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Carbon budget in the East China Sea in spring

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ABSTRACT

Results of total dissolved inorganic carbon (DIC) and total alkalinity (TA) measurements made in the East China Sea (ECS) during a geochemical expedition of KEEP (Kuroshio Edge Exchange Processes) program in May of 1996 show that ECS is a CO_2 sink during the spring season. The mean difference of fCO_2 (fugacity of CO_2) between the atmosphere and surface water is calculated to be 28 μatm, and the resulting net CO_2 invasion flux is 2.1 mol m^{-2} yr^{-1}, which gives about 0.03 GtC/yr of CO_2 uptake in this continental shelf in spring. This study supports the notion that the shelf regions can be a significant CO_2 sink. The riverine alkalinity, which discharges into ECS, is estimated to be 1,743 μmol kg^{-1} on the basis of a linear relationship between TA and salinity. The observed salinity-normalized alkalinity in ECS is higher than that in the open sea, and this excess alkalinity is estimated to be 42 μmol kg^{-1}. With the known rate of the Changjiang discharge, this excess TA gives a mean residence time of 1.2 years for the continental shelf water in the ECS. The DIC in the ECS is also found to be higher than that in the open sea. This excess DIC is estimated to be about 76 ± 70 μmol kg^{-1}, which is equal to a net carbon input to ECS of 3.9 ± 3.6 mol m^{-2} yr^{-1}. Based on the riverine alkalinity input, the equivalent riverine carbon flux from Changjiang discharge is estimated to be about 1.8 mol m^{-2} yr^{-1}. With net CO_2 invasion flux of 2.1 ± 2.8 mol m^{-2} yr^{-1}, the remaining 0 ± 4.6 mol m^{-2} yr^{-1} could come from remineralization of organic matter derived from biological pump in the shelf or terrestrial sources. Although this preliminary carbon budget implies that gas exchange and riverine input are the main sources of excess carbon in ECS, the contribution of biological carbon flux can not be ruled out because of the large uncertainty associated with these estimates.

1. Introduction

The continental shelf zone is the boundary area between land and ocean, and hence is affected heavily by the materials carried by the riverine run-off into the ocean. Nutrients are some of the major anthropogenic materials that are transported into the coastal seas. The resulting enhanced biological activity tends to draw down the CO_2 dissolved in the coastal waters, and creates a potential sink for CO_2 from the atmosphere. Other coastal areas have been reported as sinks as well. The North Sea is a net CO_2 sink in the summer (Kempe and Pegler, 1991) and the west Florida shelf is a strong sink in the spring (Wanninkhof et al., 1997). Tsunogai et al. (1997) reported that the central East China Sea is also a CO_2 sink in the autumn and winter, on the basis of their single survey line across the shelf in 1993.

The East China Sea (ECS) is located over a wide continental shelf, receiving a very large amount of riverine run-off, sediments, and anthropogenic materials from a major river system in China, the Changjiang River. To the north of this continental shelf is the Yellow Sea, which is heavily influenced by the Huanghe River discharge. As

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summarized by Perry et al. (1996), the mean annual discharge of Changjiang is estimated to be about $28.9 \times 10^3 m^3 s^{-1}$. The discharge of nitrate and silicate to the ocean is estimated to be about 6×10^{10} mol/yr and 12×10^{10} mol/yr, respectively (Edmond et al., 1985). The annual flux of dissolved phosphate is not well-known, but is believed to be much smaller than the nitrate and silicate fluxes. The warm Kuroshio current flows northward along the continental margin and begins to contact and exchange with the ECS at the northeastern Taiwan. As a result of Kuroshio intrusion to the southern ECS, a year-round upwelling of Kuroshio subsurface water takes place to the north of Taiwan (Liu et al., 1992). It has been shown that this upwelling is the major nutrient source in the southern ECS (Wong et al., 1991; Liu et al., 1992; Gong et al., 1996). The nitrate flux from Kuroshio through upwelling into the ECS is estimated to be as high as 30×10^{10} mol/yr (Li, 1994), which is five times as much as that from Changjiang discharge. It is clear that the exchange processes between the ECS shelf water and the Kuroshio water play an important rôle in nutrient supply to ECS.

The Kuroshio Edge Exchange Processes (KEEP) program of Taiwan was launched in 1989 to study the physical, chemical, biological and geological processes taking place in the East China Sea as the Kuroshio warm current interacts with the ECS shelf water northeast of Taiwan. A network of survey lines has been carried out in the ECS since the beginning of KEEP. A recent geochemical survey cruise on board R/V Ocean Research I was carried out during the period 2–15 May 1996. Water samples were taken at the selected stations in the survey network, and were shipped immediately after the cruise to Miami for determination of total dissolved inorganic carbon (DIC) at NOAA's Atlantic Oceanographic and Meteorological Laboratory and for measurement of total alkalinity (TA) at Marine and Atmospheric Chemistry Department, Rosenstiel School of Marine and Atmospheric Science (RSMAS) of the University of Miami. Additional measurements of TA for samples taken at stations mainly along the coast of mainland in this study area were carried out in Kaohsiung at the Institute of Marine Geology and Chemistry of the National Sun Yat-Sen University (NSYSU). This paper evaluates the carbon sink in this area as determined from these measurements.

