce radiological consequences.

The sequence of the above components over the next four years should allow a comprehensive assessment of any threats posed by the dumped waste as well as an evaluation of the need for remedial actions. The most urgent needs are to obtain precise data on the nature and composition of the source terms, and relevant demographic and habit information for defining potential pathways of human exposure.

The IAEA Marine Environment Laboratory is a technical arm of the IAEA whose fundamental role is to furnish Member States with information on the behavior and fate of radionuclides in marine waters. To assist the IAEA in carrying out the IASAP, the IAEA-MEL has initiated a number of activities which are described in the following sections.

Radioactivity Database

A global marine radioactivity database has been implemented at IAEA-MEL to catalogue data on radionuclides in water, sediments and biota. The data are stored in a way that facilitates interrogation and analyses, and will provide up-to-date information on radioactivity levels of the seas and oceans, snapshots of levels at given times and locations, temporal changes in radioactivity levels, and knowledge on gaps in available information. To meet these criteria and maximize the information output, the data format has been specified in a rigorous manner. Extensive detail on sample type, method of collection, location, physical and chemical treatment, and method of radioanalysis is included to allow the data to be validated and its quality assured. In addition, the database is linked to IAEA-MEL's in-house analytical quality control system which facilitates immediate checks on laboratory practice.

As part of the global database facility, the IAEA-MEL has been requested to establish and maintain a database for radioactivity in the Arctic Seas. This information will be made available to all IAEA Member States and links will also be established with the Arctic Monitoring Assessment Program (AMAP) which was initiated by the eight Arctic countries party to the Arctic Agreement. Known Arctic data owners are being contacted by the Laboratory for inclusion of their information in the database; others are urged to send relevant data directly to IAEA-MEL. This information bank on radionuclides in water, sediments and biota from the Arctic will act as a starting point for a thorough evaluation of historical data and a comparative assessment of radionuclide concentrations, inventories and source terms including their characterization. Such data will eventually be used in the evaluation of environmental radioactivity levels of the region and in the assessment of radiation doses to local, regional and global human populations as well as to marine biota.

Within the database, key areas have been selected which are actively being researched. Within the Arctic Ocean itself, there are 16 sub-areas (defined by the conventions of the International Hydrographic Organization). Beyond the confines of the Arctic Ocean, those regions of the world's oceans which have significant flows to and from the Arctic (including deep water transport) must also be considered. Data contributions from labs which were or still are active in these specific areas are especially needed. Although the global database currently contains around 25,000 data entries, there is at present only very limited information available for the Arctic Ocean, especially for the Kara and East Arctic Seas. This situation will hopefully change with our current efforts to access existing information coupled with data acquisition from ongoing and future field studies in the region. The database will be available to all participating institutions and eventually to all Member States.

Regional Field Studies

In addition to the synthesis of existing data, IAEA-MEL has also been active in acquiring real-time data on radioactivity levels in and around the Arctic Seas dumpsites. Several sampling cruises are currently planned to visit various sites within the region. During August-September 1992, IAEA-MEL participated in the first joint Norwegian-Russian cruise in the Kara and Barents Seas. One of the main aims of the expedition was to establish present levels of radioactivity in water and sediments from the dump sites. Unfortunately, it was not possible to directly sample the dumpsites in the bays along the coast of Novaya Zemlya; however, samples were obtained from a series of stations a few nautical miles from the dumpsites.

Preliminary results from shipboard measurements made by a team of Russian and Norwegian scientists showed that ^{137}Cs levels in the water column typically ranged between 2 and 10 Becquerels per cubic meter (Bq m^{-3}) at all stations (Cruise Report, 1992). Similar measurements made by the Russian team at or near these sites 10 years earlier indicated that ^{137}Cs concentrations at that time were significantly higher, generally ranging between 10 and 30 Bq m^{-3} (Vakulovskij et al., 1985). Only at one depth (320 m) in the central portion of the sea was the 1992 ^{137}Cs concentration similar to that measured in 1982. It is not evident which of several factors may have led to the apparent overall reduction in radionuclide levels; nevertheless, the preliminary 1992 ^{137}Cs concentrations clearly reflect those which are presently measured in open sea areas in northern latitudes (Figure 1).

In addition, ^{137}Cs measurements made by the Russian and Norwegian scientists on board ship indicated

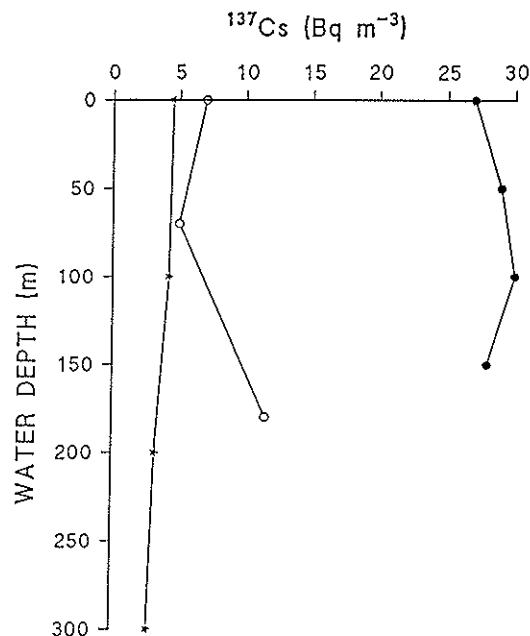


Figure 1. Cesium-137 profiles taken from the same area in the southwestern Kara Sea during 1982 (●) and 1992 (○) (Data from Cruise Report, 1992). For the purposes of comparison, a typical cesium-137 profile taken from the open northwestern Mediterranean in 1990 (★) is shown (V.E. Noshkin and S.W. Fowler, unpublished results).

that radioactive contamination in Kara Sea sediments was also very low and presented no significant radiological danger. IAEA-MEL has provided independent confirmation of the low levels through subsequent analyses of comparable sediment samples obtained during the cruise (Baxter et al., in prep.). Taken together, these field observations strongly suggest that current ^{137}Cs levels in the Kara Sea can be explained by worldwide fallout and that, at present, there is no indication of an additional input from the nuclear waste dumpsite.

Despite these preliminary indications that the waste at the dumpsites is basically still contained, there is a need to verify this by sampling in the immediate vicinity of the dumpsites. A second Russian-Norwegian cruise is now scheduled to visit the dumpsites during summer 1993, and for quality assurance purposes, IAEA-MEL has recently organized an analytical intercomparison exercise by distributing a Kara Sea sediment sample to all participating laboratories.

Radiological Assessment Model

The first step in undertaking a radiological assessment of these seas is obtaining accurate data on the nature of the source terms and their associated levels of radioactivity. The recent release of the White Book 3

Table 1. Liquid radioactive waste dumped in the Kara and Barents Seas (from White Book 3, 1993).

<i>Area</i>	<i>Activity (TBq)</i>
Kara Sea	315
(with "Lenin" ice breaker)	
Barents Sea	450
White Sea	3.7
Andreeva Guba	37
Ara Guba	74
Total	880

(1993) has substantially added to our knowledge of the dumped wastes. Tables 1 and 2 list the total activities of liquid waste and low and medium activity solid waste that have been dumped at various sites in the Kara and Barents Seas. Some 65% of the total liquid waste was dumped in the Barents Sea and its associated seas and bays, whereas for the low and medium activity solid wastes, nearly all was dumped in the Kara Sea. By far the largest amount of nuclear waste (85.1 PBq) was dumped in the Kara Sea primarily as submarine reactors containing spent nuclear fuel (Table 3). No objects with spent nuclear fuel were reported for the Barents Sea; however, the accidental sinking of the Komsomolets nuclear submarine off Bear Island in the Norwegian Sea added another 5.6 PBq to the region as high level nuclear fuel. Considering all waste types, it is noteworthy that over 95% of the nuclear debris is located in the Kara Sea.

Table 2. Low and medium activity solid radioactive waste dumped in the Kara and Barents Seas (from White Book 3, 1993).

<i>Location</i>	<i>Years</i>	<i>No. of dumpings</i>	<i>Activity (TBq)</i>
Kara Sea			
Open sea 1	1967-91	22	123
bay 2	1982-84	8	126
bay 3	1968-83	8	75
bay 4	1964-78	8	99
bay 5	1968-75	5	47
bay 6	1966-81	7	25
bay 7	1972	1	8
bay 8	1982-88	3	68
Total:			571
Barents Sea			
Kolguev Island		1	1.5
Black Bukhta (Novaya Zemlya)		1	11
Open Barents		1	4
Total			16.5
Total Both Seas			590

A major part of IAEA-MEL input into the IASAP has been to develop and test compartment models designed to describe dispersal of radioactive contaminants in the Kara and Barents Seas. In the context of Arctic assessment, we are concerned with local and extreme near-field (Kara Sea), regional (Arctic Ocean and relevant marginal seas) and global marine disper-

Table 3. Objects with spent nuclear fuel (SNF) dumped in Kara Sea and sunk accidentally in the Norwegian Sea (from White Book 3, 1993).

<i>Object</i>	<i>Location/Year</i>	<i>Depth (m)</i>	<i>Total activity (PBq)</i>	<i>Radionuclide composition</i>
Section of NSM with 2 reactors (1 reactor with SNF)	Abrosimov Bay 1965	20	29.6	fission products
Section of NSM with 2 reactors with SNF	Abrosimov Bay 1965	20	14.8	fission products
Reactor screen (OK-150) of nuclear icebreaker "Lenin" with 60% of SNF	Tsivolka Bay 1967	49	3.7	¹³⁷ Cs, ⁹⁰ Sr (1.9 PBq for each isotope) ²³⁸ Pu, ²⁴¹ Am, ²⁴⁴ Cm (0.07 PBq)
Reactor of NSM with SNF	Novaya Zemlya Depression 1972	300	29.6	fission products
NSM with 2 reactors with SNF	Stepov Bay 1981	50	7.4	fission products
Total				
5 objects including 7 reactors with SNF			85.1 PBq	
Also:				
Komsomolets NSM	Bear Island, Norwegian Sea 1989	1680	5.55	⁹⁰ Sr (1.55 PBq), ¹³⁷ Cs (2.03 PBq), ²³⁹ Pu (15.9 TBq in torpedoes)
Total			90.7 PBq	

NSM = Nuclear submarine

sion models. The preliminary assessment model described here deals only with the non-local or global radiological consequences of the Arctic dumping, hence the compartmental models chosen are particularly suited to long range and long time scale (100 y) assessments. Such models have been successfully used in other marine areas (NEA, 1985, 1989; CEC, 1990), and lend themselves to thorough sensitivity analyses for enhancing the reliability of the model predictions. This present assessment provides an update on that presented by Baxter et al. (1993) and uses a 16 box model (MEL ARCTIC2) with enhanced structure in the Arctic region, specifically the Kara Sea (Figure 2). The basis of such simple models is accurate knowledge of the oceanographic and hydrographic structure of the region. Rates of flow between the various compartments of the model have been taken from the literature. Additional information has been obtained from a collaborative study with I. Harms (Hamburg University) who has developed a 3-D hydrodynamic model for the Kara and Barents Seas which has been validated using temperature and salinity data. The remainder of the model

describes the rest of the world's seas with emphasis on the Greenland and Norwegian Seas because of their importance to Arctic flow.

The output from the oceanographic part of the model is radionuclide concentration data. The model has been carefully balanced for water flow and provides a satisfactorily accurate prediction of Sellafield ^{137}Cs dispersion through the northern seas. It also incorporates a radionuclide scavenging removal term for each compartment, this being nuclide-specific and dependent on particle concentrations and fluxes. In addition, a sensitivity analysis is currently being carried out, using the computer codes PREP and SPOP prepared at JRC Ispra, Italy.

The radiological component of the model translates resultant radionuclide concentrations in water into corresponding radionuclide concentration data for fish using IAEA-recommended nuclide specific concentration factor (CF) data (IAEA, 1985). Appropriate fisheries catch data (FAO, 1992; ICES, 1992) are then applied to the compartments of the model so that radionuclide intake by humans can be quantified, assuming that 0.5

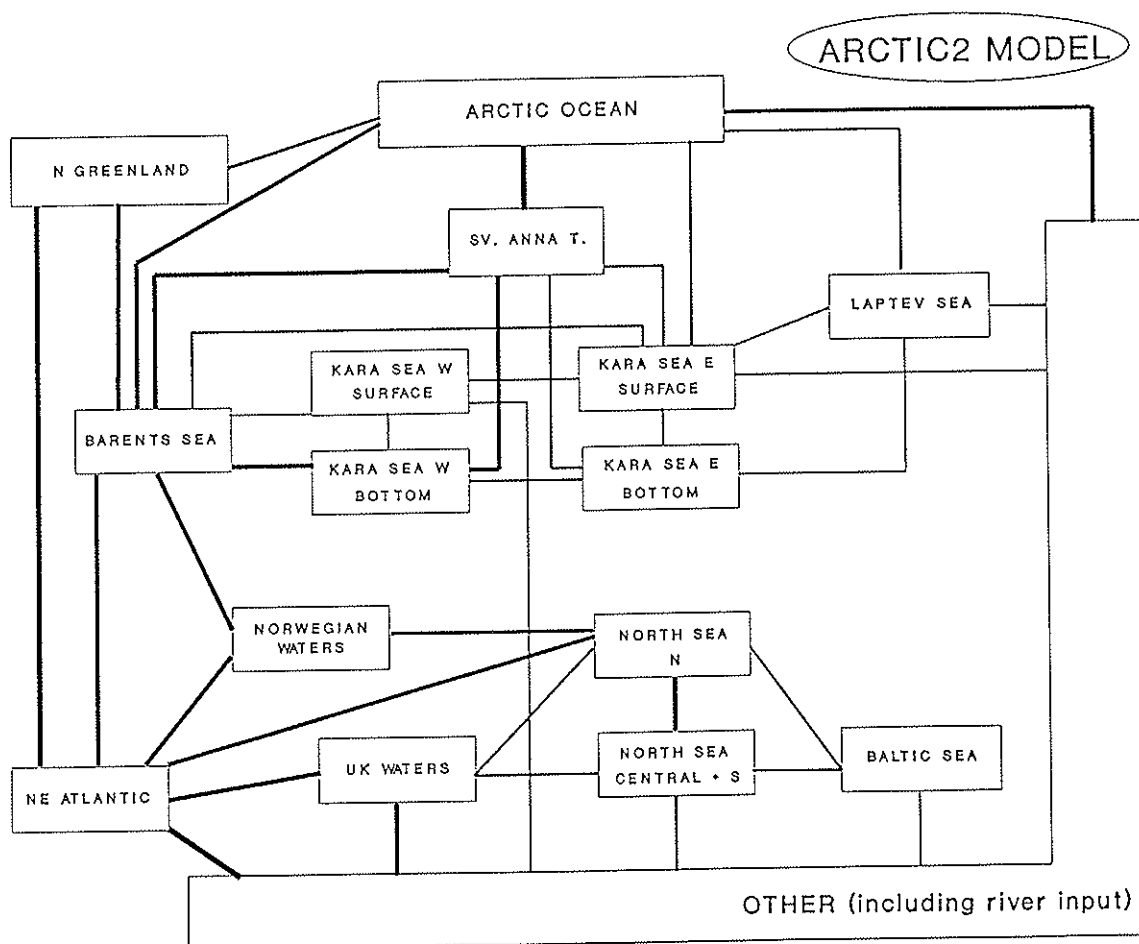


Figure 2. Preliminary box model for radionuclide transport through marine waters resulting from dumping of nuclear wastes in the Arctic seas.

of total fish weight is normally consumed except in the Arctic Seas where a factor of 0.8 is assumed. The final conversion to dose is achieved using ICRP 60 gut-transfer and dose conversion factors. Collective dose commitments are generally truncated to 1000 years or less, depending on objective and nuclide half-life.

Model Results

The model was first run based on the seven reactors in the Kara Sea and the sunken Komsomolets nuclear submarine as reported in the White Book 3 (1993). The scenario considered that 50% of the radioactivity was ^{137}Cs and that it was released over a 20-year period. The model predicts a maximum ^{137}Cs concentration of 154 Bq m^{-3} which appears in the Kara Sea bottom water. Much lower concentrations are predicted in the far field and they peak later. For example, the maxima are seen to occur at approximately 30, 35, 55, 60 and 70 years in the Barents, N. Greenland, U.K., Central North and Norwegian Seas, respectively. The highest predicted anthropogenic activities of 10^2 Bq m^{-3} still remain at 1% of the natural radioactivity levels in the sea water.

The predicted global collective dose commitment is shown in Figure 3. Only 14% of the total 110 man Sv collective dose commitment is found in the Arctic Seas. This is a result of the lack of any extensive commercial fisheries in these seas. Under the above scenario, the radiological model results show that the non-local critical group eating fish from the Kara Sea would receive a maximum dose of 15 Sv y^{-1} (Table 4). Even using a range of assumptions leading to conservative predictions, the maximum dose is approximately two orders of magnitude lower than the ICRP recommended effective dose limit of 1 mSv y^{-1} .

Our provisional modeling results suggest that the global radiological impact of dumping in the Arctic Seas would be comparable to or less than those resulting from other anthropogenic and natural sources of radioactivity of relevance on a global scale. Presently, work is underway to further improve the structure of the

Table 4. Model prediction of the maximum effective dose to a fish consumer in a hypothetical non-local critical group.

Maximum ^{137}Cs concentration in water	154 Bq per m^3
Fish concentration factor (CF)	$100 \times 10^{-3} \text{ m}^3 \text{ kg}^{-1}$
Annual fish consumption*	73 kg per year
Adult dose conversion factor (DCF) for 50-year commitment	$1.3 \times 10^{-8} \text{ Sv per Bq}$
Gut transfer factor (f)	1
Maximum dose rate	$1.5 \times 10^{-5} \text{ Sv per year}$ or $15 \text{ } \mu\text{Sv per year}$

*Estimation is based on 200 g per day consumption of fish from the Kara Sea west bottom water compartment of the model (see text).

model in terms of spatial definition, flow rates and removal processes (Baxter et al., in press), to better define source terms (radionuclide composition and activities, release rates, contribution from other sources) and to assemble other data needed to refine dose calculations (populations, habits, fish catches). Furthermore, in the future, it will be possible to address equally important aspects such as local dispersion, radionuclide transfer and dosimetry. In this respect, collaborations on numerical modeling with I. Harms and V.K. Pavlov (Arctic and Antarctic Research Institute, St. Petersburg) have begun. In addition, a review of the ecology of the region has commenced through collaboration with I.I. Kryshev of SPA Typhoon, Obninsk. For providing local radionuclide data/samples, the further assistance of S.M. Vakulovsky and A.I. Nikitin, (SPA Typhoon), of G. Matishov (Murmansk Marine Biology Institut) and of E. Kontar (P.P. Shirshov Institute of Oceanology, Moscow) should enhance the input to these local assessments.

Radioecological Considerations

Besides directly assessing the potential radiological impact arising from the dumping of nuclear wastes in

total: 110 man Sv

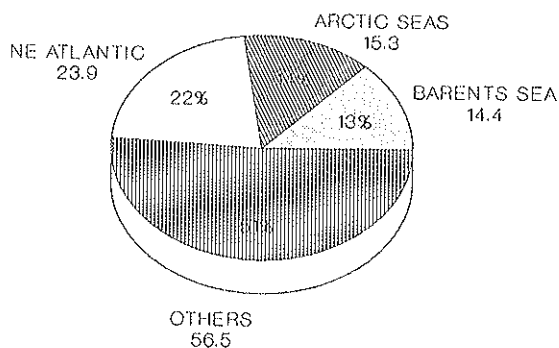


Figure 3. Model predictions form the collective effective dose commitment (man Sv) and the percentages of the total arising from the different seas. Source terms are 7 reactors dumped in the Kara Sea and the Komsomolets submarine in the Norwegian Sea. Arctic seas include the Kara and Laptev Seas.

Arctic marginal seas, it is essential to be able to predict the long-term behavior and transfer of key radionuclides in this ecosystem. To do this properly necessitates having a sound radioecological database for the region in question. In fact, present knowledge on Arctic marine radioecology is very limited compared to that obtained from temperate and tropical studies. The general lack of hard data involving the processes of radionuclide bioaccumulation and transfer through the food chain in Arctic waters has hampered validating similar models based on data generated in temperate latitudes. Therefore, IAEA-MEL has begun to examine the structure of food chains in the Kara and Barents Seas in order to identify key species that can bioaccumulate and transport the radionuclides released from the source terms as well as those organisms that would furnish a pathway of radioactivity leading to man (Miquel, 1993).

In general, the Kara Sea is poorer in biomass and species diversity than the adjacent Barents Sea. One reason is the fact that ice covers the Kara Sea for nearly three-quarters of the year and, hence, primary production is severely limited and the links in the food chain are shortened. Benthic biomass in the central Kara Sea and near the eastern coast of Novaya Zemlya where the wastes were dumped ranges from approximately 3 to 10 grams per square meter (g m^{-2}), whereas in the shallower waters off the Yamal peninsula of Russia, biomass increases dramatically to 100–300 g m^{-2} . The fish population in the Kara Sea is very low relative to that in the Barents Sea, and in the central zone of the Kara Sea, fish are generally small and extremely rare. In contrast to the Barents Sea, there is no commercial fishery in the Kara Sea, although it has been estimated that some 20 metric tons per year are being caught there primarily at the mouths and estuaries of the Ob and Yenisey rivers (G. Matishov, pers. comm.). A variety of molluscs, echinoderms, crustaceans and worms form the typical benthic fauna in the region around the dumpsites. Of particular interest is that in the deeper central portion of the sea, the diversity and biomass of molluscs, crustaceans and polychaete worms decrease markedly and large echinoderms (viz. seastars and brittle stars) become the dominant species. Since these particular echinoderms are known to take up plutonium and other nuclides to very high levels and retain them for long periods of time (Guary et al., 1982; Fowler, 1985), they should be useful bioindicators of contamination and dispersion in the Kara Sea.

Valuable insights into the possible pathways and rates of biological transfer and transport of radioactivity from the dumpsites can be gained by examining the single, well-documented case study of acute radionuclide contamination in the Arctic marine ecosystem. In 1968, a B-52 bomber carrying unarmed nuclear devices

crashed on the ice dispersing approximately 1 TBq of plutonium in the shallow waters of Bylot Sound near Thule, Greenland. Following the accident, four radioecological surveys were carried out by a Danish and Swedish team in 1968, 1970, 1974 and 1979 (Aarkrog, 1971, 1977; Aarkrog et al., 1984). These studies demonstrated that plutonium, a particle reactive nuclide, was rapidly bound by the sediments, thus becoming effectively retained in the benthic ecosystem. This was underscored by the fact that after 1968, no significant increases in plutonium concentrations were found in either the overlying waters, zooplankton, pelagic fish, sea birds, marine mammals, or the indigenous population.

The most instructive radioecological observations were noted in the benthos. Although the initial contamination was confined to an area of roughly 0.1 km^2 , by 1974 elevated plutonium concentrations in sediments were measurable up to 20 km from the point of impact (Figure 4). Plutonium concentrations in bivalve molluscs and nereid worms living within the sediments closely reflected the pattern of plutonium decrease with distance from the source observed in sediments. On the

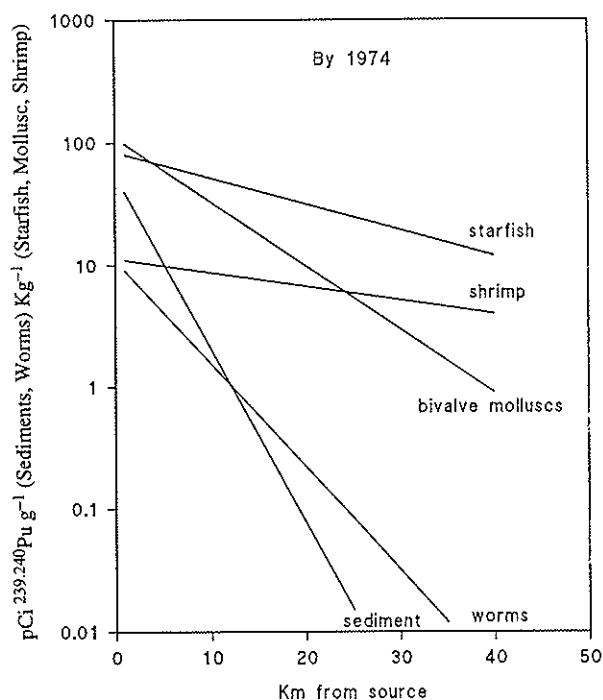


Figure 4. Plutonium concentrations in surface sediment and associated benthic species as a function of distance from the point source of contamination in Bylot Sound, Greenland, six years after the accident (data from Aarkrog, 1977).

Table 5. Estimates of $^{239+240}\text{Pu}$ inventories and transfer coefficients at Thule, Greenland (from Aarkrog, 1977).

Sample type	Biomass (g/m ²)	Inventory in Curies		Transfer from release of 1 Ci (Ci per year)
		1970	1974	
Molluscs				
Soft parts	100	2.4×10^{-3}	1.9×10^{-3}	1.5×10^{-3}
Shells	100	6×10^{-3}	5×10^{-3}	4×10^{-3}
Brittlestars*	30	3×10^{-3}	0.8×10^{-3}	0.6×10^{-3}
Shrimp*	20	1×10^{-3}	0.2×10^{-3}	0.2×10^{-3}
Worms*	10	0.5×10^{-3}	0.5×10^{-3}	—
Sediment	—	30	30	—

*Whole organisms.

other hand, plutonium levels in shrimp and echinoderms did not decrease with distance from the source as rapidly as was found for infaunal worms and bivalves (Figure 4). This suggests that the more mobile, Arctic epifauna can accumulate and transport radionuclides considerable distances from the contaminated source.

Bivalve molluscs such as *Macoma calcaria*, brittle stars and seastars generally contained the highest concentrations of plutonium among the invertebrates analyzed. Since they also represented the greatest proportion of the total biomass, most of the plutonium inventory in the biota was associated with these species. Nevertheless, the data in Table 5 indicate that during the 2-6 years following the accident, the benthos in the relatively productive waters near Thule (benthic biomass = 200-300 grams per square meter) never contained more than 0.1% of the total plutonium inventory in the sediments. By 1979, the relative distribution of plutonium between sediments and biota had not significantly changed. The *Macoma calcaria* community, which represented 38% of the biomass in the region, contained 0.2 GBq of $^{239+240}\text{Pu}$, i.e. roughly 0.02% of the $^{239+240}\text{Pu}$ in the sediments (Aarkrog et al., 1984). This translates to a transfer factor of 0.012 Becquerels per year (Bq y⁻¹) per Bq released to the sediments. Clearly, the Thule data indicate that in Arctic coastal waters, the transfer of plutonium from sediments to organisms and its eventual biological transport from the contaminated zone is a relatively slow process.

In the shallow waters of the Kara Sea, long-lived radionuclides like plutonium released from the wastes would eventually become associated with the sediments in and around the dumpsites. Given the relatively low benthic biomass (10 g m⁻²) typically found in these waters, only a very small fraction of the total radionuclide inventory in the sediments would be accumulated by these species. Nevertheless, brittle stars, seastars and bivalves (e.g., *Macoma calcaria*) are the prominent species in the Kara Sea benthos and, considering their proven ability to accumulate plutonium (i.e. high CFs) under Arctic conditions, they should be considered the

bioindicators of choice for plutonium and possibly other radionuclides in any future surveys at the dumpsites.

Conclusions

The preliminary radiochemical measurements and the modeling exercises made within the framework of an international Arctic Seas assessment program suggest that, beyond the immediate vicinity of the dumpsites, anthropogenic radioactivity enhancements resulting from past disposals in the Arctic Seas are and will continue to be low. Furthermore, the IAEA-MEL radiological model based on conservative assumptions about release rates and fish consumption predicts doses which are comparable to or less than those resulting from other anthropogenic and natural sources of radioactivity of relevance on a global scale. In order to further refine the assessment and include critical information on local doses, future work should focus on monitoring and modeling the dumpsites themselves, their immediate environments and their local transfers and consequent exposures.

At present, our knowledge of radioecological processes in Arctic marine ecosystems is quite sparse, and it is difficult to predict with any accuracy the behavior and fate of radionuclides released into the shallow waters of these seas. Based on the few Arctic data that are available, it is suggested that in the Kara Sea certain radionuclides such as the transuranics (e.g., plutonium, americium, curium) would quickly become associated with the bottom sediments in the near field and, because of the low benthic biomass in this region, their inventories in the sediments would be little affected by biological transfer and transport. For purposes of future monitoring, common Kara Sea species like brittle stars, seastars and bivalve molluscs which readily accumulate transuranics, would be ideal bioindicators for following any dispersion of radionuclides from the dumpsites.

Acknowledgments

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The Arctic Monitoring and Assessment Program

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Arctic Environmental Monitoring and Assessment Work Group

Interagency Arctic Research Policy Committee

The Arctic Monitoring and Assessment Program (AMAP) is an international program established by the Environment Ministers of the eight Arctic countries (Canada, Denmark, Finland, Iceland, Norway, Russia, Sweden, and the United States). Their agreement is embodied in the Arctic Environmental Protection Strategy which was endorsed in June of 1991 in Rovaniemi, Finland.

The Protection Strategy describes the Objectives of the AMAP. The most significant objective is the "Measurement of the levels of anthropogenic pollutants and the assessment of their effects in relevant components of the Arctic environment." The strategy directed:

1. the establishment of a Task Force, and a small Secretariat,
2. a focus on persistent organics, heavy metals, and radionuclides,
3. that AMAP be built upon existing programs, and
4. that AMAP ultimately focus on monitoring ecological indicators of contaminants as a foundation for the assessments.

The Ministers intend to use this information to make decisions about the need for additional regulation of the priority contaminants—persistent organics, heavy metals and radionuclides. The Protection Strategy also lists the international fora in which these negotiations would take place. These fora already exist outside of the Strategy group.

Monitoring Program

AMAP has developed its program in a series of meetings. At the first meeting of the AMAP Task Force, the most significant discussion was over the design of the monitoring program. Some parties argued that the mon-

itoring program should be designed on a pollutant specific basis, while others argued that it should be designed on a media specific basis. In addition, some argued that the assessment should be developed before the monitoring program, while others argued that the assessment design should follow the monitoring design. The first Task Force meeting concluded that a monitoring program should be developed along media specific lines. The Task Force further determined that individual nations or organizations should take the lead responsibility for developing individual sections. The media and the lead nations are as shown in Table 1.

Table 1. Media and lead organizations tasked with developing monitoring plans for AMAP.

<i>Media</i>	<i>Lead</i>
Emissions and Discharges	Secretariat
Atmosphere	Canada
Terrestrial	Sweden
Freshwater	Finland
Marine	Norway
Human Health	Denmark
Remote Sensing and Modeling	United States

Individual plans were developed in a series of expert meetings and were circulated among the Arctic nations. They were adopted in principle at the Second Meeting of the AMAP Task Force in December, 1992. This meeting also included discussion on cross-fertilization. The discussion focused on how one could use and enhance the media specific plans to ask questions about the pathways followed by specific pollutants. The media specific plans describe which specific contaminants

should be monitored in which specific component of the media. For example, the freshwater media is broken down into sediment, water, biota, and suspended solids. The plans also discuss their rationale, methods, quality assurance, and site selection issues. Finally, each plan identifies the highest priority measurements and labels them as essential. These media specific plans are combined into an overall plan which includes cross-cutting summaries.

The compilation of media specific plans and overviews constitutes an international plan which establishes a goal or benchmark for national implementation plans. Individual nations have compiled these and provided them to the AMAP secretariat. Elements of the US plan are summarized in Tables 2 through 5. All of these elements combined, the media specific international plans, the international summary, and the collection of national implementation plans constitutes the Comprehensive AMAP plan.

Table 2. Monitoring Persistent Organic Compounds in the Arctic—US Program Under AMAP. The columns describe the contaminants, the rows describe the media or sub-media which are being monitored. The numerical entries refer to the projects of the US program which are listed in Table 5.

<i>Program/Media</i>	<i>PAH</i>	<i>Planar-CB</i>	<i>PCB</i>	<i>DDT/ DDE/ DDD</i>	<i>HCH</i>	<i>HCB</i>	<i>Chlordane</i>	<i>Dieldrin</i>	<i>Toxaphene</i>	<i>Dioxins</i>	<i>Dibenzofuran</i>	<i>Mirex</i>
Atmosphere												
Air/Precip/Snow				21	21	21		21				
Terrestrial												
Soil	10,20		10	10	10				10	10,20	10,20	
Humus	10,20		10	10	10				10	10,20	10,20	
Lichens	10,20		10	10	10	10	10,20	10,20				
Mosses	10,20		10	10	10	10	10,20	10,20				
Freshwater												
Sediment	10,20		10	10	10	10	10	10	10	10,20	10,20	10
Water	12											
Susp Solids												
Biota	10	10	10	10	10	10	10	10	10	10		
Marine												
Sediment	3,7,21		3,21	21	21	21	21		21			
Biota	1,21		1,21	1,21	1,21	1,21	1,21	1	21			
Human Health												
Blood												

Table 3. Monitoring Metals in the Arctic—US Program Under AMAP. The columns describe the contaminants, the rows describe the media or sub-media which are being monitored. The numerical entries refer to the projects of the US program which are listed in Table 5.

<i>Program/Media</i>	<i>Cd</i>	<i>Cu</i>	<i>Hg</i>	<i>Pb</i>	<i>Zn</i>	<i>Cr</i>	<i>Ni</i>	<i>As</i>	<i>Se</i>	<i>Al</i>	<i>V</i>	<i>Fe</i>	<i>Li</i>
Atmosphere													
Air/Precip/Snow													
Terrestrial													
Soil	10	10	10	10	10	10	10	10		10	10	10	
Humus	10	10	10	10	10	10	10	10		10	10	10	
Lichens	10	10	10	10	10	10	10	10		10	10	10	
Mosses	10	10	10	10	10	10	10	10		10	10	10	
Mammals/Birds	10	10	10	10	10	10	10	10	10	10			
Freshwater													
Sediment	10	10	10	10	10	10	10	10		10	10	10	
Water	12	12	12	12	12	12	12	12	12	12	12	12	
Susp Solids													
Biota	10	10	10	10	10	10	10	10	10	10	10		
Marine													
Sediment	3,7,21	3,7,21	3	3,7,21	3,7,21	3	7						
Water	21	21		21	21								
Biota	1,7,21	1,7	1,21	1,7,21	1,7	1	1	1	1	1	1	1	
Human Health													
Blood													

Table 4. Monitoring Radionuclides in the Arctic—US Program Under AMAP.
The columns describe the contaminants, the rows describe the media or sub-media which are being monitored. The numerical entries refer to the projects of the US program which are listed in Table 5.

<i>Program</i>	<i>Media</i>	<i>Gross Gamma</i>	<i>Gross Beta</i>	<i>¹³⁷Cs</i>	<i>¹³⁴Cs</i>	<i>⁹⁰Sr</i>	<i>⁹⁹Tc</i>	<i>²¹⁰Pb</i>
Atmosphere	Air	11		11				11
	Precipitation							
	Snowpack							
Terrestrial	Soil			10,20				
	Humus			10,20				
	Lichens			10,20				
	Mosses			10,20				
	Mammals/Birds							
Freshwater	Sediment			10,20	10,20	10,20		10,20
	Water							
	Susp Solids							
	Biota							
Marine	Sediment			18	18	18		
	Water			18	18	18		
	Biota			18	18	18		

Table 5. Listing of US Projects Under AMAP.

<i>Project no.</i>	<i>Point of contact</i>	<i>Agency</i>	<i>Project title</i>
1	Becker	NOAA	Alaska Marine Mammal Tissue Archival Project
2	Hameedi	NOAA	Arctic Lagoon Oceanography
3	Robertson	NOAA	Status and Trends Program-Arctic
4	Hameedi	NOAA	Outer Continental Shelf Environmental Assessment Program
5	Hameedi	NOAA	Alaska Marine Contaminants Database
6	Hameedi	NOAA	West Dock Causeway
7	Geiselman	DOI	Beaufort Sea Monitoring
8	Imm	DOI/MMS	Monitoring and Evaluating Seabird Colonies
9	Peterson	NOAA	Atmospheric Trace Species Baseline Monitoring
10	Landers	EPA	Arctic Accumulation of Air Toxics
11	Larsen	DOE	Surface Air Sampling Program
12	Snyder-Conn	DOI/FWS	Prudhoe Bay Ponds and Lakes—Acidification Studies
13	Snyder-Conn	DOI/FWS	Prudhoe Bay Contaminants
14	Snyder-Conn	DOI/FWS	ANWR Contaminant Baseline Study
15	Treacy	DOI/MMS	Beaufort Sea Bird Monitoring
16	Treacy	DOI/MMS	Bowhead Whale Aerial Survey
17	Wainwright and Harlburt	HHS	Health
18	Codispoti	DOD/ONR	Arctic Radionuclides
19	Slaughter	USDA/FS	Boreal Forest Ecosystem Processes
20	Heit	DOE	Atmospheric Deposition of Radionuclides and Combustion Produced Organics into the Arctic
21	O'Conner	DOI/FWS	BERPAC

Other AMAP Activities

In addition to the development of a monitoring program, AMAP was tasked with the development of a Report to Ministers. This report was requested in the spring of 1992 and is to be available for the Ministerial meeting scheduled for September of 1993. This report contains both a science update and a series of draft recommendations for the consideration of the Ministers. Its development has placed a considerable burden on AMAP both in terms of developing the report, and in terms of negotiating for meaningful policy recommendations within an organization dominated by personnel with a science rather than a policy portfolio.

AMAP will begin to develop its plans for an assessment at its fourth Task Force Meeting in October, 1993.

AMAP has asked for the assistance of the International Arctic Science Council (IASC) in the review of the national implementation plans, using the international plan as a benchmark. The audit should be completed by the ministerial meeting. The Task Force has decided not to request a review of the international plan.

Issues for the Implementation of AMAP

The implementation of a broad based international monitoring and assessment program poses a significant challenge to the participating countries. While the Min-

isters directed that the monitoring program would be built as far as possible on the basis of existing programs, the disparate methods and designs of these programs need to be effectively harmonized rather than rationalized if they are to serve as the basis for a scientifically credible circumarctic assessment. In addition, there is a general recognition that assistance needs to be provided to Russia if meaningful reports on emissions or contaminant levels are to be developed for the largest Arctic nation. Finally, although AMAP is committed to the participation of indigenous peoples in its program and reports, fully effective avenues to make this participation meaningful are yet to be developed.

The Role of the United States

The United States has established an Arctic Environmental Monitoring and Assessment Work Group to interact with the Arctic Monitoring and Assessment Program. The Work Group was established by the Interagency Arctic Research Policy Committee (IARPC) which was

established by the Arctic Research and Policy Act of 1984. The Work Group is co-chaired by scientists from EPA and NOAA.

The United States has played an active role in the Task Force, but not a leadership role. No funds have been redirected to support the AMAP commitment. As requested, the United States has developed a report on remote sensing. However, efforts to define the scope of a modeling report and how it would relate to the discussion on models within the media plans have not been successful. The United States has a substantial activity in Arctic monitoring. The summary tables (Tables 2 through 5) suggest a relatively complete program. There are some significant gaps in the US program, especially with regard to human health and atmospheric sampling. In addition some of the programs listed are quite modest or have been terminated. As a result, it will be difficult for them to contribute to the AMAP assessment. Finally, the most significant gap in the US program is the absence of a meaningful integrated synthesis effort.

A U.S. Response Implementation of the Department of Defense Office of Naval Research (ONR) Program

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Before I begin getting into the meat of describing this program, I want to mention that this effort had its origin in the hard work of many individuals whose activities preceded my involvement. This group included the Alaska Congressional Delegation and members of IARPC. Since I have been in Washington, DC, I have been aided in the development of this program by an advisory committee. Bruce Molnia is on the committee, Bob Dyer is on it, Curtis Olsen is on it, Charles Newstead is on it, Martha Scott from NSF is on it, and several others. I want to recognize the help of the advisory committee. I also want to recognize the tremendous help I have received from my colleagues Tom Curtin, Ed Pope, and Leonard Johnson, at the Office of Naval Research. Leonard has found approximately a million dollars of additional monies through the Young Investigator and AASERT (Augmentation Awards for Science and Engineering Training) programs to put into this effort.

This program had its origins in a concern about problems that might arise from the disposition of radionuclides in the Arctic Ocean. But despite that concern, Senator Murkowski's remarks this morning suggest that it took some luck to get 10 million dollars appropriated for this program. As a consequence of the appropriation process, the monies came to the Department of Defense in an unusual way for money that would be spent on a program of environmental research. As a result, it took time to decide that the Office of Naval Research, with substantial collaboration from the Naval Research Laboratory (NRL), would take the lead in designing this program of research. At the same time, we were asked, and I think rightly so, to try and begin to collect data, during this summer field season. So, we

have been working on a very short time line. We are pushing the bureaucratic envelope in this sense in that we have the program moving well along, even though final approval for our plan and transfer of funds to ONR are pending. We are told that "the check is in the mail," but everything I say today must have a slightly tentative characteristic to it, until we obtain final approval for our programs.

Once we were charged with developing a program, we looked at some existing radionuclide data from the Arctic. Figure 1 shows some data from Matishov et al., from the Kola Peninsula, which is adjacent to the Barents Sea. Although these are terrestrial data on Cs-137 in lichen and reindeer, they show what a lot of the oceanic data also suggest. The main anthropogenic signal you see, occurred around the time of atmospheric testing, and these levels have gone down with time.

Scott Fowler has already done a good job of describing this Figure 2 on Cs-137 in the Kara Sea. As Scott already told you, cesium levels in 1992 were, in general, lower than in 1982, and the levels were not very alarmingly high. In talking with folks like Hugh Livingston, what I have learned is that in places like the Kara Sea, you might see the atmospheric testing signal and the signal of nuclear fuel re-processing in Europe, but you do not yet see any signs of a regional pollution effect.

After considering existing data such as those just described we decided that you do not see any evidence right now for massive or wide spread radionuclide pollution in the Arctic Ocean. When we look at the amounts of material that have been deposited, and at the amounts stored on the watershed of some of the major Arctic rivers, such as the Ob and the Yenisei, there is some concern about what would happen if there is a

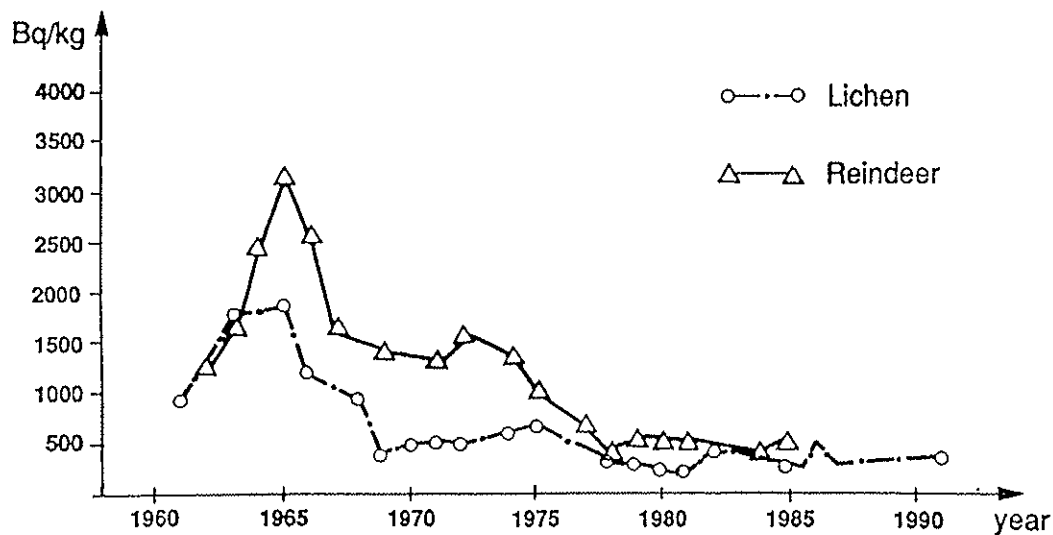


Figure 1. Average values of cesium-137 activity in lichens and in reindeer muscle on the Kola Peninsula, 1960-1990. (from Matishov et al., 1992).

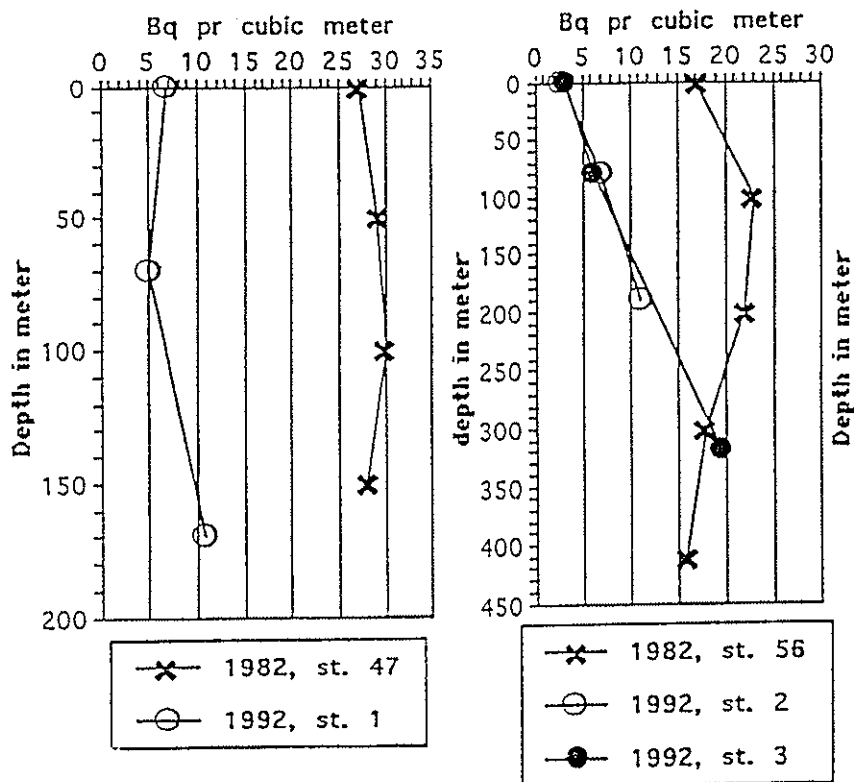


Figure 2. Cesium-137 data from the Kara Sea. Comparison of cesium-137 values from 1982, reported by Vakulovskii et al., 1985 with preliminary values from the joint 1992-FSU/Norwegian cruise.

significant release of some of this material. In addition, as you may have inferred from many of the talks this morning, the data on how the Arctic ecosystem functions in transforming and transporting radionuclides, is scant compared to many other areas. And so, we designed our program of research with these concepts in mind.

We and our advisory committee feel that this program must be characterized by scientific and technical excellence. One way we have done that is by an open solicitation process. Some of the funds are going to DOD labs, but even those were competed for within DOD. The majority of funds awarded to researchers are

a result of an open solicitation process through our Broad Agency Announcement to academia and industry, and through our asking government agencies with needed expertise to submit their ideas and their proposals. As a result of this open solicitation process, we received 135 preproposals, amounting to requests for over 135 million dollars. We will probably be able to fund about 15 proposals. Another feature of the program that we feel is very important is interagency coordination. As I said at the outset, without the existence of IARPC, this program might not exist. And members of our group at ONR regularly attend IARPC meetings and keep informed of the activities of IARPC in that manner. In addition, we have formed the advisory committee which I have already mentioned. This committee includes several representatives from DOD, and I have already mentioned some of the agency representatives from the Departments of Interior, Energy, and State and from EPA and the National Science Foundation. The majority of preproposals we received were rated not only by myself and my colleagues at ONR, but also by the advisory committee. Another aspect of the program is international participation.

Our program has a strong element of international collaboration. You heard many of the previous speakers mention that it is essential that we have close working relationships with our Russian colleagues, and we are working hard on that. Dave Nagel, who is leading the Naval Research Laboratory team, and I visited the Norwegian Embassy to help coordinate the activities of Norwegian scientists and facilities with our work. We are going to work hard on increasing the amount of international participation.

One thing that perhaps sets our program off from some of the other programs that are being mounted to look at this problem is that, being a United States program, we have a particular concern about the welfare of United States citizens. So we have a much higher interest in conditions in and near Alaska than some of the other nations who are looking into this problem.

Now, I want to briefly describe some of the activities that we plan to support under this program. They include partial support for this workshop, and for the workshop that will be held at Woods Hole on June 5-7. We are going to support and collaborate in attempting to organize and coalesce data on the problem that already exist, both in the Former Soviet Union and the United States. We are going to support some modeling activities, and we are going to support some laboratory studies on corrosion and on the biological transfer coefficients between organisms and radionuclides, in conditions that mimic Arctic conditions.

A major effort involves the collection of a large amount of data during this summer's field season. The

most definite cruise right now will be on the U.S. Coast Guard icebreaker *Polar Star*. This cruise is well along in the planning stages and it is fairly firm. One of its goals will be to obtain radionuclide data, not only from the inner shelf where we already have a fair amount, but from the outer shelf and upper continental flow. Knut Aagaard made a compelling case, I thought, this morning, for the necessity of understanding more about the currents over the slope. And one of the areas where radionuclides might deposit is in depot centers on the upper slope. We are very interested in whether or not water can travel horizontally, rapidly, along the halocline that Knut mentioned in his talk today. We know that in the Black Sea, the Chernobyl signal migrated rapidly, horizontally, along such a density gradient. This may be one mechanism that has not yet been looked at that could move pollutants from the Former Soviet Union sector to the Alaskan sector of the Arctic. A bilateral cruise that we are going to help support, and hope to get some samples from, is a continuation of the BERPAC Program, in collaboration with the Department of Interior, the National Science Foundation, and the Department of State. We hope to provide some funding for this cruise which will be on the Russian vessel *Okean*. There has been increasing concern about dumping in the North Pacific since the Yablokov Commission Report just came out, and we have hopes of getting some samples from this region from a Former Soviet Union ship, in collaboration with the FSU, Science Applications Incorporated, and other elements of the U.S. Navy. For a couple of years now, scientists from Ohio State University have been collaborating with the Murmansk Biological Institute, and they are planning a cruise this summer on the *Geolog Fersman* in the vicinity of Franz Josef Land. We are hoping to get some data from this cruise. We are in initial discussions with the Shirshov Institute concerning a cruise on the R/V *Mendeleev* to the Kara Sea. We are hoping to be able to add some resources to this cruise that will help to look into the problem of radionuclide pollution. Also, scientists from Texas A&M and Woods Hole Oceanographic Institute believe they have opportunities for sampling the estuaries of the Ob and the Yenisei rivers this summer. So, we have a very ambitious field program that is continuing to expand. I have had many sleepless nights wondering if we will be able to pull it all off, but many of us, people in this room and elsewhere, are working hard to make it happen. I think we have a good chance of making most of this happen this summer.

Another element of our program is the analysis of gravity core samples taken from U.S. Coast Guard Navy icebreakers in the 1960's and 70's in the Beaufort, Bering, Chukchi, East Siberian, and Laptev seas. These core samples are stored at Oregon State University, and we are planning to fund Dr. Nick Psias and colleagues to

take a look at these core samples, select the best ones out, and get some idea of what the total burdens of radionuclides in these core samples were, ending at about 1975. We feel that data from these cores will be very useful for comparison with cores that are taken in more recent years.

We are not going to do it alone, but we anticipate that our program will make an important contribution to the assessment of present-day nuclide levels in the Arctic and North Pacific. I should mention that a rather complete suite of nuclides are planned for analysis, including some analyses that are at the cutting edge of analytical technology such as iodine-129. We also hope to be able

to collaborate in the initial assessment of the dumped material. Of course, to do this will depend upon the cooperation of our Russian colleagues. A longer term goal is to help predict the fate of contaminants if a release occurs. We also hope that our work will contribute to the selection of monitoring sites. Even if they are not needed for radionuclides, monitoring sites will probably be needed for other pollutants. Finally, we are hoping that the data on the circulation of the Arctic Ocean that will be produced by our studies will not only be useful for understanding the problem of radionuclide contamination, but for understanding the transport of other pollutants as well.

Arctic Contamination Data Management Issues

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What Data Now Exist?

The body of data relating to Arctic contamination is relatively small. A search of the 350 entries in the *Arctic Environmental Data Directory* (AEDD) revealed only 18 data sets that contained terms that may relate to contamination of the Arctic Ocean, atmosphere, and land surfaces. AEDD is a directory supported by the Interagency Arctic Research Policy Committee which describes the major Arctic data holdings of U.S. Federal agencies. Of these, six contain data on the bottom sediments of the Arctic Ocean and adjoining water bodies, eleven relate to the chemistry of water in the Arctic Ocean and its tributaries, and one relates to pollutants. No entries exist describing measurements of radionuclides, DDT, or PCB. The largest database is the National Oceanographic Service Hydrographic Database which contains over 27 million measurements. Most of the data sets contain between 10,000 and 36,000 measurements. A few of the data sets are available on paper copy only, but most are available either online or on a variety of digital media.

An additional seven data sets that may relate to Arctic contamination were retrieved from the National Oceanic and Atmospheric Administration's (NOAA) National Geophysical Data Center *Marine Geology Digital Inventory*. Available on paper, microfiche, and in some cases, magnetic media, these principally geochemical data are drawn from the Kara Sea, the Beaufort Sea, and the North Atlantic. Inquiries to other Federal agencies prior to the Arctic Contamination Workshop did not indicate that other data are available.

Existing data sources described in AEDD are predominantly the data centers of NOAA, the U.S. Geological Survey, and facilities of the Institute of Marine Science at the University of Alaska, Fairbanks. One

related entry exists from the former Soviet Union (FSU), but the data set describes parameters of wells in the Russian Arctic, which are principally on land. One CD-ROM was produced by NOAA in 1989, the *Alaska Marine Contaminants Database*, as part of the Alaska Outer Continental Shelf Environmental Assessment Program.

What Data are Not Available?

Major data gaps appear to exist in virtually every discipline, with voids in most. There are no data sets described in the directory focused specifically on monitoring of radionuclides. Recent activity augmenting the AEDD include references to health, medical, and demographic data which may be useful in the analysis of the impact of contaminants on Arctic citizens.

The weaknesses of existing data are unknown in the context of contamination monitoring and analysis. Most of the data have been collected for purposes other than monitoring Arctic contamination. An investigation of these data would be needed to ascertain their usefulness in tracking changes in the contamination level of ocean-bottom sediments, the water column, and the Arctic atmosphere and land surfaces.

Many samples that have been taken have not been analyzed or reported upon. It is also certain that collections of data have been gathered but not documented and transferred to data repositories. A data archaeology, or a Save the Data Program, could bring many undocumented data sets to scientific use, but priorities would need to be set so that scarce resources might be focused on the data most likely to be useful to science.

Contamination data that exists in other countries is unknown in terms of period of record, geographical extent, quality, and quantity. The Arctic Monitoring and

Assessment Program (AMAP) is in the early stages of developing a directory and repository for Arctic monitoring data at the United Nations Environmental Program/Global Resources Information Database (UNEP/GRID) office in Arendal, Norway. An element of their program is to develop an index to data available in the Nordic countries plus portions of the FSU. This development is being done in cooperation with the U.S. Geological Survey which manages AEDD.

How good are the data?

Quality control has been exercised to varying degree on existing data. A few of the data sets have extensive documentation of quality control procedures used in data collection, data measurement, and data reporting. Most of the data sets do not indicate such consistency in the available documentation, although the extent to which this is true is unknown at this time. While the data set descriptions in AEDD have been reviewed extensively for consistency, accuracy, and completeness, the quality of the actual data is sometimes uncertain. For contamination data to be useful internationally, a process of review should be instituted so that scientists using the key data sets can be comfortable with the methods used to gather, calibrate, measure, analyze and store the data. This applies to data from U.S. sources and to data from other countries including the FSU.

Guidelines for Data Management

In July 1991, the Office of Science and Technology Policy (OSTP) published a set of Policy Statements for Data Management for Global Change Research. These guidelines were intended to represent the U.S. Government's position on the objective of full and open access to quality earth-science data. At the heart of the policy is "an early and continuing commitment to the establishment, maintenance, validation, description, accessibility, and distribution of high-quality, long-term data sets. Full and open sharing of the full suite of global data sets for all ... researchers is a fundamental objective." A copy of the policy statement is appended. It provides sound advice on the preservation of data archives, the use of international standards, low-cost access to and use of data, and the swift sharing of data with scientific community.

Action Plan

The outline of the following Action Plan complies with the U.S. Data Management Policies articulated by OSTP. More importantly, it produces useful results quickly so that scientists may begin work quickly with reliable data sets. It builds on the experience and recommenda-

tions of previous data-intensive science activities such as the Global Change Research Program. The Arctic Contamination Workshop must address each of the following issues if the scientific community is to build the analysis of contamination on a sound data foundation.

- Identify parameters and coverages that are most important to the understanding of the changes in Arctic contamination over time.
- Identify priorities so that the earliest and most intensive work is dedicated to acquiring, documenting, and preserving the data which is most important to understanding the problem.
- Identify the group or agencies responsible for acquiring, gathering, and documenting each of the priority parameters and coverage data sets.
- Identify the repository where each key Arctic contamination parameter will be preserved and available for future access.
- Identify documentation standards which will be sufficient to describe each of the data sets.
- Identify how each data set will be accessible by the scientific community.
- Identify partners in other countries who can be approached to share techniques and scientific data.

Expected Results

Data management is one area of endeavor where scientifically useful international results can happen quickly. Early results can be expected in the first steps of the action plan and in the construction of inter-related directories in various countries. AEDD, which is accessible internationally over the Internet, is already poised to help document and share information about Arctic contamination data sets. A team approach to identifying and documenting existing data which are not documented will yield significant useful results in the first year of activity. In the longer term, the development of needed but non-existent data through data gathering programs, or the organization of data sets from paper or other less organized media will result in new and heretofore unshareable data becoming available for scientific use.

A coherent data management activity supporting the study of Arctic contamination will help build a foundation of factual data on which a scientific understanding of contamination's implications can be built. IARPC agencies will be mobilized to contribute their data for public use. Data management provides organizations in other countries with the tools to contribute important data and information to these studies. Without an organized data management activity, the public perception of risk from Arctic contamination cannot become substantiated as fact.

**Data Management for Global Change
Research Policy Statements:
July 1991**

The overall purpose of these policy statements is to facilitate full and open access to quality data for global change research. They were prepared in consonance with the goal of the U.S. Global Change Research Program and represent the U.S. Government's position on the access to global change research data.

- The U.S. Global Change Research Program requires an early and continuing commitment to the establishment, maintenance, validation, description, accessibility, and distribution of high-quality, long-term data sets.
- Full and open sharing of the full suite of global data sets for all global change researchers is a fundamental objective.
- Preservation of all data needed for long-term global change research is required. For each and every global change data parameter there should be at least one explicitly designated archive. Procedures and criteria for setting priorities for data acquisition, retention, and purging should be developed by participating agencies, both nationally and internationally. A clearinghouse process should be established to prevent the purging and loss of important data sets.
- Data archives must include easily accessible information about the data holdings, including quality assessments, supporting ancillary information, and guidance and aids for locating and obtaining the data.
- National and international standards should be used to the greatest extent possible for media and for processing and communication of global data sets.
- Data should be provided at the lowest possible cost to global change researchers in the interest of full and open access to data. This cost should, as a first principle, be no more than the cost of reproduction and distribution. Agencies should act to streamline administrative arrangements for exchanging data among researchers.
- For those programs in which selected principal investigators have initial periods of exclusive data use, data should be made openly available as soon as they become widely useful. In each case the funding agency should explicitly define the duration of any exclusive use period.

Risk Assessment Requirements

William Cooper
Michigan State University

This is an informal summary of what, in my opinion, is the process one must take to perform a risk assessment. My experience working in the area of risk assessment is wide ranging. As Chair of the Environmental Review Board (ERB) in the State of Michigan for 14 years, the ERB ran public hearings on everything from nuclear plants, to PCBs, to dioxin, and so forth. In addition, I serve as a member of the Science Advisory Board (SAB), and on the board to examine how the U.S. Environmental Protection Agency (USEPA) should use their risk assessment methodology to set their funding priorities and their regulatory priorities, on the assumption you cannot do everything at once.

As someone mentioned earlier, it is kind of like doing an assessment without knowing your source. Because, on the way up here, you can talk about a lot of hypothetical things, but until you know what is down there, what chemical form the contamination takes, what transport mechanism you are dealing with, what exposure rates are there, it may be too early to proceed. If you cannot do good science, you should do none at all. The EPA SAB actually went through a risk analysis process for EPA Administrator William Riley, where we had to somehow rank the global warming, atmospheric, ozone, pesticide residues, ground water pollution, habitat destruction. We had less data than you have.

My presentation will outline a variety of alternative ways you can do risk assessment. You do not need perfect data before you do something, because, quite frankly, the decisionmakers, whether it is the Governor, the President, or whomever, cannot sit around and wait for scientists to cross all the t's and dot all the i's. A number of our colleagues are very unhappy with this premise, because they do not like to extrapolate beyond their data. My effort is to try to convince you that you might have to do that, and then as you iterate over time, you fill in the gaps. You do not have to wait until the

gaps are filled in before you start. My scientist friends have heard from me many times that, in terms of getting science in the public policy, if the scientists do not do it, the lawyers will, and they are not constrained by anything, either thermodynamics or evolution. So even if you are mostly wrong, it is better than the kind of Ouija board that has been used to date. So, with those kind of introductions, let me tell you the two kind of end points of risk assessment models you run into.

If you look at the history of risk assessment with human beings, it is the one developed by the Food and Drug Administration, the old Atomic Energy Commission, the National Institute of Health, and the U.S. Department of Agriculture. They basically use an individual approach that requires the calculation of some kind of dose response curve. Once they calculate the dose in a material, say seawater, they then ask the question, what is a safe level. You come up and say it is either above or below it.

Basically that whole approach to risk assessment is based on what is called a dose response curve. Generally, we do not have dose response curves in field data. We generated that data in the laboratory and extrapolate it to the field. When one is talking about probabilities of response so low enough that one cannot measure things at the level you want, one has to measure them in high levels and extrapolate to low doses. That is the reason why you hear people say, if the mice had to drink enough soft drinks to get bladder cancer, you would have to drink 10,000 gallons of soft drink a week. They think the science is bogus, but it is not bogus at all. It just demonstrates that when one wants to deal with a probability of 10^{-6} to 10^{-5} , and there is already a background level of carcinogens, you have to utilize 10 million mice per treatment per replica. What researchers do is give the test animals a high dose and assume that the mechanism is not dose dependent, and so they can use 10 mice in a replica. Now, you can decide whether you like

it or not. That is the way the field works, with only rare exceptions. You calculate a dose response curve and you come up with some kind of a probabilistic graph. If the substance is a carcinogen, one sees that there is no threshold, and you probably assume that with the radionuclides, so you take it down to the zero point. If on the other hand, it is some kind of general toxicant, we go down to some level which we call a NOEL, that is there is No Observable Effect Level. You divide that value by a safety factor of 100, and calculate an action level or a tolerance level. That is the way that FDA sets drug levels and USEPA sets pesticide levels.

The first decision you have to make, as you go through this process, are whether you are going to use a conservative, no-threshold model, and extrapolated to a level where one radionuclide is potentially a cause of cancer, *or* do you want to consider whether or not you have got repair mechanisms in the DNA, and you could set some kind of threshold. This is hotly debated by the people in the field. Again, you are going to have to make some choices, and you have got to make some judgment calls as to which way you want to go. Then you can do your risk assessment, and then we can tell you what kind of data you are going to need.

The biggest problem one has is finding out what the exposure rates are. It has been my observation that I know of no case to date where we have actually measured exposure levels in the field. This means you have got to somehow take body fat levels and back-calculate. Well, at the time we did a lot of that, we did not know the metabolism of something like dioxin. We now know and so now we can back-extrapolate, and quite frankly, we way overestimated human toxicology, human sensitivity. If you back-calculate for the women in Seveso, Italy, that we do have known point exposures with what we now know about pharmacokinetics, they all should be dead and weren't. They only got chloracne.

Again, when you get involved with these risk assessments, you have got to make your best guesses, but generally, from my experience, we way overestimate initially. Most people argue you would rather be wrong conservatively than be cheap and find out that you guessed incorrectly.

As an example, let me tell you about the work of the Armed Forces Institute of Pathology. These researchers, almost all of them veterinarians, study environmental episodes after the fact, events like the *Exxon Valdez* oil spill, the Cameroons' Lake N'goss that turned over and killed 17,000 people, and the Kuwaiti oil fires. They use these as case studies, and have shown that when we look back, most of the anticipated ecological damages never showed up. Researchers tend to over estimate the effects.

What you intuitively do is put in a bigger safety factor. In fact, the same thing is done in risk assessment

models. Researchers start with studies on beagles, white mice, or white rats, and one uses a safety factor of 10 to calculate chronic human models. If one does not have chronic data but rather acute, one must estimate chronic from acute, using a safety factor of say, 100. If you do not have the direct compound, but rather an isomer of it, one may use a safety factor of 1000.

Most of these risk assessment models are a tradeoff between hard data with the right time horizon versus a safety factor. And if the safety factor costs you too much, then you spend your money going out and getting more data. If not, you go with a conservative model. This is the kind of tinkering you have to do when you really match things, and say "How much data do you need before you can come up with a recommendation?" Oftentimes you do not have the choice of saying, "I need all the data chronically of the right species, in the right place, in the field, over a ten year time horizon, to get trend analysis." You will be lucky if you get that, and my experience in terms of advising both governors and people in Washington, you do not have the time in real life.

The most difficult thing for the risk estimate is obtaining the transport term. That term ties into both exposure and fate. A lot of the stuff we are going to be talking about is going to be environmental geochemistry. Contaminants do not stay in the form that you put them in, and they do not stay in the chemical ionic state either. Let me give you an example from our work in the Michigan.

The SAB calculated a mercury budget for Michigan, and we found mercury comes in about six different forms. There is mercury-2, both particulate and gases; mercury-0, both particulate and gases; organic mercury (methylmercury), both bound and unbound. Depending on what form the mercury was in, the transport pathways are different, the toxicities are different, and methods of bioaccumulation are different. It is unclear to me whether the radionuclides come in all those kinds of packages. I know our heavy metals do. When the radionuclides and metals combine into organic complexes, the whole chemistry, transport, exposure, and toxicity are changed again. One of the things that we need to find is whether or not radionuclides bind organically. I know they adhere to surfaces, like the example of plutonium earlier. The plutonium was on the phytoplankton and was bound to the surface. When the plankton moved, the plutonium moved, but in the particulate phase. It is nearly certain not to be in the aqueous phase. You have got to understand some of the basic physical properties before you can say to a biologist — "Here is where that stuff is, and here is the package it is in." It makes all the difference in the world in terms of what the impacts of a contaminant are.

There is a general feeling that a lot of people have that if the compound is out there, it is a risk, and it must be removed. The case of asbestos in schools is an example of that type of response. Remember that episode, where the EPA generated an epidemic of exposure by mishandling asbestos, because they went out and monitored it, and told all the school boards to clean it up. The EPA had not established cleanup standards and they had no endpoints in terms of what is clean. Further, they had no way to train people, and you could not get medical insurance for the people asked to do the removal. It was too dangerous, and they generated a social crisis by the way they mishandled the data. The potential for the same situation exists here.

One of the issues on which you have to make a decision is, if there is no exposure, you might want to leave it in place. It is probably the safest thing you could do, unless it is moving on you by sediment transport or by that glacial anchor ice dredging. For example, if you cannot show animal/human exposure, then you have got a choice, and sometimes those choices are not socially very acceptable. We are making those same types of decisions right now in the Great Lakes, and oftentimes the public does not want to hear what you have to say. As a result of our Great Lakes Initiative, we went through exactly the same debates you have going on here. We will be drafting a whole new set of laws, because we have two national jurisdictions, and eight states, which each had their own set of environmental laws. We chose to work together and negotiate one Great Lakes document. In this case, the government is setting water quality standards, which is a regulatory approach, but it is the same risk assessment that one is going to use to find out what the choices are. There are three issues that came out of this process, and they were forcefully debated. One of them has to deal with the wildlife criteria.

Up to now our water quality standards have been based on human health, fish, and zooplankton aquatic organisms. Some wanted to put in a wildlife criteria, in which the lowest number drives the regulatory approach. In this case, it is the American eagles, ospreys, lake otters, or cormorants. In the Arctic case, it would be the polar bears, seals, whales, and walruses—the types of animals that the society is very concerned about. When one gets involved with this, care must be taken since one is again making choices. There are strong debates going on right now with environmental groups in the Midwest, because they want to take the same risk assessment model that was just illustrated earlier, and apply it to the eagles. That is, a linear dose response curve, that is based on an individualistic model, that the social acceptance of the probability of dying of somebody else's legally discharged effluent has a probability of 10^{-5} . That philosophically says a baby eagle has the same right to live as

a human. There is nothing in the Endangered Species Act that says that an individual baby eagle has a right to live. It says the population has the right to live. One must protect its habitat; one cannot go out and protect all the individual wild animals. The habitat is protected in sufficient quantity, when the population has a net reproductive rate greater than one. That is, if the population is growing, it really does not make any difference if there is a 20 percent or a 30 percent infant mortality rate. It is a population approach. You worry about individuals with humans; you do not necessarily have to with wildlife. Now, you might want to, you might decide that you interpret the Endangered Species Act that every species on that list, every individual, you ought to protect to 10^{-5} . But you do not need to implement that to protect the species. I will guarantee you that. Because most populations way over-reproduce what it takes to replace themselves. And, if you wanted to argue about that I can show you all kinds of data on that stuff.

The second factor that you have got to come to grips with is the whole concept of bioaccumulation. In polar bears, about six levels up in the food chain, one looks at persistent organics (dioxin, PCBs, chlordane, DDT). These chemicals have bioaccumulation factors of 10^8 or 10^9 . Which means if you use that in part of your risk assessment, you automatically move your decimal point over nine decimal places before you even talk about amounts, or potency, or anything else. Just because of its presence, you are talking about parts per quintillion in water, for openers, just that one factor alone. We are having big debates over that because in most cases they have not measured the bioaccumulation factors directly. They are trying to predict them from the water partitioning coefficients. Those techniques do not work beyond a \log_{10} of about four, and these values have \log_{10} of five and six. These are the technical issues you are going to get into, and if you want to start predicting what level of mercury it is going to take in the water to protect those polar bears, they are probably just like the American eagles, and you are going to have exactly the same debate, as to what kind of a bioaccumulation factor do you use to estimate those body levels.

The third issue is the whole subject of mixtures. One does not talk about just one chemical. There are heavy metals, radionuclides, and persistent organics. How do you handle mixtures? This is also a hotly debated issue. One researcher at Texas A&M has come up with this toxic equivalent system, where you normalize everything to one persistent organic compound. You compare other compounds to this one with enzyme induction systems and tissue cultures. By referencing to a common scale, you can add them together. This only works if all the compounds are ones that have been compared and that all the compounds are working on the same bio-

chemical mechanisms. You cannot have neurological impacts, reproductive failures, carcinogens, and other things, because they do not add together. The compounds under discussion have very little in common. Some of them are mutagens, reproductive abnormalities, carcinogens, and someone is going to ask you, what do you do with mixtures? Ninety percent of our risk assessments are based on one compound at a time, even though we all know that your liver and your kidney—the only two organs that process toxic chemicals—have to handle all of them simultaneously. So, it's a perfectly legitimate question, scientifically it is not one where there is an easy answer, but you better have it ready, cause somebody is going to ask you, how come you did everything based on plutonium, just because you had the data, when you know that it is probably not the most important one out there because it is not very mobile.

There is another whole approach to this, and this is basically what the EPA SAB did for EPA Administrator William Riley. This approach was taken because there is no way we can put a probability on something like global warming. Who has the foggiest idea what the probability of global warming is going to be? You know we do not have a good idea what the probability of global stratospheric ozone is, although we know a lot about atmospheric chemistry and reactive gases. What we did was defined risk assessment in a completely different way. It is not a probability at all, it is a cost of being wrong. It is a type-two error in statistic, i.e. it is what happens if you fail to respond and the event takes place? What happens if for example, you do not have the guts to put on a carbon tax, at four dollars a gallon, so we can get CO₂ to a point where we actually do not measure any global warming. What is the cost of experiencing that? Then we defined the cost to be in the time-space dimension, the recovery curve. The system has to repair itself, but how long do you have to wait? How big an area and how many generations of people are going to live with the cost of being wrong? You add that up and that is the risk. That is the reason when we did it things like global warming, stratospheric ozone, destruction of habitat, and the introduction of exotic species, came up to be our four biggest ecological issues. It was not toxic chemicals.

More damage around this world has been done through the introduction of exotic biological species than all the chemists combined. It is unclear if this is the case for the Arctic, but it is definitely true in the tropics, it is definitely true in fresh water systems. When you examine these things and do risks in terms of long term ecological damage, one comes up with quite different rankings, than what you see on "60 Minutes" and read about in newspapers. Again, that is something you have got to take a look at because you might decide the risk is not that great, but the public might have the perception it is. My experience

over many cases is that, it is not an easy thing to handle, and not necessarily an easy thing to explain. In my experience, that almost 100 percent of the environmental episodes I have been involved in came across in the media as a disaster. Probably the best example was kepone in the James River.

Kepone is a really nasty compound, that lasts as long as some radionuclides. It is almost indestructible and very toxic. Our analysis resulted in shutting down the James River for about ten years. We also had dioxin in Michigan, PBB's that had been sprayed over the whole state as fire retardant. Every one these cases, ten years later, you cannot show any ecological damage. Every species that was out there is back out there. The big impact was socioeconomic. The big impact was on humans, it was not on ecology. Other than a short term blip.

The same thing is true with the *Exxon Valdez*; I just reviewed all that data and there is little evidence of long range ecological impacts. The same things is true with the Kuwaiti fire, with the reports we just got from that. So, when you talked this morning about the impact on the local indigenous people that are living off the seafood, that is probably where you are going to see the biggest impact.

In fact, it is kind of ironic, if you really want to see what a small amount of pollution does, ecologically, it is very positive. When both the James River due to kepone and the Titibiwassee River in Michigan with dioxin, the population of the fish stocks, blue crabs, and oysters, increased rapidly. In Lake Erie, when commercial fishing was discontinued due to a phosphorus episode, the fish stocks came back long before the water chemistry did. This was because the biggest impact was overfishing, and if you have got just enough pollution to take the food off the market, the stocks bounce back real fast. It is my estimate that here in the Arctic system, from my experience as a population biologist, the same situation would occur. Probably the biggest threats to your endemic fish and various economic fish populations are probably economic demands and overfishing as much as it is pollution.

With the new revelations about open ocean dumping by the Soviet Union, you have to address the statement that says, "There is a potential for release, a big plume floating around mixed up by shelf ice and containing radioisotopes with half-lives of 25,000 years." Will you do something, even if you know that cost may be too great? If you do nothing, or something, at least make sure that you get your science straight. No matter what you choose, you are going to have people out there who are not going to like the answer. If they find a weak spot in your argument, data, techniques, or analysis, they will go after you, real hard.

Regional Distribution of Contaminants in the Arctic

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Introduction

Until recently, the Arctic has been thought of as remote and pristine, far from the environmental problems associated with industrial and agricultural development of lower latitudes. The Cold War cloaked many activities in the region under a curtain of secrecy. For most of the world, the Arctic remained largely out of sight and out of mind.

First indications that the Arctic was not as remote from our activities as previously thought came with the discovery more than 20 years ago that a thick layer of winter air pollution had developed over the Arctic. This "Arctic haze," which covers a region the size of Africa, is attributed to industrial pollution emanating primarily from Eurasia (Barrie and Bottenheim, 1991; Sturges, 1991; Shaw, 1991). The fact that north of 60°N, areas of Eurasia are highly industrialized still comes as a surprise to most people, who perceive the Arctic as a region of vast, white, clean wilderness inhabited by whales, polar bears and the Inuit. In part this vision holds true for the North American Arctic, yet just across the ocean that separates and binds the eight Arctic nations, lies the expansive industrialized Russian Arctic which comprises more than 50% of the Arctic coastline.

Many of Russia's industrialized sites happen to lie under the major air transport pathways into the Arctic region and contribute to its air pollution. With the ending of the Cold War, we have also learned that more than 50% of the rivers in the former Soviet Union (FSU) are polluted with PCBs, DDT, heavy metals, radioactive

waste and viral contaminants (e.g. Feshbach and Friendly, 1992; Environmental Issues, 1993). These pollutants contaminate the coastal regions influenced by rivers, and some may also be transported across the Arctic by ocean currents and sea ice. The recently released information on deliberate dumping of nuclear materials in Siberian seas (Yablokov et al., 1993) raises even more disquiet about pollution of the Arctic marine environment.

For years, Scandinavian governments have been concerned about transboundary pollution in the Arctic. In 1989, the process leading to the Arctic Environmental Protection Strategy (AEPS) was initiated by the government of Finland in response to damage resulting from air pollution emanating from the Kola Peninsula in present-day Russia. Atmospheric pollutants have placed the once-pristine forests of northern Finland, Sweden and Norway under stress. Transboundary pollution of this magnitude had to be dealt with and rectified. By 1991, recognizing the unique vulnerability of the Arctic to transboundary environmental pollution, the AEPS was ratified by the eight Arctic nations.

Upon analysis of the documents produced for the Arctic Environmental Protection Strategy, it became apparent to the Environmental Defense Fund that one could not understand the magnitude of the transboundary pollution nor its effects on the ecosystems of the North without constructing maps of the various contaminants and their concentrations in the air, snow, water, ice and the flora and fauna of the Arctic.

With funding from the US Department of State, the

Environmental Defense Fund collected published information from research institutions and government agencies working within the Arctic region, compiling a set of about 100 maps (see Appendix). The data have been compiled from more than 75 published reports and papers. We welcome data you can contribute to this compilation.

Draft maps have been prepared and are being finalized. All data is presented at the same scale. The complete set of data will be peer reviewed, and will include the map (in color), a data file, references and brief text. Here we discuss preliminary results from our initial compilation of some data on air, water and ecosystem contamination and show one map, PCBs in polar bears, as an example.

Our goals with this project are to illustrate the distribution of pollutants as we know it today, to show where there are significant data gaps, and to indicate where monitoring programs are required. Because research is ongoing, this discussion should be viewed as work in progress.

Data Types and Caveats in Data Interpretation

Data was collected primarily for the central Arctic, but in some cases we have also included data from peripheral regions to facilitate comparison. In many cases a single or a few samples were taken from a location (such as an island) where latitude and longitude were not reported. In other cases, data locations (but not individual station values) and derived concentration isopleths from Russian institutions were provided for inclusion in the map series. Where the data are reported as a range of values in the original report, we used the average of the range.

Data quality and comparability between laboratories and methods are major problems, and ones that hopefully will be rectified under the new sampling guidelines developed by the Arctic Monitoring and Assessment Program of the AEPS. To our knowledge, the data presented in the maps represent the best available information.

There are many caveats in the interpretation of these data. Because none of the maps has enough data to show how concentrations have changed through season or time, we have included all the data for an individual topic on one map, usually representing data collected in the 1980s and 1990s. In a few cases, where no other data were available, we also used information collected in the 1970s, but published after 1980.

Interpreting pollutant loadings in species requires information on such factors as age, sex, and migration patterns. For these reasons, the data presented must be interpreted with care. Below we discuss the general patterns and point out significant data gaps that should be closed by future monitoring efforts.

Air Pollution

Since the 1970s investigators have noticed elevated concentrations of carbon, sulfur dioxide, sulfate, and heavy metals in the Arctic atmosphere, known as Arctic haze. Data on sulfate in air show the distribution of this polluted air mass in the Arctic. High concentrations of sulfate in air can be found in both eastern and western Europe, in the FSU, and in the eastern United States and Canada. However, data on atmospheric concentrations of sulfate are lacking over much of Russia. The data that do exist, in southern and western Russia, suggest high concentrations of sulfate in the Russian atmosphere. The average fall-winter-spring concentration of sulfate delineates a plume extending over the North Pole from Eurasia reaching Svalbard, parts of Greenland, Alaska and Canada.

What happens to the contaminants contained in this tongue of Arctic haze after it leaves its source and heads across the North Pole? The physics of contaminant deposition from the atmosphere during the cold Arctic winter and spring are not well understood. Data we are compiling on the contaminant levels in snow may shed some light on the regional patterns of pollutant deposition.

Water Pollution

Transport of contaminants in water, including rivers, shallow seas, surface, mid- and deep-water currents of the Arctic Ocean and sea ice, is an important aspect of pollutant redistribution in the Arctic. Because contaminant data in sea ice and the deep sea is so sparse, in the following section we focus on the distribution of some contaminants in estuarine and surface ocean environments.

Freshwater runoff from Arctic rivers has a dramatic influence on the Arctic environment. Oceanic salinities lower than 27‰ dominate much of the surface water of the Kara, Laptev, East Siberian, and Beaufort seas. This fresh water, with associated pollutants, is discharged by runoff from the Ob, Yenisey, Lena, Kolyma and Mackenzie rivers. Where actual contaminant data are sparse, the pattern of river runoff helps in predicting where riverine pollutants will be distributed. More than 50% of the Arctic seas have a strong river influence.

Many FSU rivers are polluted with heavy metals, organochlorines, pesticides, radioactive waste and viral contaminants (Feshbach and Friendly, 1992; Environmental Issues, 1993). Sections of rivers which are considered to be most polluted include most of the Kolyma River near the Russian border with Alaska, the southern and northern reaches of the Lena, the entire Yenisey and a major section of the Ob. At present we have very few actual data for pollutant levels in the FSU rivers. However, some oceanographic contaminant levels have been

monitored and released by Melnikov and Vlasov (1992), Shiklomonav (this volume) and are contained in the State of the Arctic Environment Report (1991).

Other major contaminant pathways into the Arctic Ocean include transport from the North and Baltic seas via the Norwegian Current into the Barents Sea and into the Arctic Ocean via the West Spitsbergen Current. High concentrations of pollutants in the Baltic and southern sections of the North Sea are well documented (Salomons et al., 1988). Pollutants may also enter the Arctic Ocean through Bering Strait. Marine contaminant export is predominantly through the East Greenland Current which transports water and sea ice through the Fram Strait and flows south along the Greenland margin. Water and sea ice are also discharged to Baffin Bay through the Canadian Archipelago.

PCBs in Water

Data on PCB concentrations are available for near-shore waters off the coast of Russia, Alaska, in the Japan Sea, the North Sea, off Greenland and sections of the Canadian coastline.

Elevated concentrations are observed in the North Sea, as well as some of the bays in the Kara and Laptev seas ($>10,000$ pg/l, Melnikov and Vlasov, 1992). Just how much these polluted coastal waters influence the Arctic Ocean is not known because there is virtually no information from the central Arctic Ocean.

Much lower values are observed near the Canadian Arctic Islands and east Greenland.

DDT in Water

The concentration of DDT in water has been measured off Russia, between Russia and Alaska, in the North Sea, at various locations in the Atlantic Ocean, along transects in the Pacific Ocean from the Bering Sea to northern Japan, off Canada and Greenland and in fresh waters entering Hudson Bay and the Hudson Strait of Canada.

Elevated concentrations of DDT are reported in the North Sea, and in proximity to the Ob River in the Kara Sea (2,000 pg/l, Melnikov and Vlasov, 1992) as well as in the East Siberian Sea (2,500 pg/l in Indigirka River runoff, Melnikov and Vlasov, 1992). Data is lacking on the concentration of DDT in the central Arctic region and along much of the North American coastline.

Cadmium in Water

In comparison to other metals, cadmium has been measured fairly extensively in Arctic waters. Cadmium occurs naturally, and is also released by human activities. Reported concentrations in some Russian estuaries are higher than those measured in the Baltic. Contamination of samples may be a problem with some of the earlier data reported.

Noticeable gaps in the data are located in the central Arctic Ocean and the Barents Sea.

Lead in Water

The distribution of lead in Arctic waters is very similar to the distribution of cadmium. Lead occurs naturally in the environment, and is released by human activities. Contamination of lead samples is also a major concern.

Elevated concentrations of lead are reported from the Ob and Yenisey river estuaries. Because of gaps in data availability in the central Arctic and along much of the North American coastline, it is difficult to assess the potential transport of polluted surface water to this region. Relatively clean surface ocean water is observed in the vicinity of Svalbard.

Contaminants in Fauna

Contamination by organochlorines and heavy metals has been observed in many Arctic flora and fauna. Due to bioaccumulation, many pollutants are concentrated toward the top of the food chain. In the past, sampling programs were not coordinated from one country to another. As a result, measurements tend to reflect national collection activities and often a species is analyzed only in one or two countries. Here, we discuss some organochlorines measured in beluga and polar bears.

DDT in Beluga

DDT in beluga generally ranges between 1 to 4 $\mu\text{g/g}$ in the Alaskan and Canadian Arctic (Wong, 1985; Muir et al., 1990; Becker et al., 1992). An average of 62 $\mu\text{g/g}$ was measured in the St. Lawrence estuary (Muir, 1990). New data presented by Muir and Norstrom (this volume) indicate levels between 1.9 and 4.4 along western Greenland, while the White Sea is similar to the St. Lawrence estuary with a value of 64 $\mu\text{g/g}$.

PCBs in Polar Bears

PCBs have been studied in the fat of polar bears in a relatively thorough manner in the Canadian Arctic. Here, values are less than 10 $\mu\text{g/g}$ (Figure 1: Norstrom et al., 1988). On Svalbard, the levels range from 2.9 to 90 $\mu\text{g/g}$ wet weight (Norheim et al., 1992).

In the 1970s, data were also reported from Alaska (Lentfer, 1976), Canada (Bowes and Jonkel, 1975) and western Greenland (Clausen and Berg, 1975). Recently, more data have been collected in Canada, Greenland and Svalbard.

Radioactivity

The collapse of the Soviet Union has provoked concern about the radioactive "health" of the Arctic region. During the Cold War, when the Arctic was treated as a

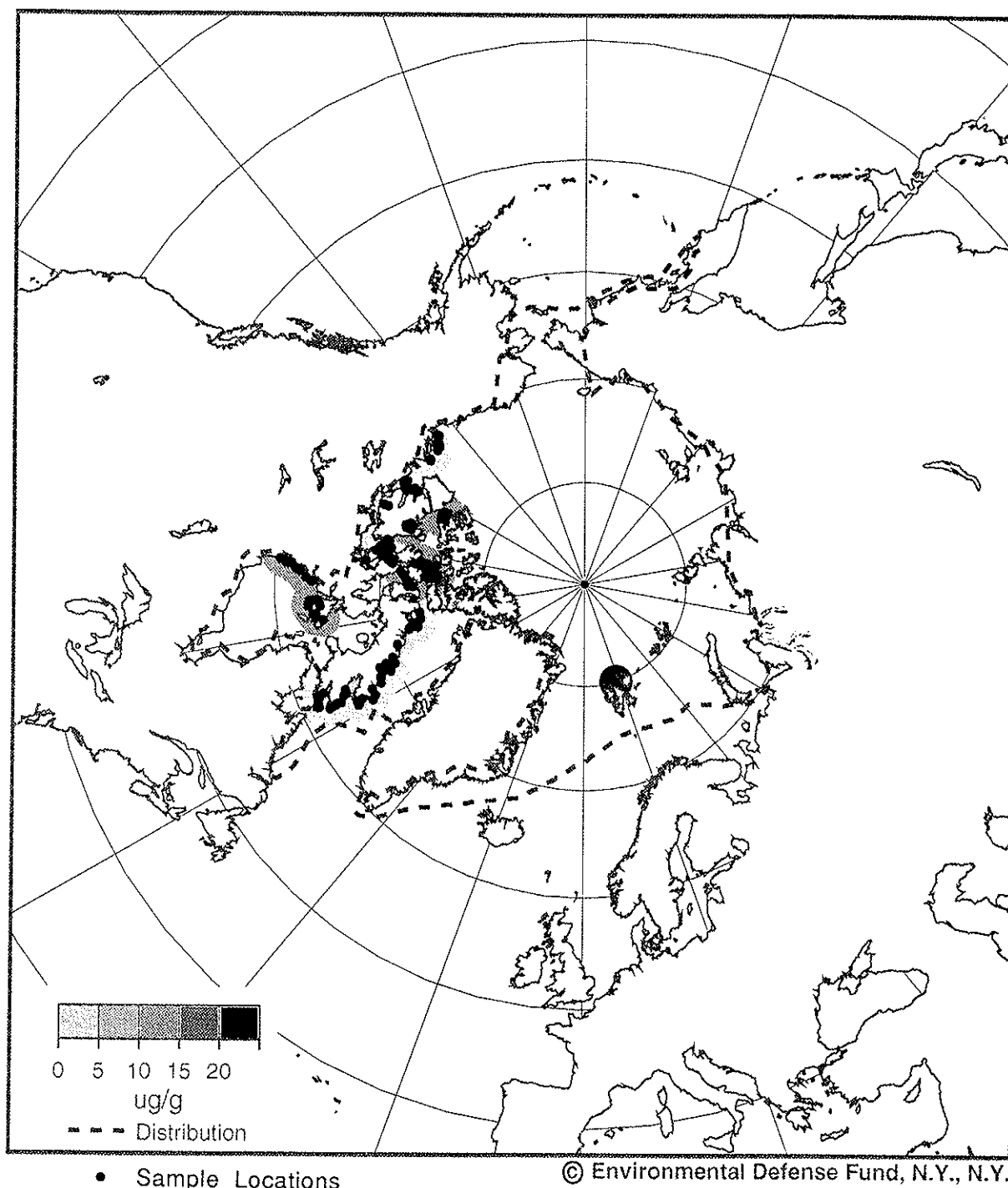


Figure 1. PCBs in polar bears (and the generalized distribution of polar bears (dashed line). PCB data are compiled from Norstrom et al. (1988) and Norheim et al. (1992). Small black dots indicate sample locations. Polar bear distribution pattern is from Stirling (1990).

vast and desolate theater of war, the FSU dumped nuclear reactors and radioactive waste in seas adjacent to the Soviet Union and the Sea of Japan. With the ending of the Cold War, information on these activities were released, including catalogues of nuclear tests, accidents, dumpsites, and so-called "peaceful nuclear explosions."

Nuclear Testing

Since 1957, 120 nuclear bombs were detonated at the two nuclear test areas on Novaya Zemlya. Eighty-six of these explosions took place in the atmosphere, three under water in the Barents Sea, five in the air over the Barents Sea, and the remainder took place inside mountains in the northern and southern test areas on Novaya

Zemlya. In 1961, the most powerful nuclear bomb in the history of the Soviet Union was detonated. Light from the explosion was observed 900 km away in Finnmark, Norway. Early in the 1960s, Norwegian authorities considered evacuating the population of Finnmark (Bellona, 1992).

The Soviet Union detonated at least 115 nuclear bombs for "civil" or "peaceful" purposes in connection with oil, geological and water reservoir activities (Yemel'yanov and Popov, 1992).

The United States has one nuclear test site in the Arctic region on Amchitka Island in the Aleutian Island Chain. Underground tests were performed at this site.

Nuclear Submarine Accidents

In addition to nuclear detonations, the Soviet nuclear submarine and icebreaker fleets have suffered numerous accidents. According to Greenpeace (Handler, 1992; 1993) more than 200 accidents on or involving nuclear-powered submarines have been reported between 1953 and 1989. At least 29 known accidents involving the Northern Fleet occurred in the North Atlantic, the Arctic Ocean, and the Barents and Kara seas.

During the same period the US nuclear submarine fleet suffered two sinkings in the Atlantic Ocean (the Thresher and the Scorpion).

Nuclear Dumping

The dumping of highly radioactive wastes at sea has been banned worldwide for almost two decades (London Convention). Spent fuels from nuclear reactors laden with cesium-137 and other isotopes were judged to be inappropriate for disposal at sea. A decade ago this moratorium was adopted under the London Convention on the dumping of low level radioactive waste. Prior to this, many nations dumped radioactive waste into the sea. At least 16 different locations were chosen by the US as dump sites in the oceans bordering the east and west coasts. Dumping took place in relatively deep water, in most cases off of the continental shelves. Following the London Convention, the US ceased dumping at sea.

Land-based Nuclear Accidents

At least 20 serious nuclear accidents took place on FSU soil, some of them far surpassing the magnitude of the Chernobyl accident. In 1957, a storage and sedimentation tank near Chelyabinsk exploded with a force of 75 tons of TNT. Twenty million curies of radioactivity were released from the tank into the environment. About 90% of the radioactive material fell in the immediate vicinity of the tank (Bellona, 1992).

The Chernobyl accident of 1986 catalyzed concern worldwide about the use of nuclear power. Within 10

days of the accident, the high altitude radioactive cloud could be traced beyond Greenland and into China and the Middle East.

Summary

Industrial and agricultural activity coupled with environmental negligence in regions within and outside of the Arctic has contributed to contamination which accumulates in the Arctic food chain. Because of a lack of data, it is often difficult to determine the actual pollutant sources. In particular, significant data gaps lie in the central Arctic Ocean, making it difficult to trace the transport of pollutants across the Arctic and determine their fate.

Expanded national and international programs are needed to inventory sources, determine transport pathways, and follow contaminants from the sources through the food chain. Although the Arctic Monitoring and Assessment Program is tasked with these activities, it needs more resources in order to carry out expanded monitoring and assessment programs.

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Appendix

Environmental Defense Fund

Arctic Environmental Atlas

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Pollutant loadings:

PCBs in snow, sea ice, water, Arctic cod, ringed seals, beluga, walrus, polar bears, murre, Arctic char, moss, caribou, human fat.
DDT in air, atmospheric deposition, snow, sea ice, water, Arctic cod, ringed seals, beluga, walrus, polar bears, Arctic char, northern fulmar, murre, caribou.
HCH in air, snow, water, sea ice, moss.
Lead in air, snow, water, walrus liver, moss, lake trout, whitefish, reindeer liver.
Mercury in Arctic cod, ringed seals, beluga liver, walrus liver, polar bears, black guillemot, reindeer liver, human hair, human blood.
Cadmium in air, snow, water, Arctic cod, ringed seal liver, beluga liver, narwhal liver, walrus liver, moss, whitefish, black guillemot, reindeer liver.

Atmospheric processes:

Arctic air mass and main zones of air flowing into and out of the Arctic region.
Sulfate in air, deposition of sulphate, sulphur dioxide emissions, deposition of nitrogen, deposition of nitrate, precipitation acidity.
Crop dusting in the 1980s - numbers of Aeroflot aircraft deployed.

Arctic warming:

Arctic temperature trends.

Ozone depletion:

Levels of chlorine monoxide.

Ecosystems:

Distribution of Arctic char, Arctic cod, ringed seals, walrus, narwhals, belugas, polar bears, black guillemot, northern fulmar, thick billed murre, lake trout, lake whitefish, caribou-reindeer.
Distribution and migration routes of bowhead, California gray and humpback whales.
Distribution of major fish stocks.
Bird migration routes.
Vegetation.
Generalized distribution of permafrost in the northern hemisphere.
Marine benthic biomass.
Protected areas.

Marine environment:

Surface ocean currents.
Watersheds, polluted water bodies, and oceanic water masses.
Sea ice drift.

Human activity:

Fossil fuels and mineral resources.
Production of fossil fuels and mining.
Nuclear and thermal power plants.
Approximate position of military bases and air and sea defense systems.
Nuclear explosions, accidents and radioactive waste sites.

Characterization of Arctic Contamination

Arctic Non-Radionuclide Contamination

The Potential Environmental Impact of Trace Metals in the Arctic

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Introduction

If given the chemical composition of a natural water, a soil, or an organism, most geochemists would agree on which constituent elements should be classified as "trace metals," yet it is impossible to precisely define the term. A "trace" in a solid might be as much as 1% (10,000 ppm) but in solution generally refers to concentrations less than 1 ppm. It depends on the matrix and the use for the composition data. The term "metal" is less ambiguous but environmentally important "metals" such as As and Se have non-metallic properties. Fortunately, a precise definition for trace metal is not needed in order to understand their possible impact on the Arctic environment. What is needed, however, is information on the general occurrence and behavior of trace metals in the environment. A brief review of this subject is, therefore, presented here. This will be followed by information specifically related to the Arctic.

