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Role of the Jiaozhou Bay as a source/sink of CO_2 over a seasonal cycle

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SUMMARY: The seasonal evolution of dissolved inorganic carbon (DIC) and CO_2 air-sea fluxes in the Jiaozhou Bay was investigated by means of a data set from four cruises covering a seasonal cycle during 2003 and 2004. The results revealed that DIC had no obvious seasonal variation, with an average concentration of 2035 μmol kg^{-1} C in surface water. However, the sea surface partial pressure of CO_2 changed with the season. pCO_2 was 695 μatm in July and 317 μatm in February. Using the gas exchange coefficient calculated with Wanninkhof's model, it was concluded that the Jiaozhou Bay was a source of atmospheric CO_2 in spring, summer, and autumn, whereas it was a sink in winter. The Jiaozhou Bay released 2.60×10^{11} mmol C to the atmosphere in spring, 6.18×10^{11} mmol C in summer, and 3.01×10^{11} mmol C in autumn, whereas it absorbed 5.32×10^{10} mmol C from the atmosphere in winter. A total of 1.13×10^{12} mmol C was released to the atmosphere over one year. The behaviour as a carbon source/sink obviously varied in the different regions of the Jiaozhou Bay. In February, the inner bay was a carbon sink, while the bay mouth and the outer bay were carbon sources. In June and July, the inner and outer bay were carbon sources, but the strength was different, increasing from the inner to the outer bay. In November, the inner bay was a carbon source, but the bay mouth was a carbon sink. The outer bay was a weaker CO_2 source. These changes are controlled by many factors, the most important being temperature and phytoplankton. Water temperature in particular was the main factor controlling the carbon dioxide system and the behaviour of the Jiaozhou Bay as a carbon source/sink. The Jiaozhou Bay is a carbon dioxide source when the water temperature is higher than 6.6ºC. Otherwise, it is a carbon sink. Phytoplankton is another controlling factor that may play an important role in behaviour as a carbon source or sink in regions where the source or sink nature is weaker.

Keywords: carbon source/sink, dissolved inorganic carbon (DIC), seasonal variation, control mechanism, Jiaozhou Bay.

RESUMEN: PAPEL DE LA BAHÍA DE JIAOZHOU COMO UNA FUENTE/DEPÓSITO DE CO_2 DURANTE UN CICLO ESTACIONAL. – La evolución estacional del carbono inorgánico disuelto (DIC) y el intercambio de flujos de CO_2 aire-mar en la bahía de Jiaozhou han sido investigados a partir de datos obtenidos en 4 campañas oceanográficas que cubren un ciclo estacional entre 2003 y 2004. Los resultados muestran que el DIC no presenta una clara variación estacional con una concentración promedio de 2035 μmol kg^{-1} C en el agua de superficie. No obstante la presión parcial de CO_2 en el agua superficial cambiaba con la estación. La PCO_2 era de 695 μatm en Julio y 317 μatm en febrero. Utilizando el coeficiente de intercambio de gases calculado con el modelo de Wanninkhof concluíamos que la bahía de Jiaozhou era una fuente de CO_2 a la atmósfera en primavera, verano y otoño, mientras que era un depósito de CO_2 en invierno. La bahía proporcionaba 2.60×10^{11} mmol C a la atmósfera en primavera, 6.18×10^{11} mmol C en verano, y 3.01×10^{11} mmol C in otoño, mientras absorbia 5.32×10^{10} mmol C desde la atmósfera en invierno. Un total de 1.13×10^{12} mmol C eran liberados a la atmósfera durante un año. El comportamiento como fuente/depósito de carbono, obviamente era diferente en las distintas regiones de la bahía de Jiaozhou. En Febrero, la parte interior de la bahía era un depósito para el carbono, mientras que la desembocadura y la parte exterior actuaba como fuente de carbono. En Junio y Julio, las partes interna y externa de la bahía eran fuentes de carbono, pero la intensidad era diferente, incrementando desde la parte interior a la exterior de la bahía. En Noviembre, la parte interior de la bahía era fuente de carbono, pero la desembocadura de la bahía se comportaba como depósito de carbono. El exterior de la bahía era una fuente poco importante de CO_2. Estos cambios están controlados por muchos factores, siendo los mas importantes la temperatura y el fitoplancton. Especialmente, la temperatura del agua era el factor principal en el control del dióxido de carbono en el sistema y del comportamiento de la bahía de Jiaozhou como fuente/depósito de carbono. La bahía de Jiaozhou es una fuente de dióxido de carbono cuando la temperatura del agua es mas alta que 6.6ºC. Si no es así es un depósito de carbono. El fitoplancton es el otro factor de control que puede jugar un papel importante en el comportamiento como fuente o depósito de carbono en regiones donde el carácter de fuente o depósito es debil.

Palabras clave: fuente/depósito de carbono, carbono inorgánico disuelto, variación estacional, mecanismo de control de la bahía de Jiaozhou.

