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Seasonal changes and controlling factors of sea surface pCO_2 in the Yellow Sea

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Abstract. Sea surface partial pressure of carbon dioxide (pCO_2) is an important parameter in the ocean carbon cycle system. By using accurate global sea surface pCO_2 data, we can directly estimate the ratio of net CO2 uptake of global ocean, which can provide a support for further research of global carbon cycle. This article mainly discussed the seasonal changes of sea surface pCO_2 and the relationships of pCO_2 with sea surface temperature (SST) and chlorophyll-a concentration (Chla) in the Yellow Sea during winter, spring and summer, based on the data obtained by the shipboard measurements in February, May and August 2010. The results showed that the correlations of pCO_2 with SST and Chla were different in different seasons. SST and pCO_2 had a strong positive correlation in the range of higher SST for both spring and summer, and a relative weak correlation in winter，which can be fitted by a quadratic curve in each season. There was a linear correlation between pCO_2 and Chla in each season. The data of pCO_2 and Chla showed a negative correlation during winter and summer, and a positive one during spring. Based on the correlation analyses, we proposed a regression equation of pCO_2 with SST and Chla as two parameters in the Yellow Sea for summer, which showed a root mean squared error (RMSE) of 16.68μatm when the shipboard-observed data were used. By using the satellite-observed SST and Chla instead of the field data, the RMSE of the result is 21.46μatm.

1. Introduction

In recent years, the research on global carbon cycle has drawn more and more attentions. As one of the most important repository of the Earth's carbon, ocean plays a vital role in regulating global atmospheric concentration of carbon dioxide (CO_2) [1]. Sea surface partial pressure of CO_2 (pCO_2) is a principal parameter in the ocean carbon cycle system [2]. Accurate global sea surface pCO_2 data can be used to evaluate the ratio of net CO_2 uptake of global ocean [2], which can support the further study of global carbon cycle.

The Yellow Sea is an important shelf sea of China [3]. Because of the influence of the input of terrigenous rivers and biological activities， the distribution of pCO_2 in the Yellow sea is complicated. Currently, some researchers have done some investigations on the distribution and controlling factors of pCO_2 in the Yellow Sea and Bohai Sea. Zhang L. and Zhang Y. have analyzed the distribution characteristics of surface seawater pCO_2 in the Bohai Sea in summer [4]; Zhang et al. have discussed the distribution and controlling factors of pCO_2 in Northern Yellow Sea in winter, spring and autumn respectively [5-7]; Jiang et al. have studied the air-sea exchange flux of CO_2 in the Southern Yellow

Sea in spring and its difference with that in summer [8]. Overall, many studies about sea surface pCO_2 focused on a single sea or a single season, few of them addressed the seasonal variability of sea surface pCO_2.

First of all, the seasonal variability of sea surface pCO_2 is recapitulated in this article. Moreover, the relationships of pCO_2 with sea surface temperature (SST), and chlorophyll-a concentration (Chla) in the Yellow Sea were discussed. Finally, a multiple regression equation of pCO_2 with SST, Chla in the Yellow Sea was proposed, and confirmed by shipboard measurement and satellite observation.

2. Data

In-situ data used in this study were derived from CO_2 air-sea exchange flux data obtained by shipboard measurement in the Yellow Sea in February, May and August 2010. The shipboard routes are shown in figure1, the blue lines stand for the route in February, while the red lines are for May and August. There were a total of 6375 sets of data records collected in the three months. A small portion of the data was removed because their pCO_2 value has significant deviation. Some were discarded due to the lack of synchronous Chla concentration data. Finally, in total 5503 sets of data were valid in our study.

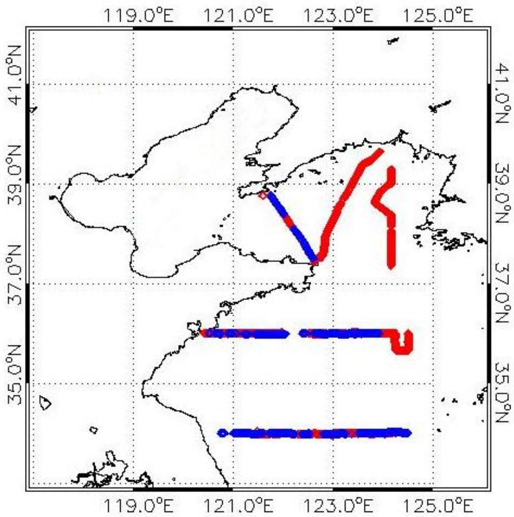

Figure 1. Distribution map of shipboard lines.

