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Summer carbonate chemistry dynamics in the Southern Yellow Sea and the East China Sea: Regional variations and controls

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A B S T R A C T

Surface partial pressure of CO_2 (pCO_2) and pertinent parameters (i.e., pH, total alkalinity, dissolved oxygen, chlorophyll a) were investigated in the southern Yellow Sea (SYS) and the East China Sea (ECS) basing on two surveys conducted in June and August of 2013. The results suggested carbonate chemistry dynamics and related controlling factors were provided with significant temporal and spatial variations in different subregions of these two continental shelf seas. The western of SYS (SYSW) was CO_2-undersaturated both in June and August, with the average FCO_2 -1.88 mmol m^{-2} d^{-1} and -3.72 mmol m^{-2} d^{-1}, respectively. The phytoplankton initiated CO_2-absorption and the suspended sediment induced CO_2-emission jointly controlled the air–sea CO_2 exchange there. The center of SYS (SYSC) also behaved as an obvious CO_2 sink (-1.57 mmol m^{-2} d^{-1}and -3.99 mmol m^{-2} d^{-1} in June and August, respectively), probably due to elevated TA/DIC ratio and the subsequent effects of spring bloom. As for the Yangtze River estuary (YRE), it changed from an obvious CO_2 sink (-1.28 mmol m^{-2} d^{-1}) in June into a very weak CO_2 source (0.04 mmol m^{-2} d^{-1}) in August. This change was probably associated with the rising of seawater temperature and monthly variation of Yangtze River discharge. The inner shelf of ECS (ECSS) experienced obvious air–sea CO_2 flux changes during from June (-8.88 mmol m^{-2} d^{-1}) to August (-0.36 mmol m^{-2} d^{-1}) as well. Biological DIC consumption in the upper layer and DIC regenerated from respiration in the subsurface jointly controlled this pCO_2 variation. As a whole, the SYS and ECS acted as an obvious CO_2 sink during summer and could absorb atmospheric CO_2 with the average air–sea flux (FCO_2) -2.68 mmol m^{-2} d^{-1}.

The summary of air–sea CO_2 flux in the ECS and SYS during recent two decades indicated the ECS served as quite a stable CO_2 sink, whereas the SYS experienced obvious change. Discharge of Yangtze River and anthropogenic nutrients loading could profoundly affect the variations of pCO_2 and FCO_2 in future.

1. Introduction

The partial pressure of CO_2 and air–sea CO_2 flux in the continental shelf seas, or the marginal seas, have been investigated substantially during the past decades (Kempe and Pegler, 1991; Liu, 2010; Thomas et al., 2005), mainly owing to its potential capacity in absorbing the ever-increasing atmospheric CO_2 and important roles in regulating the global carbon inventory (Liu et al., 2000; Sabine et al., 2004; Walsh, 1991). Recent surveys and model synthesis all indicated that the continental shelf seas generally behaved as net sinks for the atmospheric CO_2, and the integrated air–sea CO_2 flux in global continental shelf seas varied from -0.22 to -1.0 Pg C yr^{-1} (Borges et al., 2005; Cai et al., 2006; Tsunogai et al., 1999).

Intensive and comprehensive research about the oceanic CO_2 properities in continental shelf during recent decades has obtained abundant achievements. According to the investigation conducted in the "PN" transect of the East China Sea (ECS), Tsunogai et al. (1999) proposed the mechanism of "continental shelf pump" (a.k.a. CSP) to explain why the ECS could absorb atmospheric CO_2 in the rate as high as 2.92 mol C m^{-2} yr^{-1}. In general, the CO_2 absorbed by phytoplankton photosynthesis in the surface layer could be substantially conveyed into the shallow bottom water, as the result of cooling effect and settling of paticulate carbon. Afterwards, the CO_2-riched shallow bottom water is able to be transported into the open ocean continuously by advection and/or diffusion process. Although recent model estimations and field investigations have confirmed the existence and efficiency of CSP

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(Thomas et al., 2004; Yool and Fasham, 2001), the CSP in reality could not be valid in all continental shelves because the transfer of absorbed-CO_2 from the shelf to the open sea requires specific bottom topographic and hydrological conditions (Xue et al., 2011). Borges et al. (2005) and Cai et al. (2006) put forward a latitudinal trend of CO_2 sink/source pattern for the global oceans, based on adequate field investigations and literature survey. They stated the marginal seas in mid-high latitude tended to act as atmospheric CO_2 sinks, whereas those in the low-latitude tended to be CO_2 sources. Nevertheless, there are still some exceptions (e.g., the Scotian shelf sea, the northern Yellow Sea) for this latitudinal trend, owing to the specific characters of different marginal seas (Shadwick et al., 2010; Xue et al., 2012). The latest understanding about the oceanic carbon budget considers that the global shelves, or coastal seas, could be distinguished into two systems, namely the River-dominated Ocean Margin (RiOMar, McKee et al., (2004)) and the Ocean-dominated Margin (OceMar, Dai et al. (2013)). As the names suggest, the RiOMar system is generally adjacent to large rivers and influenced profoundly by riverine material inputs (Dai et al., 2013), while the OceMar system is primarily controlled by hydrological dynamics and biogeochemical properities of the open ocean. Accordingly, the carbonate chemistry and air–sea CO_2 exchange processes in these two systems would show distinctive variations.

