

# Is there a “continental shelf pump” for the absorption of atmospheric CO<sub>2</sub>?

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## ABSTRACT

Based on the results obtained in the East China Sea, we propose a new term, *Continental Shelf Pump*, as a mechanism for the absorption of atmospheric CO<sub>2</sub>. We investigated the carbonate system of the East China Sea along a single observation line traversing its central part on 5 cruises in various seasons. The directly observed fugacity of CO<sub>2</sub> dissolved in the surface water decreased with decreasing salinity and temperature as well as nutrient content. The relation has been expressed as a simple equation of these 3 parameters. Putting the observed data on the parameters in the various parts of the East China Sea in various months into this equation, we have obtained  $55 \pm 5$  ppm as an annual mean fugacity deficit of CO<sub>2</sub> in the surface water of the East China Sea, which nearly equals the directly measured mean fugacity along the observation line. The net absorption flux estimated from the fugacity deficit has agreed with the amount of carbonate transported out of the East China Sea calculated for the distributions of total dissolved carbonate and alkalinity. The distributions of density and total dissolved carbonate reveal the cause of this large deficiency, described as follows. The shallower shelf zone is more cooled than the open sea when heat is lost from the surface. This cooling produces denser water, which together with photosynthetic activity, accelerates the absorption of CO<sub>2</sub> in the shelf zone. The absorbed CO<sub>2</sub> is transformed to organic carbon and regenerated especially at the shallow bottom. Isopycnal mixing (advection and diffusion) transports the denser coastal water, especially the bottom water enriched in dissolved and particulate carbon, into the subsurface layer of the open oceans. The transport continues in the layer below the pycnocline even in the warm season and maintains the low fugacity of CO<sub>2</sub> in the surface water of the shelf zone. This is the continental shelf pump. The pump would account for a net oceanic uptake of CO<sub>2</sub> of 1 GtC/yr, if the world continental shelf zone would absorb the atmospheric CO<sub>2</sub> at the rate observed in the East China Sea.

## 1. Introduction

Continental shelf zones are usually active in biological production as summarized in IGBP (1993) and may have a significant rôle in the net absorption of atmospheric CO<sub>2</sub>, although they comprise only 7.6% of the surface area of the world oceans (Sverdrup et al., 1942). However, if the CO<sub>2</sub> fixed by photosynthesis is not transported

to open oceans, the absorption of CO<sub>2</sub> would be cancelled by the regenerated CO<sub>2</sub>, because the burial rate of organic carbon in coastal sediments is much less than primary production in the shelf zone. We have examined this problem in the East China Sea.

The East China Sea is the 3rd largest marginal sea in the world, of which 70% ( $0.9 \times 10^6$  km<sup>2</sup>) is the continental shelf zone shallower than 200 m depth, accounting for 3.2% of the world continental shelf area ( $27 \times 10^6$  km<sup>2</sup>). Its chemical hydro-

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graphy and dynamics have been fairly well studied (Edmond et al., 1985; Wong et al., 1989; Liu et al., 1992; Tian et al., 1993; Ito et al., 1994; Gong et al., 1996), but its carbonate system has been little investigated except for our preliminary study (Tsunogai et al., 1997), where we reported the results obtained from the 1st 2 of a total of 5 cruises presented here. We determined the fugacity (expressed conventionally in ppm) of  $\text{CO}_2$  dissolved in the surface water together with the water column distributions of the total dissolved inorganic carbonate, alkalinity, pH, dissolved oxygen and nutrients, as well as other hydrographic properties such as salinity and water temperature during all 5 cruises. This work is a part of the Japan–China cooperative study, the Marginal Sea Flux Experiment in the West Pacific (MASFLEX). The chief purpose of this program is to clarify quantitatively the behavior of greenhouse gases in the continental shelf water.

## 2. Methods of observation and chemical analyses

Cruises for the observations were carried out 5 times, in February 1993, October 1993, August

1994, November 1995 and September 1996, each for about 20 days inside the East China Sea (Fig. 1). The fugacities of dissolved  $\text{CO}_2$  were measured for the equilibrated air in an equilibrator of about 10 liters with an NDIR detector during sailing (Tsunogai et al., 1997). The main observation line was “PN line” connecting a station in the Kuroshio region (Sta. 1 at  $27^\circ 30' \text{N}$ ,  $128^\circ 15' \text{E}$ ) and a station near the China coast (Sta. 12 at  $31^\circ 12' \text{N}$ ,  $123^\circ 05' \text{E}$ ) in the central East China Sea across the shelf break. Unfortunately, we could not enter the region within 100 km of the Chinese coast, and we occupied 7 observation lines in the shelf break region instead of the PN line during the 5th cruise. On the PN line, we occupied 12 or 14 stations (Fig. 1) for the collection of discrete water samples from various depths at every 10-m interval, at the stations on the shelf. The 1st 3 stations were located in the Kuroshio region and the 4th one was at its edge. The water samples were analyzed for total dissolved inorganic carbon, pH, alkalinity as well as salinity, water temperature, dissolved oxygen and nutrients on board the vessel, R/V Kaiyo of the Japan Marine Science and Technology Center. The detailed sampling and analytical methods and the preliminary results