Trace metals occur naturally in the environment. Unlike DDT, PCB's, or other synthetically produced substances, their mere presence does not imply human activity. Sufficiently sensitive analytical techniques can detect some amount of all metals in almost any substance. To determine the amount accurately and precisely is, however, a challenge, and to decide what portion of the metal is natural and what portion is due to human activity is an even bigger challenge. The biggest challenge, though, is to determine how trace metals, especially those due to human activity, are affecting organisms.

In order to better understand the role of trace metals in the environment, information is needed on:

1. Amounts (concentrations) in various compartments (air, soil, water, organisms, etc.).
2. Sources to the environment (natural and human).
3. Transport mechanism and pathways between compartments (continents to oceans, sea water to sediments, etc.).
4. Transfer mechanism within compartments (sea water to plankton, fish gills to liver, etc.).
5. Ultimate fate of the metal (burial in sediments, mixing throughout oceans, etc.).
6. Effect of the metals on organisms (acute and chronic).

As a first step in understanding the role of trace metals in the environment it is essential to know the ranges in concentration that are expected to occur naturally in various media (soil, water, etc.). For soil and sediment a good guide is the average crustal abundance of each element, as given, for example by Taylor and McClennon (1985). For sea water a good compilation of modern data is given in Bruland (1983). For river water and river suspended material Martin and Whitfield (1983) should be consulted. There is no good compilation of reliable trace metal data for marine organisms but general guidance can be gotten from Eisler (1981). Many recent journal articles give trace metal data for specific organisms, but it is not always possible to decide which data represents background levels. It is also important to realize that much of the published trace metal data, especially for water and organisms, is unreliable. Data produced by anyone other than a well recognized expert should be viewed with extreme skepticism.

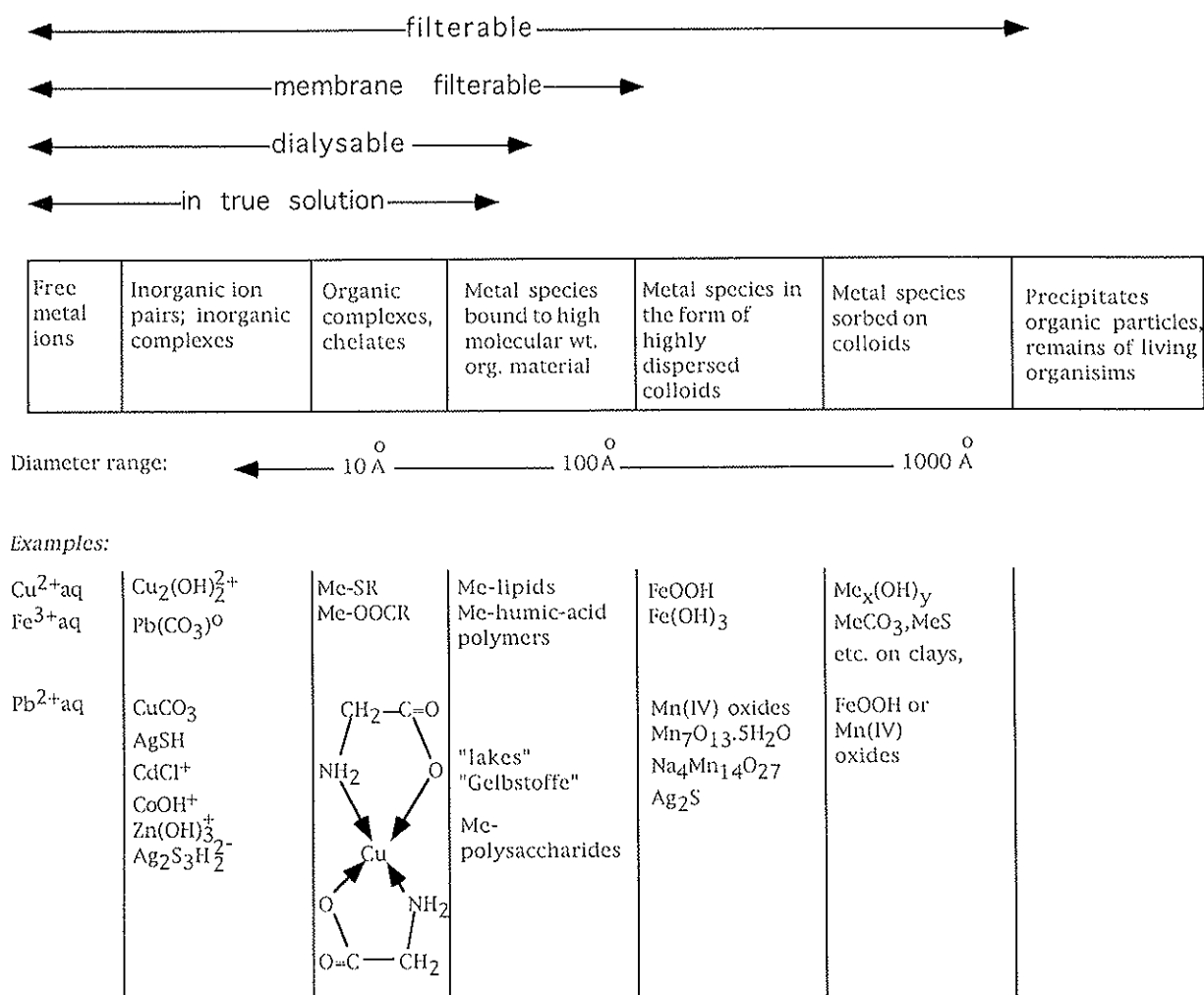


Figure 1. Forms of occurrence of metal in the environment, from Stumm and Brauner, 1975.

Sources of trace metals to the environment are both natural and due to human activity. They include:

1. Geological weathering of rocks which produces the clays and other minerals that make-up the bulk of detrital sediments and the major dissolved metals in sea water. Weathering is also a natural source of dissolved and particulate trace metals.
2. Volcanic activity, either on land or in the sea. Oceanic ridge crests (spreading centers) can be very important sources locally.
3. Diagenesis, which by Eh, pH changes, etc. can return metals to the water column from the sediments or make sediment-bound metals available to organisms.
4. Industrial processing of ores and metals. This is a classic human source of trace metals to the environment.
5. Human use and disposal of metals and metal compounds.
6. Transportation and related activity, including dredging of harbors and ship channels.
7. Energy production, including fossil fuel production and use.
8. Sewage disposal.

The possible sources of trace metals to the environment are thus numerous and it is always difficult to determine which possible source is most important for any given metal at any given location.

The environmental impact of a metal depends less on its source than on its behavior. Its behavior, including mobility, transport, transfer and biological uptake, depends strongly on the chemical and physical form of the metal. The size of the metal specie or the particle with which it is associated is critical, as this will control its response to gravity (does it quickly settle out of the water column or move with currents). Figure 1 shows a number of different forms for metals in the environment. A given metal would behave differently physically, chemically and biologically in each of the different forms and will partition itself among the various possible forms in response to environmental conditions. It is important to note that many trace metals are particle-

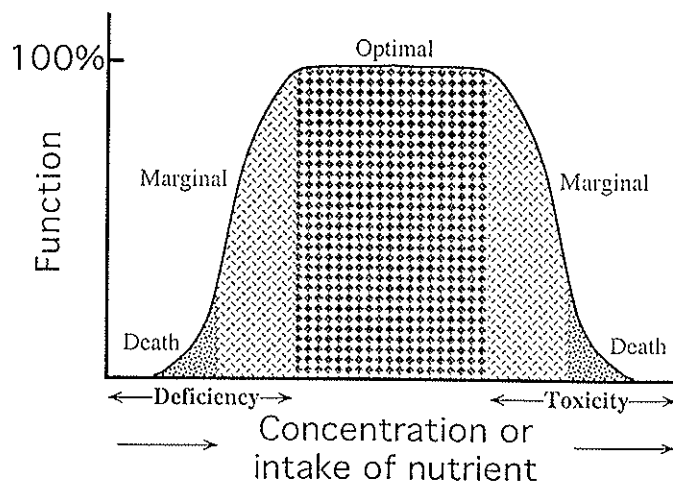


Figure 2. Relationship between biological function and trace metal concentration or intake.

reactive and will quickly associate with particles even if added to the environment in a dissolved form. Trace metal concentrations are almost always much higher in particles than in dissolved forms.

Although the behavior of a trace metal, including its biological behavior, depends on the form of the metal, there is some form of most trace metals that affect organisms, including humans. It is well known that Cu, Ni, Zn and many other trace metals are essential to life (e.g. Mertz, 1981). Perhaps all metals are essential, although this has not been demonstrated due to the difficulties in working with low or metal-free diets for experimental organisms. The toxic effects of certain trace metals are also well known; in the case of As and Pb human effects have been known for more than 2000 years. For other metals toxic effects are less well recognized. In general, however, for all metals an optimal concentration in the environment and in the organism gives optimal function (growth, reproduction, etc.) and higher or lower concentrations result in less than optimal function and ultimately death (Fig. 2).

In order for trace metals in the environment to have an effect on organisms they must, of course, be taken up by the organism. For plankton and other aquatic autotrophs this uptake is directly from solution, but for heterotrophs some or all of the uptake might be from food or from ingestion of non-food particles. In any case, at some point the trace metal must be in a soluble form and be transferred across cell membranes and possibly transferred to some vital organ within the organism. The form of the metal is very important in controlling these transfers and the resulting effects but both environmental conditions (pH, temp., etc.) and the type of organism and its condition (age, health, etc.) also play a role. Some of the factors which influence the toxicity of trace metals are summarized in Fig. 3, but what is not shown there are the large differences in sensitivity to trace metals exhibited by different organisms.

It is very common to have more than a 1000-fold difference in the concentrations of a given metal needed to elicit a biological response in different species of laboratory organisms (see, for example, any of the EPA "Ambient Water Quality Criteria" documents, or Long and Morgan, 1990). Because organisms are so variable in their response to metals, it is not possible to put numbers on the concentration axis in Figure 2.

Assessing Trace Metals Impacts

The only impact on the environment of interest involving trace metals is their effect on organisms. Effects on organisms, in turn, depend on the abundance, distribution and behavior of trace metals which, as discussed above, are subject to complex and incompletely understood processes. Impact assessment is, therefore, not easy and is likely to be controversial. Part of the problem is that it is difficult to apply laboratory toxicity data to field conditions. Laboratory toxicity tests are not easy, but can usually be conducted successfully. Ideally, they show dose-response relationships that allow establishment of trace metal concentrations above which harmful effects to a given organism will result.

The simplest laboratory toxicity tests are those that use death of the organism as the indicator of effect. Selected organisms are cultured in the lab and exposed to varying concentrations of trace metals and the number of deaths are noted after some time period (usually 48 or 96 hrs.). This establishes the concentration needed to kill 50% of the test organisms (LC50). This crude measurement has been much criticized but it does establish the rough relative toxicity for various trace metals to various organisms. This test will show, for example, that Cu is much more toxic to plankton than is As.

More subtle effects can also be sought in laboratory cultures of various organisms, for example, changes in metabolism, ability to reproduce, find food, grow, etc.

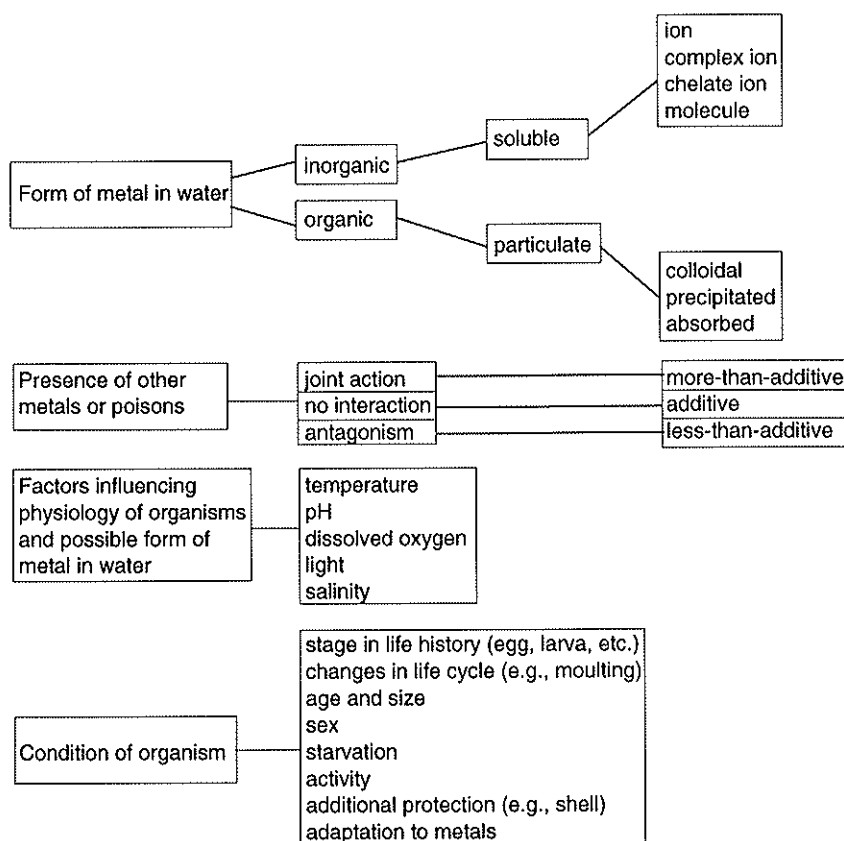


Figure 3. Factors influencing the toxicity of heavy metals (Bryan, 1976).

Biochemical changes in organisms can also be detected as a function of trace metal exposure. There is a vast literature on methods for detecting sub-lethal effects of toxins on organisms (e.g. EPA, 1988; Long and Morgan, 1990). The different tests which have been used often give conflicting results in rating the relative toxicities of different trace metals but have the advantage of indicating possible long-term effects on organisms that might not show up in short-term acute tests.

Most laboratory toxicity tests start with water or sea water as free from trace metals, complexing ligands, organic matter, etc. as is possible so the response of the test organisms can be more clearly related to the trace metal added in the test procedure. As a result, the added metal is almost always less toxic in natural water than it is in the laboratory test water. This is primarily due to complexing, adsorption and other interactions between the added metal and substances in natural water. These interactions make the metal less available to the organism (Fig. 3), especially in the free ion form which is generally the most toxic form (e.g. Sunda and Lewis, 1978). Actual ambient water or sediment from the test site can be spiked with added trace metals in toxicity tests but even in this case the form of the added metal is likely to be different from the form existing in the environment.

Regardless of the complexities of laboratory toxicity tests, even when they try to imitate the environment by using multiple metals, varying salinities, temperatures, different life stages of organisms, etc., they can never truly duplicate conditions in nature. It is necessary, then, to look for effects of pollutants in the environment. This is, however, a much more difficult task than is looking for effects in the laboratory, due primarily to the natural temporal and spatial variability in abundance of organisms (Fig. 4).

Because of the relative expense and time involved in toxicity tests and their sometime ambiguous results, many environmental assessment programs do not include them. Rather, many programs seek only to establish background concentrations of trace metals in the environment and to detect any increase in the concentration that is due to human activity. If an increase is detected its significance then becomes a critical question which can probably only be resolved by toxicity testing. In any case, when looking for evidence of human influence on trace metal concentration in the environment one could analyze air, water, sediment or organisms. For aquatic environments water might seem a logical choice, especially in view of the existing EPA criteria for trace metal concentrations in waste water and ambient water. However, ambient water, be it river

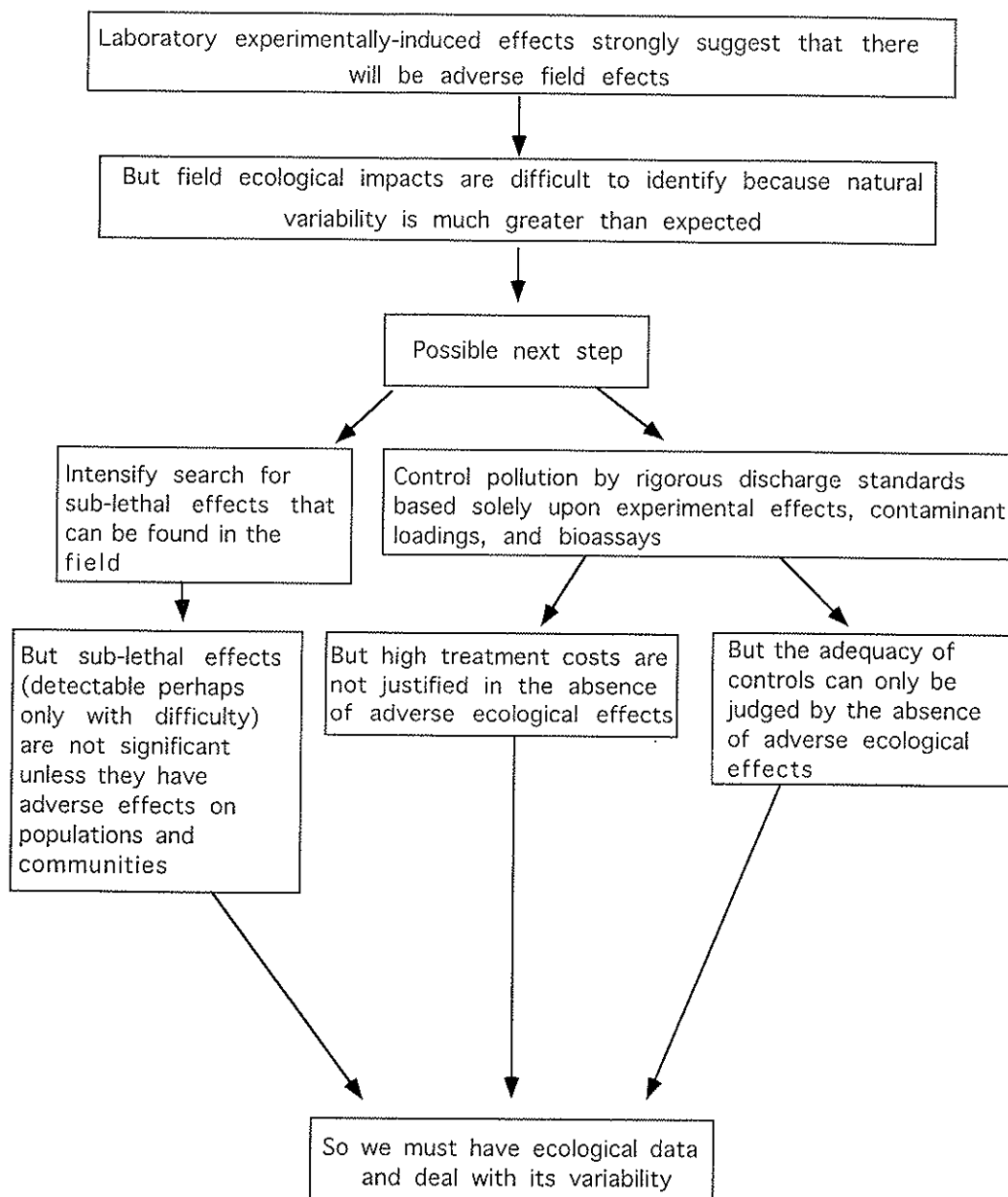


Figure 4. Considerations in environmental evaluation adapted from Lewis (1980).

water, ground water, rain water or sea water is notoriously hard to collect, store and analyze so as to accurately determine its trace metal content. Almost all dissolved trace metal data in the literature is bad, and that includes recent data produced in federal and university labs as well as data produced by commercial labs. Any water analysis project must be planned very carefully, and even if it succeeds is likely to give only a snapshot in time of a potentially varying condition.

Soil or sediment can be more easily analyzed accurately for trace metal content than can water. It also has the advantage of integrating the input function over some time so sampling need only be done once every few years in order to get a picture of the existing

condition at the site. Another advantage of sediment analysis is that it can give a historical view of pollutant input at a site. In many places sediment is laid down layer by layer, year by year, so that if a section though it is taken by coring and the different layers analyzed, a historical picture of pollutant input can be obtained. Actual dates can be assigned to the different layers by use of radiometric dating, pollen identification or other means, for example, Presley et al. (1980). Not only does a dated metal profile give a historical picture, but the sediment layers from prehistoric times give a background value for each metal that can be compared to near-surface values in order to calculate human induced enrichments.

Recognizing gross sediment contamination is easy. Certainly any sediment that is several-fold higher in a given metal than the average crustal abundance of that metal is enriched and (unless it is a deep sea clay or ore deposit) probably contaminated. However, it is harder to recognize subtle contamination because of the difficulty in establishing a background value. One possible background is values from prehistoric depths in the sediment column, as noted above. Another is sediment well away from any known point source of pollutant input. In either of these cases care should be taken to compare similar sediment types. Grain size and mineralogy largely determine background trace metal content of sediment. A fine grained sediment will almost always be enriched relative to a coarse grained one and either quartz sand or carbonate sediment will be very trace metal poor. In order to compare trace metals in two sediments, then, it is necessary to normalize to a constant grain size (i.e. divide by percent fines) or to ratio to Fe, Al, Sc or Li.

Another problem with using trace metal in sediment data is that only some unknown fraction of the metal is likely to be available to organisms. This has been much discussed in the literature (e.g. Campbell et al., 1988) especially in conjunction with disposal of dredge spoil (e.g. Lake et al., 1985). Many authors have suggested leaching sediments with dilute acids or other solutions (e.g. Campbell et al., 1988) in order to remove only the metal that could potentially be removed by organisms. Such a procedure might, in fact, give valuable information but it should not be used without also determining the total metal content in the sediment. Only the totals allow comparisons of two sediments and evaluation of data quality through analysis of sediment standard reference materials such as US NIST SRM 1646 (estuarine sediment).

If both water and sediment offer analytical and data interpretation challenges, would it not be better to analyze organisms in order to assess trace metal contamination? Certainly there are advantages to this approach. For one thing, there is no question as to bioavailability and for another concentrations are usually high enough to make analyses relatively easy, at least for common metals such as Cu and Zn. There are, however, problems. For one thing what organism should be analyzed? It is not practical to analyze everything, or even to analyze a representative specie from each major taxonomic group. Rather, only a single or a few species should be chosen. These can then be considered as "sentinels" for other organisms.

Farrington (1983) summarized the rationale for using common mussels (*Mytilus* sp.), various oyster species (*Crassostrea* and *Ostrea*) and other bivalves as "sentinel" organisms:

1. Bivalves are cosmopolitan (widely distributed geographically). This characteristic minimizes the problems inherent in comparing data for markedly different species with different life histories and relationships within their habitat.
2. They are sedentary and are thus better than mobile species as integrators of chemical pollution at a given area.
3. They concentrate many chemicals by factors of 10^2 to 10^5 compared to sea water concentrations in their habitat. Trace constituent measurements are easier to accomplish in tissues than in sea water.
4. Inasmuch as the chemicals are measured in the bivalves, an assessment of biological availability of chemicals is obtained.
5. In comparison to fish and crustacea, bivalves exhibit low or undetectable activity of those enzyme systems that metabolize many xenobiotics such as aromatic hydrocarbons and polychlorinated biphenyls (PCBs).
6. They have many relatively stable local populations extensive enough to be sampled repeatedly providing data on short- and long-term temporal changes in concentrations of pollutant chemicals.
7. They survive under conditions of pollution that often severely reduce or eliminate other species.
8. They can be successfully transplanted and maintained on subtidal moorings or on intertidal shore areas where normal populations do not grow.
9. They are commercially valuable seafood species on a worldwide basis. Therefore, measurement of chemical contamination is of interest for public health considerations.

A large data base exists for trace metals in bivalves from the NOAA "Status and Trends Program"; thus they should be included in any analysis program attempting to assess trace metal impacts.

Existing Assessment Programs

In planning a program to assess the impact of trace metals in the Arctic we should examine existing programs both to see if they have produced data on the Arctic and to see how the programs are organized and conducted. The listing below is not meant to be comprehensive but does include most of the major U.S. environmental assessment programs. It was taken from NOAA (1991).

National Oceanic and Atmospheric Administration (NOAA)

Under the FY 1991 budget, NOAA's program offices estimated funding was \$46.4 million for marine pollution research, development, and monitoring. Some

of these organizations and their specific research responsibilities are as follows:

- National Ocean Service

- National Status and Trends Program (\$5.7 million) — Quantifies the present concentrations of toxicants in U.S. coastal and estuarine waters, sediments, and tissues of key organisms; determines the temporal trends and spatial distributions of these concentrations; and monitors the biological response of indigenous organisms to contamination by subjecting them to bioassay analysis.
- Strategic Assessments Program (\$4.2 million)— Conducts assessments of multiple ocean resource uses for the Nation and its major coastal and ocean regions to determine marine resource development strategies, which will result in maximum benefit to the Nation with minimum environmental damage or conflicts among uses.
- Hazardous Materials Response Program (\$2.7 million) — Develops scientific plans and coordinates scientific input related to spills of hazardous substances occurring in coastal waters, the 197-mile Exclusive Economic Zone, and the Great Lakes.
- Damage Assessment Program (\$2.5 million) — As a Federal trustee for natural resources protected by the Comprehensive Environmental Response, Compensation, and Liability Act; the Clean Water Act; the Marine Protection, Research and Sanctuaries Act; and the Oil Pollution Act.

U.S. Department of the Interior (DOI)

- Minerals Management Service (MMS)

The MMS research program supports one of the mandates of the Outer Continental Shelf (OCS) Lands Act Amendments of 1978.

- OCS Environmental Studies Program (\$20.4 million) — Initiated by the Bureau of Land Management (now MMS) in 1974 to provide environmental information and analyses on marine and coastal ecosystems and to establish benchmark environmental conditions in all OCS areas for future identification of alterations caused by OCS activities. The program has since evolved from the benchmark environmental characterization approach to the monitoring of effects on marine ecosystems as oil and gas development occurs.

- U.S. Fish and Wildlife Service (FWS)

The FWS funded \$7.1 million for ocean pollution-related research in FY 1991 under the Research and Development Program and the National Wetlands Inventory.

- Research and Development Program (\$4.1 million) — Collects, collates, and interprets diverse information on fish species populations and habitats to provide information, methodology, and materials to assist fishery managers in decisions about the protection, enhancement, and utilization of fishery resources.

- National Wetlands Inventory (\$3.0 million) — Prepares a wetland data base in map form, conducts trend analyses for wetland change, maintains standardized mapping procedures, and correlates known wetland values.

- U.S. Geological Survey (USGS)

For FY 1991, the USGS proposed \$7.8 million for ocean-pollution-related studies under two programs.

- Geologic Division Program (\$4.0 million) — Conducts research on the physical and geological processes on the seafloor, specifically on sediment transport processes, marine deposits, and sedimentary dynamics.
- Water Resources Division Program (\$3.8 million) — Responsible for providing hydrologic data on surface and ground water, including the long-term operation of downstream gauges on major rivers and streams (yielding both quantity and quality data) and site-specific investigations of estuarine circulation, geochemistry, and ecology.

U.S. Environmental Protection Agency (EPA)

The EPA funding for research, development, and monitoring programs related to ocean pollution for FY 1991 is estimated to be \$57.2 million. The EPA assumes lead responsibility in the Federal Government for identifying, evaluating, and controlling environmental pollutants, including review of permits, setting standards, and overall regulatory activities. The EPA mandate includes the following areas of ocean pollution research and monitoring:

- National Estuary Program (\$13.7 million) — Designed to develop a series of comprehensive master environmental plans to protect and restore water quality and living resources for various estuaries throughout the Nation.
- Water Quality Research (\$11.1 million) — Relates to establishing limits on substances such as priority pollutants, toxic substances, pesticides, and carcinogens released into the marine environment.
- Environmental Monitoring and Assessment Program (\$7.2 million) — Using a regional design, conducts quantitative evaluations on available monitoring data for pollutant exposure in air, water, and soils to identify critical information

gaps. Research is carried out on ecosystem classification, monitoring network design and optimization, indicator methods for ecological condition, and quality assurance and data management techniques for multi-objective environmental monitoring networks.

- Marine Disposal Program (\$6.1 million) — Addresses the short- and long-term environmental effects of the disposal of municipal waste, industrial waste, and low-level radioactive waste in the marine environment.
- Energy-related Research (\$4.1 million) — Includes environmental studies on the impacts of waste materials produced from offshore oil and gas drilling and production platforms. Also includes permitting activity for waste discharge from offshore oil and gas platforms.

Existing Arctic Trace Metal Data

Arctic water, sediments and organisms have a natural background trace metal content, as do water, sediments and organisms everywhere. Man's influence on the trace metal concentrations can only be evaluated in terms of this natural background. After natural background concentrations in the area have been established, it will be possible to determine by what factor (if any) man has increased the background. The more difficult task of determining what (if any) harmful effect

has resulted from a given increase in trace metals can then be undertaken.

Establishing background levels of trace metals in Arctic waters will be difficult because of the analytical problems encountered in analyzing any natural water (e.g. Bruland, 1983) and the severe Arctic conditions. No reliable trace metal values for water from the Arctic are known to exist.

Background values for trace metals in Arctic sediments and organisms is complicated by the natural variability in background levels that are found everywhere. Sediments vary in trace metal content due to differences in such factors as mineralogy and grain size, as is discussed above. Trace metal concentrations in organisms not only vary with the type (species) of organism but also with age, sex, reproductive stage, health and other factors. In spite of this variability, it is possible to establish ranges in trace metal content for "normal" sediments and organisms and therefore to recognize "abnormal" concentrations which might indicate an influence by man.

Data on trace metal concentrations in Beaufort Sea sediments and organisms were obtained during a recent 3-year MMS funded study (Boehm et al., 1987; Crece-lius et al., 1991). These authors also reviewed previous trace metal work in the area (e.g. Naidu and Hood, 1972; Naidu and Mowatt, 1975; Sweeney, 1984). A brief overview of these data will be given here, along with

Table 1. Metal concentrations in average continental crust, coastal sediment and drill mud. All values in ppm dry weight except for Fe which is in % dry weight and Ba which is in % dry weight in drill mud only.

Material	Fe	Ba	Cd	Cr	Cu	Pb	V	Zn
Average crust ⁽¹⁾	3.5	550	0.10	35	25	20	60	71
Clay-rich sediment ⁽²⁾	4.65	330	0.25	105	20	28	—	150
Clay-rich sediment ⁽³⁾	3.00	740	0.15	66	19	15	—	87
Muddy sand ⁽⁴⁾	1.95	—	0.17	45	12	18	—	75
Carbonate sediment ⁽⁵⁾	0.19	—	0.15	13	1	2	—	6
Sandy sediment ⁽⁶⁾	0.06	—	0.03	4	0.3	1	—	2
Beaufort Sea sediment ⁽⁷⁾	—	339	0.18	84	22	12	114	91
Light Drill mud ⁽⁸⁾	—	2.4	<2	790	—	14	32	236
Heavy Drill mud ⁽⁹⁾	—	30.6	<2	1007	—	<10	<10	141
Alaskan OCS Drill mud ⁽¹⁰⁾	7.63	36.0	1.8	1300	88	106	235	389

(1) Average upper continental crust (95% igneous rock) (Taylor & McLennan 1985).

(2) Averages of the <63 µm fraction from 100 samples from Mobile Bay, Alabama (B.J. Presley, unpublished).

(3) Averages of 50 samples from the Mississippi River Delta (B.J. Presley, unpublished).

(4) Averages of 150 samples from 30 Gulf of Mexico bays and estuaries (B.J. Presley, unpublished).

(5) Averages of 90 samples from coastal Mississippi, Alabama, Florida. All >90% CaCO₃ (Trefry et al., 1978).

(6) Averages of 55 samples from coastal Mississippi, Alabama, Florida. All less than 10% in both CaCO₃ and clay (Trefry et al., 1978).

(7) Averages of Beaufort Sea mud samples from years 2 and 3 (Boehm et al., 1987).

(8) Seawater-gel drill mud typical of the initial phase of the drilling process (EG & G 1982).

(9) Chrome lignosulfonate mud typical of the later phases of drilling (EG & G 1982).

(10) Maximum concentrations from various studies reviewed by Boehm et al. (1987).

average trace metal data from other geographic regions for comparative purposes.

Table 1 shows the extreme variability that can be expected for trace element concentrations in different crustal materials and how these compare with concentrations found in typical oil well drill muds. This comparison is made because drill mud is one of the most common human wastes in the Arctic.

Uncontaminated carbonate, and especially quartz sand, sediments are greatly depleted in trace elements compared to clay-rich and muddy sand sediments. Drill muds vary greatly in trace metal content but are always greatly enriched in Ba and can be moderately enriched in Cr, Cd, Pb and other metals compared to typical coastal sediment. Coastal sediments can vary due to both grain size and mineralogy but sieving and analyzing only the fine grained fraction ($<63\ \mu\text{m}$) greatly reduces the variability in any given geographic area. The Beaufort Sea sediments, for example, showed great variability in trace metal content from place to place (Boehm et al., 1987) but much of the variability disappeared when only the fine ($<63\ \mu\text{m}$ or mud fraction) of the sediment was analyzed. Thus, the Beaufort Sea area showed little regional difference in trace metal content of the mud (See Table 7.2 in Boehm et al., 1987).

The Beaufort Sea trace metal values given in Table 1 are averages of the six regional averages given by Boehm et al. (1987). It can be seen that the Beaufort Sea values do not differ greatly from average crustal values or from values for sediment of similar grain size from the Gulf of Mexico. However, each geographic area does produce sediment with a somewhat different trace metal distribution pattern due to differences in mineralogy of the source material. The Mississippi River Delta sediments are, for example, considerably richer in Ba than are Beaufort Sea sediments, but are poorer in Cr. It is therefore necessary to establish background values for each area in order to recognize perturbances in background levels. This is especially true where unusual sediment types are encountered.

Some of the coastal Beaufort Sea sediments were very rich in peat (Crecelius et al., 1991) and this diluted the normal silicate background trace metal content of the sediment. At the other extreme, lead and zinc ores occur in the Arctic (e.g., Bohn, 1979) and they greatly enrich sediments, water and organisms in trace metals, both from natural weathering and due to human activity.

Boehm et al. (1987) state, "There is no evidence that oil and gas exploration and production activities have resulted in trace metal contamination of the sediments collected at stations in the Beaufort Sea Study Area." Rather they attribute differences in trace metal levels to differences in grain size and organic content and, to some extent, to differences in trace metal contents of the

suspended matter carried by the various rivers emptying into the study area. This theme was echoed by Crecelius et al. (1991) who show scatter plots of metals vs. grain size to illustrate the point. The level of contamination of sediments near drilling platforms remains to be seen, but presumably patterns of trace metal contamination similar to those seen in other areas would be found (e.g. Boothe and Presley, 1985).

Boehm et al. generally found little year to year difference in sediment trace metal concentrations at a given location, but found large differences at a few locations. These large differences were always the result of large differences in grain size, which they attribute to sediment transport into or out of a given region or to small scale spatial variability in grain size which complicates sampling. Where sediment transport is active, this will affect the distribution and ultimate fate of any anthropogenic material (such as drill mud), therefore the process deserves further study.

As has been discussed above, offshore petroleum exploration and production and other human activities can add trace metals to the marine environment and these can often be detected in bottom sediments collected near discharge points. It is more difficult to determine, however, whether or not these added trace metals are taken up by marine organisms. Most previous studies have found only limited bioavailability of metals from petroleum exploration and production activities (e.g. NRC, 1983 and references therein), nevertheless uptake has been documented in several studies (NRC, 1983). Metal uptake from mining wastes has been well documented in many studies around the world, including the Arctic (e.g., Bohn, 1979) and is a common problem. Great care will have to be exercised in order to avoid environmental damage in any mining efforts in the Arctic.

If trace metals are bioaccumulated, they could be harmful to the organism, although this would have to be documented in a separate study. As has been discussed above, bioaccumulation does not necessarily lead to biological effects. In any case, the potential for harmful biological effects from additions of trace metals to the environment by human activities makes it essential to analyze marine organisms in any environmental monitoring program.

Benthic marine organisms (bivalves and amphipods) were analyzed in the three-year "Beaufort Sea Monitoring Program" funded by MMS and conducted by Battelle (Boehm et al., 1987). Boehm et al. (1987) found rather large differences in concentrations of some trace metals in different species of bivalves and differences between bivalves and amphipods. However, they found rather small differences from place to place and from year to year for a given species of organism and no

Table 2. Trace metal concentrations in organisms from the MMS Beaufort Sea Monitoring Program (BSMP) and the NOAA Status and Trends Program (S & T). All concentrations in ppm wet weight.

Organism type	Ba	Cd	Cr	Cu	Pb	V	Zn
Amphipod ⁽¹⁾	36	0.9	1.6	115	0.2	—	109
Bivalve ⁽²⁾	25	1.5	2.9	24	0.5	6.5	75
Bivalve ⁽³⁾	26	1.3	2.4	20	0.7	5.5	66
Bivalve ⁽⁴⁾	17	12	1.7	11	0.2	1.2	65
Bivalve ⁽⁵⁾	30	11	31	23	1.0	6.8	96
Bivalve ⁽⁶⁾	23	1.3	2.0	129	<	1.6	139
Bivalve ⁽⁷⁾	60	0.2	1.5	66	0.2	0.7	72
Bivalve ⁽⁸⁾	55	0.4	0.7	89	<	0.4	85
Bivalve ⁽⁹⁾	—	0.8	0.1	25	0.1	—	350
Bivalve ⁽¹⁰⁾	—	0.6	0.4	2	2	—	100
Bivalve ⁽¹¹⁾	—	1	0.5	2	1	—	150

- (1) Alaskan amphipod average (Boehm et al., 1987).
 (2) Cyrtodaria, BSMP station 5F average (Boehm et al., 1987).
 (3) Cyrtodaria, BSMP station 6G average (Boehm et al., 1987).
 (4) Astarte, BSMP station 5H average (Boehm et al., 1987).
 (5) Astarte, BSMP station 6D average (Boehm et al., 1987).
 (6) Anonyx, BSMP station 5H average (Boehm et al., 1987).
 (7) Anonyx, BSMP station 6G average (Boehm et al., 1987).
 (8) Anonyx, BSMP station 7E average (Boehm et al., 1987).
 (9) Crassostrea, S & T Gulf Coast median (Brooks et al., 1988).
 (10) Mytilus, S & T East Coast median (Boehm et al., 1988).
 (11) Mytilus, S & T West Coast median (Boehm et al., 1988).

correlation between trace metal concentrations in organisms and the mud from which they were taken. There was no indication that petroleum-related activities have influenced trace metal concentrations in Beaufort Sea organisms.

Table 2 presents some of the trace metal in organism data from Boehm et al. (1987) and some data from the NOAA Status and Trends Program. This latter program has generated data on bivalves from the entire U.S. coastline.

Other data on trace metals in Arctic organisms include that of Bohn (1975) who determined As in a range of biota at Maarmorilik, West Greenland, before the start of lead-zinc mining in 1973. He found average background As in fish to be higher than values reported from elsewhere, but values in mussels to be lower than reported from elsewhere. In later work, Bohn (1979) gives trace metal data for algae and sea urchins from near an Arctic lead/zinc deposit and Bohn and McElroy (1976) and Bohn and Follis (1978) give data for trace metals in plankton and fish in the same area. Their papers were not studied in detail for this review, but seem not to report any unusually high trace metal concentrations.

Trace metal concentrations in marine mammals in the Arctic are of concern both because of possible harmful effects to the mammals and possible human health effects from consumption of mammal tissue.

Mercury is especially enriched in mammals and other organisms high in the food chain. Smith and Armstrong (1978) found up to 420 ppm Hg in livers from ringed and bearded seals from the Canadian Arctic. Investigators from Texas A&M have analyzed bowhead whale tissue intended for human consumption (e.g. Haubold et al. 1992), but little of that data was available for this review. Only Cd in the whale kidney appeared to be a human health problem in this data. Additional literature work and new research on trace metals in Arctic mammals is needed.

Darby et al. (1989) report trace metal data for sediment collected in 1959-1977 at 28 sites on the abyssal plain of the Canadian Basin and Beaufort Sea. Water depths were from 1000 to 3800 m, thus the sites contrasted sharply with the shallow water sites occupied by Boehm et al. (1987). Only the upper 5 cm of this mostly clay and silt sediments was analyzed. Grain size, organic and inorganic carbon, P, N, Fe, Al and Si are reported, as well as Mn, Cu, Ni, Zn, Co, Cr and V. The average data for most elements are given in Table 3 where they are compared to selected values for tropical and temperate deep sea sediments.

Different authors give different values for average deep sea clays but the contention by Darby et al. (1989) that Arctic sediments are lower than average for most trace metals appears to be true. In fact these Arctic deep sea sediments are only slightly enriched in most trace

Table 3. Differences in the average concentrations of some elements in deep-sea sediments of the Arctic Ocean (Canada Basin) and the tropical to temperate locales in the Atlantic and Pacific Oceans (from D.A. Darby, et al. 1989).

Element	Arctic Ocean ^a	Tropical-temperate oceans	Students t-test (95% confidence)
Si (%)	25.64	24.22 ^{c,d}	Insignificant
Al (%)	7.22	9.55 ^{c,d}	Significant
Fe (%)	5.02	5.57 ^{b,c,d,e} ; 5.07 ^f	Significant
Mn (%)	0.40	0.69 ^{b,c,d,e} ; 0.48 ^f	Significant
P	943	634 ^d ; 1052 ^f	Significant
Cu	60	391 ^{b,c,d,e} ; 323 ^f	Significant
Ni	78	222 ^{b,c,d,e} ; 211 ^f	Significant
Zn	103	125 ^{b,c,d}	Significant
Co	27	100 ^{b,c,d,e} ; 101 ^f	Significant
Cr	109	99 ^{b,c,d} ; 102 ^f	Insignificant
V	265	274 ^{b,c,d} ; 215 ^f	Insignificant

Note: The concentrations are in mg/g dry weight, unless stated otherwise.

a—This study (Table 3)

b—Wedepohl (1956).

c—Goldberg and Arrhenius (1958).

d—El Wakeel and Riley (1961).

e—Krishnaswami (1976).

f—Cronan (1969); samples of Pacific Ocean clays without Fe-Mn nodules.

metals over values which have been reported for near-shore Arctic sediments (e.g., Crecelius et al., 1991; Boehm et al., 1987), which are similar to other near-shore sediments (Table 1).

The most likely reason that Arctic deep sea sediments are chemically more similar to near-shore sediments than to other deep sea sediments is that they are largely glacial in origin and are transported to the deep sea either by ice rafting or by turbidity currents. There is less opportunity for them to become enriched in trace metals by volcanic, diagenetic and other processes which operate in temperate and tropical environments. The slight enrichment in trace metals in deep sea sediments from the Arctic compared to near shore ones is probably due simply to the finer grain size of the former. This simple physical difference is consistent with data from Darby et al. (1989) which shows a similar percentage of Cu, Co, Ni, and Zn in the "nonlithogenous" fraction of Arctic ocean and Beaufort sea sediments but higher "nonlithogenous" percentages in other deep sea sediments. Manganese is an exception. It is largely "nonlithogenous" everywhere.

Crock et al. (1992) produced baseline information for soils and native vegetation for the Kenai National Wildlife Refuge (KNWR), Denali National Park and Preserve (DENAP), and Wrangell-Saint Elias Park and Preserve (WSEP). For the KNWR study, *Hylocomium splendens* (feather moss, whole plant), *Picea glauca* (white spruce, twigs and needles), and soil horizons were collected and analyzed for their major- and trace-element contents. They say intensive soil or plant sampling would be needed to reliably map the geochemistry and biogeochemistry of KNWR, chiefly because of the large local variability, but give no actual data in the published abstracts. In addition to the O2 soil horizon, spruce, and feather moss, *Peltigera aphthosa* (soil lichen) were collected at DENAP and WSEP and observed baselines were determined. There is good agreement between observed baseline ranges of the three media for the DENAP and WSEP studies; but, by comparison to the KNWR baseline information, the moss, spruce, and soil seem to contain anomalously high amounts of most elements. This is most likely due to both the influence of an existing, small, coal-fired power plant at DENAP and wind-blown dust from the adjacent river valleys at DENAP and WSEP.

In a separate abstract, Crock and Gough (1992) report on investigations which were conducted near a 25 MW coal-fired plant at Healy, Alaska [Golden Valley Electric Association (GVEA)] to define current areal trends of elements in native vegetation and soils. Sampling sites were positioned at geometric intervals along three generally east-west traverses and one north-south traverse starting at 0.25 km from GVEA. Samples of

Hylocomium splendens, *Peltigera aphthosa*, and the organic-rich, O2 horizon soil were collected and analyzed for their major- and trace-element contents. In general, the concentration of most elements follows the progression: lichen < moss < soil. Most elements showed their highest concentrations near GVEA and their lowest concentrations beyond about 6 km from GVEA, but no actual data is given in the published abstract.

Summary

Trace metals occur naturally in water, sediment and organisms. Their presence in organisms cannot, therefore be taken as an indication of pollution. Even when organisms have elevated concentrations of trace metals as a result of human activity, this does not necessarily have ecological or human health significance. No evidence of harmful effects due to trace metals in the Arctic was found in preparing this review.

Considerable data on trace metal concentrations in Arctic sediments and organisms were found in preparing this review and no doubt much existing data was not found. No data on trace metals dissolved in Arctic waters were found. The data reviewed showed concentrations in both sediment and organisms from the Arctic to be similar to those found in non-polluted areas elsewhere in the world. Exceptions to this are the lower trace metal content of Arctic deep sea sediments compared to Atlantic and Pacific deep sea sediments and the higher values near ore deposits in the Arctic, which are similar to values near ore deposits elsewhere.

The generally low trace metal concentrations in Arctic sediments and organisms will make any future perturbations by human activity easier to detect. The existing data base needs to be expanded, however, to insure adequate geographic coverage both on land and at sea. Only one or a few species of organisms should be chosen for any new monitoring programs and they should be widespread geographically. In sediment sampling every attempt should be made to get fine grained sediment. Iron and/or Al should be determined along with trace metals on sediment samples.

When analyzing sediment and organism samples rigorous QA/QC procedures must be followed, including analyzing blanks, spikes, replicates and reference materials. River water and waste water may need to be analyzed but few if any sea water samples need be analyzed at this time. Water analyses need an even stricter QA/QC procedure than do sediment and organisms. No data should be entered into a data base without complete documentation on the QA/QC procedures.

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Persistent Organic Contaminants in Arctic Marine and Freshwater Ecosystems

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This report will attempt to summarize the existing state of information on spatial and temporal trends of persistent organochlorine compounds in Arctic marine and freshwater ecosystems. A relatively large data set on persistent organic compounds (i.e., organochlorines and polyaromatic hydrocarbons) already exists (for reviews see Muir et al., 1992a; Lockhart et al., 1992) and the information available on these contaminants is growing as a result of ongoing or recently initiated programs of sampling and chemical measurements in Canada, Norway and the USA. The creation of AMAP (Arctic Monitoring and Assessment Program) by the eight circumpolar countries, in which measurement of persistent organics in air, and in freshwater, marine, and terrestrial ecosystems is a major component, promises to further add to the database (AMAP, 1993).

Discussion of persistent organics in this report will be limited to organochlorine compounds: organochlorine (OC) pesticides such as DDT, chlordane and toxaphene, polychlorinated dioxins/furans (PCDD/PCDF) and polychlorinated biphenyls (PCBs). These are semi-volatile, anthropogenic compounds with very limited use in polar regions.

Polyaromatic hydrocarbons (PAHs) represent another group of important organic contaminants in the Arctic. Levels of PAHs in freshwater and marine sediments, water and biota have been discussed by Muir et al. (1992a) and Lockhart et al. (1992). Although PAHs are important toxic components of Arctic haze (Daisey et al., 1981) there are also natural sources of PAHs for freshwater and marine environments in the Arctic (Yunkers et al., 1993). Thus interpretation of PAH data is more

difficult than for PCBs and OC pesticides, which are entirely anthropogenic in origin. Furthermore PAHs do not biomagnify to the same extent as most OCs in freshwater and marine food chains.

Interest in the presence of organochlorine contaminants in Arctic marine and freshwater ecosystems arises from concerns that aboriginal peoples utilizing marine mammals and fishes in their traditional diet (Kinloch et al., 1992) may be adversely affected by chronic exposure to these pollutants (Dewailly et al., 1989). There are also concerns that the health of top predators such as small-toothed whales and polar bears may be affected because of chronic exposure to PCBs and other OCs in their diet. Studies of Arctic marine contamination have also been driven by the interest in understanding the behavior of pollutants, especially semi-volatile organic chemicals, in cold climates. Ottar (1981) raised the concern that polar regions could be a sink for semi-volatile organics and metals, such as mercury, emitted in the mid-latitudes. Wania and Mackay (1992; 1993) have evaluated the "cold condensation" effect further using a simple global meridional box model and conclude that this effect exists for volatile OCs such as hexachlorobenzene (HCB) and hexachlorocyclohexanes (HCH). Their model predicts higher concentrations for HCB in air, plants and fish in north polar regions than in temperate regions assuming a steady state scenario where HCB is emitted only in the northern hemisphere. Further support for the cold condensation hypothesis comes from recent estimates which indicate that the net flux of PCBs and chlordanes from the atmosphere to the oceans is greater at high latitudes as the air and water become colder (Iwata et al., 1993).

Pathways of Contaminants to Marine and Freshwater Food Webs

Pathways of transport of semi-volatile organics, like the OCs, to the Arctic include transport in the troposphere in gas phase and on particles, as well as via ocean currents (Barrie et al., 1992). Processes which deliver the contaminants to marine and freshwater environments include the absorption of chemicals in the gas phase by water, snow and plant surfaces, and precipitation scavenging of gas and particles from the air (Figure 1). HCH isomers, HCB, and toxaphene are the most prominent OCs in Arctic air and seawater (Patton et al., 1989; Bidleman et al., 1989) and freshwater (Lockhart et al., 1992). Concentrations of total HCHs (Σ HCH) ranging from about 1 to 6 ng/L in the Arctic Ocean are as high as those reported for more temperate ocean waters (Muir et al., 1992a). HCH, HCB and toxaphene concentrations are highest in surface waters and decline rapidly with depth in the Arctic Ocean, indicating that inputs are mainly from gas exchange with the atmosphere, as well as from river flows and melt water. Volatilization may be an important pathway of export HCB and dieldrin from seawater to air (Cotham and Bidleman, 1991). In seawater, more highly chlorinated OCs such as DDT and PCBs (Cl_4 – Cl_{10}) are associated with particles while others which are more water soluble (HCH and toxaphene) are mainly in the dissolved phase. Recent measurements of OCs in small high Arctic lakes show Σ HCH concentrations similar to sea water but much higher concentrations of PCBs (0.3–0.9

ng/L in filtered lake surface waters versus 0.045 ng/L in Cambridge Bay). The higher levels in remote Arctic lakes than in sea water probably reflect substantial contributions from snow melt runoff, as well as higher dissolved and particulate organic carbon in the freshwater environment (Reimer et al., 1993).

Bioconcentration (partitioning from water to organisms) begins with epontic ice algae or phytoplankton in surface waters (Figure 1). Concentrations of suspended particles in the Arctic Ocean are as low as those that occur in deep water of other oceans except during the brief period between late June and August (Hargrave et al., 1988; 1989; Welch et al., 1992). Particulate matter formed at this time can adsorb dissolved OCs and PAHs, especially those which are very hydrophobic, making them available for sedimentation and consumption by grazing organisms such as zooplankton. Herbivorous copepods have been estimated to consume one-third of the phytoplankton production in the Lancaster Sound marine ecosystem (Welch et al., 1992). Bioaccumulation factors (BAFs) from water to zooplankton range from about 7×10^4 for toxaphene to 2×10^6 for PCBs (Muir et al., 1992a). Copepods constitute the main dietary item of Arctic cod (*Boreogadus saida*) and the cod are thought to be the major food of ringed seal, beluga and narwhal during the summer months in Lancaster Sound (Welch et al., 1992) (Figure 1). Biomagnification factors (lipid/lipid basis) from zooplankton to cod range from about 3 for Σ HCH to about 100 for PCBs (Muir et al., 1992a).

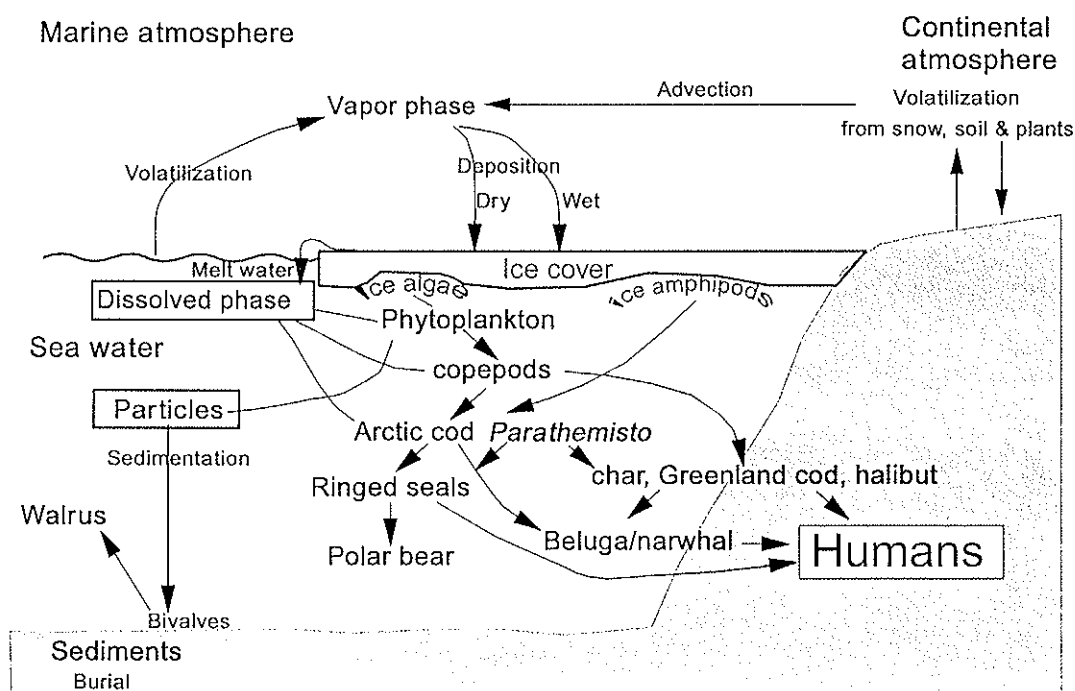


Figure 1. Pathways of transport, deposition and bioaccumulation of organochlorines in the Arctic marine environment. The food chain schematic is modified from Welch et al. (1992).

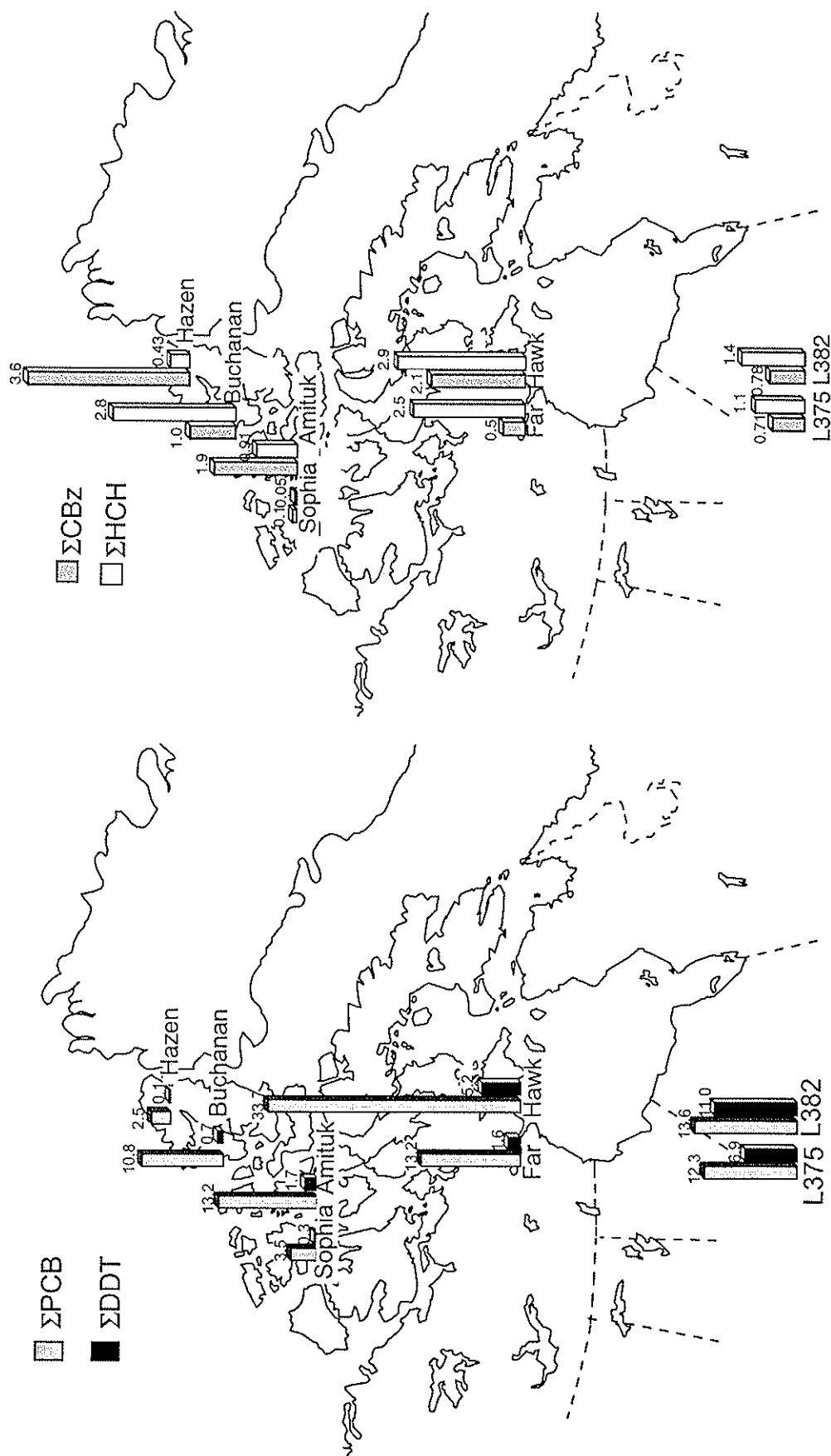


Figure 2. Spatial trends in ΣPCB, ΣDDT, ΣHCH and ΣCBZ in Canadian Arctic and mid-latitude surficial sediments (0–1.3 cm) from remote lakes.

Although the pathways and processes that deliver persistent organics to Arctic marine and freshwater food webs are understood in general terms, there are relatively few measurements of air, snow, of particle and dissolved phases in seawater and freshwater, or marine sediments, with which to validate models of transport, distribution, or of transfer to lower food chain organisms (Barrie et al., 1992; Muir et al., 1992a). Recent initiatives in Canada include a year round air monitoring study of PCBs, other OCs and PAHs at Alert at the northern tip of Ellesmere Island (Barrie, 1992), and measurements of OCs in snow and waters of rivers flowing into the Arctic Ocean in the Northwest Territories (Gregor, 1992). The transfer from seawater and snow melt water to lower food chain organisms is also being studied in Lancaster Sound (Hargrave, 1992). Detailed measurements of PAHs and OCs are also being made by Norwegian and Russian scientists in Barents Sea water, sediments and biota which began in 1991 (Klungsoyr, 1993). Russian scientists are continuing a study of hydrocarbons, metals and OCs in waters of the Siberian shelf (Vlasov and Melnikov, 1990).

Spatial Trends of OCs in Arctic Lake Sediments

The profile of PAHs, metals and OCs in sediment cores from the profundal zone of lakes has been used to infer spatial and temporal trends of the contaminants in freshwater and marine ecosystems (see for e.g., Eisenreich et al., 1989; Brownawell and Farrington, 1986). A series of sediment cores from 8 remote lakes along a north-south transect from the Experimental Lakes Area (ELA) in northwestern Ontario (49°N) to Hazen Lake on Ellesmere Island (82°N), the most northerly large lake, have recently been analyzed for PCBs and other OCs (Muir et al., 1993a). Concentrations of ΣDDT in surface slices (0–1.3 cm) were highest in the ELA cores and declined with increasing north latitude (Figure 2 [left]). PCB concentrations were quite similar, despite differences in sedimentation rates and organic carbon content, over most of the transect although lowest levels were found at Hazen Lake (Figure 2 [left]). High concentrations of ΣPCBs and ΣDDT were found in sediment from Hawk Lake, a small headwater lake (63°N), with very organic sediments. The PCB pattern in sediments from all lakes was dominated by tri- and tetrachlorobiphenyls. The more volatile OCs, especially penta- and hexachlorobenzene (ΣCBz) were found at similar or higher concentrations in more northerly lakes than at ELA (Figure 2 [right]). The results illustrate the wide extent of low level contamination of freshwater systems by OCs in the Canadian Arctic and provide additional support for the “cold condensation” of more volatile OCs in the polar region.

Spatial Trends in Contamination of Arctic Biota

In comparison with the relatively sparse data for abiotic matrices, there exists a large database on organochlorine contaminants in Arctic marine mammals, and there are an increasing number of reports for OCs in seabirds and in freshwater fish (Muir et al., 1992a; Lockhart et al., 1992). A wide range of OCs have been reported in Arctic biota including DDT and chlordane-related compounds, HCH isomers, HCB and other chlorobenzenes, mirex, PCDD/PCDFs, toxaphene, brominated biphenyls and diphenyl ethers, and PCBs. The results for total DDT-related compounds (ΣDDT) are probably the most reliable for temporal, geographic and interspecies comparisons because almost all authors have reported the same three components (4,4'-DDE, 4,4'-DDD and 4,4'-DDT). Results for PCBs are more difficult to compare among laboratories because they have been reported as equivalents of the commercial Aroclor products (generally Aroclor 1254), and most recently as total PCB congeners (ΣPCBs). The use of Aroclor equivalents overestimates PCB levels in marine mammals because of extensive transformation of congeners with adjacent unsubstituted carbons (Tanabe et al., 1988; Duinker et al., 1989). Norstrom et al. (1988) found that PCB levels in polar bears (*Ursus maritimus*) reported by Bowes and Jonkel (1975) as Aroclor 1260 equivalents were 1.9 times higher than when reanalyzed as ΣPCB. There is also considerable uncertainty about interlab comparisons of toxaphene, because like PCBs the pattern observed in biota is quite different from the technical material. However, comparison between two methods of quantification (electron capture detection and electron-capture negative chemical ionization mass spectrometry) indicated agreement within 30% for toxaphene in narwhal (*Monodon monoceros*) blubber (Muir et al., 1992b).

Beluga whales (*Delphinapterus leucas*), ringed seal (*Phoca hispida*) and polar bears have been studied most extensively for organochlorine contaminants (Table 1 and Figure 3). The latter two species have been studied over the widest geographic range, from Alaska (Chukchi Sea) to Svalbard. In contrast, information on contaminants in Arctic cod, zooplankton and phytoplankton is limited to two or three locations in the Canadian arctic archipelago (Muir et al., 1988; Bidleman et al., 1989). There have been no detailed measurements of these contaminants in any species from the Russian arctic.

Toxaphene is the most prominent organochlorine contaminant in whales (beluga and narwhal). Mean concentrations of 9.2 µg/g toxaphene were found in male narwhal from Baffin Bay (Muir et al., 1992b); mean concentrations in male beluga were within the

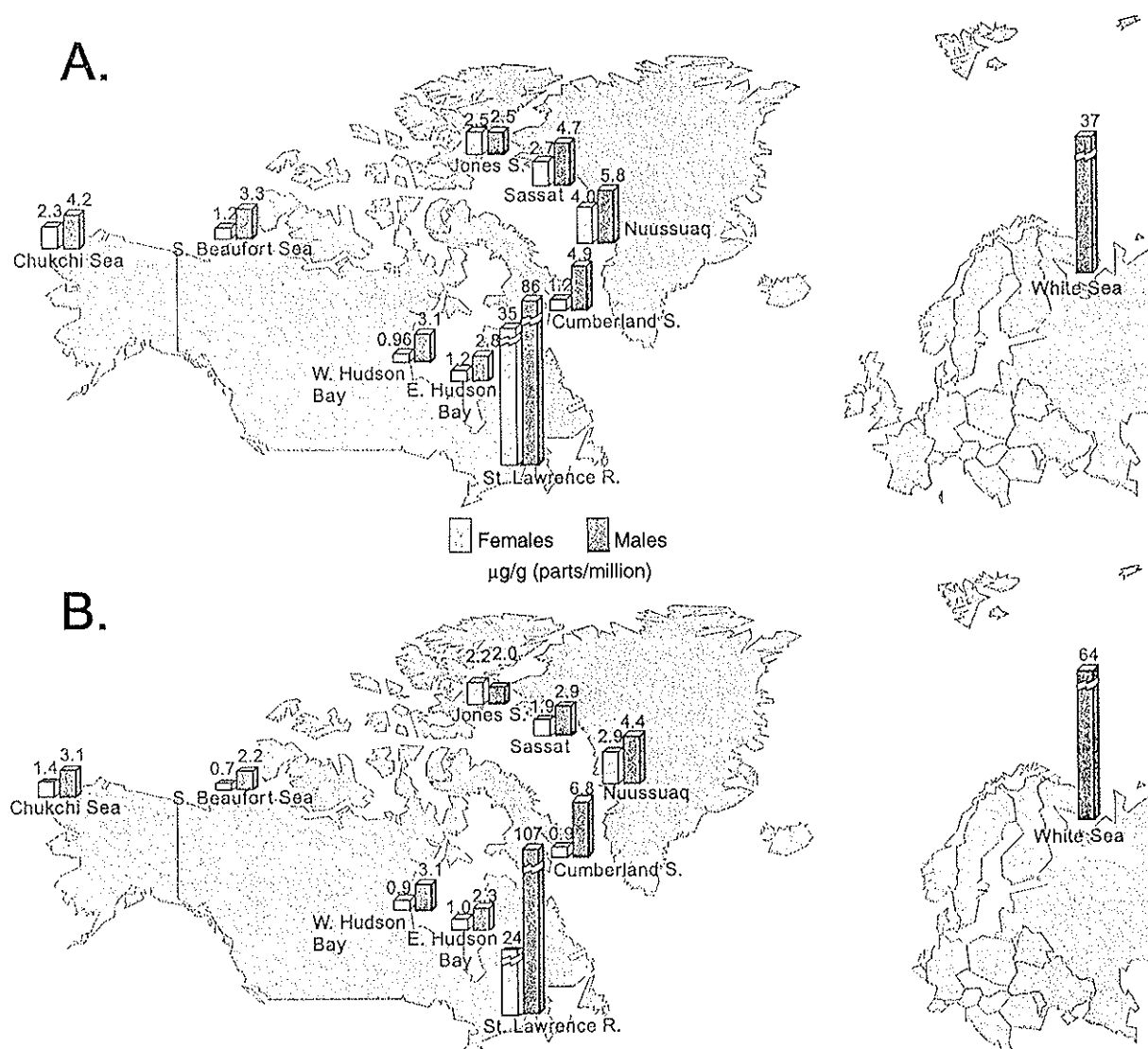


Figure 3. (A) Σ PCB and (B) Σ DDT concentrations in beluga whale blubber samples collected in the period 1983 to 1989. Results from Muir et al. (1990a); Muir (1993); Stern et al. (1993).

same range (3.8–5.8 $\mu\text{g/g}$) (Muir et al., 1990a). The toxaphene pattern in beluga and narwhal blubber is dominated by two components, an octachlorobornane and a nonachlorobornane, which account for about 70% of total toxaphene. These two components were also prominent in zooplankton and predatory amphipods analyzed by Bidleman et al. (1989). The structure of these two chlorobornanes has been identified (Stern et al., 1992) and analytical standards have been prepared (Parlar et al., 1993). Toxaphene concentrations in ringed seals are much lower (0.2–0.4 $\mu\text{g/g}$) and show a different pattern of components compared with whales or fish (Bidleman et al., 1993). Toxaphene components have recently been identified for the first time in polar bear tissues (Zhu and Norstrom, 1993) at levels similar to Σ DDT and Σ HCH. Little is known of the concentrations of toxaphene in marine mammals on a circumpolar

basis because the majority of measurements have been restricted to the Canadian Arctic and Greenland. However, toxaphene levels of 4 $\mu\text{g/g}$ were reported for a composite ringed seal sample from Svalbard (Andersson et al., 1988), which is 10-fold higher than results from the Canadian animals.

PCBs and DDT-related compounds are prominent contaminants in all marine mammals. Similar PCB concentrations (averaging about 4 $\mu\text{g/g}$ in males and 2 $\mu\text{g/g}$ in blubber of females; Table 1) are found in beluga stocks from the Chukchi Sea to Baffin Bay (Figure 3A). These levels are about 25 times lower (in males) than in blubber of dead beluga from the St. Lawrence estuary. The St. Lawrence stock has a lower reproductive rate than the Arctic animals and it has been suggested this is due to the presence of PCBs and other contaminants (Sergeant and Hoek, 1988; Martineau et al., 1987).

Table 1. Summary of overall mean concentrations of major organochlorine contaminants in Arctic biota ($\mu\text{g/g}$ fresh weight).¹

Geographical range		Beaufort Sea– Baffin Bay	Chukchi Sea– Baffin Bay	Baffin Bay	Chukchi Sea– Baffin Bay	Svalbard	Bering Sea	Bering Sea– Baffin Bay	Svalbard
Time frame		1984	1983–89	1982–83	1983–88	1986–90	1981–87	1982–84	1990–92
Species	Sex	Arctic cod	Beluga	Narwhal	Ringed seal	Ringed seal ²	Fur seal	Polar bear	Polar bear ³
No. of males & females		pooled M+F	103/105	15/6	108/94	12/8	37/0	121 M+F	10 M+F
ΣDDT	M	0.004	3.53	5.92	0.61	1.44	3.0	0.40	0.92
	F		2.10	2.54	0.39	1.46			
ΣPCB	M	0.003	4.67	5.18	0.70	1.72	1.94	5.40	26.2
	F		2.91	2.70	0.48	1.62			
$\Sigma\text{Chlordane}$	M	0.003	2.14	1.92	0.45	—	—	3.70	—
	F		1.37	1.40	0.34	—	—		
Toxaphene	M	0.02	3.75	9.16	0.35	4.0	—	—	—
	F		2.46	2.44	0.28	—	—		

1. Results summarized from the review of Muir et al. (1992a) except where indicated.

2. Includes recent results from Daelemans et al. (1993).

3. Results from Norstrom (1993).

Analysis of a single pooled sample of beluga blubber from the White Sea showed concentrations of ΣDDT and ΣPCB about 10-fold higher than in the same species in Canadian Arctic or Greenland waters and similar to levels in St. Lawrence animals (Figure 3). Unfortunately no additional beluga samples have yet become available from the Russian or Norwegian Arctic with which to further compare with Canadian animals.

Polar bears, which feed almost exclusively on ringed seals, generally have higher levels of PCBs than other Arctic biota (Table 1). A recent extensive circumpolar survey found PCB concentrations in fat of female bears ranging from 1.7 to 15.7 $\mu\text{g/g}$ (Norstrom, 1993). PCB concentrations were highest in animals from Svalbard and eastern Greenland and lowest in samples from Alaska. A comparable study has not been carried out for ringed seals but results from studies by several laboratories reviewed by Muir et al. (1992a) show a similar trend with higher ΣPCB and ΣDDT concentrations in blubber of Svalbard animals (Table 1; Figure 4A). Ringed seal populations from 10 locations in the Canadian Arctic and Alaska had ΣPCB concentrations ranging from means of 0.38 $\mu\text{g/g}$ at Lancaster Sound to 1.2 $\mu\text{g/g}$ at Southampton Island in northern Hudson Bay for males and from 0.35 $\mu\text{g/g}$ in Cumberland Sound to 0.67 $\mu\text{g/g}$ at Cambridge Bay (Figure 4A). Similar trends were seen for ΣDDT (Figure 4B). ΣPCB and concentrations in female ringed seals were quite uniform throughout the Canadian Arctic while elevated levels in males from the Hudson Bay area could be explained by the older mean age of animals. The study also found that amongst groups consisting of males of similar age, $\gamma\text{-HCH}$ and mirex were significantly higher at Hudson

Bay locations than at locations in the central and western Arctic (Muir et al., 1993b). At seven locations in the Canadian Arctic where results for polar bears and seals were available, ΣPCB levels in male seals were significantly correlated with concentrations in bear fat ($r = 0.76$; $p < 0.05$).

Spatial trends in PCBs and toxaphene, the two most prominent OCs in freshwater fish from the Canadian Arctic, were examined in a survey of burbot (*Lota lota*), a voracious deepwater fish with a fatty liver (Muir et al., 1990b). Liver samples were obtained from 9 locations along a northwesterly transect from ELA to Ft. McPherson near the Mackenzie River delta. Toxaphene concentrations did not decline significantly with latitude over the transect (Figure 5A) while ΣPCBs did decline significantly ($r = -0.613$, $p < 0.05$ for 7 sites). Significant declines in concentrations were not observed for tri- or tetrachlorobiphenyls whereas octachlorobiphenyls were much lower at more northerly locations (Figure 5B). In reviewing these results, Wania and Mackay (1993) have noted that the rate of decrease with north latitude appears to be strongly related to the degree of chlorination of the PCBs. The results provide support for the hypothesis that more volatile OCs will predominate in colder regions as less volatile compounds are removed by "condensation."

Temporal Trends in Contaminants in Marine Biota

Ringed seals represent one of the few species for which temporal trends of contaminants are known. Addison et al. (1986) concluded that PCBs declined about threefold in ringed seals from Holman Island, N.W.T., between 1972 and 1981. This decline was

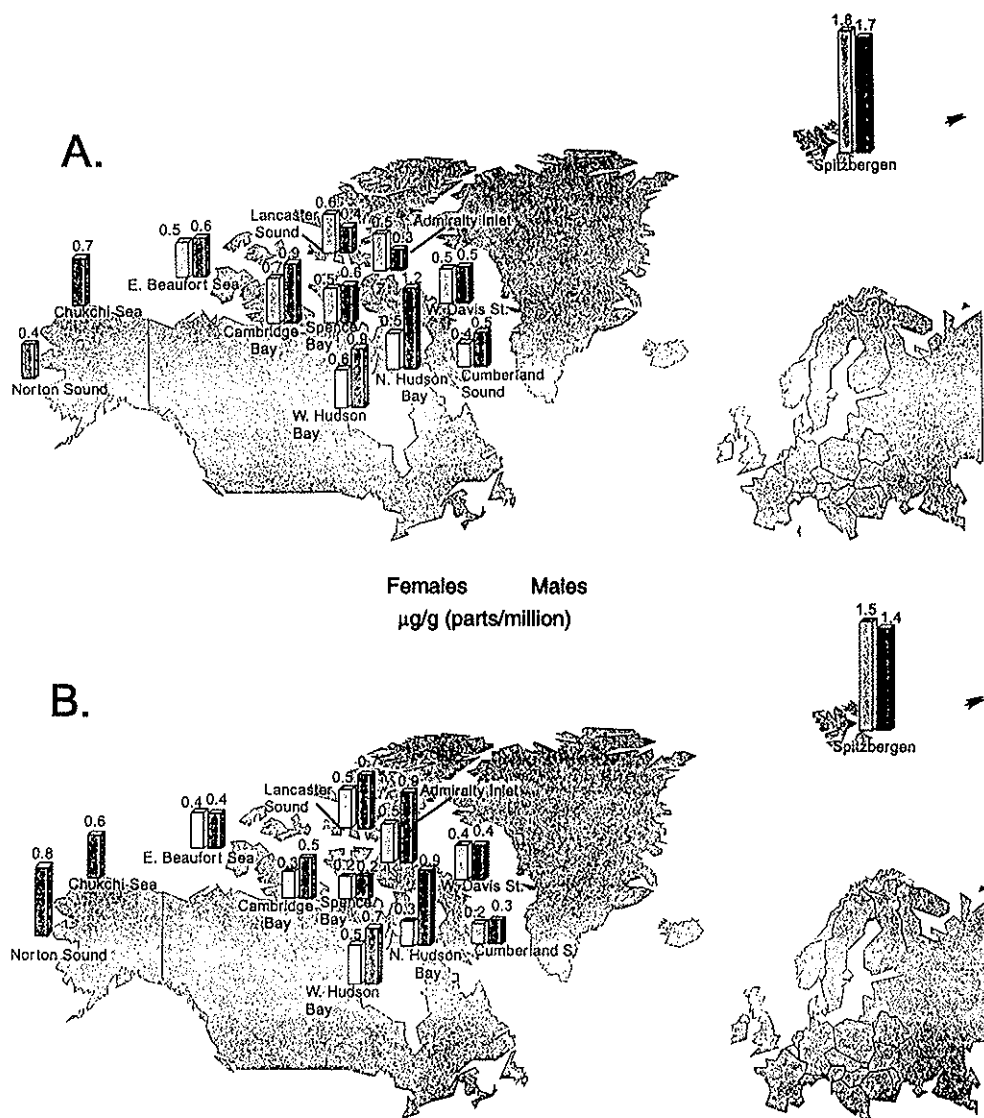


Figure 4. (A) Σ PCB and (B) Σ DDT concentrations in ringed seal blubber samples collected in the period 1983 to 1989. Results from Muir et al. (1993b); Becker et al. (1992), and Oehme et al. (1988).

similar to that observed in harp (*Phoca groenlandicus*) and grey seals (*Halichoerus grypus*) on the east coast of Canada over approximately the same time period. For Σ DDT, however, much of the decline between 1972 and 1981 could be explained by thicker blubber of the animals collected in 1981. Declines in Σ DDT were 30% to 40% in Arctic ringed seals compared with 300% to 500% in east coast seals. A similar trend in DDT and PCB levels was found by Muir et al. (1988) who compared female ringed seals from 1975/76 with a cohort from 1983, sampled in Admiralty Inlet on north Baffin Island. PCBs showed the largest decline (50%) while DDE, Σ DDT, Σ CHLOR and HCH levels differed by 25% or less between the two groups. Recently Addison (1992) has reported a 2-fold decline between 1981 and 1989 in ringed seals from Holman Island (Table 2). Kurtz (1984; 1987) did not find statistically

Table 2. Temporal trends in PCB and DDT levels in biota from Arctic Canada.

<i>Location</i>	<i>Year</i>	<i>N</i>	<i>Concentration (µg/g)</i>		
			<i>ΣPCB</i>	<i>p,p'-DDE</i>	<i>Chlordane</i>
Ringed seal blubber ¹					
Holman Is.	1972	9	3 ²	0.35	nd
	1981	15	1	0.20	nd
	1989	?	0.5	0.20	nd
Northern fulmar eggs ³					
Pr. Leopold Is.	1975	pool	1.9	0.76	0.13
	1987	pool	0.80	0.23	0.26
Kittiwake eggs ³					
Pr. Leopold Is.	1975	pool	5.2	0.38	<0.1
	1987	pool	1.6	0.13	0.11

1. Addison et al. 1986; Addison, 1992.

2. Significantly higher ($P < 0.05$) levels in the 1970s.

3. Nettlehip & Peakall (1987), Peakall, (unpubl.).

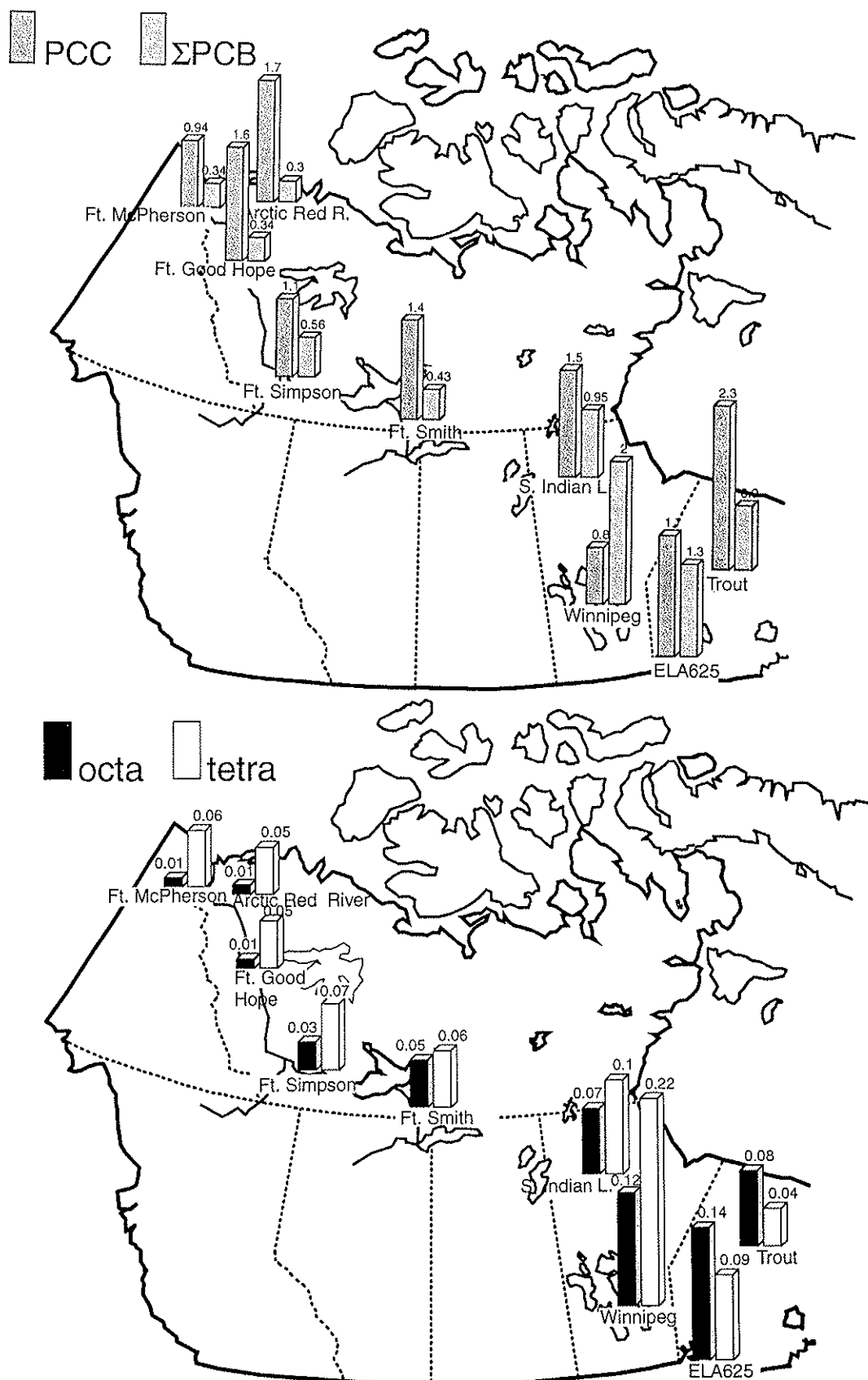


Figure 5. Spatial trends in (A) Σ PCB and toxaphene in burbot liver from remote lakes and rivers in Canada and (B) trends in total tetra- and octachlorobiphenyls in the same samples.

significant declines in ΣDDT and PCBs in 3 to 4 year old male fur seals from the Pribilof Islands collected between 1975 and 1981.

Declines of 50% to 66% in ΣDDT and from 69% to 86% in PCB in seabird eggs collected at Prince Leopold Island in Lancaster Sound were observed between 1976 and 1987 (Nettleship and Peakall, 1987; Peakall, 1989) (Table 2). Similar declines in DDT and PCB residues occurred in livers of kittiwakes (*Rissa tridactyla*) and northern fulmars (*Fulmarus glacialis*), but not in thick-billed murre (*Uria lomvia*).

BAFs from water to higher trophic level predators in the marine environment (seal, beluga, seabirds and bears) are in the order of 107 for toxaphene and HCH to 109 for PCBs, which is as high as or higher than any values reported for marine organisms in temperate climates (Thomann, 1981; Tanabe et al., 1984). BAFs of 4 to 9 for PCBs have been found between beluga/narwhal and their prey, which is similar to those reported for cetaceans in the North Sea (Duinker and Hillebrand, 1983) and in the northwest Pacific (Tanabe et al., 1984). Lower BAFs for toxaphene and HCH between obvious predator/prey links (e.g., amphipods-to-fish and fish-to-seals) of about 1 to 4 are consistent with the more rapid rate of elimination and lower bioconcentration factors reported for these compounds in laboratory studies with freshwater fishes (Niimi, 1988). Faster elimination rates give rise to reduced food chain transfer (Thomann, 1981).

Conclusions

In conclusion, there is a large data set on OCs in marine mammals in the Arctic with good spatial coverage for beluga, ringed seals and polar bears but relatively little data on the extent of contamination of the food web leading to the top predators. Circumpolar coverage is limited because of lack of data from the Russian Arctic but higher levels of most OCs in ringed seals and polar bears at Svalbard, and in a single beluga sample from the White Sea in Russia, suggest that additional measurements are needed in those regions. There is also a limited amount of information on levels and trends in organic contaminants in air, seawater and marine sediments. The situation for freshwater environments is somewhat better, where spatial trends in OCs are available for lake sediments in the Canadian arctic and for selected fishes in Canada, Alaska and Scandinavia. This information on spatial trends of contamination in marine and freshwater environments situation is improving due to ongoing or recently initiated programs of sampling and chemical measurements in Canada, Norway and the USA. A further stimulus has been the creation of AMAP in which measurement of persistent organics in air, and in freshwater, marine, and terrestrial ecosystems is a major component (AMAP, 1993).

In Canada, much of the focus has been on identifying levels of contaminants in traditional foods of native people (Kinloch et al., 1992). But given elevated levels of some contaminants particularly toxaphene and ΣPCB in narwhal, beluga and polar bear fat, as well as heavy metals, particularly of cadmium in narwhal kidneys, it is clear that studies of effects on biota themselves at the biochemical and population level are needed.

The evidence from the limited temporal trend data indicates that levels of PCBs and DDT are declining, which is expected due to bans on their use in most circumpolar countries in the 1970's. Temporal trends in toxaphene and chlordane, which were banned some years later, are not known. Spatial trends in PCBs observed in polar bears and ringed seals suggest a pattern of increasing concentrations from west to east with highest levels in Svalbard consistent with the relatively close proximity of northern European sources to the Arctic. The spatial trends observed for OCs in lake sediments and burbot liver are consistent with the hypothesis that more volatile OCs will predominate in colder regions as less volatile compounds are removed by "condensation." The existence of a cold-condensation effect implies that there will always have to be special concerns for Arctic environments due to release of persistent semi-volatile chemicals in temperate zones.

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Chronic Hydrocarbons in the Arctic

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Data concerning the kinds and amounts of natural and pollutant hydrocarbons in marine and terrestrial Arctic environments provide poor spatial and temporal coverage and are often of unknown precision and accuracy. Nevertheless, the small amount of available information indicates that pollutant as well as natural hydrocarbons occur widely in the Arctic. This presentation reviews the sources and distribution of semi- and non-volatile hydrocarbons in terrestrial and nearshore marine Arctic environments with consideration of limitations and uncertainty of the data.

Both natural and anthropogenic sources of hydrocarbons are important in Arctic environments. Natural sources include peat deposits, coal outcrops and oil seeps. Anthropogenic sources can be classified as spills, leaks and wastage associated with all human settlements and activities; losses during petroleum production and transport; and long range atmospheric transport of combustion derived hydrocarbons.

Surveys of environmental hydrocarbons in nearshore Beaufort Sea sediments off both Alaska and Canada show a natural background in the low parts per million range (roughly 5-40 $\mu\text{g/g}$; Shaw et al., 1979; Boehm et al., 1990). The results of Boehm et al., which are more recent and extensive, are summarized in Table 1. Boehm and co-workers also used a detailed examination of polycyclic aromatic hydrocarbons in sediments and potential source materials to conclude that these hydrocarbons in marine sediments are primarily derived from erosion of peaty soils of the tundra and taiga with lesser amounts probably contributed by detrital coal from numerous outcrops and residual petroleum from natural seep areas. In Canada the Mackenzie River carries to the Beaufort Sea dissolved and particulate hydrocarbons from the Athabasca tar sand region (Peake et al., 1972).

While plant waxes (straight chain alkanes with odd numbers of carbon atoms in the range 25 to 31) are the major constituents of this background array of hydrocarbons, other classes of hydrocarbons including polycyclic aromatics account for about 10% of the total at many locations in the nearshore Beaufort (Boehm et al., 1990). Boehm and co-workers also determined hydrocarbons in nearshore invertebrate animals (bivalves and an amphipod) and found detectable, but low, concentrations, lower than might have been expected in light of the sediment concentrations. These low animal concentrations may suggest that at least some of the sediment hydrocarbons are present in physical forms which have low bio-availability. While we have no direct evidence about naturally occurring hydrocarbons in the Russian Arctic, it seems likely, based on ecological and geological similarities with North America, that similar background hydrocarbons may also be present in the Eurasian Arctic.

The amount of petroleum lost to the North American Arctic as a result of petroleum exploration, development, production and associated transportation of crude oil is low. This petroleum activity has occurred during the last 25 years under increasingly stringent regulation and without catastrophic spills. The environmental debates concerning Arctic Alaska oil development have focused on industrial intrusion into the far north rather than chronic release of oil. Western knowledge about oil lost to the environment during Soviet and now Russian Arctic petroleum production is incomplete. But, given the past absence of market incentives to minimize loss, it may have been greater than in North America.

Spills, leaks and wastage of refined petroleum products occur at virtually every site of human habitation and activity. Mertz et al. (1991) have summarized the

Table 1. Regional distribution of alkane and aromatic hydrocarbons in sediments of the Beaufort Sea adjacent to Alaska. Data are ranges as reported by Boehm et al. (1990).

<i>Location</i>	<i>Alkanes (µg/g)</i>	<i>Aromatics (µg/g)</i>
West Harrison Bay	2.9–1.6	0.3–2.8
East Harrison Bay	0.5–38	0.2–10.0
Kuparuk River Delta	0.2–20	0.08–1.5
Endicott Field	0.5–4.6	0.0.1–1.1
Endicott Development Island	0.3–14	0.03–1.9
Foggy Island Bay	0.6–10	0.2–1.3
Camden Bay	0.9–18	0.05–2.1
Griffin Point	0.7–6.1	0.02–0.6

condition of the Alaska petroleum distribution system as follows. "Some of these facilities are modern, well engineered and maintained. However, others are antiquated, of doubtful engineering and have histories of neglect." Fuel spills are endemic in the Alaska Arctic, sometimes continuing undetected for months or years. While the low population of the region reduces the environmental burden of petroleum from this source, its occurrence at sites of habitation maximizes its potential for public health impact. Similar patterns of loss of refined petroleum products are likely at human settlements throughout the Arctic.

Pollutant hydrocarbons also reach the Arctic by long distance atmospheric transport. A characteristic suite of polycyclic aromatic hydrocarbons is produced during incomplete combustion of all carbon containing fuels and released as fine particulates. Examination of sediments has shown that these hydrocarbons are globally distributed as a result of atmospheric transport (LaFlamme and Hites, 1978). The well known phenomenon of Arctic haze makes clear that this region is subject to industrial pollution from lower latitudes including aromatic hydrocarbons.

With the exception of Alaska oil production mentioned above, in North America there is little heavy industry in the Arctic or along rivers draining into the Arctic and consequently few of the regional problems of coastal pollution. Data prepared by Melnikov and co-workers (1992) indicates that greater settlement and industrialization of the Russian Arctic has led to greater contamination (Table 2). Melnikov reports a series of zones of coastal petroleum pollution (sediment concentrations ranging from 10 to 790 µg/g; mean = 165 µg/g) extending from the White Sea to the Lena River delta. Pollutant concentrations in snow pack and marine waters are also reported to have similar distributions. These zones of pollution correspond to industrialized

Table 2. Regional distribution of concentration ranges of petroleum hydrocarbons in sediment of Russian Arctic seas. Data are ranges as reported by Melnikov et al. (1992).

<i>Location</i>	<i>Petroleum hydrocarbons (µg/g)</i>
Kandalakshskaya Gulf, White Sea	50–300
Coast near Kem and Belmorsk, White Sea	80–300
Dvinskaya Gulf, White Sea	50–320
Outflow zone of Severnaya Dvina, White Sea	80–320
Pechorskaya Gulf and westward, Barents Sea	15–220
Novaya Zemlya, Barents Sea	17–790
NW of Yamal Peninsula, Kara Sea	16–150
Yenisey Gulf, Kara Sea	20–300
Ob Gulf, Kara Sea	50–390
Lena Delta, Buorkhaya Gulf, Laptev Sea	10–180

embayments and river deltas, a pattern seen at lower latitudes in other developed nations.

Any attempt to reach general conclusions about chronic hydrocarbons in the Arctic must be tempered by the scarcity of the accessible data, the fact that they were collected over more than two decades, and knowledge that the accuracy, precision and comparability of the data sets are not always known. In this situation the following generalizations should be regarded at best as a roughly approximate picture. However, there is a distinct possibility that the actual conditions, at least at some locations, are quite different from what these few data suggest.

In the Arctic, as at lower latitudes, chronic petroleum pollution is a series of local and regional problems which roughly correlate with the length and intensity of human industrial activity. Terrestrial spills of either crude oil or refined products can, especially if chronic, lead to ground water and stream contamination. In regions of permafrost where freshwater sources are scarce and spilled petroleum is confined to seasonally thawed ground, the potential for drinking water contamination is considerable. From spill sites as well as from natural sources, fossil hydrocarbons tend to be dispersed mainly as water borne particulates. These can be sequestered as lake and river sediments and are gradually transferred to nearshore marine sediments. During these dispersive processes petroleum pollutants are subject to both chemical degradation and biological uptake. However, the importance of these processes in the Arctic is poorly known.

To date, the Arctic has been free of major catastrophic oil spills. However, the possibility of such an accident will continue as long as petroleum is produced and consumed in the region. The control and recovery of spilled oil in the Arctic presents special problems linked to low temperatures, ice and remoteness. Arctic peoples

and nations need to consider how much preparation is appropriate for the unlikely, but potentially extremely damaging, event of a major oil spill.

The elevated petroleum concentrations in coastal marine sediments of the Russian Arctic reported by Melnikov (10 to 790 $\mu\text{g/g}$; mean = 165 mg/g) appear to overlap with, but generally be higher than the "background" concentrations in coastal marine sediments of the North American Arctic (5-50 $\mu\text{g/g}$) reported by Boehm. While direct information about the impact of these hydrocarbon burdens on Arctic marine species or ecosystems is lacking, a first approximation to the likely biological effects may be found in the work of Long and Morgan (1990). By reviewing the extensive literature on the biological effects of petroleum (and other organic and metallic pollutants), Long and Morgan defined two parameters, the Effects Range Low (ERL), the pollutant concentration at which 10% of all studies showed an adverse biological effect (and 90% showed no effect); and Effects Range Median (ERM), the concentration at which 50% of all studies showed an effect. For total polycyclic aromatic hydrocarbons (PAH) Long and Morgan found an ERL of 4 $\mu\text{g/g}$ and an ERM of 35 $\mu\text{g/g}$.

The highest PAH value reported by Boehm is about 5 $\mu\text{g/g}$, apparently at the lower limit of possible effects (although even this conclusion should be considered tentative). Melnikov reported total petroleum hydrocarbons rather than PAH, but it is highly likely that with a mean of 165 $\mu\text{g/g}$ for that total, PAH often exceeded the ERM of 35 $\mu\text{g/g}$. Thus, this highly imprecise chain of reasoning suggests that chronic petroleum concentrations in the sediments of Russian Arctic seas may have reached concentrations which cause biological harm. This possibility, taken together with the high degree of uncertainty in our understanding of hydrocarbons in the Arctic, suggest that a policy of caution is appropriate until more precise data are available.

