DISTRIBUTION CHARACTERISTICS OF pCO_2 AT THE AIR-SEA IN THE EAST CHINA SEA AND CHANGES DURING 2004–2023

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(Received 6th Jun 2024; accepted 18th Oct 2024)

Abstract. According to the carbon dioxide (pCO_2), temperature (T), salinity (S) and pH of the surface seawater obtained from a survey of carbon dioxide (CO_2) in the East China Sea (ECS) region from 2004 to 2023, the seasonal distribution characteristics of pCO_2 in the ECS were analyzed and discussed. The results show that the overall trend of pCO_2 in the ECS region indicated a slow increase followed by a decrease over the past 20 years, with the highest peak reached in 2016. The overall carbon sequestration capacity of the ECS shows a trend of first decreasing and then increasing. This is most likely related to China's adoption of effective policies and measures in achieving carbon peak and carbon neutrality. In terms of seasonal changes, the distribution of pCO_2 in the East Sea area roughly shows the differences. The annual seasonal changes are almost similar between the continental shelf area and the outer sea area. In terms of the average distribution of pCO_2 in surface seawater of the investigated area, pCO_2 in autumn and summer is higher than that in winter and spring, while atmospheric pCO_2 level in spring and autumn is higher than that in summer and winter, and the seasons are all represented by the exchange of atmospheric CO_2. The water system in the East Sea area is complicated, and the distribution of pCO_2 in surface seawater is mainly affected by four major water systems: the Yangtze River, the continental shelf water, the Kuroshio water, and the coastal current of the Yellow Sea. It is generally affected by vertical mixing of water in winter and late autumn and biological activities in summer, late spring, and early autumn.
Keywords: *global warming, blue carbon, carbon (C) neutrality, China, seasonal variation, factors*

Introduction

Global warming is the most important climate issue human beings are facing, and attracted extensive attentions (Jiao and Yan, 2022). China has introduced many national policies, committed to the goal of achieving carbon peak before 2030 and carbon (C) neutrality before 2060 as scheduled (Jiao et al., 2021). As the largest carbon pool on earth, the blue carbon sink has become the focus of research in China and abroad (Nie et al., 2018; Zhou, 2022; Wang et al., 2021; Jiao, 2021; Huang et al., 2020; Liu and Zheng, 2021). The study of CO_2 partial pressure and flux at the sea-air interface is of great significance for understanding and utilizing marine negative emissions to achieve carbon neutrality, as well as predicting the future trend of atmospheric CO_2 content level (Polukhin et al., 2021; Jin et al., 2017, 2019; Sutton et al., 2017; Yan et al., 2018; Li et al., 2021; Akhtar et al., 2021; Dai et al., 2022). The continental marginal sea is located between the land and the vast ocean, and the terrigenous sources and pollutants enter the ocean through the continental marginal sea, which plays an important role in the global carbon dioxide biogeochemical cycle (Hu et al., 2010). The ECS is one of the most typical continental shelf marginal seas in the world, the most concentrated zone of human activities and economic development in China, and it is also the zone where various processes of land, ocean and atmosphere interact intensely (Zhang, 2003). There

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2301_489505

are more than 40 rivers with a length of more than 100 kilometers flowing into the ECS, among which the Yangtze River, Qiantang River, Oujiang River and Minjiang River are the main rivers flowing into the ECS (Ye et al., 2017). Therefore, it is of great significance to study and understand the status and changes of pCO_2 and source/sink in the ECS surface seawater.

At present, there are many studies on CO_2 at the sea-air interface in the continental shelf marginal sea area in China. Tsunogai et al. (1997) earlier concluded that the continental shelf sea is a sink of atmospheric CO_2 through the study of carbon cycle in the ECS, and proposed the hypothesis of "continental shelf pump." Zhang et al. (1997) found that most of the sea area in the ECS could be regarded as a sink of atmospheric CO_2 through two voyages in the spring and autumn of 1994. Hu et al. (2001) explained in detail in their monographs that the ECS is a sink of atmospheric CO_2 and a key process of ocean flux in the ECS. Jiao et al. (2018) calculated and comprehensively analyzed the carbon pool and flux in the China Sea and adjacent areas. Hu et al. (2010) proposed a flux model based on the TCO_2 and TA data measured in the surface seawater of the ECS in November 2007, and used the weighted average method to estimate the net flux of CO_2 between sea and air in the whole survey area. The analysis showed that the distribution of pCO_2 in the surface seawater in autumn was mainly affected by seawater temperature, while the influence of biological activities was weak. Liu et al. (2016) explored the impact of the increase of nutrient concentration in the Yangtze River on the sea-air CO_2 flux in adjacent sea areas by designing a three-dimensional ecological dynamic-inorganic carbon cycle coupling model of the ECS. In summary, previous studies on sea-air CO_2 in the ECS were based on data from several voyages or years, without studying the pCO_2 and source/sink status of surface seawater in the ECS for a long time. In addition, due to the complex biogeochemical conditions in the ECS, the influencing factors of sea-air interface pCO_2 have become complex and diverse (Tan et al., 2004; Yu et al., 2023; Chen et al., 2007, 2014; Chou et al., 2009; Zhu, 2011; Qu et al., 2013).

According to the long-term survey data of surface seawater pCO_2 at the sea-air interface in the ECS, it is of particular significance to explore and analyze the distribution characteristics and influencing factors of the pCO_2 in the past 20 years and four seasons for understanding and utilizing the blue carbon sink of CO_2 at the sea-air interface in the ECS. Therefore, this paper is based on the surface seawater CO_2 partial pressure (pCO_2), temperature (T), salinity (S), pH value and other data obtained from the survey in the ECS in each season from 2004 to 2023. In addition, in order to systematically explore the source/sink status of CO_2 at the sea-air interface in the ECS, provide relevant basic data analysis for the use of marine carbon sink to help China achieve "carbon peak and carbon neutrality," and further reveal the sea-air CO_2 flux and its influencing factors in the shelf marginal sea, the pCO_2 distribution, seasonal variation characteristics and influencing factors of the surface seawater in the survey area were fully discussed and analyzed based on the data of the four voyages in the ECS in spring (May 2022), summer (August 2023), autumn (November 2022), and winter (February 2023) during 2022-2023.

