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Numerical simulation of the transport of radioactive cloud from the Chernobyl nuclear accident

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ABSTRACT

We present a first application of a hemispheric transport model to quantitatively evaluate the spreading of radioactive debris following the Chernobyl nuclear accident. The model employed in the simulation is essentially a simplified version of the Eulerian Long Range Transport of Air Pollutants (LRTAP) model designed for continental scale applications. Meteorological data driving the model were obtained from the standard Canadian Meteorological Centre (CMC) analysis. Simulations were performed for Iodine-131, Cesium-137 and Xenon-133. The accident scenario was estimated using data presented at the International Atomic Energy Agency (IAEA) experts meeting in Vienna, in August 1986. Results of the model simulation for Iodine-131 and Cesium-137 were verified against measurements for Stockholm, Resolute, Halifax and Vancouver and indicate a relatively high level of agreement considering the simplicity of the approach.

1. Introduction

The Chernobyl accident was unique in the sense that a very large amount of radioactive material was released close to the surface and was transported by the wind in the low and middle atmosphere over most of the Northern Hemisphere.

From the time when first informations about the nuclear accident were received, the Chernobyl reactor attracted the attention of a large number of modellers working with numerical weather prediction and transport models.

One of the first regional scale simulations was reported by ApSimon and Wilson (1986) and ApSimon et al. (1986). After 5 days from the release, it was readily noticed that Chernobyl was not a regional scale problem. Continuation of the simulation with limited area models became impossible because of rapid spreading of the nuclear debris over the Northern Hemisphere.

One of the first hemispheric simulations with a three-dimensional (3D) model neglecting vertical motion, topography and wet scavenging is reported by Gudiksen and Lange (1987) and indicate good prediction of the time of arrival of the radionuclides at several locations over the Northern Hemisphere.

In Canada, we originally decided to perform a simplified tracer simulation of the transport of radioactive debris assigning to the site of the Chernobyl reactor a hypothetical source of a passive tracer with constant emission rate and duration of 5 days. The tracer simulation was performed in Recherche en Prévision Numérique (RPN) between the 29 April and 15 May 1986, in emergency mode and was used solely as an indicator of the horizontal transport of the radioactive debris, because of the rather limiting assumption of no removal of radioisotopes during the advection.

Despite the extreme simplicity of the model, the results produced were quite significant for estimating which regions would be affected by radioactive debris and when.

Daily output from the tracer model was used

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extensively for the evaluation of the regions potentially affected by the radioactive cloud. With the addition of precipitation data it served as a simple but efficient tool for predicting the radioactive fallout hazard (Gilbert, 1986). Several weeks after the accident we decided to continue work with a more comprehensive numerical model.

In this paper, we present results from the simple model simulating hemispheric transport on isobaric levels including radioactive decay and scavenging. Experiments reported here should be considered as a very first approximation to the hemispheric transport.

However, results presented indicate a high degree of correlation between idealistic isobaric advection and surface measurements. Additionally, sensitivity studies with this simple model can serve as a guidance for the subsequent work with the more complex model which is currently in progress.

2. General equations and the structure of the transport models

A comprehensive assessment of the environmental impact of nuclear accidents requires atmospheric transport model simulating advection, subgrid scale mixing, radioactive decay and removal of the radioisotopes from the atmosphere (Glasstone and Jordan, 1980). The scales of the simulation range from local to global depending on the nature of the source and the amount of radioactivity released.

The governing equations of the general atmospheric transport model are given by the following set of mass conservation equations:

$$\frac{\partial A^i}{\partial t} = -V_H \nabla_H A^i - \dot{\gamma}\frac{\partial A^i}{\partial \gamma} - \nabla_H F^i_H - \frac{\partial F^i_\gamma}{\partial \gamma} + Q^i - D^i - S^i, \quad (1)$$

where:

A^i – specific activity of the ith nuclide (Bq/kg);
V_H – horizontal wind vector;
$\dot{\gamma}$ – vertical motion;
∇_H – horizontal gradient operator
γ – z, p or $\sigma = p/p_s$, dependent on the vertical coordinate used in the simulation;
F^i_H – horizontal subgrid scale flux;
F^i_γ – vertical subgrid scale flux;
Q^i – source term;
D^i – the term describing radioactive decay;
S^i – sink term.

The D^i term describes the radioactive decay and the creation of the ith daughter product (Fontan et al., 1966). The sink term S^i represents the sedimentation of radioactive particles due to the action of gravity and wet removal by rain and snow.

The subgrid scale fluxes F^i_H and F^i_V are commonly approximated using closure assumptions dependent on the scale of the problem (Mellor and Yamada, 1974). The simple first-order closure using the concept of diffusion coefficient is most commonly used because of the simplicity of the approach.

The meteorological fields required for the solution of the set of equations (1) are usually obtained from NWP (Numerical Weather Prediction) models of the atmosphere (Pudykiewicz et al., 1985a).

Specification of the subgrid scale fluxes is usually performed by a separate turbulence model coupled with the meteorological model (Côté and Benoit, 1984).

Under special circumstances, when the tracing of radioactive debris is required over long periods of 7 to 28 days, it is more accurate and meaningful to drive the transport model from meteorological fields derived from the analysis of observational data. The analysis of the meteorological fields is generally performed in most Numerical Weather Prediction centers every 6 h. Because this time step is far too large for solving eq. (1), the analysed fields for intermediate times are obtained by time interpolation.

3. Description of the model employed in the simulation

After receiving more data about the Chernobyl accident, and given the experience gained with the tracer experiment in the situation of a nuclear emergency, it was readily noticed that in order to obtain better estimates of the activities a more complex model has to be used. Despite the availability of a 3-D transport models designed for continental scale simulations (Pudykiewicz et al., 1985a) we found the hemispheric problem too complex for the immediate application of the state of the art model.

We decided instead to pursue our original investigation of the transport of radionuclides from the Chernobyl accident using a simple isobaric advection model with the parameterization of radioactive decay and scavenging. The set of equations of the simplified model can be obtained from the general set (1) putting $\gamma = p$ and by neglecting turbulent fluxes and vertical motion:

$$\frac{\partial A^i}{\partial t} = -V_H \nabla_H A^i + Q^i - D^i - S^i. \quad (2)$$

Additionally we have simplified the D^i and S^i terms:

$$D^i = \lambda_i A^i, \quad (3)$$

$$S^i = \Lambda A^i. \quad (4)$$

The simplification of the D^i term performed indicates that we are investigating exclusively the effect of the radioactive decay, neglecting the transformation of the isotopes.

Concerning a simplified form of the sink term given by eq. (8), we combined the sedimentation and scavenging effects by coefficient Λ describing the total removal rate of the radionuclide. In general Λ could be written in the following form:

$$\Lambda = \frac{\ln 2}{\tau_s}, \quad (5)$$

where:

τ_s – is the time after which half of the material is removed from the system due to scavenging processes.

Initially we had been using a value of Λ equal to 5×10^{-6} s^{-1}, corresponding to a half life time due to scavenging of 1.6 day. Considering the average distribution of precipitation zones on the hemispheric scale we finally found this value of τ_s too small. Because of the lack of sufficient knowledge about the transport of a low-level radioactive release on the hemispheric scale, we decided to perform sensitivity experiments with our model using a varied but realistic range of values for Λ.

The values investigated were in the range 10^{-6}–5×10^{-6}, corresponding to τ_s between 8 and 1.6 days, respectively. Discussion of the results from the sensitivity experiments is presented in Section 7.

The area considered in the simulation is shown in Fig. 1. The horizontal grid of the model was uniform with a resolution of 150 km on a polar stereographic projection. The corresponding grid domain was 132×132 points centered at the North Pole. This resolution was sufficient for hemispheric scale simulations. Computations were performed initially at 5 pressure levels: 1000, 850, 700, 500 and 300 mb.

However, following the analysis of our preliminary tracer experiment, we decided to reduce the vertical structure to only two atmospheric layers, one extending from the surface up to 2000 m and the second from 2000 m up to 4000 m. The bottom layer winds were taken as the 850 mb, and the 700 mb winds were used in the upper layer.

The choice of the simple vertical structure of the model is justified in light of the fact that the radioactive material transported by the flow near the surface is diluted more rapidly and deposited on the ground earlier than that transported at higher levels. Therefore material present in the atmosphere close to the earth has in general very little importance for long and very long range transport. In the case of our model which neglects explicit parameterization of vertical mixing, this two-level approximation is consistent with the assumed simplification of physical processes.