INTRODUCTION

It has been shown that the ocean is a net sink for atmospheric carbon dioxide and can absorb 2 pg C every year (Sabine *et al*., 2000; Dyrssen, 2001; Miller *et al*., 2002; Takahashi *et al*., 2002). However, the role of shelf seas has not been fully understood yet. Some results indicate that shelf seas are a source of atmospheric carbon dioxide (Naqvi et al., 2005). However, other studies show that they can absorb about 0.2 to 1 pg C every year (Tsunogai *et al*., 1999; Liu *et al*., 2000; Frankignoulle and Borges, 2001; DeGrandpre *et al*., 2002; Chen, 2004; Thomas *et al*., 2004). It is currently uncertain whether shelf seas act as a net sink or source of atmospheric CO_2 , because shelf seas are strongly affected by both natural and human activities. On the one hand, the gradient of partial pressure between air and seawater will be reversed with the continually increasing atmospheric CO_2, so the source or sink nature may change. For example, the Weddell Sea was a relatively strong source of atmospheric CO_2 in pre-industrial times, but it turned into a CO_2 sink in recent times because of the steadily rising atmospheric CO_2 (Hoppema, 2004). On the other hand, the carbon budget of shelf seas and coastal areas has been altered dramatically by human activities. Anderson and Mackenzie (2004) modelled in detail the change of air-sea fluxes for the coastal ocean since pre-industrial times and suggested that the shallow-water ocean environment has served as a net CO_2 source throughout most of the past 300 years, but its role as a source has substantially decreased and the net flux is expected to be reversed at some point in time. Human activities are the main reason for this. Sabine and Machenzie (1991) estimated that the flux of nutrient from rivers to coastal seas has increased 2.5-fold due to human activities. In addition, particulate organic carbon, dissolved organic carbon and dissolved inorganic carbon have undergone an apparent increase too (Wollast and Mackenzie, 1989). Additional mass input has resulted in conflicting conclusions about whether shelf seas act as net sinks or sources of CO_2 to the atmosphere (Walsh *et al*., 1981). For examples, the SW of the Caribbean Sea was a source of CO_2 to the atmosphere throughout 2002, but the NE was a sink during winter and spring, and a source during summer and autumn (Olsen *et al*., 2004). Although some studies have estimated the air-sea CO_2 flux of coastal seas (Borges, 2005), more data are necessary to fully understand the coastal contribution to the marine carbon cycle.

The Jiaozhou Bay is a semi-enclosed bay situated in the western part of the Shandong Peninsula, China. The bay is surrounded by Qingdao city with an area of about 340 km^2 and an average water depth of about 7 m. The bay mouth is narrow, only about 2.5 km wide where the Bay is connected to the south Yellow Sea. There are more than 10 small rivers along the Jiaozhou Bay coast, the largest of which is the Dagu River with an annual average runoff of 21 $m^3\ s^{-1}$. Most of these rivers have become a repository for industrial and urban waste from Qingdao city. The water quality, biological species and abundance, and nutrient concentrations in the Jiaozhou Bay have been changing recently along with the rapid development of Qingdao city (Shen, 2001).

Research cruises covering a seasonal cycle were primarily designed to examine the carbon system variables and the mechanisms controlling the carbon exchange across the air-water interface during 2003 and 2004. In this paper, we describe the seasonal variation of DIC and the behaviour of the Jiaozhou Bay as a carbon source/sink. We also discuss the physical and biogeochemical mechanisms controlling the strength of the bay as a carbon source/sink.

MATERIAL AND METHODS

Sampling

In order to characterize the carbon system and its seasonal change in the Jiaozhou Bay, 22 stations were sampled on 20-21 June, 19-20 July and 19-21 November 2003, and on 21-23 February 2004 on board the *kejiao II* (Fig. 1). An ORION 420A+ pH-meter equipped with an ORION (8135BN) combined electrode was used to determine pH at 25ºC onboard. The temperature was controlled using a refrigerated circulating water bath that regulates the temperature to ±0.1ºC. The temperature was measured using a digital platinum resistance thermometer. The pH-meter was calibrated using a Tris (2-carboxyethyl) phosphine hydrochloride solution (pH 7.0) and a solution of Malic acid, MES and Tris (pH 10). The method has a shipboard precision of 0.002 pH units and an accuracy of 0.004 pH units. Salinity and temperature were measured with a Seabird CTD. Samples for the determination of total inorganic carbon were collected into plastic flasks from