Materials and methods

Sample collection and ocean current distribution in the ECS

This paper relies on the relevant reference literature of the voyage CO_2 survey and research in the ECS by Ningbo Marine Environmental Monitoring of the State Oceanic

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2301_489505

Administration. A total of 30 sampling stations were arranged, including 3 sections and 4 auxiliary stations. The schematic map of the current system includes Su Bei Coastal Current (SBCC), The Yellow Sea Coastal Current (YSCC), The arrows indicates the Yellow Sea Warm Water (YSWW), Tsushima Warm Current (TSWC), Taiwan Warm Current (TWWC), Changjiang Diluted Water (CDW), Min-Zhe Coastal Current (MZCC), and Kuroshio Current (KC). The specific distribution is shown in *Figure 1*.

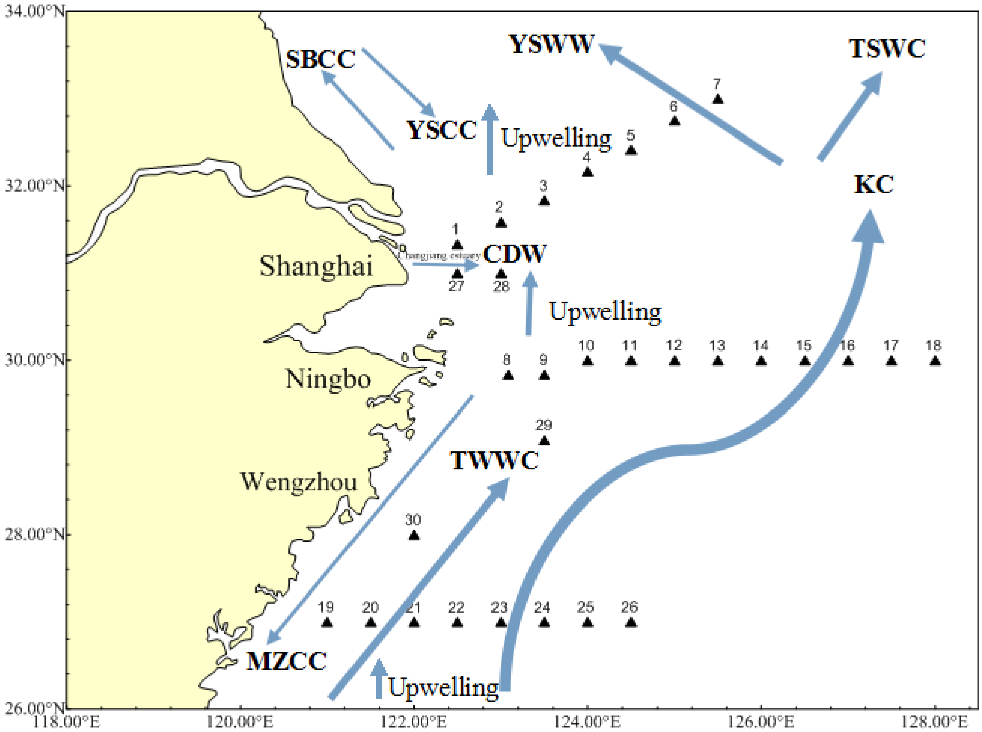

Figure 1. *Stations of the ECS and the schematic map of the current system. The numbered black triangles indicate the sampling stations*

Sampling and analysis

Forty-four cruises and/or cruise legs were conducted from 2004 to 2023 in the ECS. The observation frequency is twice a year, completing the four seasons of spring (May), summer (August), autumn (November), and winter (February) within two years. This includes spring (May 2022), summer (August 2023), autumn (November 2022), and winter (February 2023) during 2022-2023. During the cruises, sea surface water-depth sampling of seawater was conducted using a CTD self-capacitive sampler (Seabird, USA), which collects seawater samples from various levels based on the water depth and specific conditions on site. The Surface CO_2 pressure (pCO_2), temperature (T), and salinity (S) in the ECS were continuously obtained by a walking carbon dioxide analyzer, where pCO_2 was measured by Li Cor 7000 non-dispersive infrared analyzer after equilibrium dehumidification of surface seawater using a continuous flow water air balancer; Temperature T is determined by SBE 45MicroTSG (Sea-Bird Inc., Bellevue, WA, USA), obtained through aerial survey. The pH was measured on site using a 310P-01APH (Thermo Orion, USA) acidity meter for parallel double samples; The method assays were conducted using the methods outlined in the fourth volume of the marine survey code (Xu et al., 2007).

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
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Air-Sea pCO_2 was continuously measured with a non-dispersive infrared spectrometer (Li-Cor®7000) integrated into a Apollo (Apollo SciTech. USA). Surface water was continuously pumped from 2.5 to 5 m depth and measured every ~60 s. CO_2 concentration in the atmosphere was determined every ~1.5 h. The bow intake for air sampling was installed~10 m above the sea surface to avoid contamination from the ship. The barometric pressure was measured continuously onboard with a barometer attached at a level of ~10 m above the sea surface. The accuracy of the pCO_2 measurements was~0.3%.

Data processing

The mean of a dataset is the sum of all data points divided by the number of data points. The mathematical expression:

$$Mean = \frac{\sum_{i=1}^{n} x_i}{n} \quad \text{(Eq.1)}$$

x_i is the i-th data point, and n is the total number of data points.

Sum up the absolute deviations and divide by the number of data points to obtain the average deviation. The mathematical expression:

$$\text{Average deviation} = \frac{\sum_{i=1}^{n} \left| x_{i} - Mean \right|}{n} \quad \text{(Eq.2)}$$

Relative mean deviation is a method of measuring the degree of difference between each data point in a dataset and the mean, which can help evaluate the degree of data dispersion and the accuracy of experimental results. The mathematical expression:

$$\text{Relative average deviation} = \frac{\text{Average Deviation}}{\text{Mean}} \times 100\% \quad \text{(Eq.3)}$$

This study is based on the calculation of the pCO_2 annual mean、annual average deviation and relative average deviation from 2004 to 2023. The average partial the pCO_2 distribution, seasonal variation characteristics and influencing factors of the surface seawater in the survey area were fully discussed and analyzed based on the data of the four voyages mean in the ECS in spring, summer, autumn, and winter during 2022-2023.