The numerical method employed for solving the transport eq. (7) was an unconditionally stable semi-Lagrangian advection scheme developed by Robert (1982) and successively applied to the pollution transport problem by Pudykiewicz and Staniforth (1984).

Concerning the validity of our simplified model we will compare eq. (1) with $\gamma = p$ to eq. (2). It is easy to notice that the following terms were neglected:

$$\omega \frac{\partial A^i}{\partial p} \text{ – vertical advection,} \quad (6)$$

$$\nabla F^i_H \text{ – horizontal diffusion,} \quad (7)$$

$$\frac{\partial F^i}{\partial p} \text{ – vertical diffusion.} \quad (8)$$

These approximations are certainly not valid when one wants to simulate transport of radionuclides on the continental scale over time

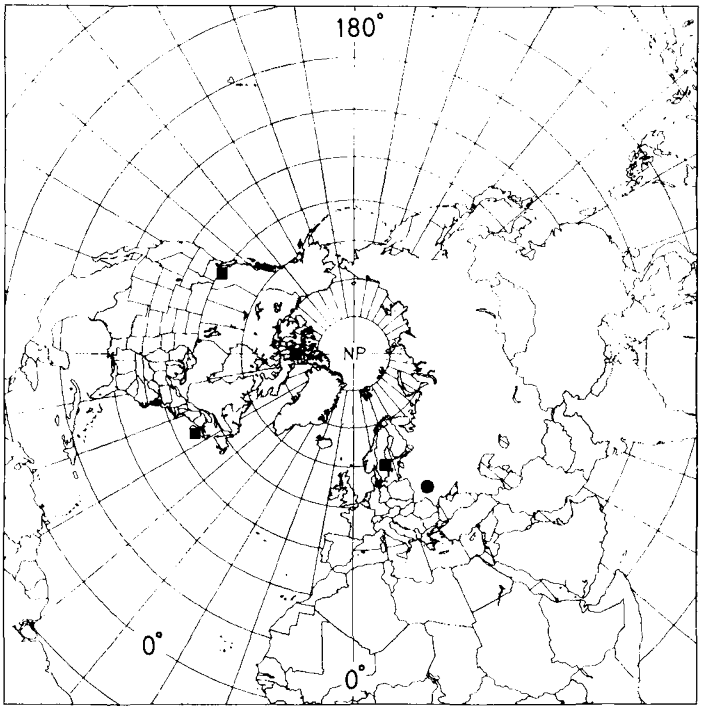

Fig. 1. Domain of the model used in the simulation. The thick dot indicates the site of the accident, the squares indicate receptors.

periods of 1 to 5 days given a deterministic and accurate form of the source term. In our simulation, because of the lack of knowledge concerning the vertical distribution of the release, and given the complex local and mesoscale meteorological phenomenae associated with the accident, we decided to describe the Chernobyl reactor release as a virtual source of the form:

$$Q^i = (f^i(t)/(2\pi\sigma_H^2 * H * \rho)) * \exp(-r^2/2\sigma_H^2), \quad (9)$$

where:

r – distance from the site of the accident;
σ_H – ΔX
ΔX – mesh interval
H – effective height of the release ($H = 4000$ m)
ρ – density of the air
$f^i(t)$ – function describing the time dependence of the release of the ith radionuclide.

The distributed form of the source term takes into account neglected effects of the short-term subgrid scale mixing and vertical advection.

In many ways the general concept behind this approximation for Q^i follows arguments presented by Eliassen (1980) in discussions of the simplified LRTAP models.

Considering that the primary objective of this preliminary study was to obtain the first approximation to the hemispheric scale transport, we felt that the above simplifications were entirely justified.

4. The source term

All the model computations were performed initially for Iodine-131 because this isotope has a very important biological impact (Glasstone and Jordan, 1980). Furthermore, because its half-life time is 8.05 days, this particular isotope has relatively large activity and could be transported over long distances. Isotopes with shorter life-times decay too rapidly to be interesting for simulation of the long range transport, whereas nuclides with longer life-times have much lower activities. Additionally, the choice of Iodine-131 in simulating the spreading of the radioactive

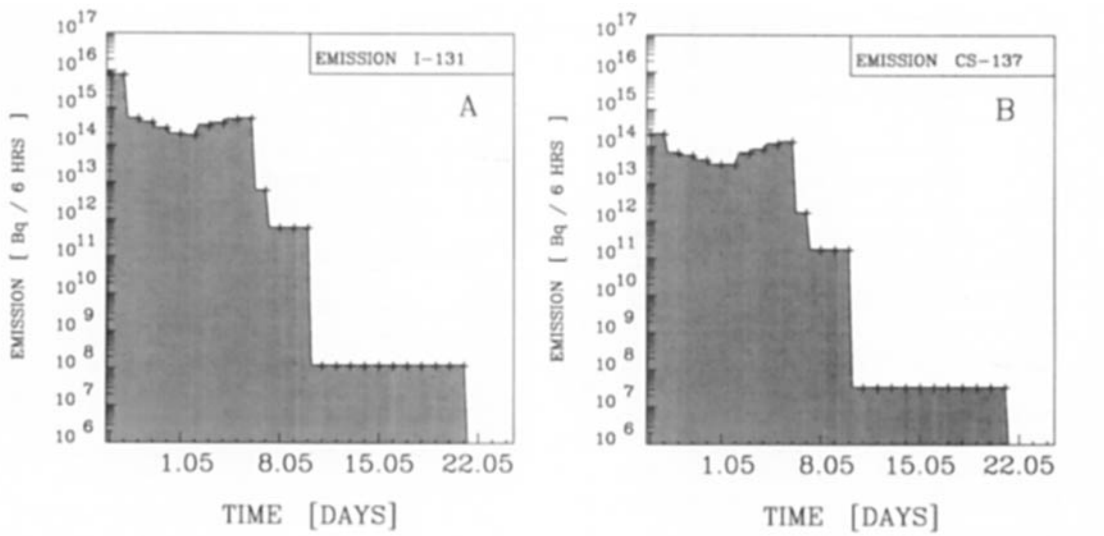

Fig. 2. Release of (a) I-131 and (b) Cs-137 from the Chernobyl reactor as a function of time. The values presented in Fig. 2 were obtained from the data presented at the IAEA meeting in Vienna in August 1986.

debris was motivated by availability of measurements performed by most European countries as well as by Canadian and US authorities.

In the later stage of our work, when more data became available, we included in the simulation Cs-137 and Xe-133. In the present paper we limit our discussion to the results for I-131 and Cs-137 because most of the currently available measurements were performed for these two isotopes.

4.1. *Accident scenario*

The accident scenario was derived from the data presented at the IAEA meeting in Vienna in August 1986. The data related to the nuclides considered in our simulations are summarized in Table 1.

After employing the information about time variability of the release given in Table 2 and considering the fact that all data are decay corrected to 6 May 1986, we obtained explicit time dependence of the release for the isotopes considered in the simulations. Results for the I-131 and Cs-137 are shown in Figs. 2a and 2b, respectively. Please note that these figures are still uncertain because the relative composition of the release was variable and no information about this effect is available.

Table 1. *Release of the radionuclides from the damaged Chernobyl reactor (as presented at IAEA meeting in Vienna in August 1986)*

Isotope	Half life time (days)	Core inventory* (Bq)	% of release
Xe-133	5.27	1.7×10^{18}	100
I-131	8.05	1.3×10^{18}	20
Cs-137	11,000	2.9×10^{17}	13

* Decay corrected to 6 May 1986.

4.2. *Representation of the source term on the grid of the transport model*

Representation of the point forcing on the grid of an Eulerian model is a common problem of numerical modelling in all fields of science

Table 2. *Daily radioactive release in Bq without radioactive noble gases. (Decay corrected to May 6)*

Date	Release (*Bq*)
26.04	4.44×10^{17}
27.04	1.48×10^{17}
28.04	1.26×10^{17}
29.04	9.62×10^{16}
30.04	7.40×10^{16}
01.05	7.40×10^{16}
02.05	1.48×10^{17}
03.05	1.85×10^{17}
04.05	2.59×10^{17}
05.05	2.96×10^{17}
06.05	3.70×10^{15}

dealing with computational fluid dynamics. The problem is particularly difficult in the simulation of the atmospheric transport processes where the gap between scales of the source and scales resolved by the model grid is enormous. There are several solutions to the source problem in Eulerian grid points models. One of them is the application of the PIC (Particle In the Cell) method by Lange (1978) or the simulation of the initial stages of the release by a series of puffs, as discussed in the review of simple LRTAP models given in Eliassen (1980).

Another approach to the source problem is purely Eulerian and is discussed by Pudykiewcz et al. (1985b) in the context of the CAPTEX tracer experiment. In the latter the release was simulated on a series of nested grids with increasing resolution.