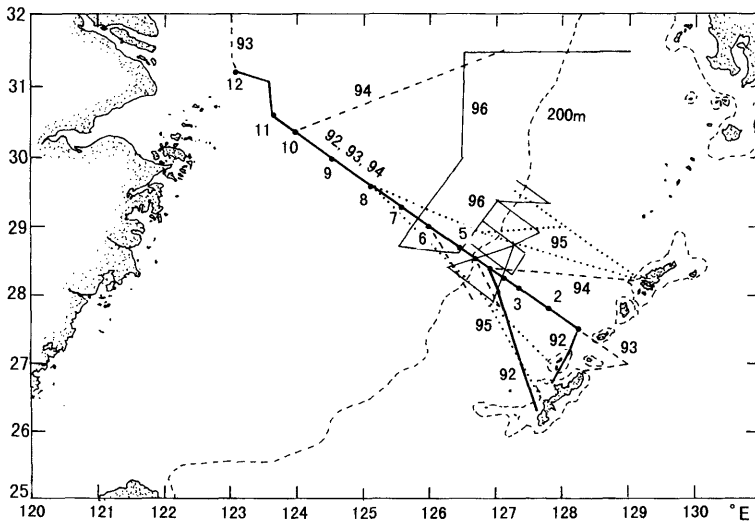


Fig. 1. The East China Sea with isodepth lines of 0 and 200 m dividing the continental shelf zone. The lines are the cruise tracks on which the fugacity of  $\text{CO}_2$  dissolved in the surface water was measured. The numerals attached to the lines, 92, 93, 94, 95 and 96 refer to the observation periods of February 1993, October 1993, August 1994, November 1995 and September 1996, respectively. The solid circles with numerals from 1 to 12 along the PN line refer to the stations with their numbers for measuring the water column inventories of various dissolved components.

have been reported in Tsunogai et al. (1997). The total carbonate concentration was determined with a coulometer by the procedure described in Tsunogai et al. (1993), and we did not employ any special procedure for other components, but all were analyzed on board the vessel. The data used in this study have been partly published together with many other components (Iseki, 1993; Kusakabe, 1993; Yamada and Iseki, 1995) and the whole data set will be distributed in future by JODC (Japan Oceanographic Data Center).

### 3 Results and discussion

#### 3.1. Parameterization of observed $f(\text{CO}_2)$ values

Fig. 2 shows the fugacities of CO<sub>2</sub> dissolved in the surface water,  $f(\text{CO}_2)$ , measured at stations along the PN line, where the discrete sea water samples were collected. The observed  $f(\text{CO}_2)$  values temporally (seasonally) and spatially (longitudinally) varied widely, ranging from 278 to 388 ppm, while the atmospheric CO<sub>2</sub> concentration was  $360 \pm 5$  ppm. The air-sea difference in the fugacity was large, up to 80 ppm undersaturated, in the continental shelf water which was generally undersaturated, while the difference was not large and sometimes oversaturated in the Kuroshio water (Fig. 2). For the seasonal variation, the  $f(\text{CO}_2)$  values were high in August and low in February. We can recognize a similarity between  $f(\text{CO}_2)$  and temperature in their longitudinal variations, if we compare those in August and February (Fig. 2). This seems to be due to the fact that the  $f(\text{CO}_2)$  values primarily reflect the temperature effect, where the solubility of CO<sub>2</sub> decreases with increasing water temperature, although the effect should decrease when the system approaches equilibration.

The  $f(\text{CO}_2)$  values were extremely low at Station 12 near the coast in August and at Stations 11 and 12 in October, where the salinities were also extremely low (Fig. 2). We can also see some similarity between  $f(\text{CO}_2)$  and salinity in their longitudinal variations, if we compare those in August and October (Fig. 2). This coincidence can be explained by the mixing of fresh water containing nutrients, which reduces salinity and  $f(\text{CO}_2)$  by combination of CO<sub>2</sub> with carbonate ion and by photosynthetic uptake of its nutrients and CO<sub>2</sub>. The undersaturated surface water near

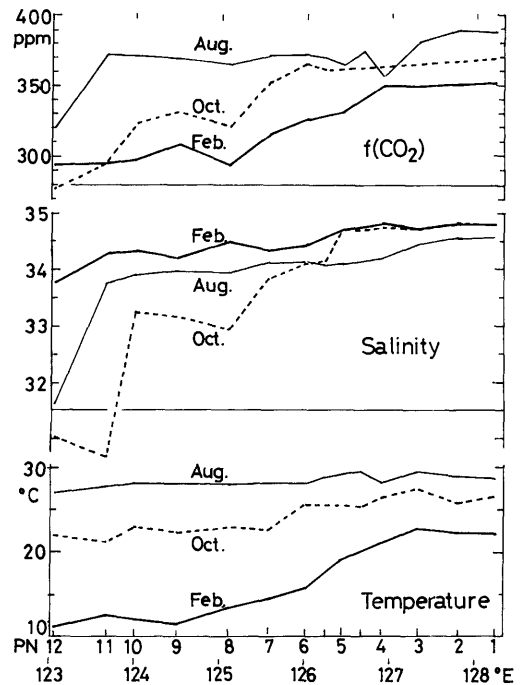


Fig. 2. The fugacity of dissolved CO<sub>2</sub> ( $f(\text{CO}_2)$ ) (ppm), salinity and water temperature (°C) in the surface water observed at the stations on the PN line. The labels to the lines, February (the thick solid line), October (the broken line) and August (the thin solid line), refer to the observation periods of February 1993, October 1993 and August 1994, respectively. The left-hand side around 123°E, is near the mouth of Changjiang (Yangtze River) and the right-hand side around 127°E, is the Kuroshio region.

the coast (Fig. 2) should absorb CO<sub>2</sub> before attaining the equilibrium state. The observed low  $f(\text{CO}_2)$  values also indicate that both the effects of cooling in the shelf zone and mixing of fresh (river) water still remain against the carbonate equilibration, which depends on the gas exchange at the surface and the vertical mixing. These findings suggest that the  $f(\text{CO}_2)$  values vary as a function of, at least, water temperature and salinity in the shelf zone.