The previous study of carbon system in the ECS (Tsunogai et al., 1997) has a focus on the temporal variations of CO_2 sink during the autumn and winter in the area north of the current study. This study provides a wider spatial coverage to include the southern ECS during the spring season. A combination of these results will give a better picture of carbon system in the coastal shelf region.

2. Methods

The cruise track of geochemical survey in the ECS during a late spring expedition of KEEP-II cruise-449 is shown in Fig. 1. Although a blanket coverage of sampling stations in the ECS is performed for various geochemical studies, only a few stations are selected for the survey of carbonate chemistry. Table 1 gives the sampling date and the location of stations where carbonate chemistry is measured. In the middle shelf area, a series of stations parallel to the shelf edge were occupied for studying north–south variations. These include stations 15, 26, 33, 44, and 52 (latitude ranging

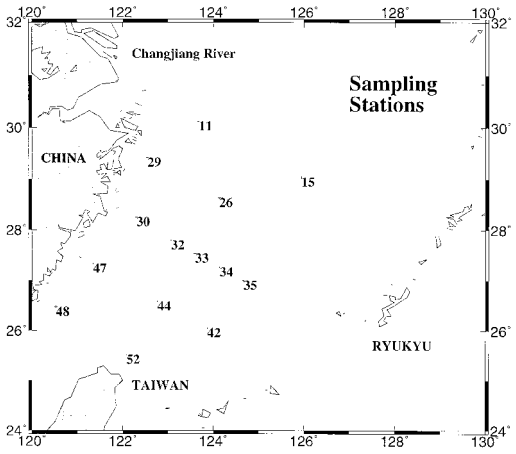

Fig. 1. Map showing the sampling stations in the East China Sea during the KEEP-II cruise 449 for geochemical studies. For both DIC and TA measurements, water samples were taken from the following stations: 15, 26, 30, 32, 33, 34, 35, 42, 44, and 52. Stations for TA measurements only: 11, 29, 47, 48. The sampling dates and the exact geographical locations of these stations are given in Table 1.

Table 1. *Sampling stations and date of occupation during the KEEP-II cruise 449 in 1996 for geochemical studies*

Station number	Sampling dates	Lat.	Long.
11	4 May	30.12	123.67
15	5 May	29.04	125.93
26	7 May	28.64	124.12
29	8 May	29.42	122.55
30	8 May	28.26	122.32
32	8 May	27.79	123.05
33	8 May	27.52	123.60
34	9 May	27.25	124.12
35	9 May	26.99	124.69
42	10 May	26.05	123.87
44	11 May	26.57	122.78
47	11 May	27.34	121.35
48	12 May	26.47	120.53
52	13 May	25.52	122.10

from 25.5°N to 29°N). To delineate the distribution of carbon across the shelf, another five stations were also occupied (30, 32, 33, 34, 35, longitude ranging from 122°E to 125°E). Station 42 is characteristic of Kuroshio water. Both DIC and TA were measured for all of these samples. Duplicate samples were collected from these stations for TA measurements in Kaohsiung. These duplicate measurements provide the quality assurance for the high precision required for studying the carbon cycle. To investigate a possible land source of alkalinity to the shelf zone, samples were taken from four additional stations (11, 29, 47, and 48) closest to the mainland coast for the TA measurements at NSYSU.

Seawater samples were taken by using the 500-ml Pyrex sample bottles, which were cleaned and pre-combusted at RSMAS, Miami, and were shipped to Taiwan for the cruise 449. Sampling was performed according to procedures outlined in a handbook of methods for the analysis of the various parameters of the carbon dioxide system in seawater (DOE, 1994). At the end of the cruise, these samples were shipped back to Miami immediately by air freight for analysis.

The total DIC was measured by coulometry method using Single Operator Multi-parameter Metabolic Analyzer (SOMMA) system developed by Ken Johnson (Johnson et al., 1993; Johnson, 1992) for the global ocean CO_2 survey under the US Global Change Program. In the coulometric analysis, all carbonate and bicarbonate species were converted to CO_2 (gas) by addition of excess hydrogen ion to seawater. The evolved CO_2 gas reacted quantitatively with ethanolamine to form hydroxyethyl carbamic acid which was titrated with OH^- ions. The end point was detected photometrically with thymolphthalein as indicator. The overall uncertainty of the coulometric DIC measurements technique was determined to be within $\pm 1.9\ \mu mol\ kg^{-1}$, based on measurements of Certified Reference Material (CRM). The precision of this method from replicate measurements of samples was determined to be within $\pm 1.2\ \mu mol\ kg^{-1}$ (Lamb et al., 1997). Water was taken from the same bottles after DIC measurements for the TA determination, which was performed by a titration system consisted of a Metrohm Dosimat titrator and an Orion 720A pH meter that was computer controlled (Millero et al., 1993).