Finally a third possibility for the source representation is the application of the idea of a distributed source given by formula (9).

In the case of our simple model we found this solution was most consistent with all other approximations. From the point of view of the grid system, this form of the Q^i term is equivalent to forcing the system with a very narrow Gaussian distribution, simulating both release and subgrid scale mixing.

4.3. The source term—vertical extension

In the case of intensive fires and explosions, such as the ones associated with nuclear accidents, extremely large amounts of thermal energy are released. The thermal jet developing over the heat source may reach heights from hundreds up to several thousands of meters, depending on the stratification in the lower troposphere and the rate of the heat release (Briggs, 1975).

In estimating the vertical extension of the Chernobyl release, we employed several techniques based on CMC temperature analysis to get the stratification around the accident site. Because of the lack of information about the actual thermal energy released to the atmosphere and insufficient knowledge of the local and mesoscale meteorological condition around the accident site we felt that these computations were too hypothetical. We finally decided to set the effective height of the release to 4000 m as some rational compromise between very different estimates.

We are aware that when 3-D models will be used, the sub-grid-scale problem of estimating the vertical distribution of the release should be solved with a nonhydrostatic model of the thermal convection on a very fine grid. At this stage, we see that our estimate is very close to the one reported by Gudiksen and Lange (1987).

5. Methodology of the experiments

The transport simulations were performed for a one-month period starting from the time of the accident on the 25 April 1986 21 GMT. The meteorological input was obtained from the objective analysis scheme of CMC driven by a hemispheric spectral model of the atmosphere (Daley et al., 1976; Rutherford, 1977).

In the first step we created a model data base by extracting from the archive system the components of the velocity, temperature, geopotential and dew point deficit on all mandatory analysis levels from 1000 to 50 mb, from 25 April–25 May 1986. The data base was created for the runs of a family of models of varying complexity. The model described in this paper by eq. (2) used only the horizontal components of the velocity.

In the second step, we started to run our model for the whole period, without restarting, with the different scavenging rates and different emission scenarios. All runs were performed for I-131, Cs-137 and Xe-133.

The set of experiments performed created an enormous amount of data so finally we decided to save maps showing the radioactive cloud only for a few selected runs. The other runs were processed using time series analysis of the radioactivity at a few receptor points, namely Stockholm, Resolute, Halifax and Vancouver.

In the following section we will present selected results describing how the radioactive cloud from the Chernobyl accident has been spreading over the Northern Hemisphere. Additionally, in the section about sensitivity experiments, we will present conclusions about the importance of scavenging for the hemispheric scale simulation.

6. Analysis of the results

After completing the experiments with a simple model we noticed that the transport of the radioactive cloud could be described in three stages. The first stage of the transport took place from the moment of explosion at 21 GMT 25 April 1986 to the end of April. The radionuclides in this stage were transported mostly over Europe. The second stage of the transport took place from the 1 May to the 7 May and could be described as the transfer of the radioactivity from the Eastern to Western part of the Northern Hemisphere. The most interesting feature of this stage was the transport of the nuclides to the polar regions and rapid injection of small amounts of the radioactivity through a narrow channel in the Canadian Arctic reaching Quebec and Ontario. The third and final stage of the transport took place after 7 May. During this stage, the radioactive cloud reached the East and West coasts of North America. The transport to the East coast occurred mostly on the lower levels, whereas the West coast was approached mostly by the material travelling across the Pacific Ocean on the 700 mb level.

6.1. *The initial stage of the transport*

On the night of 26 April, the weather situation over Europe was dominated by a strong high pressure system over the western part of Russia and a low pressure system located in the vicinity of Iceland. During the day a weak low pressure system had developed over southern Scandinavia and later moved north-northeasterly. In the region of the Chernobyl site, at the time of the accident, the wind at the 850 mb level was blowing from the southeast at 8–11 m s^{-1}. As indicated by the meteorological input of our model, this flow pattern remained quasi-stationary for the 24-hour period following the accident. The flow pattern was such that within 24 h, the radioactive cloud had already reached Scandinavia. The position of the radioactive cloud on the 27 April 12 GMT at 850 mb is shown in Fig. 3a indicating clearly that the part of the cloud with activities of more than 1 Bq kg^{-1} had spread over the central part of Sweden and turned east over Finland.

The figures displaying position of the radioactive cloud contain some additional information about the flow field. The dotted areas shown in Fig. 3 indicate regions with wind speed exceeding 10 m s^{-1}.

By overlaying information about regions of high wind speed we want to show explicitly how the transport on the hemispheric scale holds a high degree of similarity to the turbulent diffusion on the smaller laboratory scale. This effect becomes particularly evident when the scale of the cloud is larger than the scale of individual eddy like structures as indicated in Figs. 3c, d by the dotted patterns.

On the 28 April as shown in Fig. 3b the radioactive cloud crossed Scandinavia in a northwesterly direction and subsequently entered the cyclonic circulation system centered over the north-eastern sector of the Atlantic Ocean. From this moment a very strong flow spread radioactive material rapidly in the direction of Greenland, Figs. 3b, c.

The part of the cloud that originally spread over Finland was later transported in the southeast direction, back to Russia, Fig. 3c.

During 29 and 30 April, because of the change of the circulation patterns over the Baltic Sea and the Central Europe, the core of the radioactive cloud moved in a southwesterly direction crossing initially over Poland, Fig. 3c, and finally covering the Southern part of Germany, Austria and North Italy, Fig. 3d.

In the eastern part of the cloud, quite strong stationary westerly flow with the wind speeds over 10 m s^{-1} shifted radioactive material in an easterly direction across Asia, Fig. 3d. The situation shown clearly indicates that the transport pathway towards Japan was already established as early as 30 April.

The general character of this stage of the transport could be regarded as a direct manifestation of deformation properties of the atmospheric flow. Initially the continuous well-formed core of the distribution is elongated in a northwesterly direction, but after four days it started to develop a more complex structure with three arms, Figs. 3a–3d.

The transport at the 700 mb level for the initial stage of a hemispheric scale dispersion is shown in Fig. 4. The analysis of the results of the transport model at this higher level indicates that the most efficient transport took place in the easterly direction. In comparing the Figs. 3d and 4d we see that the edge of the cloud at the 700 mb level on 30 April is located much closer to Japan than at the 850 level. The transport over the Atlantic Ocean at 700 mb was less effective and inclined in the direction of the north pole.