The East China Sea Continental Shelf is known as one of the largest continental shelf seas in the world and it is composed of the East China Sea (ECS) and the southern Yellow Sea (SYS). The ECS is situated between the low- and mid-latitudes (between 25°N and 34°N) of western Pacific Ocean. The largest river of China, Changjiang (Yangze river), empties into the ECS directly at 31.5°N, 121.75°E. Being as one of the earliest investigated continental marginal seas in the world (Chen and Wang, 1999; Peng et al., 1999; Tsunogai et al., 1997 and 1999; Wang et al., 2000; Zhang and Ma, 1997), the ECS is a net sink for atmospheric CO_2 (Chou et al., 2009a, 2009b; Chou et al., 2011; Qu et al., 2013; Shim et al., 2007; Tseng et al., 2011) on an annual basis with the long-term average flux about $-1.9\ \text{mol m}^{-2}\ \text{yr}^{-1}$ (Tseng et al., 2013). The southern Yellow Sea (SYS) is a semi-closed shelf sea located to the north of the ECS and is bordered by the China mainland to the west and the Korea Peninsula to the east. There is no large river flowing into it the SYS directly and the SYS possesses a nearly closed circulation system. In the earlier studies, the SYS was regarded as a part of the ECS shelf, whereas recent field surveys founded carbonate features of the SYS were different from those of the ECS, and the SYS is evaluated as an annually net atmospheric CO_2 source (Xue et al., 2011; Zhang et al., 2010).

Under the influence of extensive anthropogenic disturbance, the East China Sea Continental Shelf is undergoing increasingly obvious changes of biogeochemical dynamics. For example, in recent decades harmful algal blooms and hypoxia have taken place more and more frequently in the Changjiang (Yangtze River) estuary of ECS (Chai et al., 2006; Wang, 2006; Zhu et al., 2011b). Moreover, green algae bloom has also occurred on a large scale in the SYS since the summer of 2008 and has become a significant marine ecology incident in SYS (Huo et al., 2013; Liu et al., 2013; Zhao et al., 2013). Therefore, the potential impact of ecological environment change on the air–sea CO_2 exchange process in the East China Sea Continental Shelf has become an important focus (Chou et al., 2013).

In this paper, the carbonate dynamics of the SYS and the ECS were investigated in detail basing on the field surveys conducted in June and August of 2013. This study focuses mainly on the distributions of carbonate parameters, the magnitude of air–sea CO_2 exchange flux, and their relationships with the related hydrological and biological features. Moreover, in order to provide a baseline for the possible changes of oceanic CO_2 system in future, we also summarized the summertime CO_2 flux in this two seas. On the whole, the results will not only help to promote the understanding of air–sea CO_2 flux in SYS and ECS, but also explore the possible influence of environmental change on the future oceanic CO_2 system.

2. Study sites and analytical methods

2.1. Site description

The SYS is a semi-closed marginal sea surrounded by the mainland China to the west and the Korea Peninsula to the east. A trough with depth 60–80 m lies in northwestern–southeastern direction in the central of it. The ECS is located to the south of SYS, bordered in the southeast by Ryukyu Islands, in the south by Taiwan, and in the west by mainland China. A line running northeastward from the Qidong Cape in north shore of Changjiang to the Cheju Island is the boundary of the ECS and the SYS. Survey stations of this study scattered mainly over the relative flat and shallow region of SYS and the inner shelf of ECS, covering an area overall about $26 \times 10^4\ \text{km}^2$.

The SYS and ECS are all characterized as temperate marginal seas, and the seasonal and spatial variability of hydrological and biogeophysical properties of them are regulated not only by the oceanic dynamics, but also more significantly to some extent by the terrigenous material importation. The Kuroshio Current (KC), the Taiwan Warm Current (TWC), and the Changjiang Diluted Water (CDW) constitute the outline of current cycling in ECS. In details, the KC enters the ECS through the shelf break off eastern of Taiwan and brings enormous oligotrophic saline warm water into the continental shelf (Chen et al., 1995). Meanwhile, the TWC flows into the ECS through the Taiwan Strait and could reach the Changjiang estuary in summer (Lee and Chao, 2003). The Changjiang (Yangtze) River, originating from the Qinghai–Tibetan Plateau and flowing through a drainage area about $1.8 \times 10^6\ \text{km}^2$, drains into the ECS with the annual water runoff and sediment load $9.6 \times 10^{11}\ \text{m}^3$ and 4.8×10^8 t, respectively (Yang et al., 2006; Zhang, 1996). The riverine discharge of Changjiang usually reaches its maximum value in summer from June to September (Wang et al., 2007). As for the SYS, an enclosed circulation pattern is developed at the upper layer of it in summer (Yanagi and Takahashi, 1993). The major components of this pattern are all localized currents, including the Yellow Sea Coastal Current (YSCC) and the Korea Coastal Current (KCC). One of the most outstanding hydrological features for the SYS in summer relies on the Yellow Sea Cold Water (YSCW), which occupies the bottom column of SYS. The Yellow Sea Warm Current (YSWC) is another remarkable hydrological features but it usually occurs in winter. Different from the ECS, the SYS usually receives little riverine discharge because there is no large river flowing into it directly.

2.2. Sampling and analytical methods

Two cruises were conducted in the SYS and the ECS (27.4°N–37.0°N, 120.5°E–124.8°E) aboard the R/V *Beidou*, during from 15 to 29 June and from 16 August to 1 September in 2013, respectively. The June cruise contained 51 stations and the August cruise had 47 stations (Fig. 1).

The sampling and analytical methods of carbonate parameters in this study were according to the recommended standard operating procedures described by Dickson et al. (2007) and the methods of Chou et al. (2009a, 2009b), Qu et al. (2014) and Zhai et al. (2014). In brief, temperature and salinity were recorded by a Seabird 9/11-plus Conductivity Temperature Depth (CTD) system (Sea-Bird Electronics, USA), and this system was also used to