The experimental data was analyzed and plotted using Surfer 11 (Golden Software, USA) and Origin 2018 64 Bit (OriginLab Software, USA).

Results and discussion

Changes in surface sea and air pCO_2 in the ECS from 2004 to 2023

Based on the changes of pCO_2 in sea air interface and atmospheric pCO_2 n the ECS region during 2004 to 2023, the annual changes in the concentrations of Surface pCO_2

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
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distribution of sea water in the ECS from 2004 to 2023 can be inferred. The highest sum of the average pCO_2 concentration of each estuary, which was 375.6 μatm, was recorded in 2016 (*Fig. 2*). There was a steady decline from 2016 to 2023. By 2023, it decreased to 366.5 μatm. pCO_2 distribution of atmosphere gradually increased over the study period, from 400.0 μatm in 2004 to 403.6 μatm in 2017 (*Fig. 3*). Starting from 2017, it slowly decreased to 402.5 μatm by 2023.

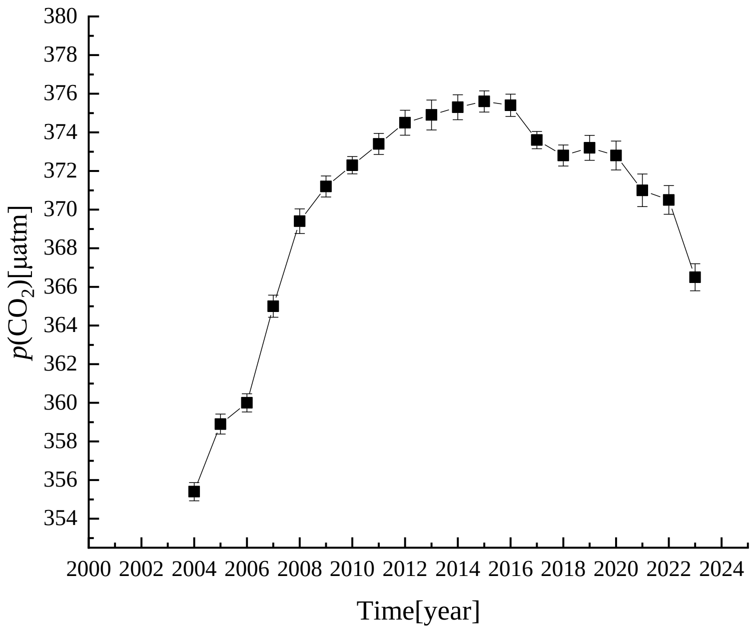

Figure 2. *Surface pCO$_2$ distribution of sea in the ECS for the period from 2004 to 2023. Error bars represent relative average deviation*

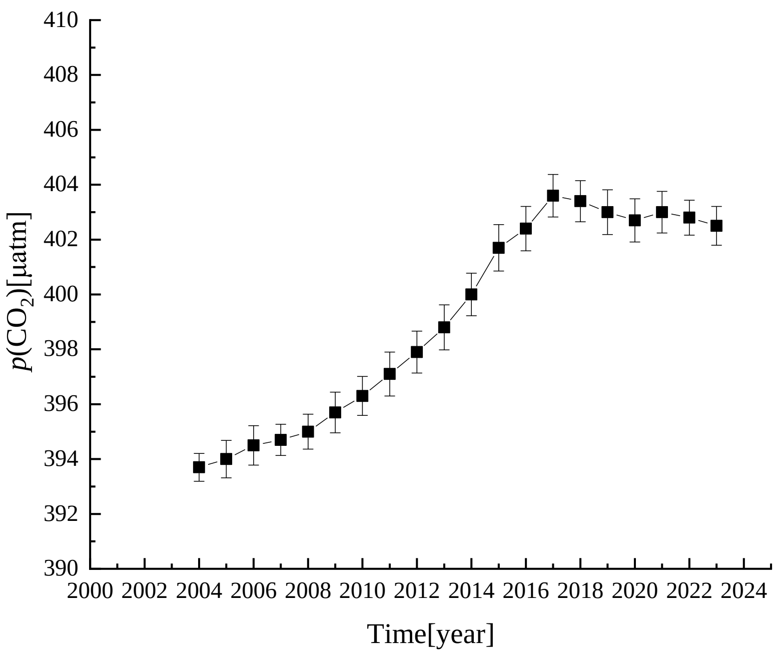

Figure 3. *pCO$_2$ distribution of air in the ECS for the period from 2004 to 2023. Error bars represent relative average deviation*

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However, Surface pCO_2 distribution of sea water in the ECS and pCO_2 distribution of atmosphere generally show an increasing trend. Since 2015, the average Surface pCO_2 distribution of sea water in the ECS have increased significantly. The annual average Surface pCO_2 distribution of sea water in the ECS in 2015 was 5.7%, which is greater than that measured in 2003. And, the annual average pCO_2 distribution of atmosphere increased to 8.6%. The annual variation of pCO_2 in the ECS region is very small, showing an overall trend of first increasing and then decreasing, with the highest value reached in 2015. The overall carbon sequestration capacity shows a trend of first decreasing and then increasing. This may be closely related to China's proactive actions in peaking carbon emissions and achieving carbon neutrality, as well as adopting more effective policies and measures (Jiao and Yan, 2022; Howard et al., 2018)

Seasonal distribution characteristics of surface pCO_2 in the ECS

The distribution of surface seawater pCO_2 in the ECS varies greatly in spring, summer, autumn and winter, which is different from the distribution of oceanic pCO_2, and fully reflects the complexity of the continental shelf marginal sea area (Wu et al., 2020; Chou et al., 2009). As can be seen from *Figure 1,* the coastal areas in the western ECS with a water depth of less than 50 m are mainly affected by the diluted water of the Yangtze River, the Fujian-Zhejiang coastal current, the North Jiangsu coastal current (mainly in summer) and the Yellow Sea coastal current (mainly in winter). Human activities have a significant impact on this sea area. The central ECS is located in the continental shelf area between the 50 and200 m isobaths, mainly controlled by the diluted water of the Yangtze River, the Taiwan warm current and the Yellow Sea warm current, with relatively active biological activities (Qu et al., 2013). In addition, the Kuroshio and Tsushima warm current with high temperature, high salinity and poor nutrition also affect the water body in the ECS.