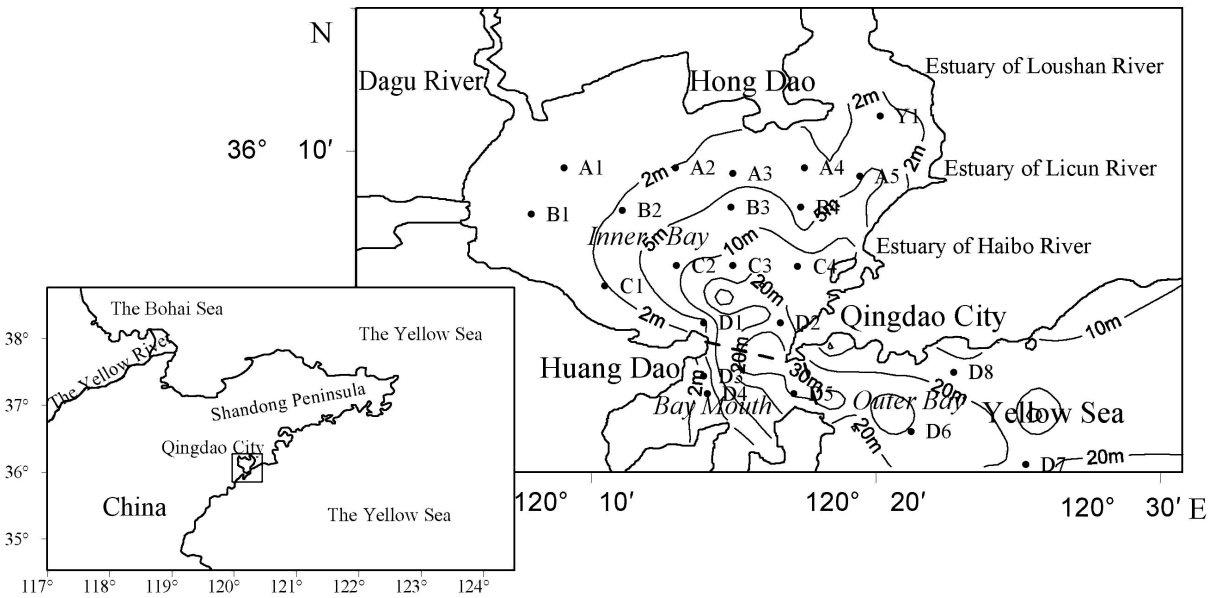

FIG. 1. – Sampling stations in the Jiaozhou Bay

10 L Niskin bottles, and then preserved with 0.5ml 10% $HgCl_2$ per 100 ml of sample, immediately sealed and stored in the refrigerator at a constant temperature of 3±1ºC. All samples were brought into the base laboratory and analysed within 2 days.

Determination of DIC and calculation of pCO_2

DIC in seawater was measured by a simple and rapid method with an airproof device designed by the authors (Fig. 2; Song *et al*., 2004). Between 100 and 150 ml of the seawater sample was placed in a conical flask, and then 10% H_3PO_4 was added to it. Therefore, the DIC from the sample was extracted as CO_2 gas by acidification and stripped by N_2 gas purified through two grades of NaOH solution (30%), and then CO_2 gas was absorbed by two grades of 0.1 mol/L NaOH solutions. Finally, the absorbed solution was titrated with a HCl standard solution of 0.01000 mol/L and the end points were detected with the indicators phenolphthalein and bromocresol green-methyl red mixture. The method was tested by analysing a primary standard of Na_2CO_3, which showed a satisfactory rate of recovery (about 99.8~100.2%). The analytical results were completely consistent with those of a TCO_2 analyser with an infrared detector. The standard deviation of replicate measurements was less than 0.3% and the accuracy was 5 μmol $^{-1}$.

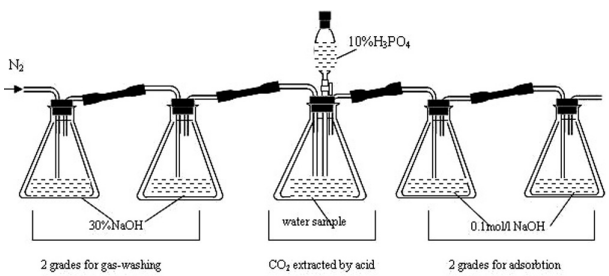

FIG. 2. – A new pre-treatment device for DIC determination in seawater.

pCO_2 can be calculated from DIC and pH, and the first and second dissociation constants of the carbonic acid, k_1 and k_2. k_1 and k_2 were calculated according to Lueker *et al*. (2000). The estimated standard deviation of the computed pCO_2 values was 1.4% and the accuracy was ±6 μatm.

CO_2 fluxes

In order to determine whether the Jiaozhou Bay constitutes a net CO_2 sink or source on an annual basis, CO_2 air-sea fluxes had to be obtained. The flux of CO_2 across the sea-air interface was estimated in June, July and November 2003 and February 2004 at each station using the equation:

$$F = ks\ \Delta pCO_2$$

where k is the gas transfer velocity (in cm h^{-1}), s is the solubility of CO_2 in seawater as a function of temperature and salinity taken from Weiss (1974). ΔpCO_2 is the gradient in CO_2 partial pressure between the seawater and the atmosphere, in μatm. Values for pCO_2 in seawater are readily calculated

TABLE 1. – Carbon dioxide system concentrations and CO_2 fluxes in Jiaozhou Bay surface waters

month		DIC μmol $^{-1}$	salinity	water temperature (ºC)	wind speed m s^{-1}	Chlorophyll *a** mg m^{-3}	pCO_2 μatm	CO_2 flux mmol $m^{-2}d^{-1}$
2	range	1765-2465	32.37-32.97	3.87-4.63	5.1-6.8	2.0-20.0	92-595	-25.6-21.6
	average	2044	32.71	4.16	5.9		317	-2.91
6	range	1913-2171	32.03-32.61	15.22-19.21	4.3-5.8	1.5-6.5	452-864	5.35-30.6
	average	2027	32.33	17.5	5.1		640	16.9
7	range	1856-2414	29.19-31.11	20.22-22.22	4.2-5.3	1.5-6.0	500-903	7.23-28.8
	average	2042	30.60	21.20	4.6		695	17.7
11	range	1642-2318	29.07-30.64	10.52-14.79	5.8-7.1	1.0-4.5	279-593	-8.57-22.6
	average	2025	30.01	12.43	5.9		419	5.40

* chlorophyll *a* data form Li C L *et al*. (2005a)

from DIC. The transfer velocity equation of Wanninkhof (1992) was used to obtain the CO_2 fluxes. The wind speed at 10 m above the sea surface (u_{10}, in m s^{-1}) was used to calculate the gas transfer velocity (k), which was gathered at every station from the anemometer on top of the ship. Air pCO_2 was determined using a Li-Cor non-dispersive infrared (NDIR) spectrometer (LI-6262) every day. The NDIR detectors were calibrated once a day with two CO_2 gas standards and an N_2 reference. The overall uncertainty of the pCO_2 measurements was less than 1% .The bow intake from which atmospheric air was pumped was installed at ~10 m above the sea surface to avoid contamination from the ship. Air pCO_2 measurements were corrected to 100% humidity at in situ temperature.