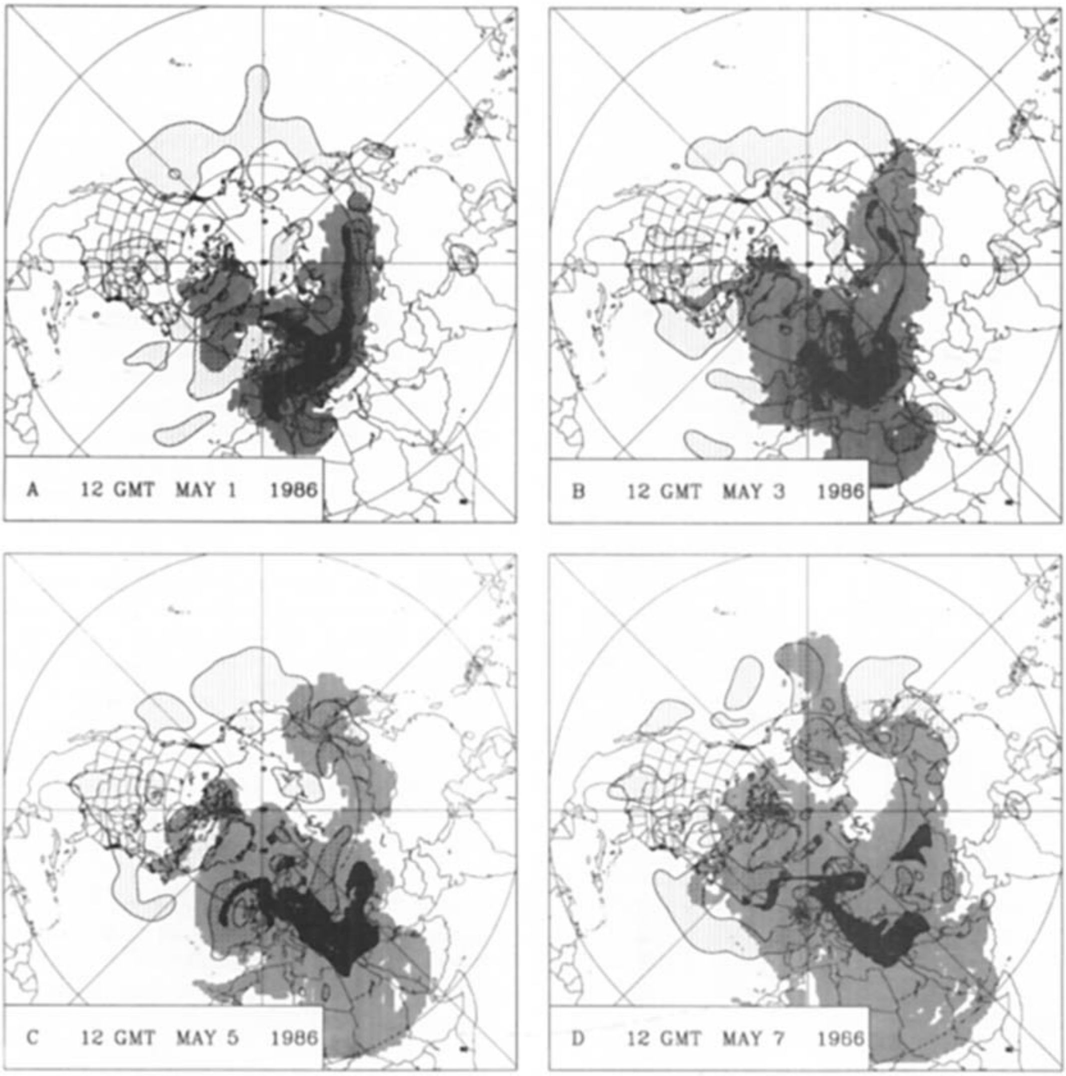

Fig. 3. Evolution of the radioactive cloud from Chernobyl during the first stage of the transport at the 850 mb level. The results shown were obtained for I-131 with the Eulerian source term and with the average scavenging rate $\Lambda = 2 \times 10^{-6}$ s^{-1}. The solid black pattern indicates regions with activity over 1 Bq kg^{-1}, the dashed pattern shows activity between 10^{-4} and 1 Bq kg^{-1}. The dotted areas surrounded by a single isoline represent regions with wind speed exceeding 10 m s^{-1}.

These differences between the 700 and 850 mb level transports simply indicate a much stronger westerly component of the flow at the higher 700 mb level.

The comparison of the activities of I-131 predicted by the model at the 850 mb level to the values obtained from the surface measurements in Stockholm (Jensen and Lindhe (1986)) is shown in Fig. 5. The model results are represented by the dashed area contained between the two lines; the upper and lower bounds of the model, defined by the following formulae:

$$f_L(t) = f_M(t) - f_\delta(t) \quad (10)$$

$$f_U(t) = f_M(t) + f_\delta(t) \quad (11)$$

$$f_M(t) = \sum_{k=1}^{4} \alpha_k f^{(k)}(t) \quad (12)$$

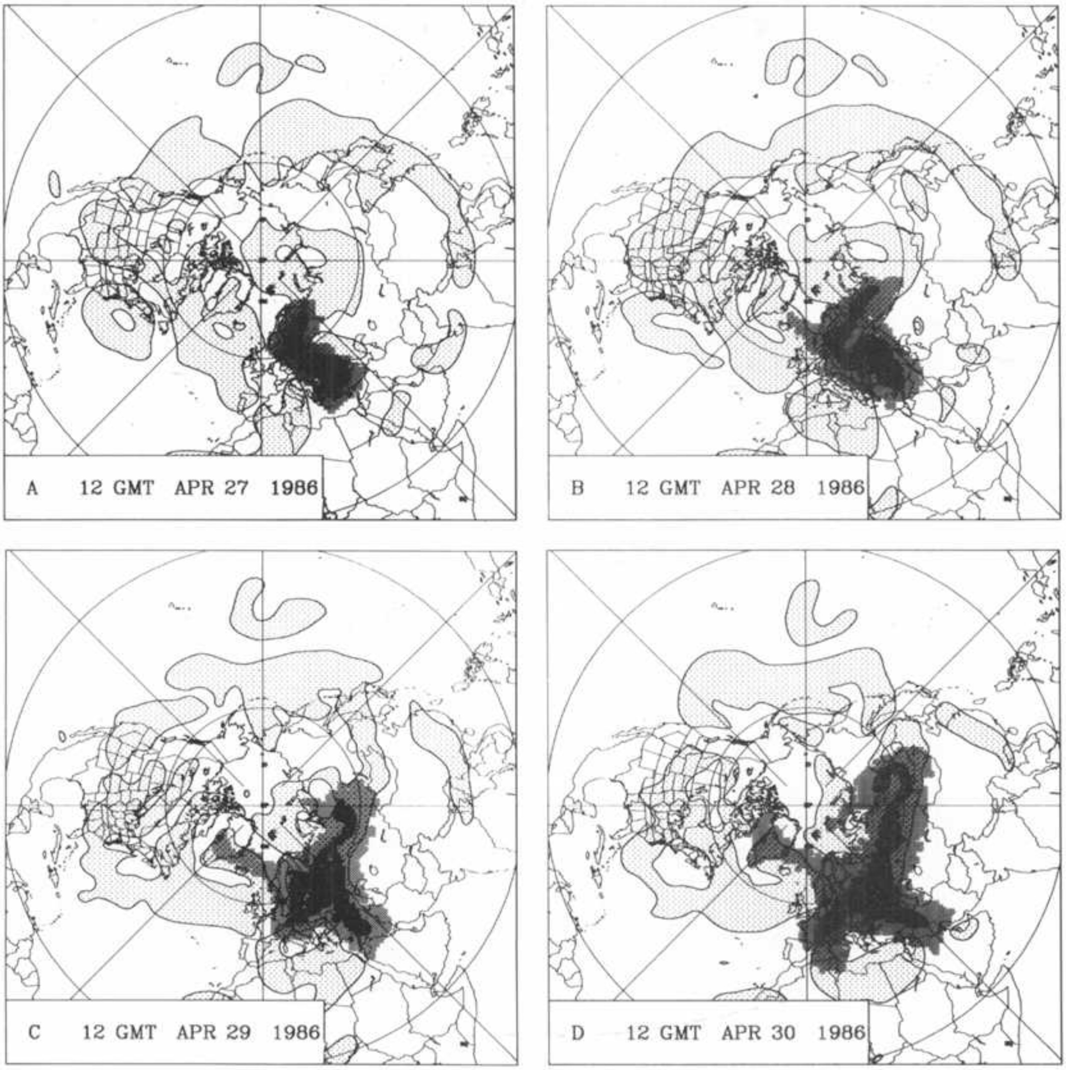

Fig. 4. Same as Fig. 3 but for the 700 mb level.

$$f_\delta(t) = \left(\left(\sum_{k=1}^{4} (f_M(t) - f^{(k)}(t))^2 \right) /3 \right)^{1/2}, \qquad (13)$$

where:

$f_L(t)$ – lower bound of the model for the particular receptor point

$f_U(t)$ – upper bound of the model for the particular receptor point

$f_M(t)$ – result of the interpolation of the grid point values to the particular receptor point

$f^{(k)}(t)$ – the grid point values from the corner of the grid cell containing particular receptor point

α_k – the weights of the interpolation.

The points corresponding to the line $f_M(t)$ are located exactly in the center of the dashed area shown in Fig. 5. We are showing the model results in this form to underline the uncertainty related to the sampling and subgrid-scale processes.

The method of the estimation of the uncer-

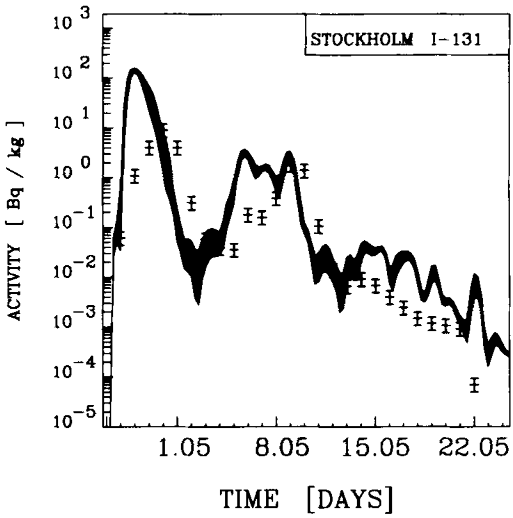

Fig. 5. Comparison of the observed and simulated time series of I-131 activity in Stockholm. The measured values are represented by vertical bars, the model results correspond to the dashed area between two lines taking into account uncertainty related to the sampling. The mesaured values were obtained from the surface measurements, the model results are from the run at 850 mb with the Eulerian source term and the average scavenging rate $\Lambda = 2 \times 10^{-6}\ s^{-1}$.

tainty bound given by (15)–(18) is very simple and only attempts to represent uncertainties related to the sampling error and the subgrid-scale mixing. In reality, because of our gross simplification of physical processes and because of the lack of the exact information about emission and the errors of the estimates of the vertical extension of the source term, the $f_\delta(t)$ is probably much larger. We are actually planning to calculate better estimates of the uncertainty bound with the next version of the model. The measured values of the activity are represented by the vertical error bars, Fig. 5. For the purposes of display we assumed that the error is 30%. This is most probably a lower bound estimate of the error of the measurements. The model values presented in Fig. 5 were obtained with the Eulerian distributed source given by formula (14). The analysis of Fig. 5 clearly indicates a very good correlation between surface measurements and simulated values at 850 mb. The trend of activity is reproduced very well over a time period of almost one month.