3. Data analysis

The Yellow Sea is a Chinese shelf sea [3], here the distribution of pCO_2 is affected by many factors, such as temperature, strong plankton activity, river input, upwelling and so on [3]. Because the routes of this experiment were not located in the near-shore area, we do not consider the impacts on pCO_2 from carbonate system caused by river input and coastal aquaculture activities. SST and Chla play an important role in affecting the distribution and seasonal variability of the pCO_2 in shelf seas. We will discuss the relationship of pCO_2 with SST and Chla in different seasons.

SST has a double impact on pCO_2. On one hand, in the absence of external exchange, the equilibrium of carbonate system in seawater would alter due to the influence of temperature. The pCO_2 will be enhanced as temperature rises [9]. On the other hand, the solubility of carbon dioxide in seawater decreases as temperature increases, which leads to a decrease of pCO_2 [10].

The impact of Chla on pCO_2 is primarily concerned with the respiration of plankton and the photosynthesis of phytoplankton [11]. Respiration absorbs oxygen and releases carbon dioxide, which makes pCO_2 rise, while photosynthesis absorbs carbon dioxide and releases oxygen, which makes pCO_2 reduce. Respiration and photosynthesis are also influenced by temperature, salinity, pH, light conditions and so on.

Due to different seawater temperature and changing of marine plankton in number and activity, pCO_2 has different distribution characters in different seasons. In order to study the seasonal variation of pCO_2, it is necessary to analyze pCO_2 variation in each season, respectively.

3.1. The pCO₂ data in winter

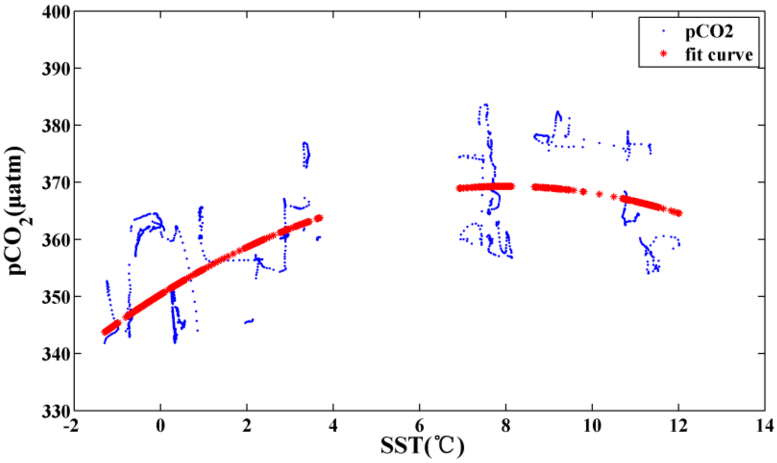

Figure 2. Scatter plot of pCO_2 against SST in winter.

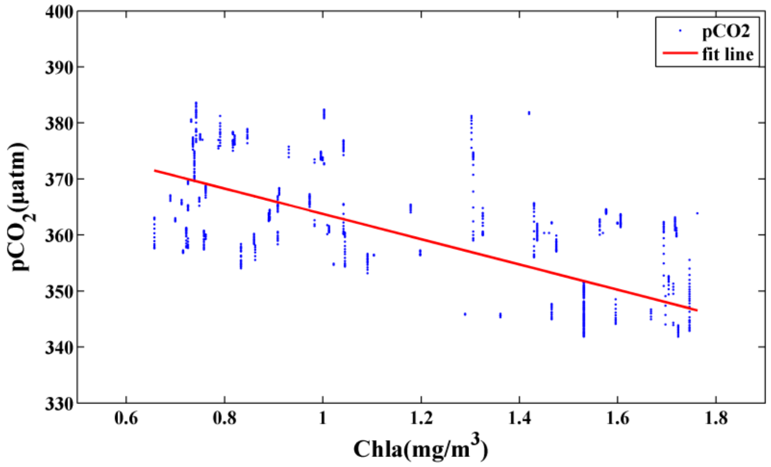

Figure 3. Scatter plot of pCO2 against Chla in winter.