RESULTS AND DISCUSSIONS

Spatial and temporal distributions of DIC

The seasonal variation of DIC was not clear, and it ranged from 2025 to 2044 μmol kg^{-1} (Table 1). Although the horizontal distributions showed different patterns in different seasons, in general the DIC in the inner bay was higher than in the outer bay except in July (Fig. 3). The characteristics of the DIC distributions are mainly determined by the plankton growth and the hydrographic conditions in the Jiaozhou Bay (Li *et al*., 2004). Particularly, Haibo River, Licun River and Loushan River receive the industrial waste and sewage from Qingdao City on the northeastern shore of the Jiaozhou Bay. Dagu River receives industrial waste and sewage from urban districts on the northwestern shore, the western and northern shores are mollusc cultivation regions, and the southeastern and southwestern shores are occupied by port facilities. Therefore, seawater in the inner bay receives a large mount of industrial and domestic sewage, which is ultimately decomposed into CO_2. Furthermore, the water exchange with the Yellow Sea is slow and the average water residence time is about 80 days in the inner bay (Zhao *et al*., 2002). For these reasons, DIC in the inner bay was higher than that in the outer bay. The reason for DIC in the outer bay being higher than that in the inner bay in July might be related to phytoplankton blooming. In July, phytoplankton grows faster in Jiaozhou Bay and decreases from the inner to the outer bay (Wu *et al*., 2004), so the DIC consumed in the inner bay was higher, causing the DIC in the inner bay to be lower than that in the outer bay.

Seasonal variability of pCO_2

Strong seasonal variation in pCO_2 was evident, with the lowest value of 311 μatm in February and the highest value of 695 μatm in July (Fig. 4 and Table 1). The CO_2 content of most waters was oversaturated with respect to the atmospheric CO_2. However, undersaturated waters were found in the southern inner bay during February and in the bay mouth during November. To discuss such a seasonal variation of pCO_2, three major processes can be invoked: (i) the river inputs; (ii) the variation in temperature; and (iii) the biological activity in the water column. Because the annual change of river input and DIC in the Jiaozhou Bay is small, the river input should not be the main reason for the seasonal variation in pCO_2. However, the average pCO_2 decreased from July, June and November to February. The higher the surface seawater temperature was, the higher pCO_2 was. Water temperature shows a strong seasonal change (Fig. 5). Temperature affects the equilibrium constants of dissolved inorganic carbon and, in particular, the solubility coefficient of CO_2. The seasonal change

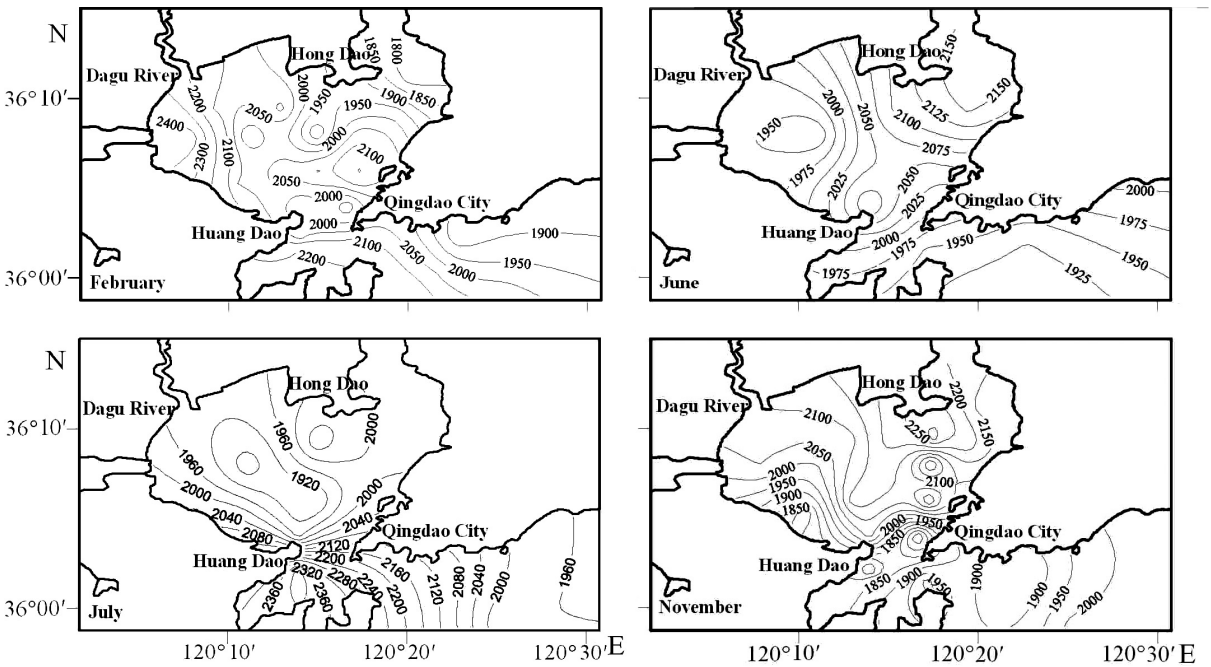

FIG. 3. – Horizontal distributions of sea surface DIC in the different seasons in the Jiaozhou Bay