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Characterization of Arctic Contamination

Arctic Radionuclide Contamination

Isotope Tracing of Arctic Water Masses

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The following is an overview of the use of the isotopes of hydrogen, oxygen, helium and carbon for tracing the movement and composition of the water masses in the Arctic Ocean. These isotopes are not considered hazardous compounds or conventional contaminations. They are tools for estimating the amount of riverwater delivered to the Arctic Ocean and how that riverwater and the water masses in general move around the Basin before leaving the system through the Fram Strait. Since most readers or participants in this meeting might not be very familiar with these isotopes and their distribution in nature, I will begin with a short summary of their behavior and how they can tell so much about the water masses.

Oxygen-18 and Tritium

Ordinary water, H_2O , contains isotopes of both hydrogen and oxygen. We are first going to discuss the oxygen isotopes.

The oxygen atoms in water are made up of three isotopes: ^{16}O , which is the normal one at 99.8%; ^{17}O , which is a very rare isotope of oxygen; and ^{18}O with a concentration of about 0.2%. All these isotopes are stable, i.e. not radioactive. When liquid water evaporates, the abundance ratios between the isotopes of oxygen, the $^{18}O/^{17}O/^{16}O$ ratios, change ever so slightly. The $^{18}O/^{16}O$ ratio is the most often measured. Small changes are accurately measured by mass spectrometers, and it is convenient to report relative differences between any water isotope composition and that of normal ocean water. That is expressed as $\delta^{18}O$. A $\delta^{18}O$ value of -1‰ means that the ratio is 1 per mille lower than for standard ocean water. See Table 1.

When liquid water evaporates there is a shift in $\delta^{18}O$ making the water vapor slightly lighter isotopically than the liquid water from which it originated. During the

Table 1. Ocean tracers, tritium and oxygen-18.

ISOTOPES (CONSERVATIVE TRACERS)	
$^{18}O/^{16}O$ ratio in H_2O	Deviation from standard $\delta^{18}O$ ‰
Warm seas	0.0
Atlantic source	0.2 to 0.3
Atm. vapor-Arctic	-10 to -30
Average	21 ± 1
<i>Tritium as HTO</i>	$TU = T/H \times 10^{18}$
Atlantic	-5 TU
Run-off	1000 to 100 TU

atmospheric transport of vapor from the warm seas to the high Arctic, the water vapor undergoes several evaporation and condensation processes, which all work in the same direction isotopically, so that the average $\delta^{18}O$ value for precipitation in the Arctic turns out to be about -21‰, i.e. there is about 2% deficiency in the ^{18}O content in the water vapor of rains and snow of the Arctic, relative to the bulk ocean water. Thus we have a situation where the precipitation in the Arctic, and thereby the rivers feeding the basin carry a signal of an ^{18}O deficiency compared to the incoming Atlantic water. This signal allows quantifying how large fraction of an Arctic water sample originates from precipitation in the catchment basin.

The situation is complicated by the fact that melting ice also forms fresh water, but the process of freezing and melting does not change the isotopic composition of the water parcel. The salinity of the Atlantic source water is 35‰. In the Arctic, the salinity will increase by freezing of ice, and decrease by dilution with ice melt riverwater. It is now very important that the run-off from the rivers have an oxygen isotope signal with it. The following is a simple example:

Consider some pure Atlantic water getting into the Barents Sea; salinity is 35 and its ^{18}O value is zero. Now part of the water freezes, thereby salinity increases in the remaining water, but the isotope composition does not change. If say 10% of it freezes, then the salinity becomes about 39‰ but the $\delta^{18}\text{O}$ is still zero. We now add to this "brine" the same amount of *riverwater* as was lost as ice and we come back to the same salinity as the sample had to begin with. However, now the $\delta^{18}\text{O}$ is lower, actually about -2‰, thus signaling the riverwater addition.

This scheme allows us not only to determine how large a part of the water sample is coming from river inflow, but also how much the extent at which a water sample has lost water by freezing or gained water by ice melt. We set up three mass balance equations for a given water sample, below. The F 's are fractions of water originating from the three sources, S is salinity, X is the $\delta^{18}\text{O}$, a is Atlantic water, r is run-off and i is ice. The first three equations have three unknowns so we can solve for the fractions of Atlantic water, of run-off water and of sea-ice making up the current sample.

Mass Balance Equations

	Atl.	Run-	Sea	Water	
	water	off	ice	sample	

Fractional Composition	$F_a + F_r + F_i =$	1	(1)
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Salinity	$F_a S_a + F_r S_r + F_i S_i =$	S	(2)
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Oxygen-18	$F_a X_a + F_r X_r + F_i X_i =$	X	(3)
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Tritium	$F_a T_a + F_r T_r + F_i T_i =$	T	(4)
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If we get good area sample coverage of the upper waters of the Arctic ocean, salinity and oxygen-18 will tell how much river water has been added to the Basin, and also how much ice has been produced. We will also see the pathway of the riverwater in the basin. At this meeting we will emphasize distribution of riverwater input and not so much on the freezing processes.

Tritium

Hydrogen has two stable isotopes, ^1H and ^2H (= D). Tritium (^3H = T) is the heavy isotope of hydrogen with the mass 3; it is radioactive with a half-life of 12 years. Most of the tritium in nature is found as water and almost all originates from the big atmospheric test of hydrogen bombs in the 1960's. Those explosions delivered HTO far up into the stratosphere. Since then there has been a steady downward transport from the stratosphere to the troposphere and by rains to land and sea.

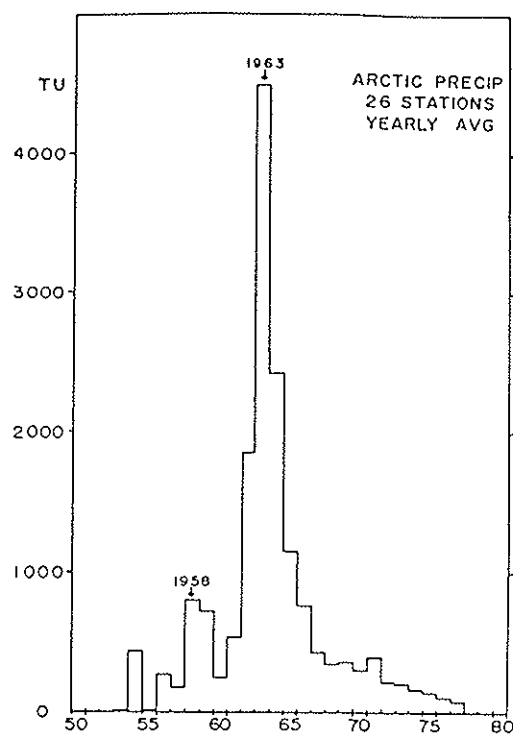


Figure 1a. Standardized yearly average tritium concentration in precipitation which feeds runoff to the Arctic Ocean.

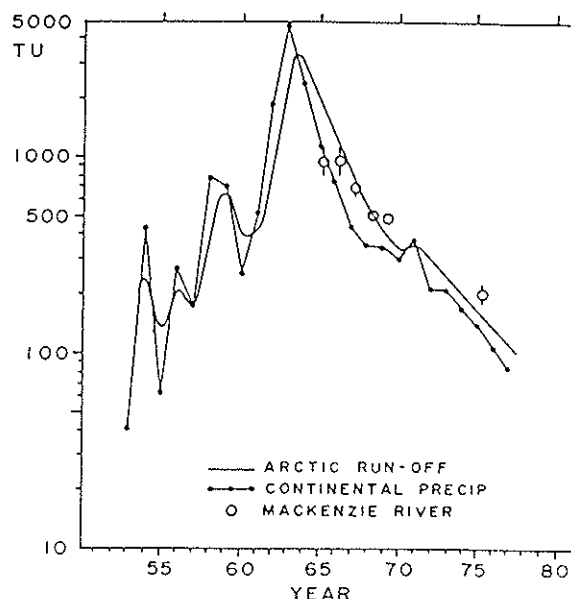


Figure 1b. Yearly TU values (log scale) of runoff to the Arctic Ocean plotted at mid-years.

The history of tritium in rain water is given in Figures 1a. and 1b., showing a very sharp peak in 1963. Tritium concentrations are measured in TU, tritium units, where 1 TU is equivalent to a T/H ratio of 10^{-18} , and 7.2 disintegrations min^{-1} g-water $^{-1}$. Due to the enormous

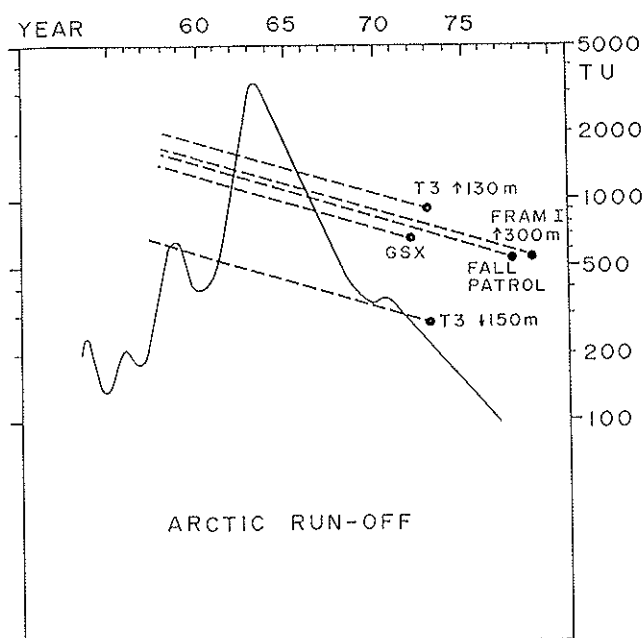


Figure 2. Some TU-value (log) of the run-off component in collected samples. The intercept between the decay line and the precipitation curve mark the "vintage" of the run-off.

dilution of the tritium in the oceans, the tritium concentration of the Atlantic water is only a few TU and quite constant.

In the previous chapter we were able to determine the proportion of Arctic water attributed to run-off, riverwater, and precipitation. If we now also measure the tritium in the same sea water and project that onto the meteoric water component, we get the TU value of that component. By comparing this TU value with the rain water TU-history since 1960 and apply the proper decay rate, we get a measure of what time has elapsed from the time the rain fell to the time we picked our water sample in the Arctic ocean. See Figure 2.

Helium-3

An additional system for measuring times on the scale of decades is to determine not only the tritium in the samples, but also the amount of the helium isotope ^3He , the stable decay daughter of tritium.

As long as a water resides at the surface, its ^3He concentration is kept constant by staying in equilibrium with the ^3He in atmosphere. If the water is sealed off by sinking, the tritium continues to disintegrate producing more ^3He . If the water is sampled carefully and both the amount of ^3He and tritium value are measured, the relationship will yield the time that has elapsed since that water was last at the surface. This is not necessarily the same time as the tritium-only time, which measures the time from the moment rain fell.

Radiocarbon

The following is essentially a variation on the radiocarbon dating principle that was originally designed by Libby around 1950.

All carbon in the biological cycle and the CO_2 of the atmosphere contains radiocarbon, ^{14}C , which is radioactive and is constantly produced by cosmic radiation; in the past this maintained a constant equilibrium $^{14}\text{C}/^{12}\text{C}$ ratio in surface ocean waters. In the last 30 years, some additional radiocarbon has been added to the atmosphere by military and civilian nuclear undertakings and the surface ^{14}C value has increased. For a sub-surface water mass the continuing decay will lower $^{14}\text{C}/^{12}\text{C}$ ratio at a rate of 1% per 80 years; a half-life of 5,700 years. By measuring the deficiency of radiocarbon, one can get a reasonably good estimate of the "age of the water"; i.e. the time since the water mass was last in contact with the air.

Radiocarbon is a tool obviously suitable for much longer time scales than tritium, and best for the deep waters of the Arctic Basin. The $^{14}\text{C}/^{12}\text{C}$ isotope ratio is quite applicable to the turnover times of the major oceans. It is also quite useful in the study of the ocean's role in the global carbon cycle, and therefore in climate studies.

Results

Knut Aagaard will give us a more comprehensive picture of the water mass transports in the Arctic, so I will here only point at a few of the results that can be gleaned from the methods that were described above. Due to the sparse data coverage in the interior of the Basin (Figure 3), it is impossible to make a detailed map of the circulation pattern.

Atlantic water is coming in from the south across the Barents Sea and along the west coast of Spitsbergen. The upper waters then begin a counter-clockwise circulation pattern, while getting mixed with run-off from



Figure 3. Map of Arctic Ocean with location of section in next figure.

Siberia. An idea of the circulation time scales at various depth can be had from the section in Figure 4. The residence time of the upper, halocline waters is roughly 10 years from the time they enter the basin until they exit through western Fram strait and the Canadian Archipelago.

The deeper layers below about 300 meters or so have considerably longer residence times. In the residence time of the Nansen Basin, the deep waters are marked about 30 years with a very large error. It has recently been revised by P. Schlosser at Lamont to be closer to 100 years.

The deep waters in the Canada Basin, behind the Lomonosov Ridge, have considerably higher ages, up to 700 years at depths below 1500m. Here, ^{14}C tells us

of ages, but the question remains unsolved how this age comes about. Are those layers "fossil" water left from a period of different climate or is there exchange at such very slow rate?

If we now go back to the upper waters of the basin we find that it is very difficult to get a detailed picture of the situation as far as direction and speed of the currents in the basin itself. However, the tritium and ^{18}O tell us that Barents Sea is an influx area for Atlantic water. From there the water apparently goes west, partly behind the Novaya Zemlya, through the Kara, Laptev, and possibly East Siberian Sea. It acquires the characteristic tritium and ^{18}O signals from the rivers of Siberia. Thus these shelf waters have a heavy component of the Siberian water. With the water comes any radioactivity

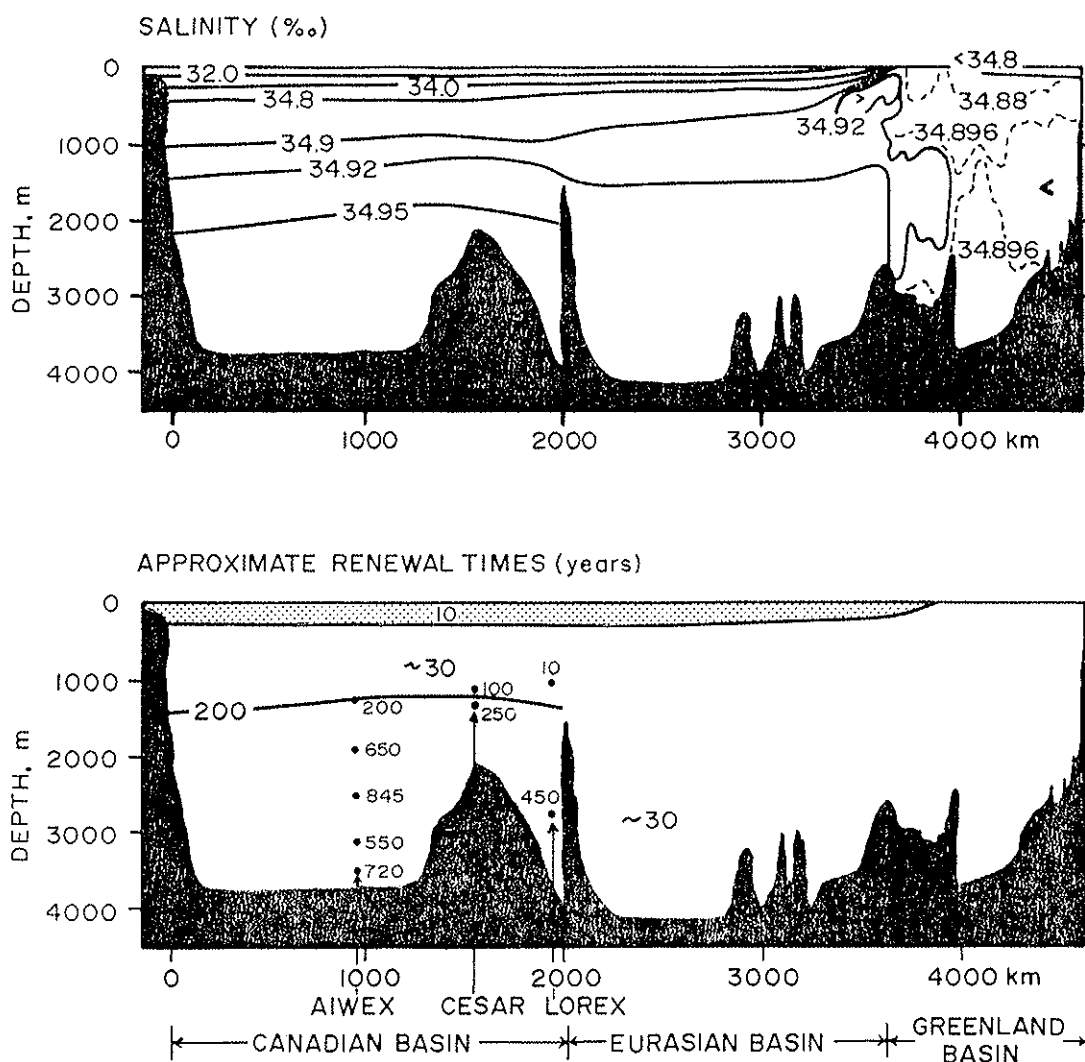


Figure 4. Vertical sections of density and of ages along track in Figure 3.

and other contaminants from Siberia and the Kara Sea. These shelf waters flow and mix with the upper few hundred meters of the Arctic ocean proper. Finally, after about 10 years, they exit through the Fram Strait.

Conclusions

The isotopes of seawater give us the possibility of tracing the fate of meteoric water, i.e. river outflow water added to the Arctic ocean. It also tells us that riverwater and thereby the upper few hundred meter layers spend roughly 10 years on their way from the Siberian rivers and Mackenzie River to the Fram Strait outflow. The amount of meteoric water that is produced in the drainage basin is of the order of 0.18 Sv (1 Sv = 1 km³/sec). (There is an addition of Bering Strait low salinity Pacific water, which is not discussed here.) The meteoric component is equivalent to about a 1.1 meter layer (one has to remember that drainage area for the Basin is much larger than the surface area of the Arctic ocean itself) and

it takes about 10 years for the riverwater to get out into the Greenland Sea, via Fram Strait.

The tritium signal in the waters of the Arctic ocean is still reasonably large and will be useful for another decade. Difficulties in applying it are increasing due to the fact that the source intensity is decreasing; the tritium values having gone down from several hundreds in rain and snow to probably around 50 TU or so today. However, tracing the river water by oxygen-18 has no time constraint.

The ¹⁴C will continue to give information on time scales of more than 100 years, primarily in the deeper waters of the Arctic ocean.

Available Isotope Data Coverage

1. Tritium Laboratory Data Report #L9, Arctic Tritium, 1973-1991. March 1993; contains all data from this time period, measured by the Miami Laboratory.

2. Isotope data from *Polarstern* 87 and *Oden-Polarstern* 91 are being assembled by Peter Schlosser, Lamont-Doherty Geological Observatory.

Needed Research

The application of isotopes to the circulation problems in the Arctic surfaces, like all other research in the Arctic, suffer from a lack of systematic, large area coverage of oceanographic data. There have been only three major cruises into the area, yielding planned and geometrically (geographically) organized data sets: the *Ymer*-80, the *Polarstern*-87, and the Arctic 91 *Oden-Polarstern*. None of them give coverage of the Canada Basin proper. Thus expeditions using heavy ice breakers or scientifically equipped submarines are badly needed.

The isotope data need to be incorporated into more sophisticated computer models than was set up by Östlund and Hut (1984). An attempt in that direction is presently under development by Dr. Schlosser et al. at LDGO, see reference.

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Advances in Nuclear Techniques for Environmental Analysis

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Introduction

Demonstrated and potential effects of anthropogenic radionuclides in marine and terrestrial environments are receiving much increased attention. In the radiation protection community, emphasis has shifted from dose limitations for individuals, which are now regarded more as boundary conditions than safety limits, to a focus on the radiation exposure burden to populations as a whole and to the estimation of a collective lifetime dose.[1] In regard to Arctic radioactive wastes, the collective population is not just the human population, but includes benthic and other marine biota. For long-lived isotopes, cumulative effects of chromosomal damage are an increasingly important issue. Thus the need for precision low-level analysis of widely disbursed and potentially long lived radioisotopes has increased.

Our understanding of the release, transport and effects of radioisotopes into the environment depends critically on our ability to accurately measure low levels of these isotopes. Detection limits, accuracy and reproducibility of each step of the analysis procedure must be well understood and controlled in order to draw conclusions regarding radiological levels and effects from limited number of samples. Sampling, processing and analysis steps are illustrated schematically in Figure 1.

Standard environmental radioisotope detection techniques are based on 1940's radiation measurement technology. Now, however, a quiet revolution is taking place as techniques from other fields are being applied to environmental measurements. Technologies such as accelerator mass spectrometry and resonance ionization mass spectrometry are being used to dramatically decrease sampling times and decrease sample size requirements while increasing sensitivity limits.

In the traditional radiation detection technology improvements are being made in detector efficiency, in ruggedization and portability, in automation of data

analysis techniques, and in greater reproducibility through yield tracers and cooperative interlaboratory cross comparisons. As a result, the reliability of and confidence in environmental data has increased significantly. Reliability has been achieved by careful control of each step of the analytical process, control of contamination, yield tracking in the concentration process, correction terms for attenuation, geometric factors and variations in detector efficiency. In broad programs such as the ONR Arctic Nuclear Contamination Program, calibration, interlaboratory comparisons, and archiving of samples and data must be standardized and specified at the beginning to assure a high level of quality control. Multiple techniques can and should be used in order to build confidence in the quantitative results.

In another important development, the ability to do near real-time field analysis of selected isotopes now exists. For the survey of marine nuclear waste dumps, sampling of water and sediment from a site can determine the extent of present leakage but provides no information on the level of potential leakage days, weeks or even years in the future. The range of α s or β s is limited, but for many γ -ray emitting isotopes an in-situ survey could be performed. The use of high resolution γ -ray spectrometers or imaging systems placed on ROVs could determine the radioisotopic contents of a barrel or other object on the sea floor and even the distribution of the radioisotopes.

Presently, most environmental samples are analyzed by radiation detection techniques. Depending on the isotope either α , β , or γ counting or spectroscopy is performed. Minimal sample preparation is required for γ -ray analysis of soil sediment samples. For β and especially α spectroscopy, much more sample preparation is necessary to concentrate the radioisotope of interest and to remove of interfering elements before the samples

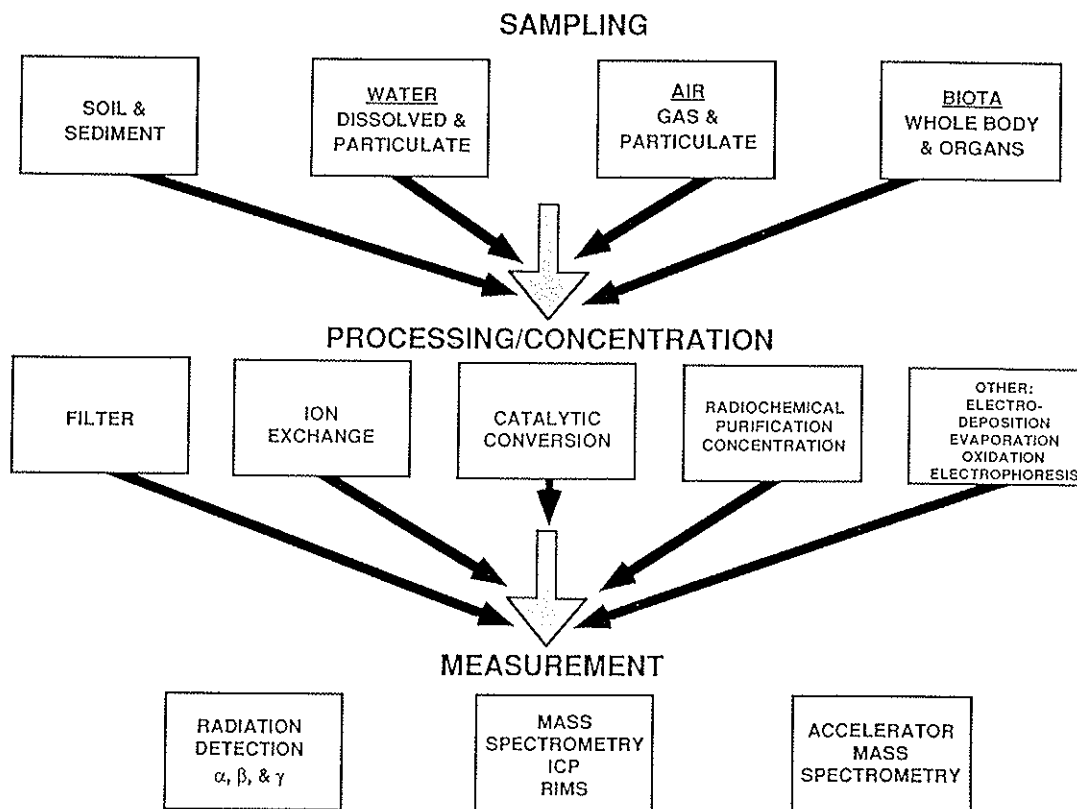


Figure 1. Analytical methodologies.

can be counted. Water samples require filtering and separation to concentrate dissolved and particulate radioisotopes for analysis. The standardization of radiochemical techniques and use of yield tracers has greatly increased the reliability of these measurements. However, new techniques have been developed that are competing with the established techniques to meet growing throughput requirements of large sampling programs, the need for greater sensitivity and the need for simpler sample preparation. The focus of the present paper is on recent progress in measurement techniques.

Advances in Techniques

Many of the techniques used in radioisotopic analysis have seen substantial improvements in the past decade. Four techniques in particular offer new tools for environmental research. Developments in inductively coupled plasma-mass spectrometry (ICP-MS), resonance ionization mass spectrometry (RIMS), accelerator mass spectrometry (AMS) and gamma spectroscopy all provide significant improvements in the state-of-the-art. Mass spectrometry techniques have the advantage of not having to wait for the decay of a radioisotope. This advantage is greater for longer lived isotopes. In many cases the sample preparation is simpler for MS than for α spectroscopy and smaller samples can be used. A major limitation of MS is the interference from

molecular ions of much more abundant isotopes. This disadvantage can be greatly reduced by RIMS and AMS techniques.

Inductively Coupled Plasma-Mass Spectrometry

Inductively coupled plasma-mass spectrometry provides both elemental and isotopic analysis across the periodic table. It was first introduced in the early 1980's and has rapidly advanced as noted by several recent reviews.[2,3,4,5] An ICP-MS system typically vaporizes and injects an aqueous solution into an argon plasma which ionizes the sample. The sample is then injected into a quadrupole mass spectrometer and the ions for a particular mass counted using a microchannel detector. The advantages of ICP-MS include ease of sample injection, detection limits of a few pg/ml and sample times of less than 10 minutes compared to one to two weeks measurement time for α counting. For example sample preparation for ^{230}Th in marine sediments has been reduced from 3 days to one day with a detection limit of 36 femto-moles (6.7 mBq) and a precision of better than three percent. [6] ICP enables the separation of ^{239}Pu and ^{240}Pu , and for ^{237}Np offers a lower detection limit than α counting.[7]

Resonance Ionization Mass Spectrometry

Resonance ionization mass spectrometry selectively

excites atoms using one or more photons of particular wavelengths. The atomic excitation and subsequent ionization is usually performed using one or more pulsed lasers. The ions are accelerated and then analyzed using time-of-flight or other mass spectrometry techniques. RIMS is a technique that can be applied across the periodic table but requires specific development for each radioisotope of interest. Systems have been developed and extensively tested for $^{81,85}\text{Kr}$ isotopes with detection limits of 10^4 atoms per liter of air.[8] The resonance ionization process is highly specific capable of eliminating isobaric or molecular ion interference. Demonstrations for U and Pu have also been conducted.

Accelerator Mass Spectrometry

Accelerator mass spectrometry uses nuclear physics accelerators to produce few MeV energy ion beams. The energies used are about two orders of magnitude greater than conventional mass spectrometry systems. AMS has two principle advantages over conventional mass spectrometry. First, the higher energies allow the use of nuclear charged particle detectors, which can accurately identify a particular isotope. The second advantage of AMS is based on the use of a tandem Van der Graaff. Sample ions are first negatively ionized in a cesium sputter ion source, accelerated, stripped of their electrons and accelerated again as positive ions. The stripping process and subsequent electromagnetic beam analysis virtually eliminates molecular interference. AMS was originally developed for ^{14}C dating and has become a standard tool for the dating of 5000-10000 samples per year.[9] Sample size requirements for AMS dating of ^{14}C are three orders-of-magnitude lower than for conventional counting. AMS has also been developed for other isotopes of geological interest such as ^{10}B and ^{36}Cl . Efficiencies of AMS systems range from 0.1% to 5% depending on the isotope. Isotopic samples as small as 10^5 atoms have been measured. Disadvantages of AMS include the cost and the need for a specific development program for each isotope of interest.

Gamma-ray Spectroscopy

Three developments in gamma-ray spectroscopy could have significant impact on the measurement of environmental samples. The first is a long term effort to develop an ultralow background high resolution gamma-ray system. [10] Developed to search for doublebeta decay of ^{76}Ge , backgrounds of 0.01-0.02 counts/keV/day have been achieved by placing the detectors 1438 m underground in the Homestake gold mine, by surrounding the detector with 7.3 cm of lead cast from 448 year old ingots recovered from a sunken Spanish galleon, 10 cm of pre-WWII lead and 10 cm of boron loaded paraffin. Further reductions were achieved

by making all detector components from radiopure materials and by using isotopically enriched germanium to minimize the production of ^{68}Ge by energetic cosmic-ray produced neutrons. This system, and the background reduction techniques learned from its development, have enabled a decrease in detection limits of several orders of magnitude for γ emitting isotopes. The detection limits are determined by the counting statistics required for the isotope of interest and the detector efficiency.

The second advancement to impact environmental sampling is the development of ruggedized high resolution detectors which are field portable. The first ruggedized detectors were developed by the detector manufacturers under contract to NRL. [11] An example of the use of a ruggedized detector array is the whole spacecraft survey of the Long Duration Exposure Facility conducted upon its retrieval to determine the level of induced radioactivity. [12] Using ruggedized detectors coupled with mechanical cooling systems it is now possible to develop in-situ high resolution detectors to survey suspected nuclear dumps in marine environments.

Finally, work is in progress to develop a Compton Imaging System using high resolution gamma ray detectors. The Compton Imager detects scattered gamma-rays using multiple position-sensitive detectors. From the position and energy information of a scattering event in two of the detectors it is possible to determine the direction of the incoming photon to within a cone of angle θ . The reconstruction of many events can determine the position of the source in addition to isotopic identification.[13] Simulations of reconstruction techniques indicate that few cm position resolution in three dimensions should be possible for a barrel positioned in front of an imaging system.

Summary

New technologies continue to improve detection limits, throughput and specificity of radioisotopic analysis. However, before the introduction of any new techniques for environmental sampling, rigorous interlaboratory and inter-technique cross comparisons must be performed to place the new techniques on the same level of quality standards as those for techniques in routine use.

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Estimated Inventory of Radionuclides in Former Soviet Union Naval Reactors Dumped in the Kara Sea

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Abstract

Radionuclide inventories have been estimated for the reactor cores, reactor components, and primary system corrosion products in the former Soviet Union naval reactors dumped at the Abrosimov Inlet, Tsivolka Inlet, Stepovoy Inlet, Techeniye Inlet, and Novaya Zemlya Depression sites in the Kara Sea between 1965 and 1988. For the time of disposal, the inventories are estimated at 17 to 66 kCi of actinides plus daughters and 1,695 to 4,782 kCi of fission products in the reactor cores, 917 to 1,127 kCi of activation products in the reactor components, and 1.4 to 1.6 kCi of activation products in the primary system corrosion products. At the present time, the inventories are estimated to have decreased to 6 to 24 kCi of actinides plus daughters and 492 to 540 kCi of fission products in the reactor cores, 124 to 126 kCi of activation products in the reactor components, and 0.16 to 0.17 kCi of activation products in the primary system corrosion products. Twenty years from now, the inventories are projected to be 3 to 12 kCi of actinides plus daughters and 303 to 333 kCi of fission products in the reactor cores, 63.5 to 64 kCi of activation products in the reactor components, and 0.014 to 0.015 kCi of activation products in the primary system corrosion products. All actinide activities are estimated to be within a factor of two.

Introduction

In the spring of 1993, a Russian report, "Facts and Problems Related to Radioactive Waste Disposal in Seas Adjacent to the Territory of the Russian Federation,"¹ was released. The findings presented in this

Russian report were the result of a scientific study commissioned by the Office of the President of the Russian Federation and headed by Dr. Alexi V. Yablokov. The Yablokov Commission, as they were later called, reported that 16 naval reactors from seven former Soviet Union submarines and the icebreaker *Lenin*, each of which suffered some form of reactor accident, were dumped at five sites in the Kara Sea. Six of these 16 naval reactors contained their spent nuclear fuel (SNF). In addition, approximately 60% of the SNF from one of the three *Lenin* naval reactors was disposed of in a reinforced concrete container and metal shell. The Yablokov Commission estimates of radioactivity were limited to the fission products in the SNF and the ⁶⁰Co in the reactor components, both at the time of disposal. With rare exception, specific radionuclides were not identified and there was no estimate provided for the current levels of radioactivity.

Without a knowledge of the specific radionuclides and their current levels of radioactivity, the health risks to man from these 16 former Soviet Union naval reactors and their SNF are difficult to predict. This report presents the results of an independent effort to provide the necessary time-dependent inventory of the radionuclides.

Background Information

The information presented herein highlights the conclusions of the Yablokov Commission and what we know or have assumed about the history of each submarine. Table 1 presents the Yablokov Commission findings for the five Kara Sea disposal sites.¹ Summarized

Table 1. Yablokov Commission findings for the former Soviet Union naval reactors dumped in the Kara Sea.¹

<i>Disposal site</i>	<i>Disposal date</i>	<i>Naval reactors discarded</i>	<i>Reactors containing SNF</i>	<i>Fission product activity (kCi)</i>
Abrosimov Inlet	1965	2 (No. 285)	1	800
		2 (No. 901)	2	400
		2 (No. 254)	—	—
	1966	2 (No. 260)	—	—
Tsivolka Inlet	1967	3 (OK-150)	0.6*	100
Novaya Zemlya Depression	1972	1 (No. 421)	1	800
Stepovoy Inlet	1981	2 (No. 601)	2	200
Techeniye Inlet	1988	2 (No. 538)	—	—
Total		16	6.6	2,300

* The SNF was not contained in the naval reactor, but in a reinforced concrete and metal shell.

for each disposal site is the disposal date, the number of discarded naval reactors and their associated ship identification number, the number of discarded naval reactors containing SNF, and the estimated fission product radioactivity in the SNF at the time of disposal. The Tsivolka Inlet entries are for the icebreaker *Lenin* and the reinforced concrete container and metal shell containing approximately 60% of the SNF from one of the three OK-150 power plant naval reactors that were discarded in 1967. The 100 kCi reported for the *Lenin* disposal result primarily from the fission products ⁹⁰Sr and ¹³⁷Cs. The two naval reactors containing SNF that were discarded in the Stepovoy inlet in 1981 are identified as being of a liquid metal cooled type. The Yablokov Commission estimates of total radioactivity are 2,300 kCi of fission products in the SNF and 100 kCi of ⁶⁰Co in the reactor components. No information was provided which would allow association of a given ship identification number with a specific submarine class or accident date.

To estimate the time-dependent inventory of radionuclides in the discarded naval reactors, reactor core operating histories and the accident date associated with each discarded naval reactor are required. Unfortunately, reactor core histories for the seven former Soviet Union submarines were not available. Therefore, an analytical model was developed to estimate the minimum reactor fuel load for each submarine whose discarded naval reactors contained SNF. As will be discussed later, the model uses as its basis Western estimates of the shaft horsepower of each submarine involved. Selection of an appropriate shaft horsepower requires a knowledge of each submarine's NATO classification.

Table 2 presents a summary of the Western estimates of the identities of the submarines whose naval reactors were dumped in the Kara Sea.^{2,3} Summarized for each

submarine is the K identification number, NATO classification, and associated reactor accident date. The two naval reactors in the K-27 are reported to have been of a liquid metal type.² All other discarded naval reactors are believed to have been of the pressurized water reactor (PWR) type.⁴ Three of these submarines, K-3, K-11, and K-19, were observed in active service some years after suffering their reactor accidents. While each of the seven identified submarines was reported to have suffered some form of reactor accident, none was reported to have sunk.

With the information of Table 2 as a basis, a NATO classification was assigned to the ship identification of each submarine whose discarded naval reactors contained SNF. Table 3 presents a summary of our deductions. Summarized for each disposal date is the number of discarded naval reactors containing SNF and associated ship identification number, the K identification number, and the NATO classification. The rationale for our selections was as follows. A recent International Atomic Energy Agency publication³ identifies three of

Table 2. Western estimates of the identities of the former Soviet Union submarines whose naval reactors were dumped in the Kara Sea.^{2,3}

<i>Submarine identification</i>	<i>NATO classification</i>	<i>Reactor accident date</i>
K-3	November	June, 1962
		September 8, 1967
K-5	Hotel/November	Mid-1960s
K-11	November	February 12, 1965
K-19	Hotel	July 4, 1961
K-22*	—	—
K-27	November	May 24, 1968
K-140	Yankee II	August 23, 1968

*No information is currently available in the open literature for this submarine.

Table 3. Best estimate association of ship identification with the NATO classification of each submarine whose discarded naval reactors contained SNF.

Disposal date	Reactors containing SNF	Submarine identification	NATO classification
1965	1 (No. 285)	K-3	November
	2 (No. 901)	K-19	Hotel
1972	1 (No. 421)	K-140	Yankee II
1981	2 (No. 601)	K-27	November

the four submarines whose naval reactors were discarded in 1965 and 1966 as the K-3, K-11, and K-19. In addition, the submarine whose two naval reactors were discarded in 1981 is identified as the K-27. Since the Yablokov Commission report specified that the minimum time period between reactor shutdown and disposal was one year, we believe that the two submarines associated with the three naval reactors containing SNF that were discarded in 1965 are the K-3 and K-19. Since the first K-3 submarine reactor accident involved no fatalities and she was observed in active service some years later,² one may infer that while both naval reactors were undoubtedly replaced, only one of the two discarded naval reactors contained SNF. Furthermore, since the K-19 submarine reactor accident involved fatalities, the accident was of such severity that she was nicknamed "Hiroshima," and she was observed in active service some years later,² one may infer that both naval reactors were removed and that each contained SNF. Thus, the K-3 was assigned to the ship identified as No. 285, and the K-19 was assigned to the ship identified as No. 901. Through a similar process of elimination, the submarine associated with the one naval reactor containing SNF that was discarded in 1972 was assigned to the K-140. The three remaining submarines, K-5, K-11, and K-22, are assumed to be associated with discarded naval reactors without SNF.

Analytical Model

The information presented herein describes (1) the analytical model used to estimate the minimum reactor fuel load for each submarine whose discarded naval reactors contained SNF, (2) the information that we know or have assumed about the operating characteristics of the icebreaker *Lenin* and each submarine whose discarded naval reactors contained SNF, and (3) the method used to predict the activation product inventories in the reactor components and primary system corrosion products of all discarded naval reactors.

With an estimate of the reactor fuel load, the reactor power, and the reactor operating history, one can proceed to calculate the radionuclide inventory associated

Table 4. Naval reactor core information for the former Soviet Union icebreaker *Lenin*.^{5,6}
Number of assemblies per reactor: 219
²³⁵U enrichment range: 4.6% to 6.4%

Naval reactor	Core histories		
	²³⁵ U loading (kg)	Operating period (MW hours)	Effective full power hours (hours)
1	80	560,000	8,600
2	76	550,000	8,500
3	129	660,000	10,000

with the SNF. Before describing the computer code that was used to estimate the inventory, the information that is required as input must be addressed. In the case of the icebreaker *Lenin*, core history information necessary to the inventory calculations was directly available from Russian sources.^{5,6} Table 4 presents a summary of the naval reactor core information for the icebreaker *Lenin*. Summarized for each of the three *Lenin* reactors is the ²³⁵U loading, the operating period, and the number of effective full power hours. From the information contained in Table 4, the average full power of each reactor is calculated to be 65 megawatts thermal (MW). Each of the three *Lenin* reactors was reported to contain 219 fuel assemblies with a ²³⁵U enrichment in the range of 4.6 to 6.4%. The reactor accident that precipitated the need for disposal of the three naval reactors and a portion of one's SNF occurred either early or late in the year of 1966, some three years after the reactors were refueled. The Yablokov Commission report states that SNF from 125 fuel assemblies, or approximately 60% of the fuel complement from one OK-150 reactor, was discarded. The number of fuel assemblies that this 60% finding implies is on the order of 208, which is in excellent agreement with the 219 fuel assemblies previously reported for each *Lenin* reactor. As such, added credence is given to the *Lenin* core history information.

For national security assets such as nuclear powered submarines, core history information like that published on the *Lenin* is virtually impossible to obtain. As such, a method for estimating the necessary reactor fuel load had to be developed. Assuming one knows the operating characteristics of the submarine, estimates of the reactor fuel load can be made from the power requirements of the submarine. For a submarine to operate at a given speed, S_i , the power requirement, P_i , in MW, is given by:

$$P_i = (\text{SHP}) (\text{CF}_1) (S_i / S_{\text{max}})^3$$

where SHP = shaft horsepower (hp) and
 $\text{CF}_1 = 0.7457 \times 10^{-3} \text{ MW/hp}$.

The overall power requirement of the reactor, P_R , in MW, is given by:

$$P_R = [(P_i / PE) + HL] / N_R$$

where PE = propulsion efficiency,
 HL = "hotel" load requirements, MW, and
 N_R = numbers of reactors.

The propulsion efficiency is that of the plant, and includes both thermal and mechanical conversion. The "hotel" load represents the total thermal power requirements of the submarine for all electric power and steam loads.

The minimum quantity of ^{235}U required to power the submarine for a specific duration, $^{235}\text{UL}_{\min}$, in grams, is given by:

$$^{235}\text{UL}_{\min} = (CF_2) (P_R) (AST) (CL)$$

where $CF_2 = 1.24$ grams $^{235}\text{U}/\text{MWd}$,
 AST = at-sea time, d/y, and
 CL = core life, y.

The minimum quantity of U in the submarine reactor fuel load, UL_{\min} , in grams, is given by:

$$\text{UL}_{\min} = ^{235}\text{UL}_{\min} / E_U$$

where E_U = enrichment of ^{235}U .

Note that the minimum quantity of U in the reactor fuel load, UL_{\min} , is not the amount that is actually predicted to be loaded in the submarine, but rather the minimum quantity of U required for the submarine to operate at speed S_i for a time period equal to the product of the at-sea time and core life. A substantially greater amount of U would be required for a full reactor load.

Table 5 presents a summary of the basic data used to estimate the minimum quantity of U in the reactor fuel load for each submarine whose discarded naval reactors contained SNF. Summarized for each of the various parameters is the range of values and the value assumed. The average speed at which each submarine was assumed to operate was arbitrarily set at 11 knots. For the shaft horsepower and maximum speed of the submarines, the average of the range of values was assumed. In the case of the propulsion efficiency, hotel load, at-sea time, and core life, the value assumed was the range limit or value that would maximize the minimum quantity of U in the reactor fuel load. The value limits on enrichment are a best estimate from the available data. While the lower range limit is considered nominal for first-generation submarines of the November and Hotel class, the inclusion of a Yankee II class submarine requires the assumption of a range in enrichment.

The radionuclide inventory in the SNF of the dis-

Table 5. Summary of the basic data used to estimate the minimum quantity of U in the reactor fuel load for each former Soviet Union submarine whose discarded naval reactors contained SNF.

Parameter	Value range	Value assumed
November class SHP (10^3hp) ^{7,8}	30.0–35.0	32.5
Hotel class SHP (10^3hp) ^{8,9}	29.5–30.0	29.75
Yankee II class SHP (10^3hp) ^{7,8,10}	29.5–45.0	37.25
November class S_{\max} (knots) ^{7,8}	28–30	29
Hotel class S_{\max} (knots) ^{8,9}	23–26	24.5
Yankee II class S_{\max} (knots) ^{7,8,10}	26.5–27	26.75
Propulsion efficiency, PE , (%) ¹¹	15–20	15
Hotel load, HL , (MW)	12–15	15
Number of reactors, N_R ^{8,9,10}	2	2
At-sea time, AST (d/y)	120	120
Core life, CL , (y)	5–7	7
^{235}U enrichment, E_U , (%) ¹²	10–36	10–36

carded naval reactors was calculated with ORIGEN2,¹³ a point (no spatial dependence) depletion personal computer code that has been used extensively to characterize spent nuclear fuel and high level waste. The ORIGEN2 fixed data library used in these estimates is that for a generic PWR fueled with UO_2 enriched to 4.2% in ^{235}U at a burnup of 50,000 MW days per metric tonne of U. A number of factors were considered in the selection of this particular library. First, 14 of the 16 discarded naval reactors are believed to be of the PWR type. Second, since the *Lenin* fuel matrix was described in the Yablokov Commission report as UO_2 , it follows that the fuel matrix in first-generation submarine naval reactors built during the same period of time was also very likely UO_2 . Third, the lowest ^{235}U enrichment in the *Lenin* reactors was quite close to 4.2%.

The highest ^{235}U enrichment considered for the former Soviet Union submarines is substantially greater than 4.2%. One might expect that as the ^{235}U enrichment is increased, there will be a proportional decrease in the production of actinides. This is not the case; as the ^{235}U enrichment is increased, the neutron energy spectrum can be expected to harden or shift toward higher energies. With this shift in neutron spectrum, more resonance absorptions are expected to occur, which, in turn, will lead to a relative increase in the production of actinides. For a ^{235}U enrichment of 36%, the use of ORIGEN2 may result in an underestimate of the actinides by as much as a factor of two. The effect of a ^{235}U enrichment of 36% on the ORIGEN2 fission product estimate is believed to be significantly less. A more accurate estimate of the actinides in the higher enrichment fuels may be calculated with the computer code ORIGEN-S.¹⁴ However, to perform this calculation, one must know either the relative shape and magnitude

Table 6. Information used to predict the radionuclide inventory in the reactor components and primary system corrosion products in the former Soviet Union naval reactors dumped in the Kara Sea.^{15,16}

Nuclide	Half-life (y)	Activity (Ci)	
		Reactor components	Primary system corrosion products
⁶⁰ Co	5.27	1.27×10^4	1.09×10^2
¹⁴ C	5,730	1.14×10^1	1.57×10^{-5}
⁶³ Ni	100.1	5.22×10^3	2.61×10^{-1}
⁵⁵ Fe	2.73	6.11×10^4	1.94×10^0
⁵⁹ Ni	75,000	4.68×10^1	1.37×10^{-3}
Total		7.91×10^4	1.11×10^2

of the neutron energy spectrum or the composition and dimensions of a reactor fuel assembly or unit cell. Since information such as this was not readily available, the limitation in the prediction of the actinide inventory associated with the use of ORIGEN2 was considered acceptable.

To predict the activation product inventories in the reactor components and primary system corrosion products of the discarded naval reactors, the results of a British calculation for a generic nuclear powered submarine one year after shutdown were used.^{15,16} Table 6 presents a summary of the British results. Summarized for each of the selected activation products are the radionuclide half-life, reactor component radioactivity, and primary system corrosion product radioactivity. Since the reactor power level of a typical first-generation British submarine is similar to Western estimates of the reactor power levels of the discarded naval reactors, it follows that the data of Table 6 may be used without exception. For the reactor components the estimated total radioactivity is 79,100 Ci, with ⁵⁵Fe, ⁶⁰Co, and ⁶³Ni as the most dominant radionuclides, respectively. For the primary system corrosion products, the estimated total radioactivity is reduced to 111 Ci, with ⁶⁰Co as the most dominant.

Characteristics of Selected Radionuclides

The inventory of radionuclides in this estimate is limited in scope. For the most part, the inventory consists of radionuclides with long half-lives or which are of concern as ingestion products, the most likely pathway of dose to man. Table 7 presents a summary of the characteristics of the selected actinide, fission product, and activation product radionuclides in the inventory. Summarized for each selected radionuclide is the radionuclide half-life, type of radiation emitted, average energy associated with each radiation type, and the annual limit on intake for ingestion. The annual limit of intake for ingestion represents the quantity of a given

Table 7. Characteristics of the selected actinide, fission product, and activation product radionuclides in the inventory.

Nuclide	Half-Life (y)	Radiation type	Average energy ¹⁷ (MeV)	Annual limit on intake ¹⁸ (μCi)
<i>Actinides</i>				
²³⁹ Pu	24,110	α	5.10	0.8
²⁴⁰ Pu	6,563	α	5.16	0.8
²⁴¹ Am	432.7	α	5.48	0.8
		γ	0.0287	
²³⁸ Pu	87.7	α	5.49	0.9
		γ	0.00176	
²⁴¹ Pu	14.4	β	0.0052	40
<i>Fission Products</i>				
¹²⁹ I	15,700,000	β	0.0415	5
		γ	0.0248	
⁹⁰ Sr	28.5	β	0.196	30
¹³⁴ Cs	2.06	γ	1.55	70
		β	0.157	
¹³⁷ Cs	30.0	γ	0.566	100
		β	0.188	
¹⁵⁴ Eu	8.8	γ	1.25	500
		β	0.227	
¹²⁵ Sb	2.73	γ	0.443	2,000
		β	0.086	
¹⁴⁷ Pm	2.62	β	0.062	4,000
¹⁵⁵ Eu	4.96	β	0.0471	4,000
		γ	0.063	
⁹⁹ Tc	213,000	β	0.085	4,000
¹⁵¹ Sm	90	β	0.125	10,000
<i>Activation Products</i>				
⁶⁰ Co	5.27	γ	2.50	200
		β	0.096	
¹⁴ C	5,730	β	0.0495	2,000
⁶³ Ni	100.1	β	0.0171	9,000
⁵⁵ Fe	2.73	EC	0.0038	9,000
		γ	0.00163	
⁵⁹ Ni	75,000	EC	0.0041	20,000
		γ	0.00232	

radionuclide that, when ingested over a period of one year, will result in a dose of 5 rem. For simplicity, the radionuclides of a given type—actinide, fission product, or activation product—have been arranged in order of decreasing toxicity. With the exception of ²⁴¹Pu, the actinides are the most toxic of the selected radionuclides in the inventory. The toxicity of ²⁴¹Pu is greater than that of ¹³⁴Cs and less than that of ⁹⁰Sr. With the exceptions of ⁶⁰Co and ¹⁴C, the activation products are the least toxic of the selected radionuclides in the inventory. The toxicity of ⁶⁰Co is greater than that of ¹⁵⁴Eu and less than that of ¹³⁷Cs. The toxicity of ¹⁴C is equivalent to that of ¹²⁵Sb.

Results

The maxima and minima in the estimated inventory of radionuclides presented herein were developed

through an assessment of the variability of two key parameters: ^{235}U enrichment and time between reactor shutdown and disposal of the SNF. The effect of ^{235}U enrichment on the estimated inventory of radionuclides was evaluated for the *Lenin* and submarine naval reactors in the following way. In the case of the SNF from one of the three *Lenin* naval reactors, the reported range in ^{235}U enrichment was assumed to be associated with a single three-reactor core load. Under a further assumption that the three *Lenin* reactors were loaded with approximately equal quantities of U, the ^{235}U enrichments of 4.6% and 6.4% were associated with the two reactors loaded with 76 and 80 kg of ^{235}U and the one reactor loaded with 129 kg of ^{235}U , respectively. In the case of the six submarine naval reactors containing SNF, the assumed minimum and maximum in ^{235}U enrichment were associated with separate reactor core loads.

The effect of time between reactor shutdown and disposal, or decay time, on the estimated inventory of radionuclides was evaluated by assuming a minimum decay time and a best estimate decay time for each naval reactor and disposal site. By definition, the minimum decay time for each naval reactor was chosen such that the estimate of the inventory of radionuclides at the time of disposal would be a maximum, and the best estimate decay time for each naval reactor was chosen such that a more realistic estimate of the inventory of radionuclides at the time of disposal would result. Table 8 presents a summary of the assumed time periods between reactor shutdown and disposal for the naval reactors dumped in the Kara Sea. Summarized for each disposal site is the disposal date, the number of discarded naval reactors and their associated ship identification number, the minimum decay time, and the best estimate decay time. With the exception of the two naval reactors that were discarded in Stepovoy Inlet in 1981, the minimum decay times were based on the Yablokov Commission finding of a minimum period of one year between reactor shutdown and disposal. The two naval reactors discarded in

Stepovoy Inlet were earlier identified with the K-27, an assumed November class submarine that suffered a reactor accident on May 24, 1968. As such their minimum decay time was established at thirteen years.

The best estimate decay time for each submarine whose discarded naval reactors contained SNF was assumed to be the time period, in whole years, between their associated accident and disposal dates. For those submarines whose discarded naval reactors are without SNF, the best estimate decay time was arbitrarily established at one year. In the case of the *Lenin*, whose reactor accident was reported to have occurred either early or late in 1966, the best estimate decay time was established at two years.

Table 9 presents a summary of the estimated activity in the SNF at the time of disposal. Summarized for each of the selected actinides and fission products are the minimum and maximum in radioactivity associated with the five disposal sites. With respect to the selected actinides, the radionuclide and disposal site with the greatest activity are ^{241}Pu and Tsivolka Inlet, the location of the *Lenin* remnants, respectively. With respect to the selected fission products, the radionuclides with greatest activity are ^{147}Pm , ^{137}Cs , and ^{90}Sr , respectively. The disposal sites with greatest total activity are Abrosimov Inlet and Tsivolka Inlet, respectively. Overall, for the time of disposal, the inventories are estimated at 17 to 66 kCi of actinides plus daughters and 1,695 to 4,782 kCi of fission products. The later range in activity compares favorably with the Yablokov Commission finding of 2,300 kCi of fission products.

Table 10 presents a summary of the estimated radioactivity for selected activation products in reactor components and primary system corrosion products at the time of disposal. Summarized for each of the selected activation products are the minimum and maximum in radioactivity associated with the five disposal sites. With respect to the reactor components, the radionuclide and disposal site with greatest activity are ^{55}Fe and Abrosi-

Table 8. Assumed time periods between reactor shutdown and disposal for the former Soviet Union naval reactors dumped in the Kara Sea.

Disposal site	Disposal date	Naval reactors discarded	Minimum decay time (y)	Best estimate decay time (y)
Abrosimov Inlet	1965	2 (No. 285)	1.0	3.0
		2 (No. 901)	1.0	4.0
		2 (No. 254)	1.0	1.0
	1966	2 (No. 260)	1.0	1.0
Tsivolka Inlet	1967	3 (OK-150)	1.0	2.0
Novaya Zemlya Depression	1972	1 (No. 421)	1.0	4.0
Stepovoy Inlet	1981	2 (No. 601)	13.0	13.0
Techeniye Inlet	1988	2 (No. 538)	1.0	1.0

Table 9. Estimated radioactivity in the SNF at the time of disposal for the former Soviet Union naval reactors dumped in the Kara Sea.

Nuclide	Disposal site activity range (Ci)										All sites	
	Abrosimov Inlet		Tsivolka Inlet		Novaya Zemlya Depression		Stepovoy Inlet		Techeniye Inlet			
Actinides												
²³⁹⁺²⁴⁰ Pu	94	474	343	374	33	167	55	280	—	—	526	1,295
²⁴¹ Am	1	149	35	98	1	58	4	190	—	—	41	495
²³⁸ Pu	23	320	125	180	9	123	10	135	—	—	166	758
²⁴¹ Pu	449	22,000	15,500	26,900	168	8,210	140	6,250	—	—	16,257	63,360
Subtotal	567	22,943	16,003	27,552	210	8,558	209	6,855	—	—	16,990	65,908
All	573	23,100	16,100	27,800	212	8,640	212	6,860	—	—	17,097	66,400
Fission Products												
¹²⁹ I	0.02	0.03	0.01	0.01	0.009	0.009	0.01	0.02	—	—	0.06	0.06
⁹⁰ Sr	89,900	100,000	34,300	44,100	31,400	35,200	42,800	44,500	—	—	198,400	223,800
¹³⁴ Cs	3,930	36,000	11,500	18,200	1,320	13,400	90	328	—	—	16,840	67,928
¹³⁷ Cs	97,900	104,000	40,000	48,900	34,300	36,700	46,700	46,700	—	—	218,900	236,300
¹⁵⁴ Eu	1,450	1,810	707	943	532	678	347	347	—	—	3,036	3,778
¹²⁵ Sb	2,500	6,620	3,160	4,120	813	2,340	142	192	—	—	6,615	13,272
¹⁴⁷ Pm	125,000	253,000	69,100	115,000	40,100	88,700	5,350	6,320	—	—	239,550	463,020
¹⁵⁵ Eu	1,570	2,430	1,020	1,260	527	850	253	275	—	—	3,370	4,815
⁹⁹ Tc	15	15	6	7	5	5	9	9	—	—	34	36
¹⁵¹ Sm	852	1,690	332	464	287	584	513	950	—	—	1,984	3,688
Subtotal	323,117	505,565	160,125	232,994	109,284	178,457	96,203	99,621	—	—	688,729	1,016,637
All	663,000	2,300,000	632,000	1,480,000	213,000	811,000	187,000	191,000	—	—	1,695,000	4,782,000

Table 10. Estimated radioactivity of selected activation products in the reactor components and primary system corrosion products at the time of disposal for the former Soviet Union naval reactors dumped in the Kara Sea.

Nuclide	Disposal site activity range (Ci)											
	Abrosimov		Tsivolka		Novaya Zemlya		Stepovoy		Techeniye		All sites	
	Inlet		Inlet		Depression		Inlet		Inlet			
Reactor Components												
⁶⁰ Co	87,700	102,000	33,500	38,200	8,580	12,700	5,250	5,250	25,500	25,500	160,530	183,650
¹⁴ C	92	92	34	34	11	11	23	23	23	23	183	183
⁶³ Ni	41,300	41,600	15,500	15,600	5,110	5,220	9,600	9,600	10,400	10,400	81,910	82,420
⁵⁵ Fe	374,500	488,000	142,000	183,000	28,500	61,100	5,810	5,810	122,000	122,000	672,810	859,910
⁵⁹ Ni	374	374	140	140	47	47	94	94	94	94	749	749
All	503,966	632,066	191,174	236,974	42,248	79,078	20,777	20,777	158,017	158,017	916,182	1,126,912
Primary System Corrosion Products												
⁶⁰ Co	748	868	286	326	73	109	45	45	217	217	1,369	1,565
¹⁴ C	0.0001	0.0001	0.00005	0.00005	0.00002	0.00002	0.00003	0.00003	0.00003	0.00003	0.0003	0.0003
⁶³ Ni	2	2	1	1	0.3	0.3	0.5	0.5	1	1	4	4
⁵⁵ Fe	12	15	5	6	1	2	0	0	4	4	21	27
⁵⁹ Ni	0.01	0.01	0.004	0.004	0.001	0.001	0.003	0.003	0.003	0.003	0.02	0.02
All	762	886	291	333	74	111	45	45	221	221	1,394	1,596

mov Inlet, respectively. Since the radioactivity in the reactor components and primary system corrosion products at a given disposal site is simply a function of the number of reactors discarded, Abrosimov Inlet is the expected site of greatest activity. Overall, for the time of disposal, the inventories are estimated at 917 to 1,127 kCi of activation products in the reactor components and 1.4 to 1.6 kCi of activation products in the primary system corrosion products. Of the 917 to 1,127 kCi of activation products in the reactor components, 161 to

184 kCi are associated with the ⁶⁰Co inventory in the 16 discarded naval reactors. On a per-reactor basis, the estimated ⁶⁰Co inventory in the reactor components is in excellent agreement with the Yablokov Commission finding of 100 kCi in the reactor components of ten naval reactors.

Table 11 presents a summary of the estimated radioactivity in the SNF at the present time (1993). Summarized for each of the selected actinides and fission products are the minimum and maximum in radioactiv-

Table 11. Estimated radioactivity in the SNF at the present time (1993) for the former Soviet Union naval reactors dumped in the Kara Sea.

Nuclide	Disposal site activity range (Ci)											
	Abrosimov Inlet		Tsivolka Inlet		Novaya Zemlya Depression		Stepovoy Inlet		Techeniye Inlet			
<i>Actinides</i>												
²³⁹⁺²⁴⁰ Pu	94	474	343	374	33	167	55	280	—	—	526	1,295
²⁴¹ Am	14	605	412	688	5	204	6	277	—	—	436	1,774
²³⁸ Pu	18	258	102	148	7	105	9	123	—	—	136	634
²⁴¹ Pu	117	5,710	4,450	7,690	61	2,990	79	3,510	—	—	4,707	19,900
Subtotal	243	7,047	5,307	8,900	106	3,466	149	4,190	—	—	5,805	23,603
All	247	7,050	5,310	8,900	108	3,450	152	4,190	—	—	5,817	23,590
<i>Fission Products</i>												
¹²⁹ I	0.02	0.03	0.01	0.01	0.009	0.009	0.01	0.02	—	—	0.06	0.06
⁹⁰ Sr	46,200	51,400	18,500	23,700	19,000	21,400	32,100	33,400	—	—	115,800	129,900
¹³⁴ Cs	0.3	3	2	3	1	12	2	6	—	—	5	23
¹³⁷ Cs	51,300	54,600	21,900	26,800	21,100	22,600	35,400	35,400	—	—	129,700	139,400
¹⁵⁴ Eu	152	190	87	116	98	125	132	132	—	—	469	563
¹²⁵ Sb	2	6	5	6	4	12	7	9	—	—	18	33
¹⁴⁷ Pm	63	155	72	119	128	345	225	365	—	—	488	984
¹⁵⁵ Eu	31	49	27	33	28	45	47	51	—	—	133	178
⁹⁹ Tc	15	15	6	7	5	5	9	9	—	—	34	36
¹⁵¹ Sm	686	1,360	271	380	244	496	468	866	—	—	1,669	3,102
Subtotal	98,449	107,777	40,869	51,164	40,608	45,040	68,389	70,238	—	—	248,316	274,220
All	195,000	213,000	80,900	101,000	80,500	86,700	136,000	139,000	—	—	492,400	539,700

ity associated with the five disposal sites. With respect to the selected actinides, the radionuclide and disposal site with the greatest activity remain ²⁴¹Pu and Tsivolka Inlet, respectively. With respect to the selected fission products, the radionuclides with greatest activity are now ¹³⁷Cs and ⁹⁰Sr, respectively. The disposal sites with greatest total activity are now Abrosimov Inlet and Stepovoy Inlet, respectively. Overall, for the present time (1993), the inventories are estimated at 6 to 24 kCi of actinides plus daughters and 492 to 540 kCi of fission products.

Table 12 presents a summary of the estimated radioactivity for selected activation products in reactor components and primary system corrosion products at the present time (1993). Summarized for each of the selected activation products are the minimum and maximum in radioactivity associated with the five disposal sites. With respect to the reactor components, the radionuclides with greatest activity are ⁶³Ni at Abrosimov Inlet and ⁵⁵Fe at Techeniye Inlet, while the disposal site of greatest activity is now Techeniye Inlet. With respect to the primary system corrosion products, the radionuclide and disposal site with greatest activity are ⁶⁰Co and Techeniye Inlet, respectively. That Abrosimov Inlet is no longer the site of greatest activity is not surprising. While the radioactivity in the reactor components and primary system corrosion products at a given disposal site remains a simple function of the number of reactors discarded, when

radioactive decay of the activation products is considered, Techeniye Inlet becomes the expected site of greatest activity. Overall, for the present time (1993), the inventories are estimated at 125 to 126 kCi of activation products in the reactor components and 0.16 to 0.17 kCi of activation products in the primary system corrosion products.

Table 13 presents a summary of the estimated radioactivity in the SNF at 20 years hence (2013). Summarized for each of the selected actinides and fission products are the minimum and maximum in radioactivity associated with the five disposal sites. With respect to the selected actinides, the radionuclide and disposal site with the greatest activity remain ²⁴¹Pu and Tsivolka Inlet, respectively. With respect to the selected fission products, the radionuclides with greatest activity remain ¹³⁷Cs and ⁹⁰Sr, respectively. The disposal sites with greatest total activity remain Abrosimov Inlet and Stepovoy Inlet, respectively. Overall, for twenty years hence (2013), the inventories are estimated at 3 to 12 kCi of actinides plus daughters and 303 to 333 kCi of fission products.

Table 14 presents a summary of the estimated radioactivity for selected activation products in reactor components and primary system corrosion products at twenty years hence (2013). Summarized for each of the selected activation products are the minimum and maximum in radioactivity associated with the five disposal

Table 12. Estimated radioactivity of selected activation products in the reactor components and primary system corrosion products at the present time (1993) for the former Soviet Union naval reactors dumped in the Kara Sea.

	Disposal site activity range (Ci)											
	Abrosimov		Tsivolka		Novaya Zemlya		Stepovoy		Techeniye			
Nuclide	Inlet		Inlet		Depression		Inlet		Inlet		All sites	
Reactor Components												
⁶⁰ Co	2,297	2,654	1,100	1,250	542	804	1,080	1,080	13,200	13,200	18,219	18,988
¹⁴ C	91	91	34	34	11	11	23	23	23	23	182	182
⁶³ Ni	34,140	34,420	13,000	13,100	4,420	4,510	8,480	8,480	10,100	10,100	70,140	70,610
⁵⁵ Fe	336	429	193	249	138	296	276	276	34,300	34,300	35,243	35,550
⁵⁹ Ni	374	374	140	140	47	47	94	94	94	94	749	749
All	37,238	37,968	14,467	14,773	5,158	5,668	9,953	9,953	57,717	57,717	124,533	126,079
Primary System Corrosion Products												
⁶⁰ Co	20	23	9	11	5	7	9	9	113	113	156	162
¹⁴ C	0.0001	0.0001	0.00005	0.00005	0.00002	0.00002	0.00003	0.00003	0.00003	0.00003	0.0002	0.0002
⁶³ Ni	1.7	1.7	0.6	0.7	0.2	0.2	0.4	0.4	0.5	0.5	3.5	3.5
⁵⁵ Fe	0.01	0.01	0.006	0.008	0.004	0.009	0.009	0.009	1.1	1.1	1.1	1.1
⁵⁹ Ni	0.01	0.01	0.004	0.004	0.001	0.001	0.003	0.003	0.003	0.003	0.02	0.02
All	21	24	10	11	5	7	10	10	115	115	161	167

Table 13. Estimated radioactivity in the SNF at twenty years hence (2013) for the former Soviet Union naval reactors dumped in the Kara Sea.

Nuclide	Disposal site activity range (Ci)											
	Abrosimov		Tsivolka		Novaya Zemlya		Stepovoy		Techeniye		All sites	
	Inlet		Inlet		Depression		Inlet		Inlet			
Actinides												
239+240Pu	94	474	343	374	33	167	55	280	—	—	525	1,294
241Am	16	701	489	822	6	258	8	339	—	—	518	2,120
238Pu	15	220	87	126	6	90	8	105	—	—	116	541
241Pu	45	2,181	1,700	2,937	23	1,142	30	1,341	—	—	1,798	7,601
Subtotal	170	3,576	2,618	4,259	68	1,656	101	2,065	—	—	2,957	11,556
All	170	3,576	2,618	4,259	68	1,656	101	2,065	—	—	2,957	11,556
Fission Products												
129I	0.02	0.03	0.01	0.01	0.009	0.009	0.01	0.02	—	—	0.06	0.06
90Sr	28,408	31,605	11,375	14,573	11,683	13,159	19,738	20,537	—	—	71,204	79,874
134Cs	0.0004	0.004	0.002	0.003	0.001	0.01	0.002	0.007	—	—	0.01	0.03
137Cs	32,320	34,399	13,797	16,885	13,293	14,239	22,303	22,303	—	—	81,714	87,825
154Eu	31	39	18	24	20	26	27	27	—	—	97	117
125Sb	0.01	0.04	0.03	0.04	0.03	0.08	0.04	0.06	—	—	0.1	0.2
147Pm	0.3	0.8	0.4	0.6	0.6	1.7	1.1	1.8	—	—	2.5	5.0
155Eu	2	3	2	2	2	3	3	3	—	—	8	11
99Tc	15	15	6	7	5	5	9	9	—	—	34	36
151Sm	588	1,166	232	326	209	425	401	742	—	—	1,431	2,659
Subtotal	61,364	67,229	25,431	31,817	25,213	27,858	42,482	43,624	—	—	154,491	170,527
All	120,344	131,372	49,857	62,361	49,471	54,485	83,316	85,257	—	—	302,988	333,475

sites. With respect to the reactor components, the radionuclide with the greatest activity remains ⁶³Ni, while the disposal site of greatest activity is once again Abrosimov Inlet. With respect to the primary system corrosion products, the radionuclide and disposal site with greatest activity remain ⁶⁰Co and Techeniye Inlet, respectively. That Abrosimov Inlet and Techeniye Inlet are now the sites of greatest activity for the reactor components and primary system corrosion products,

respectively, is not surprising. While the radioactivity in the reactor components and primary system corrosion products at a given disposal site remains a simple function of the number of reactors discarded, when radioactive decay of the activation products is considered, both Abrosimov Inlet and Techeniye Inlet become the expected sites of greatest activity. Overall, for twenty years hence (2013), the inventories are estimated at 63.5 to 64 kCi of activation products in the reactor components and

Table 14. Estimated radioactivity of selected activation products in the reactor components and primary system corrosion products at 20 years hence (2013) for the former Soviet Union naval reactors dumped in the Kara Sea.

Nuclide	Disposal site activity range (Ci)											
	Abrosimov Inlet		Tsivolka Inlet		Novaya Zemlya Depression		Stepovoy Inlet		Techaeniye Inlet		All sites	
Reactor Components												
⁶⁰ Co	166	191	79	90	39	58	78	78	951	951	1,313	1,369
¹⁴ C	91	91	34	34	11	11	23	23	23	23	182	182
⁶³ Ni	29,726	29,969	11,319	11,406	3,848	3,927	7,384	7,384	8,794	8,794	61,071	61,480
⁵⁵ Fe	2	3	1	2	1	2	2	2	214	214	220	222
⁵⁹ Ni	374	374	140	140	47	47	94	94	94	94	749	749
All	30,358	30,628	11,573	11,672	3,946	4,045	7,580	7,580	10,076	10,076	63,534	64,001
Primary System Corrosion Products												
⁶⁰ Co	1.4	1.6	0.7	0.8	0.3	0.5	0.7	0.7	8.1	8.1	11.2	11.7
¹⁴ C	0.0001	0.0001	0.00005	0.00005	0.00002	0.00002	0.00003	0.00003	0.00003	0.00003	0.0002	0.0002
⁶³ Ni	1.5	1.5	0.6	0.6	0.2	0.2	0.4	0.4	0.4	0.4	3.1	3.1
⁵⁵ Fe	0.00007	0.00008	0.00004	0.00005	0.00003	0.00006	0.00005	0.00005	0.007	0.007	0.007	0.007
⁵⁹ Ni	0.01	0.01	0.004	0.004	0.001	0.001	0.003	0.003	0.003	0.003	0.02	0.02
All	2.9	3.1	1.2	1.3	0.5	0.7	1.1	1.1	8.6	8.6	14.3	14.8

0.014 to 0.015 kCi of activation products in the primary system corrosion products.

The figures that follow depict the inventories of selected radionuclides as a function of time. The time period of interest is that from the date of first disposal to the present time (1993). In preparing these graphical presentations of the time-dependent radionuclide inventory estimates, the following convention was adopted.

Reactor cores:

- = Submarine reactors at 10% ²³⁵U and Lenin reactor at 4.6% ²³⁵U - minimum decay time
- = Submarine reactors at 36% ²³⁵U and Lenin reactor at 6.4% ²³⁵U - minimum decay time
- = Submarine reactors at 10% ²³⁵U and Lenin reactor at 4.6% ²³⁵U - best estimate decay time
- = Submarine reactors at 36% ²³⁵U and Lenin reactor at 6.4% ²³⁵U - best estimate decay time
- ◇ = Submarine reactors at 10% ²³⁵U and Lenin reactor at 6.4% ²³⁵U - minimum decay time
- ◆ = Submarine reactors at 36% ²³⁵U and Lenin reactor at 4.6% ²³⁵U - minimum decay time
- × = Submarine reactors at 10% ²³⁵U and Lenin reactor at 6.4% ²³⁵U - best estimate decay time

Reactor components:

- ▼ = Minimum decay time
- ▽ = Best estimate decay time

Figures 1–4 depict the results of the activity estimates for selected actinides in the discarded naval reactors containing SNF. Figures 5–14 depict the results of the activity estimates for selected fission products in the discarded naval reactors containing SNF. Activity estimates for selected activation products in the reactor components are depicted in Figures 15–19. Total activity estimates for the actinides, fission products, and

activation products in the reactor components are depicted in Figures 20–22, respectively.

Conclusions

Considering the uncertainties associated with certain of the analytical model parameters and in the times between reactor shutdown and disposal, the estimates presented herein agree quite favorably with the Yablokov findings for the time of disposal.

At the present time (1993), even if one assumes that the actinides are underestimated by a factor of two, the inventories of actinides and fission products in the SNF and the inventories of activation products in reactor components and primary system corrosion products are estimated to be no greater than 47 kCi, 540 kCi, 126 kCi, and 0.17 kCi, respectively. Total inventory is estimated at less than 713 kCi.

At twenty years hence (2013), even if one continues to assume that the actinides are underestimated by a factor of two, the inventories of actinides and fission products in the SNF and the inventories of and activation products in reactor components and primary system corrosion products are estimated to be no greater than 23 kCi, 333 kCi, 64 kCi and 0.015 kCi, respectively. Total inventory is estimated at less than 420 kCi.

Based upon the estimated inventory of radionuclides, Abrosimov Inlet and Stepovoy Inlet remain the disposal sites with the greatest total activity, respectively.

Recommendations

Improvements may be made in the calculation of the estimated inventory of radionuclides. To achieve the improvements desired, the following steps are recom-

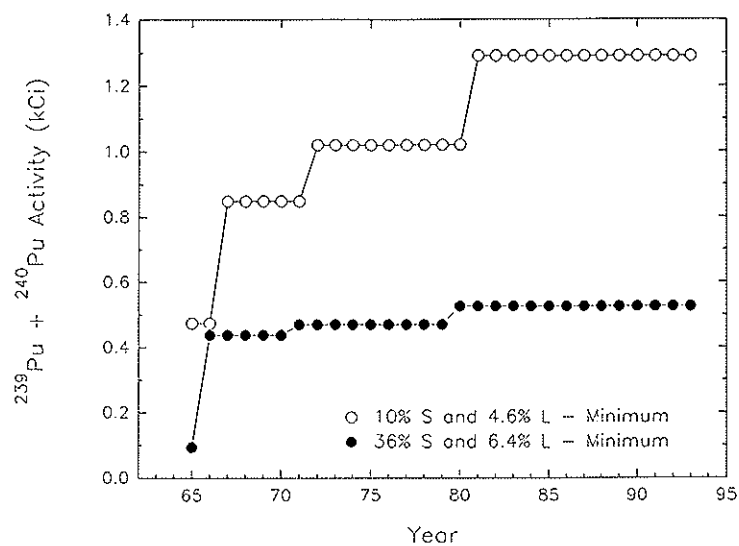


Figure 1. $^{239}+^{240}\text{Pu}$ inventory in naval reactor cores dumped in the Kara Sea.

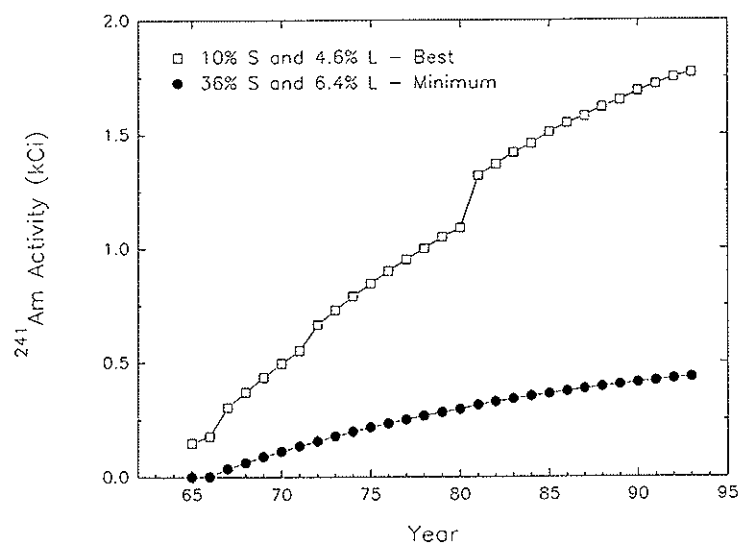


Figure 2. ^{241}Am inventory in naval reactor cores dumped in the Kara Sea.

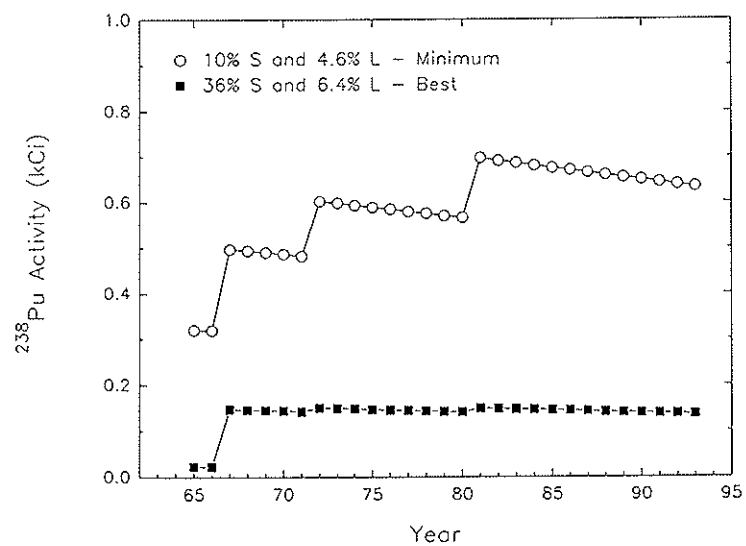


Figure 3. ^{238}Pu inventory in naval reactor cores dumped in the Kara Sea.

Figure 4. ^{241}Pu inventory in naval reactor cores dumped in the Kara Sea.

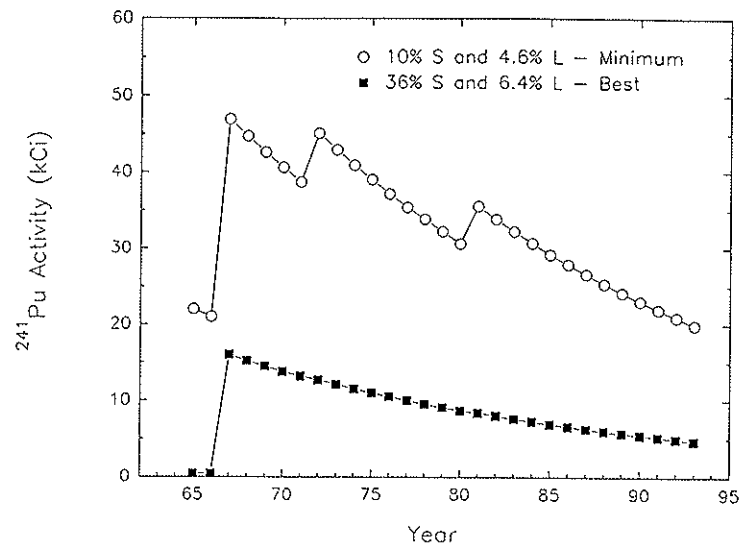


Figure 5. ^{129}I inventory in naval reactor cores dumped in the Kara Sea.

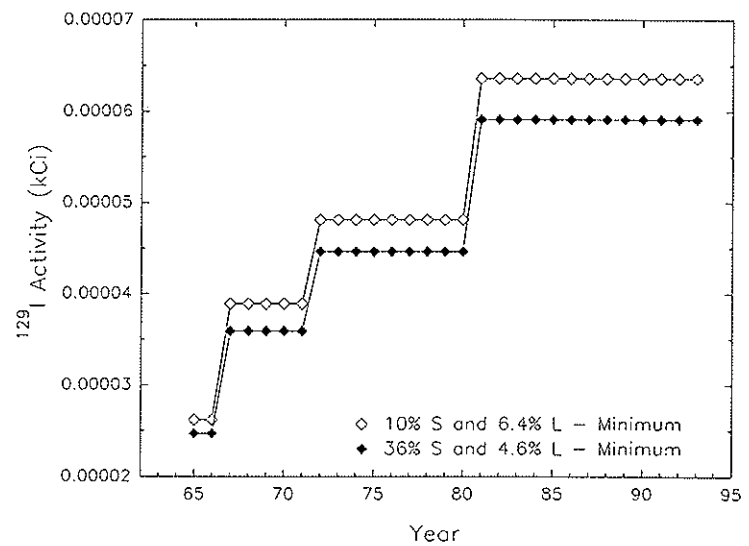
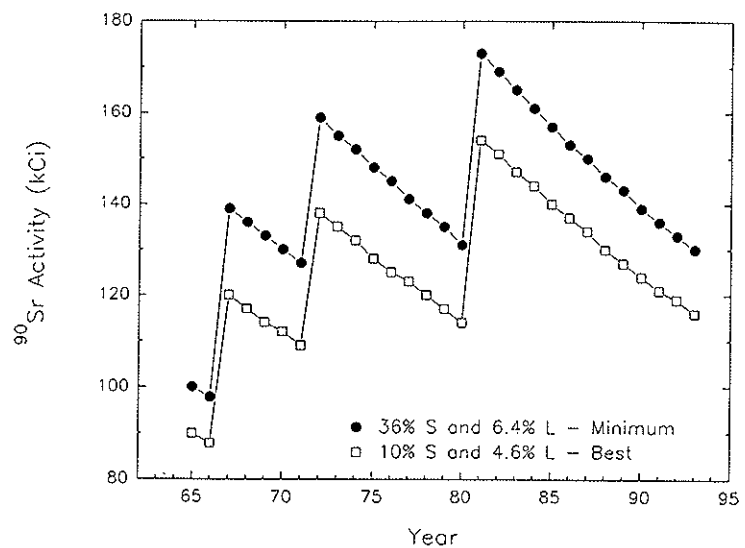


Figure 6. ^{90}Sr inventory in naval reactor cores dumped in the Kara Sea.



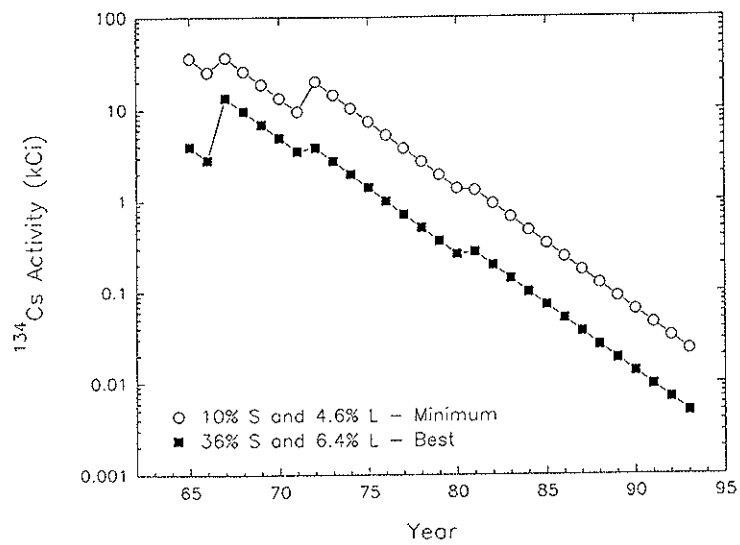


Figure 7. ^{134}Cs inventory in naval reactor cores dumped in the Kara Sea.

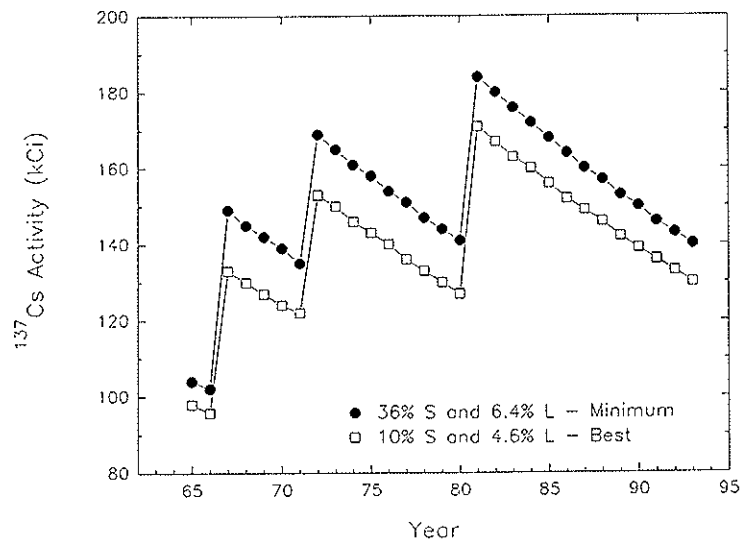


Figure 8. ^{137}Cs inventory in naval reactor cores dumped in the Kara Sea.

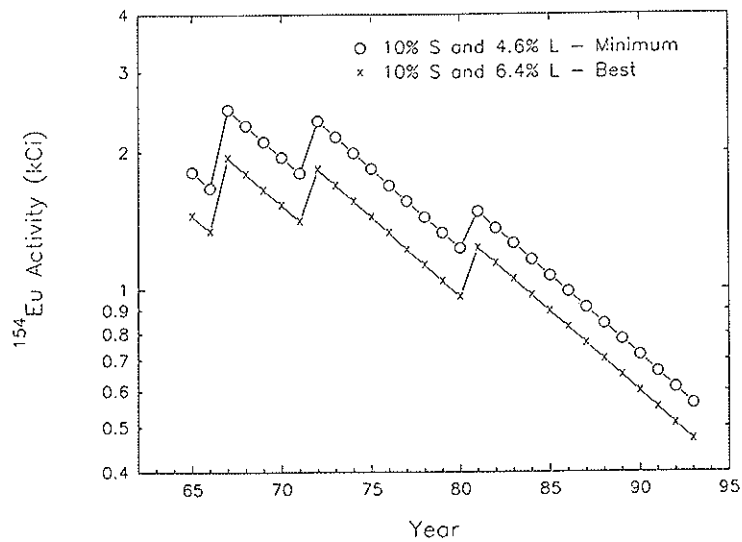


Figure 9. ^{154}Eu inventory in naval reactor cores dumped in the Kara Sea.

Figure 10. ^{125}Sb inventory in naval reactor cores dumped in the Kara Sea.

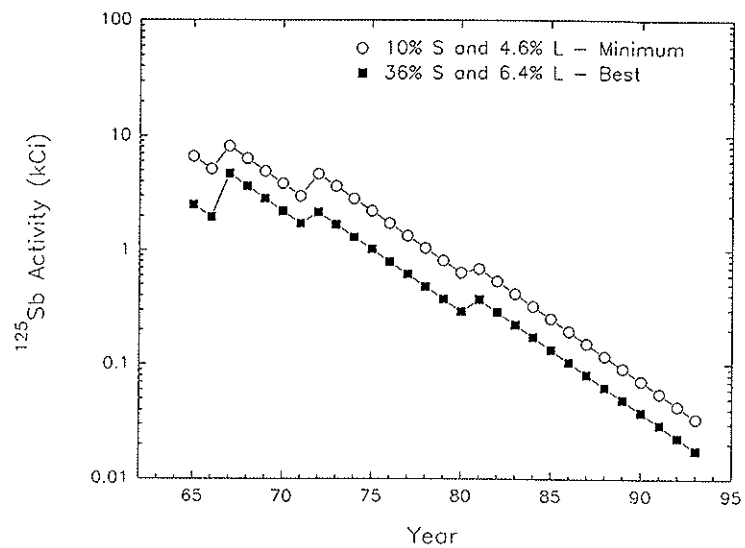


Figure 11. ^{147}Pm inventory in naval reactor cores dumped in the Kara Sea.

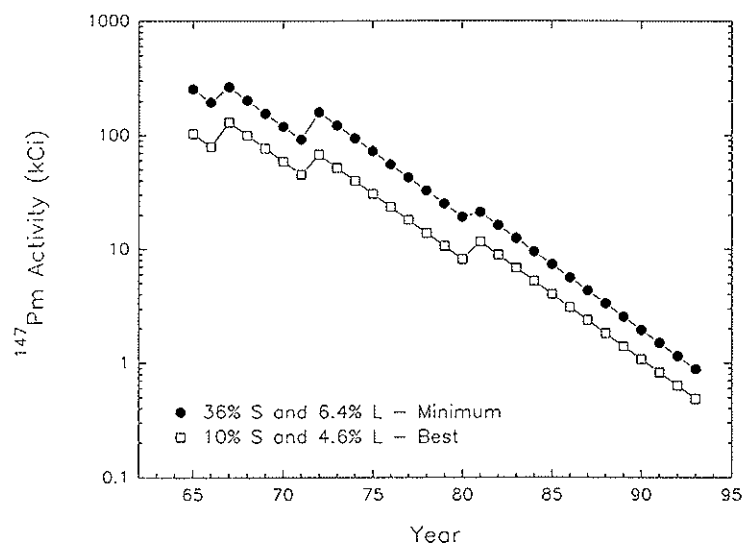
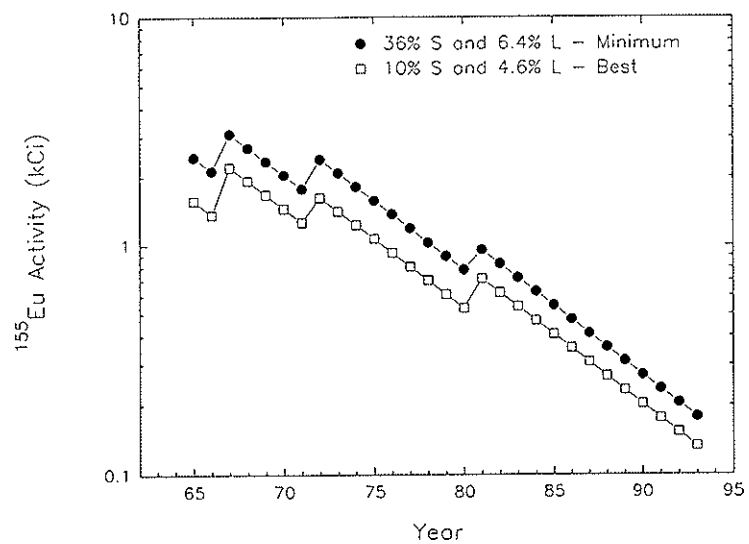


Figure 12. ^{155}Eu inventory in naval reactor cores dumped in the Kara Sea.



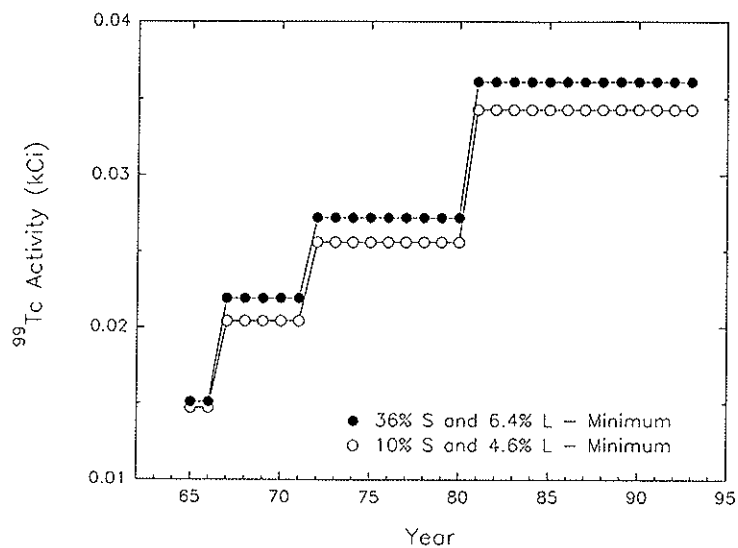


Figure 13. ^{99}Tc inventory in naval reactor cores dumped in the Kara Sea.

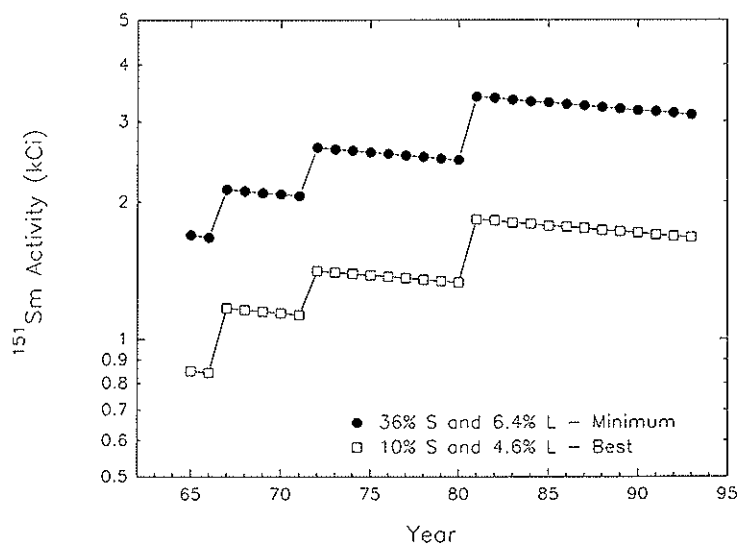


Figure 14. ^{151}Sm inventory in naval reactor cores dumped in the Kara Sea.

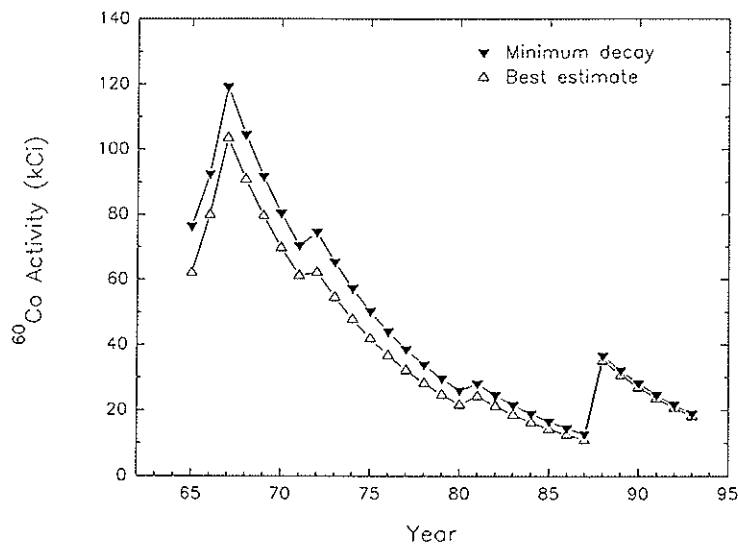


Figure 15. ^{60}Co activation in reactor components of naval reactors dumped in the Kara Sea.

Figure 16. ^{14}C activation in reactor components of naval reactors dumped in the Kara Sea.