A deviation from the above tendency, depending only on salinity and temperature, occurred in November 1995, showing high  $f(\text{CO}_2)$  values in the surface water in a limited area of the continental shelf zone, the salinity and temperature not changing significantly (Fig. 3). Fig. 3 also shows the longitudinal variations of phosphate and total

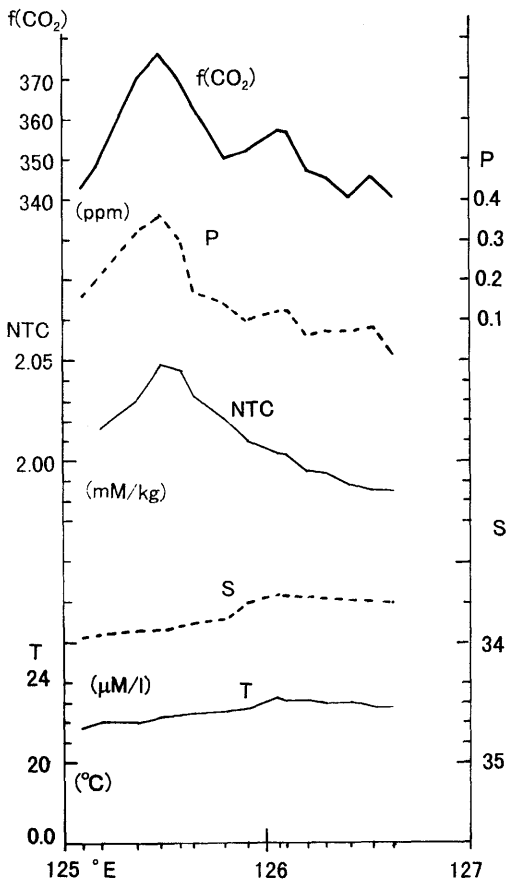


Fig. 3. The fugacity of dissolved  $\text{CO}_2$  ( $f(\text{CO}_2)$  (ppm)), phosphate ( $P$  ( $\mu\text{molP/kg}$ )), total carbonate normalized to 35 salinity (NTC (mmolC/kg)), salinity ( $S$  (no unit)), and water temperature ( $T$  ( $^\circ\text{C}$ )) observed on 19 November 1995 along a line near the PN line. The short lines displayed on the abscissa denote the longitudes of the surface water sampled.

carbonate similar to that of the  $\text{CO}_2$  fugacity. This is probably due to the turbulent mixing of the surface water, the subsurface water comparatively rich in the decomposition products of biogenic particles, which were brought up to the surface by storms or surface cooling in autumn and winter. Indeed, the sea surface was generally rough during the cruise. In particular, on 7 November 1995, 12 days before the observation, strong wind blew from a large high-pressure of 1046 hPa over the Asian continent toward a surprisingly low-pressure of 946 hPa in the Sea of Japan. This effect of

turbulent mixing on the  $f(\text{CO}_2)$  values may be evaluated by considering the concentration of nutrient. As a conclusion, the surface  $f(\text{CO}_2)$  values in the East China Sea vary approximately with a function of the surface water temperature, salinity and nutrient.

To examine the above conclusion quantitatively, we have applied a least squares method to the data obtained in the surface water of the East China Sea given in Table 1 and succeeded in expressing the observed fugacities with a simple function involving the 3 components, temperature ( $T$ ), salinity ( $S$ ) and phosphate ( $P$  ( $\mu\text{g atom/l}$ )) as follows:

$$f(\text{CO}_2)_{\text{calc}} = 6.85T + 16.10S + 99P - 372 \text{ (ppm)},$$

where  $f(\text{CO}_2)_{\text{calc}}$  is the calculated fugacity of  $\text{CO}_2$  (ppm). We have conventionally chosen phosphate rather than nitrate, because the data on phosphate are more abundant, and the Kuroshio region is famous for the blooming of blue-green algae, *Trichodesmium*, being able to fix elemental nitrogen (Asaoka, 1975). In Table 1, the observed and calculated values are compared, and the standard deviation of the differences between them is 6.6 ppm, which is about 2% of the  $f(\text{CO}_2)$  value. The standard deviation is much smaller than the observed variation or range in the shelf region.