Spring

From *Figures 4–6*, it can be seen that the overall trend of surface seawater pCO_2 in the surveyed sea area in spring is that, except for the large value in the Yangtze Estuary, the other sea areas generally show a horizontal gradient distribution from low to high from west to east. The measured value of pCO_2 ranges from 122 to 624 μatm, with an average value of 332 μatm. The first low value area appears in the west of the northeast direction of the surveyed sea area (125°E, 32°N) with pCO_2 less than 300 μatm, with a minimum measured value of 188 μatm. This may be related to the eastward expansion of diluted water in the Yangtze River after the export in spring. In addition, based on temperature and salinity data, the coastal currents of the Yellow Sea account for a larger proportion in mixed water system around 124°E and 32°N in spring. The second low value of pCO_2 is located west of 124°E, reflecting the trend of southward expansion of diluted water in the Yangtze River in spring, and the expansion trend is relatively weak. This is mainly due to the fast sedimentation rate, and an increase in the thickness of the eolian layer will lead to enhanced photosynthesis, thereby consuming a large amount of CO_2 in the water body. In addition, the runoff process and effects of Min-Zhe River entering the sea are the same as the diluted water of the Yangtze River, which also results in a lower value of pCO_2. Due to the influence of the Kuroshio, the water temperature in the open sea area is relatively higher. However, as the water moves northward, the water temperature continuously decreases, and the solubility of CO_2 in surface seawater increases, leading to a decrease in pCO_2 (Zhang, 2003).

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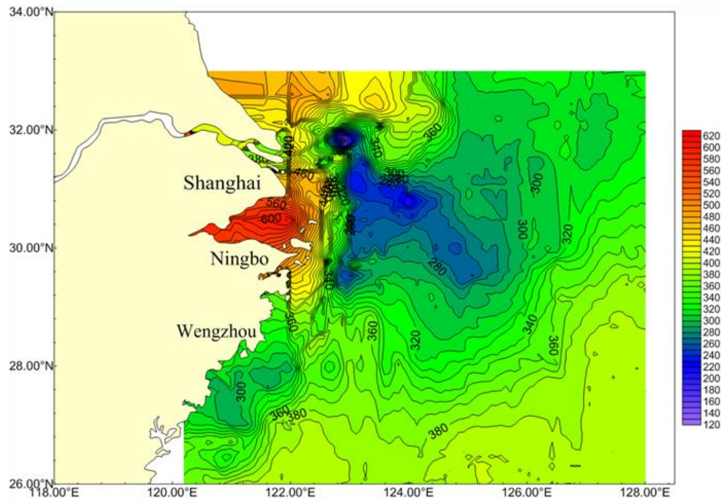