3. Results and discussion

There are duplicate samples which are used for TA measurements both in Miami and in Kaohsiung. Comparison of TA results from Miami and Kaohsiung is shown in Fig. 2. For samples with TA higher than 2240 $\mu mol\ kg^{-1}$, TA measure-

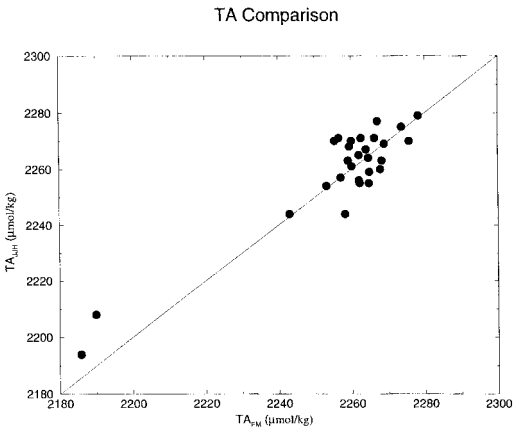

Fig. 2. Comparison of TA measurements on duplicate samples made in Miami and in Kaohsiung. The vertical axis is TA_{JJH} which is made by Dr. Jia-Jang Hung's group in Kaohsiung, and the horizontal axis is TA_{FM} which is made by the group of Dr. Millero in Miami.

ments from both laboratories are quite consistent. At lower TA values, two Kaohsiung measurements are consistently higher. The mean deviation of these data points from the diagonal ideal fit line is 4.4 ± 3.5 μmol kg^{-1}. These TA measurements are combined for establishing relationship between TA and salinity. For fCO_2 calculations, however, TA measurements made in the same samples with DIC measurements are used exclusively.

To minimize effects of fresh water dilution, evaporation, and water mixing, DIC results are normalized to a constant salinity of 35. As shown in Fig. 3, this salinity-normalized DIC (NDIC) shows a general trend of increasing concentration with depth, as expected from the enrichment of carbon derived from the biological pump, except for station 30 which is the closest to the mainland coast and is subject to the influence of riverine input of carbonate. Most of NDIC in the surface waters are within the range between 1970 and 2040 μmol kg^{-1}, except for station 30 that has a surface NDIC value of about 2250 μmol kg^{-1}. The highest water column NDIC is found at station 52 where the upwelling of nutrient-rich subsurface water took place. The waters north of station 52 have a decreasing NDIC as they are farther away from the upwelling region (stations 44 and 33). But, the trend does not extend to the two stations (15 and 26) further north. Comparison of water column NDIC at stations across the shelf, however, shows a general decreasing trend toward the open sea. It is an indication of mixing process between waters of higher NDIC of coastal origin with the water of lower NDIC of open sea.

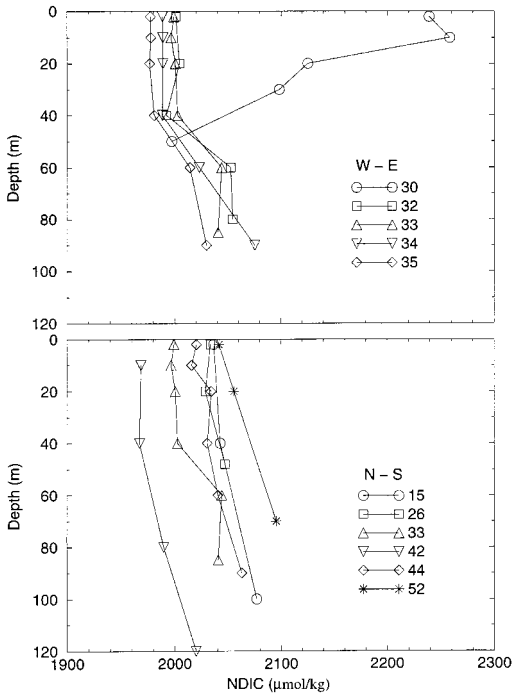

Fig. 3. The distribution of NDIC (normalized DIC to salinity of 35) with depth in the East China Sea. The upper panel shows the NDIC variations from inner shelf zone to the open sea. The lower panel shows the north–south variations along the middle shelf region. Symbols with station numbers represent observations at each station.