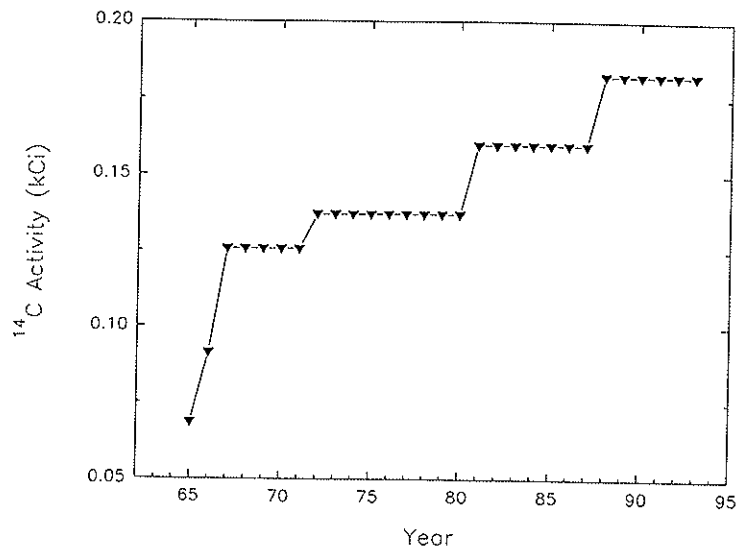


Figure 17. ^{63}Ni activation in reactor components of naval reactors dumped in the Kara Sea.

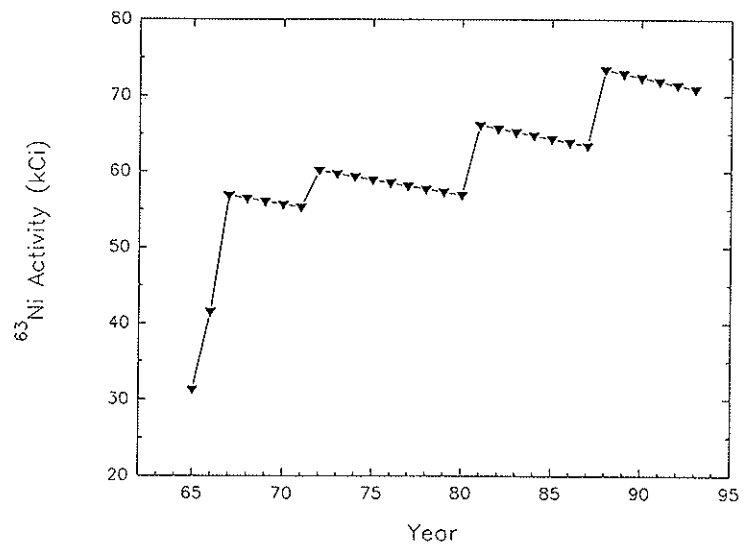
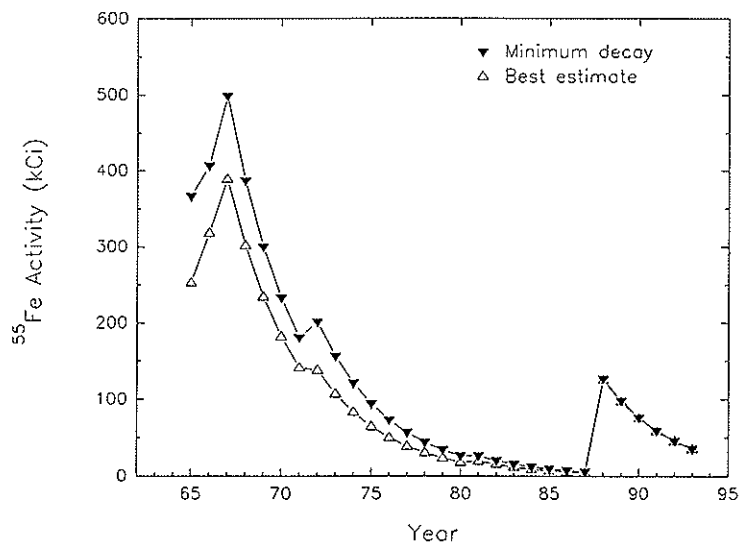


Figure 18. ^{55}Fe activation in reactor components of naval reactors dumped in the Kara Sea.



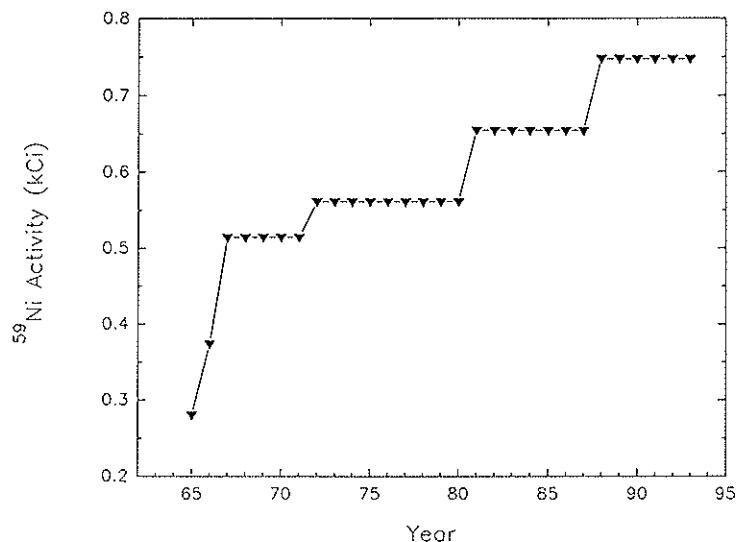


Figure 19. ^{59}Ni activation in reactor components of naval reactors dumped in the Kara Sea.

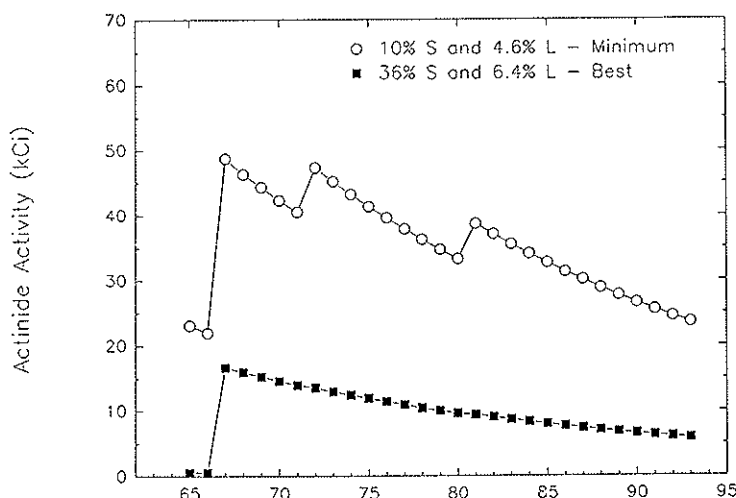


Figure 20. Total actinide inventory in naval reactor cores dumped in the Kara Sea.

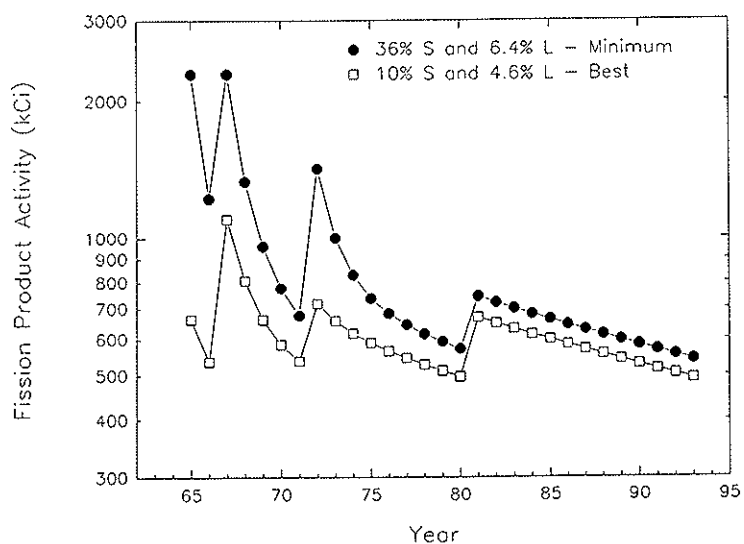


Figure 21. Total fission product inventory of naval reactors dumped in the Kara Sea.

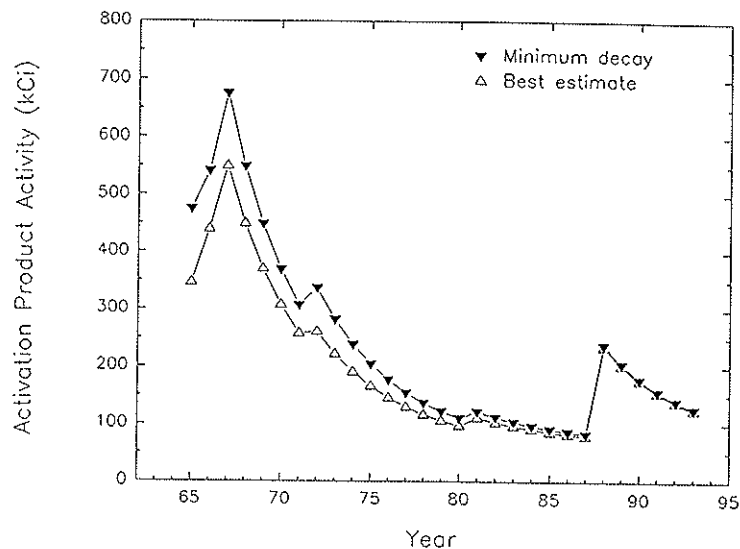


Figure 22. Total activation product inventory of reactor components dumped in the Kara Sea.

mended: (1) obtain definitive information on the time period between the shutdown date of each reactor and the date of its disposal, (2) validate the core histories of all discarded naval reactors containing SNF, (3) obtain definitive information on the materials of construction and geometry of a typical fuel assembly, and (4) obtain definitive information on the neutron energy spectrum in the reactors involved.

Acknowledgments

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Analysis and Evaluation of a Radioactive Waste Package Retrieved from the Farallon Islands Ocean Disposal Sites

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In 1946, disposal of low-level radioactive wastes was started in the vicinity of the Farallon Islands, off the coast of San Francisco, California, under the authority of the former U.S. Atomic Energy Commission (AEC). The majority of the waste was dumped at sea between 1946 and 1962. AEC licensees phased out sea disposal between 1962 and 1970 when a land disposal site became available at Beatty, Nevada. It was estimated that in excess of 75,000 drums and other containers, with an estimated inventory of 90,000 curies at the time of packaging, were disposed of at sea from 1946 to 1970. The predominant form of packaging was 55-gallon drums weighted with concrete. It was stated in the 1959 AEC annual report to the U.S. Congress that it was not required that the wastes remain within the drums after they reached the sea floor. After the initiation of sea disposal, and as the radionuclide inventories increased, changes in dumping procedures were made, primarily to reduce hazards in the handling of the waste packages prior to disposal.

In 1972, the U.S. Congress passed the Marine Protection, Research, and Sanctuaries Act, commonly referred to as the Ocean Dumping Act. The U.S. Environmental Protection Agency (EPA) was designated to administer this Act and to develop permit review procedures for the disposal of all wastes, including low-level radioactive wastes (LLW). High-level radioactive and radiological warfare agents were prohibited from disposal. To develop the technical basis for any future permit requirements for LLW disposal, the EPA sought to learn from past disposal activities.

Therefore, in 1974 EPA initiated a study of the radioactive waste packages (container + waste + solidification agent) that had been deposited in the Pacific Ocean

near the Farallon Islands. Between 1974 and 1985, EPA conducted four ocean surveys at the Farallon Islands to determine the number and disposition of containers dumped at the site, determine the physical, biological and radiochemical characteristics of the site, determine the direction and speed of deep-sea currents, collect sediment cores and grab samples around the containers for radionuclide analysis and radionuclide distributions, and recover a radioactive waste package to evaluate the integrity of the solidification agent and metal container (18 gauge mild steel) after a fixed immersion time.

Archival records related to the packaging and disposal of radioactive waste materials documented the use of three dumpsites in the Farallon Islands (Figure 1). Table 1 presents a summary of disposal site locations, usage, and inventories of materials dumped. Site 1, at a depth of approximately 90 meters, apparently was used only once, accidentally, and received about 150 containers. Site 2, centered at a depth of 900 meters, received approximately 3500 containers. Site 3, at a depth of 1700 meters, received the majority of the waste packages, about 44,000 containers containing approximately 13,400 curies at the time of disposal. Much of this radioactivity has radiodecayed.

The results of the first three EPA ocean surveys near the Farallon Islands were presented at four Congressional hearings from 1975 to 1980 (1,2,3,4). EPA also issued reports specifying the results of the waste package analysis as well as the specific recovery techniques and equipment used during recovery (5,6). In addition, reports were issued that described geotechnical and geochemical properties of the sediment, as well as demersal fishes in the dumpsite area (7,8).



Figure 1. Map of three dumpsites in the Farallon Islands.

Table 1. Pacific Farallon Islands radioactive waste ocean disposal sites.

Coordinates	Depth (m)	Distance from land (km)	Years disposal site used	Estimated no. of disposed 55-gal. drums	Estimated activity in drums at time of disposal (Ci)
37°38'N 122°58'W	90	40	1946	150	300
37°38'N 123°08'W	900	60	1951–1953	3,500	1,100
37°37'N 123°17'W	1700	77	1946–1950 1954–1965	44,000	13,400

Survey 1—1974

The first survey was conducted in 1974 at Site 2, the 900-m dumpsite. The purpose of this survey was to locate 55-gallon radioactive waste drums at the site and take sediment cores around these drums for analysis and detection of any radioactivity releases. This operation utilized an unmanned robotic vehicle, the U.S. Navy's Cable-controlled Underwater Recovery Vehicle, *CURV III*. The *CURV III*, a Remotely Operated Vehicle (ROV), was the ideal vehicle for the initial survey. Operating from the U.S. Navy salvage vessel, M/V *GEAR*, the *CURV III* took sediment samples and provided real-time television coverage allowing the operators on the surface to carefully examine and photograph waste containers of interest as well as the marine biota in the area (9). Subsequent measurements of oxygen concentrations in the bottom water indicated that this site was in an oxygen minimum zone with reduced biological epifauna and infauna compared with the deeper 1700-m site. Of particular importance was the use of the cruciform sampling device developed by the Naval Ocean Systems Center. This device, operated by the ROV manipulator and coupled with the vehicle's television system and precise propulsion control, permitted obtaining sediment samples at known distances from drums with minimum disturbance to the critical surface sediment layers.

Extensive benthic photography was taken on the mission. Figure 2 and Figure 3 show radioactive waste drums at the dumpsite. The first photo (Figure 2) shows minor implosion, while Figure 3 shows a drum with relatively severe implosion due to compression of air voids in the waste.

The results of this survey indicated plutonium-239, 240 contamination around the radioactive waste drums at concentrations ranging from 2–25 times higher than the maximum expected weapons testing fallout concentrations for this latitude and depth of water.

Survey 2—1975

Returning to the area in 1975, EPA repeated the operation at Site 3, the 1700-m dumpsite, operating from a vessel specially designed to support the *CURV III*, the U.S. Navy's YFNX-30. Results from this survey revealed only moderately elevated levels of plutonium-239, 240 radioactivity in sediments around the radioactive waste drums at this site, ranging from approximately two to four times higher than the maximum expected fallout concentrations for this latitude and depth (10).

Figure 4, taken at the 1700-m dumpsite, shows no hydrostatic pressure effects and is color coded, most probably indicating some slightly higher activity.

Figure 5, also taken at 1700 m, shows severe implosion due to hydrostatic pressure acting on air voids in the



Figure 2. Radioactive waste drum at the dumpsite. Photo shows minor implosion in drum.

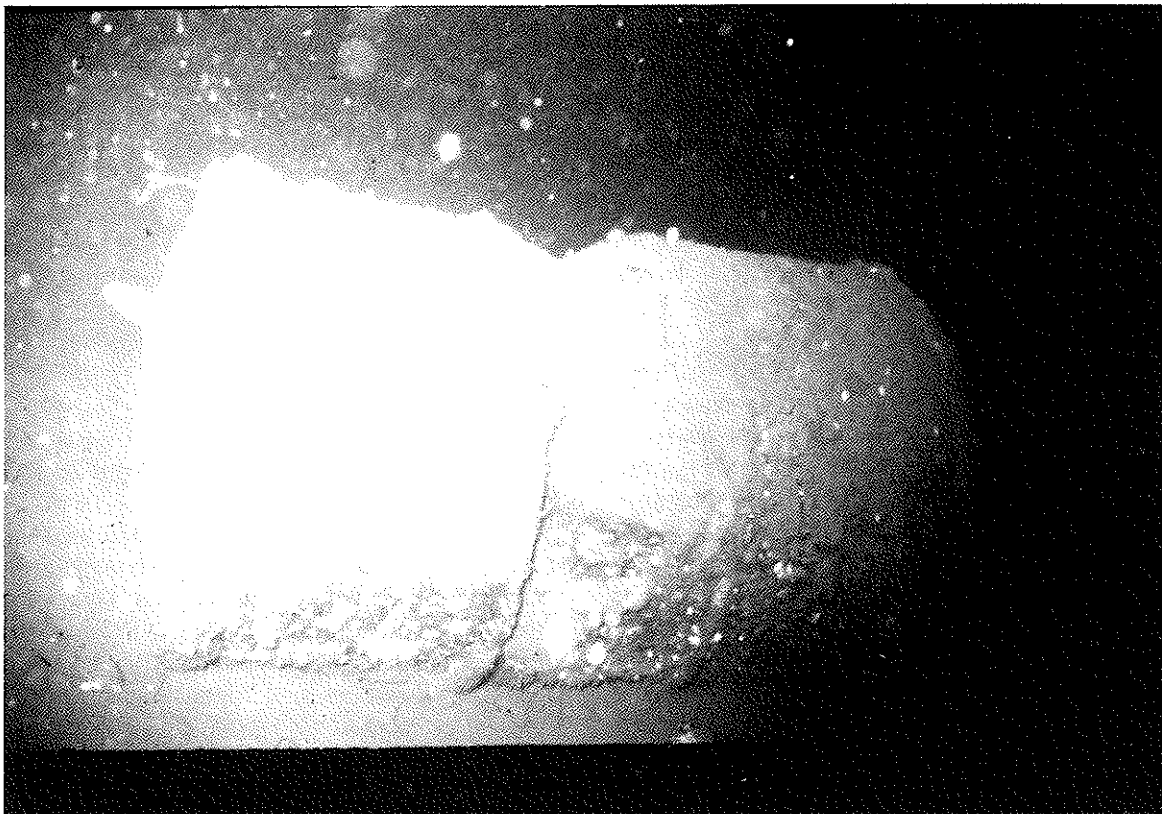


Figure 3. Photo shows a drum with relatively severe implosion due to compression of air voids in the waste.

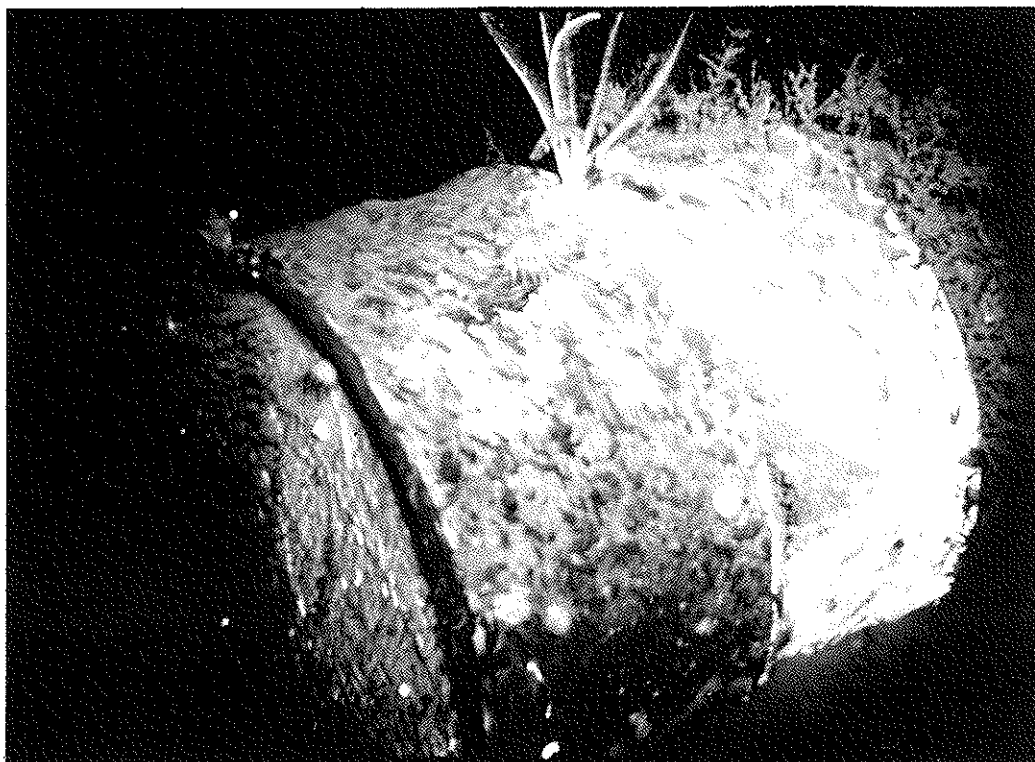


Figure 4. Photo taken at the 1700-m dumpsite shows no hydrostatic pressure effects and is color coded, most probably indicating some slightly higher activity.

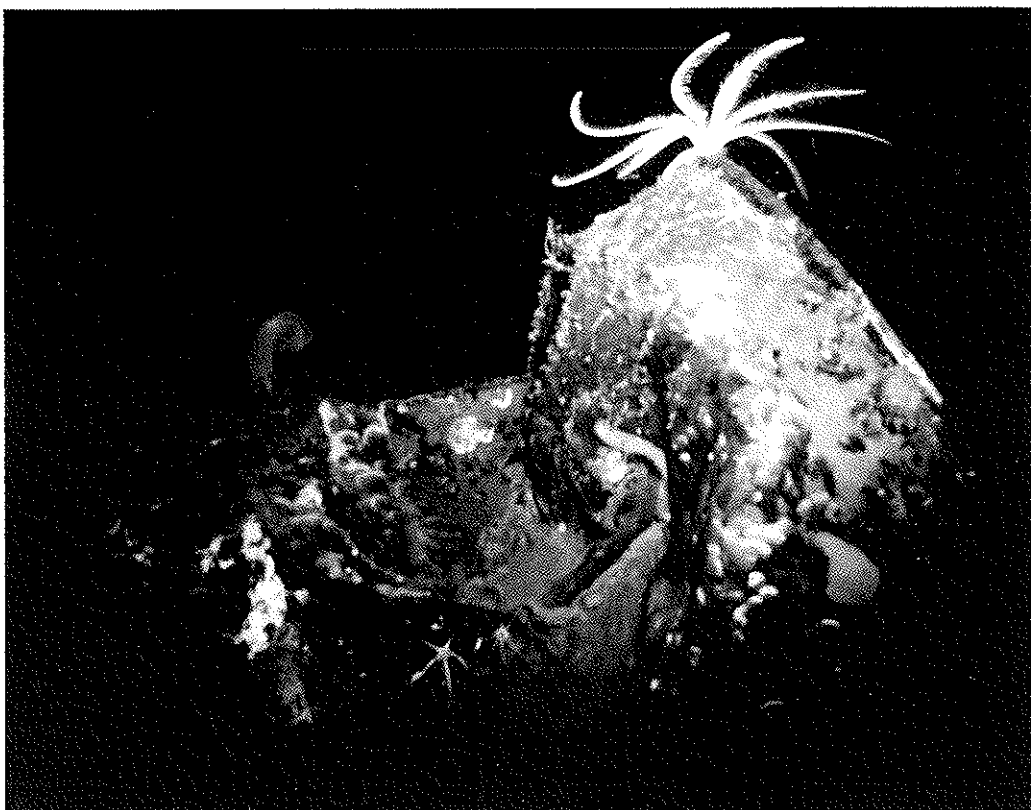


Figure 5. Photo also taken at 1700 m shows severe implosion due to hydrostatic pressure acting on air voids in the drum.

drum. Such problems could be resolved by using a homogeneous solid matrix or, in some cases, pressure equalization devices. The imploded drum reveals the typical method of packaging used for radioactive waste disposal at this site. A concrete cap, roughly 20-30 centimeters thick, was poured into one end of a 55-gallon drum; the waste material was then added (often uncompacted and containing air voids) and another concrete cap was poured over the waste. The "sandwich" structure is made visible in this photograph by the deformation of the central portion of the drum.

Survey 3—1977

EPA returned to the vicinity of the Farallon Islands in 1977 with a combined U.S./Canadian team that deployed the *PISCES VI* manned submersible (Figure 6) and two support vessels, the *PANDORA II* and the *R/V VELERO IV*, to collect additional biological, sediment, and water samples from both the 900-m and 1700-m dumpsites as the first phase of this two-phase survey.

By performing a more thorough examination and characterization of the sites, EPA sought to qualitatively identify any obviously anomalous biological distribution patterns. But no evidence of depauperate faunal invertebrate groups was found in the vicinity of the Farallon Islands. There were also no obvious differences

in abundance, diversity, or speciation of upper depth midwater fishes at the Farallon Islands compared with regions to the north or south.

A significant subject of study is the epifaunal (on the sediment surface) and infaunal (in the sediment) populations found in the dumpsite areas. Figure 7 shows a small area of the 1700-m site where there is considerable epifaunal and infaunal activity with a high density of brittle stars and worm tube castings. This also indicates a potential for bioturbation, in this case a greater probability for mobilization of any released radioactivity either downward into the sediment where it is less available for transfer to man, or upward to the sediment surface for possible transfer through food chains or into the water column. This is in contrast to lower epifaunal and infaunal populations in the 900-m site, an oxygen minimum zone.

Sediment geochemical studies performed to date suggest that:

- Bioturbation may be the most important redistribution mechanism for radionuclides released into the Farallon Islands dumpsites.
- The cation exchange capacity or capability for adsorption of released radioactivity is relatively high in the Farallon Islands sites.
- The high adsorptive capacity of the sediment cou-

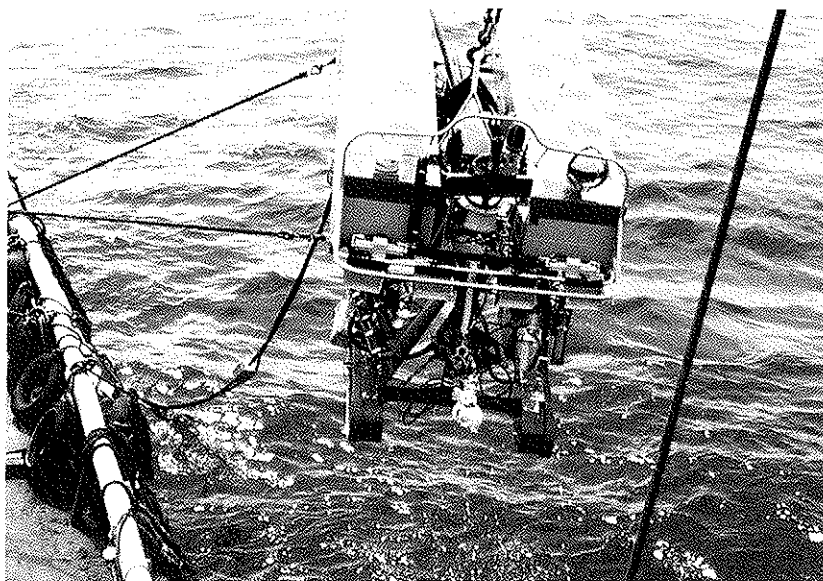


Figure 6. Photo of the PISCES VI manned submersible.

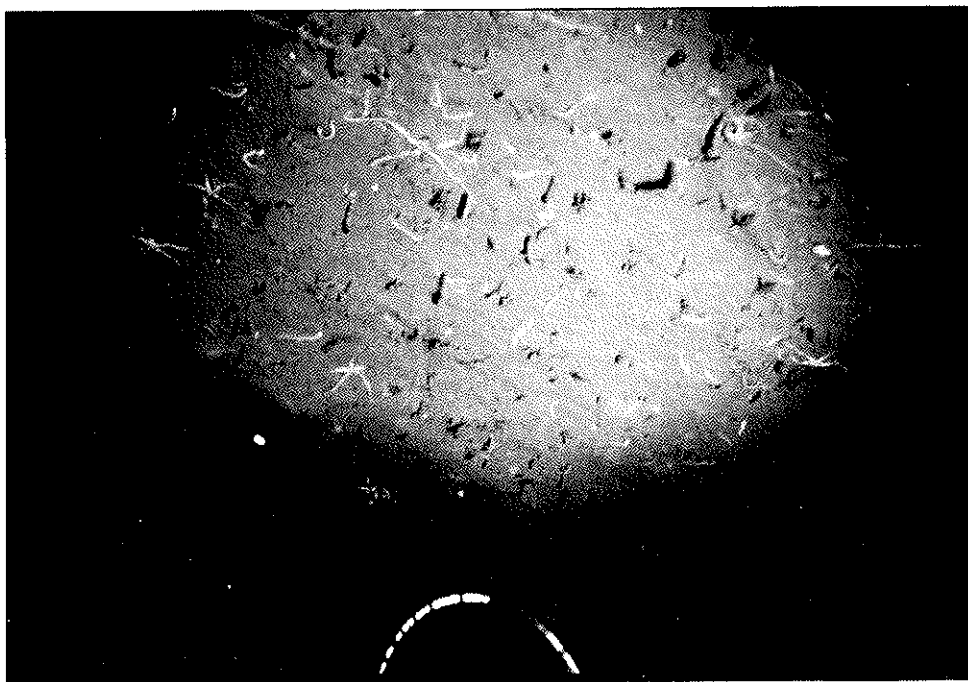


Figure 7. Photo shows a small area of the 1700-m site where there is considerable epifaunal and infaunal activity with a high density of brittle stars and worm tube castings. This also indicates a potential for bioturbation, in this case a greater probability for mobilization of any released radioactivity.

pled with the reactivity of cesium, cobalt, and plutonium to form particulates results in low pore water diffusion of these radionuclides downward into the sediments. Thus, pore water diffusion does not appear to be an important radionuclide immobilization mechanism in the Farallon Islands sites.

- There is episodic movement of coarse sediment

material downslope into the dumpsite areas which could contribute to long-term partial burial of the 55-gallon drums, and which seems to be a cause of the decreased number of epifauna and infauna at the shallower 900-m site.

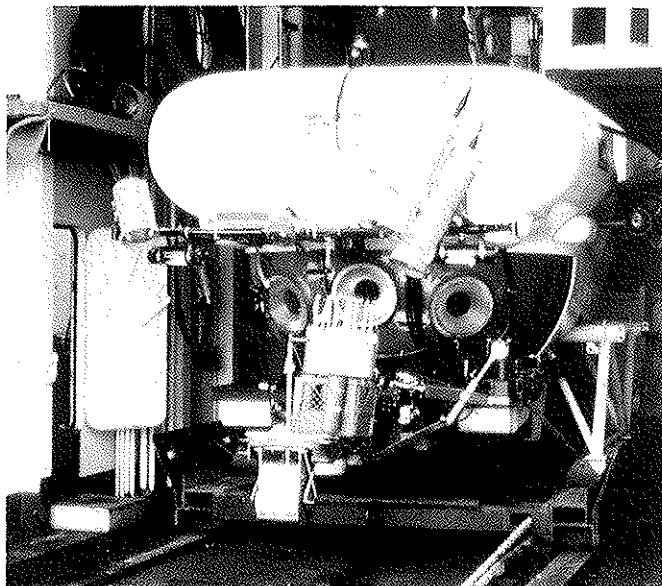
The second phase of the survey focused on three major objectives: 1) locate and recover a radioactive

waste drum, 2) deploy current meters to measure the speed and direction of any deepwater currents flowing through the site, and 3) conduct a precision coring operation around one or more of the drums to determine the extent of vertical and horizontal transport of any released radioactive materials.

On October 22, 1977, EPA completed the first radioactive waste drum recovery from a west coast dumpsite. A 55-gallon LLW drum was recovered from a depth of 900 meters to analyze the metal corrosion and matrix degradation rates in this marine environment. The method of recovery was also unique in that the drum was lifted directly by the PISCES VI submersible rather than being recovered by a surface ship.

A 55-gallon drum with no signs of hydrostatic implosion was selected for recovery. Radiation health and safety procedures were instituted aboard the receiving ship. A metal harness was placed over the drum, tightened down with a grip hoist, and lifted using two Kevlar ropes attached to the submersible. The drum recovery went smoothly and without incident. The waste package was brought aboard the R/V *VELERO IV* and placed in an overpack (jet-engine container) for land transport to Brookhaven National Laboratory for analysis. The overpack is shown in Figure 8.

Figure 9 shows a closeup of the recovered drum. The characteristic lifting eye found on packages at the 900-m site is visible to the left. Although the drum shows surface corrosion, the areas abraded by the lifting harness reveal sound steel beneath. Corrosion of the rim (chime) of the drum, where both sides of the metal were



*Figure 8. The recovered waste package was brought aboard the R/V *VELERO IV* and placed in an overpack (jet-engine container). The overpack is shown in photo.*

exposed to seawater, is evident. A close-up of the concrete cap of the recovered drum is shown in Figure 10. The wire rope lifting eye and the concrete appear to be structurally sound. Limited biofouling was evident. Another view of the corroded chime of the drum is visible at the lower left of this photo.

Characteristics of the recovered low-level waste (LLW) package revealed that the drum had lain on the ocean floor for approximately 21-26 years. The portion of the drum in contact with the sediment showed a



Figure 9. Photo shows a closeup of the recovered drum.

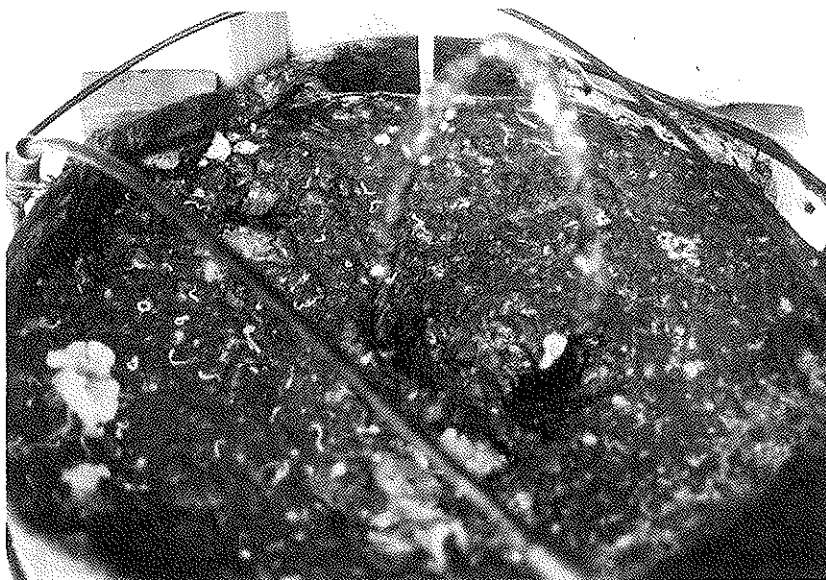


Figure 10. A close-up of the concrete cap of the recovered drum

slower corrosion rate than the surface in contact with the seawater. Calculations of corrosion rates of the container were based on the assumptions of constant rate with no induction time and show that the metal loss on the sea side of the 1.33-mm thickness container corresponds to a uniform corrosion rate of 0.019 mm/yr or a 34-year period required for a 50% reduction in thickness of a 1.3-mm sheath exposed to seawater. The metal loss on the buried side of the container corresponds to a uniform corrosion rate of 0.0025 mm/yr or a 260-year period required for a 50% reduction in thickness of a 1.3-mm sheath (11).

Perforation of the metal container through pitting corrosion occurred on both the sediment side and the side exposed to seawater, and consumed 1% of the total container surface. The low corrosion rate for the sea side of this container may result from the low oxygen level at this dumpsite, which, as previously stated, was in an oxygen minimum zone (0.5 cc/l). However, the nearly negligible corrosion rate on the sediment side of the container suggests that the alkaline sediment (pH 8–10) also plays a role in suppressing general thinning corrosion (12).

The cement waste form contained a small intact corrugated cardboard box. No radioactive contamination was detected either on the cardboard box or in the cement matrix, indicating that the waste was either a "suspect waste," or contained a short half-lived isotope. The waste form was determined to be of high integrity through measurement of the compressive strength of cores taken from the concrete matrix. There was a negligible amount of deterioration resulting from exfoliation, alkaline stress cracking, and bacterial action. It was surprising that the dissolved salts in the seawater did not cause measurable

deterioration of the waste form since sulfates in seawater attack cement very markedly.

In addition to the drum recovery objective, EPA sought to determine the direction of underwater currents flowing through the site. A progressive vector current meter was deployed at the 1700-m site during the 1975 survey and recorded the water flow for 27 days. The flow was almost due north with a slow mean velocity of 1.3 cm/sec. In 1977, current meters were again deployed in the area and EPA was able to obtain two three-month records during the same general time of year as in the 1975 survey. The first current vector record in the 1700-m dumpsite area also revealed a slow current flow almost due north. The second current vector record showed a variable speed and direction of flow, although the net direction of water movement was to the north-northwest.

EPA has performed many radioactivity measurements on the sediments and biological organisms in the two dumpsite areas. In 1975, EPA first reported finding some evidence of plutonium contamination, above maximum expected fallout concentrations, in sediments at the 900-m site (13). Further radioanalytical work was performed on biological samples collected in 1977, and results indicated no elevated levels of plutonium, cesium, or strontium in edible portions of any commercial species of fish found in the 900-m and 1700-m dumpsites.

Figure 11 is a schematic of a coring operation conducted in 1977 with the *PISCES VI* manned submersible at carefully measured distances around a LLW container at the 900-m site. The direction of the weak bottom current flow is noted on this schematic. The analytical results suggest some elevated levels of plutonium in the surface layers of these cores adjacent to the waste con-

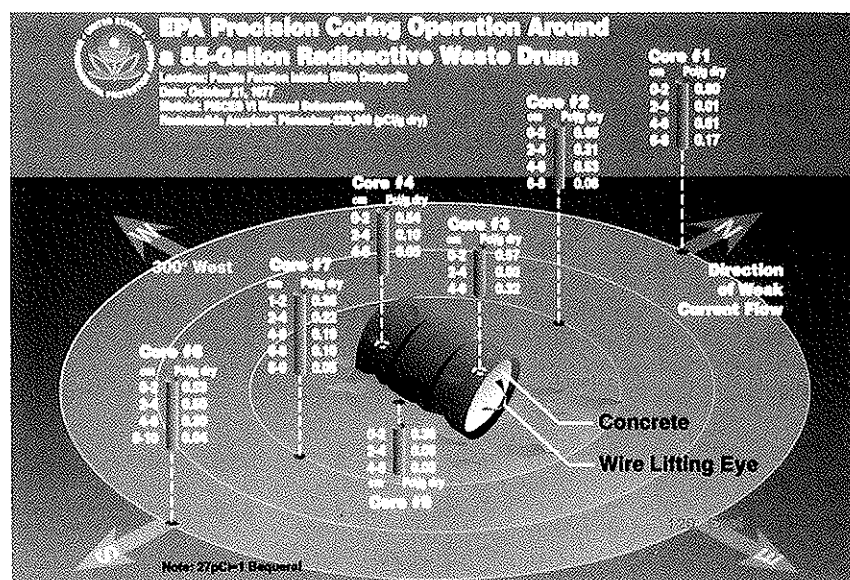


Figure 11. A schematic of a coring operation conducted in 1977 with the PISCES VI manned submersible at carefully measured distances around a LLW container at the 900-m site.

tainer, but dropping off to undetectable or barely detectable levels at depths below eight centimeters in the sediment. Analytical results from the coring operation can be found in Table 2.

Survey 4—1985

In 1985, another survey of the Farallon Islands 900-m dumpsite took place. Five manned submersible dives were scheduled but inclement weather and high sea conditions allowed the completion of only one dive, which took place on 24 June 1985 to a depth of 1030 m. Detailed biological observations were made from the viewing

ports of the U.S. Navy's Deep Submergence Rescue Vehicle AVALON (DSRV-2) (14). Modifications were made to the submersible for photographic and sediment sampling instrumentation. Geologic and geochemical features were observed and measured. The survey area was fairly uniform with smoothed microtopography suggestive of measurable local currents. The sediment was cohesive with some plasticity. A low-level radioactive waste package was identified and examined in situ. A sediment core was collected near the container for radiochemical and geochemical analysis. Figure 12 shows a schematic of the waste package, coring location, and

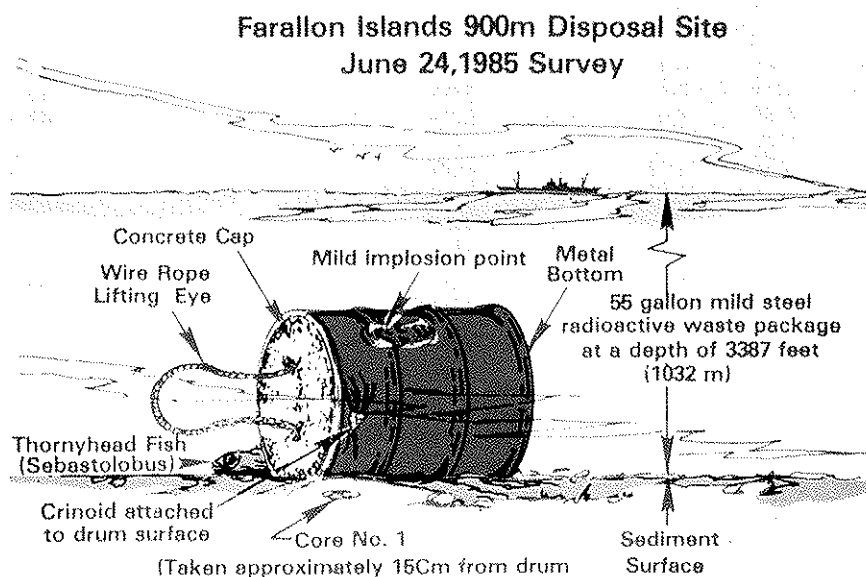


Figure 12. A schematic of the waste package, coring location, and biological features.

Table 2. Pacific Farallon Islands 900-m dumpsite, cores from PISCES VI Manned Submersible, 19–21 October 1977.

	Sample number	Depth in core (cm)	^{137}Cs	Concentration pCi/g dry		
				$^{239,240}\text{Pu}$	^{238}Pu	$^{238/239}\text{Pu}$
Core no. 1						
2 m north from drum	36563	0–2	N.D.	0.793 \pm 0.002	0.013 \pm 0.002	0.016 \pm 0.002
	36564	2–4	—	0.013 \pm 0.002	<0.027	
	36565	4–6	N.D.	0.597 \pm 0.046	0.022 \pm 0.002	0.037 \pm 0.004
	36565R*	—	—	0.627 \pm 0.052	0.032 \pm 0.004	0.051 \pm 0.008
	36566	6–8	N.D.	0.172 \pm 0.017	0.004 \pm 0.001	0.023 \pm 0.006
	36567	14–16	N.D.	0.014 \pm 0.002	0.002 \pm 0.001	0.143 \pm 0.074
36568	20–22	N.D.	0.004 \pm 0.0009	<0.001		
Core no. 2						
1 m north from drum	36575	0–2	N.D.	0.946 \pm 0.073	0.013 \pm 0.002	0.014 \pm 0.002
	36576	2–4	N.D.	0.311 \pm 0.026	0.009 \pm 0.002	0.029 \pm 0.003
	36577	4–6	N.D.	0.531 \pm 0.042	0.010 \pm 0.001	0.019 \pm 0.002
	36578	6–8	N.D.	0.075 \pm 0.010	<0.001	
	36579	8–10	N.D.	<0.004	<0.001	
	36580	10–12	N.D.	0.066 \pm 0.007	0.004 \pm 0.001	0.061 \pm 0.017
	36581	12–14	N.D.	0.030 \pm 0.030	0.003 \pm 0.001	
	36582	14–16	N.D.	Lost	Lost	
	36583	16–18	N.D.			
Core no. 3						
0 m north from drum	36536	0–2	N.D.	0.563 \pm 0.044	0.010 \pm 0.002	0.018 \pm 0.004
	36530	2–4	N.D.	0.002 \pm 0.001	<0.001	
	36528	4–6	N.D.	0.324 \pm 0.075	<0.001	
	36682	6–8	N.D.	0.003 \pm 0.001	0.007 \pm 0.001	
	36543	8–10	N.D.	<0.0004	0.001 \pm 0.0009	
	36683	10–12	N.D.	0.003 \pm 0.001	<0.0002	
	36535	12–14	N.D.	0.004 \pm 0.001	<0.0005	
	36532	22–24	N.D.	<0.0006	<0.001	
Core no. 4						
12 cm west from drum	36569	0–2	N.D.	0.542 \pm 0.051	0.015 \pm 0.003	0.028 \pm 0.006
	36570	2–4	N.D.	0.095 \pm 0.008	0.001 \pm 0.0007	0.011 \pm 0.008
	36571	4–6	N.D.	0.053 \pm 0.005	0.004 \pm 0.001	0.075 \pm 0.020
	36572	6–8	N.D.	0.010 \pm 0.001	<0.001	
	36573	14–16	N.D.	<0.0004	<0.005	
	36568	20–22	N.D.	0.0022 \pm 0.0015	0.0025 \pm 0.0017	
	36574	24–26	N.D.	<0.001	<0.001	
Core no. 6						
2 m south from drum	36542	0–2	N.D.	0.531 \pm 0.041	0.012 \pm 0.001	0.23 \pm 0.003
	36549	2–4	N.D.	0.498 \pm 0.085	0.097 \pm 0.020	0.195 \pm 0.052
	36548	4–6	N.D.	0.297 \pm 0.027	0.004 \pm 0.002	0.013 \pm 0.007
	36538	8–10	N.D.	0.039 \pm 0.004	<0.0005	
	36537	12–14	N.D.	0.008 \pm 0.001	<0.0005	
	36545	22–24	N.D.	<0.0004	<0.0005	
Core no. 7						
1 m south from drum		1–2	—	0.362 \pm 0.034	<0.005	
		2–4	—	0.216 \pm 0.018	0.004 \pm 0.001	0.019 \pm 0.005
		4–6	—	0.185 \pm 0.016	0.0034 \pm 0.0009	0.018 \pm 0.005
		6–8	—	0.104 \pm 0.010	0.002 \pm 0.0006	0.019 \pm 0.006
	36686	8–9	N.D.	0.045 \pm 0.004	0.009 \pm 0.002	
		9–10	—	0.014 \pm 0.0018	<0.0009	
		10–11	—	0.010 \pm 0.002	<0.001	
	14–16	—	<0.004	<0.0005		
Core no. 9						
0 m south from drum	36547	0–2	N.D.	0.360 \pm 0.050	0.015 \pm 0.005	0.042 \pm 0.015
	36546	2–4	N.D.	0.080 \pm 0.007	0.002 \pm 0.001	0.025 \pm 0.013
	36539	4–6	N.D.	0.034 \pm 0.003	<0.001	
	36541	8–10	N.D.	0.006 \pm 0.004	<0.001	
	36544	12–14	N.D.	<0.002	0.002	

*R = replicate.

biological features. The waste package had been immersed at least 30 years (as dated by the presence of the wire rope lifting eye) but the drum showed little biofouling or implosion and the concrete solidification matrix was in good condition. A 2000-minute gamma-ray scan using a germanium-lithium detector showed no radioactivity concentrations above background levels.

For any monitoring and assessment of past radioactive waste disposal operations in the ocean, it is important to be able to distinguish between many possible sources of radioactivity, such as nuclear weapons testing fallout, discharges from lakes and rivers, or the dumping operation itself. EPA surveys in the Pacific-Farallon Islands radioactive waste disposal areas have shown that a radioactivity release or lack of a release with respect to a specific source, in this case a LLW package, can be established by performing a few detailed examinations of waste containers including the waste form and correlating the results with supporting measurements such as radionuclide concentrations in sediments and biota, bottom topography, sediment retention characteristics for radionuclides, and current velocities.

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Measurement of Radioactivity in the Alaskan Atmospheric, Terrestrial, and Marine Environments

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Over the past three decades, the Department of Energy has been supporting scientists using radionuclides as biogeochemical tracers and clocks to monitor and quantify environmental processes affecting the dispersal and fate of contaminants within Alaska's atmospheric, terrestrial, and marine ecosystems. From measurements of both natural and minute amounts of anthropogenic radionuclides we have learned a great deal about how the earth system works. For example, much of the understanding about stratospheric/tropospheric exchange has been developed from atmospheric tracer studies using fallout radionuclides and cosmogenically (naturally) produced Beryllium-7 (^7Be). Research has been conducted into how aerosols accrete in the atmosphere using natural radon decay-series radionuclides, as well as how they and other contaminants are removed from the atmosphere by precipitation washout and dry deposition. Once deposited on the Earth's surface, scientists can monitor the rates, movements, and fate of these radionuclide tracers in terrestrial and aquatic systems. In watershed systems, both natural and anthropogenic radionuclides are used to quantify the rates that contaminants are cycled by the biota or move with runoff or groundwater. In lakes, radionuclides are used to quantify the rates at which contaminants sorb onto suspended particles or are bioaccumulated by aquatic organisms. The length of time radionuclides stay suspended in the water column before deposition and the rates at which contaminants accumulate in the sediments can also be calculated using these tracers. In addition, measured radionuclide profiles provide a tool

to date the sediment column and document the contaminant input history for an individual site.

Radionuclides and a wide variety of other substances of known or potential pollutant capacity are also introduced into the marine environment from the atmosphere, river discharge, or ocean dumping. Some of these radionuclides are relatively unreactive in the marine environment (such as cesium-137 and iodine-129) and consequently their transport pathways are mediated by water-mass movements. Other radionuclides, such as thorium or plutonium (^{238}Pu , ^{239}Pu , ^{240}Pu) isotopes, are highly reactive and have a strong affinity for association with fine-grained or biogenic particles. The movement of these reactive radionuclides, their removal from the oceanic water column and their accumulation in sediments is primarily governed by biological and sedimentary processes.

Most of the data presented in this paper were obtained by scientists at the DOE's Environmental Measurements Laboratory (EML). Some of the data, however, also comes from the scientists participating in DOE's Arctic Research Program, known as the R4D, with the four Rs standing for response, resistance, resilience to, and recovery of Arctic ecosystems to energy-related disturbances.

Atmospheric Radionuclide Input

Before biogeochemists can actually use the radionuclides as tracers for quantifying environmental processes, they have to know their source functions and their input histories. EML operates a world-wide network of

aerosol and deposition sampling stations in order to make such estimates. Five of these stations are located in Alaska; deposition samples are collected at Fairbanks, Nome, Anchorage and Cold Bay, while air filter samples are collected at Barrow.

A typical air sampling station has an air pump that pulls about a cubic meter of air per minute across filters which are collected weekly. The filters are returned to EML where individual radionuclides are analyzed. In the past, much of this effort was associated with fallout radioactivity; however, at the present time, more effort has been directed toward measurements of natural radionuclides (such as beryllium-7 and lead-210) in surface air. This surface air monitoring activity is one of Department of Energy's main contributions to the Arctic Monitoring and Assessment Program (AMAP).

Figure 1 shows the mean annual concentration, in milli-becquerels per cubic meter (mBq/m^3) in air, of beryllium-7 (^7Be), lead-210 (^{210}Pb), and cesium-137 (^{137}Cs) in Alaskan surface air. Note that ^7Be and ^{210}Pb are both natural radionuclides in the surface air of Alaska. Beryllium-7 is produced when cosmic rays strike a nitrogen atom in the atmosphere, causing it to break up into spallation products or fragments. One of those fragments, ^7Be , is radioactive and has a half-life of about 53 days. This short half-life makes ^7Be an excellent tracer for examining processes which occur on a seasonal basis. Some of the work that DOE has been supporting has been measuring the deposition of ^7Be in Arctic watersheds, determining its concentration and inventory in the Arctic snowpack, and its movement in watersheds during snowmelt. Another natural radionuclide produced by cosmic-ray interactions in the atmosphere, but this time with argon, is sulphur-35 (^{35}S). It has a half-life of about 87 days. Like ^7Be , ^{35}S is

removed from the atmosphere by rain or snowfall and accumulates in the snowpack. It serves as a convenient tracer and clock for quantifying the fate of atmospherically derived sulphur within Arctic watersheds.

Also shown in Figure 1 is atmospheric data for naturally occurring lead-210 (^{210}Pb). This nuclide is produced when its short-lived parent radon-222 escapes from soils and vegetation into the atmosphere and decays to ^{210}Pb . It is important to note that the concentrations of naturally occurring ^7Be and ^{210}Pb in Figure 1 are much greater than concentrations of man-made ^{137}Cs in Alaskan surface air, even during 1986 when the ^{137}Cs increased as a result of the Chernobyl nuclear accident in the former Soviet Union. Because these natural radionuclides are washed out of the atmosphere with each snow or rain event, more than 100,000 Curies of natural ^7Be , ^{35}S , and ^{210}Pb are deposited on Alaskan lands and waters each year. This amount is significantly less (on a per-kilometer-squared basis) than the amount of natural radioactivity deposited in more southerly mid-latitude areas of the Earth, including the other 49 states of the United States.

The latitudinal dependence of the atmospheric deposition of radioactivity is illustrated in Figure 2. This figure shows the cumulative history of fallout ^{137}Cs in latitudinal bands for the entire world resulting from atmospheric tests of nuclear weapons. The cumulative total deposition of fallout ^{137}Cs is about 0.1 Curies per square kilometer (Ci/km^2) in mid-latitude areas. Because Alaska is located at 60° to 70°N , it received about half the total man-made ^{137}Cs fallout that occurred at mid-latitudes locations such as Seattle, Chicago, or New York. The total amount of fallout ^{137}Cs deposited on the North Slope of Alaska is about 0.04 Curies per square kilometer (Ci/km^2). In the Yablokov Commis-

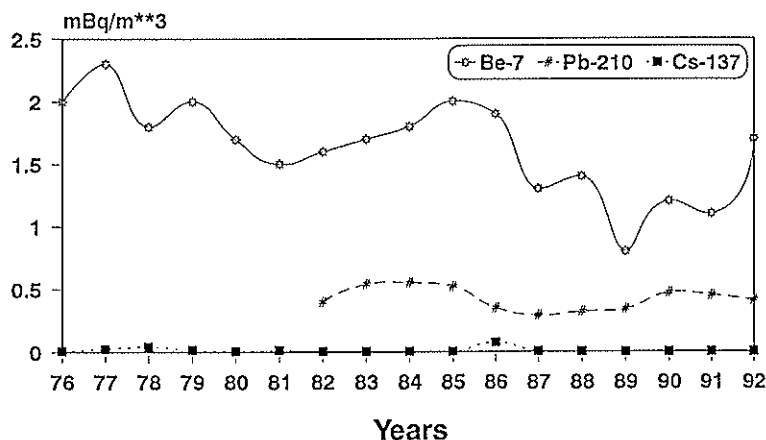


Figure 1. Annual mean observations of radionuclides at Barrow, Alaska, from the years 1976 to 1992. Values are in milli-becquerell per cubic meter (mBq/m^3). Data are for beryllium-7, lead-210, and cesium-137. The increase in the cesium concentration in 1986 is due to the Chernobyl nuclear accident.

Figure 2. Latitudinal distribution of cumulative cesium-137 deposited through 1985. Values are in becquerel per square meter (Bq/m^2). Cesium-137 calculated using strontium-90 measurements and a ^{137}Cs to ^{90}Sr ratio of 1.5.

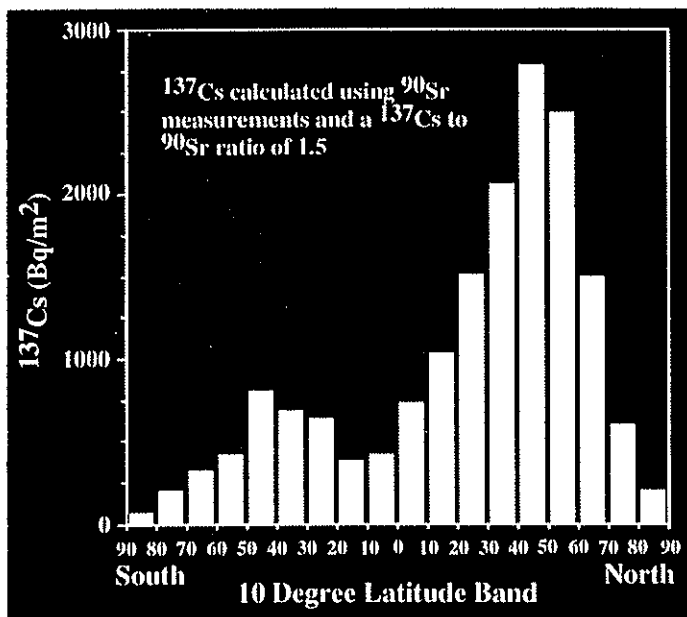
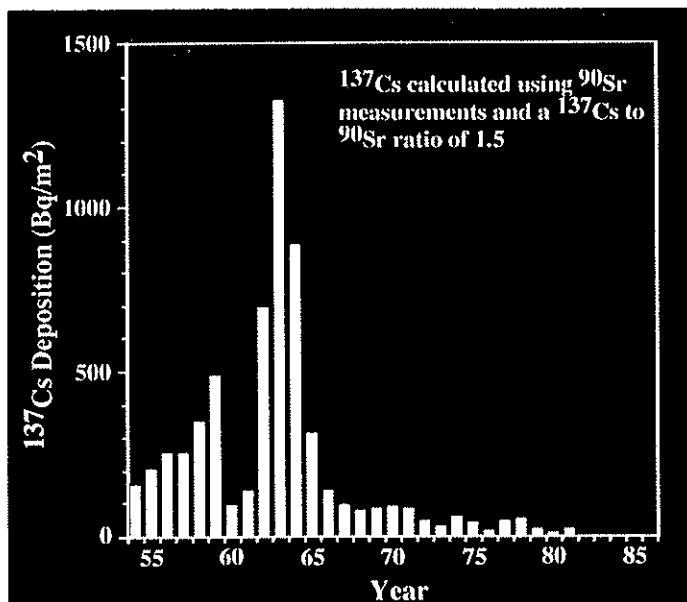


Figure 3. Annual deposition of cesium-137 in New York City for the years 1954 through 1981. Values are in becquerel per square meter (Bq/m^2). Cesium-137 calculated using strontium-90 measurements and a ^{137}Cs to ^{90}Sr ratio of 1.5.



sion report, the Russian scientists have also reported that their Arctic region received a comparable value of about 0.04 Ci/km^2 of ^{137}Cs from atmospheric nuclear tests.

Figure 3 shows the time-history of fallout for the Northern Hemisphere as measured at New York City. This fallout time-history is also similar to that for Alaska even though Alaska received about one-half the total amount of ^{137}Cs fallout compared to New York City. The variations in ^{137}Cs fallout illustrated in Figure 3 reflects a series of policy and political events, which can be seen in the records for other locations in the Northern Hemisphere, for the years 1954 through 1981. Back in 1959, the United States and the former Soviet Union had a moratorium on atmospheric testing of nuclear weapons. During the moratorium period there was a rapid decrease in fallout ^{137}Cs deposited in the Northern

Hemisphere. Then in the early 1960s as Cold War tensions flared, the moratorium was disregarded by both the United States and the former Soviet Union. Numerous atmospheric tests were conducted in the early sixties. In 1963, the United States and the former Soviet Union signed a nuclear test ban treaty, banning all atmospheric nuclear tests by the two countries. In Figure 3, one can see a drastic decrease in fallout ^{137}Cs deposition that occurred after the signing of this nuclear test ban treaty. In later years, fallout ^{137}Cs was due to French atmospheric tests in the Southern Hemisphere, and most recently by an atmospheric test in 1981, by the Peoples Republic of China.

Although Figure 3 shows data for New York City as previously stated, this is also the history of fallout input to Alaska. Cesium-137 profiles measured in sediment

cores collected from Alaskan lakes often show a peak in ^{137}Cs concentration corresponding to the year 1963, in the sediments. Therefore fallout ^{137}Cs profiles can be used to date sediments in Arctic lakes and when these measured profiles are correlated with measurements of heavy metals, persistent organic compounds, chronic hydrocarbons, and other contaminants, they provide chronologies for determining contaminant input histories at particular locations.

Radionuclides in Arctic Watersheds

The development of energy resources in tundra regions of Alaska has resulted in various types of disturbances of Arctic watersheds, including road construction and chemical spills. To better understand the con-

sequences of these disturbances on Arctic ecosystems, the Department of Energy sponsored a basic research program (R4D) on the response, resistance, resilience and recovery of Arctic ecosystems to disturbance. The R4D program was carried out along the Dalton Highway in the Innavaik Creek watershed, a tributary of the Sagavanirktok River about 150 miles south of Prudhoe Bay (Figure 4). One of the projects in this program used measurements of naturally occurring radionuclides (^7Be and ^{35}S) to examine how atmospherically derived contaminants in the Arctic snowpack move through the Arctic watershed system during snowmelt. The results from this study indicated that most of the atmospherically derived radionuclides (and by analogy other chemically reactive contaminants) were trapped within the

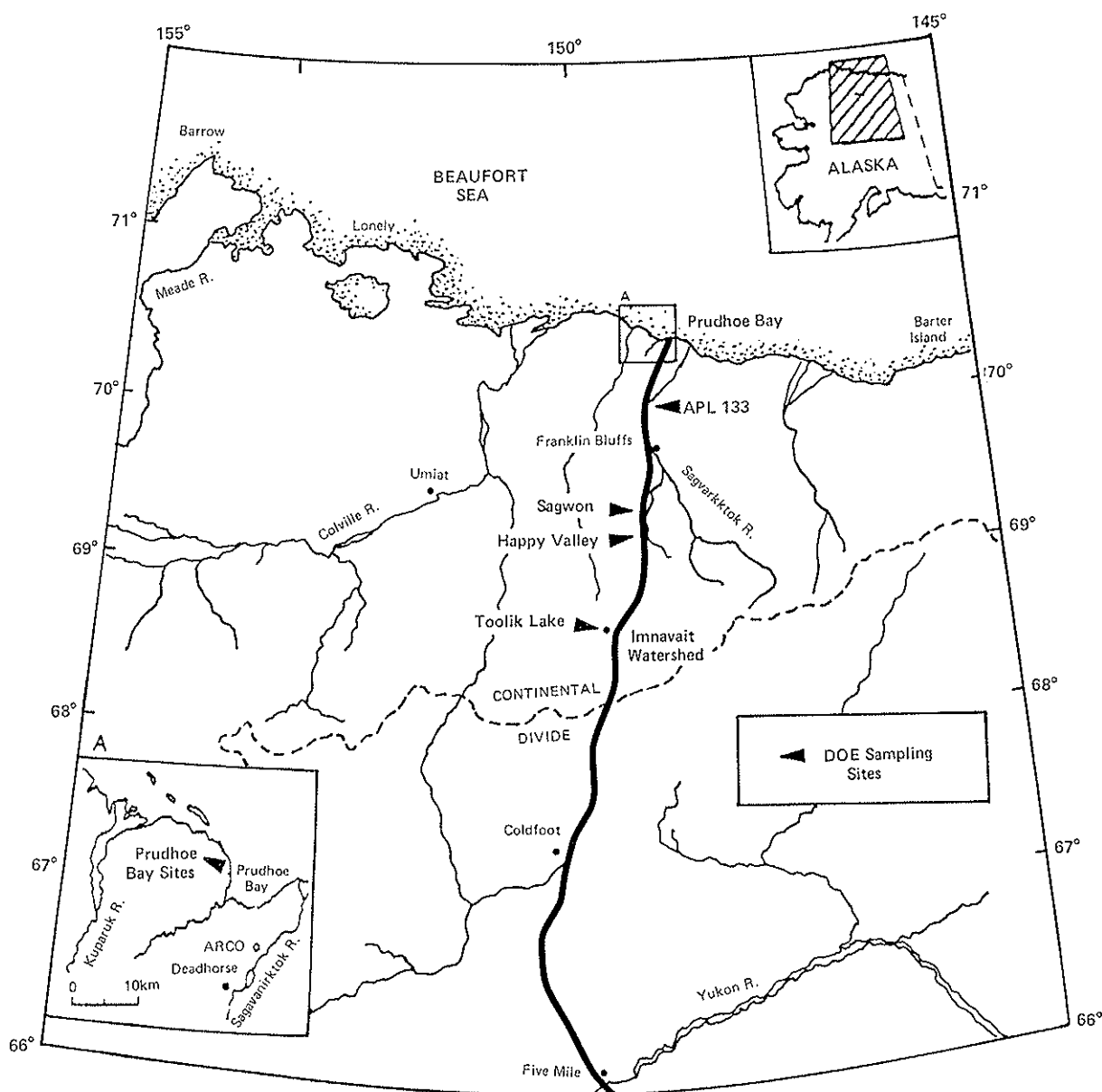


Figure 4. Map of Department of Energy sampling sites in the Innavaik Watershed, North Slope, Alaska.

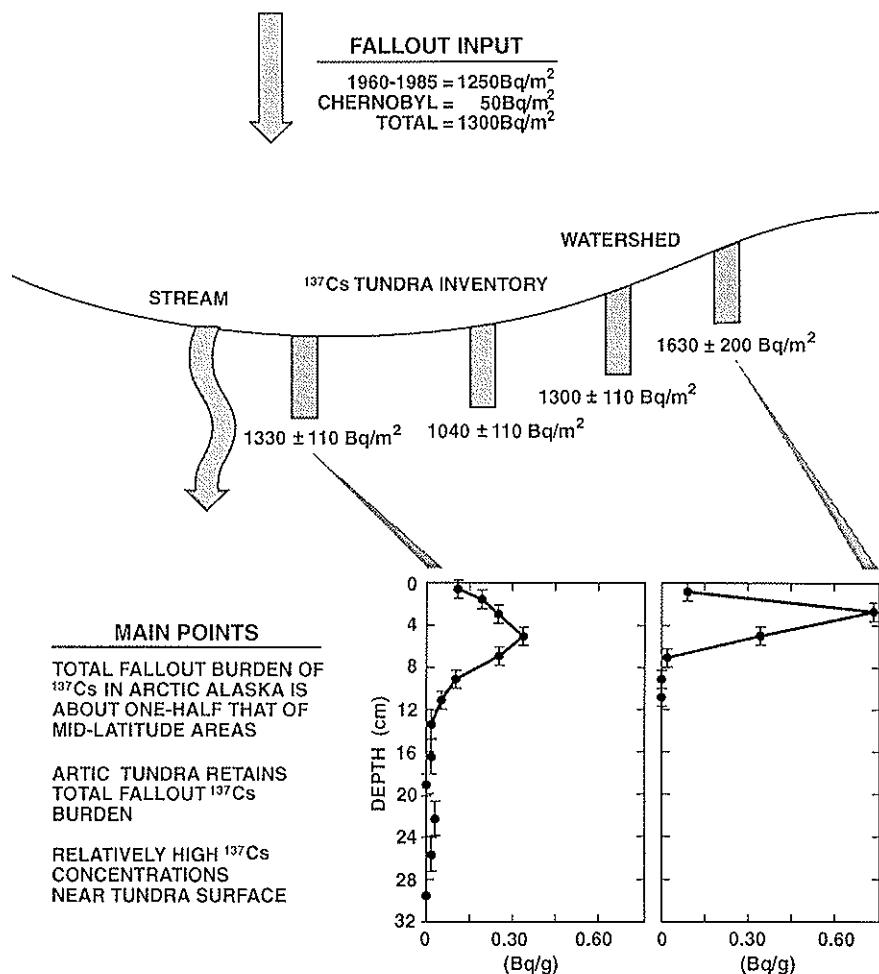


Figure 5. Representation of the cesium-137 distribution in the North Slope of Alaska. The two soil profiles show the relatively high ¹³⁷Cs concentrations near the tundra surface.

top 10 cm of Arctic vegetation immediately beneath the snowpack. This implies that only a small amount of the chemically reactive materials that are washed out of the atmosphere and deposited in the snowpack escape Arctic watersheds via stream runoff.

This observation is confirmed by the data presented in Figure 5 on the estimated source and inventories of ¹³⁷Cs in Arctic tundra areas. The fallout data for this figure was measured in Fairbanks, Alaska, and indicates a total input of about 1300 Bq/m² or about 0.035 Ci/km². In Figure 5, it is also apparent that the Chernobyl accident accounted for less than five percent of the cumulative ¹³⁷Cs inventory in this Arctic system.

It is also apparent from Figure 5 that most of the fallout ¹³⁷Cs deposited in the 1950s and 1960s (over thirty years ago) was still being actively cycled within the top 10 cm of the tundra surface. Furthermore these data indicate that there is a good match between the total amount of ¹³⁷Cs in the tundra vegetation and the total amount deposited as fallout during the past four de-

cadecades. This implies that almost the entire inventory of ¹³⁷Cs is trapped within this Arctic watershed and that very little of the deposited ¹³⁷Cs escaped into the streams and river systems.

The finding that most of the ¹³⁷Cs deposited during the past four decades is still being cycled near the tundra surface also has important implications with regard to ecosystem processes and human health. Because ¹³⁷Cs biochemically behaves like potassium, it often substitutes for potassium in the clay minerals that form soils throughout much of the world. As a result, ¹³⁷Cs is trapped in soil mineral lattices and is not bioavailable. In Arctic tundra systems, however, there is very little mineral soil. In order to grow the Arctic vegetation needs potassium, nitrogen, and other types of nutrients. As a result, fallout ¹³⁷Cs (like potassium) is rapidly assimilated as are nutrients in Arctic tundra systems and is actively cycled near the surface. In fact, ¹³⁷Cs deposited four decades ago is actually measured in plant berries today. Although the cycling of ¹³⁷Cs in Arctic

vegetation tends to trap ^{137}Cs and prevent its escape from Arctic watersheds, it also increases the bioavailability of the contaminant over prolonged periods of time.

Radionuclides in the Alaskan Marine Environments

To place measured ^{137}Cs distributions in the Arctic Ocean in perspective, Table 1 shows a ^{137}Cs profile from the Canadian basin, north of Alaska. Comparing these

Table 1. Cesium-137 in Canadian Basin waters.

Depth (m)	Bq/m ³
74°56.6'N, 159°14.0'W	
5	0.6 (17%)
200	3.0 (11%)
500	6.8 (8%)
1800	5.0 (7%)
75°50.0'N, 153°57.3'W	
5	4.7 (8%)
3800	0.1 (20%)

values with those from the Kara Sea presented earlier by Dr. Scott Fowler, it is evident that activity levels from both areas are comparable; neither data set shows unusual levels of ^{137}Cs in the water column. The two samples shown in Table 1 are approximately 400 and 500 kilometers north of Point Barrow, Alaska. There are some slight differences between the two sites, but in the upper 1800 meters of the water column, the activities of ^{137}Cs are quite comparable to those that have been measured in the Kara and Barents Seas. In the deeper parts of the Canadian Basin, at 3800 meters, the ^{137}Cs in the water column becomes difficult to measure.

Figure 6 shows sample locations where gravity cores were taken for plutonium analysis. The cores represent penetration depths between 15 and 20 centimeters. We estimate that 90 to 95 percent of the total plutonium inventory was contained in that depth interval. Two cores were analyzed to quantitate plutonium in the sediment column. A third core was analyzed to characterize the isotopic composition of the plutonium, because we believe a true understanding of plutonium provenance rests on a specific interrogation of the ratios of the different plutonium isotopes. For example, low-level irradiated plutonium (that used in nuclear weapons) is composed principally of plutonium-239 (^{239}Pu) and some ^{240}Pu , with only trace amounts of higher mass numbered plutonium isotopes. Uranium enriched fuels which has been irradiated for long periods of time have increased atomic concentrations of ^{238}Pu , reduced proportions of both ^{239}Pu and ^{240}Pu and an increased abundance of ^{241}Pu and ^{242}Pu . Plutonium-242 is largely absent from weapons-grade plutonium.

In the absence of extra ^{238}Pu , such as was put into the atmosphere by the burn-up of a SNAP-9A device in the southern hemisphere (of which some 20 percent reached the northern hemisphere), the isotopic composition of plutonium in global fallout is well characterized. For example the ratio of ^{240}Pu to ^{239}Pu in integrated fallout is between 0.18 and 0.2. By contrast, the ratio of ^{240}Pu to ^{239}Pu in fuel reprocessing waste and in weapons-grade plutonium is between 0.05 and 0.06. Given the fact that mass spectrometry techniques can be used to measure these atomic ratios to a half of one percent or less, the ratios serve as useful tools to determine the origin of plutonium in environmental samples.

The plutonium in the cores raised from the Bering and Chukchi Seas, between 60° and 70°N, would be expected to have integrated plutonium inventories characteristic of global fallout inputs at those latitudes. Unfortunately, the uncertainties in these expected inventories are large owing to the small number of samples analyzed from these latitudes. For both sampling sites, the measured plutonium inventory exceeds that expected from global fallout deposition on land (60 Bq/m², on average, with uncertainties as high as 100 Bq/m²; Figure 6); the inventory of the Chukchi Sea core exceeds that of the Bering Sea core by a factor of 2. The explanation for these elevated inventories, substantiated by $^{238}\text{Pu}/^{239,240}\text{Pu}$ activity ratios measured by alpha spec-

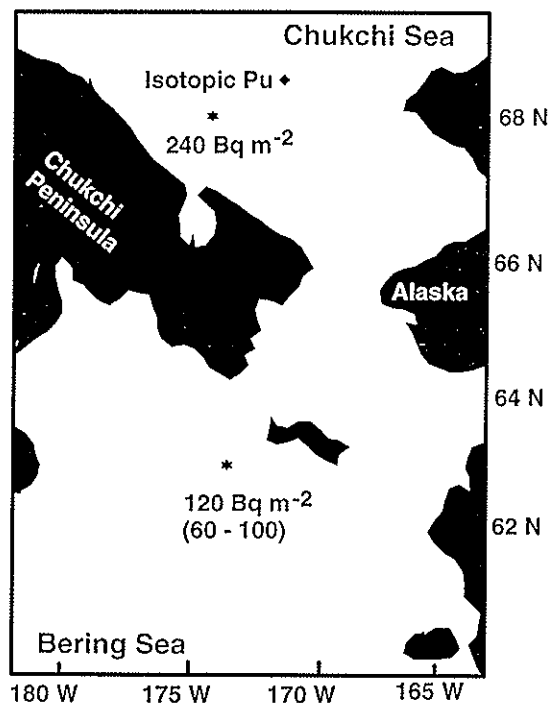


Figure 6. Map of sample sites where gravity cores taken for the analysis of plutonium. Observed activities shown by sample locations. See text for explanation of isotopic plutonium analysis.

trometry, is that plutonium in seawater advecting from the Pacific into the Bering and Chukchi Seas is being continually scavenged from the water column at these sites.

This process has been shown to operate on the continental shelf and slope off Washington State which is influenced by freshwater discharges from the Columbia River. Table 2 shows the expected fallout inventories of both ^{137}Cs and plutonium at this latitude. The measured ^{137}Cs inventory in the sediments is less than

**Table 2. Washington Shelf/
Slope (USA) Columbia
River discharges.**

	<i>Inventories in Bq/m²</i>	
	^{137}Cs	$^{239+240}\text{Pu}$
Fallout deposition	2800	85
Measured	1443	300

expected while the plutonium inventory is substantially greater than expected. Plutonium is scavenged from the water column by particulate matter contained in the freshwater discharge while ^{137}Cs is not. Mass spectrometry analysis of the plutonium isolated from the cores along the Washington coast confirm that the plutonium is exclusively of global fallout origin.

To unequivocally show that the plutonium accumulated in Chukchi and Bering Sea sediments is of global fallout origin, we analyzed contiguous 2-cm sections of a core raised from the Chukchi (Figure 6) to a depth of 10 cm (total core penetration depth). The plutonium was purified and analyzed by thermal emission mass spectrometry to determine atom abundances. The measured $^{240}\text{Pu}/^{239}\text{Pu}$ atom ratio, averaged over the entire core length, was 0.174 ± 0.016 , a value nearly identical to the global fallout average of 0.176 ± 0.014 (uncertainties represent the 67 percent confidence interval). The average $^{241}\text{Pu}/^{239}\text{Pu}$ and $^{242}\text{Pu}/^{239}\text{Pu}$ ratios are also consistent with those measured for integrated global fallout.

In the deep Canadian Basin, the picture emerges. Surface sediments collected near the hydrographic stations shown in Table 1 have plutonium activities that are more than an order of magnitude lower than those measured in the sediments of the Bering and Chukchi Seas sediments. At depths between 1600 and 1800 meters, the measured $^{240}\text{Pu}/^{239}\text{Pu}$ atom ratios range between 0.06 and 0.08 with one sample showing a ratio near 0.10. While we intend to confirm this finding by analyzing additional samples from the Canadian Basin, the data strongly suggest that this plutonium is of fuel reprocessing origin.

We also have measured, as samples of opportunity,

some iodine-129 (^{129}I) in selected Canadian Basin and other Alaskan waters. Table 3 shows that over depths of 1800 meters in the basin, ^{129}I atom concentrations show easily distinguishable differences and indicate structure that may be correlated to individual water masses. Pacific water (characterized by low salinity and high nutrients concentrations) and Atlantic water (high salinity and low nutrients) carry ^{129}I labels that are easily distinguishable, especially in light of the ^{129}I blanks prepared at EML. The Pacific water has an ^{129}I

Table 3. Iodine-129 in Canadian Basin waters (74°56.6'N, 159°14.0'W).

<i>Depth (m)</i>	<i>10⁸ atoms/kg</i>
5	2.6 ± 0.5
200	0.9 ± 0.08
500	2.3 ± 0.4
1800	0.6 ± 0.1
Pacific water	0.16 ± 0.02
Atlantic water	2.3 ± 0.08
Surface water	0.17
EML Blank	0.01–0.06 (20%)

atom concentration nearly identical to that predicted to occur for ocean surface waters (0.17×10^8 atoms per liter) labeled only by weapons fallout and fuel reprocessing emissions. It is certain that ^{129}I , like ^{137}Cs , is being imported to the Barents and Kara Seas following its release from the fuel reprocessing facilities at Sellafield (U.K.) and La Hague (France). Deconvoluting the various sources of ^{129}I in Arctic Ocean waters will be a challenging, but interesting task. In those instances where reactor cores and radioactive waste canisters have been implanted on the sea floor, ^{129}I (and ^{99}Tc) may serve as the most sensitive indicators of leakage from those objects. Both radionuclides behave conservatively in seawater and exhibit vapor pressures that facilitate their release from heated objects (reactor cores). In addition to its utility as an oceanographic tracer, ^{129}I should also prove useful in any long term monitoring program that is foreseen for the region.

Acknowledgments

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an Basin and all air filter samples were counted by Colin Sanderson and Karen Decker at EML. Kent Orlandini, Argonne National Laboratory, assisted in analyzing cores for plutonium. The surface sediments and water samples from the Canadian Basin were given by Tom

Kramer of the U.S. Geological Survey. Dr. Linas Kilius, IsoTrace Laboratory, performed the accelerator mass spectrometry measurements for ^{129}I on targets prepared at EML.

Ecological and Human Health Impacts of Arctic Contamination

Radioactive Contamination in Arctic Tundra Ecosystems

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Executive Summary

Radioecological research on worldwide radioactive fallout in arctic tundra ecosystems, particularly in northern Alaska, during 1959-1980 defined routes, rates, and concentrations of several radionuclides in arctic food chains. Two major periods of fallout upon northern Alaska ecosystems occurred: the first and most sustained during 1953-1959, and the second during 1961-1964, reflecting atmospheric nuclear weapons test regimes of Great Britain, the Former Soviet Union, and the United States. Pulses of lesser stratospheric fallout deposition occurred during 1967-1970 following nuclear weapons tests by France and the People's Republic of China. Research emphasis was on strontium-90 and cesium-137 because of their contribution to increased radiation exposures of circumpolar populations associated with caribou/reindeer harvesting. Plutonium isotopes in arctic tundra ecosystems originated from atmospheric reentry and burnup of radioactive power generators aboard satellites and the crash of a nuclear-armed bomber in northwestern Greenland.

Radionuclide behavior in arctic tundra ecosystems has been found to be generally similar circumpolarly but with important differences due to ethnic groups and practices. Our knowledge of the systems and many of the parameters provides a capability to model and understand consequences of radioactivity, both natural and man-made, in arctic ecosystems and to take effective remedial action when indicated.

Major needs are suggested to include (1) clear definition of source terms, such as accurate measurements of fallout deposition at designated study sites to improve model performance; (2) standardization of sampling and analytical methods; (3) current dietary and food-gathering studies of subsistence cultures in arctic

regions to establish valid food consumption parameters as input to risk assessment models; and (4) reestablishment of lines of communication between international radioecologists, such as the former Radioactivity in Scandinavia Committee sponsored by the International Atomic Energy Commission in the 1960s, for effectively addressing radioactive contamination in arctic ecosystems.

Introduction

Considerable interest in artificial radionuclides in tundra ecosystems, particularly those in circumpolar regions, began with simultaneous and independent reports of appreciable concentrations of worldwide fallout in successive links of the atmosphere - lichen - caribou/reindeer - man food chains of northern Alaska and Scandinavia during the 1960s (Liden 1961; Palmer et al. 1963). Several circumpolar research programs were initiated to promptly evaluate the radiation exposures of Alaskan Inuit (Eskimos) and Indians (Hanson 1966, 1967; Hanson and Palmer 1965); Saami (Lapps) (Liden and Gustafsson 1967; Madshus 1966; Miettinen and Hasanen 1967); and Soviet reindeer herders (Nevstrueva et al. 1967) because of their dependence upon caribou and reindeer (*Rangifer tarandus*) for food and livelihood. It was also important to define the mechanisms by which this unforeseen problem arose in order to avoid similar future situations, such as occurred following the Chernobyl accident in 1986. Regrettably, the existing knowledge was not utilized and precipitate reactions caused considerable confusion and anxiety among minority populations.

This section summarizes radioecological research on worldwide fallout in arctic ecosystems during 1959-1980, with emphasis on investigations conducted in

northern Alaska. The contamination resulted from nuclear weapons tests conducted by several nations both prior to and after the nuclear test ban treaty of 1963; ancillary information of radioactive debris from satellite reentry episodes is included. Emphasis is placed upon ^{137}Cs because of its greater accuracy of measurement, consistent ratios to other fallout radionuclides, and implications to radiological health in circumpolar regions.

Study Areas

Radiation ecology studies were conducted over the general area of northern Alaska between 66° North latitude and the Arctic Ocean, constituting about 310,000 km². Within this area are five major physiogeographic provinces, the northwestern terminus of the North American continental divide, four major caribou herds which constitute the largest aggregation of big game animals in North America, and several Inupiat Eskimo and Athapascan (Kutchin) Indian villages representing four major ethnic groups. A spectrum of ecosystems of varying complexity are utilized by the migratory caribou herds and by the native groups inhabiting the region, and were the subjects of our studies. Our approach proceeded from the general description of radionuclides in the northern biosphere to specific investigation of the most promising components of critical food webs, for purposes of defining routes, rates and concentrations of worldwide fallout in arctic food chains.

Source Terms

Radioactive fallout from weapons-testing consists of nuclear fission products, unexpended fissile material such as uranium-235 and plutonium-239, and a variety of activation products resulting from neutron capture by materials contained in the nuclear devices or in the environment of explosions. The type and composition of a nuclear device markedly affects the kinds of radioactivity produced, while the location and size of detonation determine the quantity of radioactivity released to the biosphere. Atmospheric burnup on reentry of satellite radioactive power generators, usually plutonium-238, has occasionally added another source of contamination to northern environments; and the Chernobyl accident released significant amounts of fission products to Scandinavian tundra ecosystems.

Radioiodine-131 is the most important constituent of prompt fallout from nuclear weapons tests, and has been measured in thyroid glands of reindeer and caribou in northwestern Alaska (Hanson et al. 1963a). Maximum values occurred nearly two months after the first of a new series of nuclear tests in September-November 1961 by the USSR. Values decreased at an effective half-time of about 15 days, indicating that the animals

were receiving decreasing increments of radioiodine during the winter months of 1961.

Thyroid glands of Colorado and Washington (41° and 47°N latitude, respectively) mule deer (*Odocoileus hemionus*) collected at the same time contained twice the ^{131}I concentrations as those of caribou collected in northwestern Alaska (68°N). Similar results were obtained in a later study involving reindeer thyroid glands from the Pribilof Islands (latitude 57°N) during late 1962 (Hanson et al. 1963b).

Seasonal injection of stratospheric fallout occurs at gaps in the upper boundary of the troposphere (tropopause), at about 40° to 50°N and 40° to 50°S latitudes. These are temperate regions with high rainfall, which accelerates deposition; as a result, northern states of the conterminous US and southern Canada have received most of the fallout on the North American continent (Whicker and Schultz 1982, p. 114). Northern Alaska, for example, has received about one-fourth as much fallout per unit area as the northern conterminous US. For Alaska, most fallout ^{137}Cs was observed in caribou samples from southern areas (57-59° north latitude, 120 cm annual ppt), median values were in caribou from central areas (64-66°, 57 cm ppt), and lowest values were in northern (67-70°, 30 cm ppt) areas.

Two major periods of fallout upon northern Alaska ecosystems occurred (Fig. 1); the first and most sustained during 1953-1959 and the second during 1961-1964 (Hardy 1973 and 1975), reflecting the atmospheric nuclear weapons test regimes of Great Britain, the Soviet Union, and the United States (Carter 1980; Carter and Moghissi 1977). Pulses of lesser stratospheric fallout deposition occurred during 1967-1970 following nuclear weapons tests by France and the People's Republic of China.

Although several fallout radionuclides can be measured routinely in tundra ecosystem components, those of major interest are strontium-90 and cesium-137 (Hanson 1967a, 1982). Cesium-137 has received most attention because it is relatively easy to measure, has a relatively long physical half-life (30 yr), and is concentrated at successive levels of food webs. Strontium-90 is important because it also has a relatively long physical half-life (28 yr) and concentrates in bone. Both radionuclides contribute to increased radiation exposures of circumpolar populations associated with caribou/reindeer harvesting.

Plutonium isotopes in arctic tundra ecosystems have been of most interest following incidents such as atmospheric reentry and burnup of radioactive power generators aboard satellites (SNAP-9A in 1964, Cosmos 954 in 1978, and Cosmos 1402 in 1983) and the 1968 crash of a nuclear-armed B-52 at Thule, Greenland (Hanson 1972).

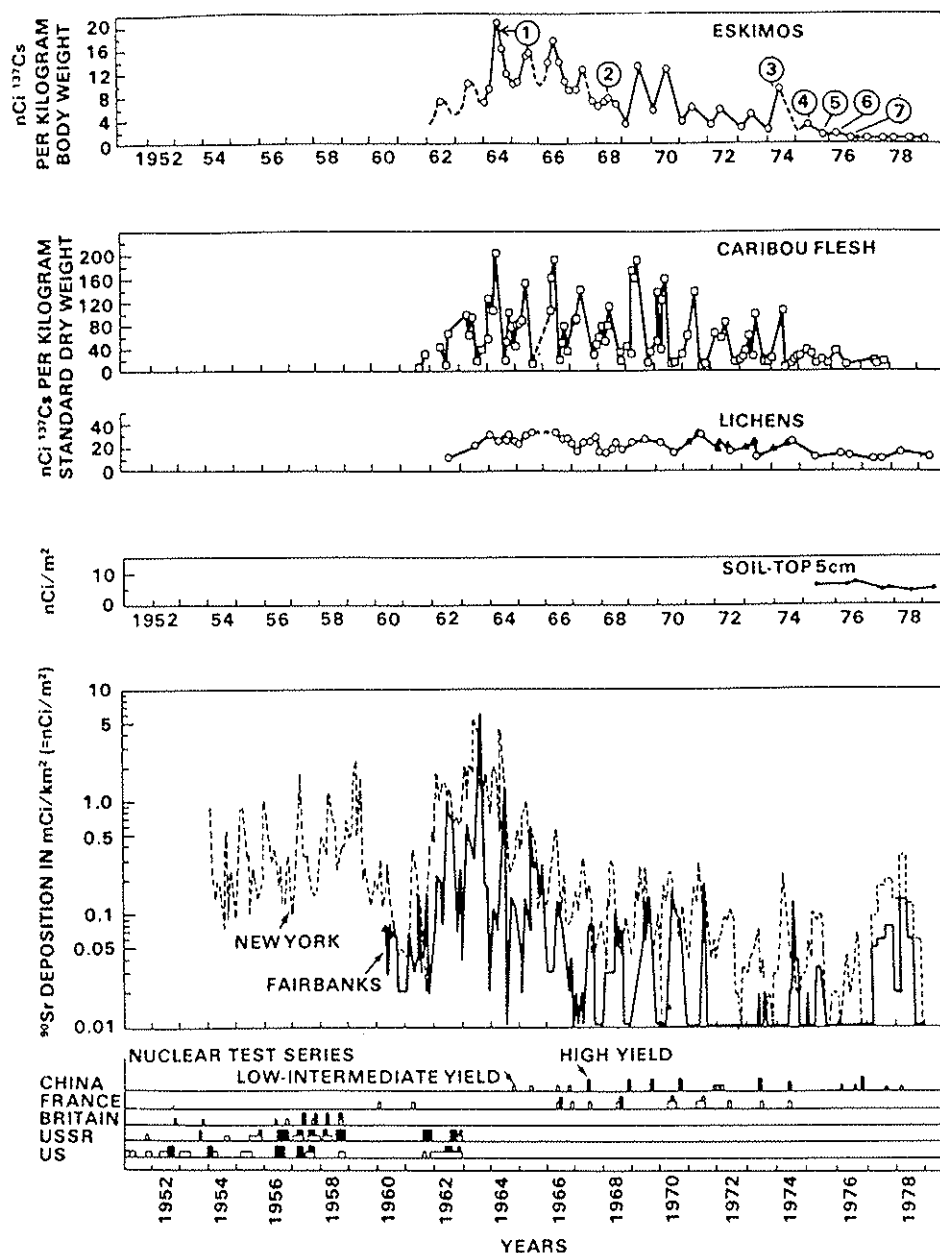


Figure 1. Fallout cesium-137 deposition in New York City and Fairbanks, Alaska, and subsequent concentrations in soils and biota of northern Alaska ecosystems during 1962-1979. A previous period of fallout deposition and ecosystem cycling in the lichen-caribou-Inuit (Eskimo) food chain during 1952-1958 is inferred from the measured deposition in New York City, the relation to similar data from Fairbanks, and ^{137}Cs concentrations in Alaska lichens during 1959-1962 (Hanson, 1982).

Radionuclide Behavior in Tundra Ecosystem Components

Soils

The correlation of worldwide fallout deposition with precipitation and the practicality of estimating the integrated fallout deposited in a geographic region by careful soil sampling have been demonstrated (Hardy

1975; Hardy and Chu 1967). The $^{137}\text{Cs}/^{90}\text{Sr}$ ratio in worldwide fallout is consistently near 1.6 ± 0.2 and the $^{137}\text{Cs}/^{239,240}\text{Pu}$ ratio is about 62. The $^{238}\text{Pu}/^{239,240}\text{Pu}$ ratio is usually 0.020-0.024. These values expedite comparisons of radionuclide behavior in various ecosystem compartments.

Inventories of ^{137}Cs in surface (top 5 cm) soils in northern Alaska during 1975-1979 declined at an effec-

tive half-time of 3.9 ± 1.4 yr, including minor (6%) increases due to fallout deposition during snow-free summer months. Much of the radionuclide loss from surface soil is a combination of surface erosion during snowmelt and percolation to depths >5 cm. Sampling of strata below lichen carpets showed 5% of ^{137}Cs and 15% of ^{90}Sr inventories were in A_0 horizons (humus layer) and 3-4% of both radionuclides were in A_2 horizons (organic mineral soil) (Hanson and Eberhardt 1973). These values represent integrated fallout deposited over several years (Fig. 1).

Plutonium in surface soils at northern Alaska and northern Greenland study sites decreased at a 0.4-0.5 yr half-time and was measured with considerable difficulty, due to the particulate nature of plutonium and large samples required to provide statistically valid measurements (Hanson 1976).

Vegetation

Direct absorption of radionuclides is the most important process by which fallout is concentrated by arctic flora. Lichens are particularly efficient accumulators of fallout radionuclides (Gorham 1959; Hanson and Eberhardt 1973), of which ^{90}Sr and ^{137}Cs are the most important radioecologically. Concentrations of ^{137}Cs in lichens are about five times those in nearby unvegetated surface (top 5 cm) soils. This is due to radionuclide loss from soil by surface erosion; to upward cycling of ^{137}Cs from underlying soil horizons; the extraordinary capacity of lichens to absorb mineral metabolites from rainwater, snowmelt, and their substrate far beyond expectable needs (Hale 1967, p. 59); and their longevity (>10 -25 yr). Comparison with other plants in northern Alaska during major fallout deposition periods showed that ^{137}Cs concentrations ($\text{nCi/g} = 37 \text{ Bq/g}$) and inventories (nCi/m^2) in undisturbed sedge (*Carex* spp.) swards that characterize many arctic tundra areas were usually 3-25% of values for nearby lichen communities, while values in new growth sedge samples were 2-4% those of lichen samples. Thus, lichens provide an enriched, long-term source of important radionuclides which tend to be concentrated in upper portions of the preferred winter forage of caribou and reindeer.

The possibility of geographical and ecological differences in ^{137}Cs and ^{90}Sr concentrations in lichen communities over the very large study area of northern Alaska was investigated during 1967 and 1972 by intensive sampling at 20 locations from northwestern Canada to the Chukchi Sea, including three locations across the wintering range of the caribou that provided critical food to the native villages. Emphasis was placed on ^{137}Cs to accommodate the substantial number of analyses involved in evaluating samples of 12 major lichen communities separated into their vegetative com-

ponents. Three-way analysis of variance of results showed no significant difference between three ubiquitous species, three physiogeographic provinces from which they were collected, or sampling years (Hanson 1973). "Student's t" test of combined means of all species tested between years indicated that there was usually a highly significant ($P < 0.01$) difference between ^{137}Cs concentrations of the nine species from the three provinces, with samples from the Arctic Coastal Plain and Arctic Foothills more similar than those of either province compared to the higher values in the Arctic Mountains (Brooks Range).

The upper 12 cm (active growing portion) of *Cladonia alpestris* (= *stellaris*) lichen communities generally contain 70-90% of the ^{90}Sr and $>90\%$ of the ^{137}Cs inventory in the lichen carpet, with some indication of fractionation between upper and lower 3-6 cm increments (Mattsson 1975; Hanson and Eberhardt 1973). ^{137}Cs is more readily translocated than ^{90}Sr and responds more readily to seasonal and diurnal patterns of photosynthetic activity in lichens (Moser and Nash 1978), resulting in higher concentrations of ^{137}Cs in upper layers of lichen mats. Experiments with ^{90}Sr and ^{137}Cs in lichens indicate that translocation along lichen thalli is primarily diffusive in character but complicated by cation exchange, similar to results with stable forms of those elements (Tuominen 1967 and 1968), especially with respect to strontium ions. This attraction of Sr to the thalli apparently retards its movement and explains the greater mobility of Cs between compartments of the lichen carpet and underlying strata.

Several circumpolar studies indicate effective half-times of about 5 ± 2 yr for ^{137}Cs and 1.0-1.6 yr for ^{90}Sr in arctic and subarctic lichen communities (Hanson and Eberhardt 1973; Liden and Gustafsson 1967; Mattsson 1975; Miettinen and Hasanen 1967).