As shown in figure 2, the SST was low in winter, ranged from -2℃ to 12℃; the Chla varied from 0.6 mg/m^3 to 1.8 mg/m^3; pCO_2 values had some ups and downs but were low in general, ranged from 342μatm to 384μatm. The relationship between pCO_2 and SST can be approximated with a quadratic curve shown in figure 2. Chla had a more pronounced effect on pCO_2 than SST in winter. The pCO_2 decreased gradually as Chla increased; there was a negative correlation between the two variables, as shown in figure 3.

3.2. The pCO₂ data in spring

As shown in figure 4, the SST in May was higher than that in February; the maximum value has reached to 16.6℃, whereas the minimum value was 9.7℃. The range of pCO_2 was also broader, started from 285μatm until 448μatm. As SST increased, pCO_2 rose rapidly as well, the correlation between them was positive in the range higher than 12℃ and negative in the range less than 12℃. Except some abnormal data, which has been marked with a green circle, the distribution of pCO_2

versus SST can be fitted by a quadratic curve in figure 4. The relationship between pCO_2 and Chla was a positive correlation in spring, which was different from in winter. There was a linear relationship between pCO_2 and Chla, with an exception of some abnormal data, which has been marked with a green circle in figure 5.

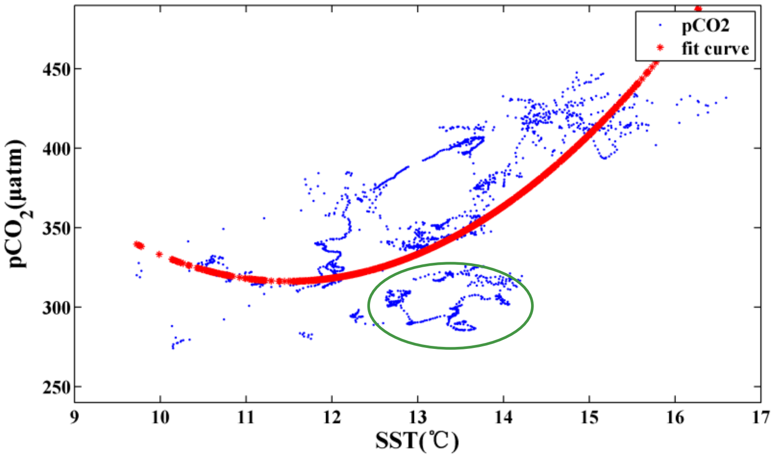

Figure 4. Scatter plot of pCO_2 against SST in spring.

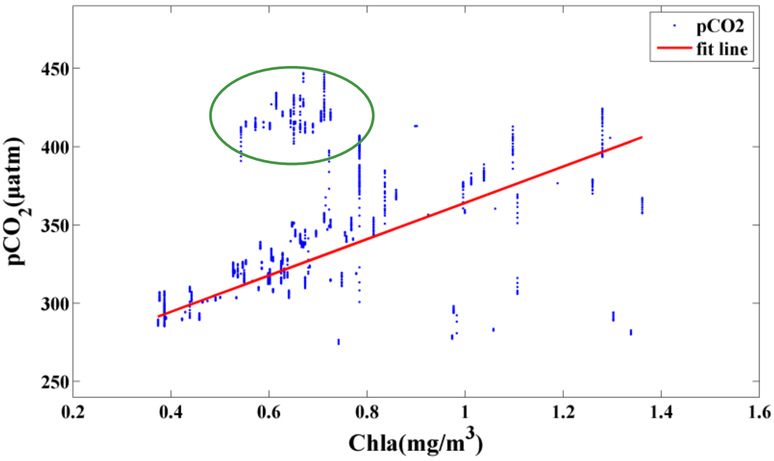

Figure 5. Scatter plot of pCO_2 against Chla in spring.