For the same reason of normalizing the DIC, the TA measurements from samples with DIC measurements are also normalized to a salinity of 35. The salinity-normalized TA (NTA) in the water column shows a near constant value with depth (Fig. 4). The NTA of about 2300 μmol kg^{-1} is typical for waters away from the coastal zone. It rises sharply for waters collected in stations near the coastline (station 30), especially for surface waters above 20 m depth. As shown in Fig. 5, measurements made in Kaohsiung for waters taken from stations 11, 29, 30, 47, and 48 (parallel to coastline) give highly elevated NTA values, ranging from 2350 to 2550 μmol kg^{-1}. The influx of carbonate rich riverine water, and hence the high alkalinity water, plays an important rôle in the distribution of alkalinity in the East China Sea.

The fugacity of CO_2 gas (fCO_2) in East China Sea can be calculated from the observed distribution of DIC and TA measured in Miami. The detailed equations for this computation are the same as those given in Peng et al. (1987). The apparent dissociation constants of carbonic acid are taken from Mehrbach et al. (1973). This choice is supported by results from a recent study of the optimal carbonate dissociation constants for determining surface water fCO_2 from TA and DIC (Wanninkhof et al., 1998). With DIC uncertainty of ± 2 μmol kg^{-1} and TA uncertainty of ± 4.4 μmol kg^{-1}, the computed fCO_2 values have uncertainties mostly less than ± 10 μatm, especially for surface water fCO_2. This uncertainty is estimated by computing the maximum range of fCO_2 variations caused by TA and DIC uncertainties. The highest fCO_2 value results from a combination of DIC + 2 and TA − 4.4, and the

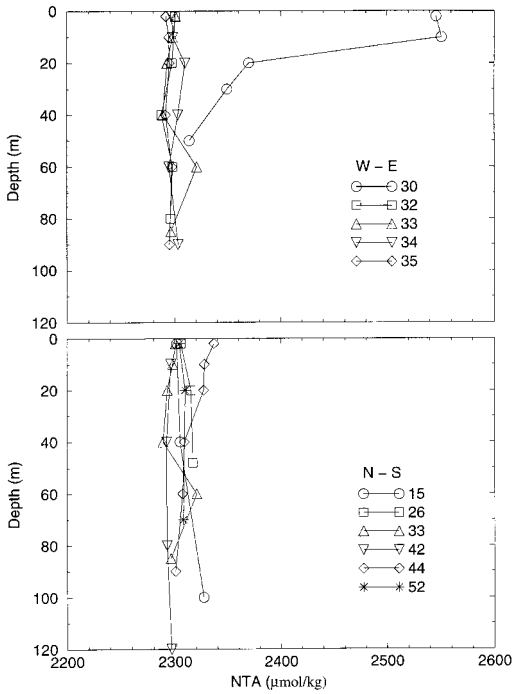

Fig. 4. The distribution of NTA (normalized TA to salinity of 35) with depth in the East China Sea. The upper panel shows the TA variation from the coast to the open sea. The lower panel shows the north–south variations along the middle shelf zone. Symbols with station numbers represent observations at each station.

lowest from a combination of DIC − 2 and TA + 4.4 μmol kg^{-1}. As shown in Fig. 6, the distribution of thus computed fCO_2 has a general increasing trend with the depth, reflecting the vertical distribution of DIC.

To estimate the fCO_2 flux across the sea–air interface, the difference in fCO_2 between the surface water and the atmosphere needs to be determined. The surface water fCO_2 computed from DIC and TA measurements is summarized in Table 2. The atmospheric fCO_2 is estimated from the observed atmospheric XCO_2 (mol fraction of CO_2) data for the month of May in 1996 at Mauna Loa Observatory (Keeling and Whorf, SIO unpublished data, provided by CDIAC). The observed atmospheric CO_2 mixing ratio of 365 ppm is equivalent to a mean fCO_2 with 100% humidity of 353 μatm over the ECS. As shown in Fig. 7, except for the station with upwelling (station 52), all surface water fCO_2 values are lower than the atmospheric value. Hence, ECS is a potential carbon sink during the month of May. The mean deficiency of surface water fCO_2 as compared with atmospheric fCO_2 is 28 ± 31 μatm. This value is statistically not different from the mean deficiency of 34 μatm in the autumn, and of 59 μatm in the winter, which were measured by the continuous underway fCO_2 measuring device in the surface waters of the region north of this study area (Tsunogai et al., 1997). Based on Wanninkhof's (1992) air–sea flux equation, the CO_2 invasion flux F can be estimated as the product of the gas transfer velocity (K), the solubility (α), and the partial pressure difference between air and water (ΔfCO_2):

$$F = K\alpha\Delta fCO_2,$$

where $K\alpha$ is sometimes referred to as the CO_2 exchange coefficient $E = 1.13 \times 10^{-3} \times W^2$, and W is the wind speed in m s^{-1}. Taking the mean wind speed observed during this cruise of 8.3 ± 2.7 m s^{-1}, this equation gives air–sea CO_2 flux of 2.1 ± 2.8 mol m^{-2} yr^{-1}. The total CO_2 flux is thus estimated to be 0.03 GtC/yr if ECS area (including Yellow Sea) is taken to be 1.25×10^{12} m^2 (Sverdrup et al., 1942). This result supports the notion that the shelf regions could be a significant CO_2 sink.