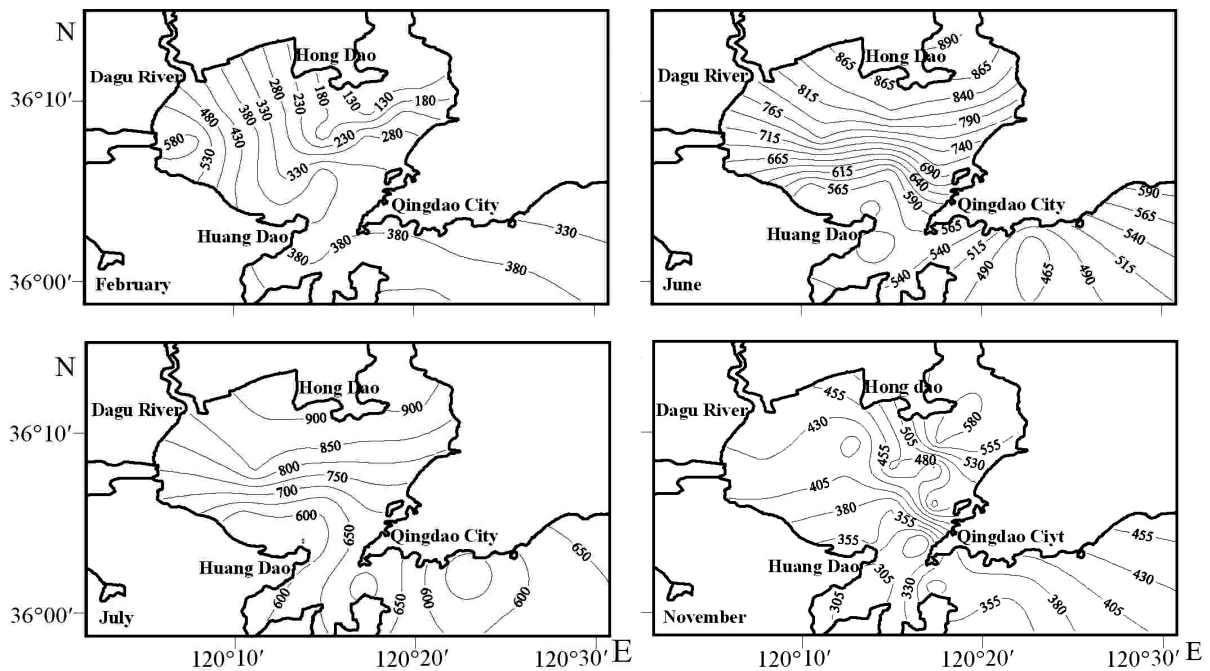

FIG. 4. – Horizontal distributions of sea surface pCO_2 in the different seasons in the Jiaozhou Bay.

in pCO_2 shows that the increase of solubility of CO_2, which was caused by the decrease in seawater temperature, was an important reason for the behaviour of the bay as a CO_2 source/sink. Therefore, temperature plays a key role in pCO_2 variation. Like DIC, phytoplankton may also influence pCO_2 in its bloom season. Although salinity in the inner bay was a bit lower than in the outer bay because of river-water input in all seasons, its distribution was clearly different from DIC and pCO_2 (Fig. 6), which showed that salinity has no influence on DIC and pCO_2.

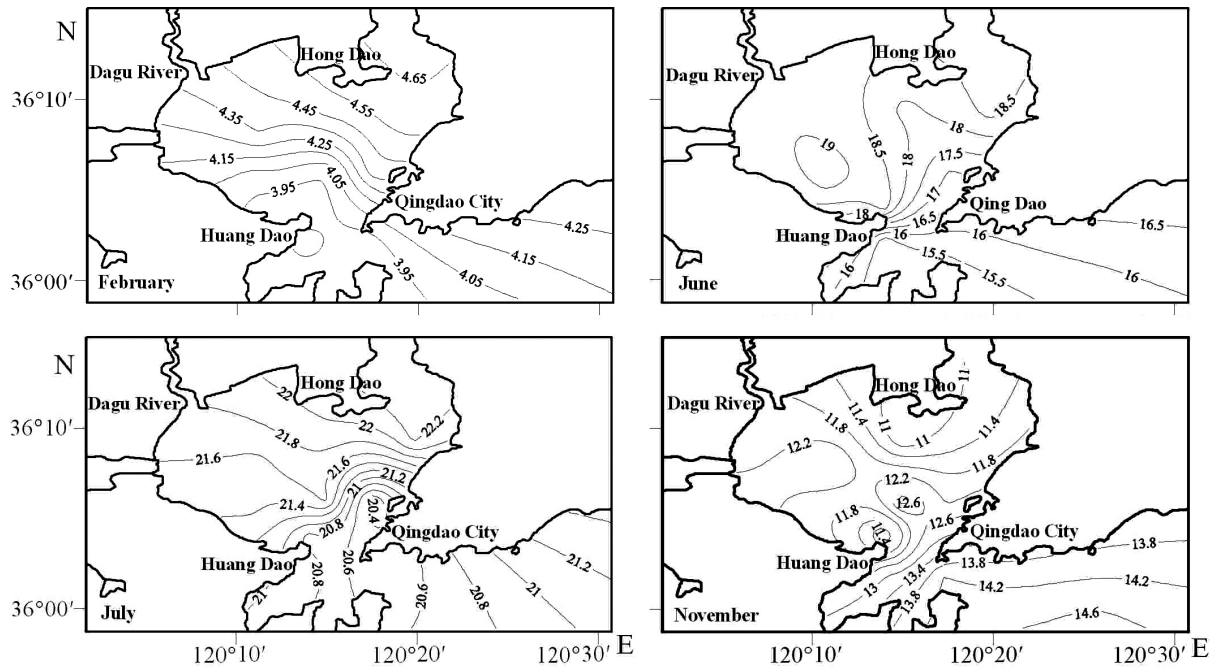

FIG. 5. – Horizontal distributions of sea surface temperature in the different seasons in the Jiaozhou Bay.