Figure 4. *The spring surface distribution of* pCO_2

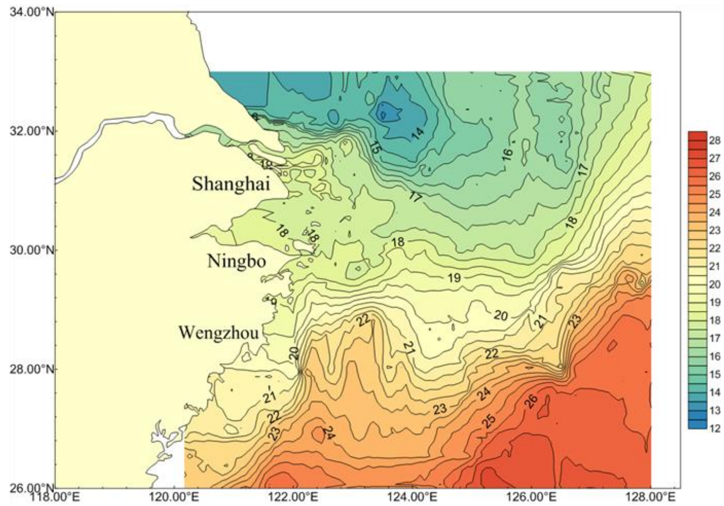

Figure 5. *The spring surface distribution of temperature*

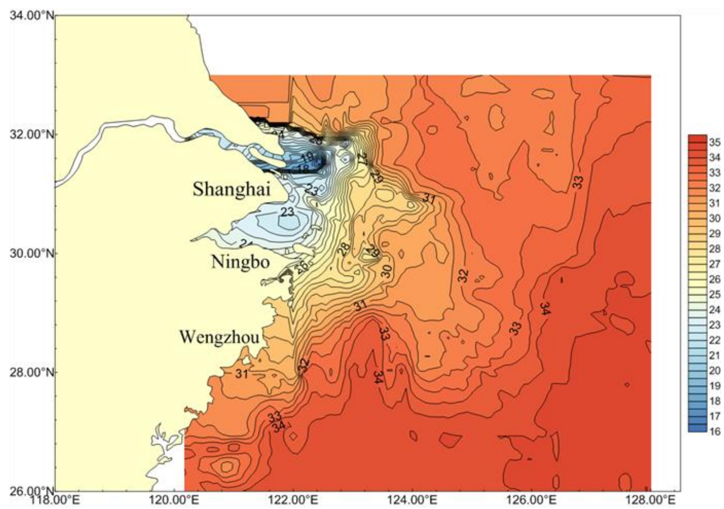

Figure 6. *The spring surface distribution of salinity*

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Summer

As can be seen from *Figures 7–9*, the rough distribution of the surface pCO_2 in the survey area of the ECS in summer is similar to that in spring, but slightly different from that in spring. The measured value of pCO_2 ranges from 108 to 946 μatm, with an average value of 373 μatm. Also, the distribution value of pCO_2 near the Yangtze River Estuary (salinity < 20) is very high (with the highest value exceeding 900 μatm), which is obviously caused by the input of the diluted water from the Yangtze River (Zhai and Dai, 2009; Chen et al., 2008). In addition, within a large range of the center (124°E, 32°N), the surface pCO_2 is below 250 μatm (minimum value below 150 μatm), and extends eastward along the 300 μatm contour line to the east of 126°E. Compared with the spring, the low value area of pCO_2 moves westward. Combined with the salinity distribution in summer (*Fig. 8*), it can be seen that the sea area is affected by the northeastward transport of diluted water from the Yangtze River, and the biological activities of the Yangtze River diluted water with high concentration of nutrient salts are particularly intense in summer, which is the reason for the low pCO_2 of surface seawater.

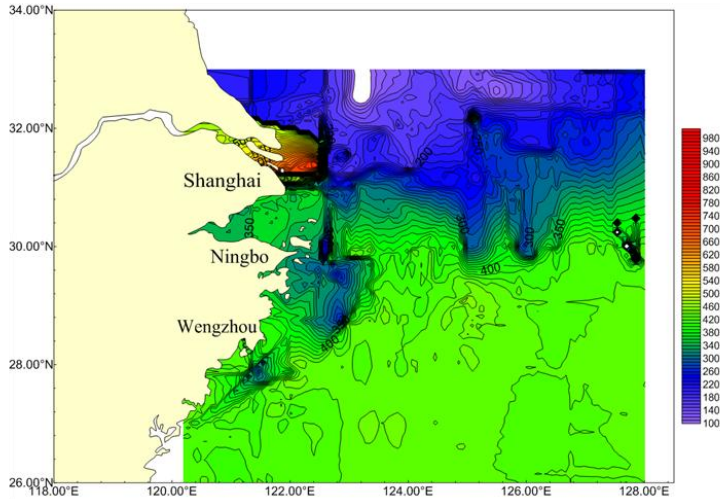

Figure 7. *The summer surface distribution of pCO_2*

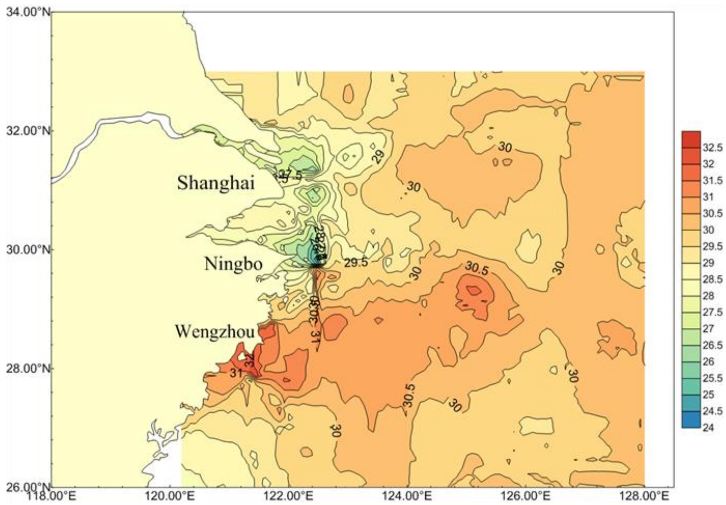

Figure 8. *The summer surface distribution of temperature*

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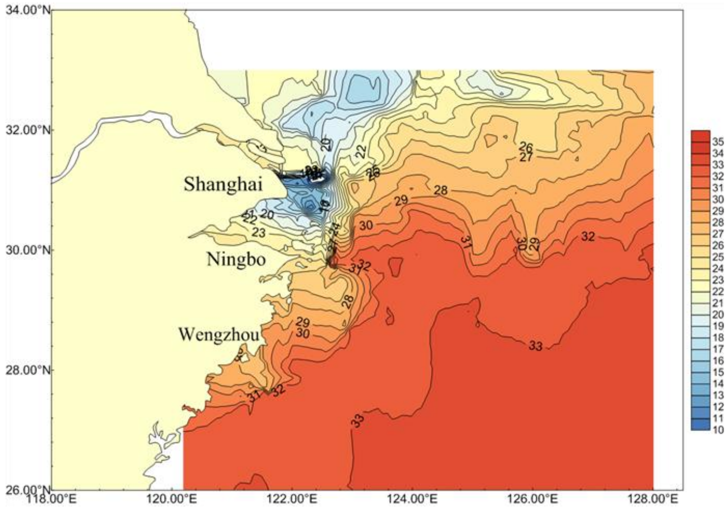

Figure 9. *The summer surface distribution of salinity*

Meanwhile, the high pH value of water (8.25~8.45) is also the evidence of the low pCO_2. In the south of the Yangtze Estuary, there is also a large low value area of pCO_2 with the center (124°E, 30°N), which constitutes a large area of low value area of pCO_2 in the middle of the ECS. This is consistent with the theory of Qu et al. (2013) that the continental shelf in the middle of the ECS is a strong sink area of atmospheric CO_2.

Autumn

It can be seen from *Figures 10–12* that the distribution of pCO_2 in autumn in the survey area of the ECS is generally lower than that in spring and summer. The measured value ranges from 325 to 548 μatm, with an average value of 389 μatm. The distribution trend is roughly opposite to that in spring, and generally presents a horizontal gradient distribution from high to low from west to east. In the west of 125°E, pCO_2 is greater than 380 μatm, and the maximum measured value is 548 μatm.