In the initial stage of the transport, the simulation performed with the Eulerian source term indicates too early arrival of the radionuclides at Stockholm. However the level of activity forecasted is very low. The reason for this is related to the point source approximation given by (9). In a hemispheric scale simulation, the error related to this particular form of the forcing term in eq. (2) is negligible because of the cancelling effect of the lateral mixing by the synoptic scale circulation systems.

In order to make our simulation valid also for a regional scale we reran all the experiments using instead a Lagrangian approximation for the source term. This was done by emitting a series of Lagrangian puffs moving on the Eulerian grid in an attempt to simulate the initial stages of the release.

The verification of the model results obtained with the Lagrangian parameterization of the source term is shown in Fig. 6. It is interesting to note that previously observed "tails" of the distributed source in the Eulerian run are now eliminated completely. Further the model results fit observations at initial time much better. During the latter stages of the transport, namely after 1 May, the difference between results obtained with the Eulerian and Lagrangian source term is negligible, Figs. 5, 6.

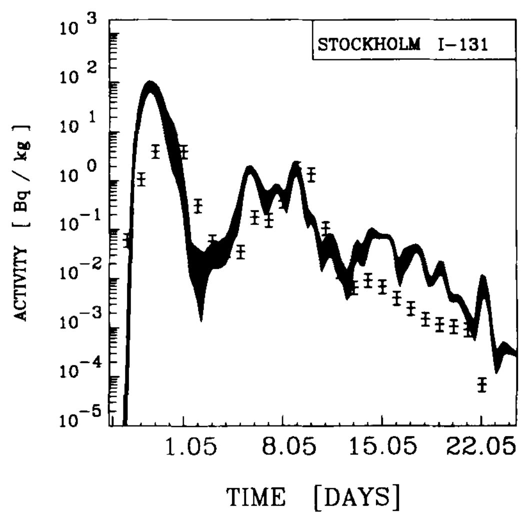

Fig. 6. Same as Fig. 5 but the model results were obtained from the run with the Hybrid Puff-in-Cell approximation of the source term. Please note that the hybrid approach allows the elimination of the early arrival of the small values at the close range receptor shown in Fig. 5.

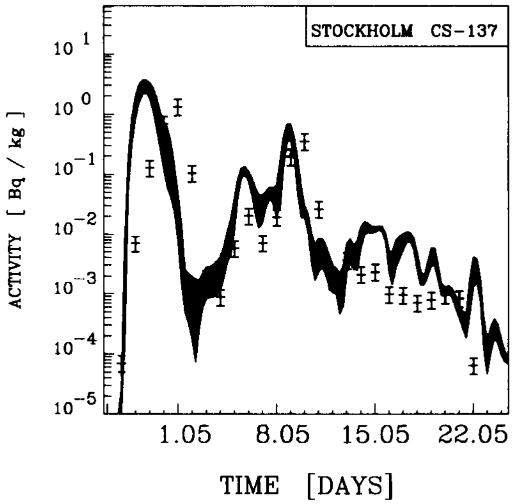

Fig. 7. Same as Fig. 6 but for Cs-137.

The verification of the model shown in Figs. 5, 6 was performed for I-131. Similar results are shown in Fig. 7 for Cs-137. Analysis of Fig. 7 indicates again a very good prediction of the trend and, surprisingly, a correct prediction of the maximum value of the activity of Cs-137. This is evident especially in the later stage of the transport, namely after 1 May.

Fig. 7 is included to show that the model can handle Cs-137 as well as I-131. In the later stages of our discussion, because of limited space, we will present only time series for the Iodine. All conclusions concerning the time of arrival and prediction of the trends are essentially the same for both isotopes.

6.2. The second stage of the transport

The second stage of the transport took place between 1 and 7 May. The most important feature of this stage was the transfer of the radionuclides to the western part of the Northern Hemisphere, most efficient initially in the polar regions. Fig. 8a shows the position of the simulated radioactive cloud on the 1 May 1986. We note that the part of the cloud with a level of specific activity exceeding 1 Bq/kg had spread over most of Western Europe turning south over France. It is interesting to note that some part of the cloud with levels of activity less than 1 Bq kg^{-1} was centered over the North Atlantic; the western edge of the cloud was close to Hudson Bay as early as 1 May 1986, Fig. 8a. In the following days, the radioactive material was transported across the North Atlantic, Central Asia, the Middle East and North Africa. The general shape of the cloud during this period resembles the patterns observed in laboratory tracer experiments demonstrating the action of turbulent eddies on a passive contaminant. In our problem, this is simply a manifestation of the eddy-like character of cyclonic circulation systems as viewed in a large space–time frame. During the 1 to 7 May period, the total horizontal extent of the radioactive cloud was much larger than the characteristic scale of a typical weather system. This explains the observed eddy character of the transport on the hemispheric scale. The turbulent-like mixing by the low pressure systems was most prominent over the Atlantic Ocean as indicated by Figs. 8a, b. A closer examination of the shape of the cloud on 1 and 3 May shows explicitly the turbulent-like action of the cyclonic circulation system centered initially over the eastern part of the North Atlantic. The time scale of the mixing process when the eddies are synoptic scale cyclones is measured in days, not in seconds like in small scale turbulence. However the general similarity to the turbulent mixing is an excellent proof of the idea of considering synoptic scale lows as eddy-like structures (Hasselmann, 1976).

Another important feature which follows from the analysis of the second stage of dispersion is detection of the very early injection of a small amount of radioactive I-131 into the regions of western Quebec and eastern Ontario, Fig. 8b. It is seen as a very narrow part of the main arctic mass of the cloud which moved rapidly south and had almost reached Lake Ontario by the 3 May.

On the eastern edge of the cloud, located over Northern Asia steady westerly flow had been transporting radionuclides towards Japan. As shown in Fig. 8b, the edge of the cloud at the 850 mb level actually reached Japan on 3 May 12 GMT.

The evolution of the cloud at the 700 mb level is shown in Fig. 9. The most evident difference with the lower level transport is a slightly more complex pattern of the initial injection of the radioactive material to Canada. Additionally because of a more prominent westerly flow component, the transport over Asia and the Pacific