The coefficient of the above temperature dependent term (6.85) corresponds to about half of the full temperature change effect, or half the equilibration value ( $360 \text{ ppm} \times 4\%/^\circ\text{C}/2 = 14 \text{ ppm}/^\circ\text{C}/2$ ). The phosphate-dependent term is also approximately half the equilibration value, if the usual biological uptake has occurred, namely proportionally with a ratio of  $C/P = 106$  in atomic ratio (Redfield et al., 1963). The regeneration of  $1 \mu\text{g atom/kg}$  of phosphate increases total dissolved carbonate by  $106 \mu\text{g atom/kg}$  or about 5% ( $106/2000$ ). Assuming the atmospheric  $\text{CO}_2$  concentration of 360 ppm and the Revelle factor of 11, we obtain the  $f(\text{CO}_2)$  increase without gas exchange,  $x$ , to be

$$11 = (x/360)/0.05$$

or

$$x = (360 \times 11) \times 0.05 = 200 \text{ ppm}.$$

The regression equation indicates that the  $f(\text{CO}_2)$  value actually increases by 99 ppm per  $1 \mu\text{g atom/kg}$  of phosphate increase (99P), which is

Table 1. Observed and calculated  $f(\text{CO}_2)$  values, and their differences in the surface water

Date	Station no.	$T$ (°C)	$S$	$P$ (μmol/kg)	$f(\text{CO}_2)$ obs. (ppm)	$f(\text{CO}_2)$ calc. (ppm)	Difference (ppm)
22 Feb. 93	1	22.0	34.80	0.06	351.4	345.3	6.1
21 Feb. 93	2	22.2	34.80	0.04	350.3	344.7	5.6
25 Feb. 93	4	21.2	34.79	0.11	349.4	344.6	4.8
25 Feb. 93	5	19.2	34.74	0.18	330.4	337.0	-6.6
27 Feb. 93	6	15.7	34.42	0.36	325.5	325.6	-0.1
5 Mar. 93	7	14.5	34.32	0.33	314.9	312.8	2.1
3 Mar. 93	8	13.4	34.49	0.27	293.8	302.1	-8.3
2 Mar. 93	9	11.5	34.21	0.50	306.8	307.2	-0.4
28 Feb. 93	10	12.1	34.34	0.40	297.1	303.6	-6.5
28 Feb. 93	11	12.4	34.40	0.38	295.4	303.0	-7.6
1 Mar. 93	12	10.8	33.80	0.40	277.8	286.0	-8.2
4 Aug. 94	0	29.0	34.78	0.00	389.9	387.1	2.8
7 Aug. 94	1	28.7	34.55	0.01	386.4	382.3	4.1
5 Aug. 94	2	28.8	34.57	0.01	388.0	383.3	4.7
5 Aug. 94	3	29.4	34.44	0.01	380.3	385.3	-5.0
12 Aug. 94	4	28.2	34.22	0.00	356.0	372.6	-16.6
12 Aug. 94	4.5	29.4	33.89	0.00	374.0	375.5	-1.5
15 Aug. 94	5	29.1	34.10	0.00	364.4	376.8	-12.4
14 Aug. 94	5.5	28.8	34.09	0.00	369.1	374.6	-5.5
14 Aug. 94	6	28.2	34.16	0.00	371.7	371.6	0.1
16 Aug. 94	7	28.1	34.18	0.00	370.5	371.2	-0.7
23 Aug. 94	8	28.0	33.97	0.00	364.4	367.2	-2.8
17 Aug. 94	9	28.1	33.96	0.07	368.7	374.6	-5.9
17 Aug. 94	10	28.1	33.91	0.10	370.9	376.7	-5.8
24 Aug. 94	11	27.8	33.92	0.10	370.7	374.8	-4.1
25 Aug. 94	12	27.0	31.64	0.10	320.0	332.7	-12.7
9 Oct. 93	1	26.5	34.79	0.05	368.3	375.0	-6.7
16 Oct. 93	5	25.5	34.32	0.02	365.7	357.6	8.1
17 Oct. 93	5.5	25.6	34.13	0.03	360.7	356.2	4.5
17 Oct. 93	6	25.5	34.11	0.04	365.8	356.2	9.6
21 Oct. 93	7	24.3	33.82	0.02	350.9	341.4	9.5
20 Oct. 93	8	22.8	32.93	0.05	320.3	319.7	0.6
19 Oct. 93	9	22.4	33.15	0.14	330.0	329.4	0.6
18 Oct. 93	10	23.0	33.24	0.01	323.7	322.1	1.6
22 Oct. 93	11	22.0	31.76	0.01	295.3	291.4	3.9
22 Oct. 93	12	21.5	31.44	0.02	294.6	283.9	10.7
19 Nov. 95	4.3	22.8	34.49	0.01	340.8	340.9	-0.1
19 Nov. 95	4.7	22.8	34.51	0.08	345.5	348.1	-2.6
19 Nov. 95	5	23.0	34.53	0.07	340.3	348.8	-8.5
19 Nov. 95	5.3	23.0	34.54	0.07	345.4	349.0	-3.6
19 Nov. 95	5.7	23.1	34.56	0.06	347.3	349.0	-1.7
19 Nov. 95	6	23.1	34.56	0.12	356.8	354.9	1.9
19 Nov. 95	6.2	23.2	34.57	0.12	357.1	355.7	1.4
19 Nov. 95	6.4	22.7	34.49	0.10	352.2	349.1	3.1
19 Nov. 95	6.6	22.5	34.27	0.14	350.1	348.1	2.0
19 Nov. 95	6.8	22.4	34.24	0.17	363.5	349.9	13.6
19 Nov. 95	6.9	22.3	34.21	0.30	369.8	361.5	8.3
19 Nov. 95	7	22.2	34.15	0.36	376.2	365.8	10.4
19 Nov. 95	7.3	22.0	34.14	0.32	371.1	360.3	10.8
19 Nov. 95	7.7	22.0	34.10	0.21	349.8	348.8	1.0
19 Nov. 95	8	21.7	34.06	0.16	343.2	341.2	2.0

The calculation has been done by introducing the observed surface water temperature ( $T$ ), salinity ( $S$ ) and phosphate concentration ( $P$ ) into the equation given in the text.

also half the equilibration value. The equation further indicates that 1 unit of salinity decrease through diluting with 3% of river water will decrease the  $f(\text{CO}_2)$  value by 16 ppm. This can be expected from the fact that the dilution reduces the equilibrium  $f(\text{CO}_2)$  with a rate of 4%/one unit of salinity, and the addition of nutrients from river water reduces  $f(\text{CO}_2)$  after the photosynthetic uptake of nutrients and  $\text{CO}_2$ .