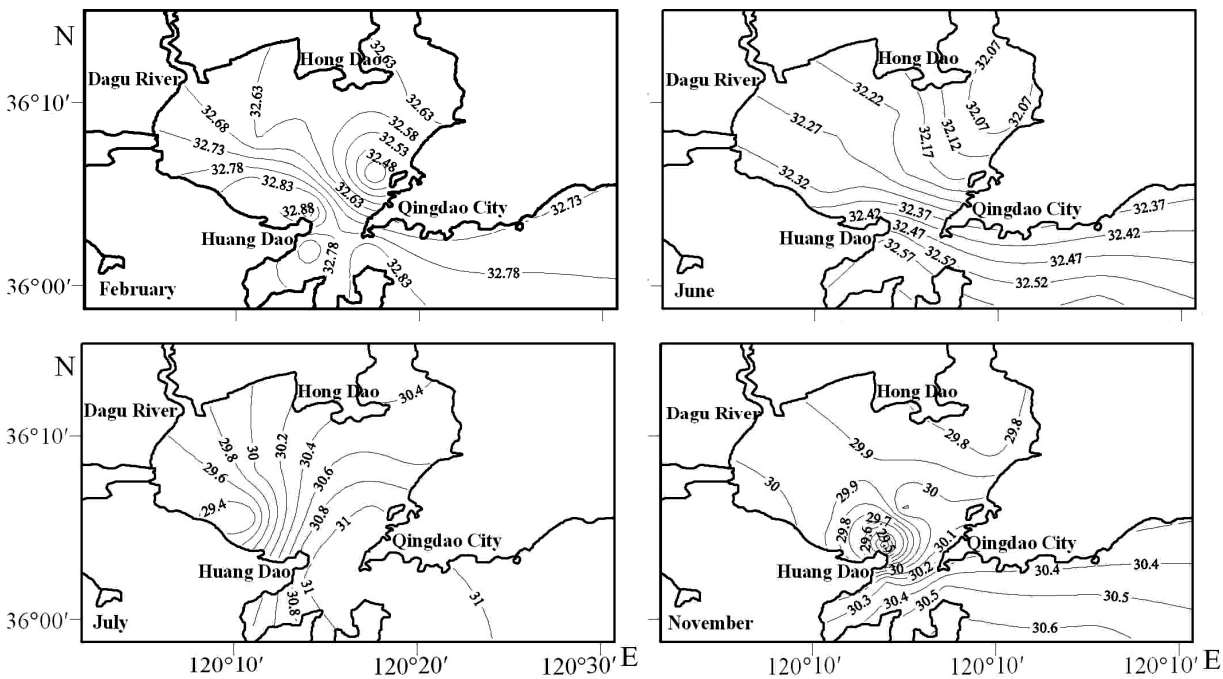

FIG. 6. – Horizontal distributions of sea surface salinity in the different seasons in the Jiaozhou Bay.

Seasonal variability of CO_2 fluxes

In order to assess the CO_2 seasonal cycle, the monthly CO_2 fluxes in June, July and November 2003 and February 2004 were calculated. The uncertainty of the fluxes was less than 15% due to the variability of pCO_2. In February 2004, the average CO_2 flux in the Jiaozhou Bay was -2.91±0.44 mmol C m^{-2} d^{-1}, which indicated that the Jiaozhou Bay absorbed atmospheric CO_2. However, it was a weak sink compared with the adjacent Yellow Sea CO_2 flux of -14.79 mmol C m^{-2} d^{-1} in winter (Song, 2004). In

June 2003, the average CO_2 flux was 16.9±2.5 mmol C m^{-2} d^{-1}, which indicated that the Jiaozhou Bay released CO_2 to the atmosphere. It was a strong source for atmospheric CO_2 and similar to the Yellow Sea in spring (Song, 2004). In July 2003, the average CO_2 flux was 17.7±2.6 mmol C m^{-2} d^{-1}, which indicated that the Jiaozhou Bay released CO_2 to the atmosphere at higher rates than the Yellow Sea in summer (Song, 2004). In November 2003, the CO_2 flux was 5.4±0.81 mmol C m^{-2} d^{-1}, which indicated that the Jiaozhou Bay released CO_2 to the atmosphere. This was consistent with the flux in the Yellow Sea in autumn (about 3 mmol C m^{-2} d^{-1}; Song, 2004), but weaker than in summer. Although the Jiaozhou Bay released CO_2 to the atmosphere in summer and autumn and absorbed atmospheric CO_2 in winter, which was consistent with the Yellow Sea, the difference in strength was very large. In addition, the Jiaozhou Bay released CO_2 to the atmosphere in spring, when the Yellow Sea is a CO_2 sink. The reason for this difference is that seawater temperature in spring increases faster than in the Yellow Sea because of the shallower waters of the Jiaozhou Bay.

Although the Jiaozhou Bay acted as a source or sink of atmospheric CO_2 as a whole, spatial differences were obvious, especially in February and November (Fig. 7). The behaviour as a carbon source or sink was opposite in different regions of the Jiaozhou Bay. In February, atmospheric CO_2 was absorbed in the inner bay, but CO_2 was released to the atmosphere in the bay mouth and the outer bay. The distributions in June and July were similar. The whole region released CO_2 to the atmosphere and the strength decreased from the inner bay to the bay mouth and to the outer bay. In November, CO_2 was released to the atmosphere in the inner bay and the outer bay, and atmospheric CO_2 was absorbed in the bay mouth.