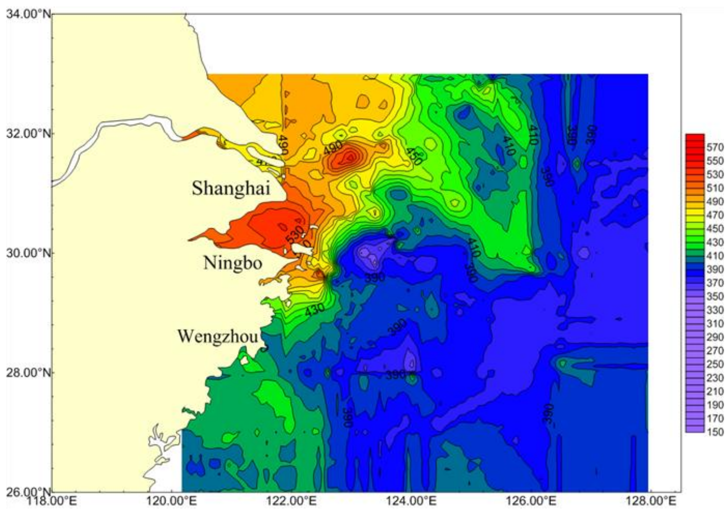

Figure 10. *The autumn surface distribution of pCO_2*

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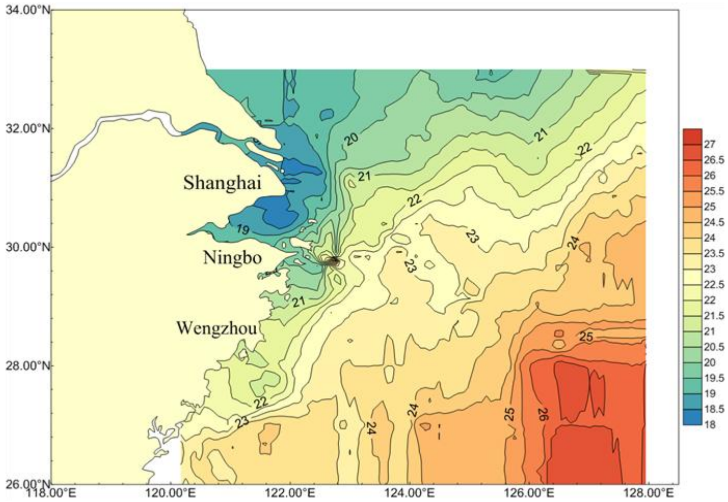

Figure 11. *The autumn surface distribution of temperature*

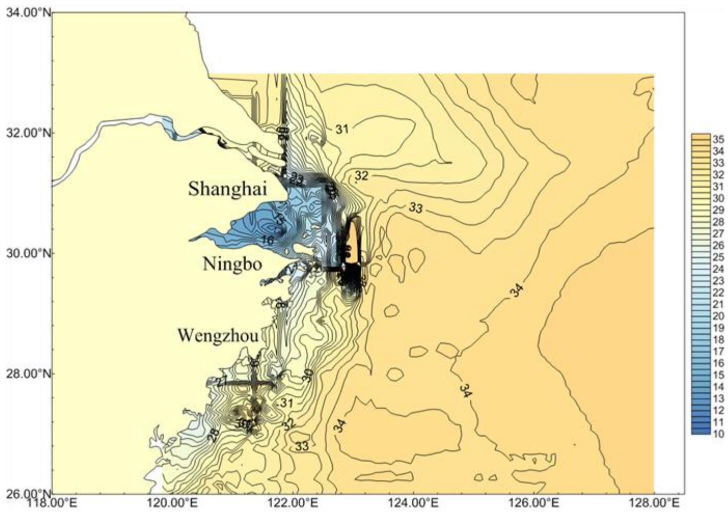

Figure 12. *The autumn surface distribution of salinity*

The pCO_2 in the Kuroshio area is about 350 μatm. The surface seawater pCO_2 in the Yangtze Estuary and the northern ECS is relatively high in autumn, with an average value of 409 μatm. In autumn, the trend of the diluted Yangtze River water extending northeast gradually weakens, while the southward trend of the Yellow Sea coastal current gradually strengthens. Therefore, the coastal upwelling and the Yellow Sea coastal current are the causes of the high pCO_2 in the northern ECS. In addition, the Yellow Sea coastal current is a strongly alkaline water, and the southward movement of the cold water masses will lead to climate warming. Under the joint influence of the diluted Yangtze River water, the surface seawater pCO_2 increases. The oceanic water component in the ECS continues to increase, and the strong vertical mixing of water makes the chemical properties of each layer of water basically similar. This usually leads to the enrichment of pCO_2 in lower water bodies. The mixing of water bodies also makes the surface seawater pCO_2 higher than the value before mixing (Ye et al., 2019).

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Winter

As can be seen from *Figures 13–15*, the distribution of pCO_2 in the surveyed sea area in winter is generally similar to that in autumn, but slightly lower than that in autumn. There is an obvious gradient distribution from high to low, from west to east. The measured value ranges from 302 to 480 μatm, with an average value of 360 μatm. The diluted Yangtze River water has little influence on the ECS in winter. The surface seawater temperature and salinity in the surveyed sea area are controlled by the Kuroshio water, the Taiwan warm current, the Yellow Sea coastal current and the diluted Yangtze River water, in order of degree of influence. The phenomenon of temperature and salinity increasing from west to east was probably the result of the Yellow Sea coastal current shifting from west to east, which contains a certain amount of diluted water from the Yangtze River and has low temperature and high pCO_2. The gradient distribution of pCO_2 was about 125°E, and the measured value of pCO_2 was higher near 128°E, with higher temperature and salinity. This may be because the sea area is located at the water fork of the Kuroshio Current and the northern end of the Okinawa Trough, where both horizontal mixing and vertical mixing modes jointly affect the water body (Ye et al., 2019).