Comparison of simulated and observed data in a deterministic model of ^{137}Cs concentrations in lichens collected at Anaktuvuk Pass during 1963-1973 (Thomas et al. 1982) demonstrated the deficiencies in our model despite intensive sampling and analysis. A major need was accurate measurements of fallout deposition rates at the lichen sampling sites, which would have greatly improved model performance in the reality of variable inputs of fallout due to discontinuous nuclear weapons test series and weather systems.

Plutonium isotopes in lichens from northern Alaska during 1967-1979 (Hanson 1980) occurred in pronounced peaks during 1968, 1972, 1974, and 1976 that correlate well with periods of high-yield (>200 kt) nuclear tests by the People's Republic of China and France, and demonstrate a 1-2 yr stratospheric residence time of the test debris. Both ^{238}Pu and $^{239,240}\text{Pu}$ isotopes show the same pattern of concentrations, with

^{238}Pu consistently 0.1 the $^{239,240}\text{Pu}$ values rather than the 0.022 ratio reported in fallout. This 5 \times enrichment was maintained throughout the series, indicating appreciable retention in the lichens. Studies of plutonium in lichen carpets of northern Alaska (Hanson 1976) and central Sweden (Holm and Persson 1975 and 1976) suggest that ^{238}Pu is more tightly bound in the upper 6 cm stratum of lichens than is $^{239,240}\text{Pu}$. Both plutonium isotopes demonstrate an effective half-time in the lichen carpet of about 6 yr, similar to ^{137}Cs and longer than that estimated for ^{90}Sr , thus representing a long-term potential for transfer to grazing reindeer and caribou.

Plutonium-239 was reported to have a mean residence time of 4.3 ± 0.5 yr in the top 3 cm of the *Cladonia alpestris* carpet in Sweden, compared to 6.1 ± 0.5 yr in the entire 12 cm carpet (Holm and Persson 1975), with the difference ascribed to growth of lichen biomass and low solubility of the fallout plutonium oxide.

Herbivores

Concentrations of ^{137}Cs in caribou and reindeer flesh samples clearly follow an annual cycle with low values during fall months and maximum values in spring months. The low values occur in animals returning from their summer range on which sedges and other fresh forage provide a diet containing relatively low amounts of fallout ^{137}Cs and substantial amounts (20 mg/g dry wt) of potassium (Batzli et al. 1980), which combines with increased summer body water turnover to produce the abrupt decline in net accumulation of ^{137}Cs in soft tissues. An effective half-time of 28 days was usually observed in caribou muscle samples obtained between late May and late August, when migration to winter ranges usually began. It is generally accepted that the rate of cesium loss is dependent upon the potassium intake rate (Wasserman and Comar 1961); experiments with reindeer (Holleman et al. 1971) showed that the slow ^{137}Cs component biological half-time was about 17 days on a dietary K concentration of 1 mg/g dry wt and about 6.7 days with a dietary K concentration of 5 mg/g dry wt. Extrapolation of a log-log plot gives a corresponding half-time of about 30 days for a K concentration of 0.37 mg/g, which was the mean value measured in 17 lichen samples collected from caribou winter range near Anaktuvuk Pass during 1964-1967.

During autumn, caribou (and reindeer) gradually shift to their winter diet composed mainly of lichens, and ^{137}Cs concentrations in soft tissues begin a steady increase through winter months; in Alaska the ^{137}Cs levels usually plateaued during January-April of each year. An appropriate ^{137}Cs tracer kinetics model applied during periods of simultaneous sampling of caribou and lichens at the same location on winter range indicated that 4.5-5.0 kg dry wt lichens were ingested

per day (Hanson et al. 1975). ^{137}Cs concentrations in caribou flesh at the end of the winter were 4.0 ± 0.9 (SD, range 3.2-5.5) times the ^{137}Cs concentration of lichens.

Comparison of ^{137}Cs levels in other important herbivores such as moose (*Alces alces*) and Dall sheep (*Ovis dalli*) on ranges near those utilized by caribou showed no significant seasonal pattern and were substantially lower than caribou values. Sheep muscle contained four times the ^{137}Cs concentration in moose muscle but only one-fourth to one-tenth of ^{137}Cs concentrations in caribou muscle. Also, ^{137}Cs concentrations in sheep muscle decreased steadily during winter, in direct contrast to the seasonal pattern in caribou. These differences were due to food habits; the sheep fed mostly on sedges, forbs, and modest amounts of lichens, while moose were observed to feed mostly on willows and other shrubs, aquatic plants, and minor amounts of grasses; during winter, moose foraged mainly on willow twigs.

Strontium-90 concentrates in bone at about 1000 times the levels in muscle of caribou and reindeer. In northern Alaska, ^{90}Sr levels in caribou bone were relatively stable near 20 pCi/g ($= 0.74 \text{ Bq/g}$) until 1962 and then began a sharp increase after the major nuclear weapons test series of 1961-1962 to 70 pCi/g in 1966-1969.

A Concentration Ratio of about 7.6 for caribou bone/lichen existed during the 1966-1969 plateau period, when a condition of 99% of equilibrium existed. During the period May 1964-November 1974 the values declined at a half-time of 56 months to levels near those measured in 1962. ^{90}Sr in flesh followed a more gradual curve of increase, peaking in years of nuclear weapons testing, similar to the ^{137}Cs pattern (Hanson and Thomas 1982).

Concentrations of plutonium in caribou bone samples during the 1971-1975 period of maximum values in lichens were barely detectable. Concentration Ratios relative to lichens were usually in the range of 0.02 for ^{238}Pu and 0.001 for $^{239,240}\text{Pu}$. This suggests that ^{238}Pu was more readily transferred through the food chain than was $^{239,240}\text{Pu}$, perhaps because it was retained in the upper strata of lichens as reported by Holm and Persson (1975); however, the tenuous nature of our values makes such a conclusion speculative, particularly because several age cohorts of caribou were sampled during any one harvest period. However, Holm and Persson (1976) reported no pronounced variation of ^{239}Pu in any organ of reindeer, and estimated biological half-times of 2-4 yr in flesh and 2-10 yr in bone from a simple compartment model.

Carnivores, Including Man

Concentrations of worldwide fallout ^{137}Cs in circumpolar food chains follow an annual cycle dependent

upon the subsistence patterns of human populations and the food habits of carnivores, particularly those associated with caribou and reindeer.

Extensive sampling of flesh of wolves (*Canis lupus*), foxes (*Alopex lagopus* and *Vulpes fulva*), and wolverines (*Gulo gulo*) in northern Alaska showed a repeated annual ^{137}Cs pattern with a rapid increase through fall and winter that paralleled the increase in ^{137}Cs concentrations in caribou. Wolves contained twice the concentrations observed in foxes and wolverines, both of which are primarily scavengers on wolf-killed caribou and consumers of small mammals that contain much lower ^{137}Cs concentrations. The Concentration Ratio for ^{137}Cs in wolf flesh/caribou flesh at 80% of equilibrium for caribou (Hanson et al. 1975) at sampling averaged 2.7.

A similar pattern occurred in ^{90}Sr concentrations in bone of wild carnivores during 1964-1969 and the same relationship was observed; maxima occurred in late winter following utilization of caribou that were increasing their concentrations and wolves contained twice the ^{90}Sr concentrations of foxes and wolverines. Wolves consume more caribou bone than do foxes and wolverines and therefore ingest a richer source of ^{90}Sr than do the scavengers.

Concentration Ratio for ^{90}Sr in wolf bone/caribou flesh at about 50% of equilibrium at time of sampling was 0.4. An effective half-time rate of about 7 years for ^{90}Sr in bone was observed in all three species of carnivores.

Measurement of ^{90}Sr in human bone samples from the native populations of northern Alaska was not feasible; therefore, two mathematical models, one based on Sr kinetics in human bone and another based on ^{90}Sr ingestion rates via caribou meat, were used to predict ^{90}Sr concentrations in skeletons of inland Inupiat (Hanson and Thomas 1982). Results showed that caribou meat contributed 97% of total ^{90}Sr intake of adult native men in 1965 and decreased to 79% in 1975 as a result of declining use of caribou for food as cultural changes promoted a shift to greater dependence upon processed and imported foods. Predicted skeletal values in adult Inupiat males were slightly lower than values reported in New York City adults until 1980 and subsequently declined by 9% per year, compared to 5-6% decrease per year in temperate zone residents. Predicted skeletal burdens in Anaktuvuk Pass residents born in 1954 and 1959 achieved maxima in 1971 and 1974, respectively; concentrations in children born in 1964 were still increasing in 1979 but had achieved a lower level than older age cohorts.

International attention has focused on appreciable ^{137}Cs body burdens of circumpolar populations of people with a subsistence lifestyle or other dependency

upon caribou and reindeer. For that reason, considerable efforts have been made to monitor such remote peoples with ^{137}Cs body burdens that were often 200 times those of subarctic and temperate regions.

Natives of northern Alaska are members of unique ethnic groups with distinctly different subsistence cultures that substantially affect amounts of fallout radionuclides, particularly ^{137}Cs , in their diets. Inland Inupiat (Eskimo) during the 1960s and early 1970s relied upon caribou for much (55-60%) of their food, while coastal Inupiat utilized marine mammals extensively (10-20% of diet) and caribou and reindeer moderately (20%) (Hanson and Palmer 1964, Hanson et al. 1964). Intergradations of both cultures occur along major river systems of northwestern Alaska, where diets included greater amounts (35%) of moose, fish, and other animal products lower in ^{137}Cs than caribou. Athapascan (Kutchin) Indians of the northern Alaska interior also utilized a broad spectrum of food resources similar to river village Inupiat, but with a greater amount of moose in their diets. Such diversity of food-gathering practices prompted our initial surveys of all major ethnic groups of northern and western Alaska (Palmer et al. 1963; Hanson and Palmer 1964), followed by definition of relationships of ^{137}Cs body burdens to subsistence activities of contrasting native cultures (Hanson 1971) and specific studies of fallout radionuclides in the arctic ecosystem associated with the lichen-caribou-nunamiut Inupiat food chain at Anaktuvuk Pass (Hanson 1967b, 1973, 1982). A simulation model of that system (Eberhardt and Hanson 1969) incorporating five years of intensive sampling provided some appreciation of the complexities involved in modeling the apparently simple system. ^{137}Cs concentrations in inland Inupiat of Anaktuvuk Pass, Alaska followed an annual cycle that closely paralleled that of the caribou that provided their major food supply during the 1962-74 period (Fig. 1). Normal subsistence harvesting of caribou occurred during fall (southward) and spring (northward) migrations of caribou; fall-harvested animals were fatter and lower in ^{137}Cs , compared to spring-harvested animals that had fed heavily on lichens during winter months. Summer maxima in adult Inupiat were about 70-80% of expected equilibrium values that were not achieved because of limited caribou meat storage capability. Children were near equilibrium with the food supply because of their smaller body mass and shorter effective half-times.

Significant departures from the expected annual pattern of human ^{137}Cs concentrations predicted by the lichen-caribou-Inupiat food chain model (Eberhardt and Hanson 1969) were due to ecological, cultural, and political factors that emphasize the importance of understanding the ecosystem structure and function. These

departures are indicated by the circled numbers atop the upper curve in Fig. 1. The apparently more variable nature of ^{137}Cs in components of northern Alaska food chains during 1962-1979 compared to similar studies in Scandinavia and USSR is due to more intensive sampling in a natural setting, rather than a controlled pastoral situation (Hanson 1967b). Comparison of results from studies in Alaska, Finland, Norway, Sweden, and USSR during the period 1962-1969 demonstrates that the general situation in which substantial ^{137}Cs human body burdens were associated with the lichen-caribou/reindeer-man food chain was very similar everywhere, although there were minor differences in levels and seasonal fluctuations.

Our lichen forage ingestion model estimated that caribou on winter range ingested an estimated 80-90 pCi ^{238}Pu and 800-900 pCi $^{239,240}\text{Pu}$ per day during the mid-1960s to mid-1970s, yet bone samples contained barely detectable amounts, usually in the 0.01 fCi/g range, for both radioisotopes. Assuming averages of 17.5 fCi/g for ^{238}Pu and 175 fCi/g for $^{239,240}\text{Pu}$ in lichens during the above period, Concentration Ratios of 0.02 and 0.001 are estimated. This indicates that ^{238}Pu was more readily transferred through the lichen-caribou food chain than was $^{239,240}\text{Pu}$; however, the tenuous nature of the values makes such a conclusion speculative.

In any case, the transfer of these radionuclides through the arctic food chains has until recently been a minor concern. Very little emphasis has been placed on radioecological studies of arctic ecosystems during the past decade and only brief concern has been expressed for fallout episodes involving the lichen-caribou/reindeer-man food chain, such as the Chernobyl accident. That situation presented an unusual opportunity to apply our considerable knowledge of the system as guidance for defining critical elements of concern and reasonable programs of action. Similarly, the 6 April 1993 explosion at the Tomsk-7 facility in Siberia has initially been of brief concern to the world in general; the radioecological implications, particularly the Russian people and ecosystems involved, need greater consideration.

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Ecological Radionuclide Concentration Measurements in Alaska

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The recent disclosure of radioactive waste disposal in the Cape Thompson area of Alaska has renewed interest and concern of the effects of anthropogenic radionuclide contamination of terrestrial systems and its implications for the radiation exposure to humans. Further awareness has been provided by disclosures of terrestrial contamination from nuclear applications, disposals and other accidents, primarily occurring in the former Soviet Union. These events enforce the importance of ongoing radionuclide concentration measurements in the environment. Concentration measurements have been made in various ecological items, such as soil, plants and animals, for the parent fissionable material (primarily the isotopes of plutonium), the long-lived fission products (Sr-90 and Cs-137) and the activation products (Na-22, Fe-55, Cs-134).

Two groups have been responsible for most of the measurements in Alaska, namely Battelle Northwest Laboratory (W. C. Hanson) and the University of Alaska Fairbanks (UAF). W. C. Hanson made measurements beginning in the late 1950's and continued until about 1980. His paper in *Health Physics* (Vol. 42, No. 2, 1982) presents much of this data and gives many of the pertinent references on radionuclide concentrations in Arctic regions. Measurements by UAF were begun in 1969 and have continued to the present. Both groups have focused attention on Cs-137 concentrations in terrestrial systems, primarily on the lichen - reindeer/caribou - man/wolf food chain. This emphasis is justified since Cs-137 has the potential of producing the majority of the radiation dose to man from fission-related radioactivity, and its pathway to man is likely to be via the consumption of reindeer/caribou meat.

In Alaska, Cs-137 concentrations increased in the late 1950's and early 1960's and reached their highest concentrations in the mid to late 1960's. In general, the levels have decreased since the late 1960's except for the slight increase in 1986 due to the Chernobyl acci-

dent (White et al., 1986, *Rangifer* No 1 Appendix 24-29; Jones, 1989, *JAVMA* 194, p. 900-902; Baskaran et al., 1991, *Arctic* 44, p. 346-350). The highest Cs-137 concentrations in lichen ranged from 900 to 1150 Bq/kg dry matter (24,000 - 31,000 pCi/kg). Levels at present are less than 180 Bq/kg (5,000 pCi/kg). The highest concentration in reindeer/caribou muscle were measured in winter in the mid 1960's and ranged from 1200 to 1800 Bq/kg (32,000 - 50,000 pCi/kg) and at present concentrations are less than 200 Bq/kg (5,400 pCi/kg). Due to intake and kinetic considerations concentrations in the wolf can be several times the average concentration in their prey.

The main support for continued monitoring of Cs-137 in the Alaska's ecosystems since 1980 has been driven by the role that this isotope can play as a tracer in ecosystem and wildlife management research. At UAF we have supported wildlife management agencies in Alaska and Canada (Yukon, NWT) with their estimation of wolf predation on caribou as opposed to moose as the major food base (Holleman and Stephensor, 1981, *J. Wild. Manag.* 45, p. 620-628; Hayes and Baer, 1986, *Yukon Renew. Res. Whitehorse*). Those wolf packs showing relatively high body burden of Cs-137 in late winter/spring have used mainly caribou as a winter food resource. Recently, we have shown that mushrooms as well as lichens constitute a source of Cs-137 for caribou. The intake of mushrooms in autumn can result in an abrupt increase in the Cs-137 body burden of caribou. This increase occurs prior to the slower winter increase due to Cs-137 in lichens (Allaye-Chan et al., 1990, *Rangifer* SI#3, p. 17-24). Fungi appear important as a means of moving Cs-137 in the terrestrial system. It is suggested that this food chain can be used to assess ecosystem health and we advocate continued monitoring of lichens, mushrooms, caribou and wolves for the dual purposes of wildlife management and possible influence on human radiation exposure.

Bioaccumulation of Radionuclides, Trace Metals, and Organic Contaminants in the Marine Environment

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The purpose of this review is to highlight a few salient features regarding the bioaccumulation of radionuclides, trace metals, and organic contaminants in marine ecosystems, and point out some generalizations that have emerged over the years which apply to these contaminants. From first principles, there is concern about the presence of toxic substances in the marine environment because these chemicals are toxic to organisms, including people. We certainly know well that organisms do not respond, by and large, to contaminants that are not in them or on them. They need to be accumulated in order for there to be any detrimental impact of the contaminants. The whole question of bioaccumulation of contaminants is therefore relevant to risk assessment models. Both transport models and radiological protection models require coefficients for such considerations as the extent to which contaminants, radionuclides, metals, and others, are accumulated in the organisms. Moreover, it is important to have a good appreciation of the rates and routes of uptake and depuration of contaminants in sentinel organisms, such as mussels and brown macroalgae, in order to be able to interpret, unambiguously, spatial and temporal trends revealed by monitoring data. It is therefore critical to understand the rates and extents to which contaminants are accumulated by marine organisms out of their environment. This will determine the extent to which they will be impacted by these contaminants as well as the extent to which they will mediate the transfer of these chemicals up food chains, potentially leading to man.

Composition and Characteristics of Radioactive Wastes

Generally, radioactive wastes consist largely (but not exclusively) of metals. Virtually all groups of metals are well represented, including alkali and alkali earth

elements, lanthanides, transition metals, and actinides (which include the man-made transuranic elements such as plutonium and americium). A representative list of the principal components of radioactive wastes is given in Table 1. This is by no means an exhaustive list, but demonstrates the types of elements, their radioactive half-lives, and their principal emissions which are present in radioactive wastes. Since radioactive and stable (i.e., non-radioactive) isotopes of the same element behave essentially identically, we can apply what

Table 1. Some principal radionuclides in radioactive wastes, their radioactive half-lives, and the principal type of radiation they emit.

<i>Radioisotope</i>	<i>Half-life (years)</i>	<i>Radiation emitted</i>
helium-3 (^3H)	12.3	beta
carbon-14 (^{14}C)	5,730	beta
iron-55 (^{55}Fe)	2.6	x-ray
cobalt-60 (^{60}Co)	5.3	beta, gamma
nickel-59 (^{59}Ni)	80,000	x-ray
nickel-63 (^{63}Ni)	92	beta
strontium-90 (^{90}Sr)	28.1	beta
niobium-94 (^{94}Nb)	20,000	beta, gamma
technetium-99 (^{99}Tc)	200,000	beta
iodine-129 (^{129}I)	12 million	beta, gamma
cesium-135 (^{135}Cs)	3 million	beta
cesium-137 (^{137}Cs)	30	beta, gamma
uranium-235 (^{235}U)	700 million	alpha, beta, gamma
uranium-238 (^{238}U)	4,500 million	alpha, gamma
neptunium-237 (^{237}Np)	2 million	alpha, beta, gamma
plutonium-238 (^{238}Pu)	86	alpha, gamma
plutonium-239 (^{239}Pu)	24,000	alpha, gamma
plutonium-240 (^{240}Pu)	6,580	alpha, gamma
plutonium-241 (^{241}Pu)	13.2	alpha, beta, gamma
plutonium-242 (^{242}Pu)	280,000	alpha
americium-241 (^{241}Am)	433	alpha, gamma
americium-243 (^{243}Am)	7,950	alpha, beta, gamma
curium-243 (^{243}Cm)	32	alpha, gamma
curium-244 (^{244}Cm)	17.6	alpha, gamma

we know about metal interactions with marine organisms and geochemical cycling of metals to the study of radioactive waste as well.

Metals have been categorized as hard metals or class A metals, soft or class B metals, and so-called borderline metals (Nieboer and Richardson, 1980). The class A type metals are typically oxygen seekers and have a greater affinity for fluorine than chlorine among the halogens. Examples of class A metals include the lanthanides, the transuranic elements, and cesium, among others. Class B metals are typically sulphur and nitrogen seekers, especially sulphur. They have a much greater affinity for sulphur than they would for oxygen for example. Mercury and silver would be good examples, as well as the platinum group metals. Because of their strong affinity for sulphur, class B metals commonly associate with proteins in biological tissue, whereas the class A metals are frequently (but not always) associated primarily with mineral phases and bone tissue. Borderline metals, those that have characteristics in part of each of these groups, include many of the transition metals (for example, cobalt, cadmium, and zinc). A detailed presentation of the position of the different types of metals on the periodic table is given in Whitfield and Turner (1987). Examples of functional groups or moieties that the different types of metals would bind to in organic compounds are given in Table 2. Note that the class A metals are primarily oxygen-seeking whereas the class B metals tend to bind to sulfhydryl and amino groups which are typically in protein.

Table 2. Some metal binding sites in organic molecules.

Functional groups sought by:

<i>Class A metals</i>	<i>Class B metals</i>
carboxylate	sulphydryl
carbonyl	disulphide
alcohol	thioether
phosphate	amino
phosphodiester	heterocyclic N: imidazole of histidine, nucleotide bases

It is critical to understand the speciation of metals in aquatic systems in order to be able to understand the bioavailability of those metals (Luoma, 1983; Sunda, 1989). There have been a great many efforts that have been conducted over the years to try to characterize the speciation of metals in both freshwater and marine systems. In model seawater, calculations show that different metals speciate very differently. Some are strictly associated with chloro-complexes, such as mercury and cadmium, while others (cesium, for example) principally exist as the free metal ion, others form

hydroxy complexes, etc. (Turner et al., 1981). However, model seawater does not fill up the ocean basins. There is, of course, a lot of dissolved organic matter in seawater, and some of that material can complex some of these metals very appreciably (e.g., Florence and Batley, 1980). A generalization can be made that those metals which are complexed by dissolved organic matter are far less biologically available than is the free metal ion (Sunda, 1989). Another generalization is that metals tend to be more particle-reactive in freshwater than they are in marine systems due to the differences in competing ions but, with a few exceptions, orders of magnitude difference in particle reactivity are not commonly observed. A notable exception would be cadmium, which is a strongly chloro-complexed in marine systems and for which its partition coefficient for both living and abiotic particles is about two orders of magnitude greater in freshwater than in marine systems.

Biological Interactions

When a phytoplankton cell is exposed to different metals, at different concentrations, and is allowed to equilibrate over time (on the order of 24 to 72 hours), one typically observes that metal accumulation in the organism is proportional to the concentration ambient, conforming with Freundlich absorption isotherms (Fisher et al., 1984). Moreover, uptake of the metals by a broad array of different types of cells is largely passive (Fisher et al., 1983a, 1984; Fisher and Wentz, 1993). That is, cells do not have to expend energy to concentrate metals out of seawater, and living and dead cells accumulate metals to essentially the same extent. Similarly, metals can passively sorb to other living "particles"—not just phytoplankton, and generally uptake conforms with Freundlich adsorption isotherms (Bjerrgaard et al., 1985).

At the time of apparent equilibrium with respect to partitioning between the metals in the dissolved phase and in the organism, one can calculate concentration factors. This can be done on a weight basis, or a volume basis, or any other basis including surface area basis, which is actually the most difficult, but probably the most appropriate since many of the metals initially associate with the particle surfaces, after which they can be transported into the organism (e.g., Williams, 1981). Concentration factors on a volume/volume basis are calculated, at time of equilibrium, as the number of moles of metal per cubic micron of organism divided by the moles of metal per cubic micron in the dissolved phase in the water. The term "dissolved" is operationally defined, defined here as smaller than 0.2 microns (that is, smaller than a bacterium).

One set of generalizations that has emerged is that concentration factors tend to increase inversely with

DOC concentrations, but DOC can influence some metals, such as copper for example, far more than it can influence other metals (Fisher and Frood, 1980). Surprisingly, americium and plutonium are not strongly influenced by naturally occurring DOC in seawater (Fisher et al., 1983c), although in freshwater systems at higher DOC concentrations they can be complexed by this material (Nelson et al., 1985). Competing ion concentrations can also lower concentration factors (e.g., Braek et al., 1980). There is still controversy over whether concentration factors decrease with increase in suspended particle load (McKinley and Jenne, 1991).

Table 3 presents geometric mean concentration factors for metals in phytoplankton, based on studies with up to 7 different algal species belonging to different algal divisions including all the major taxonomic groupings represented in the sea (e.g., diatoms, coccolithophores, dinoflagellates, chlorophytes, cyanophytes, etc.). All species studied had cells of about the same size, which is critical since smaller cells have higher surface to volume ratios and typically display greater concentration factors (expressed on volume or weight bases) for a given metal than do larger cells (Fisher, 1985). As is clear from Table 3, concentration factors range from essentially not significantly different from zero, for example, for technetium, to concentration factors in excess of 10^5 for mercury, some of the transuranic elements and thorium. The variation in concentration factors among the different types of phytoplankton for a given metal is typically quite small, but one sees many orders of magnitude difference in concentration factors among metals (Fisher, 1986). Summarizing for phytoplankton, uptake tends to be rapid, passive, and proportional to ambient concentrations. There are big differences between metals and smaller differences between species.

A curious side note here is that technetium, a very important fission product which exists in oxygenated

seawater as the pertechnetate anion, is concentrated over 10^4 by brown macroalgae such as *Fucus*, which makes it a very useful bioindicator of the presence of technetium in marine systems (Topcuoglu and Fowler, 1984). No other organism appreciably concentrates this element and it is still unknown what advantage is conferred upon the brown algae in concentrating technetium.

Partition coefficients of metals for sediments generally correlate well with concentration factors of the same metals for marine phytoplankton (IAEA, 1985). Thus, as a general trend, those metals that are reactive for phytoplankton are also reactive for abiotic particles as well and those metals which show little affinity for abiotic particles tend not to be concentrated by phytoplankton.

When considering metal uptake in diverse forms of phytoplankton and zooplankton from the dissolved phase, it can be shown for particle-reactive transuranic elements, such as plutonium, americium, and curium, that concentration factors are not only greater for smaller organisms (as expected), but that all particles seem to have an equal number of binding sites per square micron of surface (Fisher and Fowler, 1987; Fisher and Reinfeld, in press). Definitive explanations for these observations still elude us.

Animals can acquire metals from both the water (i.e., the dissolved phase) and from ingested food. In most areas of the ocean, most metals, even very particle-reactive metals such as the transuranics with very high partition coefficients, are predominantly in the dissolved phase (using the operational definition of less than 0.2 micron as dissolved). This simply reflects the relatively low particle loads encountered throughout the ocean (often in the ≤ 1 mg per liter range). Thus, even for plutonium, about 97% is typically in the dissolved phase in seawater (Fowler et al., 1983; Cochran, 1987). In coastal waters, particularly where there is suspended sediment, the particle load can increase to tens of milligrams per liter, but even there, most metals are primarily in the dissolved phase. So, from first principles, the dissolved phase can be expected to be very important for uptake into animals. This would depend on the extent to which animals assimilate metals from their food, a subject which is discussed below.

Let us first consider uptake of americium from the dissolved phase in a crustacean zooplankter (a euphausiid). Americium is used here as representative of many biologically nonessential particle-reactive elements such as the lanthanides (which, like americium, have plus three valences). After radiolabeling euphausiids from the dissolved phase, and then allowing them to depurate, it was shown that virtually all the americium was on the chitinous exoskeleton of these animals

Table 3. Geometric mean concentration factors (on a volume/volume basis: VCF) in diverse species of marine phytoplankton (nanoplankton size range). From Fisher and Reinfeld (in press).

Element	Geometric mean (VCF)	Element	Geometric mean (VCF)
cobalt (Co)	1,500	mercury (Hg)	120,000
zinc (Zn)	13,000	lead (Pb)	96,000
selenium (Se)	6,000	polonium (Po)	72,000
technetium (Tc)	3.7	thorium (Th)	420,000
cadmium (Cd)	1,000	neptunium (Np)	< 150
silver (Ag)	46,000	plutonium (Pu)	230,000
tin (Sn)	70,000	americium (Am)	160,000
barium (Ba)	810	curium (Cu)	220,000
gold (Au)	4,800	californium (Cf)	220,000

(Fisher et al., 1983b). When these animals molted, 96% of the americium was lost from the animal, so less than 4% of the americium that was taken up from the dissolved phase was retained by these animals after molting. If instead of taking up americium from the dissolved phase, animals are fed diatoms which are uniformly radiolabeled with americium, so the only source term of americium is ingested, radioactive food, it is observed that virtually none (<1%) of the americium is retained by the animal after it empties its gut. Thus, more than 99% of the americium is defecated by the animals in fecal pellets.

What happens to the radioactive fecal pellets or exoskeletons that are produced by the herbivorous animals? Again, let us consider americium as a representative particle-reactive, nonessential metal. Its retention half-time in euphausiid fecal pellets is on the order of 45 days, and this is not significantly influenced by temperature over a range of 4 to 13°C; the Q_{10} is not significantly different from 1 (Fisher et al., 1983b). Furthermore, the retention half-time of americium in the cast exoskeletons (the chitinous molts of these crustacean zooplankton) is about three days (Fisher et al., 1983b). Combining this information with sinking rates of fecal pellets, molts, and other types of biogenic debris such as marine snow, one can calculate (or build models to at least make predictions for) the influence of this sinking biogenic debris on the vertical flux of these particle-reactive elements from surface waters into deeper waters. With a phytoplankton cell sinking at a rate of less than 1 meter per day, even though the retention half-time of americium is twelve days in phytoplankton, virtually none of the americium would be retained by that phytoplankton cell, assuming it stayed intact, by the time the cell sank to a depth of 500 meters; certainly none would reach the sea floor in deep ocean basins. By contrast, for debris like euphausiid fecal pellets, which sink at rates of 100–300 meters per day, and have retention half-times for americium of 46 days, a very substantial fraction of the americium would be transported to very deep waters by this type of sinking biogenic debris (Fisher and Fowler, 1987).

Simple modeling has been done to evaluate the time necessary to remove half of the contents of americium from surface waters for different concentrations of phytoplankton and zooplankton standing crops. It was shown that residence times in surface waters are not sensitive to algal biomass but are acutely sensitive to the zooplankton biomass (Fisher and Fowler, 1987). These calculations assumed that the algae themselves have no significant sinking rate. We know, however, that some algae can form aggregates and sink at rates of about 100 meters per day (Alldredge and Gotschalk, 1989), and so phytoplankton that form such aggregates can transport

some particle-reactive metals to intermediate depths in the water column (Fisher and Wentz, 1993).

Other metals behave differently from the particle-reactive, non-essential metals like americium, however. Some metals are assimilated much more from ingested food in herbivores than are americium and plutonium. Generally, it has been observed that assimilation efficiency of ingested elements (regardless of whether or not they are biologically essential) in marine herbivorous zooplankton is directly correlated with the cytoplasmic fraction of the elements in the algal food (Reinfelder and Fisher, 1991). Thus, those elements which penetrate into the cytoplasm of phytoplankton cells get assimilated in herbivore tissue, whereas metals which remain on the surface of algal cells (such as americium) do not assimilate in the herbivores.

Concentration factors of metals in phytoplankton tend to be one to two orders of magnitude higher than they are in animals, including upper level carnivores (IAEA, 1985). Thus, there is little evidence of food chain magnification of metals (i.e., increasing metal concentrations in tissues with increase in trophic level) in marine systems. One exception is mercury, which can be methylated, and for which there is evidence of biomagnification. Cesium also shows a slight increase in concentration factors up the food chain. Thus, it would appear that the herbivorous zooplankton act as a sort of barrier in the food chain for trophic transfer of nonessential particle-reactive metals like americium. For these metals, which show very low assimilation in animals, the phytoplankton represent an enriched source, but the metals are not assimilated by the zooplankters. When a carnivorous animal eats that zooplankter, it is not going to get a large dose of americium because most of it has been lost from the animal.

Organic Pollutant Interactions with Marine Organisms

There are several notable differences between interactions of organisms with organic compounds and metals. Organic compounds tend to localize of course in lipids in biological tissue. They can be sometimes be degraded or metabolized. Degradation is not necessarily a "good thing" for the organism, however, because sometimes the degradation product is more toxic than the original parent compound (Stegeman, 1981). For organic compounds, there is much more convincing evidence that biomagnification up the food chain occurs. This is especially true for fish-eating mammals and fish-eating birds that aren't constantly immersed in marine systems, so that they have a smaller chance to depurate and equilibrate with an aqueous environment. Both organic contaminants and metals can be influenced by the same geochemical processes. It has been

shown that most organic contaminants bioaccumulate in aquatic organisms (both marine and freshwater) in a way that correlates well with the solubility of the compounds (Tulp and Hutzinger, 1978; Schwarzenbach et al., 1993), which in turn correlate well with octanol-water partition coefficients (Mailhot and Peters, 1988). This correlation can break down for some compounds with octanol-water partition coefficients exceeding 10^6 (Connell and Hawker, 1988), possibly due to the presence of colloidal material.

Suggestions for Future Research

There are several questions which need addressing to better evaluate the dangers of chemical contaminants introduced into the Arctic marine ecosystem. (1) Can sediments be thought of as a source as well as a sink for contaminants? What are the processes that mobilize contaminants, including organic contaminants and radionuclides, from sediments? Is bioturbation, a process for which there is more speculation and fact, important in this regard? How do the geochemistry and organic content of the sediment influence contaminant mobilization? (2) What are the rates and routes of contaminant uptake and depuration in sentinel organisms such as mussels? There is surprisingly little information on this. (3) Are the findings from temperate or subtropical systems, for which we have greatest amount of data, applicable to Arctic waters and biota? It is likely that they are applicable, but we need to have some confirmation of that. (4) Do assimilation efficiencies of ingested metals in animals differ predictably among different classes of metals? Can we make some broad brush predictions? (5) What are the assimilation efficiencies of ingested organic compounds in marine food chains? This is largely unstudied. (6) What is the bioavailability of colloiddally-bound contaminants? It is known that both PCBs and some metals, including plutonium, americium, and other metals which are important components of radioactive waste, are associated with colloidal material, but the bioavailability of this material is largely unstudied.

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Implications for Human Health of Arctic Environmental Contamination

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Monitoring chemicals in the arctic to determine man's impact on nature already has led to important scientific findings and has had major impacts on people who live there. For many, the arctic has been viewed romantically as a harsh, desolate, remote, and pristine environment—and was believed to be a vast area heretofore spared from the unsavory consequences of man's technologic and industrial advances and excesses. During the past decade we have seen a steady onslaught of scientific studies that have documented the transportation of anthropogenic pollutants from mid-latitudes to the arctic. Local episodes of pollution from industries have been widely publicized. People living in the arctic are very concerned by these findings and are afraid—for their health and for their environment. And reports of catastrophic environmental damage in the Former Soviet Union have raised these fears to even higher levels.

The currently proposed, but not yet funded, Arctic Monitoring and Assessment Program (AMAP) has received widespread support from circumpolar countries. The interface between scientific monitoring of the environment and implications of the results for human diet and health is an important area to consider. What are the benefits? And what are the risks?

Extraordinary changes have taken place in Alaska and in the arctic in the past 40 years. In 1993, the health of Alaskans has never been better. We have witnessed an almost miraculous reduction in life-threatening infectious diseases. The infant mortality rate has fallen to an all-time low. The death rate has fallen to an all-time low. And, the life expectancy of an Alaskan has never been higher (1).

Until only a short time ago, the life expectancy of an Alaska Native was only 47 years (1)—similar to that in Ethiopia or Bangladesh today. A special team sent to

Alaska in 1950 by Congress to assess the health status of Alaska Natives reported that the situation in Alaska was a national disgrace and that Alaska was "Unfinished Business" (2). Until recently, public health and medical efforts in Alaska were focused almost entirely on control of infectious diseases such as polio, measles, diphtheria, whooping cough, streptococcal disease, rheumatic fever, botulism, bacterial meningitis, otitis media, and especially tuberculosis. Just 50 years ago, tuberculosis caused 43% of all deaths among Alaska Natives each year.

As a consequence of the tremendous improvements in overall health status, new disease patterns have emerged. Chronic diseases such as diabetes, heart disease, and cancer that were seen infrequently or not at all just 40 to 50 years ago now are common place. And new epidemics have emerged.

Arctic residents, and particularly Alaska Natives, now are experiencing an epidemic of tobacco-caused cancer. In 1950 there were 6 deaths from lung cancer—in 1988 there were 143. In 1950, only one Alaska Native died from lung cancer; from 1980 to 1989, 24 died each year. In 1950 the death rate among Alaska Native males from lung cancer was 5.6/100,000; it is now 89/100,000 (Tables 1-3) (1). And, as the use of smokeless tobacco has skyrocketed; we have now seen oral cancers in teenagers.

In a recent article in *Science* entitled "Toward the Primary Prevention of Cancer," Brian Henderson and his co-authors concluded, "the widespread public perception that environmental pollution is a major cancer hazard is incorrect" (3).

Yet, consider the results of a recent investigation into a cluster of 10 cancer cases that occurred from 1983 to 1986 in a remote Alaskan village of 207 residents

Table 1. Lung cancer deaths in Alaska.

<i>Year</i>	<i>Cases</i>
1950	6
1980	85
1988	143

Table 2. Lung cancer death rates in Alaska.*

	<i>Native males</i>	<i>Non-native males</i>
1950	5.6	6.3
1980-1989	88.9	71

*(per 100,000)

Table 3. Lung cancer deaths and tobacco dependence deaths.

	<i>1950</i>	<i>1980-1989</i>
Native		
Lung cancer	1	244
Tobacco	0	48
Total population		
Lung cancer	6	1,176
Tobacco	0	267

Table 4. Cancer diagnoses in villagers 1972-1986.*

<i>Year</i>	<i>Type of cancer</i>
1972	1 colon; 1 genital
1978	1 thyroid
1983	1 esophagus
1984	5 lung
1985	1 lung; 1 bladder
1986	1 lung; 1 stomach

*Data provided by the CDC's Arctic Investigations Laboratory, Anchorage, Alaska.

(Table 4) (4). Of 7 residents who were diagnosed with lung cancer, all had significant exposure to cigarettes with up to 74 "Pack Years" (Table 5) (4). Although 74% of villagers believed cigarettes were an important cause of cancer, many strongly believed the cancers were due to environmental causes such as chemical contamination of drinking water (from fluoride and chlorine), radioactive fallout from atmospheric weapons testing, changing from traditional to "Western" diet, indoor air pollution (including radon), and depletion of the ozone layer (Table 6) (4).

While historically, cancer among Alaska Natives was essentially unknown, today it is common and often bewildering. Bewilderment has its roots in sorrow and

Table 5. Smoking habits of residents diagnosed with lung cancer.

<i>Code number</i>	<i>Age began smoking</i>	<i>No. of years of Smoking</i>	<i>Packs per day</i>	<i>Pack years</i>
1	10	53	1	53
2	25	18	0.5-1	9-18
3	12	52	0.5	26
4	12	60	1	60
5	17	53	1	53
6	21	37	1.5-2	55.5-74
7	16	20	1.5-2	30-40

Table 6. Six native theories of cancer causation in rank order by percentage of household in agreement.

1. Drinking water contamination/chemicals 34/46 (74%)
1. Smoking cigarettes 34/46 (74%)
2. Fall-out from nuclear testing in China or Russia 14/46 (30%)
3. Change from traditional to "Western" diet 8/46 (17%)
4. Indoor air pollution from wood smoke, etc. 7/46 (15%)
5. Outdoor air pollution and ozone layer depletion 4/46 (9%)

fear but is aggravated by our general lack of understanding of risks in our personal lives. This distortion is fed by sensationalistic reporting by the news media, and by inappropriate linking of scientific research findings to exaggerated claims of adverse health effects in order to obtain funding or to mobilize political support.

All studies have shown that we constantly overreact to trivial risks and ignore much more substantial threats to our health and safety. In contrast to indifference and unthinking acceptance of many common injuries and diseases, environmental hazards often evoke our strongest emotions. One of our greatest challenges is to use our knowledge to enable us to make informed choices.

We perceive risks taken voluntarily differently than those that we believe we are subjected to without our choice. For example, in 1913, Earnest Shackleton, in an ad to solicit a crew for an expedition to the South Pole wrote, "Men wanted for hazardous journey. Small wages, bitter cold, long months of complete darkness, constant danger, safe return doubtful. Honor and recognition in case of success." Shackleton found himself with 5000 applicants for 28 positions.

Without a clear understanding of how to interpret findings from environmental monitoring, it is all too likely that we will respond to documentation of the presence of pollutants with "Ready, Fire, Aim." Our apprehension is well grounded in history:

- After the *Exxon Valdez* oil spill in Alaska, \$18.2 million was spent to rescue 222 otters; less than half are thought to have survived (5).
- Alaskans spent \$30 million to remove chrysotile asbestos from a state office building in Juneau, although scientific studies (6-8) suggested this to be unnecessary and very probably harmful.

- Alaskans spent more than \$6 million to remove lead ore from the town of Skagway, although studies proved the ore to be relatively inert and not to contribute to the body burden of lead of community residents. (9)

The impact of the discovery of environmental pollutants in the arctic has been heavily felt. Episodes have occurred with the discovery of many of the pollutants proposed as priorities in the Arctic Monitoring and Assessment Program, especially heavy metals, organic hydrocarbons, and radionuclides. Even if the toxic effects on human health have been trivial, headlines and human impacts are not.

The discovery of high levels of mercury and arsenic in a localized area of a playground in the midst of Nome serves as an example. Health warnings were posted and press releases sent out before any consultation with health officials or the local community. Nome residents (and incidentally, local and State health officials) awoke to find "moonsuited" technicians in the playground and newspaper headlines claiming that residents faced a higher lifetime risk of cancer and other illnesses. The ensuing health assessment found no evidence that residents were exposed to the metals found at the playground and no evidence of any increased health risk (10).

Results of monitoring marine mammals for heavy metals have found high levels of mercury and cadmium for many decades. Based on quantitative risk assessment calculations extrapolated from studies of occupationally exposed workers, press releases advised Alaska Natives to cease consumption of walrus and seal because levels exceeded regulatory guidelines. A more comprehensive health risk assessment by the National Centers for Disease Control, Indian Health Service, and State Health Department found that the heavy metals discovered were not absorbed by humans consuming these foods (11), and that significant beneficial effects are to be expected from marine mammal subsistence consumption. After a one-year study in 1986, findings were provided and discussed with villagers. After many meetings and widespread discussion, things pretty much returned to normal—until last year when the entire chain of events was repeated with different players.

Another example of the tremendous concern over environmental contaminants is the recent controversy over the reports of potential contamination of Alaska salmon with polychlorinated biphenyls (PCBs) and dioxin. First came a major assessment of potential adverse health effects from environmental contamination from pulp mills in Southeast Alaska. Soon afterward *Consumer Reports* published a report, widely covered by the news media, about seafood quality. Studies to date have shown these fears from organic hydrocar-

bon contamination of potential adverse health effects from consumption of Alaska salmon to be groundless. Although there was no connection between publication of an editorial in *Science*, "Excessive Fear of PCBs," (12) and the Alaska incidents, no headlines or news media reported this more assuring message to the public.

In spite of media reports to the contrary, we have good evidence that the heavy metals have been present in the arctic for a very long time (13,14). The discovery of extremely well-preserved mummies that are 500 years old in Greenland has provided valuable scientific evidence. Among the many analyses performed, several heavy metals were measured in hair from the human bodies and from the seal-skin garments. Cadmium levels were similar to those found today. Mercury levels in the mummies were less than found today, but were still comparatively high. As expected, lead levels showed the greatest increase (Table 7) (13,14). Interestingly, although many believe that cancer did not exist in Eskimos before the 1950s, one of the bodies showed evidence of cancer, most probably a nasopharyngeal carcinoma.

It is essential that we learn more about these metals and chemical contaminants in the arctic. There also is a unique opportunity for *bipolar* research—or it will be of great interest to know the comparable levels of these heavy metals and organic hydrocarbons in the Antarctic. Of special interest will be the potential to expand monitoring for these specific environmental pollutants to obtain more information on the composition of omega-3 fatty acids found in seafood and marine mammals. Whereas the results of monitoring for environmental pollutants will have little immediate benefit to human health, further understanding of fish oils may provide many benefits to the health of all.

Great interest exists in studying the effects of dietary seafood that is high in omega-3 fatty acids. This interest traces its origins to two Danish physicians, Bang and Dyerberg, who observed a low incidence of cardiovascular diseases in Greenland Eskimos and who showed a strong association between this lack of heart disease and a marine-based diet (15-17). Their subsequent studies documented many important effects of omega-3 fatty acids (18-19).

Omega-3 fatty acids are polyunsaturated fatty acids in which the first double bond occurs between the third and fourth carbon atoms from the methyl terminal of the fatty acids. The most abundant long chain omega-3 fatty acids are EPA (eicosapentanoic acid, 20:5) and DHA (docosahexanoic acid, 22:6). These are found in phytoplankton, consumed in the food chain, and found in seafood in high amounts (20).

Saturated fatty acids have no carbon to carbon double bonds and are found mostly in animal tissue (e.g.,

Table 7. Trace element concentrations (mg/kg) in human and animal hair samples, obtained by atomic absorption spectrometry. Means and 95% confidence intervals (in parentheses) are indicated.

Element	Human samples				Animal samples			
	15th century		20th century		15th century		20th century	
	No.	Mean	No.	Mean	No.	Mean	No.	Mean
Hg	6	3.1 (2.3-4.2)	22	9.8 (6.8-13.5)	9	0.6 (0.5-0.7)	10	2.6 (1.8-3.7)
Cd	6	0.5 (0.3-4.2)	22	0.4 (0.3-0.5)	9	0.3 (0.3-0.5)	10	0.8 (0.6-1.0)
Pb	6	0.7 (0.3-2.1)	22	6.0 (3.5-10.3)	9	0.4 (0.3-0.4)	10	1.9 (1.2-1.8)
Cu	6	8.8 (5.3-14.6)	18	16.5 (13.6-19.5)	9	15.1 (12.0-14.6)	8	10.0 (7.7-12.9)
Se	5	2.8 (2.3-3.5)	10	0.8 (0.7-0.9)	9	2.3 (1.9-2.9)	8	2.4 (2.0-3.0)

Taken from Meddelelser om Grønland, Man & Society 12 - 1989.

stearic, palmitic). Linoleic acid is an omega-6 fatty acid—the first double bond from the methyl terminal of the fatty acid is between the sixth and seventh carbon atoms. Linoleic acid is present in many vegetable oils (20).

Omega-3 fatty acids cannot be synthesized by humans. Omega-3 fatty acids exist in high amounts in marine mammals and fish. Marine mammals also have high amounts of monoene lipids. Two highly active families of compounds are derived solely from omega-3 and omega-6 fatty acids, prostaglandins and leukotrienes. Derived from omega-3 fatty acids are those prostaglandins that are anti-thrombogenic while those from omega-6 fatty acids are highly thrombogenic. Prostaglandins (thromboxanes and prostacyclines) are highly vasoactive and very important in clotting of blood (20). Leukotrienes are very important in inflammation and the immune system. Omega-3 fatty acids inhibit chemotaxis and migration of monocytes and attenuate the inflammatory response.

Historical evidence provides strong clues to the importance of omega-3 fatty acids.

- There exist writings dating to the 11th century of observations of excessive bleeding tendencies in Greenland Inuit. Norsemen recorded that after fighting, wounds inflicted upon Inuit would not stop bleeding (13,14).
- In the early 1900s there were recorded frequent nosebleeds, numerous hemoptysis in association with tuberculosis, and excessive bleeding at childbirth (18).
- A study of cardiovascular deaths from 1980-86 among Alaska Natives, based on death certificates, found Alaska Natives had a much lower death rate from cardiovascular disease and atherosclerosis

than non-Natives (162 vs. 242, PR = 0.67). Far fewer aortic aneurysms were found among Alaska Natives than Alaska non-Natives (1 vs. 88) (21).

A recent study showed that Alaska Natives had less atherosclerosis in coronary arteries and abdominal aortas than non-Natives (22). Additional preliminary findings also suggest that Alaska Natives have a different balance of omega-3 and omega-6 fatty acids in the walls of coronary arteries and in adipose tissue than non-Natives. The differences in Alaska Natives compared to non-Natives are related to their high dietary intake of omega-3 fatty acids found in traditional arctic foods, marine mammals and fish.

Risk management and public health advice must separate the possible from the probable. Benefits and risks must both be weighed, and trade-offs fully considered. To respond to documentation of the presence of pollutants in the Arctic environment, we will need to involve fully the expertise of the public health community and, in turn, arctic people.

The federal Department of Health and Human Services (DHHS) will need to take seriously its obligations under the Arctic Research Policy Act of 1984 and become actively involved in the Interagency Research Policy Committee. DHHS will need to commit its resources and expertise to evaluating the implications of arctic environmental contaminants for human health.

We will also need to involve local residents and communities in this effort. To do so will require funding to enable meaningful participation. We will need to improve communication, particularly to enhance listening skills of scientists and researchers. Through a sustained commitment, we can strive to build participation and establish trust.

Although we have much to learn and our scientific

knowledge is incomplete, many studies have provided scientific information that can be used to provide public health advice with considerable confidence. Based on our present understanding, the levels of certain arctic environmental contaminants are below levels that would warrant any public health concern or action to restrict consumption of subsistence foods.

- Arctic haze: Levels of pollutants causing arctic haze are so low that they do not pose a human health concern.
- Long-distance deposition in the arctic of radionuclides from atmospheric weapons testing in the 1950s and 1960s: Levels documented are so low as not to pose a public health concern.
- Radiation at Cape Thompson: Levels are so low as to pose no human health risk.
- Mercury levels in fish, seal, walrus, whale: Levels found provide no reason for people to reduce or restrict consumption of these foods.
- Cadmium in marine mammals, moose, caribou, and reindeer: Levels found provide no reason for people to reduce or restrict consumption of these foods.
- PCBs and Dioxins: Levels detected are so low as to pose no reason to reduce or restrict consumption of fish, marine mammals, or other subsistence foods.

Summary

That levels of anthropogenic contaminants and naturally occurring trace metals are low is gratifying news for immediate public health concerns about human health. But this is not a reason for complacency. We need much more research to improve our understanding and to enable us to prevent or ameliorate adverse effects on the fragile arctic ecosystem and arctic environment. We must have adequate data to monitor trends. And we must prevent further contamination.

The proposed Arctic Assessment and Monitoring Program provides a superb opportunity for bipolar science and research. Essential will be the meaningful involvement of arctic indigenous people in all aspects of the monitoring program. Critical will be the restoration of trust between agencies, researchers, and local people.

"Here was a nation obsessed by science, whose explorers were charged with collecting everything from skins of the Arctic tern to the shells that lay on the beaches. Here were men of intelligence with a mania for figures, charts, and statistics, recording everything from the water temperatures to the magnetic forces that surround the Pole. Yet few thought it necessary to inquire into the reasons why another set of fellow humans could survive, year after year, winter after winter, in an environment that taxed and often broke the white man's spirit." (23)

- We should affirm the intrinsic integrity and value of the environment and our duty to protect it for its own sake.
- We should be realistic about the limited immediate potential benefits to human health in the arctic from results of monitoring these environmental pollutants, although the long term benefits may be great.
- A successful program of environmental monitoring will anticipate the need to develop a partnership with local people and to interpret results in a way meaningful to local residents.
- We also must plan now for a process that will empower arctic people to make informed choices and to be in command of their lives.

Finally, AMAP should be a part of an overall commitment by the State and federal governments to improve the health status of Alaska Natives and other arctic indigenous people. The health status of Alaska Natives in 1993 is worse than Alaska non-Natives. Cancer caused by tobacco is epidemic. Illnesses and injuries caused by alcohol are epidemic.

We must realize that no death, illness, cancer, birth defect, or other adverse toxicologic effect ever has been found in an Alaskan caused by PCBs, dioxin, DDT, DDE, mercury, cadmium, arsenic, ozone, arctic haze, radionuclides, or radon. We must remind our Government that it spends millions of dollars to abate these environmental contaminants but does little in comparison to prevent and control tobacco, alcohol, and injuries.

There is great need for the proposed arctic environmental monitoring program. Results will help us to focus health programs on the major threats to human health and to focus all of our programs on the need to protect the arctic environment for ourselves and future generations.

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Effects of Persistent Organic Contamination on Ecosystems and Human Health

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Introduction

Recent advances in technology have enabled scientists to probe deep into the workings of organisms at the molecular and cellular level. As scientists have unlocked the secrets of embryonic and fetal development with their microscopic and chemical probes, they have become more aware of the remarkable sensitivity of the developing organism to the slightest perturbation, such as a foreign chemical in the uterus in mammals or the egg in fish, birds, and reptiles. Much of what follows leans on this new literature as we look at the effects of persistent organic contamination on ecosystems and human health.

When dealing with the effects of contamination from the molecular and cellular to the ecosystem level, it is important to consider the following:

- First, the same contaminants that are reported in the tissue of wildlife and humans in the industrialized areas of the Northern hemisphere are also reported in wildlife and humans in the Arctic (1).
- Second, when determining the hazards of exposure to these chemicals, we have traditionally focused on the health status of the directly exposed animal or human (2). However, within the last ten years, wildlife biologists have demonstrated that the adverse health effects of persistent chemicals are most often expressed in the offspring of the exposed animals, not in the adult animals themselves (2). Recent epidemiological evidence supports this transgenerational pathway of contaminants and effects on human progeny as well (2,3,4).
- The third point, therefore, is that in order to deal with this insidious problem, it is time to revisit how we address risk. Currently, cancer is most often used as the health endpoint when determining risk. And consequently, for regulatory purposes, cancer risk estimates are used to determine safety standards for

human and wildlife exposure. This leaves human and wildlife populations vulnerable to transgenerational health effects that in most instances are not expressed as cancer. What follows provides an argument for broadening the scope of risk beyond cancer to include not only the health of the animals or humans that are exposed but also to include the health of their offspring.

Background

In July, 1991, twenty one scientists from Canada, Europe, and the US convened at the Wingspread Conference Center, Racine, Wisconsin, to share their knowledge relative to the topic of the meeting, "Chemically Induced Alterations in Sexual Development: The Wildlife/Human Connection." The scientists represented seventeen disciplines: anthropology, zoology, medicine, psychology, ecology, toxicology, comparative endocrinology, and physiology to mention a few. Many had never attended a forum outside their discipline before and most did not know each other. At the close of the three-day meeting the group reached agreement in a consensus statement (5):

We are certain of the following:

A large number of man-made chemicals that have been released into the environment, as well as a few natural ones, have the potential to disrupt the endocrine¹ systems of animals, including humans.

¹ The endocrine system is made up of cells in glands that produce chemicals called hormones. Hormones are transported via blood or tissue fluids to other cells in the body where they exert their effect. They regulate response to stress, coordinate regulation of metabolism among muscle, liver, and fat, and coordinate function over time, such as the changes required for normal sexual function and reproductive ability. The endocrine system plays a critical role in regulating development.

**We estimate with confidence that:
Unless the environmental load of synthetic hormone disruptors is abated and controlled, large scale dysfunction at the population level is possible.**

The above conclusions could not have been reached with certainty by one scientist working solely in a single discipline. It was only after hearing from the entire group and using a "weight of evidence" approach, based on the parallels among wildlife, laboratory animal, and human experiences, that the group reached consensus. For example, early in the meeting wildlife biologists and toxicologists reported on evidence of damage to the endocrine systems in wildlife. Next, wildlife toxicologists told how they were able to induce the same damage in confined wild animals by exposing them to the same chemicals that the animals are exposed to in the wild (6).

Probably the most stunning information presented at the meeting was from the basic scientists; those who do comparative endocrinology and comparative physiology. They reported that it only takes the slightest shift in the ratio of estrogen (female hormone) to testosterone (male hormone) in the uterus to change the course of development of the embryo, fetus, or newborn organism. They pointed out that there are many axes (stages) where change can take place during sexual development and that these changes can be very subtle, irreversible, and sometimes devastating. They also said that the timing of the change is critical (7).

After hearing a pharmacologist (8) describe the demasculinization and feminization of male rat pups whose mothers were exposed to only one, very low-dose meal of dioxin (0.064, 0.016, 0.4 and 1.0 $\mu\text{g/kg}$ body weight) on day 15 of gestation, the group began to realize that extremely low doses can have a tremendous effect on the developing embryo, fetus, or breast feeding organism, even though the adult may not show any measurable change at all. This research reemphasized the sensitivity of the embryo and that only "one hit" during prenatal development can have an irreversible effect on the offspring.

Next the group heard from the scientists who had been working with the cohorts of individuals whose mothers took diethylstilbestrol (DES) (a manmade estrogen-like chemical) during their pregnancies to prevent miscarriages (9). Although DES is not widely dispersed in the environment, it provides a model for humans and wildlife vulnerable to chemicals that behave like estrogens. Several million pregnant women took DES between 1948 and 1971 and thus many individuals were exposed to DES during fetal life before the product was removed from the market. As the oldest individuals in the cohort of *in utero*-exposed individuals are reaching their mid-40s, more and more information is accumulating about

the delayed, long-term effects of their prenatal exposure. For example, loss of fertility has been reported in both males and females (10). The epithelial tissue of the reproductive tract of the women often is abnormal contributing to fertility problems (9). Both sons and daughters suffer more frequent and severe periods of depression compared with their unexposed counterparts. Thirty five to 40% of the women exposed prenatally to DES say they are bisexual or homosexual (11). DES exposed females are more prone to autoimmune diseases and their immune systems are different, although what that difference means has not been determined (12,13).

The group agreed that prevalence of many of the effects initiated in the fetus would not be detected under the present public health system of recording birth defects and cause of death. As the endocrine, immune, and nervous systems develop, their basic architecture can be undermined. These changes may not be visible in the form of physical or morphological changes at birth. In humans, the effects might be expressed more in changes in functionality, often identified as syndromes of unidentified etiology, rather than specific diseases—e.g., immune systems that do not function normally (12); neuro-endocrine systems that are not programmed correctly (8); and brains that cannot facilitate an individual's fullest motor, behavioral, and cognitive potential (3). For wildlife this could mean premature death (14). For humans, the full extent of loss of function may never become public record.

The DES story is an example of how functional deficits are overlooked by the current health registry system. It has taken 40 years (two generations) to compile a data base on the health of individuals exposed in the womb to DES. The history of the DES cohort provides a model of what can happen if exposure to an estrogen-like compound takes place during development. In the case of DES, the effects generally were not recognized until puberty or adulthood. Only the individuals that were affected by DES fully realize the impact on their quality of life. It is yet to be determined what this loss of potential means at the population level.

The Chemicals

Further evidence has come to light since the Wingspread meeting to support the conclusion that a number of manmade chemicals are capable of crossing the placental barrier and can affect a developing organism. These chemicals look like, or interfere with, the internal, naturally produced hormones, neurotransmitters, inhibiting substances, and growth factors, important natural chemicals necessary for programming growth and function (Figure 1). Each natural chemical compound has a receptor site in or on a cell where it binds

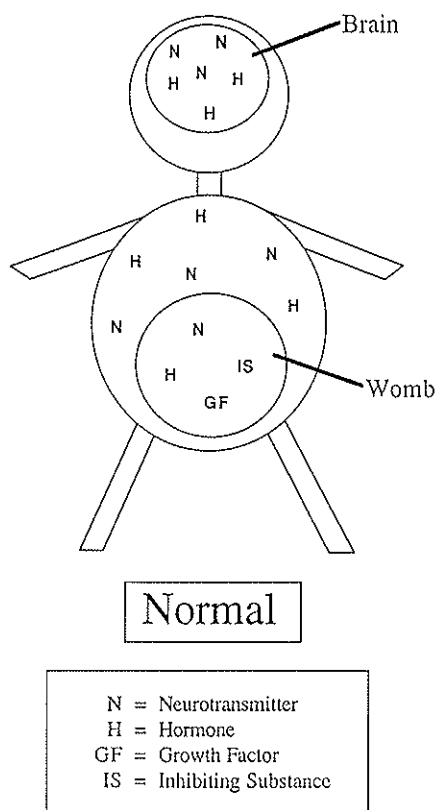


Figure 1. As an individual develops in the womb or the egg, every step is under control of chemicals produced by the mother or the developing individual. This phenomenal process takes place with very slight changes in the ratios among neurotransmitters, hormones, growth factors, and inhibiting substances.

and initiates a response or a series of responses, sometimes called a cascade of effects (15). Unfortunately, many synthetic chemicals can interfere at the receptor site in the cell by mimicking naturally produced compounds and turning the system on or off or causing an inappropriate increase or decrease in activity (Figure 2). On the other hand the foreign material can block the natural message at the receptor site; or it can interfere with how natural hormones are produced internally. Dose, genetic predisposition, sex and stage of development of the exposed individual, and structural differences among the vast number of chemicals in the environment make predictions of outcomes difficult.

Just how many chemicals are capable of disrupting embryonic, fetal, and early postnatal development? Table 1 is a representative list of known endocrine disruptors. Many of these are pesticides (herbicides, fungicides, insecticides, and nematocides); as well as industrial chemicals, including PCBs, PBBs, dioxins, and furans. As interest has shifted toward investigating the

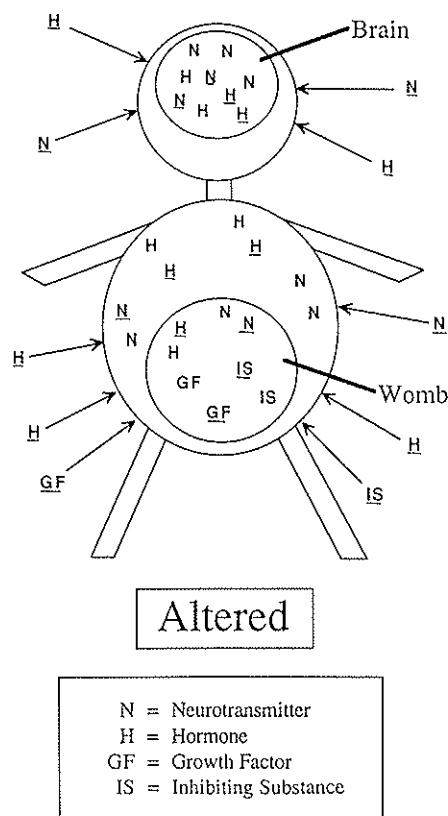


Figure 2. A number of synthetic compounds can penetrate the womb or the egg and interfere with the signals of naturally produced hormones, neurotransmitters, growth factors, and inhibiting substances during the early stages of development when the endocrine, nervous, and immune systems are undergoing differentiation.

mechanism of action of chemicals found in the environment this list continues to grow. Some industrial materials that were thought to be benign, such as components of plastics and detergents, are also endocrine disruptors. They have tested positive for estrogenicity, as measured by cell proliferation², in an *in vitro* human breast cancer cell assay (16).

Certain classes of chemicals appear to be more likely to disrupt the endocrine system, among them, the organochlorine compounds. Structure oftentimes does not predict whether a compound will disrupt the endocrine

²This assay measures proliferation of estrogen-sensitive cells; this is the hallmark action of estrogens in their target cells. This assay is the equivalent of the rat or mouse assays that have been traditionally used to reveal estrogenic effects in the uterus and vagina. The assay may be used to advantage to screen compounds for their ability to mimic estrogen action, and predicts that positive results in this model are indicative of the ability of these compounds to produce comparable effects in the animal. Therefore, this assay only measures one of the many pathways that may lead to endocrine disruption.

Table 1. Synthetic chemicals that are widely dispersed or released in the environment that are known endocrine disruptors or developmental toxicants. See Reference 5.

<i>Herbicides</i>	<i>Fungicides</i>	<i>Insecticides</i>	<i>Industrial Chemicals</i>
2,4,-D	Benomyl	beta-HCH	Cadmium
2,4,5,-T	Ethylene thiourea	Carbaryl	Dioxin (2,3,7,8-TCDD)
Alachlor	Fenarimol	Chlordane	Lead
Amitrole	Hexachlorobenzene	Dicofol	Methyl mercury
Atrazine	Mancozeb	Dieldrin	PBBs
Metribuzin	Maneb	DDT and metabolites	PCBs
Nitrofen	Metiram-complex	Endosulfan	Penta- to nonylphenols
Trifluralin	Tri-butyl-tin	Heptachlor and H-epoxide	Phthalates
	Vinclozolin	Lindane (gamma-HCH)	Polycarbonates
<i>Nematodes</i>	Zineb	Methoxychlor	Styrene
Aldicarb	Ziram	Parathion	
DBCP		Oxychlordane	
		Synthetic pyrethroids	
		Transnonachlor	

system. To date, there is no inexpensive, quick protocol to screen compounds for *all* the effects manifested by endocrine disruption. Multigenerational, low-dose exposure studies using laboratory animals are the only sure way to rule out endocrine disruption.

The Evidence of Damage: Wildlife

The evidence of widespread transgenerational loss of function among wildlife became evident in the late-1980's when I was working on a book about the state-of-the-environment of the Great Lakes with five policy analysts from The Conservation Foundation, Washington, DC, and the Institute for Public Policy, Ottawa (2). Following an extensive literature search, in cooperation with the Canadian Wildlife Service, Environment Canada, The Canada/US International Joint Commission, the U.S. Fish and Wildlife Service, and academicians, we discovered that since 1950 each of the species listed

in Figure 3 have suffered reproductive problems and population instability around the Great Lakes (17). All of the species listed on the y-axis are near the top of the Great Lakes food web and depend on fish from the Lakes. The health problems listed on the x-axis were in most instances reported in the offspring, not the adult animals. Comparative studies demonstrate that the effects reported in the Great Lakes animals were not being expressed in populations of the same species carrying lower body burdens of persistent chemicals and/or not feeding from the Lakes. For example, if you go to the Great Lakes today, you might see bald eagles along the shore-line or on islands during the breeding season. However, immigrant pairs feeding on food resources from the lakes lose their fertility after several years on the Lakes (18). Their productivity is significantly less than that reported in inland populations not dependent upon fish from the Lakes (19). In almost every instance

Species	Population Decline	Reproductive Effect	Eggshell Thinning	Metabolic Changes	Deformities	Target Organ Damage	Behavioral Changes	Hormonal Changes	Immune Suppression	Generational Effects	Tumors
Bald Eagle	X	X	X	X	X		X			X	
Beluga Whale	X	X	N/A		X	X		X	X	X	X
Black-Crowned NH	X	X	X		X						
Caspian Tern	X	X		X	X		X			X	
Chinook/Coho Salmon	N/A	X	N/A			X		X		N/A	X
Common Tern	X	X		X		X	X		X		
D.C. Cormorant	X	X	X	X	X	X	X			X	
Forster's Tern	X	X		X	X	X	X			X	
Herring Gull	X	X	X	X	X	X	X	X	X	X	
Lake Trout	X	X	N/A	X		X	X			X	
Mink	X	X	N/A	X		X				X	
Osprey	X	X	X								
Otter	X		N/A								
Ring-Billed Gull		X		X	X				X		
Snapping Turtle	X	X		X	X	X				X	

Observed effects that have been reported in the literature.

Figure 3. Effects in Great Lakes wildlife that have been reported in the literature. Cells not marked do not necessarily mean there is no effect, only that no citation was found. See References 2 and 4 for citations.

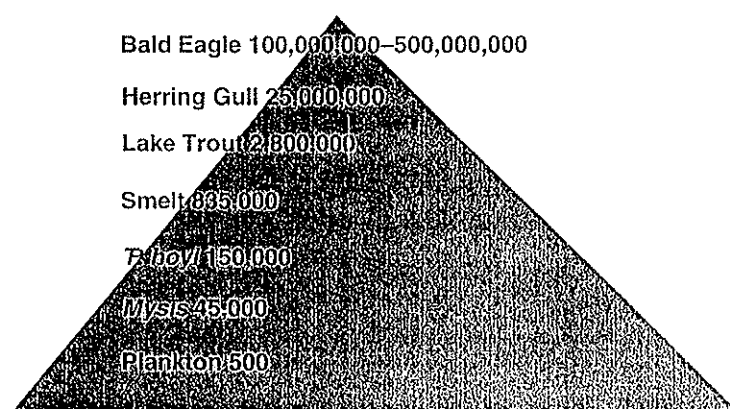
elevated concentrations of a suite of organochlorine chemicals were reported in the animals' tissue—these are the same chemicals that are found in tissues of many animals and humans throughout the world.

Biomagnification

Animals at the top of a food web become targets for the phenomenon of biomagnification by chemicals that are fat soluble, water insoluble, and do not break down readily. For example, the persistent, fat-loving chemical, PCBs, in Lake Ontario can biomagnify 25 million times from the water to a herring gull (Figure 4) (20). Millions of plankton at the bottom of the food web are preyed upon by larger filter feeding animals of microscopic size. The animals get larger at each higher tier in the pyramid. As the pyramid narrows, fewer and fewer prey are consumed. The final consumer in Figure 4 is the bald eagle. It could very well have been a human, except that most humans are not obligate fish and bird eaters. PCBs can biomagnify 100 million times from the water to a bald eagle at the top of the Great Lakes food web (21). This perhaps is because the bald eagles nesting along the shoreline of the Great Lakes often build their nests near colonies of nesting water birds (e.g., herring gulls). The bald eagle is a lazy bird and will always choose the easiest option to meet its caloric needs. Fishing is not easy in the Great Lakes, and therefore the Great Lakes bald eagles seek out the easy prey, birds. The herring gulls hold higher concentrations of toxic chemicals than the fish, thus increasing the bald eagles risk from exposure.

Cancer

Cancer was not frequently reported nor did it have a measurable effect on attrition among the affected populations (Figure 3). Tumors were reported only in the beluga whale (22) and some fish species (23). DNA adducts of polyaromatic hydrocarbons (PAHs) such as benzo-a-pyrene were found in the livers of the animals with cancers. The cancer/polyaromatic hydrocarbon relationship is one of the strongest cause-and-effect linkages made to date by researchers in the Great Lakes region (24). Researchers have induced the same tumors in the laboratory with contaminated sediments and chemicals extracted from the sediment. By comparison, the other health effects on the matrix were more associated with the persistent organochlorine chemicals. The matrix illustrates that perhaps society's fascination with, and fear of, cancer has contributed to the inattention to the less obvious but equally devastating effects of some widely dispersed chemicals. It is understandable that developmental effects were overlooked because the effects are difficult to see and often delayed, expressed in the second generation. Even the effects in the directly exposed adult animals are not easy to identify, such as behavioral changes, loss of fertility, and gradual wasting. All of the effects listed on the matrix are still observed today among various Great Lakes wildlife populations during the breeding season. These effects are visible only to vigilant wildlife biologists and others who have the patience and equipment to make long-term observations of the animals.



Adapted from Canadian Fish & Wildlife Service, 1988 and Norstrom *et al.*, 1978.

Figure 4. Biomagnification pyramid of polychlorinated biphenyls (PCBs) in the Great Lakes food web from the water to the bald eagle. PCBs are generally not detected in a standard water assay. However, because of their persistence they are picked up by microscopic animals, who are then consumed by larger animals and so on until they reach concentrations that are readily detectable in animal tissue. As PCBs move up the food web from prey to predator they increase in predator tissue in many instances more than ten fold.

Sensitive Endpoints: A Case Study

When observing wildlife populations, obvious endpoints of high-dose exposure, such as structural birth defects and outright mortality, are far easier to observe than low-dose functional deficits that are not expressed immediately after exposure. A case study is presented to demonstrate the difficulty of recognizing subtle effects and sensitive end-points resulting from ambient exposure to multiple chemicals in wildlife. The subjects in this study are Forsters terns (26). Forsters terns fly along the shoreline and marshes of lakes and eat small fish, frogs, and insects. The terns in this study were nesting on a confined waste disposal facility, an island, constructed by the Army Corps of Engineers in Lake Michigan from contaminated dredge material. Signs on the island read, "Hazardous Materials, Stay Off." As a result it is a great place for birds to nest; no predation; no people.

This particular population of Forsters terns was first observed in 1983, and again in 1988. The control in this case was a population of Forsters terns from an inland lake, Lake Poygan, that was not dependent on the Lake Michigan food base. The work was done by a multidisciplinary team of ecologists, chemists, histopathologists, veterinary pathologists, toxicologists, biologists, and wildlife managers. The logistics in 1983 were unbelievably arduous because of an elegant egg-switching scheme in which eggs were taken from Lake Michigan nests and switched with Lake Poygan eggs. In addition, eggs from both locations were taken to a laboratory where they were artificially incubated. In the egg-switching component of the study the team was able to determine that lack of parental attention contributed to some of the egg and chick mortality in the Lake Michigan population. In the Lake Michigan colony, incubation took longer and egg hatchability was significantly less than in the control colony. The chicks that managed to hatch were lighter in weight, did not gain weight, and by the 17th day 35% had died from wasting—a metabolic problem. In the case of wasting, chicks have difficulty converting energy in the yolk or in the food their parents bring them into muscle in order to grow. On day 17 the parents and fledglings abandoned the area. The median PCB concentration in the eggs that year was 22.2 ppm (med.). The eggs were also assayed for their liver enzyme activity potential using dioxin as the standard³, since dioxin is the most powerful liver en-

zyme inducer known to date. This is an inexpensive and relatively easy photometric assay compared with the tedious and expensive chemical analyses required to determine contaminant concentrations. The eggs' liver induction potential was equivalent to 2,175 ppt of dioxin (2,3,7,8-TCDD) (TEQs).

In 1988, part of the team went back to the island to see if conditions had improved in response to reduced discharges into Lake Michigan by industries in the area (26). They found duration of incubation, hatching, and chick viability normal up to the 17th day, similar to the control colony on Lake Poygan. The team admits that if the weather had been bad, they probably would not have gone back on day 18. But the weather was great, and they went back to find that some of the chicks were dying from what appeared to be wasting. By day 31, the colony suffered the same mortality as in 1983. It is important to note that if wasting had been delayed for several more days, the researchers would have undoubtedly missed this effect. It is not known how late in development wasting is expressed. Other latent effects that may have developed were not reported because the short-term and long-term fate of the chicks that fledged was not tracked in either year.

Both PCBs concentrations and dioxin toxicity equivalents were lower in 1988 than in 1983; 7.3 ppm PCBs (med.) and 913 ppt dioxin enzyme TEQs. If this study had been used to establish water quality or biological standards, without the additional information gained after the 17th day, 7.3 ppm of PCB might have been considered a safe concentration in Forsters tern.

Marine Mammals

A synthesis of the marine literature reveals that toothed marine mammals appear to be suffering a suite of health effects similar to those affecting the Great Lakes animals (Figure 5). Note that filter-feeding, baleen whales do not fit the pattern; they feed lower in the food web. As in land-based animals, cancer is not frequently reported among marine mammals. Other than the St. Lawrence beluga whales (also listed in Figure 3) one tumor was reported in a gray seal (27). A number of large-scale marine mammal die-offs were reported in 1987. In each incident mortality was the result of viral infections; the viruses were a new strain of the canine distemper virus specific for each species (28,29,30,31,32). Affected were Baikal seals, ringed, grey, and harbor seals in the Baltic,

icals that behave like dioxin (certain PCB congeners). In this case, dioxin (2,3,7,8-TCDD), is used as the standard because it induces more activity on a weight to weight basis than any other compound. Dioxin therefore is given a value of one and all other compounds are assigned a value less than one. The assay provides a measure of net enzyme induction in a sample (in this case, the Forsters terns' eggs) of all dioxin-like compounds, allowing for synergy and antagonism, and is reported as dioxin enzyme toxicity equivalents (TEQs).

³ In this case, the activity of a specific enzyme of the cytochrome P-450 system is measured in an *in vitro* rat liver hepatoma cell culture assay. The activity of arylhydrocarbon hydroxylase (AHH) for instance, is associated with birth defects, immune suppression, wasting, and porphyria in laboratory animals. The induction assay is based on the amount of fluorescence produced when the enzyme induces the hydroxylation of a specific chemical, such as dioxin, or other chem-

Marine mammal	Population decline; Strandings	Reproduction & endocrine impairment	Immune system compromise	Organ damage	Infection & health decline	Tumors
Dolphin bottlenose	X	X	X	X	X	
striped	X		X	X	X	
Porpoise Dall's		X				
Sea lion California	X	X		X	X	
Seal Baikal	X		X		X	
grey	X	X			X	X
harbor	X	X	X	X	X	
ringed	X	X		X	X	
Whale beluga	X	X	X	X	X	X
sperm	X				X	

Figure 5. Abnormal health effects observed in marine mammals. See References 27-32 for citations.

North, and Wadden Seas, striped dolphin in the Mediterranean Ocean, and bottlenose dolphin in the Atlantic Ocean. Historically, nothing like this had been reported before. Elevated concentrations of organochlorine chemicals were reported in the mammals' tissue. However, it is still to be determined if the chemicals were the underlying cause of mortality.

Specific Cases of Endocrine Disruption

A vast amount of literature has been published since the mid-1950s describing endocrine system anomalies in wildlife on the North American continent. For example, tern chicks have been born with adult plumage; white body feathers and black head feathers, instead of down. This phenomenon is an example of abnormal ontogeny, in other words, sexual development out of sequence. Somewhere early in development the chicks got the wrong signals. Chicks have also hatched with crossed bills, missing eyes, clubbed feet, and gastroschisis, a condition where the ventral abdominal wall does not close. Oftentimes the yolk of the egg from which the chick hatched is still protruding from the stomach, a sign of wasting.

In the more highly contaminated areas of the Great Lakes today, the phenomenon of two female herring gulls sharing a nest is not uncommon (33). In these colonies the males form what have been described as "fraternities." The males do not pay much attention to the females, and a pair of females attempt to hatch two clutches of eggs in a single nest. Hatching success is poor in these nests. The eggs usually are not fertile. In the mid-1970s this condition reached 17% prevalence off the coast of Santa Barbara, California (25).

In the mid-1970s at the height of unregulated dumping of chemicals into the Great Lakes, Glen Fox, Canadian Wildlife Service, archived egg and chick samples. Several years later he gave the samples to Michael Fry, University of California, histopathologist, who examined their gonads and found that the male birds were

growing oviducts and the females were growing an extra oviduct. Fry was able to induce the same gonadal condition in confined kestrels and gulls with DDT, and some of its substitute products, methoxychlor, dicofol, and kelthane (34,35,36). He noted that the exposed males often did not develop mature plumage and did not display the normal dominant behavior of males.

During the summer of 1990, a graduate student at the University of Wisconsin collected 17 double crested cormorants with crossed bills. She was surprised to find that they were all females (37). The next year Great Lakes wildlife biologists collected 95 female cormorant chicks with crossed bills and five males with flattened "Donald Duck" type bills (38). None of these birds could have survived in the wild with deformed bills. It has not been determined yet whether the crossed-bill birds are all genetic females or whether half of them might be males that look like females. Regardless of the sex of the birds, a problem exists.

Egg mortality among various double crested cormorant colonies around the Great Lakes was compared with dioxin equivalents in the eggs using the rat liver enzyme bioassay mentioned earlier. As dioxin toxicity equivalents approached 100 ppt, egg mortality became a problem in the colonies (39). In addition, the toxicity of the cumulative body burden of all the chemicals—the net effect of the contaminants on enzyme induction in the liver—was measured. Again this study required a great deal of team work among researchers from two governments and across many disciplines; logistically it was very difficult. It represents a breakthrough in monitoring because it moves beyond traditional quantitative monitoring of contaminants in animal tissue.

Dr. John Leatherland, University of Guelph, reports (40) that there are virtually no fish in the Great Lakes that do not have an enlarged thyroid.⁴ Lack of iodine

⁴ The thyroid is an endocrine gland that plays a role in growth and metabolism.

was ruled out as the cause. In most instances the enlarged thyroid is not visible without microscopic examination. Recently, however, the thyroids in Lake Erie fish have become so large they are rupturing and as a result are visible. No direct links have been made between organochlorine chemicals and this condition, leading Leatherland to believe that something else in the Great Lakes system is the cause. Leatherland's work stresses the importance of looking beyond the suite of chemicals that we have been focusing on for the past 40 years and developing methodologies to detect other contaminants in the ecosystem, such as widely dispersed herbicides or certain detergents with known endocrine effects.

The herring gulls around the Great Lakes are also troubled with abnormal thyroids. Over the years the Canadians have used the herring gull to monitor the effectiveness of regulatory action in the Great Lakes, not only monitoring their contaminant loading, but their thyroid hormone ratios as well. The Canadians have plotted spatially the thyroid hormone ratio (T3:T4) in the gulls throughout the lakes. Using this parameter they have demonstrated a pollution gradient from the pristine to the more highly contaminated areas (41).

Sport fishing is a major source of income for many who live around the Great Lakes. Canada and the US spend 48 million dollars a year stocking the Great Lakes with top predator fish species and as a result have created a multibillion dollar sports fishing industry (2). Most of the stocked male fish commence maturing precociously but do not reach sexual maturity. At the age they should be spawning the males look much like females (30). Dr. John Leatherland also finds that in most cases the males have both female and male gonads. This condition occurs in other Great Lakes fish species that are not as economically important, especially the Cyprinids, but in this case, it does not appear to interfere with their ability to reproduce.

Developmental Effects in Rats Fed Lake Ontario Fish

Dr. Helen Daly, State University of New York, Oswego, feeds Lake Ontario coho salmon to rats and at the end of twenty days on a diet of 30% fish, the rats cannot cope with stress; they become hyperreactive to changes of scenery in their cages or slight food deprivation (42). At the end of sixty days on a diet of 10% fish, the rats display the same effect. Every rat in her study is affected suggesting that this is a consistent, across the board, population effect unlike cancer studies where it would be unusual for all the rats to be affected. She also fed Lake Ontario fish to female rats from the time they got pregnant through the first week of lactation; their offspring could not cope with stress either even though

they were never fed fish. Daly also found that the effect was easier to measure in the pups than in the adults. Daly's studies leave no doubt that something in the fish was passed on to the offspring that had an effect on their development. Daly catches the fish for her studies on Lake Ontario where the city of Oswego regularly holds fishing derbies.

The Human Connection

A series of reports on the nervous and reproductive systems of humans and laboratory animals are presented. These studies provide arguments that many chemicals often found in fish can lead to developmental aberrations in humans.

Nervous System Effects

Drs. Joe and Sandra Jacobson have followed the outcome of offspring from women who ate Lake Michigan fish two to three times or less a month for at least six years preceding pregnancy (43). They measured PCBs in umbilical cord blood and breast milk and correlated the concentrations of PCBs with health effects measured in the offspring. It is important to note that although the Jacobsons focused on PCBs in their research, PCBs are not the only contaminant in fish and may only be an indicator of other compounds in the fish. The number of years and amount of fish the mother ate prior to her pregnancy were inversely associated with the baby's gestation period, skull circumference, birth weight, and altered behavioral development—not just with the fish she ate during pregnancy. At birth, the babies exhibited motor, behavioral, and cognitive deficits that correlated with cord serum PCBs in a dose response manner (44). As measured by trained technicians, the effects in the babies were subtle, but they were consistent and significant. At age four the children were tested again and found to have short-term memory problems and were still smaller than children of similar age (45,46). During testing at age four, 17 children refused to take the test. These turned out to be the children of the mothers with the highest breast milk PCB concentrations in the study.

About the same time the Jacobsons began to work with their cohort, a team at the National Institute of Environmental Health Sciences under the guidance of Dr. Walter Rogan measured the organochlorine chemicals in the breast milk of more than eight hundred women who gave birth to babies in North Carolina (47). The newborns in this study were also tested for several parameters of neurodevelopment. The babies of women with elevated PCB concentrations in their breast milk were more hyporeflexive and hyporeactive. Although this study and the Jacobsons' study were done independently and with different study designs, several results

were similar. In each study it was concluded that the effects in the infants were the result of prenatal exposure to PCBs. And when the mothers' breast milk PCB concentration exceeded one part per million, neurotoxic effects were measurable.

A cross-fostering study (48) in which rat pups at birth were switched between control mothers and those treated with a German PCB analog (Chlophen-A30) revealed that neurobehavioral effects detected in the rat pups were also the result of prenatal exposure.

Tilson, Jacobson, and Rogan (49) reviewed the literature on the neurotoxic effects of PCBs in rodents, primates, and humans and found that the neurotoxic effects reported in the Rogan and Jacobsons' studies occurred at doses 10,000 times lower than the dose required to initiate a similar neurotoxicological effect in the rat. Results such as this raise questions whether the safety factors used in risk assessment equations are large enough to protect human health.

The Rogan/Jacobson studies highlight the difficulty of determining exposure pathways. When breast milk concentrations were extrapolated for comparison between the Jacobson and Rogan studies, the mean concentration of PCBs in the North Carolina cohort was slightly higher than it was in the Lake Michigan fish eaters, yet very few of the North Carolina women ate fish. Exposure is one of the least understood components of the risk equation.

Reproductive System Effects: Male Fertility

Dr. Dorothea Sager, University of Wisconsin, Green Bay, gave rat mothers five oral doses of Aroclor 1254, a commercial PCB, from the day they gave birth to day 9 of lactation (50). In repeated studies, when the male rats reached sexual maturity, their sperm had difficulty penetrating ova, and if the ova were penetrated the zygotes were not viable.

Drs. Moore, Mably, and Peterson, University of Wisconsin, Madison, fed one meal of dioxin to pregnant rats on day 15 of gestation, approximately the day that sexual differentiation starts in the rat (7). They found that the males were demasculinized and feminized over a dose response gradient. Changes included behavioral, biochemical, physiological, and morphological parameters. Sperm count was reduced by 75%. This study reveals that bioaccumulation is not necessary to effect changes of the endocrine system in the developing organism. Timing, in this case, was the critical factor. A "hit" during a critical time in gestation can disrupt the development of the endocrine system.

Dr. Brian Bush and coworkers, (51) Wadsworth Laboratory, Albany, New York, tested the sperm and semen of men attending a fertility clinic and found that reduction in sperm motility was associated with three

PCB congeners⁵. Only one of the congeners was a dioxin-like compound. Until recently, only those PCB congeners that are structurally similar to dioxin, were considered toxic. However, Bush found that 2,4,5,2',4',5'-hexachlorobiphenyl, found in everyone's body, was among those congeners related to a defect in sperm motility. Congener 2,4,5,2',4',5'-hexachlorobiphenyl comprises approximately 45% of Eastern Arctic, Canadian, Native Americans' and polar bears' PCB burden (52), whereas it comprises approximately 20% of the PCB burden in people living in temperate climates. Whether this difference is of significance has not been determined.

A team of reproductive specialists reported in the British Medical Journal (53) that between 1938 and 1991 sperm count worldwide has dropped about 45%. After factoring in the accompanying reduction in amount of ejaculate, which dropped by 25%, they estimated that the sperm count reduction was as much as 50%. Using a meta-analysis approach, the authors did an exhaustive search of the literature and carefully reviewed sperm count studies. After eliminating those reports where disease or improper laboratory techniques could bias the results, they used 61 studies representing 14,947 men.

In a follow-up paper in Lancet, one of the authors of the above paper, Dr. Niels Skakkebaek and a reproductive biologist from the UK, Dr. Richard Sharpe (54) hypothesized that reduced sperm count is the result of *in utero* exposure to increased estrogens or estrogen-like compounds. They discussed dietary factors that include natural and/or synthetic compounds that can affect prenatal development of Leydig and Sertoli cells that are essential for sperm production as males mature. This is an irreversible problem, similar to the problem of sperm count reduction in the dioxin-exposed rat embryos.

Conclusion

The problems of reduction in short-term memory and fertility are only two examples of loss of function—health problems that do not appear on birth records and are not often recognized by primary care physicians. Both problems could have been caused in the womb,

⁵ There are 209 different PCBs, 177 toxaphenes, 135 furans (PCDFs), and 75 dioxins (TCDD) depending upon the number and position of chlorine substitutions on the parent aromatic benzene ring. These are called congeners. PCBs are further segregated as homologues, such as mono-, di-, tri-, tetra-, through the octa-chlorinated biphenyls. Isomers belong to the same homologous class. The toxic effects of PCB congeners with no chlorine substitution in the ortho position are the same as 2,3,7,8-TCDD (dioxin) but with reduced potency. These particular congeners are not readily metabolized by fish and therefore accumulate in fish tissue.

and both are irreversible. The prevalence and magnitude of these effects at the population level in terms of their social and economic consequences must be taken into consideration when weighing benefits and costs in risk analyses. The evidence from the wildlife literature alone, provides a strong argument for broadening the scope of risk assessments beyond cancer and factoring in the costs of loss of human potential in the risk equation.

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Trace Metals Case Studies

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One of the benefits of coming last is I can get stimulated by the comments of the last two speakers. So I've got some very specific challenges that I think I'd like to point out as I go along. Dr. John Middaugh mentioned the fact that basically we kill a lot more people with alcohol, and accidents, and so forth. There's no question that if you were to define the four biggest killers in our environment, it's alcohol, diet, tobacco, and automobiles. There is an order of magnitude greater risk for all four of those. The big difference is between voluntary and involuntary risks. The big factors are all voluntary risks. People choose those things by choice. What we've done as a society is we've boxed ourselves in; we set up a public health service, and we codify the rules in public health code. Then we tell people they can drink the water and it's going to be safe; i.e. nondegradation.

We also express it as action levels and tolerance levels in food under the Delaney amendment, and say there won't be one molecule of a carcinogen. We've embodied laws at both state and federal levels, all over this country, promising people that we can be affluent and squeaky clean all at the same time. We've been hung on our own petard. I guess the other aspect is you say you haven't found a dead body with those nine different compounds in Alaska. Three of them I know something about, the PCBs, the dioxins, and the mercuries; which is what I'm going to talk about now. The effects are on the neurocrest cells as they enfold in the embryo, and quite frankly you won't see a dead embryo that size. It'll look like a heavy menstrual flow and your data won't even record it as a mortality rate. That's part of the issue that Theo Colborn was pointing out, but a lot of these things that we know about are not things that are going to show up in your public health statistics. So, I wouldn't take too much of a safety factor in that you

haven't seen it yet. On the other hand, Dr. Colborn points out the fact that we've got all these toxic chemicals in the Great Lakes, that happens to be my home state, Michigan, and I take it a little bit personally some of the statements she made about the Great Lakes. I fish a lot, and at the same time, yeah, you can see Jim Ludwig's cross bill cormorant, and you can look at various eaglets not having nesting success along the lakes compared to upstream. At the same time, both of those populations have increased significantly in the last twenty years. We didn't have cormorants twenty years ago. They've gone up two hundred fold in twenty years. And we just took the bald eagle off the endangered species list, because we've got a very ample population. The point is the populations have increased, and the difference depends on what your goals are in terms of protecting an individual or worrying about a population. That's something that we can debate when we debate on Friday. One of the things that is a little bit funny is you see all these mechanisms in the laboratory, and very seldom we see the effects in the field. The populations tell us one thing, but the mechanisms, if they were strong enough, should show up at the population level. That's one of the things that you try to balance in science.

The thing I was asked to do this afternoon was to walk you through, briefly, something I haven't done myself, but I was involved with it. We have an Environmental Science Board for our Governor in the State of Michigan. I am his Science Advisor. The first thing we asked them to do, here about six months ago, was to look at mercury. Mercury is, of all the airborne toxicants that bioaccumulate in aquatic food chains, the one that gives us the most grief. We have PCBs in fish. They show up in the Great Lakes, they don't show up in the inland

lakes. We have mercury in the inland lakes, we don't have mercury in high concentrations in the Great Lakes. Both of them are airborne. We've done a mass balance now on both of those toxicants, and about 85 percent of them were airborne in the Great Lakes. They are not point sources, they are nonpoint sources, and they are coming from both wet and dry deposition. Why you find the PCBs accumulating in the larger, colder lakes, and the mercury in the warmer, more eutrophic lakes, is probably the rate of methylization, in terms of making mercury available. I'm not sure why it is in terms of the PCBs in the inland lakes, but there's a lot about the chemistry and the energetics of food chains that are quite different, between these two classes of bodies of waters that cause the end points to be very different.

When we actually did the mercury analysis, it was done by a Science Advisory Board of about nine people in the State of Michigan. We have a lot of universities there, a lot of very good expertise. We asked them about four different questions. First of all, "Where's the mercury coming from?" "What are the sources, what are the pathways?" Obviously one of the questions is, is there something you can do about it? By the way, I do have a copy of this report. We gave it to Governor Engler last Friday before I left. I promised I would not release it to the newspapers until he had a chance to do it himself. You very rapidly find out in the political process, there's no such thing as a pleasant surprise. If you want to see this, you can take a look at it. By the time I get back I'm sure these things will be on the street and I'll get you copies of them. It really is a pretty good report, from what I can tell.

Basically, in terms of the mass balance, about 50 percent (these are rough numbers) of the mercury right now in the State of Michigan is natural, nonanthropogenic mercury. Mercury unfortunately looks like it cycles mostly in the terrestrial ecosystem. These volatilized materials are cycling between the terrestrial and atmospheric media. I call it the tumbleweed theory. Most of our winds in Michigan come out of the southwest, and these materials volatilize in a good hot July day off the soils, then they come back down as snow and rain. Eventually, they get caught up in the aquatic food chain, which is kind of a shunt. Once they get caught up there, they tend not to come back out again or they keep rolling north until eventually you're going to get some kind of an imaginary line along Canada where the maximum soil temperatures in the summer aren't warm enough to revolatilize them, and that's probably where they'll stack up. This sounds similar to the model that was attributed to Don McKay this morning.

You tend to see that kind of thing and it makes a lot of sense. About 50 percent of the mercury is just sitting there cycling, on a daily basis. It could very well be that

the background includes the accumulation of mercury released by anthropogenic activities up to the 1960's, when we started getting data, and now we call it background. Once it's out there, it's going to cycle on you and you can't get it out again. Of the 50 percent that's anthropogenic right now, as far as we know, half of it's coming from combustion of coal, the other half of it is coming from incinerators, predominately because of mercury batteries. About a quarter of that used to be mercury from latex paint. EPA has banned, basically, latex mercury paint, and so probably the two major sources are going to be incineration and the combustion of coal.

Now, when you get involved with one of these risk assessments, understand the fact that if it turns out that isn't a correct mass balance or the correct partitioning in terms of the loading rates, you might recommend the wrong mitigation approach. You're talking about major economic expenditures. If I have to go into a coal fired plant and strip mercury out of the hot stack gases it will be expensive. Electrostatic precipitators don't work with mercury. You can inject sulfides in the hot gases and they take it out. It drops out as mercuric sulfide but it's only about 40 percent efficient. The only technology I've seen has come out very recently and I think they're starting to talk about doing it. You inject a highly granulated, very fine, charcoal spray into the hot stack gases. It takes out the mercury, but you can't recycle the charcoal. You can't get it back off the carbon. If you've got to retrofit these new treatment processes into coal fired plants, you're talking about some big bucks. You'd better be right. I mean that's what it translates into. The governor is going to say, hey, are you really sure you know what you're talking about, because if he says he supports a change, he's going to take a real beating from all kinds of places.

In Michigan, we've got fish warnings in most of our lakes. If you go and mess around with somebody's fishing, then you've got their attention. Deer hunting and fishing are the two things you don't mess with in Michigan. We started putting fish warnings on lakes, and it gets people's attention real fast. All of the sudden, they want to shut down every incinerator in the State of Michigan. That's what motivated this kind of a mass balance.