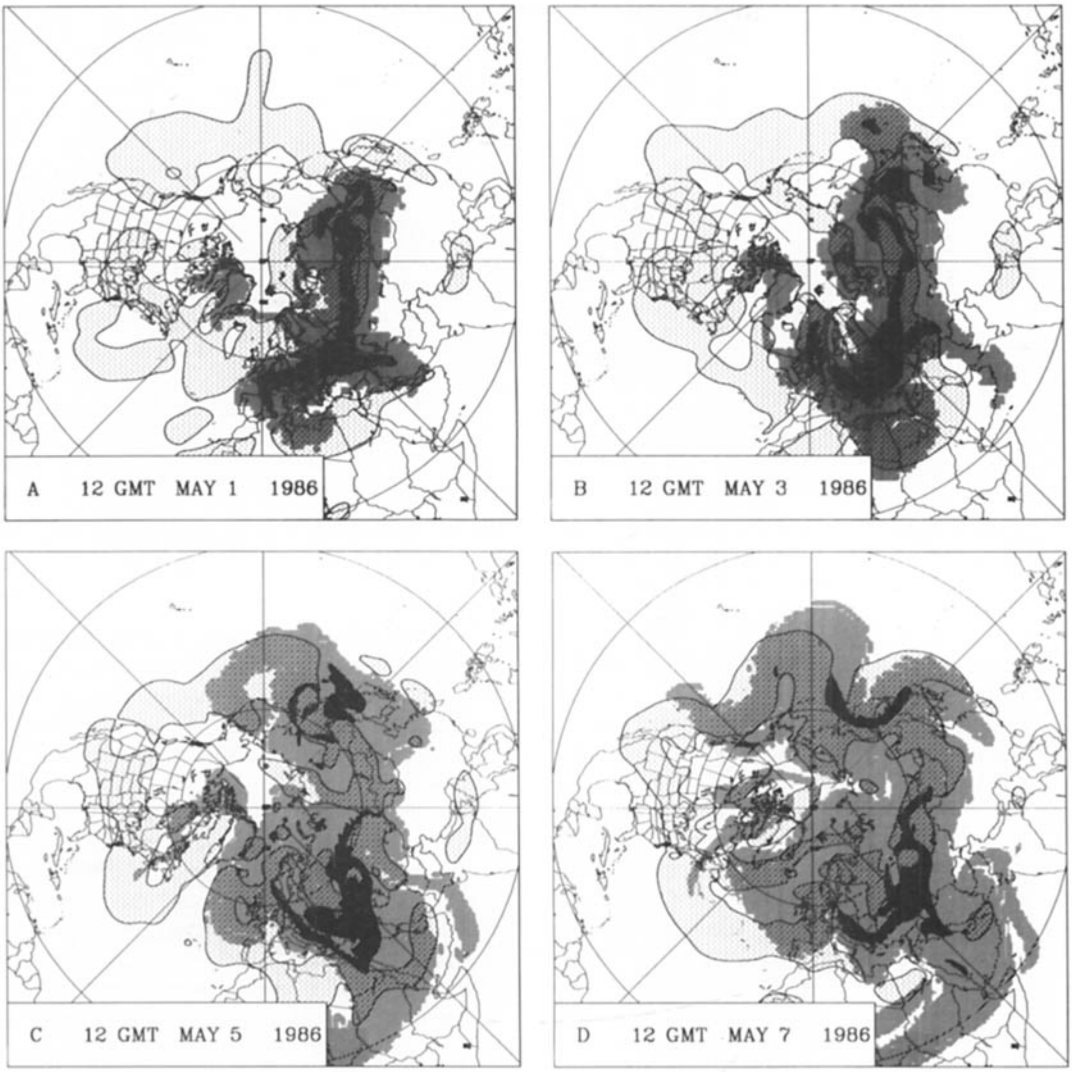

Fig. 8. Evolution of the radioactive cloud from Chernobyl during the second stage of the transport at the 850 mb level for I-131 and with the average scavenging rate $\Lambda = 2 \times 10^{-6}\ s^{-1}$. The patterns and isolines are described in the legend of Fig. 3.

Ocean is much more efficient than at lower levels, Figs. 9a–9d. At the end of the second stage of the transport, radionuclides at the 700 mb level approached the west coast of North America, Fig. 9d.

In order to verify the validity of the maps shown in Figs. 8, 9, we will present the model verification for the Canadian arctic station—Resolute. Comparison of the model results for I-131 at the 850 mb level to the surface measurements is shown in Fig. 10. It is easy to note that the model is again very good in predicting the time of arrival of the cloud at Resolute as well as depicting the general trend of the observed radioactivity. The verification of the time of arrival presented in Fig. 10 is an important experimental proof of the early polar injection of radioactive Iodine over Canada as indicated earlier in Fig. 8b.

A comparison of the model results at the 700

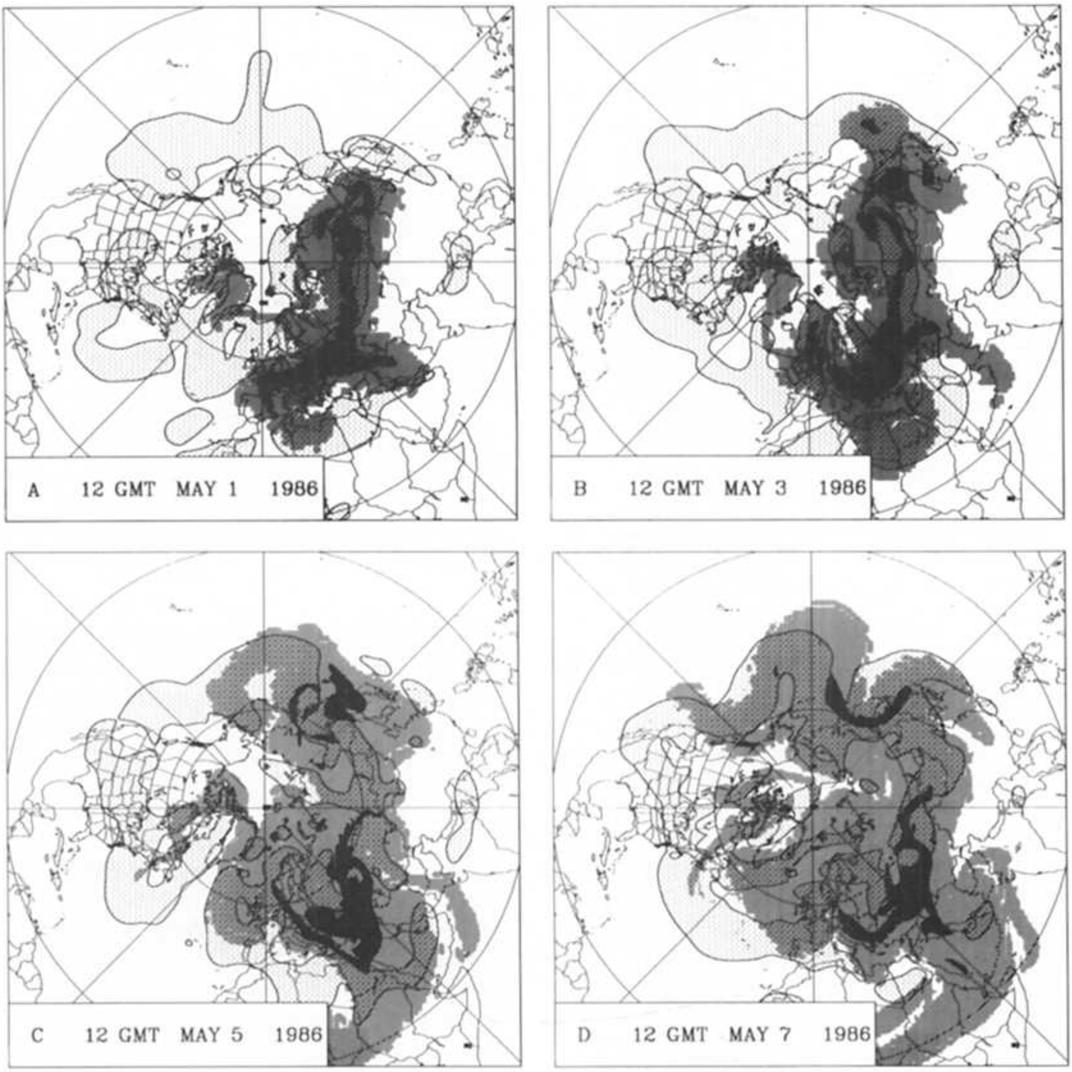

Fig. 9. Same as Fig. 8 but at 700 mb level.

mb level to the surface measurements is shown in Fig. 11. The time of arrival as indicated by Fig. 11a is good and corresponds to the situation displayed in Fig. 9a.

6.3. The third stage of the transport

The third stage of the transport began after 7 May when the arctic masses of the cloud at 850 mb moved south and, together with the Atlantic part of the cloud, were transported rapidly towards the East coast of North America.

As indicated in Fig. 12a, the edge of the simulated radioactive cloud at 850 mb had finally reached Canada almost two weeks after the Chernobyl accident. This was a second injection and at this time was much more serious than the short term injection discussed in the previous section and shown in Figs. 8b, 9b. In the following days the low pressure systems developing along the East coast of North America had been mixing part of the cloud located along the coast thereby increasing the spread of radioactive

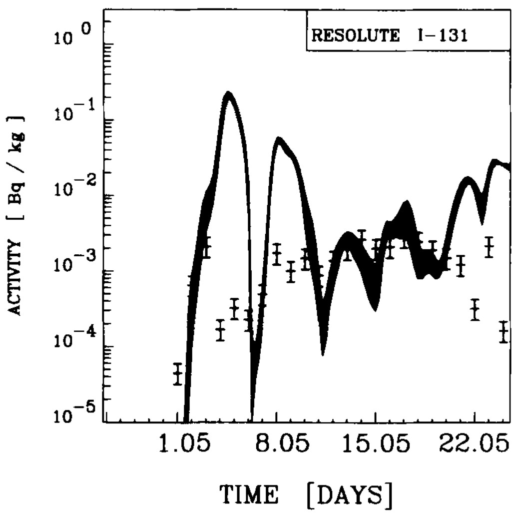

Fig. 10. Same as Fig. 5 but for Resolute. The relatively good time of arrival of I-131 at Resolute is confirmation of the validity of the maps shown in Figs. 8a and 8b.