3.3. The pCO_2 data in summer

SST in summer was relative high, ranged from 21℃ to 29℃. The maximum value of pCO_2 has reached up to 450μatm, and even the minimum value was higher than 348μatm. As shown in figure 6, pCO_2 rose rapidly as SST increased, the correlation between them was positive in the range higher than 23℃ and negative in the range less than 23℃, which could be fitted with a quadratic curve. Because of high temperatures and adequate lighting in summer, the photosynthesis efficiency of phytoplankton improved a lot. Chla had a significant negative effect on pCO_2. With Chla increased from 0.4 mg/m^3 to 1.4 mg/m^3, pCO_2 decreased from 450μatm to 348μatm. As shown in figure 7, the two variables present with a significant linear relationship.

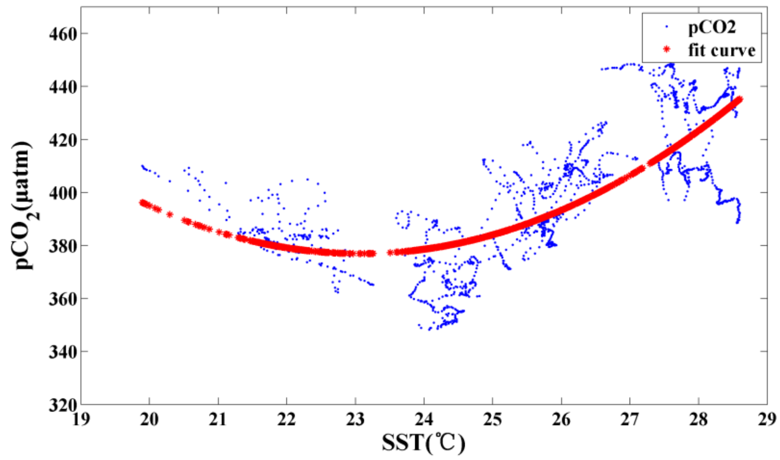

Figure 6. Scatter plot of pCO_2 against SST in summer.

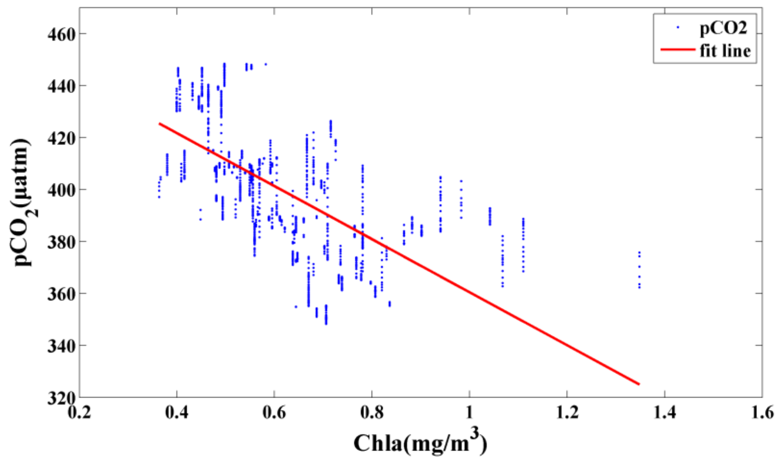

Figure 7. Scatter plot of pCO_2 against Chla in summer.

3.4. Seasonal variability of pCO_2

According to the analysis above, the distribution of pCO_2 could be effected by both SST and Chla. The correlations between them are different in each season.

SST and pCO_2 had a strong positive correlation in the range of higher SST for both spring and summer, and a relative weak correlation in winter. The relationship between Chla and pCO_2 was a little complicated, which presented a negative correlation in winter and summer, and a positive one in spring. The reason why Chla has a different correlation with pCO_2 in spring maybe is that the effect of SST on pCO_2 is larger than that of Chla. In addition, there may be other factors related to the distribution of pCO_2 such as salinity and wind speed.

3.5. Multiple regression analysis

According to the analysis above, temperature change and plankton activity are two important influencing factors of pCO_2. The relationship between pCO_2 and SST could be fitted by a quadratic curve, whereas Chla and pCO_2 had a significant linear relationship.