If you've got to treat mercury in terms of incineration gases the same way, it's going to be really kind of dicey. If you look at the mercury coming out of the hot stack gases, it's very different than if you get about 150 yards down wind where the gases start to cool, and they shift their structural configuration. In terms of mercury, probably most of it mercuric chloride, mercury 2. When you look at the plume downwind you find a lot of gaseous mercury. A lot of it's been essentially convert-

ed over to mercuric sulfides. That might not sound like something different, but it makes a big difference in terms of what it does, in terms of the environmental fate and transport. If it's in the gaseous phase, it tends to come out by being scavenged by snow and rain. If it's in the troposphere above the cloud level, it doesn't come out as fast. If it's particulate, it turns out to be the foci for droplets of rain and snow, and it's scavenged very nicely, with a much greater efficiency. If it's big particles and it doesn't go very far and drops out as dry deposition. If it's small particles, tied up in the hydrological cycle, it can go hundreds and hundreds of miles. So, just those slight chemical changes, in terms of knowing the combustion chemistry makes a big difference. It isn't just mercury coming out of the stack. You've got to know what species it is, and you've got to know how it's reactive as it goes from a hot phase to a cooling phase.

That's one thing in terms of talking about coal, but incinerators where you've got uncharacterized feed stock going in there are much more of a problem. You've got all kinds of other chemical reactions. Most of these incinerators are great big black boxes. They haven't the foggiest idea of all the kinds of things coming out of the stacks. It's not just a matter of monitoring it in the stacks. So, that's the reason we got involved with this kind of a study.

Right now in terms of the safety factors, we have our own fish warnings in Michigan. We're using 0.5 parts per million. The federal government is using 1 part per million. To show you the role of science and public policy, the feds used to have 0.5 also, both FDA, USDA and EPA. If you remember back in the late 60's, some scientists developed the atomic absorption spectrophotometer, a way you can measure mercury, and some grad student at New York University and his professor measured mercury in tuna fish and by God it was over 0.5. Then they went out and measured it in swordfish and it was over 0.5. They had a big hullabaloo, and they shut down the tuna fish industry for a while. The swordfish guys had a problem, they couldn't get little swordfish. The tuna guys mixed albacore with small tuna and got away with it, even though it was against the law. The swordfish guys couldn't blend it, and they only harpooned big swordfish. So they had a problem. The industry asked for 1.5 per million, the feds hung on to 0.5, and they went to court in Florida for about a year. Now, remember, one thing very interesting about mercury, it's the one toxicant I know where we have really good human data. We're not extrapolating from enzyme induction, tissue culture, or from rats, or from Great Lakes' fish, we're talking about human data. We have the Minamata Bay incident in Japan, we have the seed corn episode in Iraq. We had a similar episode in

New Mexico. Mercuric oxide is a fungicide, and you treat seed corn with it, the same way they treated paper with it. Mercury is a very effective fungicide, and some of these poor people took the seed corn and ate it, couldn't afford to wait and plant it, and a whole bunch of them died. So we have good human data on mortality rates and toxicology. If there's any way we can do a risk assessment on humans, it would be with mercury. It goes way back to the mad hatter, remember the guys who were mad in Alice in Wonderland because they floated their felt on mercury. The issue went to court for a year, and both groups brought in all their experts, and they argued back and forth, and neither one of them could make the case. The judge split the difference at 1.0 ppm.

It gives you some idea how can you really stand up there when you know you've got two competing groups with a lot of economic, and political, and social interests and look at these numbers and say can you tell the difference between 0.5 and 1.5. Could you actually go out and measure a human health effect or an ecological effect, with either one of those two numbers? In most cases I'm not sure we could. We are debating the impacts at very low levels of concentration. If there are differences in effects, they're going to be damn subtle.

Which brings up another problem, of trying to go out and validate these numbers, except for very few exceptions, there's no good match between the chemical insult and the pathology. There's no good diagnostic end point. I've been involved with a number of these epidemiological studies, from dioxin at Dow Chemical, and Agent Orange with the veterans with soft tissue carcinomas. We had PBB in Michigan, and we had three of these epidemiological studies designed to demonstrate impacts, where we knew the dose, we knew who got it, we knew how much for how long. And in none of those cases did we show anything. About the only place I know where field epidemiological studies work is with asbestosis and with vinyl chlorides where you've got a one to one match between the chemical and the pathology and nothing else causes that, so you've got a diagnostic tool you can use. Most of these chemicals of concern have no specific end points that you could use for specific diagnostic analyses. An awful lot of these things are stress induced, and you die from some other kind of virus outbreak or something else, and what really killed you was the stressor, but you don't see that. What you see is the result of reducing your immune response and you've got something else associated with the impact.

This is what happened to those pathologists from the Armed Forces Institute of Pathology, that did the *Exxon Valdez* reclamation with the sea otters. A whole lot of those sea otters died, and their interpretation was, peo-

ple brought the otters in, they put the otters in cages, the otters were stressed, they quit feeding, and metabolized their body fat. This caused the release of a bunch of toxicants and reduced the otters' immune systems, resulting in a massive outbreak of herpes. When the otters were released, they took the herpes with them. There have been heated debates on whether they actually killed more otters because of that secondary release. So the veterinarians are having a real interesting discussion, whether you can bring anything in a cage like that and turn it loose safely. These people are pros. They are not amateurs. These are people that are going around making a living doing this. There's an honest debate as to how do you interpret these type of mechanisms when it comes to going out into the field and trying to quantify these effects.

It's the same problem we're having with mercury. The ESB has some very fine epidemiologists on it, and they went through the records of all the events of mercury in humans, and the only data set they could find, that in their professional judgment was worth using, was the Iraqi data. That's the one where you could draw a dose response curve between the dose that people got and the response. The response was, basically, reproductive failure. That was the end point they used. It was not cancer. For a long time we got hung on these cancers as an end point, and they aren't the ones that you're going to see in most cases. So, they used the reproductive failure, and they got a dose response curve. It looks like there's a threshold and it's about 200 parts per million in human hair. Hair turns out to be by far the best thing to monitor, not blood, and not fat, but hair. In fact, I think, was that hair data you had was 9.8 in Alaska. In Michigan, our human value was about 8 to 10, so we've got about exactly the same levels. If you take your 200 and divide it by a safety factor of 10, you're down to 20, which is just about where we divided our subjects up into high fish eaters and low fish eaters. For women who have eaten about 70 pounds a year, the mercury levels are up around 20. The average consumption is about 40 pounds or less, and the mercury levels are down around 8 to 10. So our recommendation to the governor is we don't have a demonstrative health problem with mercury. I'm talking about humans now. The margin of error is very low, and so now it's very important to decide if mercury is steady state or is it increasing or is it decreasing. Because you might not have a problem right now, but you might very well have one in the very near future. You've only got about a safety factor of 10 parts per million.

So, how comfortable do you feel about that? Table 1 and 2 (ESB report, 1993) present the actual gaseous and particulate discharges of mercury. The ambient concentrations of depositions in gaseous concentrations in

Table 1. Concentrations of total gaseous mercury in Michigan and Chicago.

<i>Location</i>	<i>N</i>	<i>Mean (ng/m³)</i>	<i>Maximum (ng/m³)</i>
South Haven	38	2.0	4.3
Lake Michigan	25	2.3	4.9
Ann Arbor	10	2.0	4.4
Detroit 05	10	3.7	8.5
Detroit 01	10	>41.0	>70.0
Chicago	58	8.7	62.7

Table 2. Particulate mercury measurements in Michigan and Chicago.

<i>Location</i>	<i>N</i>	<i>Mean (pg/m³)</i>	<i>Maximum (pg/m³)</i>
South Haven	18	18.6	29.0
Lake Michigan	9	28.4	54.0
Ann Arbor	10	100.0	300.0
Detroit 05	10	297.0	1230.0
Detroit 01	10	342.0	1086.0
Chicago	16	97.5	518.0

Table 3. Estimated atmospheric deposition to the Great Lakes (µg/m²/yr).

<i>Lake</i>	<i>Wet deposition</i>	<i>Dry deposition</i>	<i>Total deposition</i>
Superior	15.2	11.34	26.54
Michigan	15.8	11.34	27.14
Huron	15.2	11.34	26.52
Eric	16.8	11.34	28.14
Ontario	17.8	11.34	29.14

urban areas are much more than in rural areas. South Haven and Lake Michigan are right across from Chicago. The background levels for gaseous mercury is about 2. The mercury from Chicago isn't getting across the lake but is most likely ending up in the lake. Down around the Detroit area you also have pretty high concentrations. The particulates are the same way.

If you actually look at the distribution of deposition (Table 3), you find a very uniform rate over all the lakes. This is Steve Eisenrich's data out of Minnesota. He's the one who does the mass balances, both on PCBs and mercury, and he's a really good geochemist. About 60% of the deposition in the Great Lakes are wet deposition, and about 40% are dry.

For the last five or six years, we've been bringing the Johnson's Sea Link, that little submarine from Harbor Branch, to do deep water diving in our Great Lakes and to take sediment cores. These are Dave Long's sediment cores of the Great Lakes looking at the mercury profiles. When you first look at these, the interpretation is we

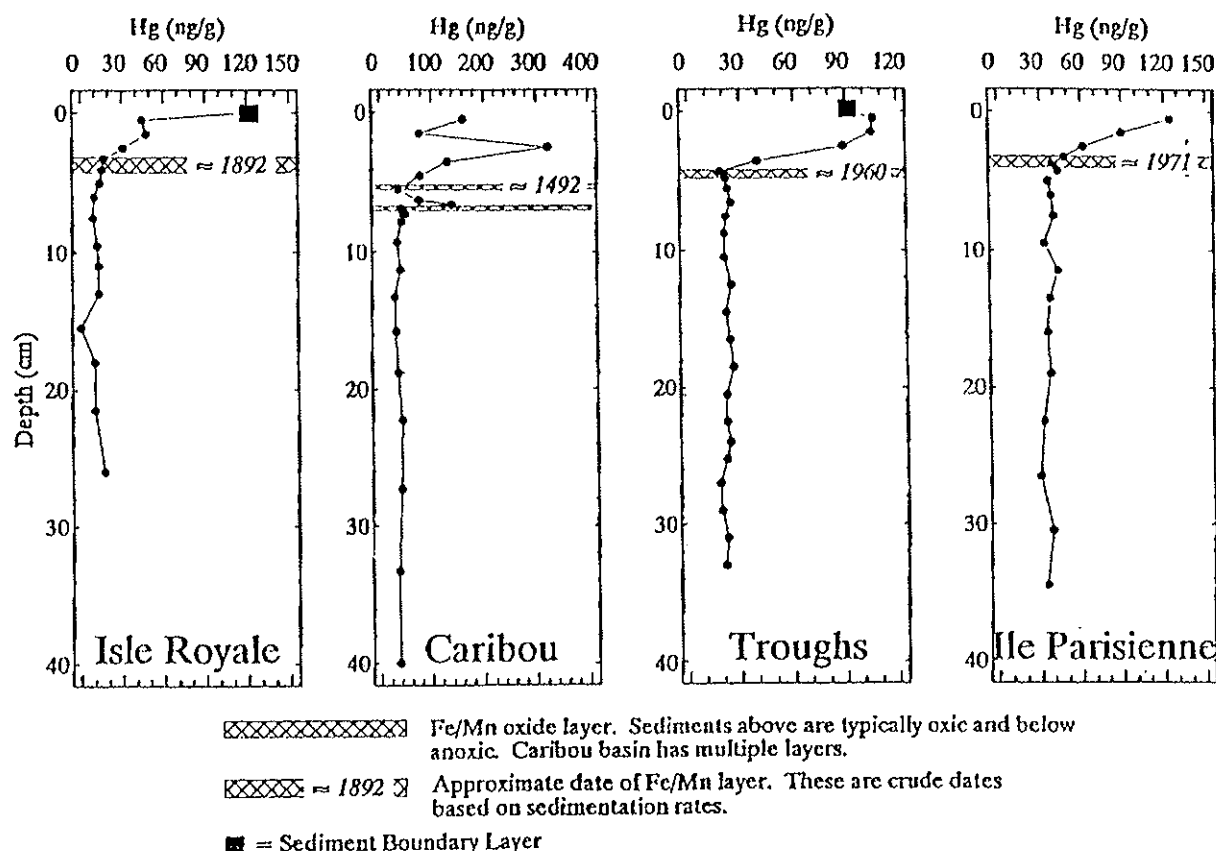


Figure 1. Mercury concentrations in selected basins of Lake Superior (from Strunk, 1991).

must have a big increase in mercury emissions and deposition in the lake, because the very recent sediments, the ones at the top, have a great big increase in concentration (Figure 1). Well, it turns out that you've got to be real careful, we can't use that data at all in terms of trend analysis, because of diagenesis. What's happening, where those horizontal marks are, is where the sediments go from being aerobic to anaerobic, and as soon as you do that you mobilize the mercury off its complex and it migrates to the surface. If there is an increase in mercury deposition in those cores, it's hidden by the fact that mercury is mobile within the core, as a function of where that aerobic-anaerobic zone is located. Now, I don't know whether that happens with your radionuclides or not. We saw some core data this morning, and the question that I was going to ask somebody is whether or not you get that same vertical migration, whether or not you've got that same kind of very sharp banding between aerobic and anaerobic sediment. It's definitely true of mercury in our sediments.

The recommendations made to the governor are that they spend their money not shutting down incinerators, and not running around trying to dredge sediments. It looks like we're still in that safe zone, so they should

spend their money setting up a monitoring system to determine the trend in mercury deposition. We very much want to determine whether or not the trends are again either steady state, increasing, or decreasing. The whole response that you'd recommend depends on the trend analysis. The recommended design of the monitoring system is one year you measure human hair, the next year you measure mercury in sediments, the next year you measure mercury in water or fish, and then maybe in eagle feathers if you want to get a wildlife sentinel, and then in year five you start over again. It will take you about 15 years to get enough data points to get a trend. Because with only two points, you're bound to get a straight line. If you want to do a regression analysis, the minimum you need is about 5, and so you've got about 20 years before you're going to really identify a trend. Someone might say, well, can we afford to wait 20 years. Based on these kinds of analysis, and based on what we know about mercury, I'm not sure you have a choice. In terms of a science answer, in terms of saying specifically what should you do, we know that either way there's a certain element of risk of being wrong. I really wanted to present the mercury case study, because mercury is one of the toxicants that Kathy Crane reported researchers found in polar bears

and seals. It is a major concern in terms of the Eskimos consuming mercury. I don't know how our 70 pounds per year compares with their fish consumption. If the consumption is similar and if you use a normal kind of risk assessment, you're on the brink, looking over the edge, but you're still standing there.

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Russian Concerns and Perspectives on Arctic Contamination

Radioactivity in the Arctic

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Each living object of the biosphere exists in a radiation field of both natural and induced origin. Actually the induced exposure dose is usually smaller than that from natural background radiation. The situation is different for the territories subjected to radioactive pollution due to damage or inadequate handling of radioactive substances.

The radioecological characteristic of any territory will include the following parameters (see Figure 1):

1. Gamma background of the territory;
2. Natural radionuclide concentrations in elements of human food chains;
3. Induced radionuclide concentrations in elements of human food chains;
4. Concentrations of natural technologically induced radionuclides in human food chains;
5. Concentrations of natural and induced radionuclides in potable and non-potable water;
6. Concentrations of radon and short-living decay products in indoor air;
7. Sources of natural and induced radionuclides on observed territory;

8. Human irradiation doses.

Radiological prediction includes data on kinetic parameters of radionuclide migration in the natural and industrial spheres as the basis for calculations of probable human irradiation doses. In necessary instances measures for reducing probable irradiation doses are worked out.

Information on the radiation factor for territories of the Russian north (Murmansk, Arkhangelsk, Vologda regions, Komi Autonomous Republic, Yamal-Nenetsk national territory, Taimyr territory, Choukotka) began to appear in the end of 1960s (1-5).

Natural gamma background radiation ranges between 7 and 13 milliroentgen/hour and is showing no difference from that of so-called "normal areas" (10).

As a result of the past nuclear weapon tests in Novaya Zemlya, there exist three to four sites, of 1-2 km diameter, where the power of the exposure dose may amount to 3 milliroentgen/hour (6).

Concentrations of natural radionuclides (uranium-238, radium-226, thorium-232 and potassium-40) in the environmental objects are showing no important differ-

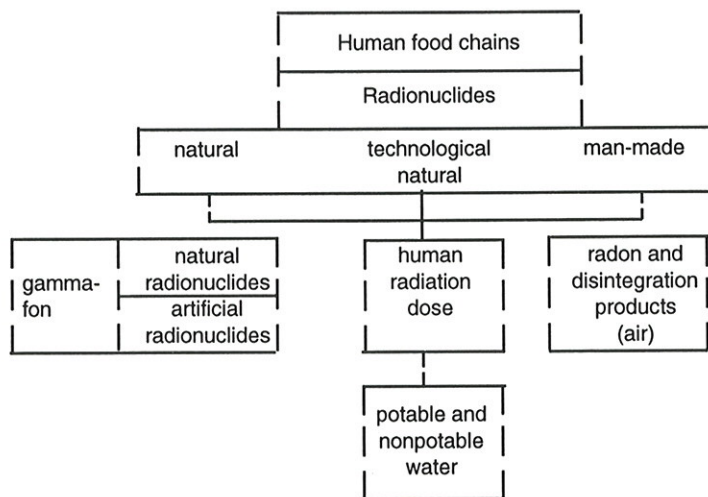


Figure 1. Scheme.

Table 1. Concentration of natural radionuclides in natural objects.

Region	Concentration of radionuclides (Bq/kg)				
	K-40	Ra-225	Th-228	Rb-210	Lit.
In soil					
Novaya Zemlya	100-800	5-20	5-35	—	(11)
Average in World	370	25	25	—	(10)
	(100-700)	(10-50)	(7-50)		
In lichen and mosses (Bq/kg of dried mass)					
Novaya Zemlya	200-900	2-50	4-57	—	(11)
Murmansk region	—	10	2	340	(2)
Komi ASSR	—	13	4	250	(2)
Taimyr national okrug	—	—	—	300	(2)
Yakutskaya ASSR	—	11	8.5	154	(2)
Chukotsk poluostrov	—	14	3.0	115	(2)
North countries	—	—	—	185-370	(12)
In bone tissue of reindeers, (Bq/kg of humid mass)					
Novaya Zemlya	<100	<6	<8	—	(11)
Murmansk region	—	26	26	560	(2)
Taimyr national okrug	—	22	6	525	(2)
Yakutskaya ASSR	—	18	11	380	(2)
Chukotsk poluostrov	—	13	16	570	(2)
In muscles of reindeer (Bq/kg of humid mass)					
North countries	—	—	—	1-7.4	(12)

ences from those registered for "normal areas," whereas concentrations of lead-210 and polonium-210 in lichens, tissues of reindeer, and humans are substantially above those for "normal areas" (see Table 1).

As shown by these estimates, it is only in years of maximal environmental pollution that the radio-

nuclide-induced irradiation dose in deer tissues is comparable to that from natural radionuclides (6,12).

The literature does not contain adequate data on the content of induced radionuclides, other than strontium-90 and cesium-137, in natural environments. Information on possible migration of underground test

Table 2. Concentration of artificial radionuclides in natural objects (Bq/kg).

Region	Soil (dried mass)		Lichens (dried mass)		Lit.
	Cs-137	Sr-90	Cs-137	Sr-90	
Novaya Zemlya	<5	—	20-500	200	(11)
Murmansk region	0.036*	0.021*	220-440†	110-150†	(6)
Komi ASSR	0.026*	0.019*	170†	150†	(6)
Taimyr national okrug	0.023*	0.014*	240†	150†	(6)
Yakutskaya ASSR	0.016*	0.010*	240†	150†	(6)
Chukotsk poluostrov	0.014*	0.011*	350†	170†	(6)
In organisms of north deers (humid mass)					
	Cs-137 (muscles)	Sr-90 (bones)			
Murmansk region	600†	745†			(6)
Komi ASSR	630†	—			(6)
Taimyr national okrug	300†	400†			(6)
Yakutskaya ASSR	260†	—			(6)
Chukotsk poluostrov	350†	370†			(6)

* Concentrations calculated on the level of global fallout with terms: soil layer 0-5 cm, soil density 1 g/cm³.

† Average data for the 1980-1986 years have been used. Maximum values, occurring on the years 1963-1967, were more than those listed in the table by approximately 10-fold (5,6).

formed radionuclides into the subterranean waters is also missing. There is a most urgent need for reliable information on the sites and volumes (in terms of general and specific activity) of dumps of radioactive wastes in the water area of Novaya Zemlya archipelago.

Thorough information is required on the intensity of radionuclides migration over terrestrial and marine trophic food chains, especially in areas of subterranean and submarine dumps of radioactive wastes such as ship and nuclear submarine moorage sites, and locations for the recharge, storage, and transportation of radioactive wastes.

Average concentrations of cesium-137 in the surface and deep waters of the Barents Sea are equal to 12.6 ± 0.3 and 19 ± 1 respectively and in fish organisms they reach 0.8 Bk/kg of the raw mass (7-9).

It should be noted that complete radioecological assessment of any territory, especially in the North and the Arctic, seems impossible without studies of the behavior of natural radionuclides in the environment, i.e. without knowledge of natural "pedestal" of biotic irradiation dose on which the induced radionuclide radiation dose is superimposed. For instance, knowledge of radon component of the background impact on human beings in the conditions of the North is still insufficient.

At present there is a growing understanding of the fact that, besides human response to the radiation impact, responses of other objects of natural environment should be studied searching for responses of separate ecosystem.

Searches for the response of natural organisms to low-level radiation exposure may be feasible only on the background of other pollutant impacts—those of heavy metals, nitrogen oxides, sulphur, and organic compounds.

Response of natural organisms and systems to light exposure of pollutants of non-radioactive nature is also poorly understood. Thus the integrated ecological analysis of human impacts on the environment is required which would incorporate the combined effect of all pollutants emitted and discharged from industrial and agricultural enterprises.

Summing up, a double purpose may be formulated. On the one hand, the radiation factor assessments should include not only human response, but the response of the surrounding environment as well. On the other hand, the response analysis should be based not only on the radiation factor, but take due account of the impact of other pollutants. Monitoring systems, its amount and adequacy for environmental status control are being developed to comply with this double purpose.

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Radiation Hazards for the Human Population of Siberia

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In the Altay kray, on the Kazakhstan–Russian border (see Figure 1), radioactive contamination is a great concern, due to its geographical location in the south of Western Siberia in the immediate vicinity of China and Kazakhstan. Among the main sources of radioactive contamination of the environment in this region, the following have been identified: a series of powerful nuclear explosions conducted on the Semipalatinsk test site and in China, the accident at the Chernobyl nuclear power plant, nuclear tests on Novaya Zemlya, combustion products of organic fuel in boilers, heat and power plants, dusting from ash dumps, and also sources of radioactive contamination of natural origin.

Radioactive contamination of soil in the territory of the Altay kray is determined mainly by the accumulation in the soil over many years of fallout from long-lived strontium-90 and cesium-137 that had been emitted into the atmosphere during nuclear weapons tests. In addition, mineral fertilizers applied directly into the soil are a significant source of its radioactive contamination. Contamination of surface waters is caused by the wash-off of strontium-90 from the soil surface by atmospheric precipitation.

In Novosibirsk oblast (also on the Kazakhstan–Russian border), radiometric sampling of atmospheric fallout (according to the monthly data from the Center for Monitoring Environmental Contamination) indicated that during 1990–1991 the fallout density did not exceed the established control value of 110 becquerel per square meter (Bq/m^2) per day in terms of total beta activity, and on average was 0.7 Bq/m^2 throughout Novosibirsk oblast. At the permanent sites for recording radioactive contamination, the mean values of fall-

out density are as follows: $0.8 \pm 0.5 \text{ Bq/m}^2$ in the cities of Bolotnoye and Karasuk, $1.0 \pm 0.4 \text{ Bq/m}^2$ in the city of Barabinsk, $1.5 \pm 0.7 \text{ Bq/m}^2$ in the city of Novosibirsk, and $1.4 \pm 0.7 \text{ Bq/m}^2$ in the town of Ogurtsovo. The maximum radioactive fallout was 6.3 Bq/m^2 in Barabinsk, 10.0 Bq/m^2 in Novosibirsk, and 18.5 Bq/m^2 in Ogurtsovo.

The radioactivity of the surface atmospheric layer was caused by fallout from the stratosphere of products of the decay of radioactive substances during nuclear tests conducted in previous years. Basically the radioactive contamination is determined by the presence of substances such as cesium-137; in a number of cases contamination by thorium-232 from the soil was noted.

The soil dose rate is, on average, 20–50 microrad per hour ($\mu\text{r/hr}$), yet in some cases the maximum dose goes up to $275 \mu\text{r/hr}$ (in the exclusion zone of the tailing dump of the Production Association Khimkontsentrat in the city of Novosibirsk, which results from the production activities of this enterprise).

The available official data on the contamination of air, water and soil in Novosibirsk oblast do not provide the full picture of the environmental situation in this region (and its constituent areas), yet they can effectively indicate zones of possible anthropotechnical stress, which can result in damage to the health of the population.

In Tomsk oblast, a substantial increase in the background radiation is found at the mouth of the Chernilshchikova Channel where water coming from the Tomsk-7 area flows into the River Ob; 100 m from the bank, water registers $30 \mu\text{r/hr}$, and the general background is $30\text{--}35 \mu\text{r/hr}$. It must be taken into account that contam-

inated water at the measuring point has been already diluted substantially with water from the Chernilshchikova Channel of the River Ob. The fact that the general background radiation in the River Ob and its tributaries is significantly lower (1-4 $\mu\text{r/hr}$) than the above values suggests that industrial production in the city of Tomsk-7 is related to these levels of the atmospheric background and river background in adjacent areas.

In the Krasnoyarsk kray, in 1989-1991 the Krasnoyarsk Scientific Center of the Siberian Branch of the Russian Academy of Sciences conducted investigations of the radioecological conditions of the Yenisey River. An airborne gamma-ray survey and comprehensive investigations were performed 1,000 km downstream of the discharge from the Mining Chemical Integrated Works, using a specially equipped vessel. Over 600 samples of water, bottom sediments, soil, fish and vegetation were taken along a section 1,000 km long. The investigations covered the entire radionuclide composition of contaminants, including plutonium, tritium, and also cesium-137 and phosphorus-32 (the main dose-forming radionuclides).

It was found that in the zone of displacement of discharged water from the integrated works, sodium-24 and manganese-56 reached the highest concentration, 2.6×10^{-7} curies per liter (Ci/l) and 2.3×10^{-7} Ci/l respectively, exceeding the 76/82 radiation safety standards by 10 and 2 times, respectively. In the town of Atamanovo, the first settlement downstream from the discharge site, the concentration of certain nuclides in water was below permissible concentrations due to decay and dilution, but the total activity in water was close to the upper limit of the permissible value.

The content of long-lived radionuclides (cobalt-60, cesium-137, europium-152, 154) on the bottom of the Balchugovsky Channel, for the average water content, was about 1 Ci. The entire reserve of technogenic nuclides in the tailings of the islands that were studied is estimated at approximately 17 Ci. The distribution of radionuclides through the bed varies greatly along the length of the river.

During the investigation, much attention was given to the study of radioactive contamination of fish. Altogether over 40 specimens of thirteen nonmigratory and migratory species of fish were analyzed. The main nuclides accumulating in fish tissue were phosphorus-32, zinc-65, cesium-137, and, close to the source of activity, sodium-24. Contaminated fish were caught at a great distance from the site of discharge, both downstream and upstream. Technogenic radionuclides were found in fish caught close to the city of Krasnoyarsk. The maximum concentration of phosphorus-32 (5.0×10^{-7} Ci/kg), which is the principal nuclide produced,

was found in a grayling caught in the area of the town of Pavlovshin (60 km downstream from the discharge). The analysis that was performed indicates that practically throughout the entire 1,000-km-long sector of the river under study, contaminated fish consumed by the local population is the major component of the possible dose load.

The density of contamination of the flood plain in terms of total technogenic nuclides varied with the distance from the source, from 160 to $0.2 \mu\text{Ci/m}^2$. According to the data from the Institute of Biological Problems of the North of the Far Eastern Branch of the Russian Academy of Medical Sciences, in Chukotka the general γ background of natural radioactivity is 15-30 $\mu\text{r/hr}$ (which does not exceed permissible levels and is somewhat different from other areas).

In the north of the Krasnoyarsk kray the γ background is 25-30 $\mu\text{r/hr}$. In the Magadan oblast, the γ background is 15-30 $\mu\text{r/hr}$, with cesium-137 and strontium-90 (i.e. products of nuclear decay after explosions) making practically no contribution to the radioactive background in the North.

The radioactivity of venison muscles was determined as $0.1-2.7 \times 10^{-9}$ Ci/kg which is 0.03 per kg (or 3%) and is permissible for these products.

In the city of Mirny (basin of the Vilyuy River) the γ background does not exceed permissible levels.

According to data from the Leningrad Institute of Radiation Hygiene, the natural radioactive background in the North is high, which is typical of the North in general. Reindeer moss accumulates and absorbs radioactive substances, which may result in a higher radioactive background in deer and in human bodies. It is known that radionuclides play a greater role in the state of health than the γ background.

Sociological and demographic studies tracking the connection between contamination of the environment with radionuclides, chemical agents, and also the physical components of the radiation factor, are currently underway in the Altay kray. It was revealed that in 40 years, starting in 1950 (the time of the first nuclear tests), a complex demographic situation has developed in the kray, partly due to an increase in environmental stress.

During the period from 1950 through 1990, its population increased from 2,396,200 to 2,828,300. The total population increase was 432,100 or 18.0%. This amount of population growth over 40 years cannot be accepted as sufficient.

Certain indices of population morbidity and mortality are indicators of some sort of increase in the ecological stress throughout the area.

From 1950 through 1990, unfavorable trends were revealed in this region in the dynamics of cancer mor-

idity. They were characterized by a progressive growth trend, close to a linear one (the increase in primary morbidity indices was 4.6 times). The most unfavorable changes in primary morbidity indices were observed for malignant respiratory tumors (an increase by more than 50 times), malignant skin tumors (by 3.4 times), malignant breast tumors (by 4.6 times).

The incidence of malignant digestive organ tumors also increased, but during the recent decade, the trend has stabilized and even shown a decrease.

An increase in the morbidity indices was also observed for hematologic neoplasms (primary morbidity rose by 1.2 times, susceptibility to disease by 2.4 times). Yet their dynamics showed periods of increase (1974-1975 and 1989-1990) and decrease (1979-1980).

Other malignant tumors, examined separately, manifested either stabilization of primary morbidity (malignant tumors of the urogenital organs), or decrease (malignant tumors of the cervix), while susceptibility to the disease increased.

Among other indicative nosologies, the most unfavorable changes were characteristic of the morbidity of children in the region (up to 14 years of age) with anemia due to iron deficiency (an increase in primary morbidity was 4.7 times), neonatal morbidity (indices increased by 2.3 times), including the hemolytic disease (by 2.5 times), and congenital anomalies (by 1.8 times). There has been an unfavorable trend in the frequency of toxemias of the second half of pregnancy.

The mortality from malignant tumors has increased markedly in the region: by 6.9 times for the entire population, by 9.1 times for men, and by 5.2 times for women.

Since the mid-1960s, male mortality from malignant tumors has been higher than that of women, and the gap has been widening (from 1.1 times in 1970 to 1.5 times in 1990). An increase in the level of mortality from oncological diseases is characteristic of all major age groups of the population. The mortality index for the working-age population increased by 3.8 times; for retirees by 6 times; and for children by 18.3 times.

Of all malignant tumors, those of the digestive organs have been the leading cause of mortality in the region. Mortality from this cause progressively increased from 17.7% in 1950 to 64.9% in 1990. Men displayed higher mortality from this cause than women. Most individuals who died from malignant tumors of the digestive organs were in the retirement age group.

Malignant tumors of the respiratory organs are the second most important cause of death from malignant tumors among the region's population, and their percentage has been constantly increasing. During the period from 1950 to 1990, mortality indices increased (from 1.65% to 56.02% or by 34 times). The mortality

level among men was increased by 3.3 to 7.2 times higher than among women.

Women's mortality has been increasing constantly also from malignant tumors of the breast (from 2.4% to 14.2%). The highest increase occurred from 1959 to 1970 after which the rate of increase was somewhat slower.

Malignant tumors of the urogenital tract have a significant place in the structure of mortality of women in the kray from malignant tumors (up to 25%). The period from 1950 to 1965 showed a sharp increase (by 3.4 times) in women's mortality from this cause. In the last 20 years, however, mortality of working age women from this cause has decreased substantially (from 38.3% to 10.7%). In the past 20 years, mortality of the male population from malignant tumors of the urogenital tract also increased by 2.4 times (from 3.3 to 7.9%).

The mortality level from hematologic neoplasms in the kray increased between 1969 to 1990 (from 4.87% to 8.68%). The mortality of men from this cause is higher than that of women (by 1.2-1.7 times).

The incidence of mortality from the diseases of the endocrine system also showed a constant growth trend, which peaked in 1981-1985 and was followed by a slight decrease. The mortality of women due to this cause is 1.5-2 times higher than that of men.

Analysis of indicative morbidity (malignant tumors, thyrotoxicosis, neonatal morbidity) and mortality (from malignant tumors, infant mortality, stillbirth, and congenital anomalies) shows with a high degree of probability that the radiation factor had and continues to have a place in the contamination of this region. The investigation shows a direct effect on the health of living generations as well as a delayed effect (a combination of the direct effect of environmental contamination and the effect on subsequent generations through the maternal generation, which was directly exposed to the radiation. Although detrimental characteristics are eliminated from the population (decreased birth rate, increased mortality), remote consequences of the radiation factor may still be manifested in many subsequent generations.

An in-depth study of the effects of radiation contamination on the health status of the population is needed, using the data on the radiation load in the kray and sociohygienic cohort analysis, which would permit a sufficiently accurate determination of the effect of radioactive contamination of the environment on the health of the population.

In Novosibirsk oblast, a high level of morbidity with malignant tumors is found in the Maslyanino, Kochenevo, Kolyvan, Chistoozernoye, and Kargat rayons, and also in the city of Novosibirsk (over 250 cases per 100,000 people).

Mortality from lung cancer is the highest (over 40.0 per 100,000 people) in the Chistoozernoye, Ubinskoye, Bagan, Kochenevo, Ust-Tarka, Ordynskoye, Moshkovo, Toguchin, Kolyvan, Suzun, Maslyanino, Bolotnoye, and Zdvinsk rayons, and also in the city of Berdsk. A low level (less than 30.0 per 100,000 people) was found in the Barabinsk, Vengerovo, Dovolnoye, Kochki, Severnoye, Tatarsk, and Chany rayons. In this regard, the Moshkovo Rayon was classified in the group with "very poor" health, and confirmed that cancer of the stomach accounts for much of the mortality from tumors. The Kolyvan Rayon is in the same situation. Negative transitions (to a worse health group) were also made by the Tatarsk (from "medium" to "poor"), Ust-Tarka and Bagan (from "below medium" to "poor"), and Severnoye (from "good" to "below medium") rayons.

Comprehensive evaluation of all four indicators (mortality and morbidity in the entire class of malignant pathology, and also mortality from lung and stomach cancer) provides the most accurate concept of the connection between environmental factors and the development of tumors. In this case, the Chistoozernoye, Kochenevo, Moshkovo, Kolyvan and Maslyanino rayons come under the "poor" state of health rubric. In addition, according to the previous analysis, pulmonary pathology is the leading factor in the two former rayons,

and that of the gastrointestinal tract in the latter two. Various kinds of malignant tumors are prevalent in the Maslyanino rayon.

According to recent studies, the unfavorable radiation situation in the city of Novosibirsk and the Moshkovo rayon could be traced to soil and air contamination with radioactive and chemical substances from the Khimkontsentrat enterprise, in particular to illegal dumping sites for waste from this and other enterprises in the Moshkovo and Novosibirsk rural areas. In the Maslyanino rayon, the contamination of farmland by mineral fertilizers and pesticides is the highest in the oblast (200-210 kg per person per year and 70-80 kg per hectare of land under cultivation).

In the city of Tomsk, an increase in the incidence of oncological diseases related to environmental pollution was found. Thus in 1976, the incidence of malignant tumors was 107.9 per 100,000 people, while in 1986 it jumped to 277.4 per 100,000 people, i.e. by 2.5 times. The Research Institute of Oncology of the Siberian Branch of the Russian Academy of Medical Sciences, and the Computer Center of TIASUR analyzed satellite photographs of the city of Tomsk and found that an IR photograph dated June 19, 1988, in the 0.8-0.9 micron range superposed on the city map of the same scale indicated that the dark spots matched industrial enterprises of the city.

Assessment of Marine Contamination in the Eurasian Arctic Shelf by NPO SEVMORGEOLOGIA

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I would like to start my presentation with an introduction of our organization. It is still in the process of permanent changes. Everything in my country is subject to changes in our country right now. The structure of the Geological Survey of Russia is also being changed permanently. At this moment, I am a member of an association for research and development in the world ocean which is called *SEVMORGEOLOGIA*. For many years, this was a State enterprise which included several units. Now all these units have become independent enterprises, and they have all joined together to form this association. It is probably a little bit loose, because at present, it has no legal power with respect to its member organizations, but we still are very much attached to each other. This association *SEVMORGEOLOGIA* includes the old All Union Research Institute of the World Ocean Geology and Mineral Resources, *VNIIOKEANGEOLOGIA*, the unit where I worked as a Deputy Director. We also have three Expeditions. One is in St. Petersburg, the Polar Expedition for Offshore Geological Exploration, another is the Arctic Marine Expedition, based in Murmansk. This unit is responsible mostly for oil and gas regional research in the Arctic shelf. The third is in Norilsk, and is the traditional expedition of our institution. It is the last on shore unit we have left.

Our Association manages eight research vessels of many different types, but the RV *Geolog Fersman*, a *Morskoi Geolog* class vessel with 5500 tons of displacement, is the most common. Unfortunately, it is not ice strengthened, so we have to use favorable ice conditions to work in the Arctic seas. It is actually a big fishing trawler converted into a research ship.

From this platform, we can do research of the water layer. We have radiometry, hydrometry, a bottom profiler, and equipment for coring and taking specimens. There are also a number of facilities for express analyt-

ical research onboard the ship. Using these ships, the Association accomplished two successive cruises into Barents and Kara Seas in 1991 and 1992. Processing of the results from the 1991 cruise is nearing completion. The 1992 field data are still being processed, so I will report on essentially the results of the first year.

Figure 1 is a location chart of the cruise we made in 1991 in the Barents and Kara Seas. One can see the ship track and the number of stations visited in this area. Figure 2 is a map of the sampling locations from the 1992 field season. There is no ship track plotted on the figure, but the number of collection stations in the Barents Sea is quite significant.

Preliminary results from sampling of the bottom sediments are presented in Figures 3-6. Figure 3 shows the distribution of hydrocarbon. One can observe the largest anomalies, which are in excess of 500 parts per million, are in the vicinity of the Kola Peninsula, the White Sea, and offshore southeastern Novaya Zemlya. The exact source of this contamination is unknown, but the most apparent source is probably heavy vessel traffic, fuel storage on shore, and waste disposal.

Figure 4 shows the phenol distribution in the bottom sediments. Obviously, this distribution reflects the effect of wood processing, which is a very heavy on shore activity around the White Sea and at the mouths of the major Siberian rivers, the Ob and Yenesei. The rest of the area is virtually clear of all phenol contamination.

Figure 5 shows the distribution of total pesticides in the bottom sediment. The distribution is similar to the one seen for phenol, but there is a largeigmatic anomaly east of Novaya Zemlya. We do not know the source of this anomaly. The maximum shown on this map is in excess of 1 part per million.

Figure 6 shows the distribution in bottom sediments of gexachlorcyclogexan. It shows a similar distribution

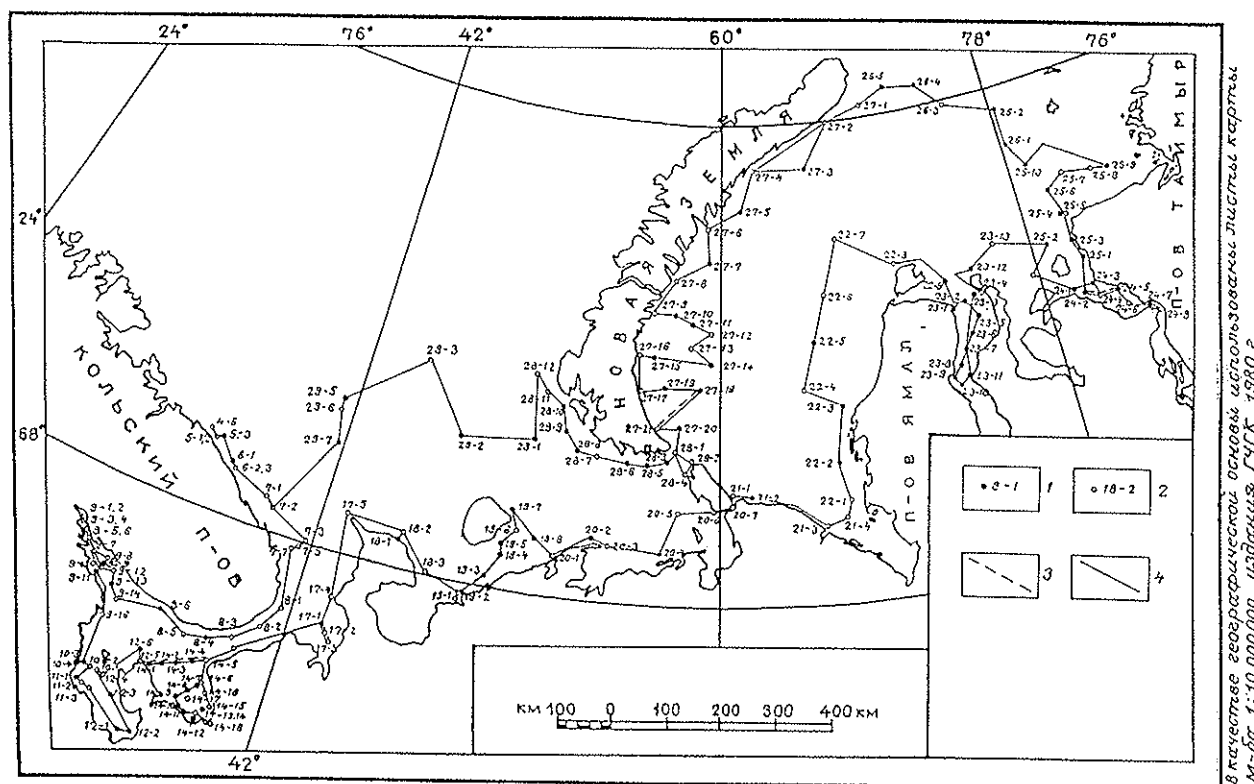


Figure 1. Chart of the geoecological cruise of the R/V Academician Karpinsky, 1991. (1) Bottom sampling stations, seismic probing/penetration, hydrochemical sampling; (2) Bio-dredging, plankton trawling, and underwater T.V. collection site; (3) Seismic profiling; (4) Bathymetry/echo sounding.

to Figure 5, but there are unexplained anomalies in excess of 0.5 parts per million around the southeast of Novaya Zemlya. There is no apparent source.

Figures 7 - 10 show the distribution of heavy metals in the bottom sediments. Figure 7 is for lead, Figure 8 for zinc, Figure 9 for cobalt, and Figure 10 for nickel. The distributions are very similar. The common features for all four metals is high concentrations in the White Sea and offshore of the major rivers, the Yenesei and Ob. There are also very noticeable anomalies close to Novaya Zemlya, which are readily explainable by the presence of all these metals in bedrock on Novaya Zemlya. These maps show some of the contamination is probably natural distribution, natural contamination, coming offshore from Novaya Zemlya. Another prominent feature in the distribution of heavy metals is an anomaly which is related to the Gulf Stream current. We never expected it to be so prominent, but apparently it is there. One must remember that these distributions of contaminating substances do not always adequately describe the real environmental stress. In an effort to assess and quantify the environmental stress, biotesting of specimens collected in 1992 field season.

Figure 11 is the only map compiled from the results of the 1992 cruise. It shows the areas of the most toxic sea bottom environment. This was determined by strong inhibition of test organic species. At the 166 specimen

sites visited, almost 80 percent indicate the presence of toxic environment. Surprisingly, such environment was observed in same areas which we regarded ecologically safe. And probably one of the best examples is around Spitsbergen and near Franz Josef Land. We never expected that the toxic sea bottom environment and water environment would be so prominent in these areas.

Some of the 1991 data were also processed by a gradient procedure which is shown in Figures 12 - 16. Figure 12 shows cesium-137 in bottom sediments. This is not just the observed content of cesium, it is gradient data. What is plotted on this and the following maps is actually the distribution of components in bottom sediments expressed in standard deviations, not in real measured concentrations. For cesium-137 (Figure 12), one can see small fields of increased concentrations which generally indicate a low level of radioactive pollution. Figure 13 shows manganese. There are two large contaminated areas, north of the Kola Peninsula and in the Kara Sea. The one in the Kara Sea is believed to be related to a supply of manganese to the sea environment from Novaya Zemlya bedrock exposures.

Figure 14 shows the distribution of phosphate (PO_4). One can see a slightly increased content of phosphate in bottom sediment is typical of the whole Barents Sea with peak concentrations close to the Novaya Zemlya

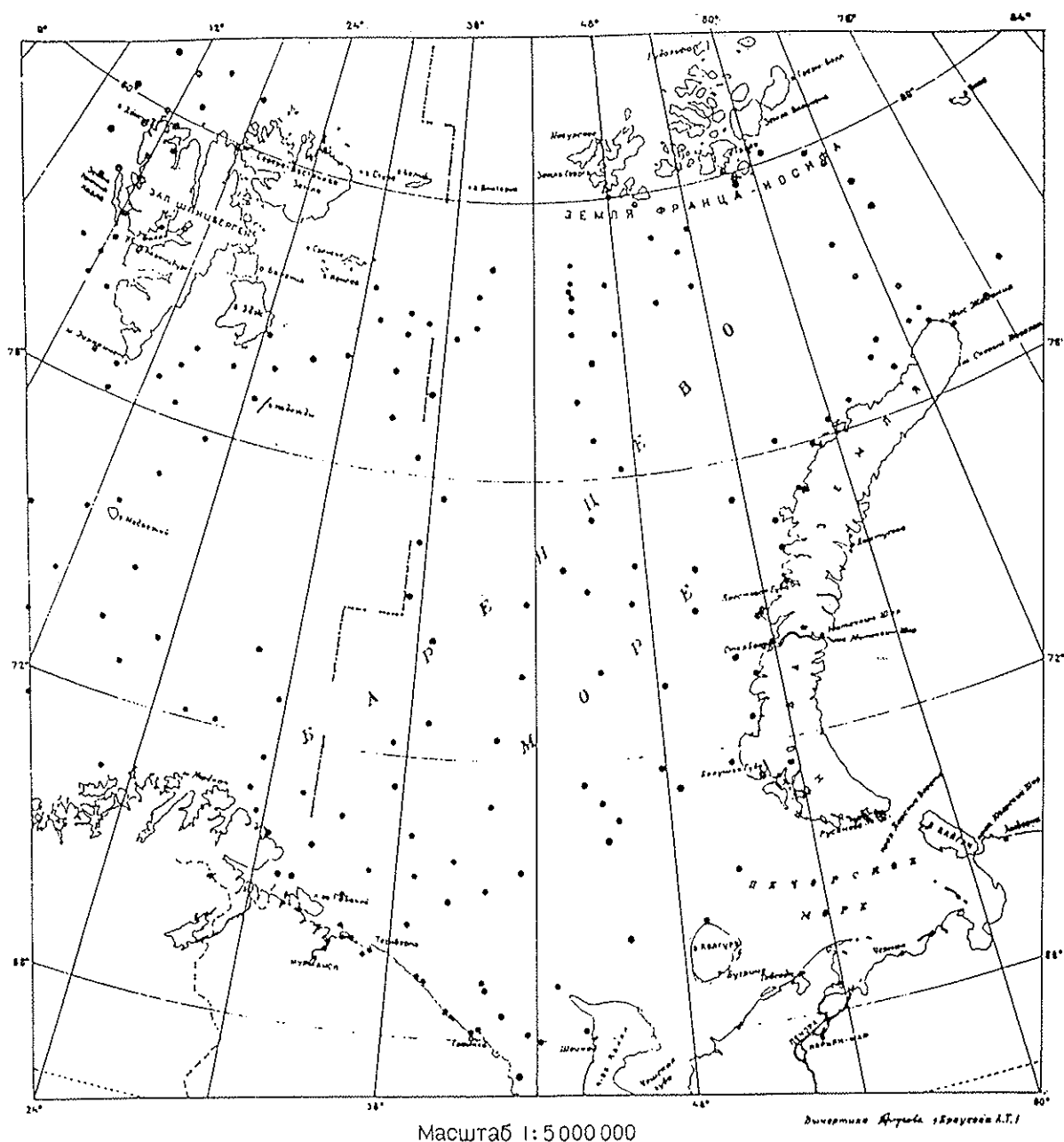


Figure 2. Map of the sampling locations for the 1992 cruise.

coast. We do not know to what extent such distribution is related to natural radionuclide pattern.

Figure 15 shows pesticide, DDD. Two concentrations are obviously related to Novaya Zemlya, but the most significant concentration is connected with the discharge of the Yenesei River.

Figure 16 shows hydrocarbons in near-bottom water, which form an apparent large scale anomaly west of Novaya Zemlya. The most likely source of this anomaly is of course the large oil and gas, essentially gas fields, known in this area, the Shtockmen, Murmansk, and Prirazlomnoye fields, the fields which are actually under consideration for future development right now.

This suggests probably natural contamination with no technogenic input.

When one examines the integral characteristics of these geochemical distributions I have shown, a rather complicated picture emerges. There is a correlation between chlororganic components and heavy metals in bottom sediments in the most contaminated regions, while water in the same areas is contaminated essentially by chlororganics only. Natural radionuclides are the most prominent near the Taymyr and Yamal Peninsulas.

The conclusion we were able to make at this stage is that preliminary results of environmental studies in the western Eurasian offshore indicate appreciable levels of

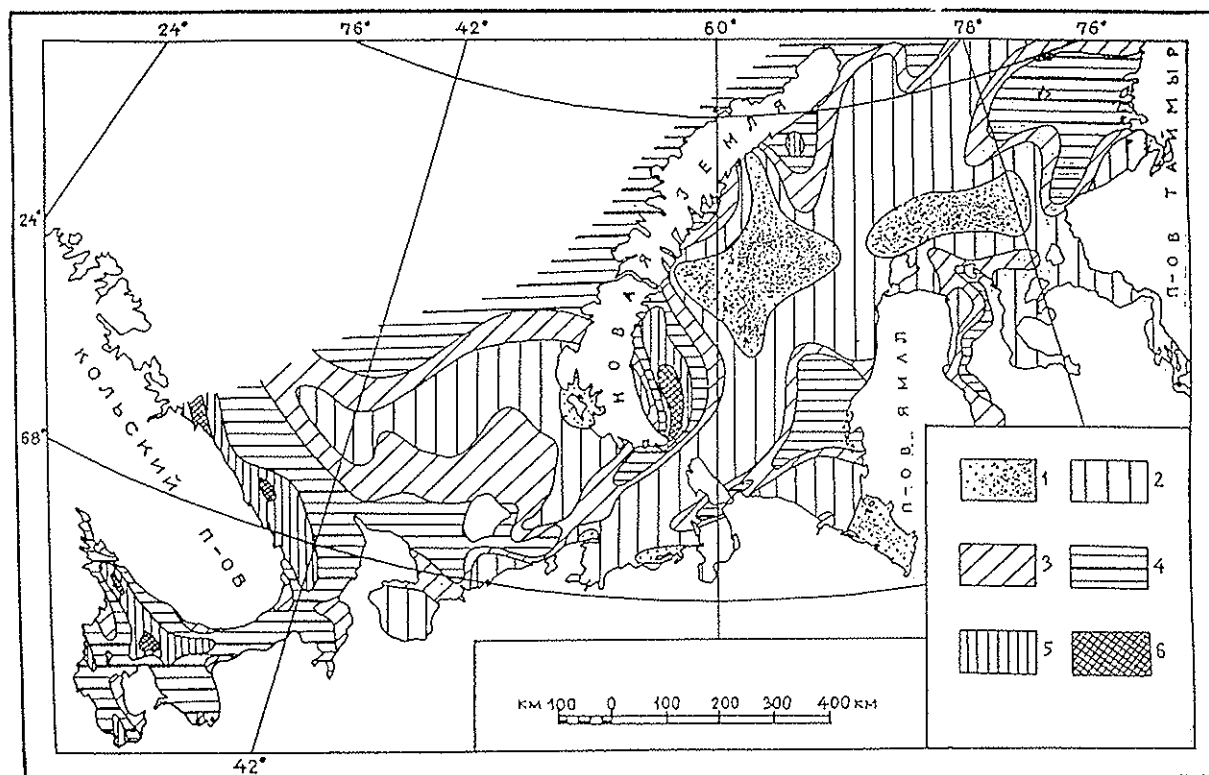


Figure 3. Distribution of oil hydrocarbons in the bottom sediment. Values in mg/kg (i.e. parts per million). (1) <10; (2) from 10 to 30; (3) from 30 to 100; (4) from 100 to 300; (5) from 300 to 500; (6) greater than 500.

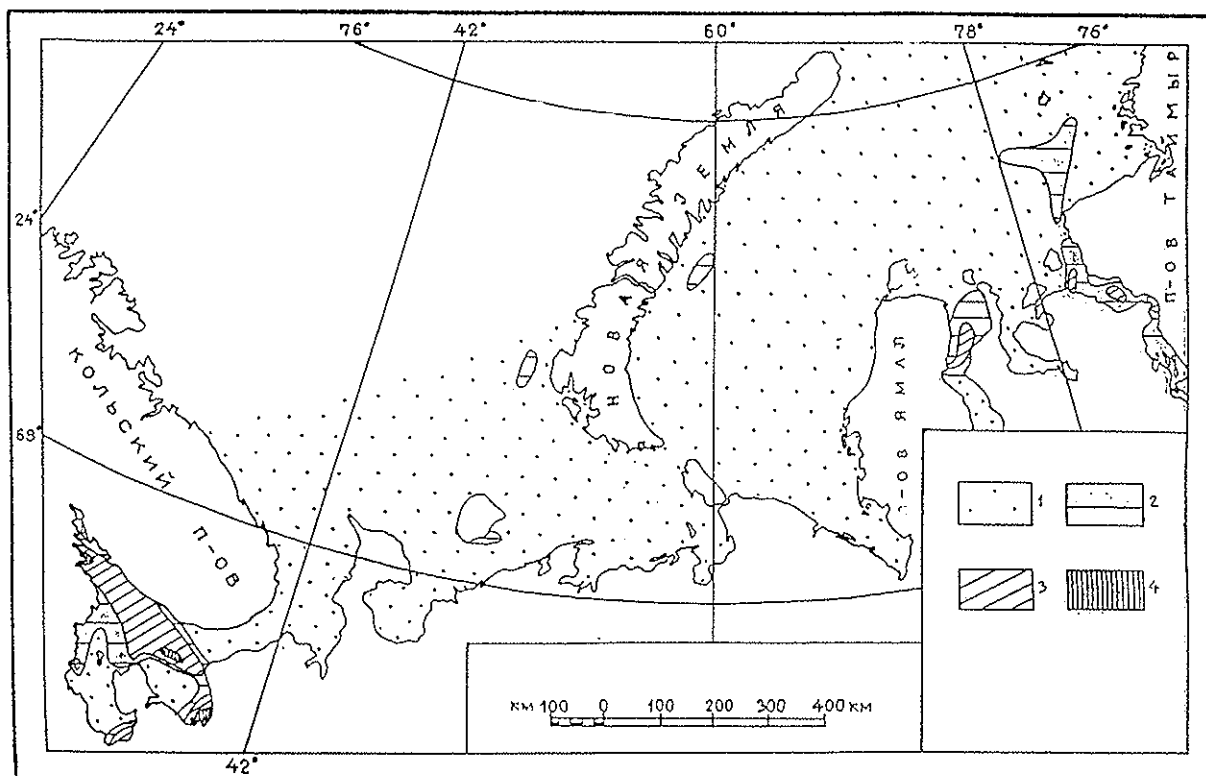


Figure 4. Distribution of phenols in the bottom sediment. Values in mg/kg (i.e. parts per million). (1) not detected; (2) from 1 to 3; (3) from 3 to 10; (4) greater than 10.

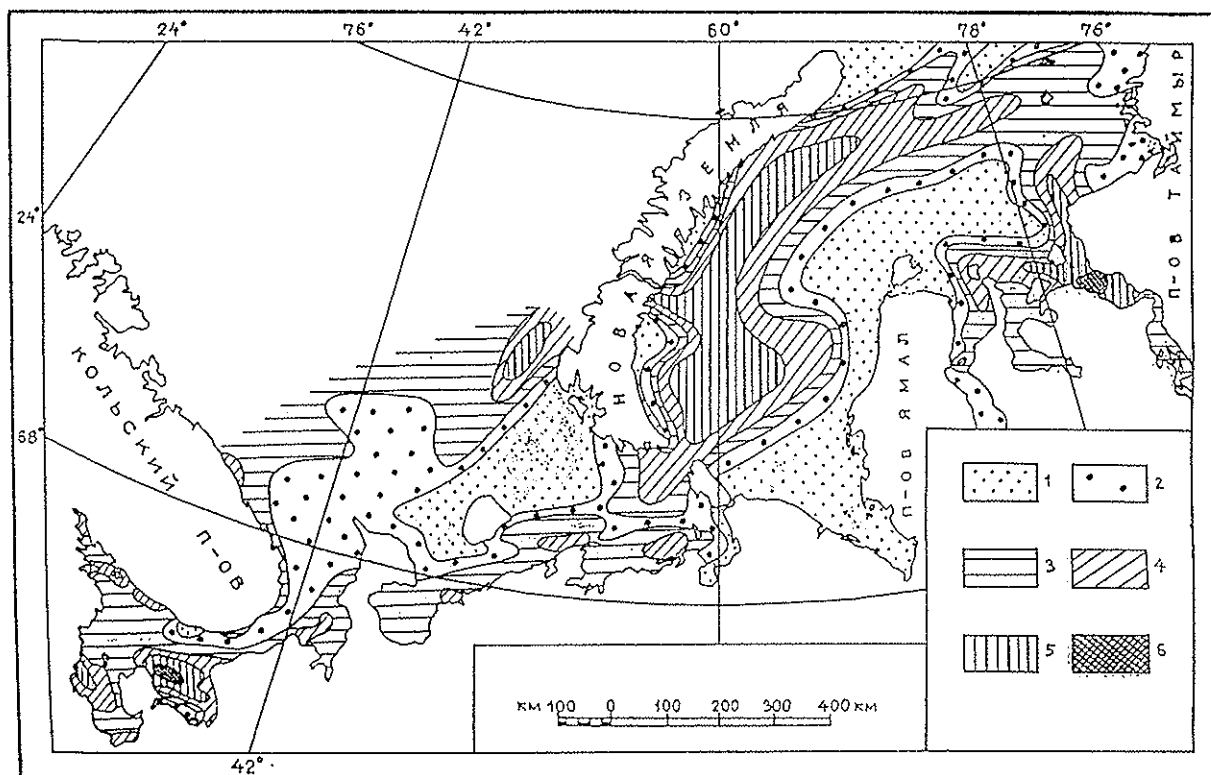


Figure 5. Distribution of total pesticides (DDT, DDD, DDE) in the bottom sediment. Values in mg/kg (i.e. parts per million). (1) not detected; (2) less than 0.03; (3) from 0.03 to 0.10; (4) from 0.1 to 0.3; (5) from 0.3 to 1.0; (6) greater than 1.0.

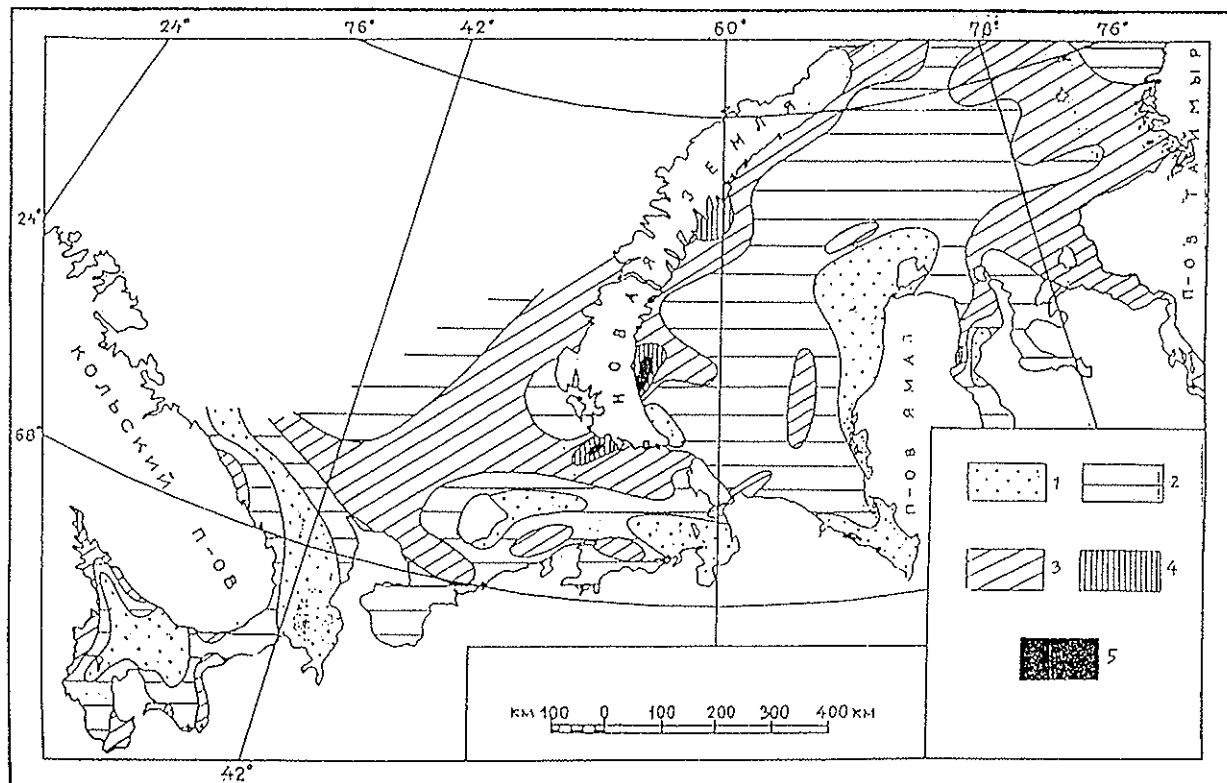


Figure 6. Distribution of $\alpha + \gamma$ HCH (hexachlorocyclohexane) in the bottom sediment. Values in mg/kg (i.e. parts per million). (1) not detected; (2) less than 0.1; (3) from 0.1 to 0.3; (4) from 0.3 to 0.5; (5) greater than 0.5.

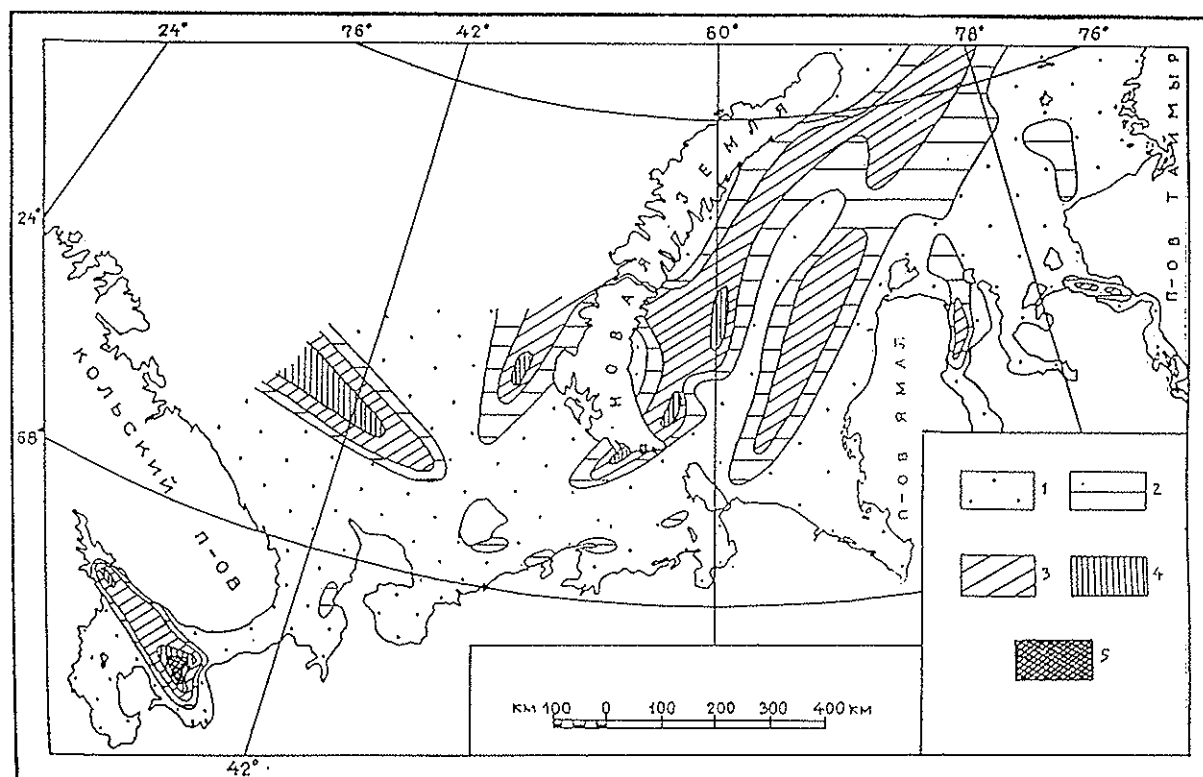


Figure 7. Distribution of lead (Pb) in the bottom sediment. Values in mg/kg (i.e. parts per million). (1) less than 10; (2) from 10 to 100; (3) from 100 to 300; (4) from 300 to 500; (5) greater than 500.

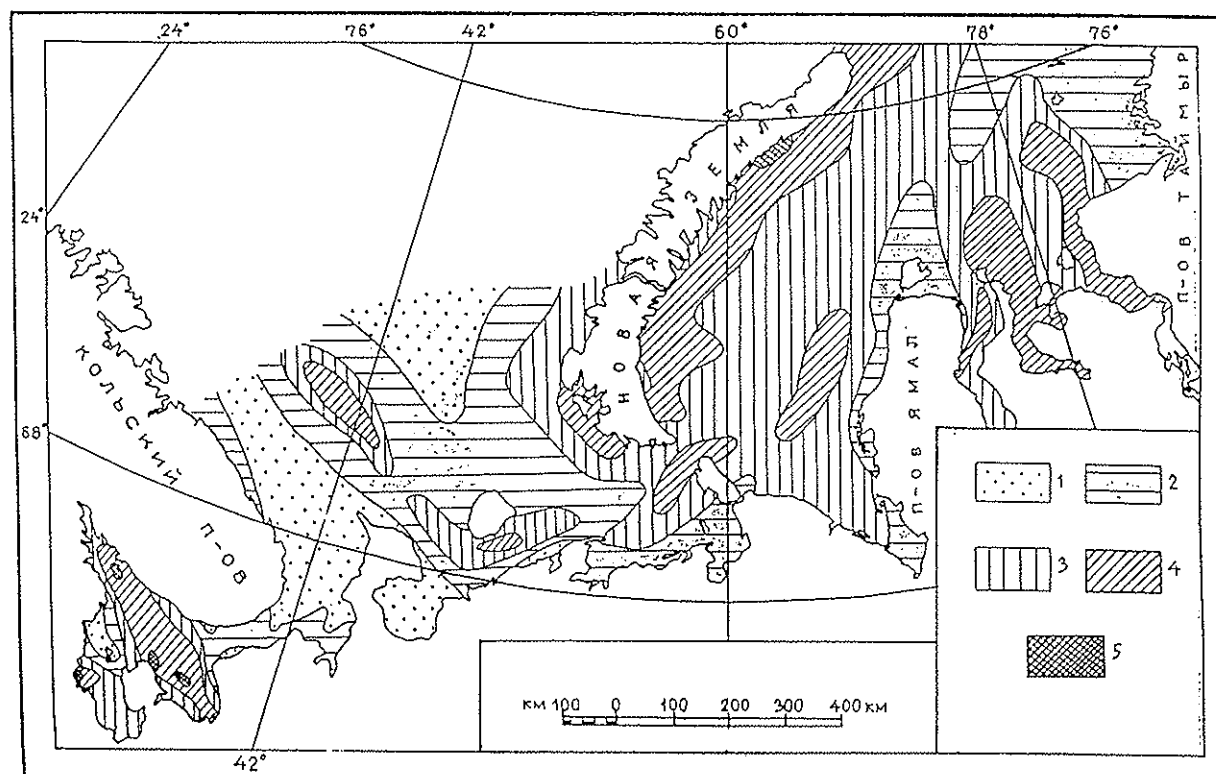


Figure 8. Distribution of zinc (Zn) in the bottom sediment. Values in mg/kg (i.e. parts per million). (1) less than 10; (2) from 10 to 30; (3) from 30 to 100; (4) from 100 to 150; (5) greater than 150.

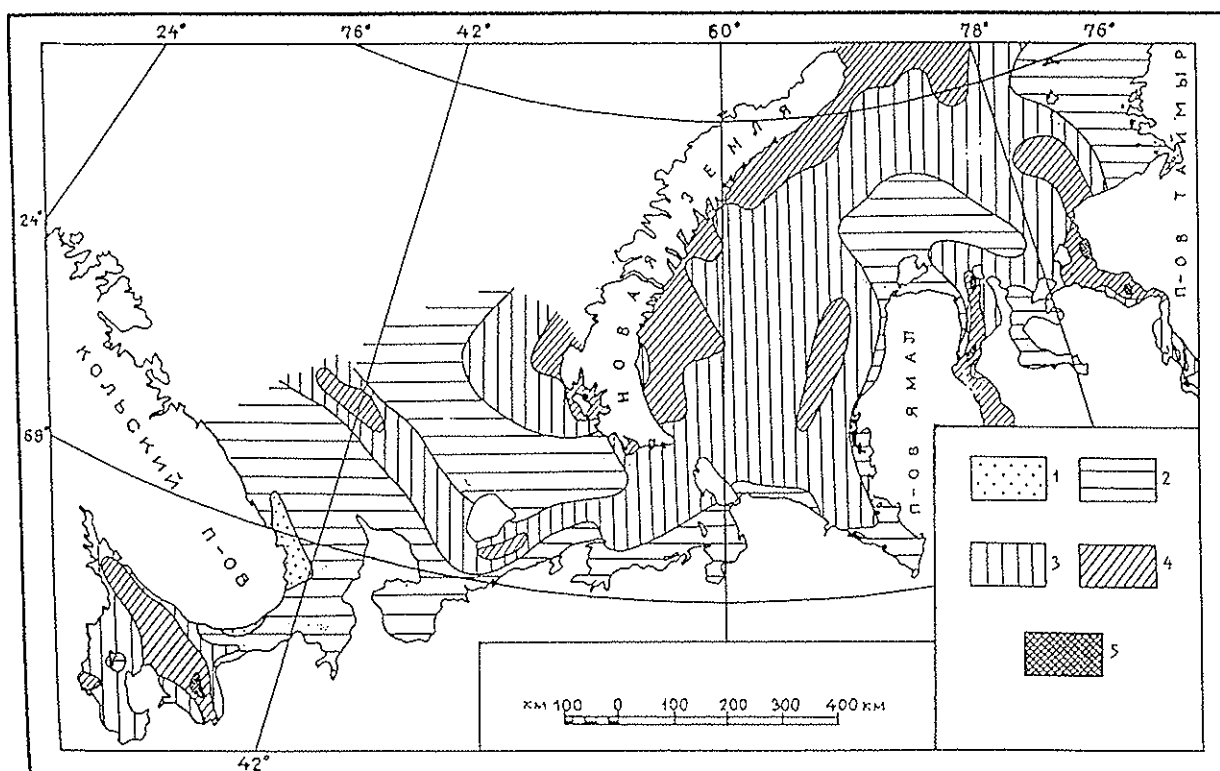


Figure 9. Distribution of cobalt (Co) in the bottom sediment. Values in mg/kg (i.e. parts per million). (1) less than 3; (2) from 3 to 10; (3) from 10 to 30; (4) from 30 to 50; (5) greater than 50.

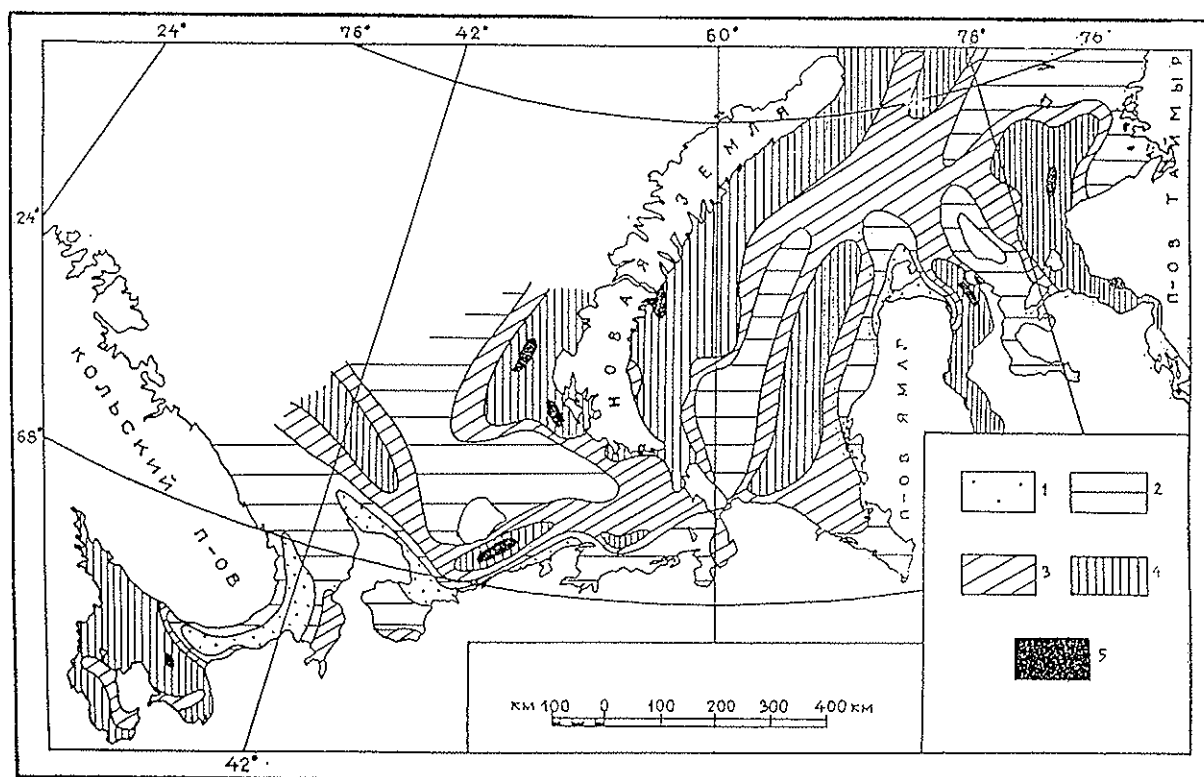


Figure 10. Distribution of nickel (Ni) in the bottom sediment. Values in mg/kg (i.e. parts per million). (1) less than 3; (2) from 3 to 10; (3) from 10 to 30; (4) from 30 to 100; (5) greater than 100.

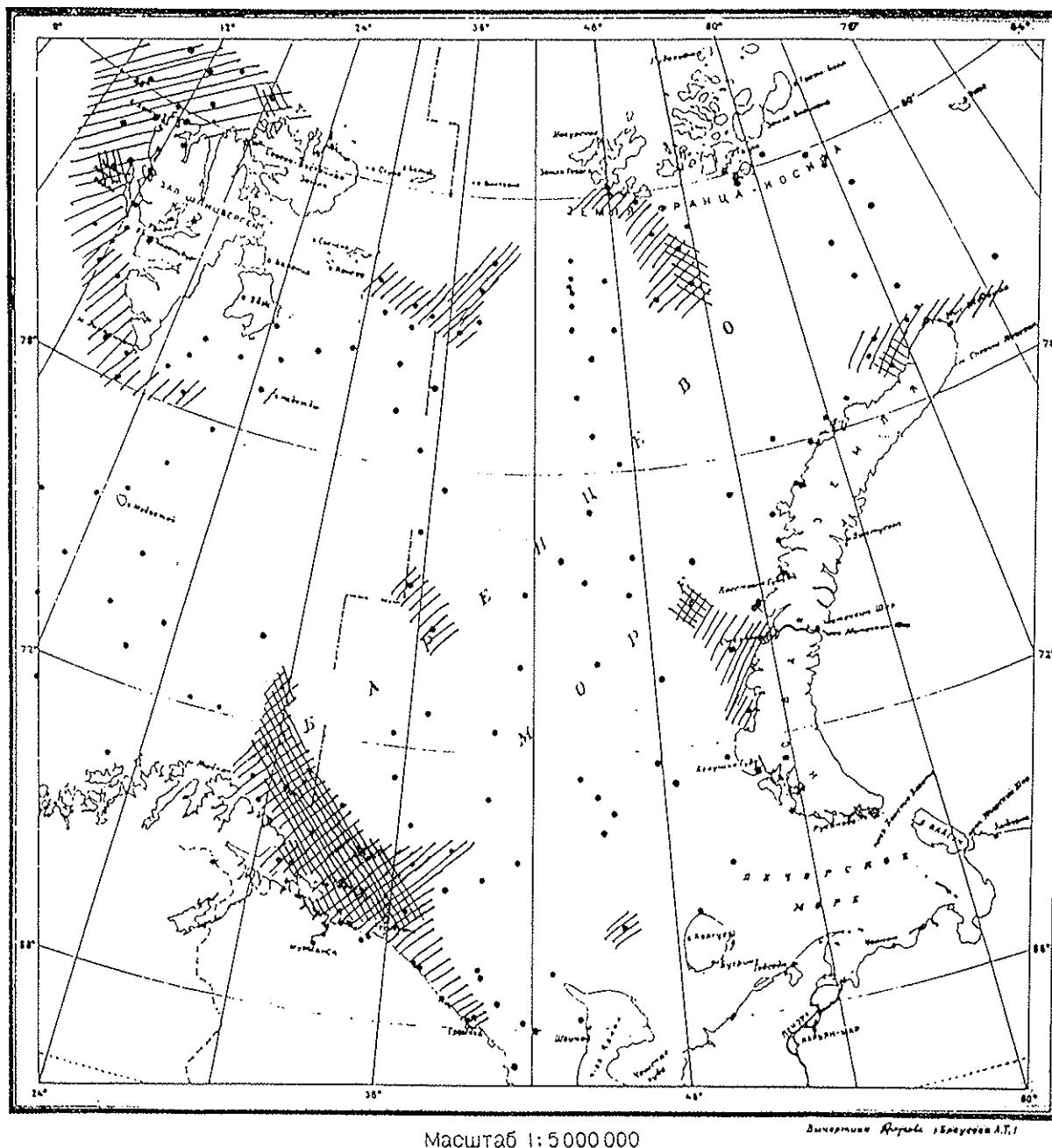


Figure 11. Map of toxic sea bottom environments based on data collected on the 1992 cruise.

contamination by natural and anthropogenic compounds. Along with adverse technogenic effects seen adjacent to the Kola Peninsula and the White Sea, some unexpected environmental conditions were observed in other areas of the Barents Sea, previously considered ecologically safe, such as Svalbard, in the vicinity of Franz Joseph Land, north of Novaya Zemlya and also in the Gulf Stream path. At the same time in the central Barents Sea there are extensive regions where contamination was beyond the sensitivity threshold. A distant reflection of anthropogenic influence in benthic communities was recorded only locally. It is marked by a decrease in both species diversity and total population offshore the Murmansk area, and the Belushka settle-

ment on Novaya Zemlya, as well as in the mouth of the Ob and Yenisey Rivers. Scarce data suggests a similar situation in the vicinity of Svalbard. Available data also suggests the trans-national nature of contamination in the Barents sea bottom environment and possibly in other parts of the Arctic system, characterized by large scale circulation processes. It is clear that environmental problems in the Arctic can only be solved through international intellectual, financial, and logistic cooperation, and implementation of complex, multidisciplinary studies based on a unified approach. Our institution, *VNIIOKEANGEOLGIA*, would be happy to offer our labor and logistic resources for collaboration with any interested institutions in the study of this issue.

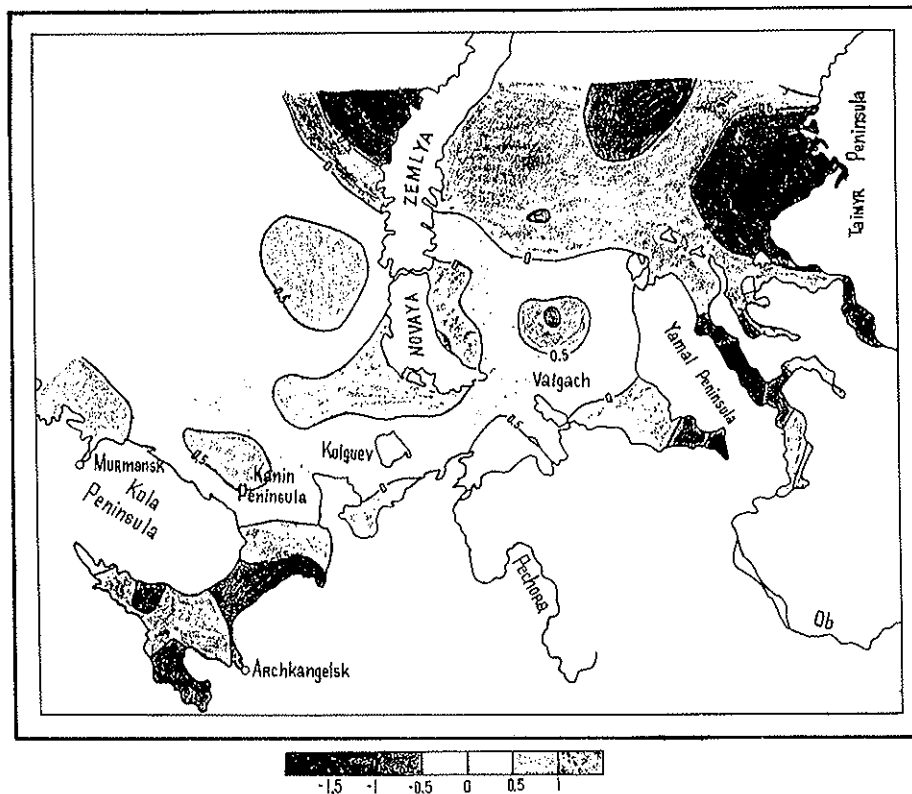


Figure 12. Map of the standard deviation in the concentration of cesium-137 (^{137}Cs) in bottom sediments.

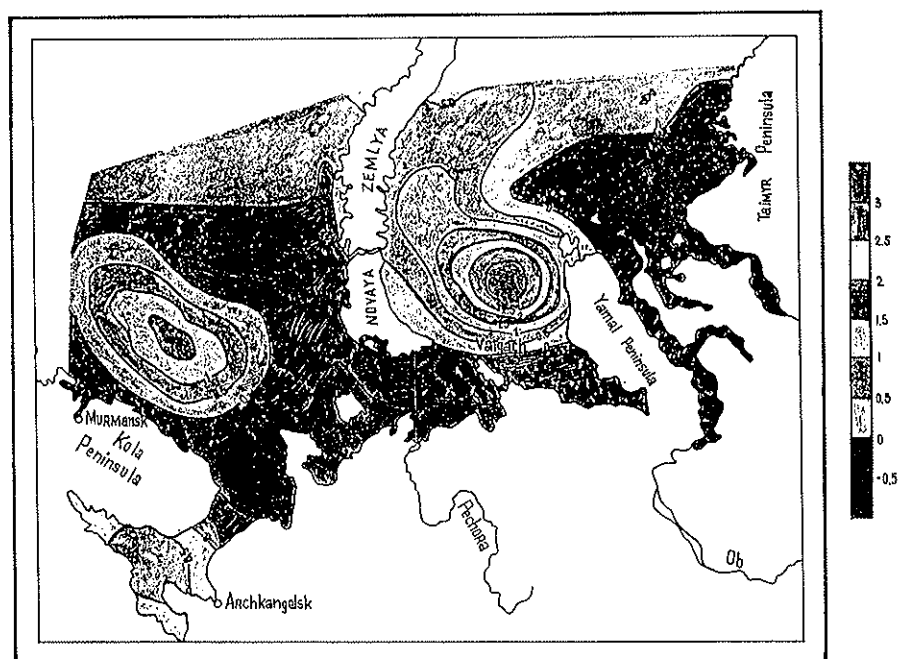


Figure 13. Map of the standard deviation in the concentration of manganese (Mn) in bottom sediments.

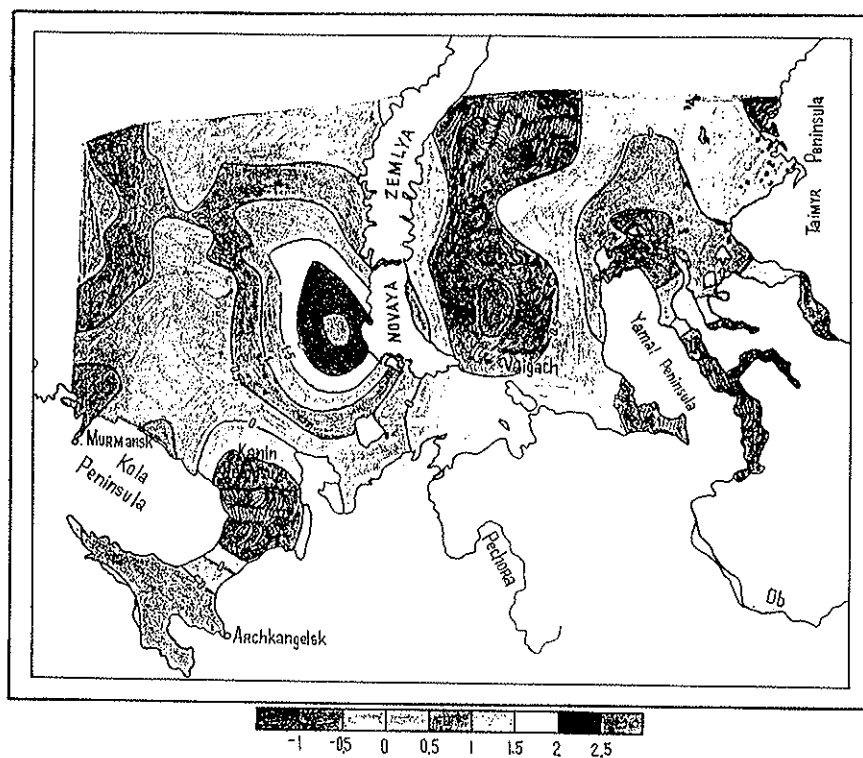


Figure 14. Map of the standard deviation in the concentration of phosphate (PO_4) in bottom sediments.

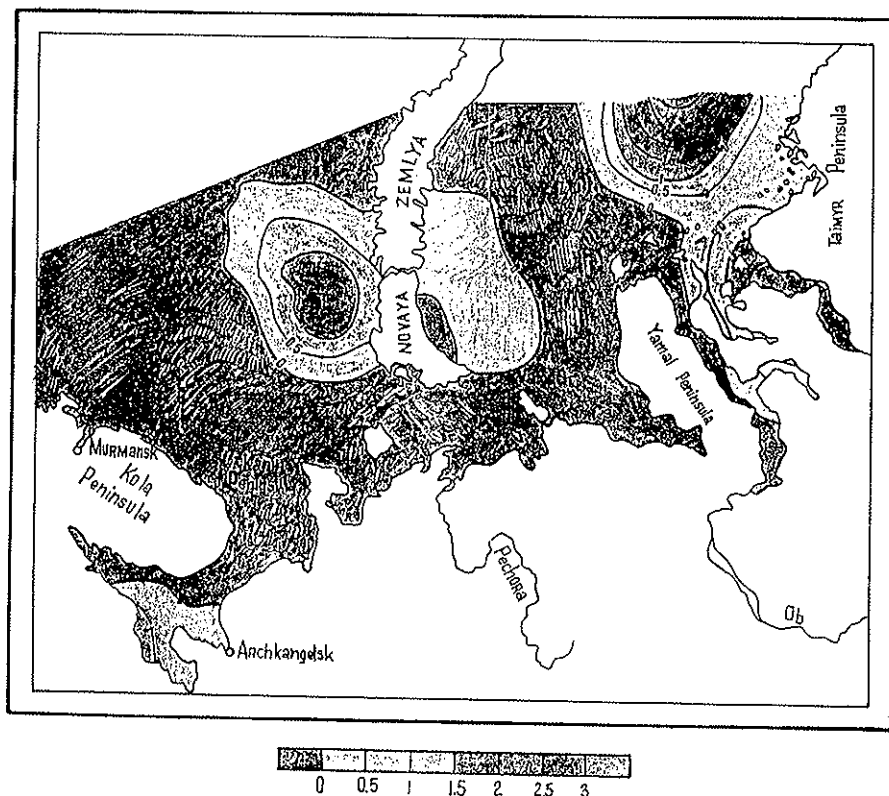


Figure 15. Map of the standard deviation in the concentration of pesticide, DDD in bottom sediments.

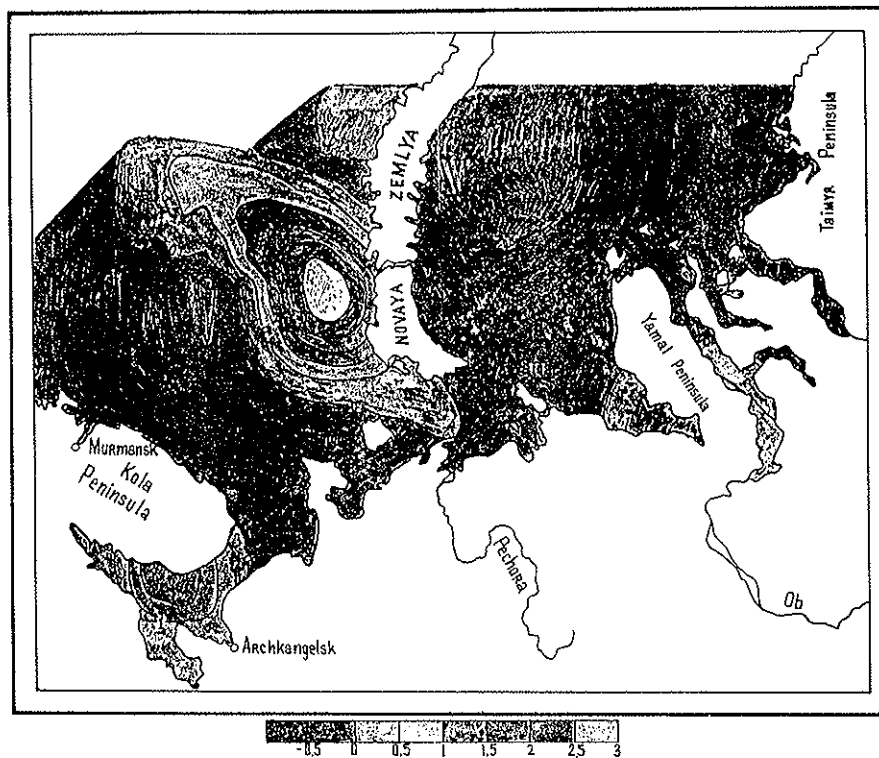


Figure 16. Map of the standard deviation in the concentration of oil hydrocarbons in near-bottom water.

Marine Biological Resources of the Russian Arctic and the Pollution Threat

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The study of biological resources of the Russian Arctic goes back to the expedition sent by the Russian Academy of Sciences to the Barents and Kara seas in 1771. The research history is represented in publications by Zenkevitsch (1963), Pavshikov (1981), Alexeyev and Galkin (1981), Golikov et al. (1983), and Golikov and Scarlato (1989). One of the first tasks was the study of specific composition and distribution of flora and fauna with primary attention on marketable species. Traditionally all the collected zoological material was stored at the Zoological Institute of the Russian Academy of Sciences and the botanical material at the Botanical Institute, both of which are located in St. Petersburg.

According to the marine research laboratory data (presented by B.I. Sirenko), the total amount of hydrobiological samples from the Arctic seas stored at the Zoological Institute is about 14,000. Due to better accessibility and marketable value, the major part of the samples (10,800) is accounted for the European waters—those of the Barents and White seas. As more than one sample is taken at every station, the Arctic sea collection of the Institute is presently containing over 90,000 samples. Most of the collected material has been identified at the specific level of accuracy and has been catalogued. The total number of species of aqueous arctic animals included into the catalogue is 4,296: 3,746 (87%) invertebrates and 550 (13%) vertebrates. Their taxonomical arrangement (basic groups of invertebrates) is given below:

Crustacea	about 500 species
Foraminifera	450
Mollusca	427
Nematodes	340
Bryozoa	340
Polychaeta	280

According to the ecological grouping, the arrangement is as follows: macrobenthos 68%, meiobenthos 26%, plankton 6%. Owing to the fact that the organisms unknown either for science or for the arctic fauna are still being discovered and that some animal groups (Nemertini, Nudibranchia) have been only slightly touched by investigations, it may be assumed that the actual number of the Arctic animal species shall amount to 5,500.

The largest numbers of animal species are found on the west which is experiencing a strong influence of warm, organically rich waters of the Atlantic. Moving further eastward, we are witnessing the reduction in the number of animals inhabiting the sea: around 2,500 species of invertebrates found in the Barents Sea, 1,850 in the Kara Sea; 1,084 in the Laptev Sea; 962 in the East Siberian Sea and 946 in the Chukchi Sea.

During the period of its useful life (160 years) the Zoological Institute has published 51 Determination guidebooks on various animal groups having reference to the Arctic fauna. The work on the inventory of the Arctic fauna is proceeding at present. The growing interest in this type of studies is explained by the prospects of industrial development of the North, pri-

marily oil and gas production, and assignment of the international status to the North Sea Route. The appropriate studies of the Arctic flora are being provided by the Botanical Institute of the Russian Academy of Sciences.

Following the decision of the Government of Russian Federation, the Red Book of the Republic listing rare and endangered species protected by legislation has been issued (Elisseyev, 1985).

The book lists 39 names of species and subspecies inhabiting the arctic seas and coasts, including one name of mollusc, 1 name of fish, 21 species of birds and 15 of mammals.

The Arctic marine invertebrate fauna is relatively young, its age ranging between 1.5 and 1.8 million years. Its historical roots are in the Pacific fauna; however, the influence of the Atlantic waters are predominant at present. Sufficient endemism (3% genera and 18% of species) justifies the formation of independent Arctic biogeographical area in which three provinces can be established:

- 1) Deep-water Arctic province (deeper than 600-800 m),
- 2) Subsurface Arctic province (depths ranging between 10 and 600-800 m), in its turn separated by the Novosibirsk islands into West Arctic and East Arctic subprovinces,
- 3) Estuarine-arctic province affected by river runoff up to 10 m deep (Golikov et al. 1983).

Production capabilities of the Arctic biota are insufficient, except those of non-freezing South Western section of the Barents Sea. The primary production is limited by long-term polar nights and the screening effect of ice and river sludge. Transfer of allochthonic

Atlantic material into the Arctic is an important factor. Along with decaying of the Atlantic current, the indices of biotic quantitative development are being reduced in the west-east direction as well as with depth (see Figures 1-3).