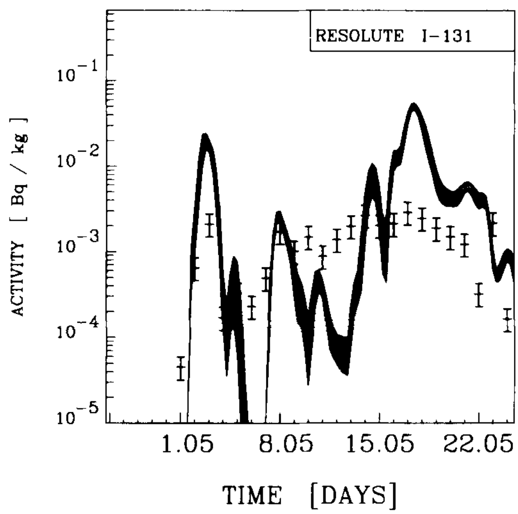

Fig. 11. Same as Fig. 5 but for Resolute with the model results at 700 mb.

material south. On 11 May the edge of the cloud had already reached Florida.

The part of the cloud transported over the Pacific at 850 mb was gradually approaching the west coast of North America. However, the amount of radioactive material transferred by this route was much smaller than over the Atlantic sector. Modelling the transport at lower levels, namely up to 2000 m above the surface, is insufficient to explain the large activities observed on the Canadian west coast. Figs. 13a and 13b show the cloud structure simulated at the upper 700 mb level. The analysis of the results indicates that in this case the most efficient transport occurred in the westerly direction, moving the radioactive cloud westerly across Asia and the Pacific Ocean towards North America.

A closer examination of Fig. 13a indicates distinct eddy-like patterns over the Pacific Ocean, very analogous to those observed at the lower level. However, the scale of the eddies is now much larger, especially in the Pacific sector of the radioactive cloud. On Figs. 14, 15 we present results for Halifax during the third stage of the transport when the radioactive cloud was intercepted in North America. The model results agree very well with measurements taken on the Canadian East coast, indicating the high accuracy of the dynamics and numerics of the model. Simulated and observed time series indicate that the predicted arrival of the main part of the cloud at Halifax is exact to within 6 h, Fig. 14. The first very small spike of the radioactivity shown by time series produced by the model corresponds to the polar injection on 3 May (Fig. 8b). The lack of this maximum in the measurements could be attributed to the underestimation of the scavenging over the North Atlantic and also to the lack of a proper representation of the deposition of the radioactive material. However, the model is again very good in depicting the trend and the duration of exposure at this particular receptor site. The analysis of the results for Halifax, Figs. 14, 15, indicates that for this receptor site, the surface measurements are much more coherent with the low level transport as confirmed by the analysis of maps shown on Figs. 8, 9, 12, 13. Verification of the model results for Vancouver is shown in Figs. 16, 17. It is easy to notice that the model simulation at 700 mb is more coherent with observations than for the 850 mb level, contrary to the situation at Halifax.

The general conclusion from the comparison of Figs. 14–17 is that the transport to the East coast could be explained by the simple isobaric advection at 850 mb whereas the transfer of the radioactive matter to the West coast requires additional analysis of the higher level.

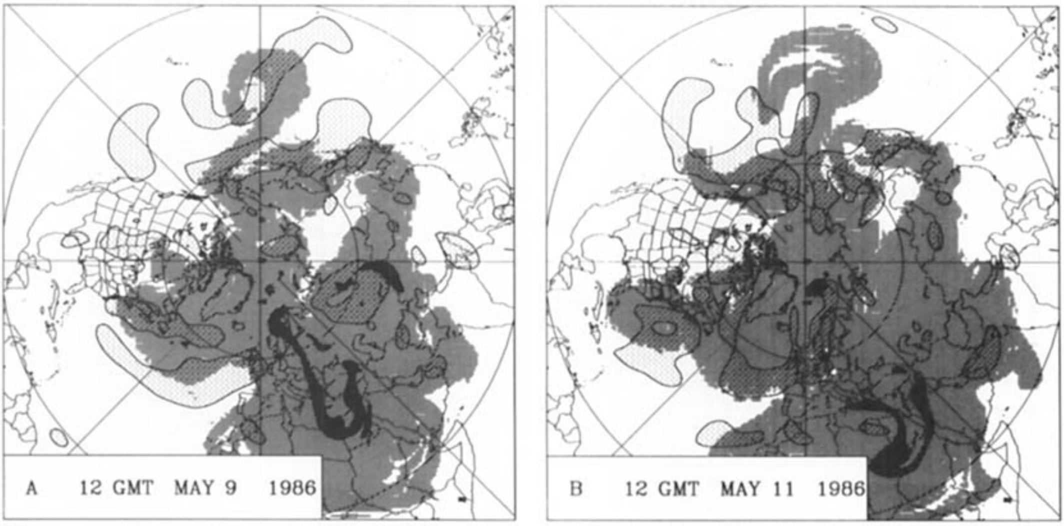

Fig. 12. Evolution of the radioactive cloud from Chernobyl during the third stage of the transport at 850 mb for I-131 and with the average scavenging rate $\Lambda = 2 \times 10^{-6}$ s^{-1}. The patterns and isolines are described in the legend of Fig. 3.

7. The sensitivity tests

The most critical parameter of our simple model is the coefficient Λ describing the average rate of removal of radioactive matter from the atmosphere. In order to investigate the sensitivity of the model to the particular choice of Λ, we reran all the experiments with different values of the average scavenging rate coefficient. The values investigated were in the range 1×10^{-6} to 5×10^{-6} s^{-1} corresponding to values of the half life time due to scavenging of 8 and 1.6 days, respectively.

The results of experiments for Iodine-131 are summarized in Tables 3 and 4 for 850 and 700 mb, respectively. The quantity presented in the tables is the correlation coefficient r defined by the following formula:

$$r = \frac{\sum_{i=1}^{N} (x_i - \bar{x})(y_i - \bar{y})}{\left(\sum_{i=1}^{N} (x_i - \bar{x})^2 \sum_{i=1}^{N} (y_i - \bar{y})^2 \right)^{1/2}}, \tag{14}$$

where:

N – number of points in the sample
x_i – logarithm of the observed activity
y_i – logarithm of the simulated activity
$(\bar{\ })$ – bar symbol indicates the time average value.

The correlation coefficient is thus a measure of the coherence between observed and simulated activities over the time period of our numerical simulation. Because of the extreme variability of the activities the correlation coefficient was computed for the logarithm of activities instead of the quantity itself. This we feel prevents biasing the results towards extremely large activities which are not most representative for our extended range simulation of the transport processes.

The first conclusion from the analysis of the data in Tables 3, 4 is that the transport to the different sampling points could be explained relatively well by isobaric advection at 850 and 700 mb levels. Namely the most significant transport level for Stockholm and Halifax was 850 mb, whereas for Vancouver it was 700 mb. For Resolute, located in the Canadian Arctic, the observed values of the activity of I-131 indicate strong correlation to the simulated values at both 700 mb and 850 levels. The last statement becomes clear when we consider Figs. 8, 9 showing the early polar injection of the radioactive matter to the Canadian Arctic, which took place on both analysed levels. After analysis of

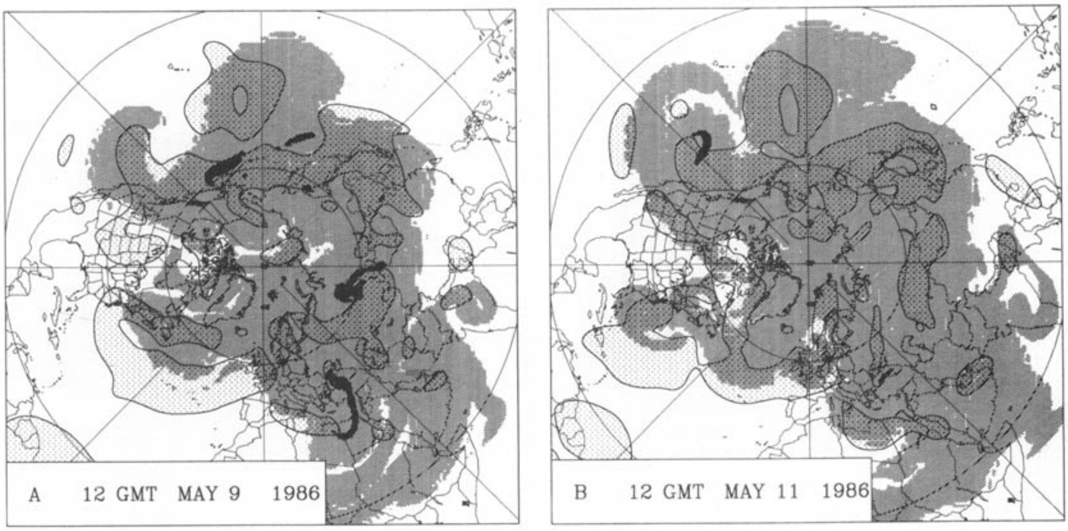

Fig. 13. Same as Fig. 12 but at 700 mb.