Ono T, Saino T and Kurita N proposed a second-order multi-regression equation to fit pCO_2 with SST and Chla [2], as shown as

$$pCO_2 = A\mathrm{T} + B\mathrm{T}^2 + C\mathrm{Chla} + D\mathrm{Chla}^2 + E \quad (1)$$

Equation (1) has good agreement with observations in some regions of the North Pacific (20° N-50° N，140° E-200° E). However, ONO's equation was not quite suitable for the Yellow Sea which presents different hydrological properties. This study simplified the regression equation by removing the second-order variable of Chla, because the relationship between pCO_2 and Chla was always linear correlation as analyzed above. The modified regression equation is shown as

$$pCO_2 = AT + BT^2 + C\mathrm{Chla} + D \quad (2)$$

Through carrying out a multiple regression analysis of pCO_2 obtained in the Yellow Sea in August 2010 with SST and Chla data obtained by the shipboard measurement, we can obtain equation (3), i.e.

$$pCO_2 = -85.8\mathrm{SST} + 1.8\mathrm{SST}^2 - 21.1\mathrm{Chla} + 1395.7, \ \mathrm{RMSE} = 16.68 \quad (3)$$

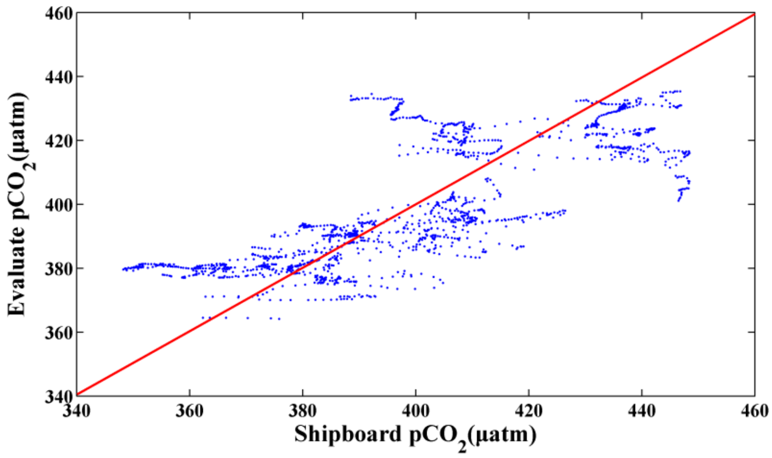

Figure 8. Results of the multiple regression of pCO_2 in summer.

As shown in figure 8, the horizontal ordinate represents the pCO_2 obtained by the shipboard observations, while the vertical ordinate stands for the pCO_2 evaluated by SST and Chla.

By using the satellite monthly averaged SST and Chla data, downloaded from the NASA Goddard Space Flight Center (http://oceans.gsfc.nasa.gov), to replace the field data in equation (3), we can achieve the evaluate data of pCO_2 in the Yellow Sea in August 2010, the root mean square error between the evaluate pCO_2 and the field pCO_2 is 21.46μatm.

4. Conclusions

Through analyzing the data including pCO_2 and other parameters obtained by shipboard in February, May and August 2010, we found that the relationships of pCO_2 with SST and Chla were different in different seasons. The pCO_2 and SST had a strong positive correlation in the range of higher SST for both spring and summer, and a relative weak correlation in winter. The distribution of pCO_2 could be fitted with SST by a quadratic curve in each season. The pCO_2 and Chla were negatively correlated in winter and summer, and positively in spring. They were linearly correlated in each season.

We further fit the pCO_2 data in summer using multiple regression equation with SST and Chla data obtained by shipboard measurement and satellite observation in August 2010, and obtained that the RMSE of regression equation is 16.68μatm and 21.46μatm, respectively.

As a perspective for future improvement, we will do further exploration about the influence factors of pCO_2 to achieve a better result. To accurately evaluate the pCO_2 using satellite-observed SST and Chla instead of shipboard data, if not impossible, will be of great significance for monitoring the CO_2 air-sea exchange flux in the Yellow Sea.

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