Filtration type usually forms over half of the biomass; meiobenthos is dominating in mass for many bottom biocenoses (Golikov and Scarlato, 1989). The distribution and structure of marine biocenoses in the Russian Arctic have been studied rather unevenly with more complete knowledge of the Barents, White and Chukchi seas. The general principles of plankton functioning were assessed by Zelikman (1977) who has noticed marked variations in its seasonal development. Pavshits (1980) had analyzed the unique planktonic material collected from hardly accessible central areas of the Polar Ocean by a set of drifting stations. Substantial progress in the studies of bottom biocenoses of polar seas was achieved by using skin-diving for collection of material: it became possible to extend studies upon formerly inaccessible small depth areas and substrata unsusceptible to dredging. In a 20-year period, under the leadership of Professor Golikov, eleven Arctic expeditions were organized with skin-diving on shelves of Franz Josef Land, Kola peninsula, Novosibirsk islands, Chauna inlet of the East Siberian Sea, Wrangel Island and other areas (see Golikov and Scarlato, 1989). The characteristic feature of all the Arctic seas with the exception of the southwestern part of the Barents Sea is the development of cryocoenoses including microalgae suspended to the lower ice surface, copepods feeding on it and the whole of the food chain from polar cod to dolphins, seals and, finally, polar bear (Mel'nikov, 1989).

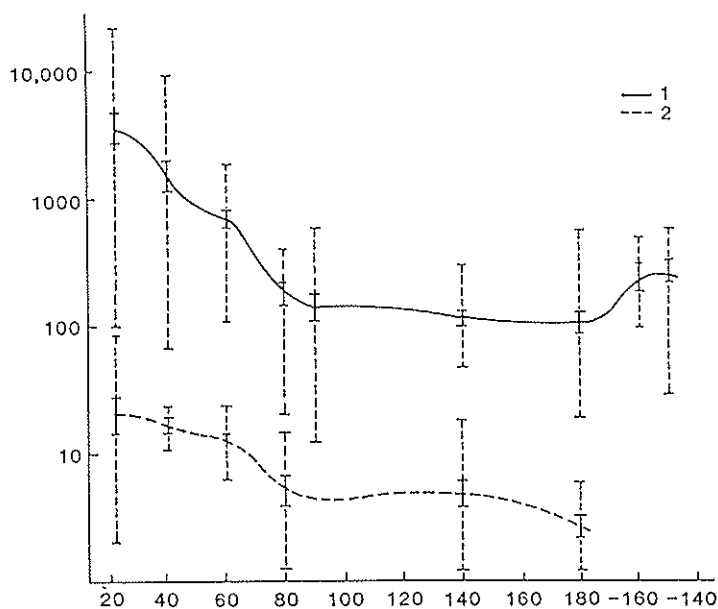


Figure 1. Biomass of (1) benthos and (2) plankton in different areas of the Arctic Basin. Abscissa: longitude in degrees; Ordinate: biomass in g/m^2 . (from Golikov, Scarlato, and Pavshits, 1983).

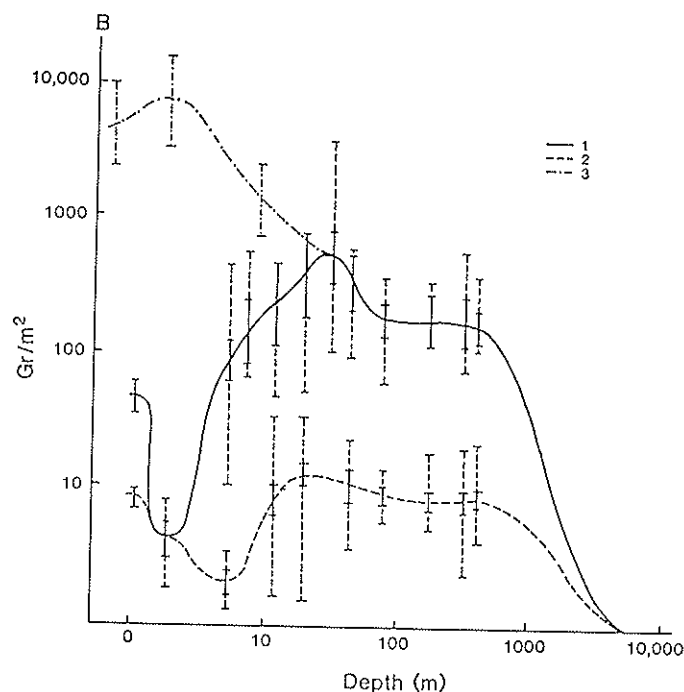


Figure 2. Relationship between (1) benthos and (2) plankton biomass and depth as a factor in the Arctic and boreal (3) waters of the Arctic Basin. Abscissa: depth on logarithmic scale in meters; Ordinate: biomass in g/m^2 .

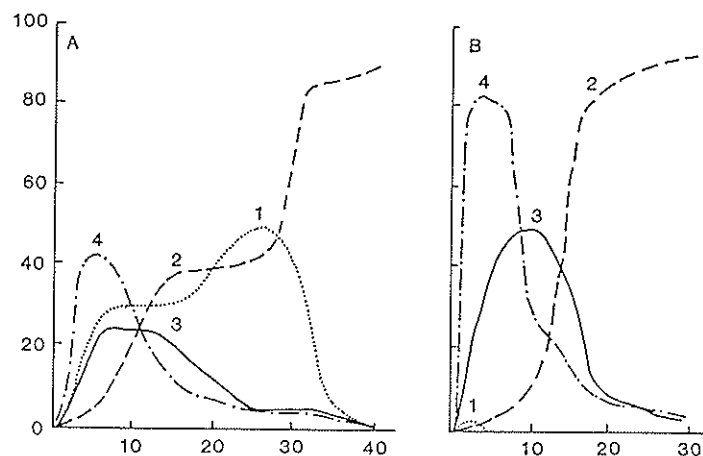


Figure 3. Percentage of biomass of benthos trophic groups at different depths in the Arctic Ocean in ice-free areas in summer (A) and in perennial sea ice-covered areas (B). 1: macrophytes; 2: filterfeeders; 3: detritophages; 4: predators. Abscissa: depth in meters; Ordinate: percentage of trophic group in biocenosis biomass at a given depth (from Golikov and Scarlato, 1989).

The specific feature of the Russian Arctic is powerful effect of great rivers—the North Dvina, Pechora, Ob, Enisei, Lena, Kolyma and others whose total annual inflow into the sea is amounting to $5,000 km^3$. The influence of the rivers on sea productivity is two-fold. On the one hand, they are bringing into the sea warmer waters bearing food detritus and biogenes; on the other hand, the river suspensions are serving a barrier to sunlight penetration and thus to photosynthesis.

According to generally accepted provision (Khlebovich, 1974, 1990) freshwater fauna disappears at salinities of 5-8‰, the last representatives of euryhaline marine fauna can tolerate the same salinity limits. Specifically brackish water fauna is also abundant here.

In relation to commercially used resources it should be noted that whale fishing and walrus fishing has been practically totally banned in the area; they can be fished

in limited quantities by only the indigenous people for whom they serve traditional objects of fishing. In Russia such people are riparian Chukchis and Eskimos. Considerable commercial fisheries in the Russian Arctic had been existent only in the Barents Sea; here on the shelf of the northwestern coast of Norway, the breeding area of principal Barents Sea commercial fishes is located (Ponomarenko, 1982). Maximal commercial catch was registered in 1968-1969 followed by both overall reduction of catches and substitution of more valuable and long-living species (cod, turbot, banded-sea perch, herring) by less valuable species with short life cycles: capelin, polar cod (Moiseev, 1977). This can be estimated as degradation of ecosystem which is beginning to lose its activity in the fish chain; species with a shorter life cycle are spending more energy for respiration than for growth (Karpevich, 1985). In the Barents

Sea the mollusc *Chlamys islandicus* and some shrimps are also caught commercially, though on a minor scale. Sea farms for growing mussels *Mytilus edulis* have been organized in the White Sea.

Commercial fishing in other seas is substantially below that of the Barents Sea and is only of local significance. However, it should be noted that estuarine brackish waters serve feeding ground for various valuable species of migratory fish, such as arctic salmon *Salvelinus* sp. and *Coregonus* sp. etc. The west coast estuaries are used as a spawning route for the most precious fish of the Russian north, *Salmo salar*. Local stocks of this fish with specially valuable properties can be often met in the rivers. They may be made use of during acclimatization or artificial breeding. Preservation of their genofond is highly advisable.

In order to make basic assessments of the impact of contaminants on the Arctic marine biota, it seems useful to take a look on the polar space from the North Pole. And to reject the traditional opinion of the Arctic being limitless area of white silence. In this case one realizes that the Polar ocean occupying only 3-4% of the surface of the World Ocean is nothing but a specific sort of the "mediterranean" sea. This semi-closed waterbasin has three accesses and one exit on the water side; thus it can be treated as an indivisible ecosystem. The main access is the Atlantic waters entering by the Norwegian and Irminger currents; another access is the Pacific waters entering through the Strait of Bering whose current is five times less efficient than the Atlantic one. The third access is freshwater runoff of the great rivers which, in its turn, is also five times less efficient than the Pacific one. It is quite evident that these natural routes are the transporters of pollutants from outside. The expected impact from pollutants introduced by the Atlantic waters must be important due to European industrial discharges. This may be vividly justified by tags and labels on all the garbage thrown by sea onto the shores of Barents and even Kara seas. There was information that some combinations of radioactive isotopes are witnessing their British origin.

The pollutant impact from the Pacific waters entering through the Strait of Bering, if any at all, should be many times less important than that from the Atlantic waters.

The impact of river transported pollutants and toxicants on the Arctic ecosystem should cause serious anxiety. It is evident that everything collected by a river from vast catchment areas and not processed during transport, is carried into the marine-brackish water mixing zone. The set of transported pollutants would vary for each particular river depending on the character of economic activity in the catchment zone. It can be assumed that an important amount of pesticides and hydrocarbons would be transported by the Ob while radioactive iso-

topes are more probable in the Yenisey. Whatever the difference between substances transported by various rivers, there are grounds to assume that the character of their sedimentation, chemical and biological processing in the estuarine salinity gradient will be especially highly variable in a narrow 5-8‰ range (Khlebovich, 1974, 1989, 1990). Unfortunately this general concept cannot yet be supported by particular case studies due to the fact that such data has for many years been closed.

Besides the above three accesses into the Arctic marine ecosystem, there exists another one connected with aerial transport of dust and aerosols into the water or ice surface.

The following pollution sources will also locally impact the Arctic sea biota beside the impacts of the basic natural accesses:

- Integrated impacts of cities and ports;
- Oil and coal fields;
- Radioactive waste dumps, past testing grounds of nuclear weapons;
- Aerial and aqueous transfer of waste from mining and metallurgical industries;
- Discharges along the North Sea Route.

Due to the fact that oil is remaining one of most common pollutants of marine arctic water, here are some of my personal impressions of participant of air expedition into the Arctic for the assessment of so called oil spots or oil films. They were discovered in the following situations:

- 1) In near-town or -port river estuaries;
- 2) At the edges of thawing ice;
- 3) After departure of water following flooding of low tundra marsh land (locally named "laidas");
- 4) In areas of operation of fish catching flotillas;
- 5) In areas of whale gathering.

All these instances of oil spots occurrence are well known to polar aviation crews. Our comments to these findings should be following:

- Case I is evidently connected with actual anthropogenic oil pollution.
- Case II is related to intensive ice-edge reproduction of phytoplankton and zooplankton feeding on it. This can be confirmed by direct hydrocarbon analysis of such film identifying total similarity between its components and the extraction of planktonic copepod *Calanus finmarchicus* mostly abundant at that time (Dmitriev, Russanov, 1984). Evidently, this film is in no way related to oil or man.
- Case III should be mostly related to removal of natural organic material; however, local removal of oil products is not excluded.
- Case IV is connected with washing fish grease off the ship decks. Though of anthropogenic origin, this source has nothing to do with oil pollution.

- Case V is related to natural plankton "thickening" attracting whales feeding on it.

Evidently, differential assessment of "oil film" would assist in avoiding errors while conducting ecological patrols in the Arctic.

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Radionuclide Sources of Arctic Contamination

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The territory of the former Soviet Union is characterized by the great variety of radionuclide sources in the environment. Very limited information is known in open literature about the sources, inventories, and transport patterns of radionuclides in the Russian sector of Arctic Ocean. Only during last three years some data was summarized in the book "Atom Without Stamp 'Classified'..." and by Bol'shakov et al. (1991), Bradley (1991), Bradley (1992), Bradley and Schneider (1990), Chukanov et al. (1991), Kossenko et al. (1990), Nazarov et al. (1991), Sivintsev et al. (1992), Yablokov et al. (1993), and others.

Today it is clear that the Arctic environment has been seriously polluted by radionuclides from different sources during last 40 years. Among the main sources of the radionuclides in the Russian sector of the Arctic we can indicate the following:

1. Explosions of nuclear weapons testing;
2. Radioactive waste disposal into the seas;
3. Marine accidents with nuclear-powered submarines;
4. Base regions for war and civil ships with nuclear reactors;
5. River waters which transferring the radionuclides from:
 - radiochemical plants of the military industrial complexes for the production of the nuclear weapon components (Chelyabinsk-40, Krasnoyarsk-26, Tomsk-7, and others);
 - East-Ural radioactive trace resulting from Kyshtym (1957) radiation disaster;
 - areas of setting off atomic explosions for peaceful uses;
 - nuclear power stations and temporary nuclear waste repositories resulting from their activity.

In the paper some important peculiarities of the main sources of the radionuclides in the Russian sector of the Arctic will be described.

Explosions of Nuclear Weapons Testing

Nuclear weapons testing has been the first major single source of radioactive contamination of the Arctic. According to data presented by Monetti (1993) a peak in Sr-90 atmospheric deposition of 68 to 690 Bq/m² (personal communication) is observed during either 1962 or 1963 which is concurrent with a period of extensive atmospheric weapons testing.

The large amount of radionuclides globally dispersed in the Arctic environment are due to fallout from 87 atmospheric nuclear weapons tests (from 1955 to 1962) in the former Soviet Union at Novaya Zemlya, an island in the Arctic Ocean. On this nuclear testing polygon, the former Soviet Union has carried out the largest atmospheric nuclear explosion in history, a 50-60 megaton blast in October, 1961, and 42 underground and 3 underwater nuclear tests have occurred there, for an aggregate total of 273 megatons (Sivintsev et al. 1992) approximately.

A total of 467 nuclear explosions, including 132 atmospheric tests from 1949 to 1963 were carried out at the Semipalatinsk nuclear testing site, situated in headwaters of Ishym and Irtysh Rivers, western tributaries of the Ob' River.

Radioactive Waste Disposal into the Seas

The dumping of radioactive waste at seas and oceans began in 1946 when the United States sank containers of radioactive waste in the Pacific Ocean some 80 km off the California coast. Over the decades 12 countries including Belgium, Great Britain, France, Germany,

Italy, Japan, Netherlands, New Zealand, South Korea, Sweden, Switzerland and United States declared that they had dumped radioactive wastes at more than 50 sites in the northern part of the Atlantic and Pacific Ocean. The International Atomic Energy Agency has estimated that these nations from 1946 to 1982 dumped a total of 1.7 million curies of radioactive refuse into the world oceans (Calmet, D., and K.L. Sjoblom, 1992).

Recently, the report of governmental commission headed by Dr. A.V. Yablokov (Yablokov et al., 1993) says the Former Soviet Union dumped 2.5 million curies of radioactive wastes, including 18 nuclear reactors from submarines and an icebreaker. Sixteen of these reactors cast into the shallow waters of the Kara Sea, six still contain nuclear fuel. Most of these reactors lie in shallow inlets at depths of only 20 to 50 meters, one sits at 300 meters in depression off the eastern coast of the Novaya Zemlya. The preliminary measurements (Yablokov et al., 1993) indicate that concentrations of dangerous radionuclides in the sea water remain relatively low ($\sim 5 \times 10^{-10}$ curies) near the sunken reactors, suggesting that major leaks have not yet developed. Today unclear what their long-term radiological effects will be as the corrosion processes with sea water slowly releases fission products into the environment.

In theory, the possibilities of the ocean to dilute liquid radioactive wastes can make them essentially harmless. But localized releases of radionuclides high concentration can do real damage when picked up by marine life. Fortunately, the Kara Sea is frozen nine months of the year and has little biological activity. The fishing grounds of the Barents, White and Norwegian seas lie hundreds of kilometers away. Such distances limit but do not eliminate the physical and biological migration of radionuclides from dumped radioactive wastes.

Marine Accidents with Nuclear-Powered Submarines

Naval vessels, particularly submarines, began using nuclear reactors for propulsion in 1954, with the commissioning of the U.S. military submarine *Nautilus*. Naval nuclear reactors now number almost 550, with some 360 vessels nuclear-powered. According to W.M. Arkin and J. Handler (1989) between 1954 and 1988, there were 212 confirmed accidents involving nuclear-powered vessels.

As the most threatening source of nuclear contamination some specialists focused on the *Komsomolets*, a nuclear-powered submarine that caught fire on April 7, 1989, and sank in 1,680 meters of water near the edge of the Barents Sea. In addition to a nuclear reactor, the vessel has two torpedoes armed with plutonium.

Base Regions for War and Civil Ships with Nuclear Reactors

Russia has a backlog of 100 nuclear submarines tied up at sea awaiting final disposal. Many of the decrepit submarines still have nuclear fuel in their reactors because of a lack of facilities to remove and store the highly radioactive fuel. One of the fuel-crammed floating bases, called the *Lepse* appears to be leaking. Four sites have been noted (Bradley, 1992; Emelyanenko and Popov, 1992) as storage areas for nuclear waste from the Russian North Fleet in the Kola Peninsula region. They are at Murmansk (home port for naval vessels having a total of 220 reactors), Severomorsk (home of the Russian North Fleet), Litsa (a submarine base is located about 45 km from Norway), and Kildin (an island in the Barents Sea about 120 km from the Norwegian border).

Continental Sources of Radionuclides for Arctic Ocean

Radiochemical Plants of the Military Industrial Complexes

Discharges of radioactive waste from nuclear fuel reprocessing operations in Europe (Sellafield, UK; Cap la Hague, France) have resulted in a substantial increase in the inventory of radionuclides in the Arctic waters.

The region of the activity of the radiochemical plant "Mayak" represents the highest contaminations in the territories of Russia, which were contaminated by radionuclides (Bol'shakov et al., 1990; Bradley, 1992; Chukanov, 1991; Drozhko et al., 1993; Hauge and Nil-en, 1992). "Mayak" is a Soviet war-industry nuclear center established in South Urals at the end of forties for nuclear bomb manufacturing. Until recent times five reactors for plutonium production worked here. However the environmental safety problems were not properly attended to, when policy rather than principle was a decisive factor in the Former Soviet Union.

On the territory of the radiochemical plant "Mayak" serious pollution exists. Storing of high-level wastes in special vessels began in 1951, and earlier, from 1948 to 1951, wastes were poured directly in nearest river Techa, which is branch of river Ob'. As a result the Ob' basin was polluted for more than 1000 km, toward the Arctic Ocean.

From 1951 middle-level wastes began to pour into the neighboring Lake Karachai (the radiation level of this lake reaches 120 MCi) and such contamination will continue until 1994, for technical reasons. Pollution reaches ground waters and spread for several kilometers. Pollution of the nearest river Mishelyak is possible. Until adopting a final deactivation plan for the region

temporary measures are carried on. For decreasing surface and water-atmosphere interchange the lake is filled in with igneous rocks and empty concrete blocks in some areas. Currently the area of the lake decreased from 0.45 to 0.20 square km.

For prevention of radiation pollution spread by the river Techa, it was dammed above the dangerous zone, and the water led through a special channel around the contaminated stretch to a junction several kilometers below. Besides since 1951 the cascade of dams was built in the old Techa river bed. The total volume of these man-made reservoirs reaches 380 million cubic meters, and in sediments radioactive elements occur with an activity level of 200,000 Ci has been accumulated. Rains, eroding banks of the river Techa and reservoirs, enlarge the damaged area.

East-Ural Radioactive Trace

On September 29, 1957 one of the most severe disasters in the nuclear engineering history took place here. The disaster is known as Kyshtym Catastrophe. High-level wastes were poured into vessels of 250 cubic meters each. The content of one of vessels started to boil and explosion occurred with a power was equivalent to 70 tons of trinitrotoluene. About 20 MCi were developed. There has been 90% radioactivity fallout on to the storage site. The rest of the contamination, consisted of isotopes of strontium, cesium, cerium, ruthenium and others (2 MCi) were dispersed over area of 1000 square km. Inhabitants of 23 neighboring villages (10.2 thousand people) were evacuated.

Areas of Setting Off Atomic Explosions for Peaceful Uses

The use of peaceful nuclear explosions was apparently quite widespread in the Russian sector of the Arctic Ocean. They were used on the Kola peninsula; in the northern areas of the Pechora coal fields; in Perm' District; and Yakutia, for study the earth's "deep structures," extinguish gas fires, stimulate gas wells, and create storage cavities in salt formations. Available information was summarized by Bradley (1992) as follows:

- From 1972 to 1984, three (up to two kilotons) nuclear devices were exploded in an apatite mine about 20 km east of Kirovsk on the Kola Peninsula;
- Peaceful nuclear explosions, detonated in the northern Urals in 1976, were reported to have left an artificial lake 400 meters wide by 600 meters long which has dose readings of 1.5 rem/hr on the surface and 5 rem/hr at depth of 12 meters;
- Three nuclear explosives (5-kiloton) placed 200 meters underground were set off 20 km from the city of Krasnovichersk (300 km northeast of Perm'),

which lies between the Kama River, a tributary of the Volga which flows into the Caspian Sea, and the Pechora River, which flows into the Kara Sea.

- Twelve peaceful nuclear explosions were conducted near the town of Udachnyi in Yakutia (near the Arctic Circle), including one which caused a release of radioactive materials to the atmosphere as well as to the surrounding area.

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Quality of Continental and Marine Waters in the Arctic Basin of Russia

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Water as the main component of the environment has been subject to intensive human influence. The development of industry, intensification of agriculture and urbanization have resulted in the contamination of natural waters. This problem has acquired a global character and it knows no national frontiers. On one hand, water, like air, is the carrier of all the pollutants. On the other hand, water, like soil, is the accumulator of pollutants. Atmospheric emissions from stationary industrial sources of contamination on the territory of the Russian Federation was 31 million tons in 1991. About 35 percent of this amount was attributed to the Asian part of Russia. As compared to the previous year, the emissions had decreased by seven percent. But this resulted not from the improvements of the ecological situation, but from the decrease in industrial production output.

The total average long-term runoff of the Russian rivers is 4270 km³. About ninety percent of this volume flows in the basins of the Arctic and Pacific Oceans. These water resources are distributed as follows over the seas of the Arctic Basin: the White Sea—227.4 km³/year; the Barents Sea—214.5; the Kara Sea—1369; the Laptev Sea—753; the East Siberian Sea—220.4; the Chukchi Sea—39.1 km³/year. The average long-term runoff from the largest rivers of the Arctic Basin is as follows: the Yenisey—630 km³/year, the Lena—521, and the Ob—400 km³/year. Less than eight percent of the annual total river runoff discharges into the basins of the Caspian and Azov Seas, where over eighty percent of the Russian population lives and where Russia's main agricultural and industrial potential is concentrated. On the whole, Russia is rich in fresh water resources; there are 28,500 km³/year of fresh water per capita. But the river

runoff is very unevenly distributed over the territory of the Russian Federation, and corresponds neither to the distribution of population density, nor to the pattern of industrial enterprises' location. Thus, the water supply per one square kilometer of territory varies from 125,000 km³ in the Central Chernozem Region to 576,600 km³ in the Volga-Vyatsk. As for per capita values, there are 26,700 km³ of water in the Central Chernozem Region and 90,600 in the Northern region.

In Russia, the monitoring of polluted waters is carried out at 1341 water bodies, including 1154 rivers, 80 lakes, and 67 reservoirs. Observations are also carried out at 2647 sites.

The most widespread pollutants in the surface waters are oil products, phenols, readily oxidizable organic substances, copper and zinc compounds; in some places, ammonia and nitrite nitrogen, lignines, xantogenates, anilines, methylmercaptan, formaldehyde, etc. Huge amounts of contaminants are brought into natural waters with wastes from industrial enterprises: ferrous and non-ferrous metallurgy, chemical, petrochemical, oil- and gas-processing, mining, and pulp-and-paper industries. Municipal and agricultural enterprises also pollute surface waters in the adjacent areas. Agricultural lands, pastures and livestock farms have a considerable effect in the content of organics and nutrients in the water sources. The present-day level of waste water treatment is such that even waste waters, when subjected to advanced biological treatment, still contain enough nitrates and phosphates to bring about intensive eutrophication of natural water bodies.

In many water bodies, the concentration of pollutants exceeds the Maximum Permissible Concentration (MPC), set by sanitary and microbial standards, by

many times. In the surface waters, the exceedance of the MPC for some pollutants was observed in the following percentages of the samples analyzed:

oil products	40-45%
organic compounds	0-35%
phenols	45-60%
anion-active detergents (synthetic surface active substances, or synthetic surfactants)	6-8%
ammonia nitrogen	25-40%
copper compounds	70-75%
zinc compounds	0-35%

The following amounts of pollutants (in thousand tons) were discharged with the wastes in 1991:

oil products	0.3
suspended solids	1203.0
total phosphorus	7.4
ammonia nitrogen	190.7
phenols	0.3
synthetic surfactants	11.0
copper compounds	80.8
iron compounds	49.2
zinc compounds	2.1

The unique aspects of the surface water pollution in the sea basins of Russia are characterized in the following sections.

The Barents Sea Basin

The small rivers of the Kola Peninsula are heavily polluted. Mean annual concentrations of copper and nickel in the waters of rivers Nuduai and Koloss-Yoki exceed the MPC dozens and hundreds of times. Nickel and copper compounds are intensively accumulated in Lake Imandra, thus endangering living organisms of all trophic levels which inhabit the lake. In the Severnaya Dvina River, its tributary—the Puksa River—is heavily polluted (up to 50-100 MPCs) with ammonia nitrogen, phenols, and lignosulphonates. The same heavy pollution is typical for River Peleshma.

The Kara Sea Basin

Along its whole course, from the source to the mouth, the Ob River is contaminated with oil products and phenols. In the Tom River, at the Kemerovo site, highly toxic substances such as aniline, caprolactam, formaldehyde, and methanol are found. Mean annual concentrations of oil products, ammonia nitrogen, copper and zinc in the Iset River waters downstream of Ekaterinburg exceed the MPCs dozens of times. Table 1 presents the observed values of maximum concentrations of some pollutants in the Ob River. The Yenisey River near Krasnoyarsk is also heavily polluted with lignosulphonates and volatile acids. The Bratsk and Ust-Ilimsk reservoirs are contaminated with wastes from wood-processing enterprises, and the content of methylmercaptan and hydrogen sulphide exceeds the MPCs hundreds of times.

The Arctic Ocean Sea Basins

(the Laptev, East Siberian and Chukchi Seas)

The content of pollutants in the upper course of the Lena River exceeds the MPCs by 1 to 7 times and by 1 to 4 times in its middle and lower course. During spring and periods of flooding, the concentration of suspended solids, manganese and lead increases in the Kolyma River waters.

At present, the total discharge of industrial and municipal waste waters into the following seas can be summarized as follows. (Note that the brackets in volumes of untreated waste water discharges are given.)

White Sea	380×10 ⁶ m ³ [11×10 ⁶ m ³]
Barents Sea	110 [100]
Kara Sea	29 [24]
Laptev Sea	2 (1.9)
East Siberian Sea	12 [0.05]
Chukchi Sea	58×10 ⁶ m ³ [1.5×10 ⁶ m ³]

At present, radioactive pollution on the territory of the Russian Federation is caused by the following:

- globally distributed long-living radioactive iso-

Table 1. Maximum concentrations (mg/l) of some pollutants at locations on the Ob River. Similar data can be given for other Siberia river basins.

Settlement	Ammonia nitrogen	MPC	Nitrite nitrogen	MPC	Phenols	MPC	Oil products	MPC	Copper	MPC
Barnaul (city)	2.00	5.1	—	—	0.006	6	0.49	9.8	10.0	10
Kamen'-na-Obi (town)	—	—	—	—	0.021	21	0.46	9.2	5.0	5
Novosibirsk (city)	1.18	3	0.400	20	0.034	34	1.04	20.8	16.0	16
Kolpashevo (town)	—	—	0.139	7	0.025	25	0.61	12.2	9.0	9
Prokharino (village)	—	—	0.314	15.7	0.088	88	0.65	13.0	11.0	11
Alexandrovskoe (village)	12.40	31.8	0.525	26.2	0.304	304	0.58	11.6	9.0	9

Table 2. Input of pollutants into the Arctic seas (in tons).

	<i>White Sea</i>		<i>Barents Sea</i>	
	1990	1991	1992	1991
OP	5178	3967	10891	2294
Phenols	52	22	140	130
Surf.	969	1486	1140	564
SS	—	—	778680	40640
S-Cmp	—	—	854115	36263
Cu	—	—	536	16
Zn	—	—	1420	2
Fe	—	—	77760	1373
Cr	—	—	824	0.004
Total N	—	—	10010	13826
Total COP	0.297	0.297	—	1.090

It is clear from the table that observation data are not available for all seas. Many substances are not measured at all and some data causes doubts.

Abbreviations: OP: Oil products; Surf.: synthetic surfactants; SS: Suspended solids; S-Cmp: Sulphur compounds; COP: chlororganic pesticides.

topes, products of nuclear weapon tests, carried out in above- and underground testing;

- emission of radioactive substances from the IV block of the Chernobyl Atomic Power Plant in April-May of 1986;
- planned and emergency disposal of radioactive substances into the environment by atomic industry plants;
- emissions into the atmosphere and discharge into the water of radioactive substances from operating atomic power plants in the process of their normal operation;
- imported radioactivity (solid radioactive wastes and radioactive sources).

The occurrence of the east Ural radioactive trace allowed us to make a contour of the territory, located in the Ekaterinburg, Cheliabinsk, and Kurgan regions. Its area is about 4,000 km² (according to some other sources, 26,700 km²). The cesium-137 content in the soils on this territory is one Curie per square kilometer (Ci/km²) or higher. This contamination resulted from accidents that occurred in 1949-1951, 1957, and 1967, as well as from the operation of the group of enterprises "Mayak." It produces plutonium, and deals with the utilization and disposal of radioactive wastes. Taken for the trace on the whole, the soil pollution density with cesium-137 varies from 0.1 to 5.0 Ci/km². The ratio of cesium-137 to strontium-90 is on average 0.42. Gamma radiation from radioactive elements, in particular from cesium-137, reaches 60 µR/h.

As a result of the radioactive wastes discharge by the group of enterprises "Mayak," the density of soil pollution with cesium-137 and strontium-90 in the flood plain

of the Techa River (until the point where it flows into the Iset River) varies within 1-270 and 1-265 Ci/km², respectively. Lake Karachai is an open reservoir of liquid radioactive wastes on the territory of the group of enterprises "Mayak." In 1967, a drought resulted in the intensive wind erosion of the lake's banks and in wind-spreading of the silty bottom sediments, contaminated by radionuclides. These radionuclides were spread by the wind to a distance of 50-70 km from the lake. About 415,000 people fell victim to this accident.

Another accident of interest occurred at the Tomsk-7 Radiochemical Plant, where, due to pressure increases up to 17 atmospheres (the maximum admissible pressure at such plants is 12 atmospheres), in a hermetically closed apparatus, the capacity casing failed and about 250 m³ of liquid radioactive mixture was discharged. The apparatus contained 20 m³ of weakly radioactive uranium liquor, that comprised 500 g of plutonium. (However, plutonium-239, which is most dangerous to people, was not found in the discharged liquor.) Now, the radiation level varies from 35 to 400 µR/h; this is mainly zirconium, rhutenium, and niobium isotopes with a half-life of about one year or less. The area of the territory that was subject to radioactive contamination is less than 120 km², while the area of the radioactive pollution itself is 35 km².

The radioactive situation within the proving ground, Novaya Zemlya, and its adjacent areas in the extreme North regions can be characterized as follows.

(1) The average level of surface pollution of the territory with radionuclides is the highest for the whole western region and exceeds the values typical for Alaska and Greenland by 2 to 3 times. The average density of the surface pollution with cesium-137 is 90 mCi/km² and approaches the level of global background pollution that is typical for the middle latitudes of the Northern Hemisphere.

(2) The concentration of cesium-137 in the soils of areas lying beyond the Arctic Circle diminishes in the eastward direction, which testifies to the pollution of areas adjacent to the proving ground by radioactive products of nuclear weapon tests in the atmosphere, as a result from the prevailing eastward transport of air masses.

(3) On the island, there are zones, characterized by increased radioactive background; these are the places of nuclear weapon tests. The value of gamma radiation in these places reaches dozens and hundreds of micro-roentgens per hour (µR/h) at the present time. The areas of these sites is not large and they have the status of sanitary-protection zones.

(4) Underground nuclear weapon tests on the island did not contribute appreciably to the increase of radioactive pollution of the natural environment of the proving ground territory with long-lived radionuclides.

(5) The content of technogenic radionuclides in the drinking water utilized on the island is usually several orders of magnitude lower than their MPC, set by the radioactive safety standards.

In the waters of rivers flowing over the territory of Russia, cesium-137, strontium-90, as well as tritium can be found. These radioactive substances find their way into the rivers due to runoff from watersheds, contaminated by the global emission of these isotopes, originating from previous nuclear weapon tests in the atmosphere. In 1991, the concentrations of strontium-90 and tritium in the river water differed only slightly from those of 1990 and were on average, 0.3×10^{-12} Ci/l and 1×10^{-10} Ci/l, respectively, which is 3 to 4 orders of magnitude lower than the MPCs set for such kind of contamination.

An increase in the radioactive pollution level was observed in the Yenisey River waters, where cooling water from direct-flow reactor of the Krasnoyarsk Mining-Chemical Plant are discharged. In the sites of polluted water discharges, short-lived isotopes (sodium-24 (^{24}Na), chromium-51 (^{51}Cr), manganese-54 (^{54}Mn), and arsenic-76 (^{76}As) were observed. The concentration of ^{24}Na was 2.6×10^{-7} Ci/l, which is nine times higher than the established standard, while the concentrations of other isotopes was 5 to 100 times lower than the standard. In the village of Atamanovo (the first settlement downstream of the discharge point) the concentration of ^{24}Na was 1.3-2 times lower than the standard.

At present, systematic control of dioxin concentration in the environment is not carried out in the Russian Federation. There are no appropriate facilities, standards and specialists in regional laboratories, which makes it impossible to implement large-scale sample analyses.

Oil- and gas-extracting enterprises in western Siberia are concentrated mainly in the Ob-Irtysh Region, where forestry and wood industry are highly developed. These enterprises have destroyed the natural-resource basis of traditional economic activity and the place of aboriginal population living. According to experts' estimates, the area of all sorts of disturbances in natural lands makes dozens and hundreds of million hectares. The Ob River pollution with industrial and municipal waste waters reduces fish resources under the conditions of low assimilation capacity of northern rivers. In the main regions of wood cutting, the forests are exhausted to a great extent, and coniferous trees in them are gradually replaced by less valuable small leaf-bearing trees.

In accordance with the Decree of the Presidium of the Russian Federation Supreme Soviet, the intra-branch Commission on Estimating Radioactive Wastes Disposed in the Sea, was formed. It has already published the materials about 16 nuclear reactors, lying in the Kara Sea, and the fuel was not unloaded from 6 reactors, mounted on submarines.

All these reactors are referred to a group of polluted ones, so they cannot be disposed of in the sea, because they contain highly toxic radioactive wastes. Besides, liquid radioactive wastes were regularly discharged into the waters of the Arctic seas. The pollution of the Barents Sea reaches 319 Curies; the Kara Sea, 2,419,000 Curies. At present, the levels of radioactive contamination of the Arctic seas do not tend to increase and the concentration of radionuclides in their waters are not increasing. But radioactive wastes are disposed in metallic or concrete containers, which will inevitably fail in 10-30 years and thus create the ecological danger.

The problem of monitoring and planning the observations over currents' dynamics and pollutants' transport in water bodies remains very acute. In addition to engineering difficulties, inherent in it, requirements to the accuracy, this problem is of principal methodological and economic importance. Natural isotopes ^2H , ^3H , and ^{18}O can play a very important role. These isotopes can give new information on the origin and dynamics of water masses in hydrological systems. Appreciable experimental material has been collected at the Laboratory of Isotope Studies of the Water Problems Institute of the Russian Academy of Sciences. This material contains valuable information on the concentration of oxygen and hydrogen isotopes in the atmospheric precipitation, riverine and marine waters of the Arctic Ocean basin. At this laboratory, the methodology of researching and determining zones of mixture of waters of different origin, as well as pollutants' proliferation brought by river waters into the seas, has been documented. In particular, the zone of the influence of the Ob and Yenisey Rivers' runoff into the Kara Sea has been determined. A model predicting the proliferation of polluted zone has also been developed. The zone predicted by the model reaches a depth of 30 m in the Kara Sea and in the White Sea it is spread over the whole sea depth. The difference in the isotopic composition of oxygen in the riverine waters of the Yenisey and Ob inlets has been revealed, and this has allowed researchers to estimate the ranges of mixing the Yenisey and Ob river waters in the desalinated fresh water zone of the Kara Sea.

The Yablokov Commission Report on Soviet Radioactive Waste Dumping at Sea Additional Comments

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As it was indicated in Section 4 of the Yablokov Commission report, on January 1, 1993, the Northern Fleet stores about 21,000 spent fuel assemblies (SFA) at different facilities. One such facility is located in Andreyev Bay at the Western Litza navy base.

As one can see in Table A2 of the report, there was discharge of liquid RW at Andreyev Bay of up to 1,000 curies. The year of discharge is indicated as 1982. However, it requires some explanation. Especially taking into account that later in *Izvestiya* newspaper the date of the accident in Andreyev Bay was shown as 1989.

In reality abnormal conditions existed for several years and liquid RW discharge took place in several steps.

The facility in Andreyev Bay for wet storage of SFA consisted of two tanks, "left" and "right." In February 1982 "the leakage" appeared at the right tank. Later, in December 1982, the left tank started to leak. It has made the radiation situation around the storage building rather serious. Activity of discharge water was about 2×10^{-3} Curies per liter (Ci/l). The loss of water in the right tank was about 3 tons per day. Decrease of water level in the right tank unfavorably influenced the radiation situation. At the beginning of 1983 due to construction work in the vicinity, the leakage in the right tank increased up to 30 t/day. It required some urgent measures. A special appliance was used to decrease the activity concentration in water to about 5×10^{-5} Ci/l. It significantly reduced the danger of heavy pollution of the bay waters.

Gradually, both tanks were drained and the very difficult job of unloading the tanks from fuel assemblies was done. The final unloading of the left tank was finished in 1986, and the right tank in 1989. It closes the accident in Andreyev Bay.

The current radiation situation in Andreyev Bay is characterized by the next figures:

- activity of sea water is less than 7 pCi/l
- volume activity of air aerosols is $\sim 10^{-14}$ Ci/m³·day
- fallout activity is $\sim 3 \times 10^{-12}$ Ci/m²
- volume activity of drinking water is $\sim 2 \times 10^{-12}$ Ci/l
- activity of plant tissues is $\sim 5 \times 10^{-9}$ Ci/l.

These figures permit us to describe the situation as acceptable. However, in some spots rehabilitation could be necessary.

Besides the facilities of the Navy for storage of SFA, significant quantities of it are stored by the Murmansk Shipping Company. The bulk of this is stored on the floating technical bases *Lepse*, *Imandra* and *Lotta*. The estimate of the total activity stored at these 3 floating bases (about 2 km from the city of Murmansk) is as follows:

<i>Lotta</i>	3385 SFA	5.8 MCi
<i>Imandra</i>	1201 SFA	3.5 MCi
<i>Lepse</i>	624 SFA	0.74 MCi.

Floating base *Lepse* required special attention while internal leakages of technological volumes took place. By radionuclide composition, the inventory for *Lepse* is as follows: ⁹⁰Sr–390 kCi, ¹³⁷Cs–350 kCi, ^{238,239}Pu + ²⁴¹Am + ²⁴⁴Cm–17 kCi.

From 1990 *Lepse* stays in Murmansk and is not coming out. The volumes where SFA is stored are to be filled by concrete mixtures, but before the water should be taken away. From February 1992 the evaporation of water by heating it to 35°C has been going on. After final filling of all volumes on *Lepse* by concrete mixtures, it should be disposed of.

Accumulation of SFA at Kola peninsula as one can see is very high. Further, 1,200 bundles of SFA are kept

Table A2. Characteristics of Liquid Radioactive Waste Discharge in Northern Seas

Year	Area 1		Area 2		Area 3		Area 4		Area 5	
	Volume, m ³	Activity, Ci (TBq)	Volume, m ³	Activity, Ci (TBq)	Volume, m ³	Activity, Ci (TBq)	Volume, m ³	Activity, Ci (TBq)	Volume, m ³	Activity, Ci (TBq)
1960			760	0.21						
1961			930	16.5						
1962			850	4.61						
1963			1054	358.15						
1964			910	153.11						
1965			6520	963.62						
1966			3540	366.84	1220	5.97			449	1.01
1967			144	30.17	530	2.2			2000	2.69
1968	353	2.81			1357	0.50			1400	1.52
1969	316	109.51	3416	51.87	1290	0.29			750	0.41
1970	2703	65.42			4370	96.13			2257	0.56
1971			2371	20.65	1096	3.62			1549	1.41
1972	850	5.9	930	19.5	4101	101.33			2560	8.40
1973	882	22.0	4057	76.6	3872	129.36			885	4.00
1974			8645	265.7	3155	321.3			838	0.80
1975	1947	430.0	4720	55.27	851	15.3	835	6.35	1610	8.16
1976	1800	63.0	6229	75.9	2788	811.9			830	11.20
1977	1500	68.32	4150	47.35	860	1.5			870	8.70
1978	340	30.19			5170	90.25				
1979	604	12.01			7286	78.42				
1980	650	27.06	3405	22.32	3957	37.67			800	8.00
1981			2146	268.27	2130	201.06	906	3.99	2755	21.13
1982	1250	169.0	1745.4	11.07	1476.6	18.52			1855	9.70
1983	685	72.41	1772.1	265.34	472	11.06			3247	22.34
1984			5125.4	222.13	820	5.99	740	2.78	1614.8	51.38
1985					2376.6	65.85			3980.5	21.9
1986			900	10.59	870	29.49	1410	5.74	3410	23.73
1987			1740	34.8	780	14.7	2211	22.38	2063	20.61
1988	364.5	5278.51								
1989					2472	39.76	875	1.41	2752	11.10
1990			751	0.84			1267	7.12	5913.6	59.03
1991							263.2	3.99	2382.8	19.61
Total	14244	6356 (235)	66811	3341 (123)	53300	2082 (77)	8507	54 (2)	46772	317 (12)
										Total, Areas 1-5
										Volume, m ³
										Activity, Ci (TBq)
										189634
										12153 (450)

by the Pacific Fleet and it corresponds to 8,400 SFA.

Besides spent nuclear fuel, every year at repairing facilities about 6,000 tons of RW and 20,000 m³ of liquid RW are produced. The accumulation of RW is faster than the construction of the facilities for storage and the problems nowadays becomes urgent.

To solve the problem the special "State program for handling, recycling and disposal of radioactive wastes and spent nuclear fuel for the 1993-1995 period and through 2,005" was accepted. Now the financing of the "immediate measures" for this program has started. The main directions of work relating to maritime nuclear activity are shortly summarized here.

- The general technical and economic assessment of the complex problem of treatment of SNF from

transport nuclear reactors should be provided by Minatom, Minprirody, Minoborony (Ministry of Defense), etc.

- The special technological appliances for unloading of SNF and its transportation for reprocessing should be made by Minatom, Minoborony.
- The special bases for reloading of SNF at Northern and Pacific Fleets should be constructed by Minoborony and Mintrans.
- The special technology for reprocessing of SNF, which cannot be reprocessed at present, should be developed by Minatom.
- The work on the creation of an industrial complex for conditioning of all liquid radioactivity waste from radiochemical plant, WWER-reactors and

transport nuclear reactors should be further pursued.

- The technical solution for utilization and disposal of floating base *Lepse* should be found (Minatom, Mintrans, Ros komoboronprom, Minstroï).
- The problem of the treatment of RW, formed in the process of exploitation and after decommissioning of transport nuclear reactors should be solved. The solution should include:
 1. The basic information for the choice in European and Far Eastern regions the places for regional facilities for treatment, temporary storage and disposal of SRW and LRW, which are formed in the process of exploitation and after decommissioning of transport nuclear reactors.
 2. The development of the concept of treatment of reactor sections in transport nuclear units, which will provide the safe isolation from the biosphere.

3. The development of technology and technical appliances for temporary storage, treatment and disposal of RW, produced by transport nuclear units.
4. Modernizing of the existing and construction of the new floating facilities for treatment of LRW.
5. Construction at the repair workshops of the facilities for treatment of RW.
6. Development of technology and technical appliances for utilization of reactor sections of nuclear submarines after accidents.
7. Organizational and technical measures for utilization of RW produced by the exploitation, unloading, repair and final disposal of nuclear transport units.
8. The study of radioecological consequences of dumping RW and accidents with nuclear submarines, the development of rehabilitation measures in the case of their necessity.

Radionuclides in Groundwater of Hydrocarbon Fields in the European North and West Siberia

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There is a high, natural concentration of radium-228 and radium-226 isotopes in field water of Ukhta, Urengoi, and Medvezhje oil and gas fields. The source is probably organic rich rocks. Surface contamination occurs at the well sites and on the surrounding terrain from drilling mud and hydrocarbons spilled during the course of pulling drill strings and tool withdrawals, recovering of casing, extracting cores, and flushing the wells.

Analysis of the accompanied water from some hydrocarbon fields shows an increased concentration of naturally radioactive isotopes, uranium-238 and thorium-232. According to the Russian governmental radiation standards (RRS-76/87), the allowable concentrations (or AC) of radionuclides in drinking water are: for radium-226, 5.4×10^{-11} curies per liter (Ci/l); for radium-228, it is 8.8×10^{-11} Ci/l.

It was noted as early as 1928 that the accompanied water of the Yarega Oil Field (the area of the city of Ukhta, the European north of Russia) showed the radium-226 concentrations of 2.88 to 7.4×10^{-9} Ci/l (1). Similar radium-226 concentrations were observed by the Isotope Methods Laboratory of VSEGINGEO in 1983, using water samples from the Ukhta Oil Field. This water in the late 1920s was used in Ukhta City by a small plant producing radium for constant scintillation compositions (for aviation devices) (2).

In preparation for geoenvironmental mapping of the territory of the Urengoy oil and gas condensate field (West Siberia) (see Figure 1), the largest field in Russia, we have established that the industrial waste water, such as the accompanied water in the exploited wells, contain the following concentrations of radioactive isotopes:

At Integrated Treatment Gas Plant 1 (ITGP-1) = 13 times the allowable concentration (AC) for radium-226 and 16 times the AC for radium-228;

At ITGP-5 = 16 times the AC for radium-226; 17 times the AC for radium-228;

At ITGP-15 = 26 times the AC for radium-226 and 60 times the AC for radium-228.

A slightly lower level, but still three to seven times the allowable level for radium, was observed in waste water of some exploited wells of the Yrengoy field. It is obvious that the increased radium content in groundwater is connected, first of all, with the concentration of natural uranium-238 and thorium-232 radionuclides in deep-located rocks. The activity of mother natural radionuclides, measured by a gamma-spectrometer in core samples in the wells from a depth of 2700 to 3900 meters, was calculated for uranium-238 to be from 15 to 91 becquerel per kilogram (Bq/kg). The total activity of mother and daughter products ranged from 210 to 1276 Bq/kg, respectively. For thorium-232 observed values were from 21 to 210 Bq/kg, for mother products, and 214 to 814 Bq/kg of total activity. A slightly lower radioactivity is observed for rocks and ground water in the Medvezhiy gas condensate field.

Considering that radium isotopes are some of the most biologically active radionuclides, we plan during carrying out geoenvironmental investigations and mapping on a scale of 1:200,000 of the territory of the Urengoy Field in 1993-1995 to clarify the following questions:

1. What is the amount of industrial waste water at all 15 Integrated Treatment Gas Plants (ITGPs), and

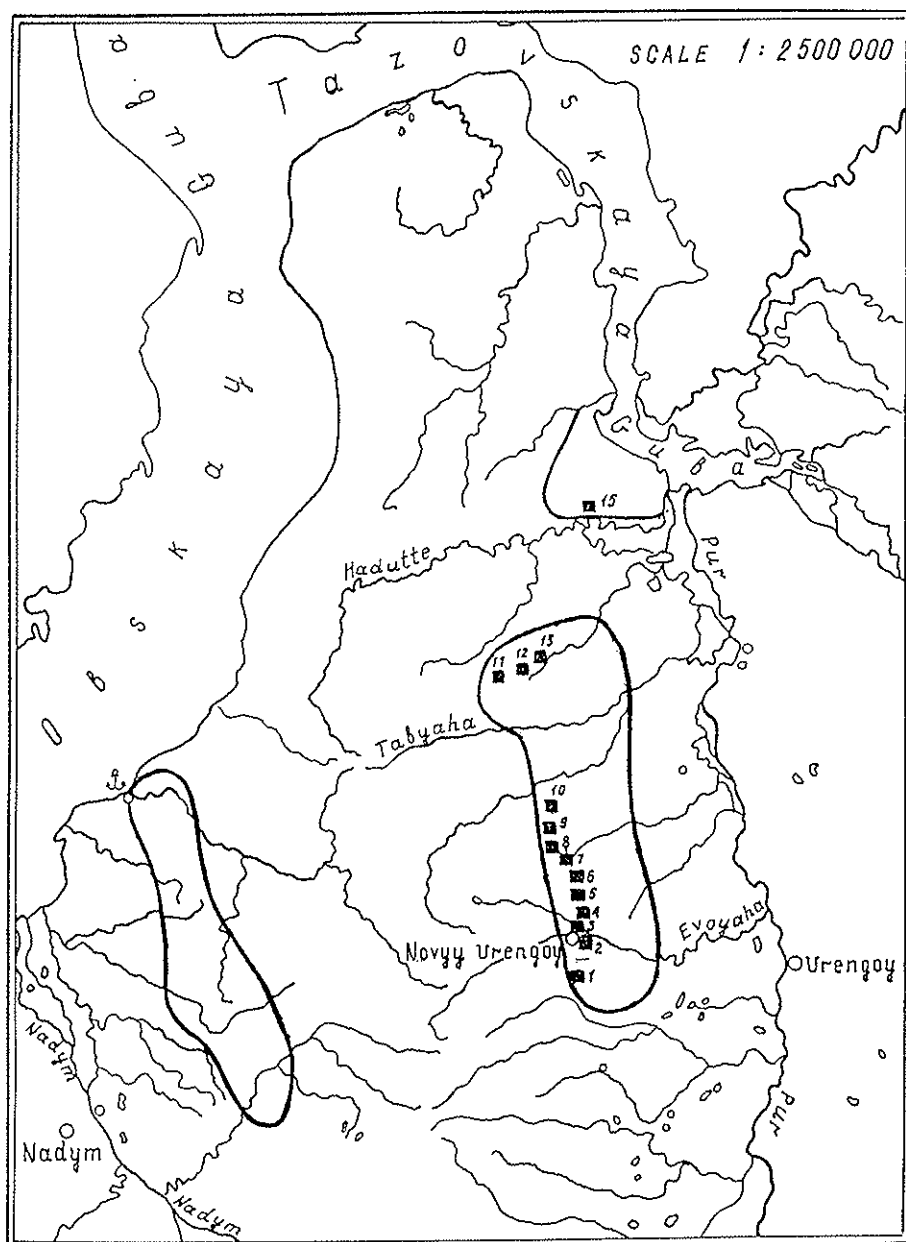


Figure 1. Location of the VSEGINGEO study area. Gas processing plants shown by solid squares.

what pollutants such as radionuclides, heavy metals and hydrocarbon are present? What is the level of contamination in the areas surrounding the ITGPs and individual well sites?

2. What migration paths do the contaminants take under conditions of discontinuous permafrost (deep seasonal thawing)? Do they percolate under lakes and river-beds underlying taliks? Is there a hydraulic connection of surface water with the inside- and under-permafrost ground water?
3. What is the possibility of penetration of natural radionuclides into the Arctic basin with both ground and surface water?

To help answer these questions, along with the testing pollution levels in soils, vegetation cover, and surface water, we plan to drill and test two boreholes of 450 meters (m) deep, two boreholes of 300 m, 4 boreholes of 150 m, 16 boreholes of 50 m deep, and a few hundred of boreholes having a depth of 10 to 12 m.

Of special interest to us are the investigations of isotopic composition of samples of rocks, surface and ground water in the areas of underground nuclear explosions conducted for the purposes of deep seismic surveying in the Tazovsky Peninsula (in the northeast of Yamburg Settlement, 1974 and in the east of the City of Novy Urengoy, 1988).

The locations of the wells with atomic explosions for deep seismic surveying are shown on several published maps. The wells were drilled and exploded during the period 1974-1982. The territory under VSEGINGEO study (1993-1995) has two wells: (1) northeast of Yamburg, at the mouth part of the Poylova-Yakha River Valley ("Gorizont 2," 1974), and (2) east of the city of Novy Urengoy ("Rubin 2," 1988). Besides, the West Siberian Artesian Basin has several additional sources of radioactive contamination from underground nuclear explosions, i.e.:

- to northwest of the city of Beloyarsk ("Kraton 1," 1978);
- to northwest of the city of Surgut ("Kimberlit 1," 1979);
- to southeast of the city Nyagan ("Angara");
- to south of the city Igarka, on the left shore of the Yenisey River ("Kraton 2," 1978);
- in the area of middle stream of the Bolshaya Kheta River;
- to northwest of the city of Igarka ("Rift 1," 1982).

Three approaches are to be used in studying radioactive contamination from underground nuclear explosions in deep wells:

1. Inspect the contamination of surface water, ground water of taliks, soils and biota in the areas of explosions (Yamburg, Urengoy).
2. Obtain water samples in deep exploratory wells and analyze chemical and isotopic composition (Urengoy and Yamburg fields, Tazovskaya Bay and possibly the geophysical field on Gydan Peninsula). In case isotopes of uranium, plutonium, cesium-137, cobalt-60 or others are found, modeling will be conducted from source areas to predict migration and dissolution of chemical elements into the deep aquifers of the West Siberian Artesian Basin.
3. Obtain water samples in deep wells of VSEGINGEO in the Urengoy Field, define the availability or absence of a hydraulic connection across the entire profile, and conduct hydrodynamic and hydrochemical modeling.

In addition to these sources of radioisotopes, the Ob and Yenisey Rivers transport radioactive pollution from the chemical plants of the cities of Chelyabinsk (Miass, Iset, Tobol Irtysh, Ob rivers), the city of Tomsk (Tom, Ob rivers) and the city of Krasnoyarsk (Yenisey River). Surveys, carried out by the ecologists of Krasnoyarsk in 1990 have shown that the contamination of flood plain soils is observed for different chemical elements at a distance of 500 to 1500 km within a narrow shoreline of 5 to 50 meters width. Among the polluting elements are plutonium-239 and 240, cesium-137, and cobalt-60.

Because of the contamination of the vast territories

on the east slope of the South Ural mountains by the industrial complex "Mayak" (Chelyabinsk-40), the transport of radionuclides through hydrographic network of the River Ob is probable. The greatest contribution to the environmental contamination was made by three radiation accidents. The first in 1949-1956, released highly active radioactive wastes into river systems of Techa-Iset-Tobol. The total activity of the releases was 2.6 MCi (4). The second was on September 29, 1957, when an explosion of a tank containing radioactive waste occurred. The yield of the explosion is assessed as equivalent to 70-100 tons of TNT (5).

The relatively low content of cesium-137 (^{137}Cs) in the radionuclide mixture from the explosion is explained by technological processing used in the radiochemical plant. The practical absence of cesium in the mixture was not taken into account by foreign investigators. From the total quantity of 20 megacuries (20 MCi) to 2 MCi went into the air to the height of 1000 m, and were dispersed into the north-east direction (5,6). The distribution of contamination according to its level of activity is given in Table 1.

Table 1. Radionuclide composition of the Mayak nuclear accident on September 29, 1957 (5).

<i>Radionuclide</i>	<i>Half-life</i>	<i>Rad. type</i>	<i>% of activity</i>
^{89}Sr	51 days	β, γ	~0
$^{90}\text{Sr} + ^{90}\text{Y}$	28.6 years	β	5.4
$^{95}\text{Zr} + ^{95}\text{Nb}$	65 days	β, γ	24.9
$^{106}\text{Ru} + ^{106}\text{Rh}$	1 year	β, γ	3.7
^{137}Cs	30 years	β, γ	0.036
$^{144}\text{Ce} + ^{144}\text{Pr}$	284 days	β, γ	66
^{147}Pm	2.6 years	β, γ	~0
^{155}Eu	5 years	β, γ	~0

In the affected territory there are several steppe lakes without surface water exchange and three small rivers. The main accumulation of contamination took place in deposition on the lake and river surfaces. The radionuclides and subsequent runoff for many years placed radioactive elements in these water sources. A decrease in radionuclide concentration occurred after five to six years, due to the half-lives of the isotopes released. Strontium-90 (^{90}Sr) has moved in the silt to a depth of more than 30 cm and is concentrated mostly in the layer 0-15 cm (5). The principal agent of radionuclide migration is by surface and underground water movement and withdrawal (5). Table 2 lists the dimensions of the contaminated region by level of strontium-90.

Runoff from previously contaminated areas concentrated radionuclides in Lake Karachai (Mayak). When the lake dried up due to a drought in the spring of 1967, the third accident occurred. As a result of drought,

Table 2. The distribution of the area due to the level of contamination by strontium from the September 29, 1957 Mayak accident.

<i>Surface density of ^{90}Sr (Ci/km²)</i>	<i>Surface area (km²)</i>
0.1–2	15,000
2–20	600
20–100	280
100–1000	100
1000–4000	17

winds blew radionuclides over about 50 km and overlapped the trace from the 1957 accident. The additional contamination was about 0.1 Ci/km² for the area of 2700 km². Total activity was 0.6 MCi (4).

The extremely high level of radioactive waste (more than 900 MCi) (4) on the small territory, runoff of radionuclides due to accidents, contamination of surface water reservoirs, and the hydrologic network of the Ob River basin, all require that detailed studies of radionuclide migration into the river waters, regional drainage basins, and Arctic Ocean, must be conducted.

The most effective method for determination of radioactive contamination to the Arctic Basin from the above-mentioned chemical plants is to obtain soil and water samples from the profiles crossing the flood plains of Ob (the area of Tadibe-Yakha, Se-Yakha or Tambey Settlements) and Yenisey (the area of Ust-Port

or Golchikha Settlements). Increased concentrations of radionuclides in river water can be detected, perhaps, after accidental emissions from the plants. Typically, the "usual" industrial wastes of the plants disperse very quickly in the large quantities of water in these large rivers.

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Zones of Relatively Enhanced Contamination Levels in the Russian Arctic Seas

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This article presents the results of the multi-year observations of the levels of the main groups of pollutants in the surface waters, bottom sediments, and snow cover of the seas of the Russian Arctic. The generalizations are made on the basis of the data from complex hydrochemical and hydrological surveys of the water areas of the Arctic seas, as well as the data of the common state environmental monitoring system in the Russian Arctic for the period 1987 to 1992. The data used are taken from the archive of the ecological data on the pollution of the Arctic region, collected by the specialists of the State Enterprise "Monitoring of the Arctic" (St. Petersburg).

The composition of the pollution, its volume and pathways into the Arctic seas are determined by a number of factors, including the physical-geographical features typical for each region, industrial development of the adjacent territories, local population, presence of urbanized regions, and the presence of industrial and agricultural enterprises.

The main sources of contaminants, incoming to the seas of the central Arctic are:

- outflow of river water and particulates, suspended in water and polluted by both industrial and everyday discharges;
- direct discharge of industrial and everyday wastes into the marine environment by enterprises and villages along the Arctic coast;
- maintenance of all kinds of transport (marine and river fleet, aviation, timber transport by waterways, cars, and pipeline transport);
- construction and maintenance of engineering structures on the Arctic Ocean Shelf;
- transport of pollutants by atmospheric flows, including long-distance trans-boundary transfer;

- pollutant transport by water masses of the central Arctic Ocean;
- dumping of industrial wastes and soils, extracted during dredging works;
- chemical treatment of agricultural fields.

Pollution of Water Bodies

The toxins incoming to the Russian Arctic seas are classified into five groups: heavy metals, petroleum hydrocarbons, detergents, phenols (technogenic, lignine distraction product), and organochlorine compounds (HCH isomers, DDT and its metabolites, PCBs).

Pollutant concentrations in the snow cover of the Arctic seas are determined by both long-distance (regional) and short-distance (local) atmospheric transfer. A large number of factors participate in the formation of the pollutant fields in sea water and bottom sediments. In the seas of a closed type, the White Sea for example, the main source is from the river runoff and discharges of industrial, communal, and agricultural enterprises of the coast, with the factor of mixing with the oceanic waters being of secondary importance. In the seas of an open type marine, ocean currents begin to have a significant influence. The factor of atmospheric transfer is also of secondary importance.

Mean concentrations of pollutants in the water of the Arctic Seas (Figure 1) are at the level of the geochemical background, which is lower than the Limits of Admissible Concentrations (LAC) with regard to all components under consideration (Table 1). The zones of enhanced pollution concentrations relative to the background level are observed in all seas without exception. The criterion for the identification of such zones is a stable, significant excess of the pollution level, by several pollutants, over the mean level. The observed

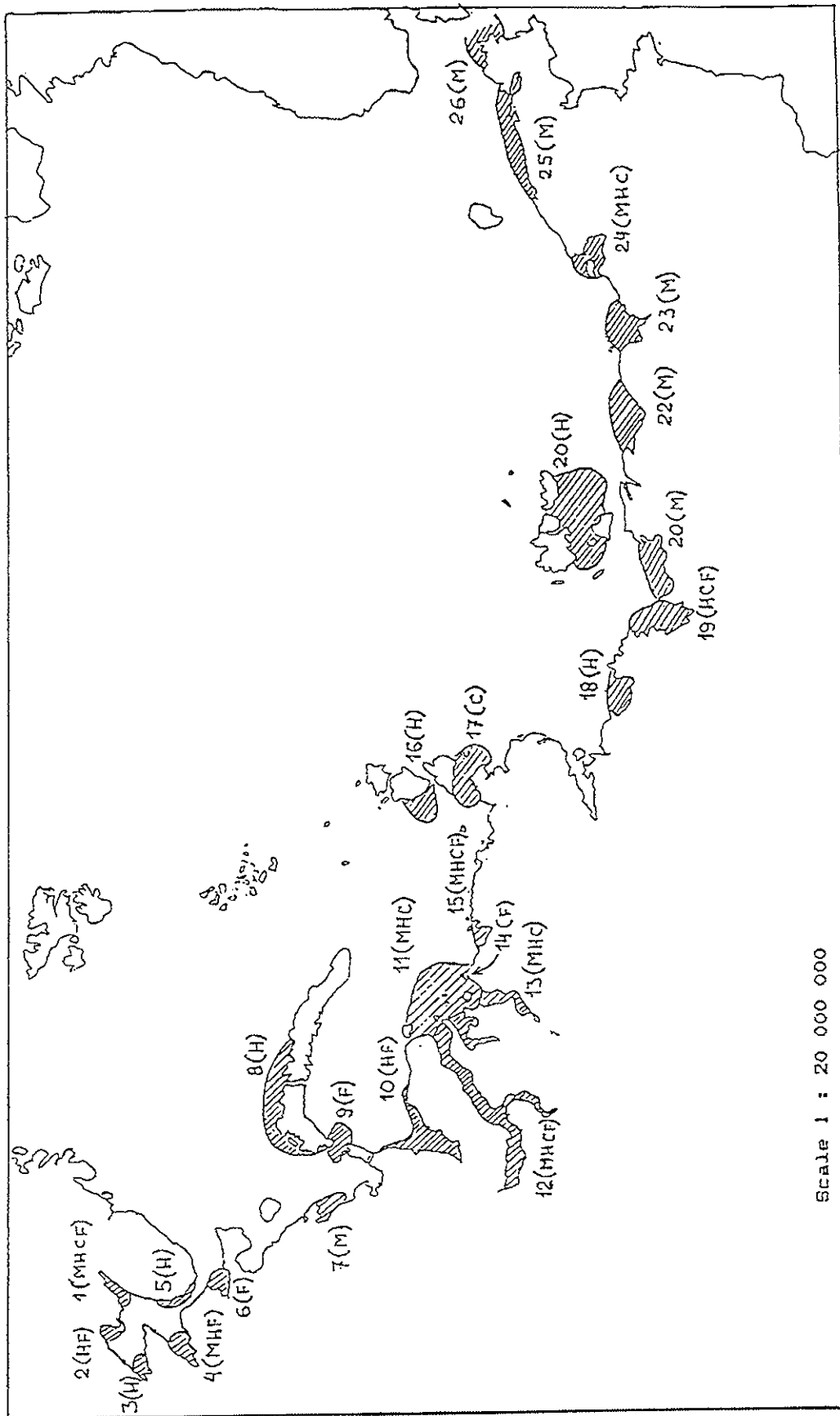


Figure 1. Distribution of zones of relatively enhanced water pollution in the Arctic seas.

Table 1. Zones of relative enhanced water pollution of the Arctic seas.

Concentrations of Pollutants in Water														
N zone	Location	Heavy Metals (µg/l)								Petrol H-carbs µg/l	OCC ng/l		Phenols µg/l	Dets µg/l
		Mn	Pb	Fe	Ni	Co	Cu	Zn	Sn		DDT	HCH		
White Sea														
1	Kandalaksha Gulf	0.1-3.3		0.1-6.0	0.1-0.5					5-80 30	0-1.9 3			
2	Coast near Kem', Belomorsk									3-70 20			3-5	70-170 130
3	Onezhskaya Gulf									2-50 15				
4	Dvinskaya Gulf	0.1-3.5	0.1-1.4	0.1-28.0		0.05-0.2	0.1-0.5	1.0-3.5		5-85 20			3-5	70-180 110
5	SE coast of the Kola Peninsula									2-250 2			1.5-2.5	
Barents Sea														
6	Mezenskaya Gulf												3-5	50-160 10
7	Pechorskaya Gulf	0.1-2.0	0.1-0.6	0.1-7.4	0.1-0.2		0.1-0.3	0.9-2.7						
8	Novaya Zemlya, NS coast									0-150 12			1.5-2.5	
9	Karskie Vorota Strait													30-110 85
Kara Sea														
10	Baidaratskaya Gulf									2-85 20		0-1.5		30-790 100
11	Outflow zone of Ob and Yenisey	0.1-4.0		0.6-15	0.06-1.7		0.1-2.0	0.5-4.0		0-30 15		0-3.0	1.5-2.5	
12	Ob Gulf	0.1-30	0.1-1.5	0.6-30	0.1-2.0		0.1-2.6	0.5-8.2	0.1-0.2	2-40 15				
13	Yenisey Gulf	0.1-35	0.1-1.8	0.5-28	0.7-2.4	0.05-0.2	0.1-2.5	0.5-8.3			0-2.0		1.5-22 8	10-100 50
14	Vega Strait												1-9 4	0-170 80
15	Pyasinskiy Gulf	0.1-35	0.1-2.0	0.7-35	0.2-2.6	0.05-0.3	0.1-3.0	0.5-7.8		0-60 20		0-3.0	0-7 5	10-740 50
16	SN coast of Severnaya Zemlya									5-60 27				
17	Vilkitsky Strait											0-2.3		
Laptev Sea														
18	Loeneksy Gulf									3-130 80				
19	Tiksi Bay, Buorkhaya Gulf									5-290 70		0-5.0	0-16 6	0-20 8
20	Outflow zone of the Yana	0.2-5.0	0.05-0.2	0.6-16.3			0.1-1.4	0.5-9.0						
East Siberian Sea														
21	Southward of the Anjou Islands									0-50 15				
22	Outflow zone of Indigirka	0.2-5.0	0.07-0.2	0.6-15			0.1-1.5	0.5-8.0						
23	Outflow zone of Kolyma	0.2-5.0	0.05-0.2	0.6-16			0.1-1.5	0.4-9.0						
24	Chaunskaya Gulf	0.2-5.0	0.05-0.2	0.6-16			0.1-1.5	0.4-10.0	0-0.12	2-62 16	0-0.5	0-4.0	0-3 2	0-5 1
Chukchi Sea														
25	Coast from Long Strait to Kolu-chinskaya Gulf	0.2-5.0	0.03-0.2	0.6-15			0.1-1.7	0.4-9.0						
26	Bering Strait					0-0.22								
Mean concentration in water of the Arctic seas **		1.42	0.31	4.1	0.40	0.22	0.35	2.34	0.09	12	1.7	1.9	2	20
Limits of admissible concentrations (LAC) in water used for fisheries ***		50	10	50	10	1	5	5		50	10	10	100	100

NOTES:

Some data from the Tiksi Administration for Hydrometeorology

** — Data of the State Enterprise "Monitoring of the Arctic"

*** — Taken from a Summarized List of LAC and approximately safe impact levels of harmful substances for the water of fishery reservoir N 12-04-11 dated 09.08.90.

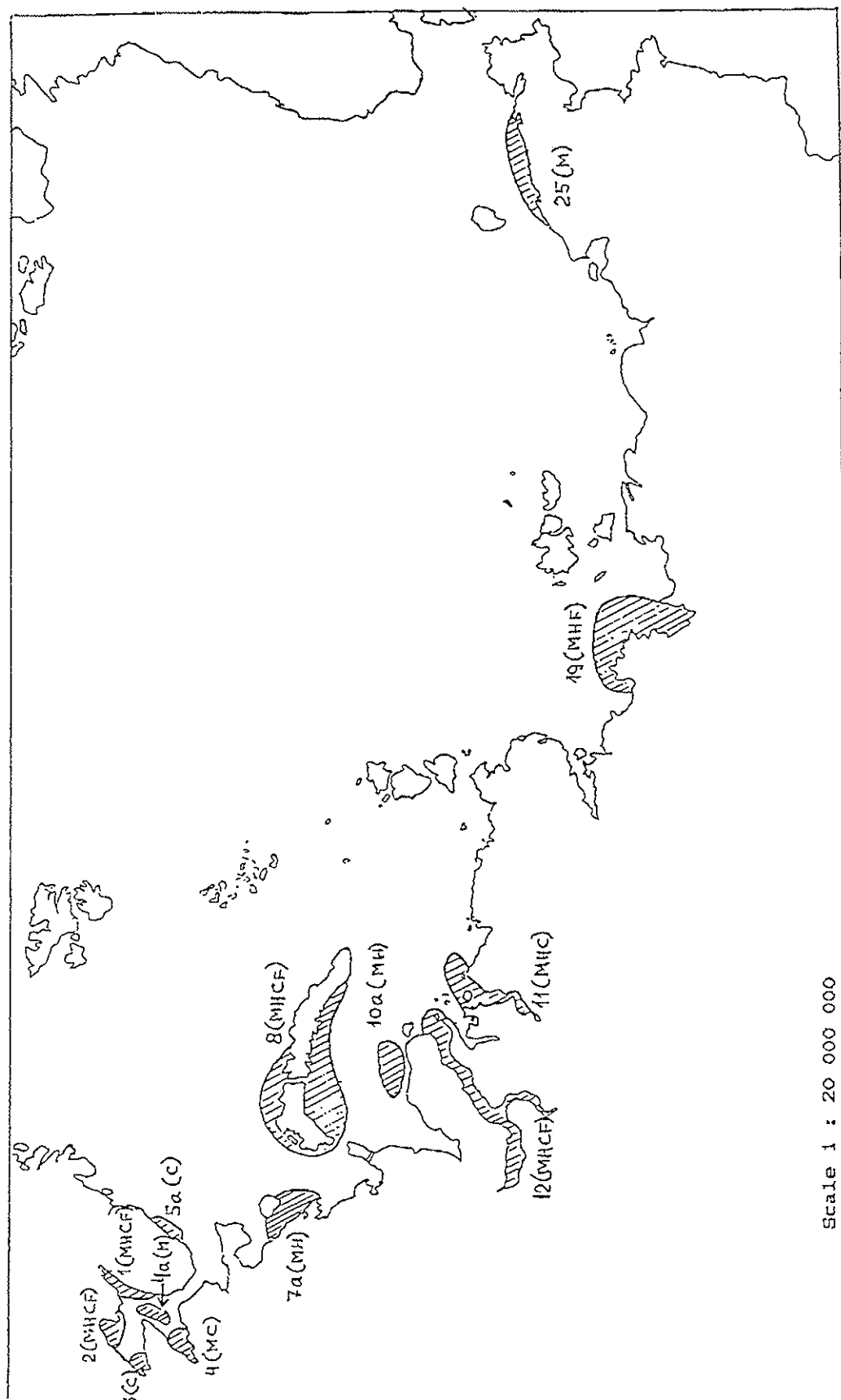


Figure 2. Distribution of zones of relatively enhanced pollution of the bottom sediments in the Arctic sea

zones differ by the extent area, component and pollution levels. More often these zones are located at the coast of seas and areas of mixing water with polluted river runoff. A typical example is the Pyasinsky Bay of the Kara Sea. The water in that area has the following concentrations of pollutants:

- manganese up to 35 µg/l,
- iron up to 35 µg/l,
- lead up to 2 µg/l,
- nickel up to 2.6 µg/l,
- cadmium up to 0.3 µg/l,
- copper up to 3 µg/l,
- zinc up to 7.8 µg/l,
- petroleum hydrocarbons up to 60 µg/l,
- organochlorine compounds of the HCH group up to 2 ng/l,
- phenols up to 7 µg/l,
- detergents up to 740 µg/l.

The Yenisey Bay and the Ob Gulf are being characterized by similar compositions and levels, but with a much larger area. The Kandalakshskaya and Dvinskaya Gulfs of the White Sea are characterized by somewhat lesser concentrations. Most of the zones are characterized by an elevated pollution by petroleum hydrocarbons, organochlorine compounds of the HCH group, phenols, and detergents. The concentrations of these contaminants reach respectively up to 290 µg/l (Tiksi Bay), 5 ng/l (same place), 22 µg/l (Yenisey Bay), and 790 µg/l (Baidaratskaya Gulf). The largest cadmium concentration is found in the Bering Strait (0.22 µg/l).

Pollution of Bottom Sediments

Elevated concentrations of pollutants in bottom sediments of the Arctic seas (Figure 2) are usually found at the coast and in the zones of the outflow of the large rivers. Thus the enhanced pollution by all determined components of the bottom sediments is clearly seen for the Ob Gulf, Yenisey Bay, and the Lena River delta area. The concentrations of pollutants in those zones reach values of:

- iron: 68000 µg/g,
- lead: 277 µg/g,
- nickel: 113 µg/g,
- zinc: 150 µg/g,
- cobalt: 65 µg/g,
- petroleum hydrocarbons: 390 µg/g,
- organochlorine compounds of the DDT group: 1.7 ng/g,
- phenols: 7 µg/g.

Thin suspensions, carried by the river water are sometimes transported by the currents over large distances during the mixing with sea water. These contam-

inants sink into the quieter hydrological regions, resulting in the formation of the zones with elevated pollution in the bottom sediments. These zones have sets of pollutants, typical for the river runoff, but at a significant distance from the river mouths. The regions of the central part of the White Sea and to the southeast of the Novaya Land Archipelago can be considered as the examples of such zones. Bottom sediments in those zones are relatively polluted by heavy metals. Observed values include:

- manganese up to 35000 µg/g,
- lead up to 600 µg/g,
- iron up to 68000 µg/g,
- nickel up to 125 µg/g,
- zinc up to 170 µg/g,
- cobalt up to 65 µg/g,
- petroleum hydrocarbons up to 790 µg/g.

Pollution of Snow Cover

The distribution of zones with elevated pollutant concentrations in the snow cover of the Arctic seas (Figure 3) can be compared to similar zones, which have been identified in water and bottom sediments. The snow cover contamination is governed by the regional and local air transport of pollutants from the sources of different intensity and distance. The pollutant concentrations in the identified zones are characterized by the values which are close to the background level. The areas of these zones are sometimes quite large. The extended zones of the coastal regions of Taimyr, the Laptev and East Siberian Seas can be identified by the level of heavy metals with the concentrations exceeding the averages ones by 2. to 2.5 times. Another zone of intensively polluted snow cover is the Chaunskaya Gulf. Petroleum hydrocarbons and organochlorines from local sources of the industrial complex of the Pevek town are the source of the contamination.

In conclusion concerning the designation used in the figures and tables. In Figures 1 through 3, the shaded areas delineated zones with relatively elevated contaminant levels. Each zone has a number. In brackets the number of the zones are followed by the initial letters of the name of the main group of pollutants by which this zone was identified (M: heavy metals, H: petroleum hydrocarbons, C: organochlorine compounds, F: phenols and detergents).

Tables 1 through 3 present the ranges of the pollutant concentration changes in the zones shown in the figures. The zone numbers in the tables coincide with the zone numbers in the respective figures. For reference the tables give mean pollutant concentrations over all seas and surface water, also with the limits of admissible concentrations.

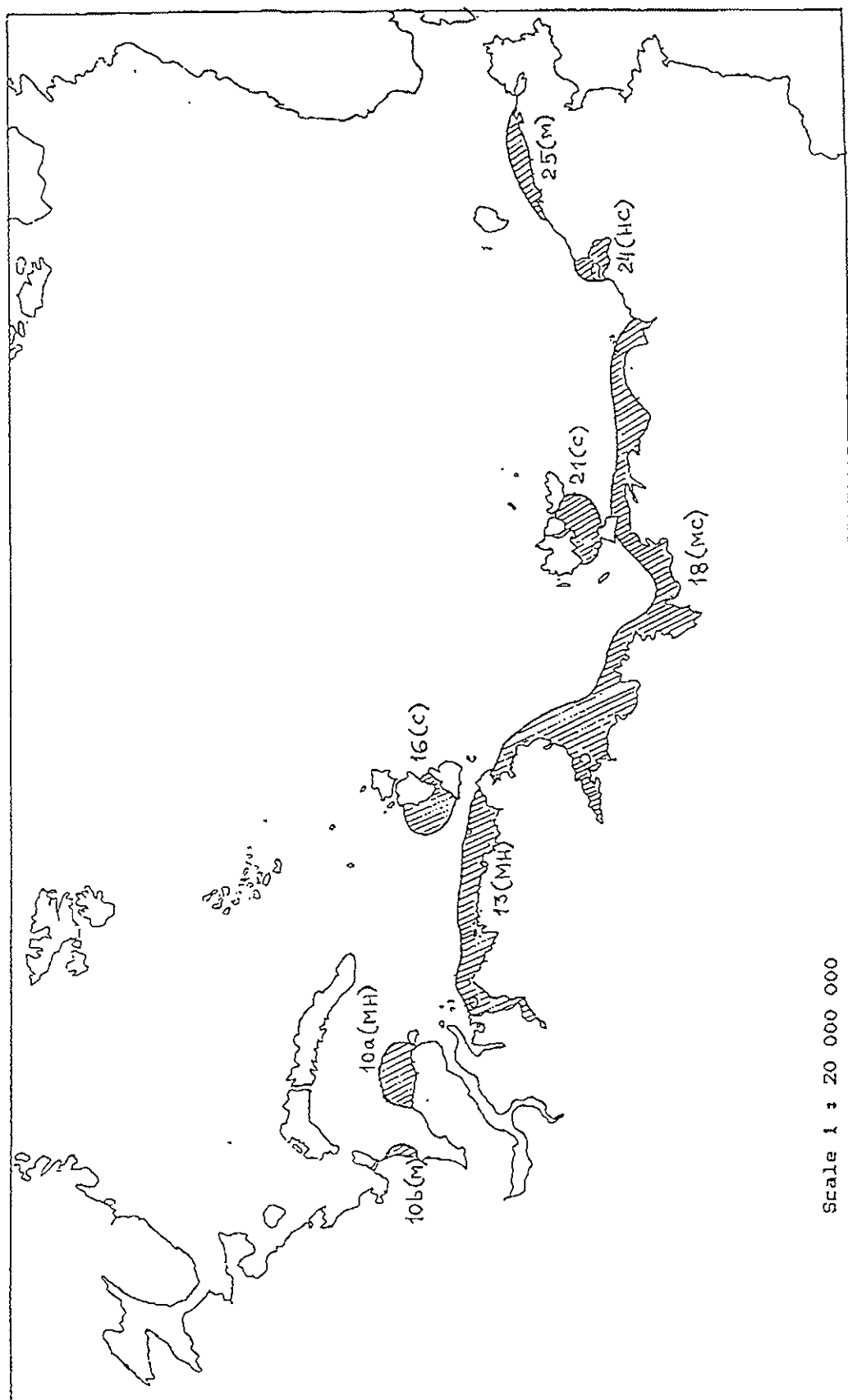


Figure 3. Distribution of zones of relatively enhanced pollution of the snow cover in the Arctic seas.

Table 2. Zones of relative enhanced pollution of bottom sediments of the Arctic seas.

		Concentration of pollutants in sediments									
N		Heavy metals (µg/l)						Petrol	OCC (ng/l)		Phenols
Zone	Location	Mn	Pb	Fe	Ni	Zn	Co	H-carbs µg/l	DDT	HCH	µg/l
White Sea											
1	Kandalaksha Gulf	500-23000	6-530	30000-50000	10-90	20-150		50-300	0.09-2.70 0.25	0.06-0.74	0-17.4 4
2	Coast near Kem', Belomorsk			25000-50000	50-115	73-160	20-45	80-300	0.09-3.1 0.25	0.05-0.29	0-5.3 2
3	Onezhskaya Gulf		40000	30000-						0.10-0.20	
4	Dvinskaya Gulf				35-60	80-90	15-30	50-320		0.05-0.31	
4a	Outflow zone of Severnaya Dvina	15000-35000	125-600			90-170	30-65	80-320			
5a	NE coast of the Kola Peninsula								0.13-0.27	0.15-0.23	
Barents Sea											
7	Pechorskaya Gulf & westward coast		8-65		4-124	10-110	12-31	15-220			
8	Novaya Zemlya area	670-25000	6-460	18000-68000	30-125	30-160	10-45	17-790	0-0.88		0.05-0.71
Kara Sea											
10a	NW of the Yamal Peninsula	2000-67000	90-240		30-85	70-120	30-35	16-150			
11	Kara Yenisey Gulf & outflow zone of Yenisey		9-260	50000-68000	20-100	35-160	10-65	20-300	0-1.69	0.10-0.29	
12	Ob Gulf	8-277		22-113	40-150	16-53	50-390	0.4-0.33	0.11-0.37	2-7	
Laptev Sea											
19	Lena delta, Buorkhaya Gulf	140-2800	4-52	8480-55300	2-60	1-150	8-44	10-180			0-6.4
Chukchi											
25	Coast from Long Strait to Kolu-chinskaya Gulf	90-550	5-60	6860-49420	2-75	2-151	3-33				
Mean concentration in bottom sediments of the Arctic sea *		3406	60	36173	44	70	23	165	0.1	0.1	3

* Data of the State Enterprise "Monitoring of the Arctic," total compositions were analyzed for metals, water extracts for other pollutants.

Table 3. Zones of relative enhanced pollution of the snow cover of the Arctic seas.

		Concentration of pollutants in melted snow water								Petrol		
N Zone	Location	Heavy metals (µg/l)							H-carbs µg/l	OCC ng/l		
		Mn	Pb	Fe	Ni	Co	Cu	Zn		Sn	DDT	HCH
Kara Sea												
10a	NW of the Yamal Peninsula	0.1-0.69	0.1-0.83	0.5-13.2	0.1-0.34	0.05-0.20	0.1-0.47	0.5-3.0		1-40		
10b	Coast near Amderma								0.85			
13	Coast from Yenisey Gulf to Cape Cheluskin	0.1-0.73	0.1-0.78	0.5-14.0	0.1-0.4	0.05-0.18	0.1-0.50	0.5-3.1		1-35		
16	SW coast of Severnya Zemlya Island									0-1.0	0-2.2	
Laptev Sea												
18	Coast from Cape Cheluskin to the mouth of Kolyma	0.1-0.76		0.5-17.1	0.1-0.45		0.1-0.2	0.5-2.8			0-2.3	
East Siberian												
21	Southward of the Anjou Islands										0-2.3	
24	Chaunskaya Gulf											
Chukchi Sea												
25	Coast from Long Strait to Kolu-chinskaya Gulf	0.1-0.68	0-0.40	0.5-16.8	0.1-0.53	0.1-0.29	0.1-0.21	0.5-2.6				
Mean concentration in snow cover of the Arctic seas *		0.23	0.17	3.5	0.24	0.15	0.12	1.2	0.15	14.5	0.53	1.88

* Data of the State Enterprise "Monitoring of the Arctic."

Federal and Non-Federal Ecological Programs Of Russia (with an emphasis on the problems of the Arctic and the North)

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Federal Scientific-Technical Programs for Ecological Studies

The state scientific-technical policy of Russia is being implemented by the Ministry for Science and Technical Policy of the Russian Federation through the Federal scientific-technical programs. The Arctic topics are presented mainly in two programs: "Comprehensive Studies of the Oceans and the Seas of the Arctic and Antarctic for the Period up to 2005," and "Global Changes of the Environment and Climate."

The ecological policy of Russia is formed by the Ministry for Environmental Protection and Natural Resources of the Russian Federation, established in January, 1992.

The new Ministry considered one of its priority tasks to create the State Scientific-Technical Program, which would allow one to mobilize the available research potential in Russia for addressing the immediate problems of ecology and nature use.

The aim of the program is to develop scientific bases and practical recommendations to help in shaping the ecological policy of Russia, under the conditions of both a transition to market economy and ecologically safe nature use. Eight major directions for the ecological policy have been taken under the program:

1. Strategy of the ecological safety of Russia (18 projects, Head - Corresponding member of the Russian Academy of Sciences [CM RAS] O.S. Kolbasov).
2. Methodology and systems of the assessments of the environmental state and information support to the ecological safety of nature use (78 projects, Head - CM RAS, G.A. Zavarzin).
3. Quality of habitat and human ecology (39 projects,

Head - Academician of the Russian Academy of Medical Sciences G.F. Rumyantsev).

4. Ecological risk and safety (50 projects, Head - Dr. S.A. Pegov).
5. Regional ecological problems and concepts of the ecologically valid nature use and management (19 projects; Head - Dr. N.F. Glazovsky).
6. Protection, use and regeneration of natural resources (103 projects, Head - CM of RAS G.V. Dobrovol'sky).
7. Industrial ecology and ecotechnology (35 projects, Head - Academician of RAS S.V. Yakovlev).
8. The system for provision of ecological safety and nature use management in the new public-economical situation (58 projects, Head - Deputy Minister for Ecology and Nature Use of the RF - Dr. A.A. Averchenkov).

Total number of projects in the program is 400. It was agreed that the program would be carried out in two phases: I in 1992, II in 1993-1995. The cost of the first phase of the Program for 1992 is 120 million rubles.

The goal of the first phase is to form conceptual, methodological, and methodical bases to improve and develop scientific, standard, legal, economical, technical, informational, and organizational provisions for the ecological safety and nature management.

The people who developed the program "Ecology of Russia" faced an extremely difficult task; suffice it to say that a number of the preceding efforts to create a similar program were not completed. The authors of this program have decided upon dividing it into two stages of which the first presents conceptual-methodical basis and is actually a preparatory stage.

Due to time shortage during the creation of the first

stage of the program, not all problems of ecology are indicated fully and objectively. However, the program is formed, the funds are allocated and it has been initiated.

Three projects in this part of the program were devoted to the ecological problems of the North and the Arctic. For the first time a comprehensive generalizing work has been carried out for the Arctic region. It includes both the conceptual and methodical approaches to the assessment of the ecosystem state, improvement of ecological situation, and identification of the regions of the ecological risk. The actual data on the ecosystem state have been collected and the probability of the disturbance of the stable state of natural complexes has been estimated. In addition main directions of further studies following from the results of this work have been formulated.

The information collected on this problem shows "truths" that have been known to ecologists for a number of years. Promising techniques for analysis of the ecological data and their use for nature management have been proposed. It was impossible to fulfill many projects in just a one-year time frame. However, the presented materials and summaries indicate a significant advance in the solution of corresponding problems.

The results of the work on many projects can be recommended as a basis for completing the guiding documents and preparing a system of methodical instructions and recommendations for practical purposes. Some reports need to be closely studied because of the interest to various specialists.

At the present time the second phase of the program has begun. The Ministry formed the Federal Comprehensive Task Scientific-Technical Program "Ecological Safety of Russia (1993-1995)." An important feature of this program is the fact that the List of the Included Projects was made on the basis of the requests of the territorial nature protection bodies, administrations of the territories and ecological agencies of local Soviets, that is, potential users of the scientific-technical products. The list is published in the last issue of the newspaper "Green World" for 1992 (special issue).

The general aims of the program are scientific provision of the ecological safety of Russia in the conditions of the formation of market economy, and the establishment of the Russian State by concentrating efforts of scientists and practical workers for the solution of most acute ecological problems by both practical and basic methodologies.

The implementation of the program should result in the development of the scientific bases for the long-range ecological policy of Russia and creation of a respective set of practical measures of legal, economical, organizational character, both ecological norms and require-

ments, and methods and technical means for providing the ecological safety of the country. The program should also result in forecasting the ecologically negative daily tendencies and developing measures (in advance) for their decrease or prevention.

Main principles of the program formation are (1) wide discussion of the aims, objectives and scope of the program, (2) maximum consideration of the applications for a research work of the potential users of scientific-technical products, and (3) competition of the proposals to fulfill the requests of the users.

The selection of the research works (projects) for the program should be on a competitive basis, using such criteria as:

- Compliance of the planned scientific-technical products with the actual practical needs and their direction towards the solution of applied acute ecological problems;
- Adaptability of the planned scientific-technical products to the rapid use of these products by the user;
- High scientific quality of the results of research works providing the competitive scientific-technical products at the market of scientific-technical services;
- Time and cost of the implementation of the research works.

In accordance with the Public Law "On the natural environmental protection" and the Decree of the Government of Russia — N 638, of August 27, 1992, the Ministry for Environmental Protection and Natural Resources of the Russian Federation had legalized the research works included into the program. The fund should be transferred for the indicated purpose to the account of the Ministry specially opened for this purpose.

The relations of the Ministry for and the executors of the program projects will be on the basis of bilateral agreements for creation and transfer of scientific-technical products. During the negotiations on such agreements, the requirements for the research projects are formulated, the cost of the work is determined, questions concerning the rights for ownership for the scientific-technical products are addressed, and the responsibility of the parties for breaking the agreements are settled. This creates a strict legal basis for the relations of the parties and allows them to solve possible disputes legally.

The scientific-technical products created under the program projects can be used in the activity of the central body and institutions under the administration of the Ministry, or they can be passed to the interested bodies of the central power and administration, institutions, and enterprises, according to the conditions defined the agreements.

The Supreme Soviet and the RF Government allocated for the implementation of the first stage of the program (1993) 6.87 billion rubles.

The program includes applied (609 projects) and basic-methodological (32 projects) studies.

The sub-program of applied studies includes the following areas:

1. Strategic problems of the ecological safety provision in the current economic state of Russia (8 sections; 149 projects).
2. Factors of ecological danger and risk (5 sections; 55 projects).
3. Medical-sanitary-hygienic provisions of the human ecological safety (6 sections; 47 projects).
4. Recreation territories and human ecological prosperity (3 sections; 13 projects).
5. Ecological monitoring. Ecological mapping. Information provision for ecological safety (5 sections; 137 projects).
6. Regional problems of the ecological safety. Extreme ecological situations and disasters (10 sections; 75 projects).
7. Priority problems of global ecological safety for Russia (5 sections; 48 projects).
8. Problems of ecological safety of industry energetics, transport and communal economy (7 sections; 122 projects).
9. Ecological problems of agricultural production (6 sections; 28 projects).
10. Rational use and renewal of natural resources (4 sections; 85 projects).
11. Preservation of bio-variety and protection of natural ecosystems (3 sections; 53 projects).
12. Ecological education. Ecological viewpoint. Ecological problems of the cultural-historical centers (8 sections; 36 projects).

All topics of this sub-program are made up on the basis of the proposals of the potential users of the research results.

The sub-program of basic-methodological studies includes the following areas:

1. The theory of functioning and regeneration of natural ecosystems (7 projects).
2. Analysis of the ecological consequences of the predicted social, political, economic and technical development of Russia (8 projects).
3. Scientific bases of nature use, protection and renewal of natural resources (10 projects).
4. Methodological aspects, ecological risk problems (7 projects).

The topics of the sub-program of basic-methodological studies are based on the proposals of the institutes and leading scientists of the country, the producers of scientific-technical products.

Various sections of the program include 20 projects, directly aimed at the solution of the ecological problems of the Arctic and the North. The studies under these projects will be presented as the following set of scientifically sound results:

- Controlled parameters of the ecological monitoring of natural complexes and ecosystems;
- Assessment criteria and methods, as well as series of the assessments themselves of the state of natural complexes, terrestrial and water ecosystems and permissible limits of the anthropogenic loads on them;
- Ecological requirements to the economic activity in the Arctic region;
- Programs to renew the traditional forms of nature use by indigenous peoples and recommendations for flora and fauna conservation.

Some projects are aimed for obtaining estimates of radioecological situation at the territory of the Novaya Zemlya archipelago and adjacent areas of the Barents and Kara seas, development of improvement recommendations, an assessment of the ecological situation at the Northern Sea Route (by available data), and development of the program of necessary ecological expeditions.

The program "Ecological Safety of Russia" includes the projects corresponding to all sections of the "Strategy for Arctic Environmental Protection," adopted in 1991 by the representatives of the governments of eight Arctic countries.

At present the evolution of the program of 1993 is being completed on the basis of expert estimates and competitive consideration of the applications, with the total number of applied projects exceeding 2000.

Federal (Economic) Ecological Programs to be Implemented

The first state implementation ecological program was made on the interagency basis under the guidance of the USSR Ministry of Nature in 1991. It envisaged a system of practical measures in various regions of the country and economy branches, aimed to improve the ecological situation in stages up to 2005. The program was published for general public discussion and was coordinated with the nature protection bodies of the USSR republics. The disintegration of former USSR and social-economic reforms, however, prevented its fulfillment.

The Ministry of Russia pays a great deal of attention to the practical measures for the improvement of the ecological situation. However, the destructive tendencies of the administration-territorial units toward sovereignty break traditional economic relations. General production recession and new economic (market) rela-

tions have presented a considerable obstacle to the solution of ecological problems, often making them of second priority among the present-day problems.

The Ministry prepared the list of priority ecological programs and sent it to the government:

1. Protection and renewal of the variety of species of flora and fauna, conservation of the biota resources.
2. Forest renewal and forest production increase, extended reproduction of forest resources.
3. Wastes.
4. Rational use of water resources and water quality renewal.
5. Conversion to ecology.
6. Participation of Russia in the ecological situation improvement in the basins of international seas.
7. Production of ozone-safe freon and provision of the fulfillment of the international obligations of the RF on the ozone layer protection.
8. Protection and rational use of natural resources of the Russian Arctic.

The funds to develop and to implement these programs have not yet been allocated. The program "Ecological Safety of Russia" envisages the project titled "To develop the draft Federal Ecological Program."

In the framework of this project it is proposed to develop the listed implementation programs as mutually coordinated parts (sub-programs) of a unique state program implemented on the basis of new economic principles (payment for services, discharges and emissions of pollutants, penalties for accident situations, etc.).

Regional Ecological Programs

In 1990-1991, more than 70 ecological programs were developed, for all regions of the RF, which examined specific nature protection measures. Part of the programs are now in the implementation stage.