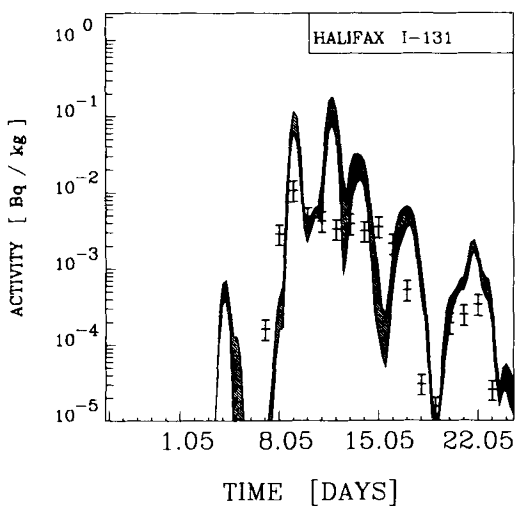

Fig. 14. Same as Fig. 5 but for Halifax. The time of arrival of the main Atlantic part of the cloud is excellent. The first small spike shown by the model corresponds to the latest stages of the early polar injection, Fig. 8c.

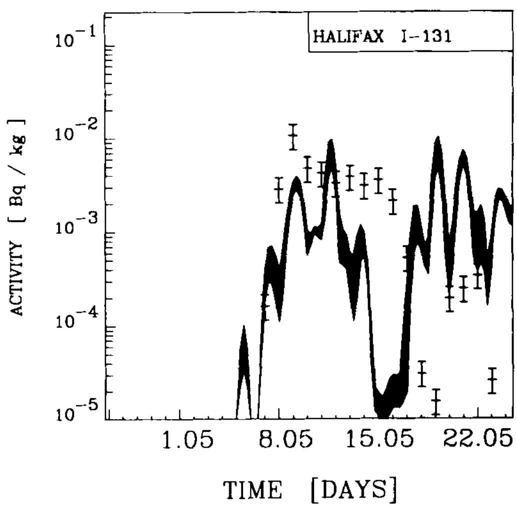

Fig. 15. Same as Fig. 5 but for Halifax with the model results at 700 mb.

the dependence of the correlation coefficient on Λ, performed at the significant transport level, we can readily notice the different behaviour of the model sensitivity for the close range and remote receptors.

The changes of the Λ don't affect significantly verification scores for Stockholm, whereas correlation at the remote receptors is very strongly dependent on the average scavenging rate.

The reason for this fact becomes clear when we notice that the total error of our simple model is a sum of three major terms. The first is the error of prediction of the average horizontal advection, the second is related to neglecting the vertical variations of the activity, finally the third is caused by a lack of explicit information about

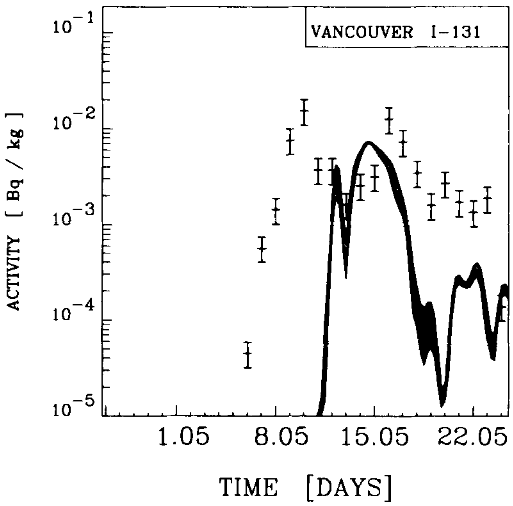

Fig. 16. Same as Fig. 5 but for Vancouver. The modelling of the transport of the I-131 at low levels is not sufficient to explain properly the arrival of radioactive matter at Vancouver.

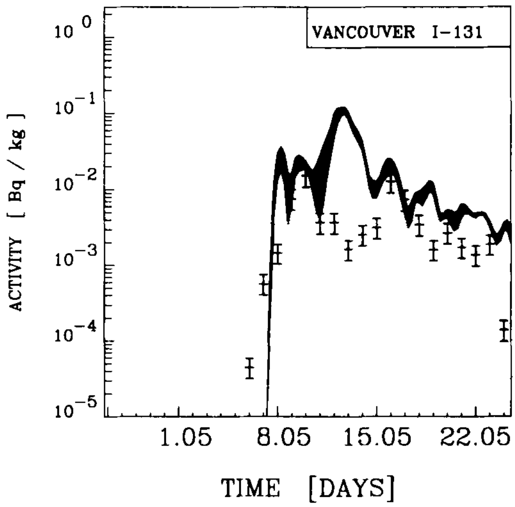

Fig. 17. Same as Fig. 5 but for Vancouver with the model results at 700 mb. Fig. 17 shows clearly that the simulation of the isobaric advection at 700 mb explains well the transport to the west coast of North America.

Table 3. *Correlation coefficient computed from the 850 mb runs with different values of Λ for I-131*

	$\Lambda = 5 \times 10^{-6}\ s^{-1}$	$\Lambda = 4 \times 10^{-6}\ s^{-1}$	$\Lambda = 2 \times 10^{-6}\ s^{-1}$
Stockholm	0.8150	0.8329	0.8177
Resolute	0.2606	0.4117	0.6540
Halifax	0.7033	0.7581	0.8538
Vancouver	0.3505	0.4273	0.5835

Table 4. *Correlation coefficient computed from the 700 mb runs with different values of Λ for I-131*

	$\Lambda = 5 \times 10^{-6}\ s^{-1}$	$\Lambda = 4 \times 10^{-6}\ s^{-1}$	$\Lambda = 2 \times 10^{-6}\ s^{-1}$
Stockholm	0.7069	0.7012	0.5516
Resolute	0.4131	0.5878	0.7619
Halifax	0.5310	0.6264	0.5274
Vancouver	0.6642	0.8232	0.9073

wet removal. For the receptors located in relatively close range to the source the error related to the deviation from the vertical homogeneity is most probably dominant. For the remote receptors, on the hemispheric scale, we can assume that the neglected vertical processes could be described as a stochastic random walk process (Papoulis, 1984), removing strong vertical variability of the activities of the I-131. Therefore for the remote receptors, the dominant term in the total error is related to the parameterization of the removal. This explains that the overall statistical performance of the model, measured by the correlation coefficient is much more dependent on Λ for the remote receptors than for the receptors located close to the source.

8. Conclusion

The results presented should be considered as a first approximation of the transport of the radioactive debris from the Chernobyl nuclear accident. However, the time series presented indicate clearly the relatively good accuracy of the transport model. Particularly, the model ability to predict accurately the time of arrival of the radioactive debris at Stockholm, Resolute, Halifax and Vancouver and the general trend in the time series at all receptor sites investigated reflects the accuracy of the employed numerical advection scheme and the quality of the analysed wind fields driving our transport model.

Despite the fact that isobaric advection on the 850 and 700 mb levels was sufficient to explain the time of the arrival and even the observed values of the activities at several receptor points spread over the Northern Hemisphere, we are aware that all the neglected processes given explicitly by eqs. (6)–(8), should be included.

The most important shortcoming of the present model is the assumption of a constant scavenging rate and the lack of a parameterization of the removal of the radioactive debris by rain. We are currently performing a more complete analysis of the environmental impact of the Chernobyl accident with a state-of-the-art version of the model such as described by eq. (1) including an explicit parameterization of the wet scavenging. The transport model is still driven by analysed meteorological fields along with a hemispheric Numerical Weather Prediction Model acting as a dynamic interpolator.

Considering the relatively good accuracy of the simple model, we can expect that the application of the more complex version could be helpful in solving the problem of estimating the amount of radioactive release using measured data about activities, even from remote receptors.

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