The plot of all TA measurements, normalized to salinity of 35, including those along the coastline, versus inverse-salinity (1/S) gives a tight linear relationship (Fig. 8). To avoid inducing spurious variance, the relationship between TA and S needs to be derived from the linear regression of TA and S without salinity normalization of TA measurements. Such regression gives the following linear relationship:

$$TA = 1743 + 15.16S$$

with a correlation coefficient of 0.90. Extrapolating the data for a river water with $S = 0$, the TA is obtained to be 1743 μmol kg^{-1}. This is about 10% higher than 1582 μmol kg^{-1} estimated by Tsunogai et al. (1997). Degens et al. (1991) reported a value of 141 mg kg^{-1} for HCO_3^- in Changjiang River. Assuming that the riverine TA is mainly composed of bicarbonate ions, the equivalent TA is 2311 μmol kg^{-1} which is about 33% higher than this estimate.

Taking the mean annual Changjiang discharge of 28.9×10^3 m^3 s^{-1} (Perry et al., 1996), the total

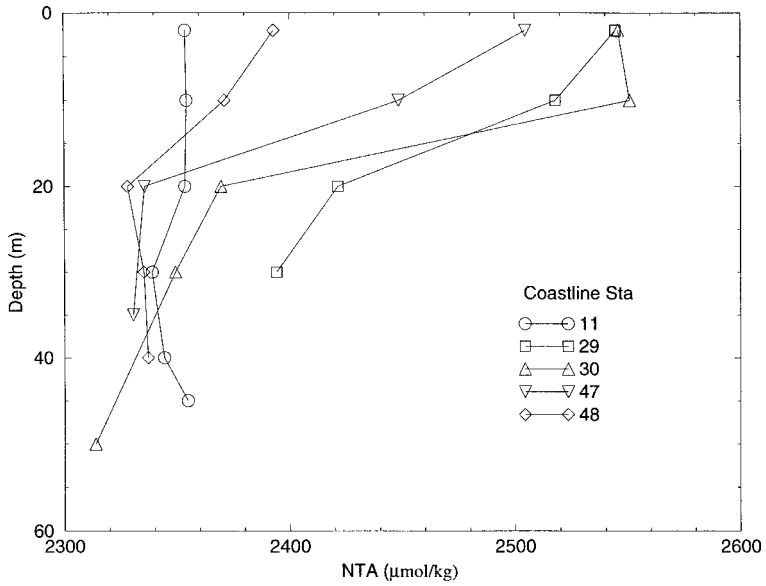

Fig. 5. The distribution of NTA (normalized TA to salinity of 35) with depth for stations along the coast in the East China Sea. Symbols with station numbers represent observations at each station.

amount of alkalinity added to the ECS is estimated to be 1.6×10^{12} mol yr^{-1}. With this excess alkalinity input, we can expect that the TA of shelf water in ECS should be higher than the open ocean water such as Kuroshio water (KW). Examination of T–S diagram for sampling stations in this study indicates that KW can be clearly represented by waters in station 42 which show the characteristic T–S property of KW (Gong et al., 1996; Liu et al., 1992). The water column average NTA in station 42 is 2294.5 ± 2.3 μmol kg^{-1}, which is taken to be the alkalinity of KW. The excess alkalinity of ECS shelf water can be obtained by subtracting this NTA value from the measured NTA. To estimate the mean excess alkalinity of the ECS shelf water, we summarize all TA measurements including those made along the mainland coast. These sampling stations are divided into three zones: (1) inner shelf zone, including stations 11, 29, 30, 47, and 48; (2) middle shelf zone, including stations 26, 32, 33, and 44; and (3) outer shelf zone, with stations 15, 34, and 35. This division is based on the approximate distance of each station from the coast. The station 52 is excluded for the reason that it is a location of upwelling, and it represents a typical Kuroshio subsurface water (Gong, personal communication, 1997). First, the mean water column NTA is computed from all samples taken at each station. The zonal mean NTA is then estimated from the mean NTA of each station within each zone. The zonal excess NTA is obtained by subtracting 2294.5 μmol kg^{-1} (mean NTA of station 42) from the zonal mean. As shown in Table 3, the inner shelf zone has an excess NTA of 106 μmol kg^{-1}, which is an order of magnitude higher than that in the middle and outer shelf zones. This is to be expected because of its proximity to the source of excess alkalinity. The mean salinity of inner shelf (Table 3) is about 32.7, which is much lower than that of the rest of shelf (S larger than 34.4). Based on the equal weight for each zone, the average excess NTA in ECS is estimated to be 42.4 μmol kg^{-1}. Using open ocean mean NTA of 2277.3 μmol kg^{-1} in autumn, and of 2278.9 μmol kg^{-1} in winter, Tsunogai et al. (1997) estimated a total mean excess NTA of 24 μmol kg^{-1} in their 1993 survey north of this study area.