In summary, the distribution of pCO_2 in the surface seawater of the ECS in spring, summer, autumn and winter has its own characteristics. In different seasons, different water systems have different effects on the pCO_2 of the surface seawater, showing certain characteristics of seasonal changes. In general, the pCO_2 value measured in the survey area in spring is between 122 and 624 μatm, with an average of 332 μatm; in summer, except for the extremely high value of pCO_2 in the sea area near the Yangtze Estuary (salinity < 20), the measured value of pCO_2 is between 108 and 946 μatm, with an average of 373 μatm; in autumn, the measured value of pCO_2 in the survey area is between 325 and 548 μatm, with an average of 409 μatm; in winter, the measured value of pCO_2 in the survey area is between 302 and 480 μatm, with an average of 360 μatm. The atmospheric pCO_2 in the ECS is relatively stable, and the spatiotemporal distribution of pCO_2 in the nearshore atmosphere is higher than that in the open sea. Meanwhile, the spatiotemporal distribution of pCO_2 in the nearshore atmosphere also objectively reflects the human influence on land. The atmospheric pCO_2 in the ECS does not change much in the horizontal gradient, with the average value of 475 μatm in spring, 413 μatm in summer, 445 μatm in autumn and 406 μatm in winter.

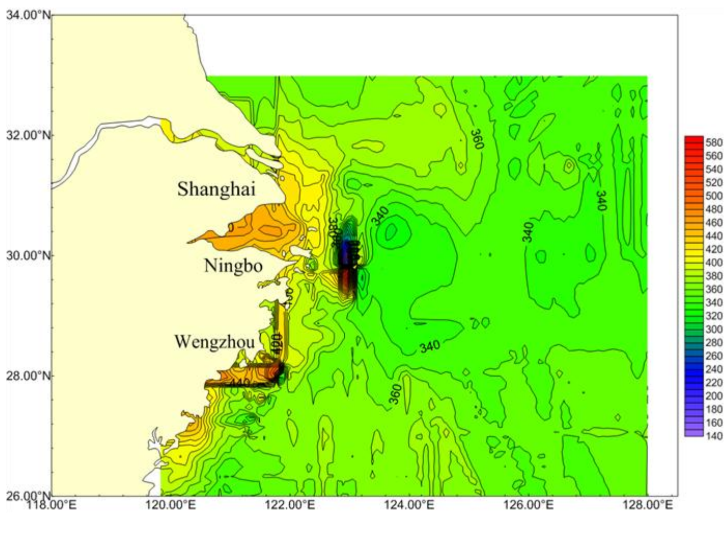

Figure 13. *The winter surface distribution of* pCO_2

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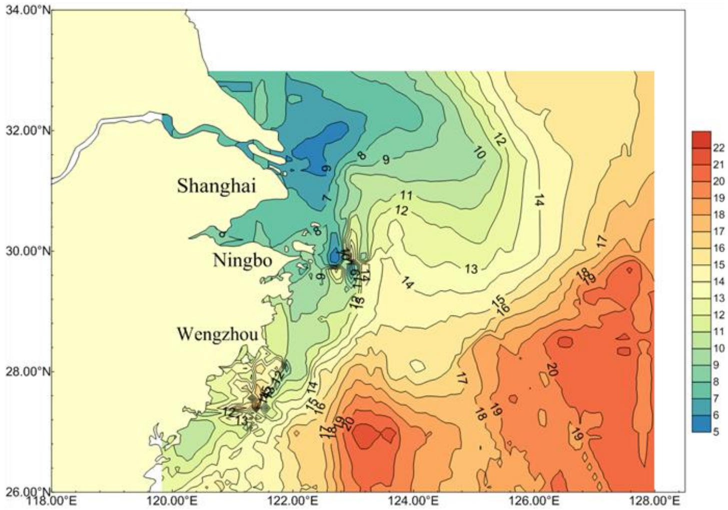

Figure 14. *The winter surface distribution of temperature*

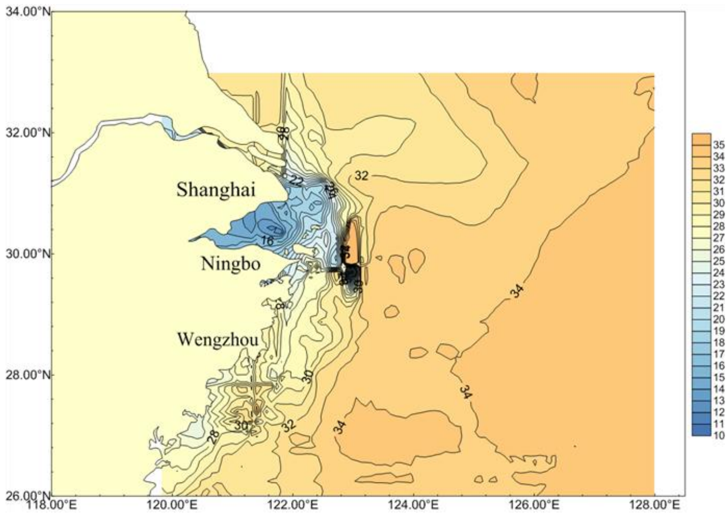

Figure 15. *The winter surface distribution of salinity*

It can be seen that the concentrations of pCO_2 in surface waters is higher in autumn and summer than that in winter and spring. The distribution of pCO_2 in air are spring in autumn and summer than that in summer and winter. Because of the complexity of the ECS water system, the distribution of pCO_2 in the ECS shelf area reflects the above seasonal variation rule, which may be due to the vertical mixing of water in winter and late autumn and the influence of biological activities in summer, late spring and early autumn (Jiao et al., 2011, 2013; Zhang et al., 2019). This is slightly different from the seasonal variation of pCO_2 in the surface waters of the northern Pacific Ocean reported by Takahashi et al. (1993) which may be due to the influence of human activities on the distribution of marine pCO_2 in the past 30 years.