These 3 numerals of the coefficients do not therefore seem to be unreasonable when we consider the gas exchange rate, the residence time of water, the vertical mixing and the biological production processes in the East China Sea. Of course, this equation is rather fortuitously obtained and peculiar to the East China Sea, a simple water system where the Kuroshio water of almost constant salinity and less variable temperature is the only source of saline water and the yearly precipitation is almost balanced by the yearly evaporation within the sea (Yanagi, 1994); however, it may be worthwhile to examine the relation in other seas and oceans.

The above empirical regression equation is next applied to other dates and places in the entire East China Sea by introducing the available data on water temperature, salinity and phosphate in the surface water. Besides the published papers cited above, we have utilized the hydrographic data observed operationally by Nagasaki Marine Observatory (1992–1994) and Seikai National Fisheries Research Institute (1992–1996). The satellite images have provided abundant data on the water temperature, but the data on phosphate are limited. Fortunately the concentrations of phosphate are usually low and not very significant in the calculated  $f(\text{CO}_2)$  values.

Fig. 4 shows the distributions of  $f(\text{CO}_2)$  in February and August reproduced with the regression equation and the observed data on the parameters. In February (Fig. 4A), when the  $f(\text{CO}_2)$  is at a minimum, the higher  $f(\text{CO}_2)$  values around 350 ppm are found in the southern Kuroshio region and the lower ones, less than 220 ppm, are found in the northern part and the region off Changjiang. The pattern in the central part is due

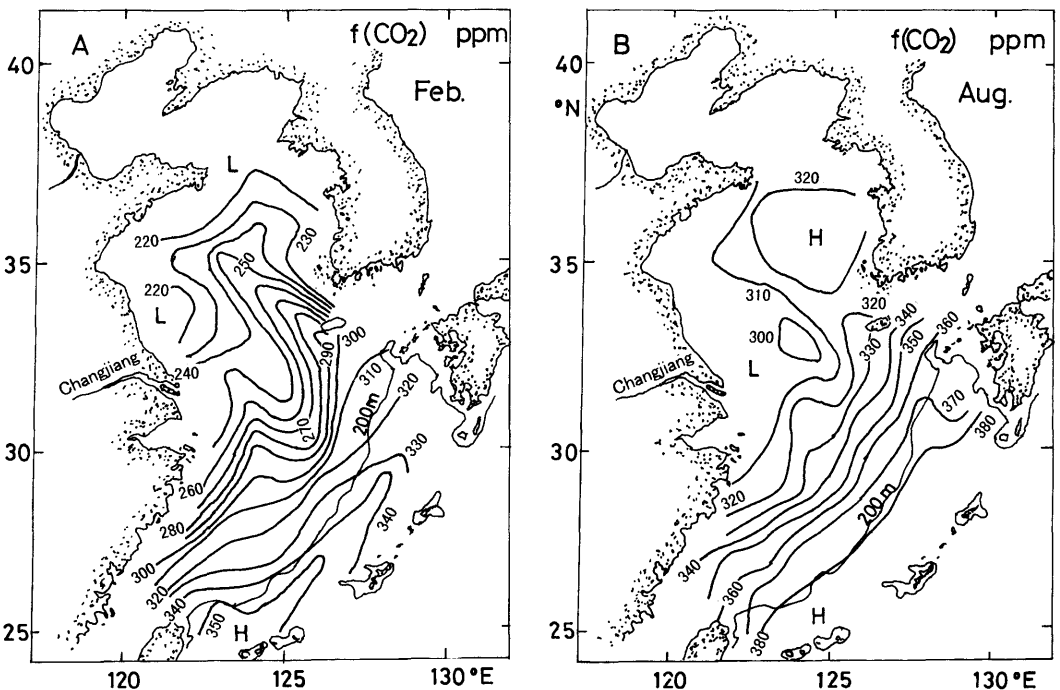


Fig. 4. Distribution of reproduced  $f(\text{CO}_2)$  values (ppm) in February (A: Feb.) and August (B: Aug.) in the East China Sea including the Yellow Sea.

to a Kuroshio branch flowing into the north-western part and returning toward the southeast. It is interesting to note that the  $f(\text{CO}_2)$  decreases or the air-sea difference increases with flow. In August (Fig. 4B) when the  $f(\text{CO}_2)$  is maximum, the Kuroshio water is supersaturated with respect to the atmospheric CO<sub>2</sub>, but the lower  $f(\text{CO}_2)$  values, less than 300 ppm, are found in the region off Changjiang. The isopleths of  $f(\text{CO}_2)$  are almost parallel to the 200 m isodepth line, the boundary of the continental shelf. The spatial variation in August is smaller than that in February, and the longitudinal variation is generally larger than the latitudinal variation, although the  $f(\text{CO}_2)$  decreases toward the north.