As requested by the Supreme Soviet and the Government, eight more programs are planned. They will address the issues of industrial ecology for the regions and industrial complexes of the Urals, Mordovia, Western Siberia, Tyumen, and Amur regions.

The program "Improvement of the ecological situation and increase of the resource and economic potential of the Volga basin (Renewal of Volga)" is being prepared.

The government has also approved the development (but not funding) of the Comprehensive Program for provision of protection and rational use of the natural resources of the Baikal Lake Basin.

The development of some federal-regional programs is planned under the program "Ecological Safety of Russia" (1993). For example:

- Renewal of small Russian rivers ("Small rivers of Russia");
- Provision of the ecological safety of rivers, lakes and seas of Russia ("Clean" waters of Russia);
- Prevention of pollution and degradation of the soil cover of Russia ("Renewal of the soils of Russia");
- Renewal and reproduction of the fauna and flora of Russia.

The same program envisages the development of a system of measures to improve the ecological situation in various regions of Russia, including the industrial regions of the North and the Arctic.

Branch Ecological Programs

Some Ministries and Agencies of Russia have their own branch programs, which contain to various extents, ecological, hydrometeorological, and nature protection projects, as well as programs for the Arctic and northern regions. For example, Rosgidromet supervises the implementation of the task scientific-technical program "Studies of the Arctic and the Antarctic, hydrometeorological regime of the World Ocean and the seas of Russia." Another example of agency programs is the ecological studies conducted for the development of a system of trunk gas lines in Yamal-West. These programs have, however, a serious shortcoming. They a priori (deliberately or indeliberately) have to serve the interest of the agency. That is why the RF Public Law "On the natural environment protection" required obligatory state ecological examinations before providing financing and implementation of the works on all projects and programs. The administration of the Ministry for Nature and of the Ministry for Science of Russia in February, 1993, adopted the "Provisions for the ecological examination and registration of Federal Scientific-Technical Programs and projects of ecological direction."

The aim of the ecological examination of programs and projects of ecological direction that are submitted for approval to the Ministry of Nature of Russia is to consider whether they meet the requirements of the RF Public Law "On the natural environment protection," its sublaw acts, international agreements in the field of environmental protection and use of natural resources, as well as to test them for compliance with the ecological safety.

Ecological Public Organizations and Their Activities

Non-federal programs of ecological studies and nature protection measures are being fulfilled under the activities of many public organizations. Traditionally, these organizations were united by the All Russia Nature Protection Society established in 1924. This orga-

nization had many active members and a rather complex structure including branches at all levels: in the republics, regions, towns, districts and even at big enterprises. Their efforts were most active in educational institution with ecological classes, "Green patrols," "Blue patrols," and programs for cleaning and planting in the territories.

After 1985, on the wave of perestroika (rebuilding), glasnost (openness), and democracy, the volume of negative ecological information sharply increased. The tensions present in the ecological situation under these new conditions resulted in the explosion of emotions, enthusiasm, and energy. In various regions of Russia, first in areas with the most acute ecological problems, new informal ecological organizations and groups appeared. These were not part of the structure of the traditional Society of Nature Protection.

Almost all the non-governmental ecological organizations and groups active today appeared in 1987-1989. Most ecologists who are members of the informal structures are also members of the Social-Ecological Union with the Central Board in Moscow. In March 1992, the Social-Ecological Union together with the American Ecological Organization started the publication of the ecological journal "In the other hand" in English.

In October 1991, the first issue of the first international ecological journal "Econord," was published, in cooperation between High People School Svaivik (Norway), High People School Malmfelten (Sweden), and Kola regional ecological information center. "Econord" also receives economic support from the Ministry of Environment of Norway.

According to this journal, in mid 1990, there were 127 ecological organizations in the northwest of Russia. With the efforts to mitigate or at least stop the most acute local ecological problems, and in some cases due to the loss of members' belief in a favorable outcome, membership in the Greenpeace movement decreased. In many regions, the number of informal ecological organizations declined. For example, in only the northwest of Russia from 1990-1992, 36 such organizations were dissolved. This mainly seems to be due to the fact that the basis of "ideologies" of these organizations was to protest, with a very small number wishing to contribute to constructive decisions. The decrease of activity of Greenpeace was also a result of the political struggle which caused political speculations.

Lack of professionals is an evident weakness of Greenpeace. There is mutual suspicion of Greenpeace and specialists left from the "old" times, when one not only disregarded the warning of specialists, but used them as a screen for practically non-controlled activity in the ecologically vulnerable northern regions.

The activity of Greenpeace is quite important in the regions where ecological problems have an international resonance (Kola peninsular, the Barents, Kara, White seas, Chernobyl, Ladoga, etc.). For example, in Murmansk, from 1990 to 1992 the number of informal ecological organizations increased from 15 to 24. Strengthening the relations between the specialists and informal organizations produced a large positive effect and specific results. Many publications can serve as an example: journals "Severnyie prostory," "Econord," "Atom without the 'classified' mark - viewpoints (Moscow-Berlin, 1992)," etc.

Among the most known unofficial ecological organizations one can list the following (by territories from the northwest to the northeast):

1. Kola peninsula. The Murmansk city public-political club "civil initiative" carried out in 1988-1989 a number of open hearings and round table discussions on the state of the ecology of the Kola peninsula. At the same time separate ecological groups were acting; e.g. "Kola" in Kola town, "Econord" in Apatity and "Green path" in Murmansk. In 1989-1990 "ecologists" from Murmansk established contacts with other countries. The first place was given to antinuclear problems in joint actions. On April 1, 1992, the Murmansk Ecological Center was opened. The main function of the Center is to obtain information and send it to the environmental protection organizations. The two largest newspapers of Murmansk publish weekly the ecological materials prepared by the Center. The most active members in the towns of Nickel, Zapolyarny, Murmansk and Apatity provide measures for spread of the ecological information and for education.
2. Arkhangelsk. The ecological group at the Pomorsk State University and the association "Ecology of the North."
3. St. Petersburg. By mid 1990 there were 65 ecological groups; the most known are: "Delta," "Rescue," "Let us save the world and the nature," "Greenpeace" of St. Petersburg, Izhorskoye Greenpeace, "Six section" group (Kirishi), association "Green World" in Sosnovy Bor, etc.
4. Karelia. The association "Nature" (Petrozavodsk, Medvezhiegorsk, the Committee "Ecology and Life" of the People's front of Karelia, the Republican "Association of Greenpeace of Karelia."
5. Komi Republic. A conventional committee for saving the Pechora River, the fund "For taiga saving," the "Social-Ecologic Club."
6. Novgorod. The city club "Ecology."
7. Cherepovets. The city ecological club.
8. Pskov. The city movement of Greenpeace.

9. Yamal peninsular. The association "Yamal to descendants."
10. Yakutsk. In 1991, the Public Committee for the protection of the Lena River Basin was formed. Its objectives are to clarify the ecological state of the Lena Basin, to invite wide public to the development of necessary nature protection measures, inter-regional coordination of actions.

There are no data on the existence of public organizations at Chukotka.

Many informal organizations have much in common:

1. Most of them do not enjoy numerous membership; however all practically have unofficial supporters whose number can exceed several times the number of the members of the organization.
2. Almost all ecological organizations aim to register officially, which gives them a possibility to conduct political work, obtain information from the authorities, and have accounts in the banks, etc.
3. Practically all ecological organizations are in difficult financial conditions and are devoid of the possibility to conducting research programs. Their efforts are mainly directed to organize public actions.
4. The All-Russia Nature Protection Society considers as its main goal to introduce knowledge in the area of ecology to form "the correct public opinion" and to increase social control for the state of the ecological situation. New ecological groups are addressing the more specific tasks related to their own regions.
5. Some "informal ecologists" publish their own newspapers and journals so that they can influence public opinion.
6. The leaders of the majority of the ecological organizations look into the future with optimism believing that the membership of these organizations will by all means be increasing though not very rapidly.
7. Some organizations are oriented to the protection of indigenous peoples and their habitat, to addressing the problem of traditional uses of nature in the present conditions, and the use of traditional skills of indigenous and local people in the protection of the environment. Activity of these organizations is predominately aimed to solve the problems of

nature use in northern regions. Sometimes this sharpens social and ethnic aspects of the problem on the whole.

Conclusion

In recent years (mainly since 1989-1990) there is an increasing movement in Russia aimed at the solution of ecological problems. Both public organizations and a system of state nature protection bodies headed by the Ministry for Environmental Protection and Natural Resources of the Russian Federation are participating in this movement.

The Ministry carries out a wide range of ecological studies. The results of these studies serve as a basis for the programs of practical importance, aimed at the solution of the present day problems of protection and improvement of the environment and the rational use of natural resources in various regions of the country (including the Arctic and the North).

The public ecological movement has many specific achievements (closure or substantial change of the ecologically dangerous enterprises, formation of reserves, natural memorials, distribution of the previously inaccessible ecological data, etc.). However a constructive solution of ecological problems at all levels can be provided only by the state system on the bases of a corresponding system for provision of the ecological safety and nature use management in the new public-economical situation.

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Assessment of the Ecological State of the West-Arctic Shelf by Benthos

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Methods, objects and registration characteristics choice for the process of organizing and conducting monitoring in the Arctic and subarctic regions is a basic problem which must be seriously worked up by highly skilled experts. In our work, we are ruled by the following considerations. Chemical and physical methods of analysis in the monitoring procedure can detect only the presence of technogenic force in the environments, but not their biological effects. This can not be accepted with satisfaction. Only biological methods are able to assess the consequences of the pollution in terms of ecosystem disturbances and because of that they must be paid a special attention.

As objects of marine ecosystems biomonitoring, organisms of neuston, plankton, nekton and benthos can be used. The latter group must be considered as the preferable one because it possesses an important advantage as compared with the others: benthos is mostly stable temporally, it is characterizing the local situation spatially, it is able to reflect the ecosystems changes in retrospective for a long period of time. But benthos characteristics can be investigated on different levels of system organization: suborganism, organism, population-species and community. Nowadays the opinion about the high capacity of population-species and community levels in presenting the information about environments quality integrally, taking into account cumulative effect of all forms of anthropogenic impacts and in all combinations of abiotic factors, becomes more and more popular among specialists. These two levels correspond to what is called an ecological monitoring.

Structural and functional characteristics may be used as indices of population and community state. The latter ones suffer from grave shortcomings: they are not spe-

cies specific; in quite different situations their value may be the same and frequently they do not reveal regular changes along the anthropogenic factors gradients. Structural indices, especially presented in the form of "absolute" ones (composition, ratio of organisms with different characteristics, etc.) must be regarded as more valuable, at least, in the nature conservation aspect. These considerations were taken into account for the implementation of the biological program conducted on the geoecological expeditions, organized by Association for Marine Geological Research and Exploration "SEV-MORGEOLOGIA" (SMG) in the north European seas.

The principal goal of the expedition work was to study the physico-chemical and biological characteristics of the west-arctic shelf near-bottom water, bottom sediments and benthos organisms. Material was recovered aboard the R/V *Akaddemik Karpinski* and the R/V *Geolog Fersman* in 1991-1992, at depths of 12 to 1540 meters in the White, Barents, and Kara Seas, the Sea of Norway, and the Greenland Sea. At geoecological stations a complex set of investigations, including hydrological, geological and biological sampling, underwater photography, and TV-observations were made. For the assessment of the environment and biota contamination, specimens of bottom sediments and benthos mass-species organisms were collected for analysis. Concentrations of heavy metals, persistent organics, oil products and radionuclides were collected from the material. Investigations were conducted by scientists from All-Russia Research Institute for Geology and Mineral Resources of the World Ocean "VNIIOKEANGEOLGIA," Arctic and Antarctic Research Institute (AARI), Northern Branch of the Institute for Nature Conservation and Reserves (VNII Priroda), other Russian agencies involved in systematic Arctic research, and some special-

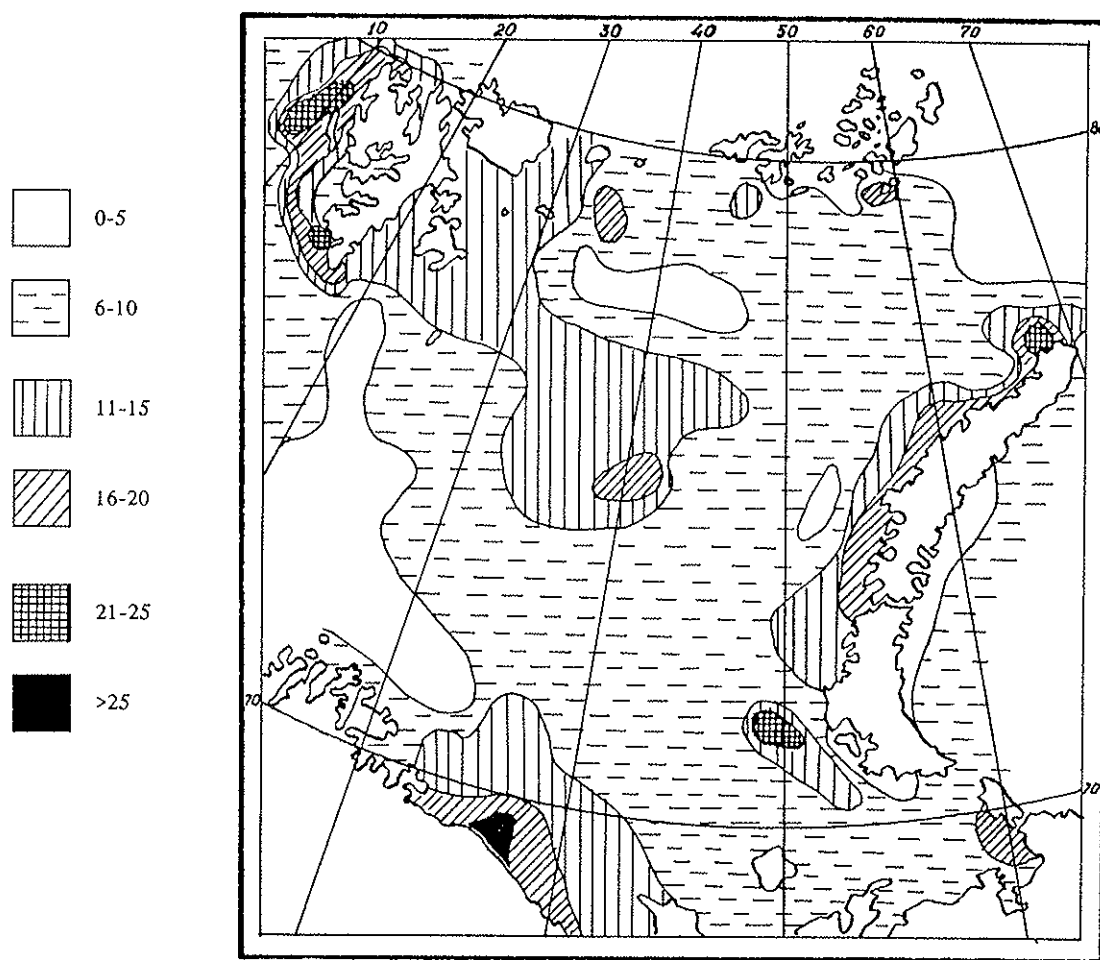


Figure 1. Benthos specific diversity of the Barents Sea shelf based on the investigations during 1991-1992 (number of species per quantitative sample).

ists from Norway and Canada. Complete analysis of the obtained information is supposed to be finished by the end of 1993. The preliminary results of the biological research program are discussed in this paper.

During the two expedition seasons, more than 150 full quantitative benthos samples were obtained by OKEAN grab (it covers an area of 0.25 m^2). More than 170 qualitative benthos samples were also obtained by means of Sigsbi trawl and standard dredge. More than 3000 underwater photographs were analyzed. For mass benthos species length/weight structural research was conducted with more than 2500 individuals being measured and weighed. In the analysis of contaminant concentrations in benthos organisms, more than 400 specimens were collected. At present systematic treatment of biological samples has ended, univariate benthos classifications according the traditional hydrobiological methods are also complete. Structural changes among the bottom inhabitants of the Barents Sea during the last 60-70 years are being investigated statistically.

For the study area, the bottom-communities compo-

sition includes more than 300 species of invertebrates and algae (correctness of identification is adjusted by the leading specialists of Zoological and Botanical Institutes of Russian Academy of Sciences). The per station distribution of species diversity was heterogeneous and reflected the environments formed in concrete marine regions (Figure 1). Sample value of species diversity varied in intervals from 0 up to 28 species per single quantitative unit. Benthos biomass changed from 0 up to 12 kg/m^2 , and its distribution as a whole corresponded to the natural (undisturbed) regularities (Figure 2). Significant differences in bottom inhabitants composition and structure were revealed in comparison of our results with the results obtained by scientific workers of the Oceanographic Institute (Academy of Sciences, Moscow) in 1920-1930s (Brotskaya and Zenkevich, 1939). Some of these differences could be interpreted by the differences in the approaches to the material presentation. In particular, a rather large number of communities, singled out in our work on the same shelf area, probably are connected with a more formal-

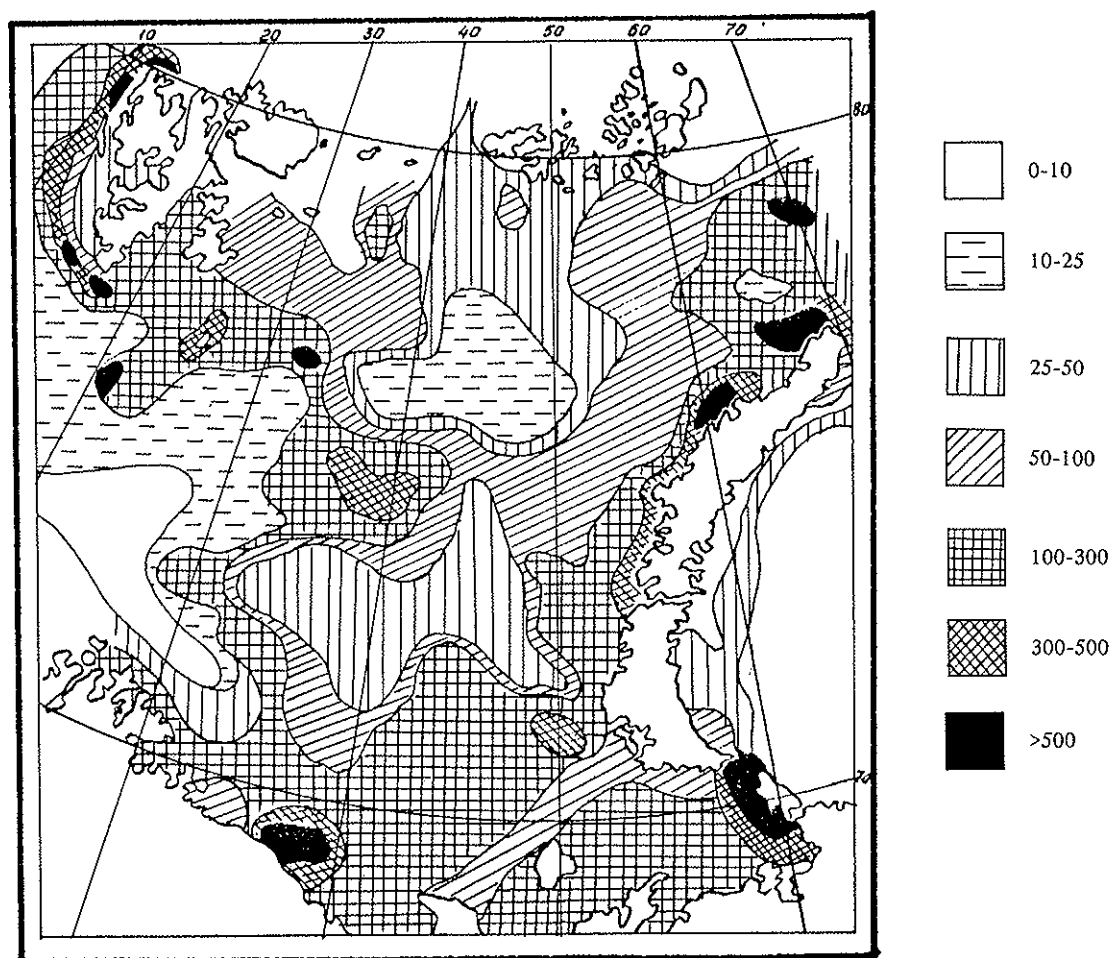


Figure 2. Distribution of benthic biomass of the Barents Sea shelf based on the investigations performed during 1991-1992 (g/m^2).

istic conforming to the dominant principle which was the base of classification (Figure 3). At the same time, some species, which were abundant 60 to 70 years ago, were not found in our survey at all (i.e. *Waldheimia cranium*). Qualitative benthos changes during this period were examined in a classical ANOVA (Table 1).

Table 1 shows that Polychaeta biomass significantly decreased all over the Barents Sea. Spinculoidea + Priapulioidea as well as Echinodermata biomass and/or relative abundance had changed locally, in distinct sea regions. The causes of this changes must be analyzed more completely (on the species level), which is supposed to be done in future. The same observation is true for the trophic zones map of the west-arctic shelf, worked out in our investigation (Figure 4). It differs from the ones offered earlier by Kuznetsov (1980).

Some benthos mass-species populations show structural changes, engendered by natural causes and are connected with increasing of the environment's "arcticness." These have been seen on the Svalbard shelf for *Strongylocentrotus droebachiensis*, *Nicania montagui*,

Table 1. Force of latitude (A), longitude (B), temporal factor (C) and their interactions (AB, AC, BC) on the absolute and relative biomass value of the main macrobenthos groups of the Barents Sea according the results of three-way analysis of variance.

Object	Level of significance P (%)					
	A	B	C	AB	AC	BC
Spongia	N/5	5/0.1	N/N	5/0.1	N/N	N/N
Coelenterata	N/N	N/N	N/N	N/N	N/N	N/N
Nemertini	N/N	N/N	N/N	N/N	N/N	N/N
Polychaeta	1/N	N/N	1/N	N/N	N/N	N/N
Spinculoidea + Priapulioidea	N/N	N/N	N/N	N/N	5/N	N/N
Bryozoa	N/N	N/N	N/N	N/N	N/N	N/N
Brachiopoda	N/N	N/N	N/N	1/1	N/N	N/N
Gastropoda	N/5	N/N	N/N	N/N	N/N	N/N
Bivalvia	N/5	N/5	N/N	N/5	N/N	N/N
Crustacea	N/N	N/N	N/N	N/N	N/N	N/N
Echinodermata	5/1	N/5	N/N	N/N	5/5	N/N
Tunicata	N/N	N/N	N/N	N/N	N/N	N/N
Total biomass	N	N	N	N	N	N

Upper row—biomass, lower row—roups quota in total biomass.
N—non-significant for the chosen level of significance ($P > 5\%$).

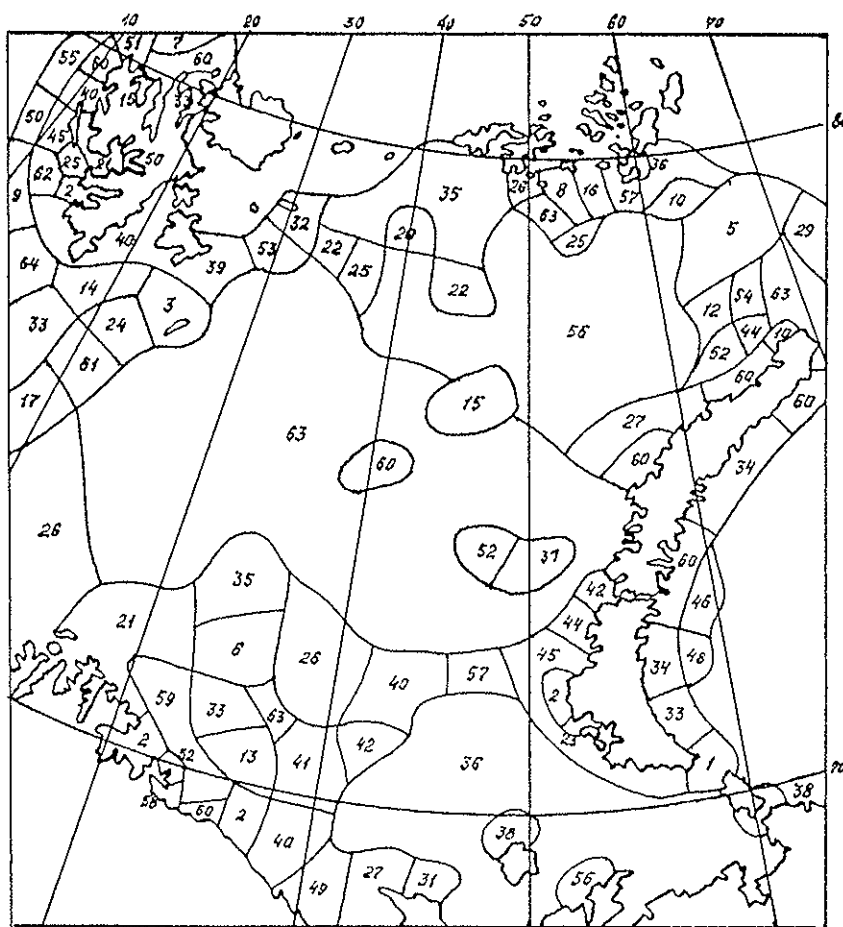


Figure 3. Biocenoses of the Barents Sea shelf formed on the dominance principle on the basis of the investigations performed during 1991-1992 (numeration on systematic principle).

Elliptica elliptica, and manifested in the decreasing size of the individuals in the populations. This was seen in locations from the 76 to 80°N and from a depth of 20-30 m to a depth of 200 m. Statistically significant natural differences in the growth of the bivalves, *Hiatella arctica*, near the Franz Joseph Land and Novaya Zemlya Archipelago were also discovered. In the first region the same length organisms were in 1.5-2 times more massive than in the second one.

Considerable disturbances of the initial benthos structure (in comparison with the biological "norm" for environments under investigation) were registered only in rare cases mostly not far from the coast of Murman and Novaya Zemlya (Kola Inlet, settlement Belushka and some others). These disturbances were expressed in the bottom organisms species diversity and biomass decrease. At present, mathematical multivariate data analysis is being carrying out. The results of work will be presented in a form of maps, constructed by means of

polythetical numerical classification fulfilled on base of different signs. Explaining tables for these maps will characterize natural and disturbed benthos state in different environments. Besides that, dependence of the most informative biota indices from the main abiotic factors (including the anthropogenic ones) is supposed to be described in a form of prognostic models. Their calculation will be drawn according with Group Method of Data Handling (GMDH), which is based on the self-organizing principle.

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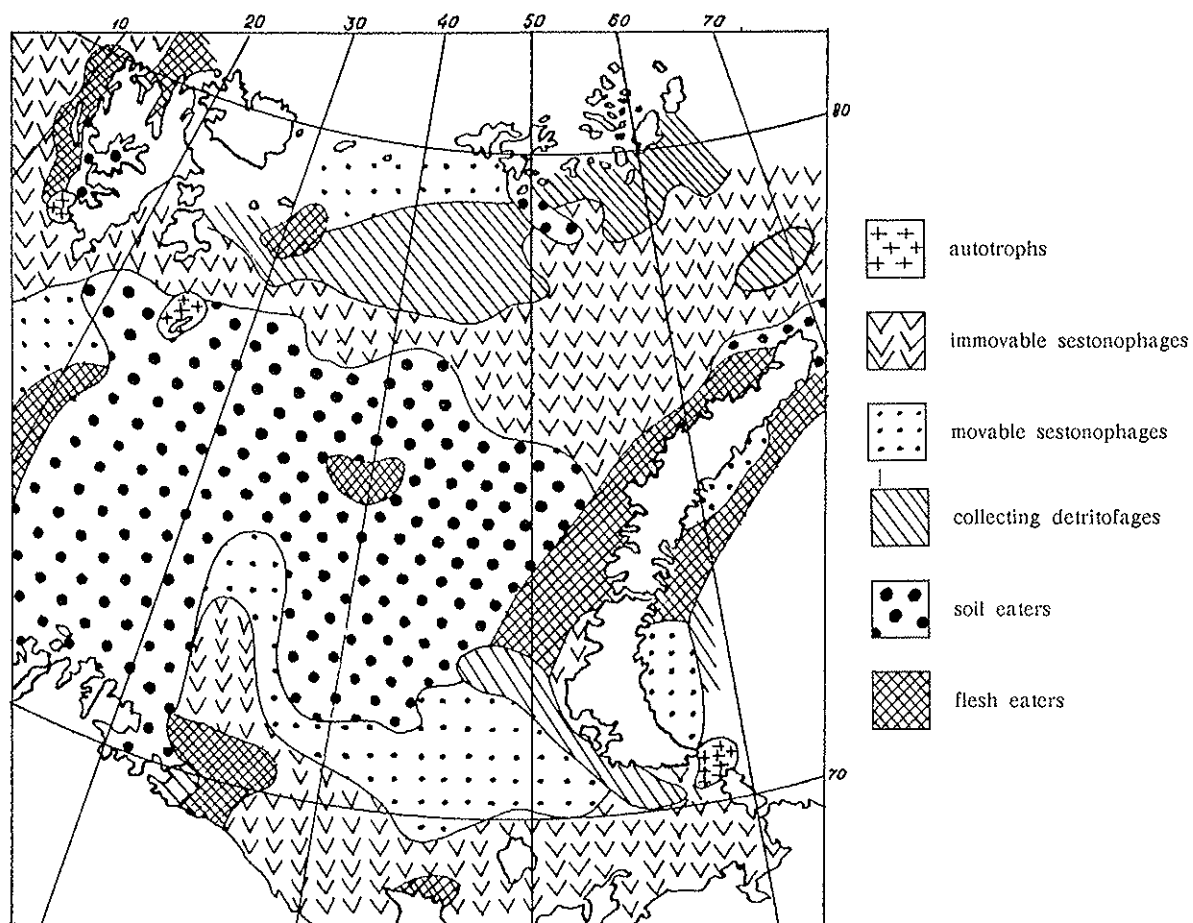


Figure 4. Trophic zones of the Barents Sea shelf formed on the dominance principle on the basis of the investigations performed during 1991-1992.

Studying Water, Sediment and Contaminant Runoff of Siberian Rivers

Modern Status and Prospects

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Introduction

The natural environment of the Arctic is greatly influenced by river and sediment runoff, as well as by different contaminants both natural and man-made, inflowing with river water into the entire catchment basin of the Arctic Ocean. Out of the total volume of river runoff (5140 km^3 per year) incoming to the ocean, the rivers of Russia discharge 56%, or 2890 km^3 /year. Annually hundreds of millions of tons of suspended sediments and dissolved salts are transported to the ocean, the greatest portion from the Siberian rivers.

In the last few decades, along with the runoff of water, sediment and natural ions, the Arctic began to be loaded with enormous amounts of contaminants because of intense activities of man in the river catchments. This has taken place in all countries located in river basins of the Arctic Ocean, especially in Russia with its 70% of river runoff incoming to the Arctic. In the territory of Russia, the basins of such Siberian rivers as the Ob and Yenisey were being intensely developed because of the rich mineral resources, oil fields, and gas deposits that were discovered, but also as a result of the large industrial centers built in the region, as well as the intense shipping lanes created there.

Studying the dynamics and qualitative composition of the contaminants incoming to the Arctic regions with the river runoff is of great importance for monitoring and protecting the Arctic environment and improving Arctic Ocean water quality.

Water and Sediment Runoff

The stationary network of hydrological stations of the Russian Federal Service for Hydrometeorology and Monitoring of the Natural Environment (Roshydromet) is the major source of initial data for studying water and sediment runoff. The water level and runoff of Siberian rivers in the lower reaches are being studied at 63 level

and 35 runoff observational stations, which is obviously insufficient for so large territory. Location of major stations is shown in a diagram (Figure 1). Table 1 gives major characteristics of runoff of 13 large and mid-sized Siberian rivers at the lowest gauging sites. On a number of rivers these sites are located at a distance of 300-600 km from the mouth. Catchments of the indicated rivers cover 83% of the entire Asian catchment area of the Arctic Ocean and on the whole they characterize well enough the regime of surface water income to the ocean. Total annual runoff of the above rivers is about 1800 km^3 , its year-to-year variability being insignificant. (The variation coefficient of the Yenisey runoff is $C_v = 0.08$, for the Lena it is 0.10, and for the Ob, 0.17).

Intrayear runoff distribution for Siberian rivers is rather homogeneous; minimum discharges are observed in winter period when even some large rivers are able to be fully frozen. During spring flood, May until July-August, about 60-75% of the annual discharge occurs (Table 2, Figure 2), with typical monthly discharge during one spring month being 30-40% of annual volume.

Until recently man's activities in the basins of Siberian rivers (construction of reservoirs, irrigation, industrial and public water consumption, etc.) slightly affected the annual discharge in the lower reaches. The greatest value of annual discharge decrease, due to anthropogenic factors, is characteristic of the Ob. It is about $18\text{-}20 \text{ km}^3$ /year, or 5% of annual runoff. As for the rest of large Siberian rivers, these values are within 1%. Insignificant are also man's effects on intrayear distribution of the inflow of Siberian rivers to the Arctic region. Even construction of the largest reservoirs in the upper reaches of Yenisey and in the basin of Angara, a tributary to Yenisey, slightly affected the intrayear runoff distribution in the lower reaches of the river.

The network of observational stations for suspended



- Symbols for kinds of observations:
- Water level
 - ◊ Level, water quality
 - ✦ Level, water quality, sediments
 - ▽ Level, water discharge
 - Level, water discharge, sediments
 - + Level, discharge, water quality
 - ✳ Level, discharge, water quality, sediments
 - water quality in places where stations are unavailable

Figure 1. Location of basin standard network of observation stations.

Table 1. Hydrological characteristics of Siberian rivers inflowing to the Arctic Ocean.

River - section	Drainage area (km ² × 10 ³)	Distance from mouth (km)	Onset of observation	Long-time ave. discharge c(m ³ /s)	Volume of runoff (km ³)	Low discharge (m ³ /s)	Maximum discharge (m ³ /s)
Ob - Salehard	2950	287	1930	12,600	397	2840	36,700
Pur - Samburg	95.1	86.0	1939	897	28.3	204	6,300
Taz - Sidorovsk	100	259	1962	1050	33.1	161	6,300
Nadim - Nadim	48	110	1955	458	14.4	12.5	4,710
Khatanga - Khatanga	275	217	1961	2,220	70.0	—	24,400
Yenisey - Igarka	2440	697	1967	18,100	571	3,910	131,000
Olenok - 7.5 km from mouth of Pur River	198	210	1964	1,020	32.2	1.1	15,800
Lena - Kyusyur	2430	211	1934	16,500	520	1,000	132,000
Anabar - Saskilah	78.8	209	1954	416	13.2	94.2	9,000
Yana - Jangkli	216	381	1938	929	29.2	0.37	8,270
Indigirka - Vorontsova	305	350	1936	1,590	50.2	6.52	7,550
Kolyma - Sredne -Kolymsk	361	641	1927	2,220	70.0	50.7	17,000
Anguzma - near bridge 174 km	26.4	121	1944	271	8.6	0	3,720

sediments is much more scarce than that for water runoff. In the lower reaches of the Russian rivers inflowing to the seas of the Arctic Ocean, observations of sediment runoff are being carried out at 23 sites, more than half of which are located in the north of the European part of Russia (see Figure 1). Observations of sediments are conducted by the standard technique developed at the State Hydrological Institute. The program of studies includes collecting single water samples for turbidity at a gauging site and time-to-time measurements of suspended sediment discharge with

simultaneous sampling to determine grading sediment composition. The runoff of suspended sediments is calculated by both turbidity measurement data on single samples, and by the diagrams of the relationships between discharges of suspended sediments and discharges of water.

Major runoff characteristics for suspended sediments of Siberian rivers in the lower reaches are presented in Table 3. Under the natural conditions in the lower reaches, the large Siberian plain rivers are characterized by turbidity within 12-50 g/m³. On rivers in

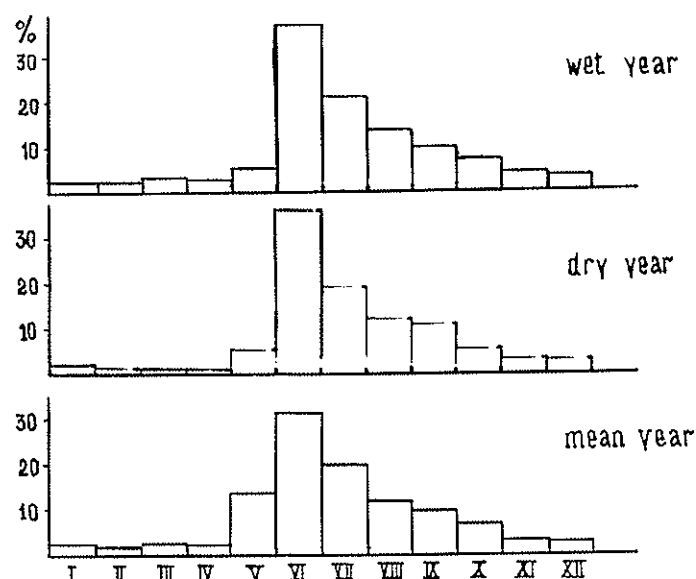


Figure 2. Total inflow of the Siberian rivers to the Arctic Ocean (percent per month) for years characteristic of water availability.

Table 2. Intra-year distribution of the Siberian rivers runoff inflowing to the Arctic Ocean in years average in water availability.

River - section	Monthly runoff distribution % of annual flow											
	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Ob - Salehard	3.1	2.5	2.2	2.2	9.8	21.6	19.5	15.2	9.5	6.9	4.0	3.5
Pur - Samburg	2.8	2.4	2.1	2.1	6.0	35.3	16.2	9.2	8.8	6.7	4.7	3.7
Taz - Sidorovsk	2.2	1.9	1.6	1.4	5.6	35.3	22.6	8.4	7.6	6.5	4.0	2.9
Nadim - Nadim	2.9	2.5	2.4	2.6	14.8	31.5	11.2	7.9	8.7	7.0	4.9	3.6
Yenisey - Igarka	3.3	3.5	3.5	3.4	9.5	38.9	11.7	7.4	7.4	5.9	2.9	2.6
Olenek - 7.5 km from mouth of Pur River	0.1	0.0	0.0	0.0	2.4	58.6	19.3	7.7	8.7	2.4	0.6	0.2
Lena - Kyusur	1.3	1.0	0.7	0.6	2.6	37.3	20.0	13.8	12.5	7.1	1.7	1.4
Anabar - Saskilah	0.0	0.0	0.0	0.0	1.1	63.8	16.5	10.2	6.4	1.4	0.5	0.1
Yana - Jangkli	0.0	0.0	0.0	0.0	5.6	33.4	27.2	21.0	10.9	1.5	0.3	0.1
Indigirka - Vorontsova	0.2	0.1	0.1	0.0	1.7	30.0	29.6	22.2	12.3	3.7	1.2	0.7
Kolyma - Sredne - Kolymsk	0.4	0.3	0.2	0.2	7.2	39.2	19.7	15.0	12.2	3.7	1.2	0.7
Anguzma - near bridge 174 km	0.0	0.0	0.0	0.0	1.4	44.0	26.2	17.2	8.7	1.9	0.5	0.1

Eastern Siberia with great slopes and current velocities the values of turbidity are more significant; in a number of basins they are distorted because of intense human activity in the river valleys related to gold mining. Preliminary estimates indicate that 50-60 million tons of suspended sediments annually come to the Arctic with the Siberian river runoff. Eighty to ninety percent occur in the spring flood. It should be mentioned that the cited values characterize, but not fully, the total inflow of sediments to the ocean, because they do not take into account the role of the Arctic zone itself. For instance, the studies made recently in the State Hydrological Institute on erosion and sediment runoff formation on slopes on the Yamal peninsula show that under the conditions of permafrost, developing thermokarst and intense anthropogenic load (when developing

oil-and-gas fields), there are areas with catastrophic erosion and sediment runoff amounting to 4000-8000 tons per hectare per year.

The Network of Observations of Water Quality

Monitoring of surface water quality in Russia is conducted by the administrative organs of Roshydromet at the network of steady observational stations. Observations are carried out according to complex programs including measurements of physical, chemical and hydrobiological indices. The network observations are based on the following principles: they should be complex and systematic; sampling has to agree with water regime phases; water quality indices are to be determined by the same methods at all stations.

In Siberian river basins, the observational network

Table 3. Mean annual turbidity and sediment runoff of rivers inflowing to the Arctic Ocean (within the catchments of the Kara, Laptev, and East Siberian Seas).

River - section	Drainage area (km ² × 10 ³)	Distance from mouth (km)	An average over the period of record			
			Onset of obs.	Sediment discharge (kg/s)	Turbidity (g/m ³)	Annual sediment (runoff, 10 ³ t)
Ob - Salehard	2953	312	1938	480	40	15,200
Pur - Samburg	95.1	86	1941	22	25	690
Yenisey - Igarka	2440	697	1941	220	12	6,900
Anabar - Saskilah	78.8	209	1967	12	29	380
Olenek - 7.5 km from the mouth of Pur	198	210	1971	38	41	1,200
Lena - 4.7 km from Stolo	2460	—	1958	350	29	11,000
Omoloï - Nami	10.8	—	1979	1.1	30	36
Yana - Yubileinaya	224	157	1973	110	116	3,500
Alazeya - Andryushkino	29	—	1979	3.1	77	98
Kolyma - Kolymsskoe I	526	—	1977	280	115	12,000
Polyavaam - 8 km from the mouth of the Glubokaya River	6.81	195	1972	2.0	48	54

Table 4. Number of stations for hydrochemical observations in the basins of rivers inflowing to the Arctic Ocean (the status for 1991).

River basin	Total number	Including major rivers
Ob	237	15
Yenisey	156	13
Lena	88	10
Pur2	2	
Taz	4	4
Anabar	1	1
Olenek	3	3
Omoloï	1	1
Yana	9	5
Indigirka	5	2
Alazeya	1	1
Kolyma	41	6

numbers approximately 550 constant observational stations. Table 4 shows their distribution over basins. The network density in the region in question is much lower than in the European part of Russia. It is 9-10 stations per 100 thousand km² in the Ob River basin and 1-4 in river basins in Eastern Siberia. At present, in the lower reaches of large Siberian rivers, there are 18 observational stations for water quality combined in the majority of cases with hydrological gauging sites. This allows the estimation of the dynamics of total contaminant income with river runoff to the Arctic zone.

The earliest hydrochemical observations in the lower reaches of Siberian rivers date from the 1930s. At approximately half of stations, observation were started in the 1940s-1950s; however the programs of water quality observations began to be conducted in full volume only since the last half of the 1970s.

Hydrochemical observations by the most full program envisage determining 30-50 indicators within four major groups of chemical substances:

1. Physical properties, major ions, dissolved gases: temperature, transparency, suspended substances, pH, oxygen, carbon dioxide, ion sum, hardness, Ca, Mg, Na, K, HCO₃, SO₄, Cl, Eh.
2. Natural and contaminating organic substances: color, chemical oxygen demand (COD), biochemical oxygen demand (BOD), phenols, petrol products, detergents.
3. Biogenic ingredients and inorganic contaminants: total nitrogen, nitrates, nitrites, ammonium, total phosphorus, phosphates, silicon, copper, nickel, cadmium, ferrum, zinc, chromium, lead, mercury, manganese, sulphides, cyanides, fluorine, iodine, cobalt.
4. Specific organic contaminants and pesticides: resins, asphaltens, pesticide dusts, hexachlorane, etc.

Frequency and composition of observations at each station depend on its category (four categories at all) established taking account of a number of factors: economic significance of water object, pollution, value as a natural object. Depending on the category of station the frequency of observations varies from a daily one to once a month or season. At lower parts of the large Siberian rivers, where stations of categories 3 and 4 are located, the frequency of sampling is 5 to 14 times per year. Samples are taken as a rule on three verticals at two or three levels at each.

Natural Quality of River Waters

Under the natural conditions the quality of river waters in Siberia is formed under the influence of

climate, soil and vegetation, geomorphological and geological structure. Excessive moistening of soil-ground thickness, low temperatures and widespread permafrost cause the formation of slightly mineralized river waters (50-200 mg/l) with hydrocarbonate ions and calcium ions. On all rivers, distinctly expressed intrayear variations are recorded in the concentration of dissolved substances due to the character of water income to the river system. In spring high-water period, there are minimum values of water mineralizing (within 30-100 mg/l). In winter low-water period, when river system is fed by ground waters, mineralizing reaches maximum values (150-400 mg/l). For rivers with intense discharge of head ground waters (e.g., Lena, Olenek), mineralizing increases in winter period up to 500 mg/l with increasing chloride and sodium ions in the ion composition.

The content of dissolved organic contaminants in river waters is characterized by indicators of color and chemical oxygen demand (COD) and changes considerably over the territory depending on the extent of catchment swamping. It is water humus content that has the most considerable effect on these indicators. In the spring period, the water color index is the greatest, with the most considerable color index pertaining to river waters formed in tundra zone. COD varies in spring within 10-60 mgQ/l and it is 2 to 3 times less in winter low-water period.

Acidity indicators in stream waters of large rivers are within the limits typical of neutral water reaction ($\text{pH} = 6.8-7.2$). However, in individual parts of hydrographic network, river waters can have an elevated acidity ($\text{pH} \leq 6.5$), because of a great role of swamp nutrition. As for the chemical content of biogenic substances, there are predominately compounds of nitrate nitrogen, silicon, and ferrum. Migration of the two last is carried out to a great extent in a colloidal state. The presence of mineral compounds of nitrogen and phosphorus in pure waters of Siberian rivers is associated mainly with biochemical destruction of natural organic substances as well as with falling atmospheric precipitation. Analysis of natural hydrochemical characteristics made at the State Hydrological Institute for river catchments in Siberia shows that the total amount of mineral compounds removed from one square kilometer of catchment area to the Arctic zones is within 14-19 tons per year; removal of dissolved organic substances makes up 2 to 6 tons from one square kilometer per year. It should be mentioned that natural geochemical migration of microelements with river runoff is studied but insufficiently because of the scarcity of full-scale observational data on Siberian rivers in the pre-industrial period. This information is available only for some river catchments.

The Dynamics of Contaminating Siberian Rivers

The intensity of man's activities in the territory of Siberia, especially beginning with the 1970s, caused considerable changes in the chemical composition of river waters. The levels of contamination depend on volumes and composition of chemical substances incoming to water bodies as well as on their self-purification ability. It should be mentioned that until now the pollution and self-purification processes, migration, accumulation, and transformation of chemical substances in water systems of Siberia have been studied, but insufficiently.

Major sources of man-made pollution of natural waters in the territory under consideration are the developed oil-and-gas fields, poly-metallic ores, petroleum, gas and petrochemical industries, metallurgic, machine-building industries as well as wood pulp and paper industry, etc. The intense development of large cities on river banks (Novosibirsk, Omsk, Irkutsk, Krasnoyarsk, Tomsk, Kemerovo, etc.) with populations of more than 0.5-1.0 million people has led to a considerable organic and biogenic substance loading of rivers incoming with waste waters, river transportation inserting a considerable contribution into water pollution of large rivers. One more source of polluting the river catchment area is dust-gas emissions into the atmosphere of contaminating substances from industrial enterprises as well as from burning casing-head gas on oil fields. High sorption ability of swampy soils and peat bogs widely distributed in Siberia promotes accumulating on catchments different contaminants, which creates the conditions for secondary pollution of river systems.

The materials of regular observations at the Roshydromet network show that at the majority of controlled objects, water quality does not correspond to the specification requirements imposed in Russia upon the economic and drinking water installations as well as fish industry. Criteria of estimating water pollution in the shape of the so-called admissible concentration limit (ACL) are given in Table 5. It should be mentioned that these norms developed for other conditions cannot be fully applicable to the ecosystems of Siberia, especially in its Arctic zone existing under the extreme conditions of unstable equilibrium.

The territorial unevenness of anthropogenic load on water objects and their different self-purification ability caused considerable differences in the extent of contamination of Siberian rivers. Figure 3 presents the modern level of water contamination by major indicators in the streams of the three major rivers of Siberia. These data do not refer to certain sites; they characterize mean annual concentrations over the length of main

Table 5. Criteria of estimating water contamination accepted in Russia.

<i>Ingredients and indicators</i>	<i>Limiting index of harmfulness</i>	<i>Admissible concentration limit (ACL) mg/l</i>
BOD full	common requirements	3.0
Nitrogen nitrate	toxicological	9.1
Nitrogen nitrite	toxicological	0.02
Nitrogen ammonium	toxicological	0.39
Oil products	fishing industry	0.05
Phenols	fishing industry	0.001
Copper compounds	toxicological	0.001
Zinc compounds	toxicological	0.01
Chrome six-valent compounds	sanitary-toxicological	0.001
Sulphate ions	sanitary-toxicological	100.0
Chloride ions	sanitary-toxicological	300.0
Mercury compounds	sanitary-toxicological	0.0005
Sulphades	general sanitary	absent

river channels. They are obtained by statistical processing of water samples observed over a year at all observational stations on the main stream from river-head to mouth. As seen in Figure 3, the Ob River is to be considered as most contaminated. In its basin, large industrial centers of Siberia are concentrated. In addition, the river channel accepts a portion of sewage from the industrial Urals. Stream waters of Yenisey are very contaminated; however, this is much less for the Lena River. It could be also mentioned that, as a whole, in the last few years (since the late 1980s to the early 1990s), there is some stabilization of the contaminated major Siberian water courses in question. Unfortunately, this

stabilization is reached at a high level of contamination: for example, on the three rivers mean annual concentrations of petroleum products, phenols and copper are 2-5 ACL (admissible concentration limit).

The calculations made at the State Hydrological Institute show that a relative duration of the runoff period for river waters contaminated with phenols, petroleum products, and copper ions recorded at a number of sites of river systems in question amounts to 60-90%. This indicates that contamination is distributed over the greater part of annual volumes of river runoff.

Because of the large length of major water systems of Siberia, contamination levels at individual river sites

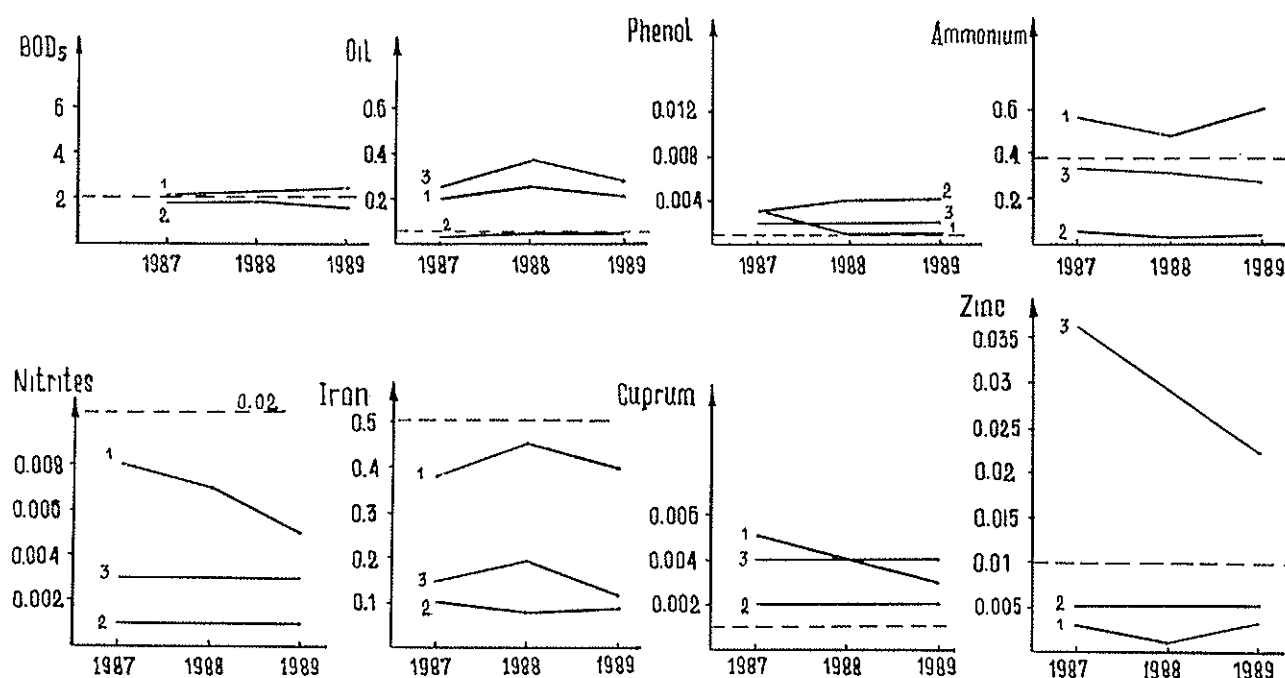


Figure 3. Modern contamination level of stream waters of major Siberian rivers (mg/l); 1—Ob, 2—Lena, 3—Yenisey.

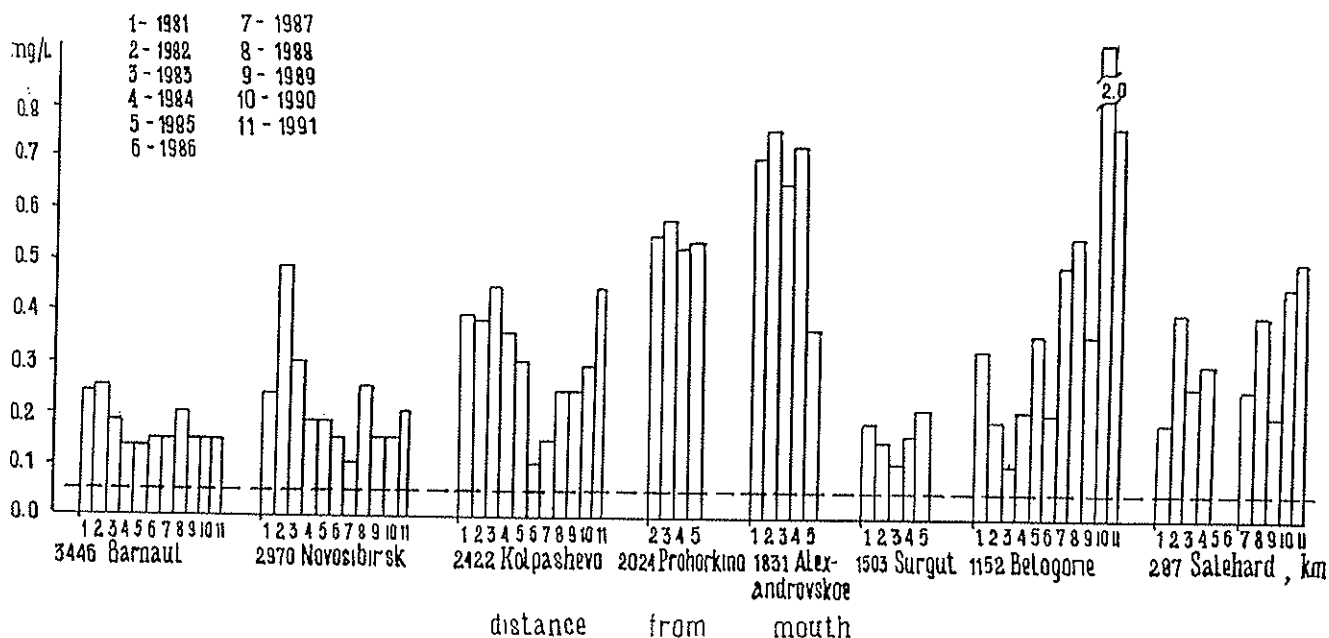


Figure 4. Changes in mean annual oil-product concentrations over the length of the Ob River for years 1981-1991.

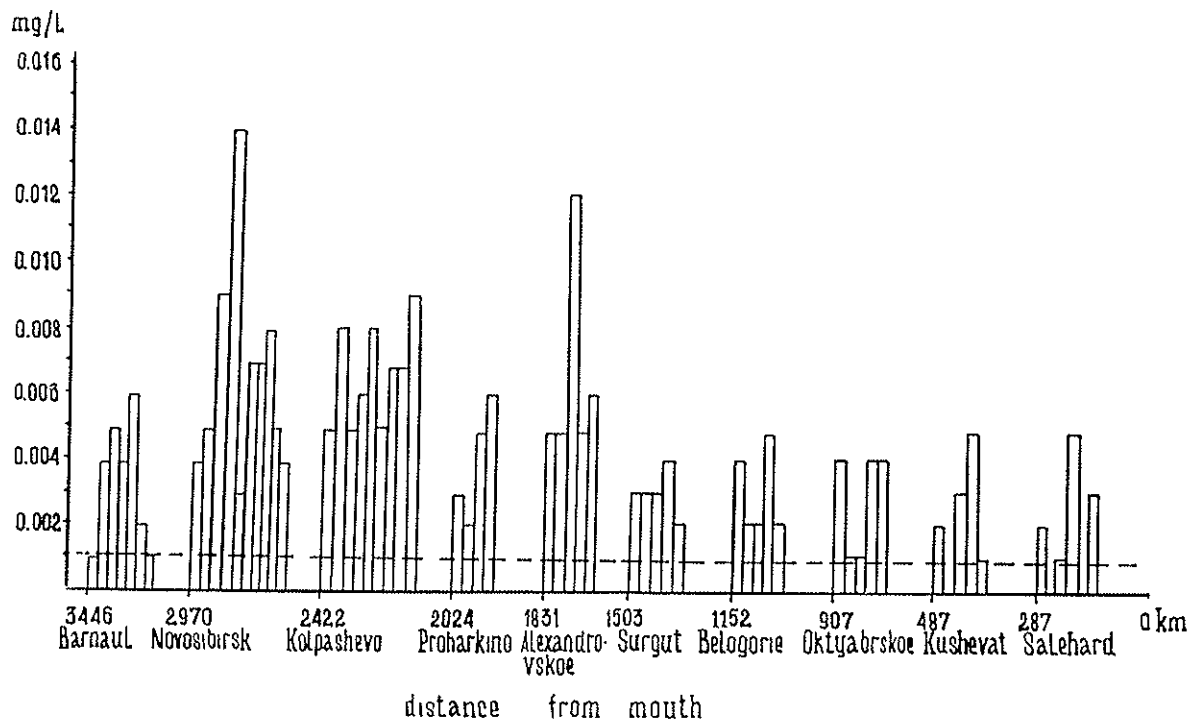


Figure 5. Changes in mean annual phenol concentrations over the length of the Ob River for year 1981-1990.

are far from being equal. Changes in the mean annual concentrations of petroleum products and phenols over the length of Ob for the last decades are shown in Figures 4 and 5. Differences in concentrations are quite stable over the entire long-term period in question. Extremely high levels for oil pollution of Ob (above 10 ACL, Figure 4) are characteristic of the middle and the lower reaches of the river (Alexandrovskoye, Belogor-

ye), which is, primarily, due to intense oil production. In the mouth zone (Salekhard), due to self-purification and dilution processes, the level of oil contamination is being considerably lowered. Maximum phenol contamination (up to 12-14 ACL) is observed near Novosibirsk where chemical enterprises are located. Down stream of the river, the content of phenol is lowering by 2 or 3 times (Figure 5). Comparison of annual contamination

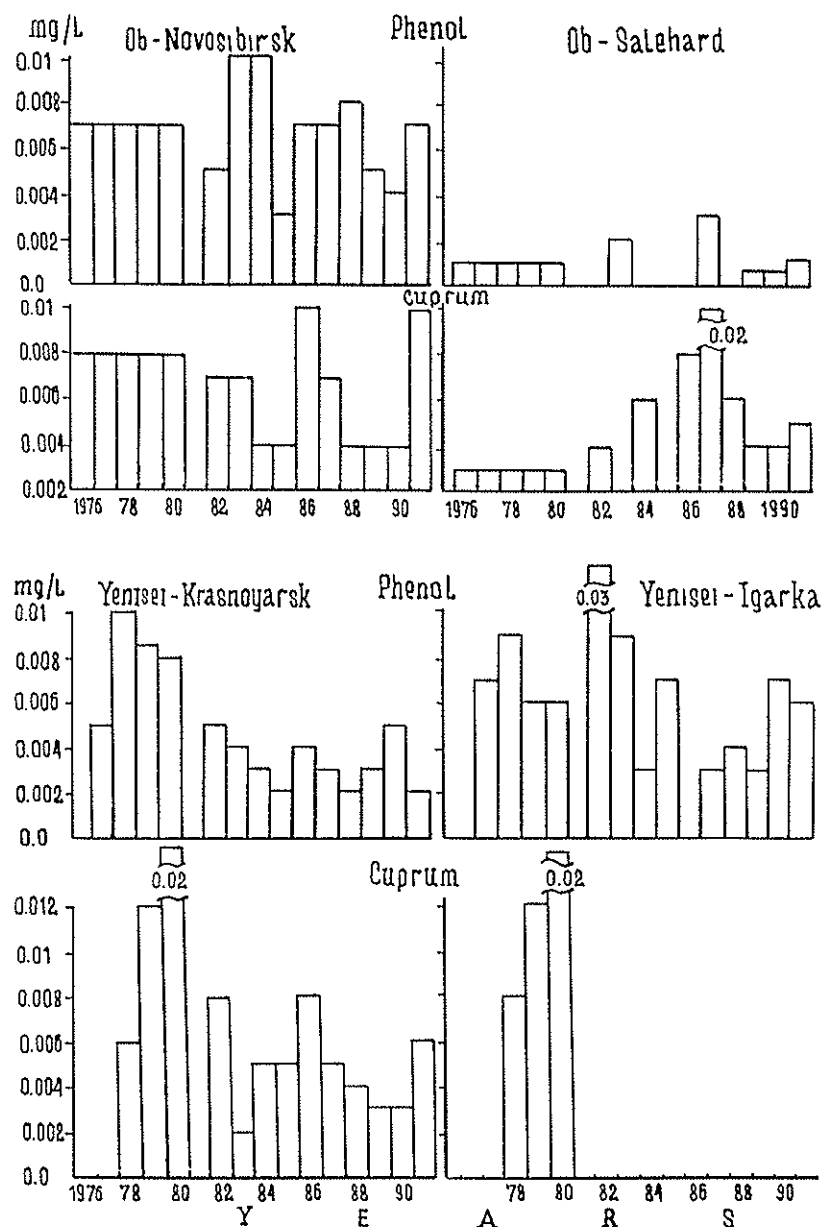


Figure 6. Dynamics of the Ob and Yenisey Rivers contamination for years 1976-1991.

values for phenol and copper over 1978-1991 for Ob and Yenisey at the upper and lower sites shows considerable differences in changing concentrations at the length of indicated rivers (Figure 6). For the Ob River, phenol and copper concentrations drastically decrease from the upper reaches to the mouth. In the channel of Yenisey this does not take place: the concentrations in the lower reaches even somewhat increase. This seems to be due to industrial sewage discharge into the river below Krasnoyarsk.

Successive lowering of the phenol and copper contamination extent of Yenisey near Krasnoyarsk can be considered as the response of water system to the envi-

ronment protection measures taken in this region. Nevertheless, at almost all observational stations on the Ob and Yenisey, the contamination of oil products, phenols and copper are significant and several times above ACL values.

Contamination of other large Siberian rivers (Lena and Kolyma) are shown in Figures 7 and 8. Contamination levels on these rivers are noticeably less; however, they are still above ACL. As for Lena, there is some decrease in oil product concentration and increase in copper from the upper and middle reaches to the mouth sites. A considerable year-to-year variation of Lena contamination with oil products is seemingly due to the

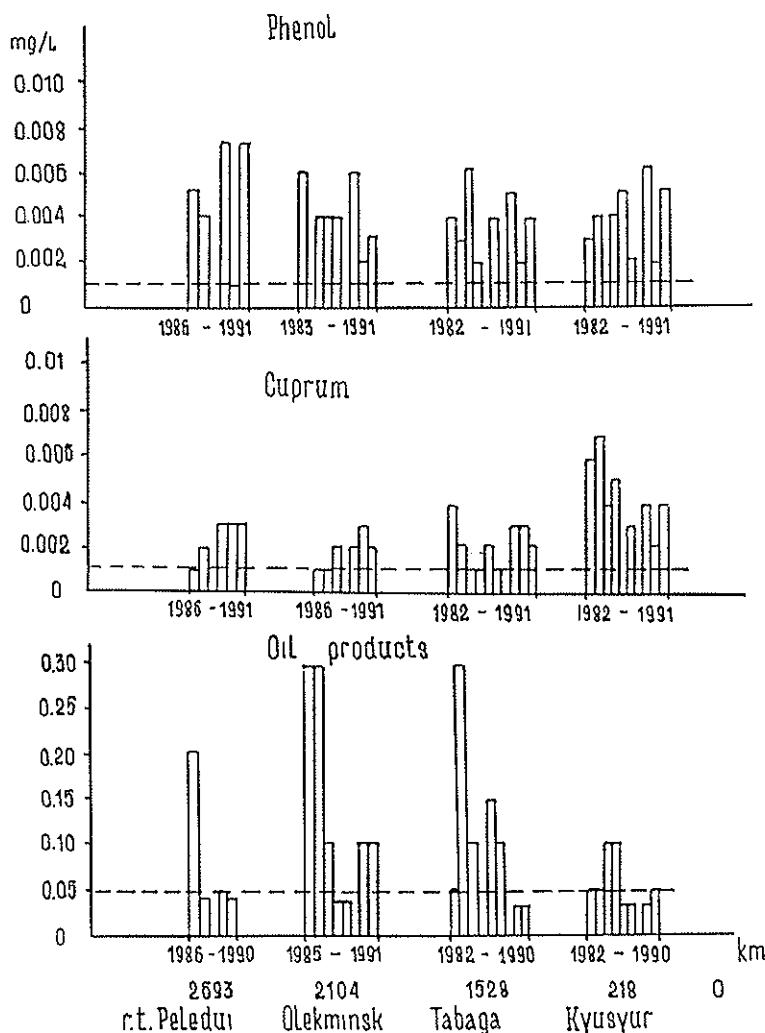


Figure 7. Changes in mean annual phenols, oil products, and copper compounds over the length of the Lena River for the years 1982-1991.

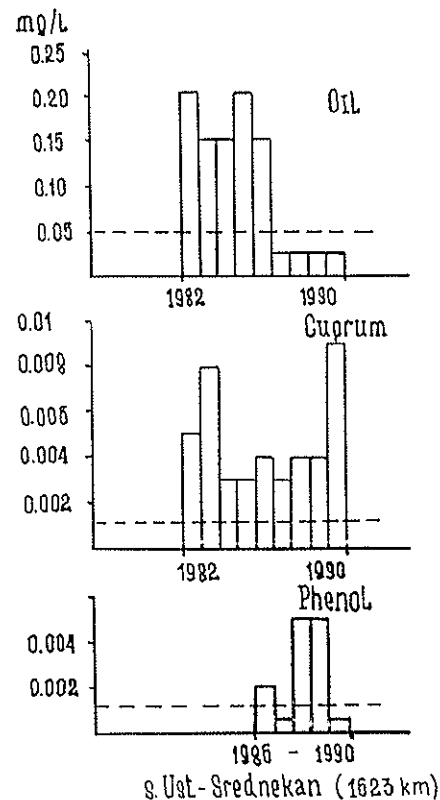


Figure 8. Dynamics of Kolyma River contaminants by the phenols, oil products, and copper compounds during the period 1982-1990.

emergency discharges from the water transport being the only cargo transport means in this basin.

To assess the modern income of contaminants to the Arctic zone, it is necessary to know their concentrations at the lower sites of Siberian rivers. These data for some contaminants are averaged over 1987-1990 and presented in Table 6. As a whole they characterize a rather significant contamination of Siberian rivers in their lower reaches, where concentrations of contaminants are appreciably above ACL values and as for oil products they reach 7-8 ACL for Ob and Yenisey.

Removal of Dissolved Contaminants with River Runoff

The assessment of the removal dynamics for dissolved contaminants inflowing to the Arctic zone over

a long-term period is based on the studies made at the Hydrochemical Institute of Roshydromet (Rostov-on-Don, Russia) over 1976-1980 as well as on the approximate results obtained at the State Hydrological Institute over 1987-1991. It should be mentioned that the 1975-80 period can be indicative of the mean annual removal of contaminants to the Arctic zone over the last 15-20 years. Intensifying man's activities in the basins over the subsequent years has been compensated for by more drastic measures taken to protect the natural environment. The runoff of dissolved contaminants from Siberian rivers is calculated for separate groups: inorganic contaminants include a group of major ions (ion runoff), of microelements, and of biogenic substances. Data on organic substances were determined individually. The ionic and microelement runoffs were

Table 6. Concentrations of some contaminants in the lower reaches of large Siberian rivers averaged over 1987-90, mg/l.

River	Organic contam. by BODs	Nitrogen ammonium	Oil products	Phenols	Microelements	
					Cu	Fe
Ob	2.10	0.88	0.35	0.002	0.003	0.8
Yenisey	1.70	0.43	0.40	0.003	0.005	0.38
Lena	1.32	0.04	0.05	0.004	0.003	0.21
Yana	—	0.03	0.07	0.004	0.003	0.32
Indigirka	1.70	0.60	0.06	0.04	0.004	1.00
Kolyma	2.66	0.68	0.025	0.003	0.005	0.6

calculated by direct method. Calculations are made for each year, concentrations of components being weighted by water runoff in high- and low-water periods. The calculation errors are no more than 20-30%. Calculations of organic and biogenic contaminant removal are made for each year by mean concentrations and annual river runoff values. Then they are averaged over a long-term period. Data on organic contaminants are obtained by multiplying the values of chemical oxygen demand (COD) by coefficient 0.75. Calculation error for organic contaminant runoff is roughly estimated at 20-50%, for biogenic elements at 30-60%.

The results of estimating the runoff of dissolved contaminants to the Arctic zone summarized for major rivers are cited in Table 7. For all groups of contaminants the largest removal occurs on the three major rivers: Ob, Yenisey and Lena because of their high water availability.

The hydrochemical runoff of specific contaminants and its interannual dynamics for Siberian rivers can be presently estimated very approximately because of lack of full-scale data.

The annual removal of easily oxidizing organic contaminants, as for BOD, varies over recent years within 10^3 t/y: 1390 for Yenisey-Igarka, 1180 for Ob-Salekhard and 995 for Lena-Kyusyur, which amounts to 10-30% of the total removal of organic substances

calculated by the values of river water oxidation susceptibility. The oil product removal over 1987-88 makes up 10^3 t/y: 162 for Ob-Salekhard, 232 for Yenisey-Igarka and 60 for Lena-Kyusyur. As compared with the previous period of 1981-85, the runoff of oil products would increase by 30% for Ob, by 50% for Lena and 35% for Yenisey.

The largest removal of such man-made contaminants as phenols falls on Yenisey: 2.15×10^3 t/y. The removal of phenols from the Ob River catchment is 0.81×10^3 t and from the Lena River catchment 1.43×10^3 t. Comparison with the previous period indicates a decreased removal of phenols over recent years by 30% for Ob and by about 50% for Yenisey. However, because of large variability of observed concentration values, these data can be considered as very approximate. To obtain more reliable data on the dynamics of removal, it is necessary to conduct a comprehensive scientific research.

On the Possible Prospects of Future Studies

The available standard network observations of water, sediment and contaminant runoff are insufficient to obtain a reliable and detailed estimation of the income of all kinds of contaminants to the Arctic Ocean: rare observational network and lack of samples to be analyzed do not allow for studying chemicals accumu-

Table 7. Mean annual removal of dissolved contaminants by major rivers of Siberia to the Arctic zone over 1976-80.

River - station	Sum of ions, 10^3 , tons	Organic contam. 10^3 , tons	Nitrates 10^3 , tons	Phosphates 10^3 , tons	Silicium 10^3 , tons	Sum of microele- ments, 10^3 , t	Cuprum incl., 10^3 , tons
Ob -Salekhard	49,800	3680	25.4	18	1860	78.89	5.5
Yenisey-Igarka	41,300	8420	5.62	5.88	1600	89.19	3.0
Khatanga-Khatanga	8,490	—	—	—	—	12.47	0.3
Anabar-Saskylakh	513	—	—	—	—	0.973	0.08
Olenek-Taimylyr	14,300	—	—	—	—	8.09	0.17
Lena-Kyusyur	47,800	7,840	225	3.57	1030	80.65	1.5
Yana-Dzhangky	1770	535	1.52	0.254	54.6	3.9	0.29
Indigirka-Vorontsovo	3730	628	1.91	0.559	104	7.07	0.25
Kolyma-Srednekolymsk	2970	774	4.96	0.782	143	8.1	0.34

Note: Sum of microelements = B, F, I, Cu, Zn, V, Mn, Ni, Mo.

lation and transformation in the river systems, in particular, below closing sites in mouths and estuaries; there are almost no systematic observations of radionuclides, their transport and accumulation on catchments and in streams under the influence of various natural and anthropogenic factors.

To minutely study the removal of contaminants with river water and sediment runoff to the Arctic Ocean, the State Hydrological Institute and the US Geological Survey have prepared preliminary proposals on organizing during 3-5 years complex research on studying the processes of accumulation and transformation of natural and man-made chemical substances and radionuclides in river system and on the catchments of Siberian rivers.

Goals and Aims of Research

Allowance is made for solving the following problems:

- Revealing the natural mechanisms governing the income to the river systems of contaminants and radionuclides from the surface of catchments and their transfer by streams up to closing sites;
- Reliable estimation of the modern river removal of contaminants and radionuclides to the Arctic Ocean;
- Developing proposals on organizing the monitoring over changing contaminants and radionuclides removal to the Arctic Ocean.

Subjects of Inquiry

The two Siberian rivers Ob and Yenisey have been chosen as top priority subjects. This choice can be explained by several reasons.

First, these are the largest rivers in Siberia collecting water from the vast catchments embracing several geographical zones; high water availability of rivers and active processes of transport and dilution of contaminants create good conditions for their studying.

Second, the basins of these rivers are subjected to most intense anthropogenic loading; large amounts of various chemicals income to the rivers whose migration routes are studied but insufficiently.

Third, in the river basins, the stations of standard observations of water regime characteristics, sediment runoff, chemical composition of surface water are being operated for many years; although the network density is insufficient, it is still denser than in other basins of Siberian rivers.

It can be added that in the basins of contaminated rivers in different years the studies were conducted that touched individual aspects of the problem in question.

In spite of the above similar features, Ob and Yenisey differ in the natural conditions of the basins and kinds of anthropogenic load. As a whole, these two rivers are indicative as for Siberian conditions of water and sedi-

ment runoff formation as well as of the removal of contaminants to Arctic Ocean.

The Processes in Question and the Technique

To solve the problems raised, allowance is made for studying the following basic processes determining the removal of contaminants and radionuclides:

- Water and sediment runoff in river channels and flood-plains;
- Transformation of basic contaminants along the length of river;
- Changes in concentrations of radionuclides in river systems;
- Accumulation and desorption of radionuclides on flood-plain swampy territories and their income to streams;
- Migration of contaminants and radionuclides associated with river sediments in the bottom-stream system, taking into account the variability of channel forms;
- Accumulation and transformation of sediments, contaminants and radionuclides in mouths and estuaries;
- Transport of contaminants and radionuclides with bottom ice.

To study the above processes, it is supposed to use all the modern research methods applicable in hydrology: analysis of the available observational data and the results of scientific studies, the methods for analyzing spatial and time variations of regime characteristics, the methods for mathematical and physical modeling and the methods for modern laboratory analysis. It is planned to carry out a wide complex of field studies on experimental plots and selected river sites as well as at steady observational stations.

Major Kinds and Stages of Work

In accordance with goals, tasks and accepted methodology the following kinds and stages of work are chosen:

1. Developing a detailed program and the methods for observations, mathematical and physical modeling of processes in question, scientific analysis and summarization;
2. Creating the historical and current data base;
3. Carrying out detailed observations at the stations of standard network;
4. Organizing and conducting expedition ship observations at the sites of Ob and Yenisey;
5. Organizing and carrying out studies on experimental plots;
6. Carrying out laboratory analyses and experimental work.

Expeditionary ship observations are carried out with

the aim of studying the processes on the length of the rivers in question; the total extent of routes on each river is up to 1000 km. Observations are conducted in the periods of floods and summer-autumn low-flow.

Experimental plots of four kinds are to be organized to solve various scientific problems.

A swamp plot is to be located on the flood-plain of Ob to determine the chemical composition of boggy water, radionuclide concentration in the swamp thickness and to reveal the routes of their migration.

An erosion plot is to be located in the basin of small tributary of Ob or Yenisey in the zone of active erosion to determine the mechanism of washing out soil and grounds and estimate the removal of contaminants and radionuclides.

Channel plots are organized in the lower reaches of rivers (three on each river) to study the processes of radionuclide migration with suspended and bottom sediments taking into account the type of channel process.

Mouth plots are established to study the dynamics of

transport of natural and man-made contaminants under the conditions of interaction with sea waters.

Basic Executors and the Dates of Work Fulfillment

Work is planned to be fulfilled during 3-5 years. The following basic researchers are supposed to be invited from Russia: the State Hydrological Institute, the Water Problem Institute, the Arctic and Antarctic Research Institute, the Hydrochemical Institute and administrative territorial boards of Roshydromet. In addition, it is planned to invite other specialized institutes and laboratories, in particular those that are experienced in the field and laboratory studies of radionuclides. It should be mentioned that experienced American specialists, in particular, of the US Geological Survey, are expected to take an active part in the studies at all stages.

Implementation of the above proposals will allow for obtaining a reliable estimate of removal of various contaminants to the Arctic Ocean and developing a complex of measures for the natural environment protection in the Arctic.

Adaptation Possibilities of Energetic and Functional Systems of Animals in the North in Connection with the Problems of Environment Contamination

N. A. Chermnykh, Executive Secretary
Institute of Physiology Komi Science Centre
Ural Division, Russian Academy of Sciences

Scantiness of adaptive possibilities of functional systems of the organism in conditions of Arctic contamination is determined by a number of specific regularities:

- Compressed in time and extremely tense period of early post-natal ontogenesis is most sensitive to the impact of both natural and anthropogenic factors. The risk for animal death at this period is very high.
- Evolutionary development of adaptive systems of the organism of northern animals was realized through perfection of morphological structures (first of all, heat insulating ones: fur, vascular heat-exchangers, specific structure of respiratory system and others) and ethological reactions. These mechanisms are so unique and, at the same time, conservative, that exclusion or impossibility of their realization caused by damaging factors of environment, are disastrous for the organism.
- Physiological mechanisms of adaptation of aboriginal animals to natural arctic conditions are aimed at fulfillment of energy-preserving. These systems

working at the limits of their possibilities are the most vulnerable to anthropogenic factors effect.

- Seasonal rhythm of life cycles, physiological functions, regulatory systems of animal organism is characterized by strict, fixed in time, alternation of a short phase of intensive metabolism with periods of complete or relative rest, and has the peculiarities of a "strong" system. Functional state of the organism, possibilities of adaptive systems, their stability depend on the season and in their own are vulnerable to the impact of strange, outside agent. It is known that one and the same influence of an irritant (damaging factor) in different phases of life cycle has qualitatively different response reaction.

The data on ecological physiology of animals of northern territories available at the Institute of Physiology of Komi Science Centre may serve as a basis for the model of Arctic ecosystems contamination for the assessment of the basis state of an organism and the damaging factors' power and the prognosticating the state of ecosystems.

Evaluation of Airotechnogenic Pollution of Ecosystems of Barents Region

G. Kalabin, Director
Institute of North Industrial Ecology Problems
Kola Science Centre
Russian Academy of Sciences

It is quite obvious that the global ecological processes are made up of local and regional situations. That's why objective information about the environmental quality in potentially endangered regions is required to elaborate an effective nature protection strategy. The northern regions of Russia: Norilsk, Taymyr, Yamal and Kola Peninsula give cause for the greatest alarm. In these regions ecosystems are at the equilibrium limit, the anthropogenic stress here can provoke irreversible

changes in the balance of nature. In this presentation, processes of air transfer of pollutants in the near ground layer of the atmosphere are examined. It is possible to examine these problems using mathematical modeling in both local and regional levels. In this study, the results of analyses for sulphur and heavy metals isolation, as well as their accumulation in the surface water, in the soil and forests of the Kola Peninsula are presented.

Mining and Metallurgical Waste as a Source of Arctic Contamination and a Remedy for Northern Environment Protection

Vladimir T. Kalinnikov, Chairman
Kola Science Centre
Russian Academy of Sciences

Mining and metallurgic enterprises form the major part of the technosphere in the Euro-Arctic regions. There is a common opinion that they are responsible for large scale pollution of the Arctic environment with heavy metals and other dangerous contaminants. As for emissions from smelting plants, the conclusion is evident and proven. But the role of mining wastes in the hydrosphere and atmosphere contamination in the Arctic is not known. The Kola Peninsula is selected as a model area for such an estimation. Kola Mining enterprises produce 250 million tons of crushed rocks and sandy "tails" annually.

Most of the wastes accumulate in depressions in the ground or lakes, used as tailing stores. As a result of it, small artificial sandy deserts or stone barrens are formed in areas of mining activity. Before the extraction, rocks do not have any features of "polluters" for the environment, even if the content of potential pollutants is very high. This is because the chemical exchange between massive solids and the hydrosphere is restricted.

After the crushing and transfer into water-penetrated dumps, the chemical reactivity of rocks increases many times and some trace or accessory components appear as pollutant agents. For instance, in the Lovozero mining area, the wall rock hosted titanium ore bodies contain up to 10% of easy water soluble fluorides (NaF

etc.). In the beginning, mining lakes in the area surrounding the Lovozero massif area were free of fluorine. But after 20 years of mining activity, the fluorine concentration in Lovozero Lake has increased up to 10 mg/l. In the largest lake of the European North, Imandra Lake, the salt contamination has increased 2-3 times under the influence of apatite-nepheline mining enterprises. Both above-mentioned lakes are the main sources of fluvial tributaries to the White and Barents Sea basins.

The similar situations are characteristics of other lakes in the central and western part of the Kola Peninsula. The whole picture and the tendency of contaminant migration in the system: lakes-rivers-marginal seas is clear, but the detailed mechanism and digital models for correct calculation are not yet available. This is because of scarce data.

There are some ways of diminishing the negative influence of the dumps on the Arctic environment. Traditionally, all attempts are focused on the all-round utilization of polycomponent ores. A new approach is the transformation of tails and slag wastes into "cleaning" materials (absorbents, coagulants etc.) or building materials. The Kola Science Centre offers different advanced technologies to convert industrial tails into valuable goods for tackling environmental problems in the Euro-Arctic region.

Research into Bottom Sedimentation in the Arctic

Dr. V. V. Makeyev
Northern Branch of the Russia Research Institute
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St. Petersburg, Russia

The Russian Arctic has abundant lakes. Actually, in every region of the Arctic there are hundreds of lakes, varying in size, genesis, and age, in which sediment accumulation is underway. Due to specific character of sedimentation in lakes, bottom sediments represent a wonderful source of information on the state of environment and the processes occurring in the basins. This permits us to solve a reverse problem—of using sedimentation data for obtaining thorough and continuous information on the state of environment and its changes in prolonged time intervals for any region of the Arctic.

Results of many years of investigations of bottom sediments and sediment accumulation in lakes of the tundra and polar desert zones in the Yamal, Taimyr, Severnaya Zemlya and Bovosibirsk Islands performed by the author are presented for discussion. The investigations have been of a multi-purpose character and include studies of the hydrological and hydrochemical state of water masses, and inflow of water and sediments into lakes, both at present and in the past.

On the basis of data on variability of thickness, lamination, grain size, and mineralogic composition

and other parameters, the basic changes in the parameters of the environment, including climate, have been reconstructed for a number of Arctic regions for a period of the last several thousand years, and the periodicity of these changes disclosed.

In this case, changes induced by man-made activity are being observed only in the uppermost sediment layers.

In the opinion of the author, investigations of lake

sediments in the Arctic continue to be promising, especially concerning studies of man-made environmental impacts and their consequences in relation to water ecosystems.

Unfortunately, in present-day Russia these studies have practically stopped due to the economic situation. I venture to address our American colleagues with a proposal to support the continuation of these studies in the form of joint projects.

Sources of Technogenic Radionuclide Pollution (STRP) in the Southern Arctic Ocean

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STRP in the southern Arctic Ocean are radionuclides from the Eurasian continent. These are associated with human economic activity and are typified into technogenic and natural technogenic ones. Among the technogenic sources are all objects of the atomic industrial complex, i.e. reactor plants at atomic production plants (APP), on vessels, in research centers, nuclear explosions (underground and aboveground) for peaceful purposes and testing of nuclear weapons. From these sources, the natural environments are polluted with long-lived artificial radionuclides: cesium-137, strontium-90, plutonium-239, 240 and some others. Natural technogenic sources due to human impacts on natural concentrations of radioactive elements in the course of production and exploration of mineral resources, result in the intensifi-

cation of the migrational properties of radioactive elements, as well as during industrial production of nuclear fuel. This, primarily concerns production of U, U-bearing ores, rare earth elements, thorium and petroleum, are containing elevated concentrations of Ra and U. STRP are classified under constantly acting ones, i.e. reactor plants, mining complexes, etc., and those of a short-term action, i.e. nuclear explosions, accidents at APPs or radiochemical works. The considered sources are also qualified in terms of the means of transfer of pollutants, both due to natural factors, i.e. atmospheric, aqueous etc., and at the expense of anthropogenic ones, i.e. burial or storage radioactive waste etc. The paper represents an attempt at assessing the total radionuclide pollution of the southern Arctic Ocean.

Radionuclides in Ecosystems of Barents and Karsky Seas, Arctic Archipelagos and Coastline

G. Matishov, Director

Murmansk Institute of Marine Biology

Russian Academy of Sciences

The author summarizes results of radioecological research; analyses samples of seafloor deposits, hydrobionts and sea-water, as well as samples of lichen from

Novaya Zemlya and Franz-Joseph Land and Kola Peninsula; discusses problems of artificial radionuclides transportation in the Arctic in 1960s and at present.

Problems of Protection of Arctic Natural Environment (The Research under the National Programme on Science and Technology in the Arctic)

Vladimir Pavlenko, Director
Arctic Research Centre
Russian Academy of Sciences

The report presents "generalized information on research work in the field of ecology and Arctic environmental protection in the frame of the aforementioned national program. The report includes both analysis of biodiversity, problems of adjustment, and results of research plus assessments of formation of biological

productivity of Arctic seas in Russia under the conditions of increase; of technogenic and anthropogenic pressure of development of methods of Arctic different regions monitoring (Kola Peninsula, Yamal, Taimyr, Chukotka, islands of the Arctic ocean); human ecology, including indigenous people."

Use of Methods of Northern Ecological Physiology of Man and Animals for Monitoring the Environment and Assessment of Real Consequences of Arctic Contamination

M. P. Roshchevsky, Director
Institute of Physiology and
Chairman of the Komi Science Centre
Ural Division Academy of Sciences of Russia

Is the possibility of using present day human and animal ecological physiology achievements for monitoring the environment and assessment of the consequences of Arctic contamination real?

Compressed in time, orthogenesis is typical for the development of vertebrates in the North. In ungulates, we discovered negative chemical heat-regulation typical for northern animals. Extreme natural influences and any additional anthropogenic (toxic) impacts may cause the hampering of adaptive possibilities of an organism. Changes due to anthropogenic influence, such as habitual pasture migrations, may serve as a typical example. Analogous problems arise in fish spawning in concrete water-reservoirs. Contamination in the Arctic, even in small doses, results in

ecologo-physiological consequences. Morphological ways of evolution are strongly determined genetically, while functional (physiological) adaptive mechanisms are especially fragile, namely in northern conditions.

The problems that are studied by our Institute will be covered in the report, namely:

- 1.1 Frailness of adaptive possibilities of energetic and functional systems of animals in the North.
- 1.2 Physiology of man in closed (insular) population groups.
- 1.3 Genetic predisposition to stability of animal survival in the North.
- 1.4 Ecologo-physiological peculiarities of hormonal provision of the reproductive function in women in the North.

Levels of Contamination of Arctic Marine Birds in Flocks by Heavy Metals, Chlorinated Hydrocarbons, Cesium-137

T. Savinova, Senior Researcher
Murmansk Institute of Marine Biology
Russian Academy of Sciences

The author presents results of Russian-Norwegian research on contamination of flocks of Arctic marine birds that was done under the program of AMAP. In 1991, there were defined levels of contamination, presence of ten heavy metals, chloride-origin persistent

organics, polychlorous bidenites (22 individual congeners) and cesium-137 in marine birds in flocks in the area of Spitsbergen, Franz-Joseph Land, Medvejy island, West and East Murman islands, and the Norwegian coast.

Risk of Radiation in the North

A. V. Tkachev, Director

Institute of Physiology (Archangelsk Branch)

Ural Division, Russian Academy of Sciences

The biological and medical problems of radiation risk in the polar region have appeared from the start of the nuclear testing in the North, on the Novaya Zemlya archipelago. From 1955, till the present time, 132 nuclear explosions have been set off in that region, including 90 of the most powerful in the atmosphere. Disposal of non-operational reactor installations, vessels, and containers with radioactive wastes in the water adjacent to Novaya Zemlya are widely known. The radiation situation is also complicated by the presence of atomic icebreakers and submarine fleets in the Arctic Sea and by different kind of emergencies caused by them. Thus the problem of radiation risk exists in reality and demands detailed description and search for solutions and correct decisions.

There are some difficulties in the objective estimation of the situation, in attempts to determine the impact

of radiation impact on flora, fauna and humans. The period of intensive activity at the test site coincided with the "Cold War" period. The atmosphere of suspiciousness and secrecy which was typical for that time has led to negative results. Still today we are not aware of many data from that time.

We analyzed different data about the dynamics of health level in settlements in the Russian North European Part. We can point out the importance as follows: the unfavorable dynamics of demographic processes, birth rate decrease, and infant mortality increase. The aboriginal population has the strongest manifestation of above mentioned observations.

It must be mentioned that the radiation risk problem in the Far North is not settled. Research carried on in this field lacks information and very often is followed by emotional speculations.

Selected Meetings of Interest

Listed here is a compilation of recent and forthcoming meetings, workshops and conferences on Arctic or northern topics and activities. Readers are invited to submit information on upcoming meetings, as well as reports on national or international meetings attended, to Editor, Arctic Research, Office of Polar Programs, National Science Foundation, 4201 Wilson Boulevard, Arlington, Virginia 22230.

1993

Sea Level Changes: Measurements and Analysis
9–10 December 1993, London, United Kingdom
Contact: PSMSL, Proudman Oceanographic Laboratory, Bidston Observatory, Birkenhead, Merseyside L43 7RA, United Kingdom
Fax: 44-51-653-6269

1994

Sea and Ice–Climate Interactions: The Deep Sea Floor as a Changing Environment
8–13 February 1994, San Feliu de Guixols, Spain
Contact: Josip Hendekovic, European Science Foundation, 1 quai Lezay-Marnésia, 67080 Strasbourg Cedex, France

Circumpolar Ecosystems in Winter 3
16–21 February 1994, Churchill, Manitoba, Canada
Contact: CEW-3, Churchill Northern Studies Centre, P.O. Box 610, Churchill, Manitoba R0B 0E0, Canada
Phone: (204) 675-2307
Fax: (204) 675-2139

Winter Cities '94
5–10 March, Anchorage, Alaska
Contact: Zarin Caldwell
Phone: (907) 343-4714

Conference on Oil Spill Response in Dynamic Broken Ice
7–8 March 1994, Anchorage, Alaska
Contact: D.F. Dickins Associates Ltd., Suite 210, 1290 Hornby Street, Vancouver, British Columbia V6Z 1W2 Canada
Phone: (604) 684-0516
Fax: (604) 684-2357

Seventh International Cold Regions Engineering Specialty Conference
7–9 March 1994, Edmonton, Alberta, Canada
Contact: Dr. Daniel W. Smith, Department of Civil Engineering, University of Alberta, Edmonton, Alberta T6G 2G7, Canada

Polar Tech '94
22–25 March 1994, Luleå, Sweden
Contact: CENTEX, Lena Allheim Karbin, Luleå University of Technology, S-95187, Luleå, Sweden

ISOPE-94; The Fourth International Offshore and Polar Engineering Conference
10–15 April 1994, Osaka, Japan
Contact: ISOPE, P.O. Box 1107, Golden, Colorado 80402-1107
Fax: 1-303-420-3760

XIXth European Geophysical Society General Assembly
25–29 April 1994, Grenoble, France
Contact: EGS 94, c/o LGGE BP 96, 38402 St. Martin d'Hères Cedex, France

Third Circumpolar Symposium on Remote Sensing of Arctic Environments

16–20 May 1994, Fairbanks, Alaska
Contact: Ken Dean, Conference Chair, University of Alaska Fairbanks
Phone: (907) 474-7364
Fax: (907) 474-7290
E-mail: kdean@geewiz.gi.alaska.edu

An Advanced Study Institute Summer School on Physics of Ice-Covered Seas
6–17 June 1994, Savonlinna, Finland
Contact: Matti Leppäranta, Department of Geophysics, P.O. Box 4 (Favianinkatu 24 A), SF-00014 University of Helsinki, Finland

ISCORD 1994—International Symposium on Cold Regions Development
13–16 June 1994, Espoo, Finland
Contact: ISCORD '94 Symposium Secretariat, c/o Association of Finnish Civil Engineers RIL, Meritullinkatu 16 A 5, SF-00170 Helsinki, Finland
Phone: +358 0 1356300
Fax: +358 0 1357669

Bipolar Information Initiatives: The Needs of Polar Research—15th Polar Libraries Colloquy
3–8 July 1994, Cambridge, United Kingdom
Contact: William Mills, Scott Polar Research Institute, Cambridge CB2 1ER, U.K.
Phone: 0223-336557
Fax: 0223-336549
E-mail: wjm13@uk.ac.cam.phx

International Symposium on Spectral Sensing Research '94 (ISSR '94)
10–15 July 1994, San Diego, California
Contact: Science and Technology Corporation Meetings Division, Attn: ISSR '94, 101 Research Drive, Hampton, Virginia 23666-1340

International Symposium on the Role of the Cryosphere in Global Change
7–12 August 1994, Columbus, Ohio
Contact: Secretary General, International Glaciological Society, Lensfield Road, Cambridge CB2 1ER, U.K.

International Conference on the Arctic and North Pacific: Bridges of Science Between North America and the Russian Far East
25 August–2 September 1994, Anchorage Alaska, and Vladivostok, Russia
Contact: Dr. Gunter Weller, Geophysical Institute, University of Alaska, Fairbanks, Alaska 99775-0800
Fax: (907) 474-7290
E-mail: gunter@dino.gi.alaska.edu

**1994 International Conference on Arctic Margins
5–9 September 1994, Magadan, Russia**

Contact: Kirill V. Simakov, North East Scientific
Centre, 16 Portovaya Street, Magadan, 685000 Russia,
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(7-41) 3 223-0953 (Kirill Simakov, Russia)
(907) 271-6545 (Dennis Thurston)
Fax: (907) 271-6565

1995

**ISOPE-95: 5th International Offshore and
Polar Engineering Conference**

11–16 June 1995, The Hague, The Netherlands
Contact: Technical Program Committee, Attn: Prof. Jin
S. Chung, ISOPE, P.O. Box 1107, Golden, Colorado
80402-1107
Phone: (303) 273-3673
Fax: (303) 420-3760

**International Symposium on Glacial Erosion and
Sedimentation**

20–25 August 1995, Reykjavik, Iceland
Contact: Secretary General, International Glaciological
Society, Lensfield Road, Cambridge CB3 0ET, U.K.

**EISMINT International Symposium on Ice-Sheet
Modeling**

October 1995, Strasbourg, France
Contact: C.S.M. Doake, EISMINT, British Antarctic
Survey, High Cross, Madingley Road, Cambridge
CB3 0ET, U.K.

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