Analysis of changes surface pCO_2 in the ECS

As shown in *Figure 1*, the water depth in the western coastal area of the ECS is generally lower than 50 m, which is mainly affected by the diluted water of the Yangtze

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River, the Fujian-Zhejiang coastal current, the northern Jiangsu coastal current (mainly in summer), and the Yellow Sea coastal current (mainly in winter). The central shelf area of the ECS is located between the isobath of 50-200 m, mainly controlled by the Yangtze River diluted water, Taiwan warm current and the Yellow Sea warm current, and the biological activities are relatively active. The ECS is an open sea area east of the 200 m isobath, which is affected by the Kuroshio and the Tsushima Warm Current all year long and has the characteristics of high temperature, high salinity and malnutrition. The diluted water of the Yangtze River is one of the most important factors affecting the pCO_2 distribution in the surface seawater in the ECS, and it forms two important water masses in the west of the ECS together with the Taiwan warm water,. The Taiwan warm water originates from the Taiwan Strait and the Kuroshio, and usually extends northward along the coasts of Fujian and Zhejiang until it meets the coastal waters (Qu et al., 2013; Ye et al., 2019). In winter, the diluted water of the Yangtze Reiver flows to the south along the coastline in a very narrow range, but in summer, when the river runoff is large, it points to Jeju Island in South Korea, and even reaches the Tsushima Warm Current area (Takajashi et al.,1993). The Taiwan warm water is ocean water with high salinity and low suspended solids content, while the Yangtze River diluted water is the water with low salinity, high nutrient salts and high suspended solids content. The Taiwan warm water and the Yangtze River diluted water are the main sources of salt and fresh water in the ECS, respectively. Their distribution and variations control the temperature and salinity, circulation structure, seawater circulation and material flux in the region, and also affect the occurrence and development of fronts, fishing grounds and even red tide phenomenon (Di et al., 2023; Bai et al., 2023). In addition, along the northeast direction north of the Yangtze Estuary, it is controlled by the Yellow Sea coastal current in winter, and is significantly affected by the Yangtze diluted water in summer (Lie, 2003). In the relevant surveyed waters, the distribution of pCO_2 in winter and summer showed a basically opposite trend due to the rising of the subsurface waters of the Taiwan Warm Current and the Kuroshio along the continental shelf edge. The pCO_2 of the Kuroshio and its affected waters shows an opposite distribution characteristic compared with that of the continental shelf area in the same season. As for the distribution of pCO_2 in the Kuroshio and its affected waters, although the seasonal variation is small, it still reflects a different distribution trend compared with that in the continental shelf area, which is lower in winter and autumn, and higher in summer and spring. This is consistent with the seasonal variation trend observed by Ionue et al. in the equatorial Pacific Ocean. The Kuroshio water flowing northward from the equatorial Pacific Ocean should have more characteristics of oceanic water systems (Inoue et al., 1987). Secondly, in winter, due to the strong vertical mixing, the contribution of the subsurface and even middle layer high CO_2 water to the surface seawater pCO_2 cannot be ignored. In summer, the direct contribution of the groundwater to the surface seawater pCO_2 is almost imperceptible due to diapause. It can be seen that due to the complex circulation in the ECS, the distribution of surface seawater pCO_2 is relatively uneven, mainly affected by the four major water systems: the Yangtze River water, the ECS continental shelf water, the Kuroshio water and the Yellow Sea coastal current. In winter, the pCO_2 of the ECS continental shelf area is lower than that of the atmosphere; in spring and summer, the pCO_2 of the ECS continental shelf area is lower than that of the atmosphere, which is mainly affected by biological activities. The distribution of pCO_2 in the surveyed sea area in autumn is similar to that in winter, but higher than that in winter. In general, the distribution of pCO_2 in the surface seawater of the ECS presents the difference of “coastal area-continental shelf area-open sea area,” but

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
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the average value of pCO_2 in the surface seawater of the ECS is lower than that of the atmosphere, and they are all the sinks of atmospheric CO_2. In addition, although the Kuroshio and its affected waters exhibited opposite natures to the continental shelf area of the ECS during the same season, their contribution to the CO_2 in the entire ECS is limited. From the above discussion, the overall performance of the ECS is equivalent to a net sink of CO_2 throughout the year, and the carbon flux is one million tons (Gt) (Qu et al., 2013). Therefore, the blue carbon sink of the ECS plays an important role in the regulation of atmospheric carbon dioxide. It can make an important contribution not only to China's "carbon neutrality and carbon peak," but also to the blue carbon sink of the entire ocean (Xiang et al., 2022; Cao and Wu, 2023; Ye et al., 2020; Huang et al., 2024).

Conclusion

Based on the analysis of pCO_2 at the Air-Sea Interface in the ECS in the last 20 years, it is concluded that concentrations of pCO_2 began at 355.4 μatm per year in 2004, reached a maximum of 375.6 μatm in 2015, and slowly decreased since 2016 to 366.5 μatm per year in 2023. Considering the scale of this study, we advocate the adoption of continuous annual marine environmental monitoring, which will provide reliable data support for decision-making of China's marine environmental management authorities. This may be closely related to China's proactive actions in peaking carbon emissions and achieving carbon neutrality, as well as adopting more effective policies and measures.

From the distribution characteristics of pCO_2 in surface waters of the ECS in spring, summer, autumn and winter, it can be found that the distribution of pCO_2 in the ECS presents a difference among "shoreline area, continental shelf area, and outer sea area." The distribution of pCO_2 in surface waters of the ECS exhibits clear seasonal variations. Concentration of pCO_2 in surface waters is higher in autumn and summer than that in winter and spring. The distribution of pCO_2 in air is spring in autumn and spring than that in summer and winter.

In general, the four seasons in the ECS are the sink of atmospheric CO_2. Due to the complexity of the ECS water system, the distribution of pCO_2 in surface waters in the ECS is mainly affected by the four major water systems: the Yangtze River water, the ECS continental shelf water, the Kuroshio water and the Yellow Sea coastal current. It is influenced by vertical mixing of water bodies in winter and late autumn and the biological activities in summer, late spring, and early autumn. In addition, although the Kuroshio and its affected waters exhibit the opposite nature within the ECS continental shelf area during the same season, the contribution to the entire ECS CO_2 is limited.

Acknowledgements. This research was funded by the Ningbo Municipal Bureau of Science and Technology Key Research and Development Plan (2023Z045, 2023Z146); Natural Science Foundation of China under contract Nos 42076156; National Oceanic Administration ECS Branch Youth Marine Science of China No. 202209. Finally, the relevant data support issued by Ningbo Ocean Fishery Bureau is hereby grateful.

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