We have obtained the total mean deficiency in the  $f(\text{CO}_2)$  value of the East China Sea surface water to be  $55 \pm 5$  ppm in its continental shelf zone south of 36°N and east of 123°E. In the estimate, we have first computed the monthly mean values of the 3 parameters independently for every 1° longitude interval in the continental shelf zone of the East China Sea, using more than 1000 observed data. The uncertainty of the mean value, 5 ppm, is simply 3% (which is a reciprocal of the square root of 1000) of the range, 150 ppm. This total mean  $f(\text{CO}_2)$  value coincides fairly well with a mean value obtained during the 1st 2 cruises, 50 ppm, reported previously (Tsunogai et al., 1997).

A deficiency of 55 ppm in the  $f(\text{CO}_2)$  value gives a net absorption rate of 35 gC/m<sup>2</sup>/yr or 1.0 GtC/yr over the entire continental shelf area of the world oceans, if the CO<sub>2</sub> exchange rate is 15 mol/m<sup>2</sup>/yr in the preindustrial era (280 ppm) or the gas exchange velocity is 2.5 m/day, which is 70% of a world mean value of 21 mol/m<sup>2</sup>/yr obtained from the natural <sup>14</sup>C balance (Broecker et al., 1960; Tsunogai, 1989; Tsunogai et al., 1997). The 30% reduction is only a tentative assumption. The gas exchange rate in the shelf region may be somewhat smaller than that in the open oceans, because it depends on the sea surface roughness or wind waves which grow with increasing fetch (Ebuchi et al., 1992). This is supported by the smaller gas exchange velocity of 1.5 m/day or somewhat more depending on the proportion of the surface relating to the Japan Sea Proper Water, obtained from the vertical profile of radiocarbon in the Sea of Japan (Tsunogai et al., 1993). This CO<sub>2</sub> flux agrees with the dissolved carbonate flux

from the East China Sea to the open sea obtained in our previous paper (Tsunogai et al., 1997). According to the paper, the amounts of total dissolved carbonate transported from the East China Sea to the pelagic ocean is 70 gC/m<sup>2</sup>/yr for the continental shelf area, which is obtained from the distribution of total carbonate and the residence time of water in the East China Sea, and a sum of the atmospheric input and the river input of bicarbonate and terrestrial organic matter decomposed. The residence time,  $0.8 \pm 0.3$  years, has been obtained from the alkalinity budget. The alkalinity budget also gives the river input of bicarbonate of 20 gC/m<sup>2</sup>/yr for the East China Sea continental shelf area. Some terrestrial organic matter decomposed within the sea could share the above total outflux, and the sedimenting flux of organic carbon should be considered (Chen, 1996).

### 3.2. *Continental shelf pump: the reason why the East China Sea absorbs so much CO<sub>2</sub>*

The large CO<sub>2</sub> absorption flux obtained in the East China Sea can be understood by considering the distribution of water properties. Fig. 5 shows the sectional distribution of density in February, October and August along the PN line. In October and August, the shelf water was strongly stratified, but the density surfaces of the subsurface water on the shelf were shallower than those in the Kuroshio region. This implies that the isopycnal mixing, including diffusion and advection, transports the shelf subsurface water into the deeper layer of the Kuroshio region. In February, the winter cooling produced the well-mixed denser waters on the shelf, and the isopycnal mixing also sends the waters into the deeper layers of the Kuroshio water. Of course, the isopycnal mixing including advection does not mean that occurring only along the PN observation line, but that occurring in the whole East China Sea including advective flow into the Japan Sea and the Kuroshio region.

Furthermore, Fig. 6 plotting the normalized total carbonate (NTC) to a salinity of 35 against the density and the distance from the coast (longitude), tells us that the isopycnal mixing induces a net transport of dissolved inorganic carbon to the open sea. The normalization is essential for depiction of a component having a small non-conservative nature like dissolved carbonate. All the 3