With continental shelf water volume of 4.5×10^4 km^3 (LOICZ), the total excess alkalinity is estimated to be 2×10^{12} mol. Using the riverine alkalinity input rate estimated above, the mean residence time of the ECS water in continental shelf can be calculated to be 1.2 year. Because of

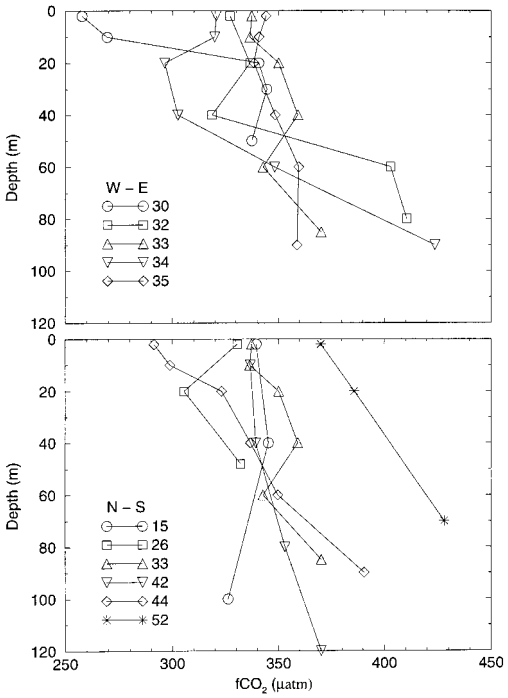

Fig. 6. The distribution of fCO_2 with depth in the East China Sea. The upper panel shows the variations from the coast to the open sea. The lower panel shows the north–south variations along the middle shelf zone. Symbols with station numbers represent observations at each station.

Table 2. *Difference of fCO_2 between atmosphere and surface water*

Station number	Lat. (deg.)	fCO_2 (µatm)	ΔfCO_2* (µatm)
15	29.04	339.6	−13.4
26	28.63	330.5	−22.5
30	28.25	257.8	−95.2
32	27.80	327.1	−25.9
33	27.53	337.3	−15.7
34	27.26	320.6	−32.4
35	27.00	344.1	−8.9
42	26.05	336.7	−16.3
44	26.58	291.3	−61.7
52	25.52	370.1	17.1
mean			−27.5 ± 30.9

* $\Delta fCO_2 = fCO_2)_{sw} - fCO_2)_{atm}$, with $fCO_2)_{atm} =$ 353 µatm.

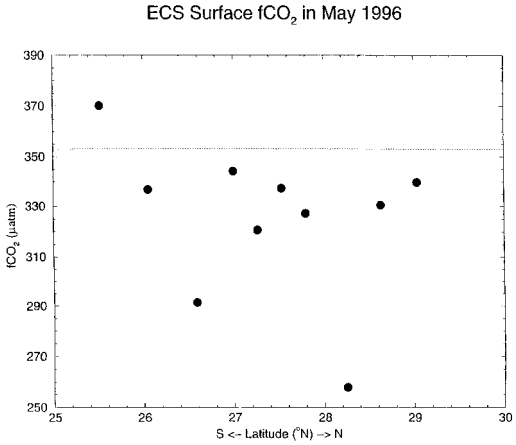

Fig. 7. The distribution of surface water fCO_2 with the latitude. The atmospheric fCO_2 is shown as a dotted line.

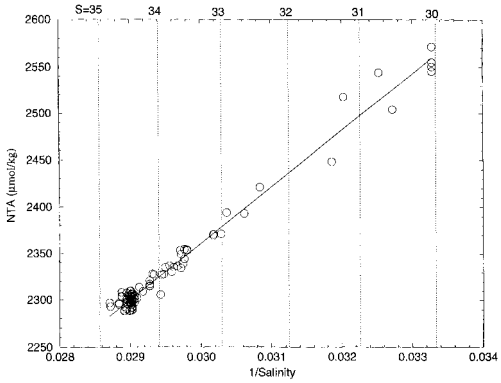

Fig. 8. Plot of salinity normalized TA with the inverse of salinity. The line represents the least squares linear regression.

rather large zonal difference in the amount of excess NTA, this mean residence time is subject to a large uncertainty on the order of ±0.5 year. This is to be compared with 0.8 ± 0.3 year reported by Tsunogai et al. (1997) based on their lower estimates of both excess NTA and the riverine input. Using salt balance, Li (1994) reported a residence time of about 1 year. Hence, this study supports the mean residence time of ECS shelf water on the order of 1 year.