Factors determining the behaviour as a CO_2 source or sink

Using the CO_2 fluxes mentioned above and considering the surface area of the Jiaozhou Bay as 340 km^2, its strength as a carbon source/sink for the 4 study months was calculated as follows: it released 1.53×10^{11} mmol C in June, 1.61×10^{11} mmol C in July and 4.90×10^{11} mmol C in November, and absorbed 2.65×10^{11} mmol C in February.

Many researchers have reported that the sea surface temperature (SST) is the primary factor that controls the variability of sea surface pCO_2 (Bates *et al*., 2000; Takahashi *et al*., 2002; Olsen *et al*., 2004; Wang *et al*., 2005). Between 40° and 60° latitude in both the northern and southern hemispheres, heat flux resulting in low temperature has long been recognised to be a major mechanism that causes the area to be a net sink of atmospheric CO_2 (Sarmiento and Gruber, 2002; Takahashi *et al*., 2002). Therefore, SST should play a key role in CO_2 fluxes across the seawater-air interface. Long-term observations of the hydrography, wind and salinity, which are the important factors influencing the CO_2 fluxes, indicate that they change little in one season, and only the temperature changes considerably (Table 2). Therefore, the variability of temperature may be a major factor in the seasonal variation of the CO_2 flux in the Jiaozhou Bay. The good correlation between CO_2 fluxes and the measured temperature in June, July and November 2003 and February 2004 indicates that temperature was the most important factor influencing CO_2 flux variations in the Jiaozhou Bay (Fig. 8). Based on the statistical results, the Jiaozhou Bay was a source of atmospheric CO_2 when SST was higher than 6.6ºC, and a sink when it was lower. SST also affects the equilibrium constants of dissolved inorganic carbon and, in particular, the solubility coefficient of CO_2. Solubility, and the first and second apparent ionisation constants of H_2CO_3 decrease with the increase in SST, so pCO_2 rises. It is reported that pCO_2 may rise by ~4% when temperature increases 1ºC (Borges and Frankignoulle, 2002). In the

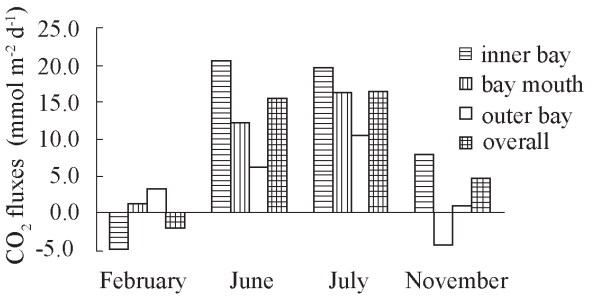

FIG. 7. – Average CO_2 fluxes in difference regions of the Jiaozhou Bay

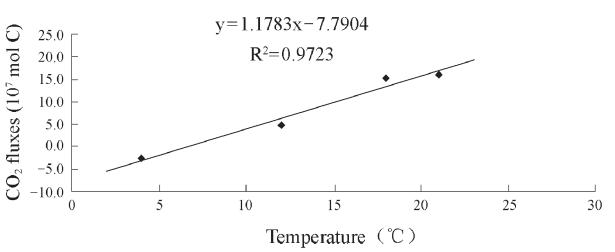

FIG. 8. – Relationship between CO_2 fluxes and SST in the Jiaozhou Bay.

TABLE 2. – Hydrographic and meteorological parameters and CO_2 fluxes in the Jiaozhou Bay during one year.

Season		winter			spring			summer			autumn	
Month	1	2	3	4	5	6	7	8	9	10	11	12
∗wind speed (m/s)	6.1	6.0	5.5	5.8	5.3	5	4.7	4.7	5.1	5.5	6.4	6.3
∗∗SST (ºC)	4.9	4.3	6.0	9.6	13.9	18.2	22.0	24.7	24.5	20.0	14.8	10.0
∗∗∗Salinity		31.9			31.55			30.80			31.63	
CO_2 fluxes (mmol $m^{-2}d^{-1}$)	-2.17	-2.66	-0.84	3.86	9.39	15.0	19.9	23.5	23.2	17.3	10.7	4.38
Total CO_2 fluxes(10^7mol C)	-2.03	-2.50	-0.79	3.51	8.83	13.7	18.7	22.1	21.1	16.3	9.67	4.11

∗From China bay records (The edit committee of china bay records, 1992), average wind speed between 1960 and 1979; ∗∗average SST was observed at a fixed station every day by the Jiaozhou Bay Marine Ecosystem Research Station between 2002 and 2004; ∗∗∗From Yang and Wu (1999)

Jiaozhou Bay, 6.6ºC was the critical temperature: pCO_2 in seawater was higher than atmospheric CO_2 partial pressure when the temperature was higher than 6.6ºC; otherwise, pCO_2 was lower than atmospheric CO_2 partial pressure.

To assess the annual variability of the behaviour as a carbon source/sink, CO_2 fluxes were calculated from January to December using the regression equation mentioned above and average SST between 2002 and 2004 (Table 2 and Fig. 9).

The Jiaozhou Bay was a CO_2 sink in winter due to the low temperature and absorbed about 5.32×10^{10} mmol C. In spring, it was a CO_2 source and released 2.60×10^{11} mmol C. In summer, it was a strong source and released 6.18×10^{11} mmol C. In autumn, as in spring, it was a source and released 3.01×10^{11} mmol C. Over the year, The Jiaozhou Bay acted a net CO_2 source and released 1.13×10^{12} mmol C.