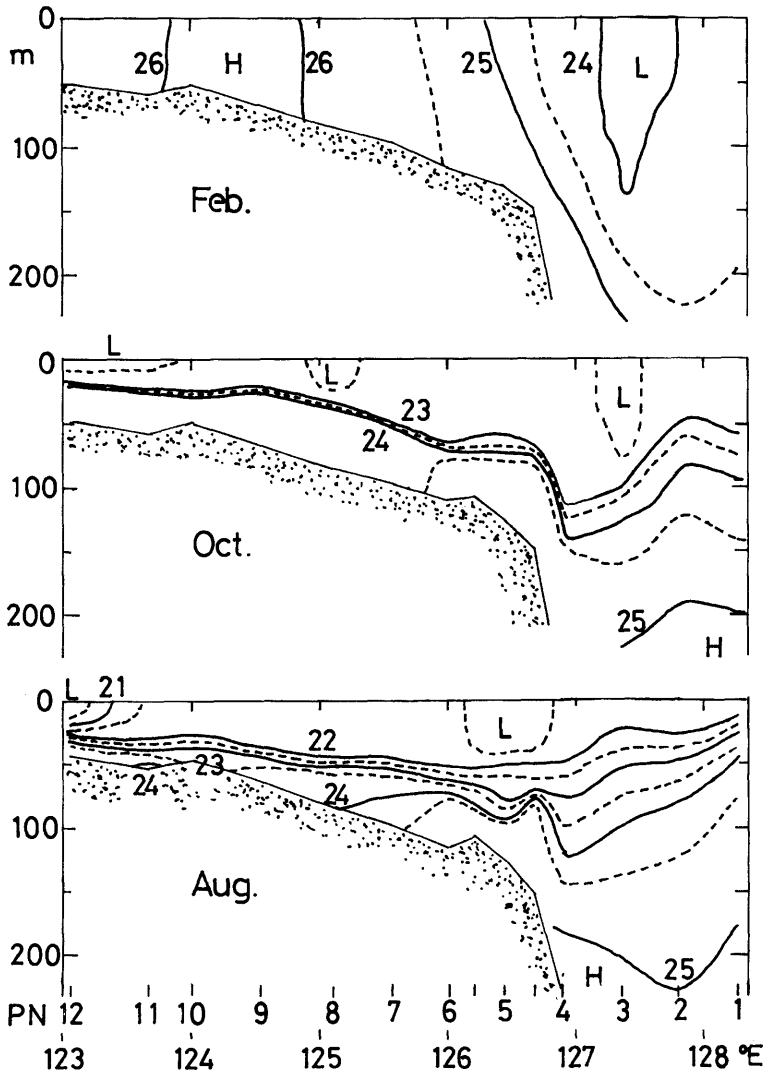


Fig. 5. 3 sections of density ( $\sigma_t$ ) along the PN line in February 1993 (Feb.), October 1993 (Oct.) and August 1994 (Aug.). The bottom depths at the respective stations are also connected.

profiles in February, October and August indicate the increase in NTC from the Kuroshio region toward the coast. The largest increase exceeded  $200 \mu\text{molC/kg}$  at the  $\sigma_t$  surface of 24 in October. The large increase in October and August is primarily due to the biological pump, namely the formation of organic particles in the euphotic layer and the regeneration in the subsurface layer, because the dissolved oxygen content was depleted in the shelf-bottom water. The increase in

February, however, about  $80 \mu\text{molC/kg}$ , is largely due to the solubility pump or the winter cooling except at Station 12, because the water was saturated with dissolved oxygen and the normalized alkalinity increase between Stations 11 and 4 was  $40 \mu\text{eq/kg}$ , corresponding to a  $20 \mu\text{molC/kg}$  increase. In October and August, the tendency of increasing dissolved carbonate toward the coast still remains, even after subtracting the effect of the biological activity using the dissolved oxygen



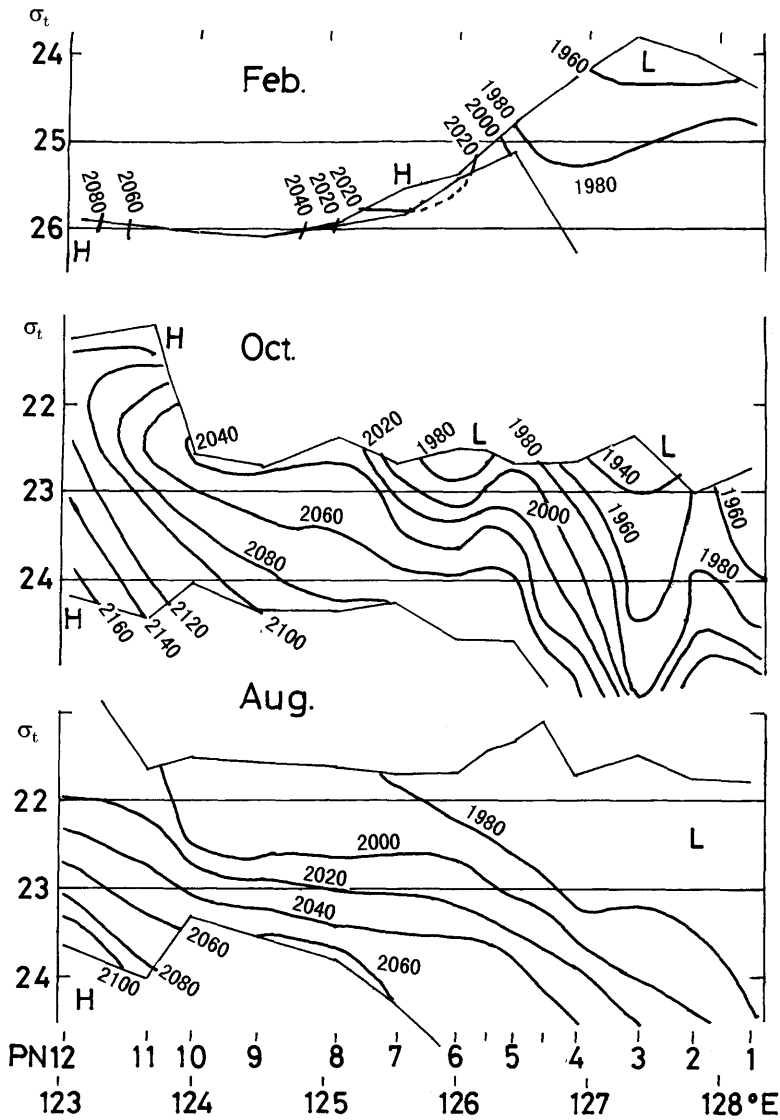


Fig. 6. 3 sections of total dissolved inorganic carbon normalized to salinity of 35 ( $\mu\text{g atom/kg}$ ) shown against density ( $\sigma_t$ ) along the PN line in February 1993 (Feb.), October 1993 (Oct.) and August 1994 (Aug.). In February 1993, the water undersaturated in the oxygen content is excluded, which was found in the Kuroshio region below 150–200 m depth.