To examine the carbon cycle in the continental shelf water, analysis of DIC in the ECS has been

Table 3. *Excess NTA (μmol/kg) in the East China Sea*

Zone (station nos.)	Mean *S*	Mean NTA	SD	*n*	Excess* NTA
inner shelf (11, 29, 30, 47, 48)	32.708	2400.9	50.8	5	106.4
middle shelf (26, 32, 33, 44)	34.286	2306.3	10.7	4	11.7
outer shelf (15, 34, 35)	34.436	2303.6	6.7	3	9.1
Kuroshio water (42)	34.686	2294.5	2.3	4	—
mean					42.41

* Excess NTA = mean NTA − 2294.5 (μmol/kg).

carried out in a similar way as TA. The mean NDIC in station 42 is taken to be the KW open seawater, and that in station 52 represents the Kuroshio subsurface water. The excess NDIC is defined as the difference between the observed NDIC and the mean NDIC at station 42. As given in Table 4, station 30 is the only DIC sampling location in the inner shelf zone. It has the highest mean water column NDIC because of its proximity to the riverine carbon load. The excess NDIC of 157 μmol kg^{-1} is about 4 times that in the middle and outer shelf zones. The mean excess of these three zones is 76 ± 70 μmol kg^{-1}. The high standard deviation reflects the difference of carbon distribution in the shelf. Previous study (Tsunogai et al., 1997) showed that the excess NDIC was 108 μmol kg^{-1} in autumn, and 83 μmol kg^{-1} in winter in good agreement with our work. Taking the shelf water volume to be 4.5×10^4 km^3, the total excess DIC of this study in spring is estimated to be 3.5×10^{12} mol. With a mean residence time of 1 year, and the total continental shelf area of 0.9×10^{12} m^2, the net carbon input flux is estimated to be 3.9 ± 3.6 mol m^{-2} yr^{-1}.

The excess carbon found in ECS could come from various sources, such as riverine input, air–sea gas exchange, and biological pumping. As given above, the net air–sea CO_2 flux into the shelf water is estimated to be 2.1 mol m^{-2} yr^{-1}. The difference of 1.8 mol m^{-2} yr^{-1} from the total excess flux could be attributed to riverine and respiration inputs. However, the riverine carbon input based on the excess TA estimate is equivalent to about 1.8 mol m^{-2} yr^{-1} which leaves a biological carbon flux of 0 ± 4.6 mol m^{-2} yr^{-1}. Although this implies that gas exchange and riverine carbonate input are the main sources of excess DIC in ECS, the contribution of organic carbon either from biological pump within the coastal waters or riverine terrestrial source can not be ruled out because of the large uncertainty associated with these estimates. Because of not enough DIC and TA measurements in this study, this preliminary conclusion needs to be verified in the future when more carbon data are available. Tsunogai et al. (1997) reported results of previous survey north of this study area. Using their autumn data, they estimated that the excess NDIC flux to ECS was 5.8 mol m^{-2} yr^{-1}, in which 3.3 mol m^{-2} yr^{-1} came from air–sea gas exchange and 1.7 mol m^{-2} yr^{-1} from riverine carbonate input. The remaining 0.8 mol m^{-2} yr^{-1} was attributed to decomposition of terrestrial organic carbon carried in the river discharge.

Table 4. *Excess NDIC (μmol/kg) in the East China Sea*

Zone (station nos.)	Mean *S*	Mean NDIC	SD	*n*	Excess* NDIC
inner shelf (30)	32.239	2143.7	—	1	157.4
middle shelf (26, 32, 33, 44)	34.286	2026.4	10.7	4	40.0
outer shelf (15, 34, 35)	34.436	2017.9	30.7	3	31.5
Kuroshio water (42)	34.686	1986.4	24.6	4	—
mean					76.3 ± 70.3

* Excess NDIC = mean NDIC − 1986.4 (μmol/kg).

4. Conclusion

Results reported here are based on a limited sampling during a single cruise for DIC and TA measurements in the East China Sea in spring of 1996. To adequately characterize the carbon cycle in ECS, a more systematic carbon observing program will need to be carried out, especially, more measurements are needed in the inner shelf zone right off the coastline where the excess carbon from land source is entering the shelf sea. To obtain a better representation of fCO_2 distribution, a continuous monitoring of surface water fCO_2 during the expedition will have to be performed. These preliminary results, however, point to the potential of a significant carbon sink in the continental shelf region.

5. Acknowledgment

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REFERENCES

Degens, E. T., Kempe, S. and Richey, J. E. 1991. Summary: biogeochemistry of major world rivers. In: *Biogeochemistry of major world rivers* (eds. Degens, E. T., Kempe, S. and Richey, J. E.), ch. 15, 1991 SCOPE. John Wiley & Sons Ltd., pp. 323-347.

DOE. 1994. *Handbook of methods for the analysis of the various parameters of the carbon dioxide system in sea water*, version 2 (eds. Dickson, A. G. and Goyet, C.). ORNL/CDIAC-74.