On a global scale, some researchers have reported that ocean margins act as CO_2 sinks (Boehme *et al*., 1998; Tsunogai *et al*., 1999; Frankignoulle and Borges, 2001; Miller *et al*., 2002; Thomas *et al*., 2004), while some others consider that they are CO_2 sources (Borges and Frankignoulle, 2002; Cai *et al*., 2003; Olsen *et al*., 2004; Ito *et al*., 2005). For example, the Caribbean Sea was a CO_2 source throughout 2002, but the northern and eastern parts were a net CO_2 sink of around 0.5-1 mol C m^{-2} y^{-1}, and the southwestern part was a net CO_2 sources of about 0.5-1 mol C m^{-2} y^{-1} (Olsen *et al*., 2004). The South Atlantic Bight is a strong CO_2 source with an average rate of 2.5 mol C m^{-2} y^{-1} (Wang *et al*., 2005). The northern South China Sea acts as a source with an average sea-to-air CO_2 flux of 7 mmol CO_2 m^{-2} d^{-1} in summer and 1-3 mmol CO_2 m^{-2} d^{-1} in spring and autumn (Zhai *et al*., 2005). Compared to these regions, The Jiaozhou Bay is a strong CO_2 source on the whole. Figure 9 shows the annual change in the behaviour of the Jiaozhou Bay as a carbon source/sink, indicating that it was a CO_2 sink from January to March, and acted strongest in February. Then, it was a source from April to December and especially from July to September. In one year, the Jiaozhou Bay changed from a source to a sink between December and January of the following year, and it changed from a sink to a source between March and April.

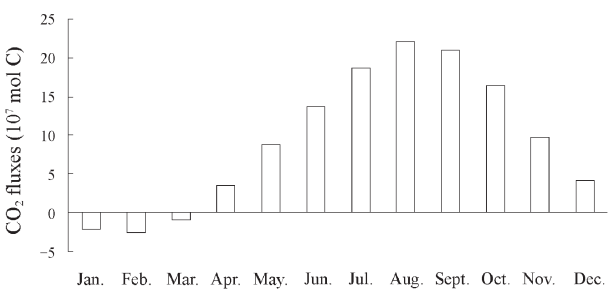

FIG. 9. – Monthly CO_2 fluxes in the Jiaozhou Bay.

Although part of the carbonate in sediments may be released to the overlying water and participate in the pelagic carbon cycle (Li, 2005b), its influence on CO_2 exchange across the air-water interface is indirect, and we do not discuss it here. We only focus on seawater temperature that influences CO_2 solubility and abundance of phytoplankton that can consume CO_2 in seawater.

The growth of phytoplankton will continuously consume CO_2 in seawater, and then CO_2 in atmosphere is propitious to be transported into seawater (Carrillo and Karl, 1999). The growth of phytoplankton shows a marked seasonal variability in the Jiaozhou Bay (Qian *et al*., 1983). Long-term observations show that the peak of chlorophyll *a* frequently occurs in winter and summer, with a mean of 4.72±3.15 and 4.33±2.57 mg m^{-3}, respectively. In spring, the mean chlorophyll *a* drops to 2.78±2.43 mg m^{-3} and the lowest concentration is obtained in autumn, only 1.95±0.80 mg m^{-3} (Wu *et al*., 2004). The highest phytoplankton concentration is in

February, and then it decreases gradually. From May, chlorophyll *a* increases again with the water temperature increase, and reaches its second peak in August, but the values are only half those in February. The seasonal changes in chlorophyll *a* are higher in the northern shallow area than in the southern area and the outer bay. The highest value occurs in February (monthly average concentration, 15.52 mg m^{-3}), when it is nearly 30 times higher than in December (0.55 mg m^{-3}) in the northern area of the bay (Li *et al*., 2005a). The horizontal distribution patterns show that the concentration of chlorophyll *a* decreases from the northern to the southern inner bay, and it is higher in the inner bay than in the outer bay. The distributions of chlorophyll *a* and pCO_2 were completely consistent with each other in February. However, the strength as a carbon source/sink was not correlated with the total phytoplankton biomass. For example, the Jiaozhou Bay was a strong source in September but the phytoplankton bloom did not turn it from a source to a sink. Therefore, it is obvious that the influence of phytoplankton is limited in months when the carbon source is strong, and it does not determine the strength as a carbon source in the high temperature season. Nevertheless, phytoplankton might still play an important role in the switch from carbon source to sink in regions where the source or sink is weaker. For example, phytoplankton abundance in the inner bay is higher than that in the bay mouth. Moreover, the inner bay was a sink of atmospheric CO_2 and the bay mouth was a weaker source in February.

The monthly variability as a carbon source/sink was consistent with the change in seawater temperature, which shows high annual variation in the Jiaozhou Bay, being highest in August and lowest in February. According to the clear correlation between the distribution of SST and strength as a carbon source/sink, the Jiaozhou Bay is a strong carbon source in August and a sink in February. The strength as a carbon source continually decreases and the area ultimately becomes a carbon sink as the temperature falls from the highest to the lowest level. It is clear that the influence of temperature on behaviour as a carbon source/sink is very great in the Jiaozhou Bay. Under the condition of global warming, seawater temperature will increase and the increase in the strength of seawater as a carbon source will be inevitable. The Jiaozhou Bay may therefore turn from a sink to a source even in the months with the lowest temperatures.

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