contents and the Redfield ratio ( $C/O = 106/276$ , Redfield et al., 1963). The increase in the subtracted NTC in the shelf zone relative to that in the Kuroshio region is 50–100  $\mu\text{molC/kg}$ , although the increase in October is larger than that in August. The increase due to bicarbonate in river water is 0–50  $\mu\text{molC/kg}$ , indicating that

the solubility pump is working for the shelf subsurface water even in the warm season.

Summarizing the above findings, we would like to propose a new term, the continental shelf pump, as an explanation of the observed large net absorption of CO<sub>2</sub> in the East China Sea. The scenario is as follows. The surface water after releasing heat

to the atmosphere is cooled in mid- and high-latitudes, and even in low-latitudes in winter. The cooling is greater in the shallower continental shelf zones, because the bottom prevents the further convection of cooled water. This cooling in the continental shelf zone dissolves more atmospheric  $\text{CO}_2$ , but the formation of denser water is more important for the pump. The continental shelf zones are usually biologically more active. The high biological activity accelerates the absorption of atmospheric  $\text{CO}_2$ , but this condition is not necessarily essential for the pump, because the shelf water always has a higher concentration of dissolved carbonate regenerated at its shallow bottom, as compared to the open sea water. Finally, the isopycnal mixing, including advection and diffusion of the shelf water with the deeper open sea water, makes the net transport of dissolved inorganic carbon from the shelf zone into the subsurface layer of the open ocean, very effective. The warming of the shelf water in low-latitudes or other regions in summer may, conversely, lessen the above effect, but the warming as well as the addition of fresh water develops a pycnocline, below which the transport of  $\text{CO}_2$  into the open ocean still continues.

Is the East China Sea comprising 1/30 of the world shelf zones unusual and the absorption of  $\text{CO}_2$  in the sea exceptionally high? We know some coastal seas release  $\text{CO}_2$  to the atmosphere at times (Hoppema, 1991; Frankignoulle et al., 1996; DeGrandpre et al., 1997), while similar  $f(\text{CO}_2)$  deficiency has also been observed. For example, the deficiency,  $-23$  ppm, observed in summer in the North Sea by Kempe and Pegler (1991) is nearly the same as our summer value. The southern East China Sea is located at a boundary for the net heat loss or gain in the yearly heat budget (Yanagi, 1994), where the pump works well in the warming season (Figs. 5, 6). In the world shelf zones, the heat loss making the Earth's climate mild should also occur in the cooling season and the continental shelf pump should work well as discussed above. Even in their warming season, the developed pycnocline should prevent the return of regenerated carbonate to the surface and the carbonate should be transported into the open ocean by the water movement. The Kuroshio current flowing along the shelf margin and its two branches flowing on the shelf through the Taiwan Straits at the southern end, and the Tsushima

Strait at the northern end, may enhance the pump. In any case, the effect should reflect the residence time of the East China Sea water, 0.8 years (Tsunogai et al., 1997). At present, we cannot judge whether this residence time is much different from a mean residence time of the world shelf waters. Conversely, the oligotrophic Kuroshio water reduces the effect of enrichment of regenerated carbonate in water on the shelf, which would weaken the pump. Watanabe (1993) has depicted the not seriously eutrophicated East China Sea. The specific run-off to the shelf region (the ratio of entire run-off to the area of the continental shelf), introducing nutrient into the shelf water, should also relate to the continental shelf pump via the biological pump. The specific run-off is not large in the East China Sea, 1.3 m/yr, as compared to the world mean, 1.35 m/yr (Sverdrup et al., 1942; Lerman, 1981; Degens et al., 1991, Yanagi, 1994).

If the mechanism proposed above, the heat loss at the surface forming denser bottom water enriched in carbonate on the shelf, and the mixing with open sea water, is applicable to the world shelf zones, it seems unlikely that its mean net absorption flux of  $\text{CO}_2$  is much (say, more than 50%) different from 1 GtC/yr, although, of course, we need more observations in the various shelf regions to demonstrate this "continental shelf pump". This  $\text{CO}_2$  flux absorbed in the coastal sea and transported to the open oceans is a significant error if modellers neglect it in the oceanic carbon budget (Orr, 1993; Siegenthaler and Sarmiento, 1993), because the oceanic uptake of anthropogenic  $\text{CO}_2$  is now calculated to be  $2.0 \pm 0.8$  GtC/yr ( $5.6 \pm 2.2$  gC/m<sup>2</sup>/yr) (Houghton et al., 1995). Determining the total  $\text{CO}_2$  contents dissolved in the water column, we have obtained a large increase rate in the dissolved  $\text{CO}_2$  in the western North Pacific ( $10 \pm 2.2$  gC/m<sup>2</sup>/yr; Tsunogai et al., 1993), and discussed the cause by studying the North Pacific Intermediate Water (Tsunogai et al., 1995; Tsunogai 1997). The large discrepancy, however, may be partly due to carbonate transported into the water by this continental shelf pump.

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