Edmond, J. M., Spivack, A., Grant, B. C., Hu, M.-H., Chen, Z. and Zeng, X. 1985. Chemical dynamics of the Changjiang estuary. *Cont. Shelf Res.* **4**, 17–36.

Gong, G.-C., Lee Chen, Y.-L. and Liu, K.-K. 1996. Chemical hydrography and chlorophyll: a distribution in the East China Sea in summer: implications in nutrient dynamics. *Cont. Shelf Res.* **16**, 1561–1590.

Johnson, K. M., Wills, K. D., Butler, D. B., Johnson, W. K. and Wong, C. S. 1993. Coulometric total carbon dioxide analysis for marine studies: maximizing the performance of an automated continuous gas extraction system and coulometric detector. *Mar. Chem.* **44**, 167–189.

Johnson, K. M. 1992. *Operator's manual: single operator multi-parameter metabolic analyzer (SOMMA) for total carbon dioxide (C_T) with coulometric detection*. Brookhaven, NY, 70 pp.

Kempe, S. and Pegler, K. 1991. Sinks and sources of CO_2 in coastal seas: the North Sea. *Tellus* **43B**, 224–235.

Lamb, M. F., Feely, R.A., Bullister, J. L., Johnson, G. C., Wisegarver, D. P., Taft, B., Wanninkhof, R., McTaggart, K. E., Krogslund, K. A., Mordy, C., Hargreaves, K., Greeley, D., Lantry, T., Chen, H., Millero, F. J., Byrne, R. H., Hansell, D. A., Chavez, F. P., Quay, P. D., Guenther, P. R., Gardner, W., Richardson, M. J. and Peng, T.-H. 1997. *Chemical and hydrographic measurements in the eastern Pacific during the CGC94 expedition* (WOCE section P18). NOAA Data Report ERL PMEL-61, 235 pp.

Li, Y.-H. 1994. Material exchange between the East China Sea and the Kuroshio current. *Terrestrial Atmospheric Oceanic Science* **5**, 625–631.

Liu, K.-K., Gong, G.-C., Lin, S., Shyu, C.-Z., Pai, S.-C., Wei, C.-L. and Chao, S.-Y. 1992. Response of Kuroshio upwelling to the onset of northeast monsoon in the sea north of Taiwan: observations and a numerical simulation. *J. of Geophys. Res.* **97**, 12511–12526.

LOICZ (Land–Ocean Interactions in the Coastal Zone). Reports and studies no. 5. *The International Geosphere–Biosphere Programme*. A study of global change (IGBP). Stockholm, 1993.

Mehrbach, C., Culberson, C. H., Hawley, J. E. and Pytkowicz, R. M. 1973. Measurement of the apparent dissociation constants of carbonic acid in seawater at atmospheric pressure. *Limnology and Oceanography* **18**, 897–907.

Millero, F. J., Zhang, J.-Z., Lee, K. and Campbell, D. M. 1993. Titration alkalinity of seawater. *Mar. Chem.* **44**, 153–165.

Peng, T.-H., Takahashi, T., Broecker, W. S. and Olafsson, J. 1987. Seasonal variability of carbon dioxide, nutrients and oxygen in the northern North Atlantic surface water: observations and a model. *Tellus* **39B**, 439–458.

Perry, G. D., Duffy, P. B. and Miller, N. L. 1996. An extended data set of river discharges for validation of general circulation models. *J. Geophys. Res.* **101**, 21,339–21,349.

Sverdrup, H. U., Johnson, M. W. and Fleming, R. H. 1942. *The oceans: their physics, chemistry and general*

biology. Prentice-Hall, Englewood Cliffs, New York, 1087 pp.

Tsunogai, S., Watanabe, S., Nakamura, J., Ono, T. and Sato, T. 1997. A preliminary study of carbon system in the East China Sea. *J. of Oceanography* **53**, 9–17.

Wanninkhof, R. 1992. Relationship between wind speed and gas exchange over the ocean. *J. Geophys. Res.* **97**, 9393–7382.

Wanninkhof, R., Hitchcock, G., Wiseman, W., Vargo, G., Ortner, P., Asher, W., Ho, D., Schlosser, P., Dickson, M.-L., Anderson, M., Masserini, R., Fanning, K. and Zhang, J.-Z. 1997. Gas exchange, dispersion, and biological productivity on the west Florida shelf: results from a lagrangian tracer study. *Geophys. Res. Lett*. **24**, 1767–1770.

Wanninkhof, R., Lewis, E., Feely, R. A. and Millero, F. J. 1999. The optimal carbonate dissociation constants for determining surface water pCO_2 from alkalinity and total inorganic carbon. *Marine Chemistry*, in press.

Wong, G. T.-F., Pai, S.-C., Liu, K.-K., Liu, C.-T. and Chen, C.-T. A. 1991. Variability of the chemical hydrography at the frontal region between the East China Sea and the Kuroshio northeast of Taiwan. *Estuarine Coastal Shelf Science*, **33**, 105–120.