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Seasonal variability of air–sea CO_2 fluxes in the Yellow and East China Seas: A case study of continental shelf sea carbon cycle model

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ABSTRACT

An inorganic carbon system module was established and coupled with a physical–ecological model based on the concept of continental shelf sea carbon cycle. Seasonal air–sea CO_2 flux (FDIC) distribution in the Yellow and East China Seas (YECS) are simulated and the model results are in good agreement with observations. The simulations suggest that the YECS serve as a strong sink (-7.1 ± 3.6 mmol m^{-2} day^{-1}) of atmospheric CO_2 in winter and a moderate sink (-1.6 ± 0.8 mmol m^{-2} day^{-1}) in spring. In summer, sink areas occupy the Yellow Sea (YS) and the adjacent sea of the Changjiang Estuary, while the middle and outer shelves of the East China Sea (ECS) act as moderate sources of atmospheric CO_2. In fall, substantial carbon sources occur over the Changjiang Bank and the Subei Shoal.

Dissolved inorganic carbon (DIC) variations in the euphotic layer and sea surface temperature (SST) are the key parameters to control the FDIC. DIC concentration relates to solubility, algae consumption and physical transport. According to the topographic features and the relationship between partial pressure of CO_2 in surface water and SST, the YECS are divided into three typical subregions, namely the central YS, the Changjiang Bank, and the middle shelf of the ECS, to examine the key processes in regulating the total DIC variations in the euphotic layer and study the influential factors of the seasonal pattern of FDIC. The results imply that, in the central YS and the Changjiang Bank, biological effect plays a critical role in DIC removal in the euphotic layer and facilitates the sea to be a sink in spring and summer. In fall, horizontal advection transports DIC out of the central YS area leading this area to be a sink of atmospheric CO_2, meanwhile vertical mixing provides DIC for the euphotic layer over the Changjiang Bank inversing this area to be a source. In winter, the low temperature exerts an essential effect on carbon sink which strength is enhanced by the intensive wind in the YECS. In the middle shelf of ECS, seasonal cycle of air–sea CO_2 flux is mainly controlled by the SST seasonality. The Kuroshio Subsurface Water intrusion behaves as a net DIC source for the euphotic layer in the shelf of the ECS. The dynamic phytoplankton production and various ocean circulations cause the YECS to form distinctive subregions and thus induce the seasonal and regional changes in air–sea CO_2 fluxes.

1. Introduction

Air–sea CO_2 fluxes (FDIC) in continental shelf seas exert an essential effect on global carbon balance because of the strong carbon fixation through the intensive phytoplankton growth (Walsh, 1991; Muller-Karger et al., 2005). Previous reviews have suggested that open continental shelves at mid-high latitudes act as sinks of atmospheric CO_2 (Cai et al., 2006; Chen and Borges, 2009), especially in large river plumes, because of the strong photosynthesis promoted by riverine nutrient enrichment (Chen et al., 2012). This point was supported by evidence from the outer Changjiang Estuary in the East China Sea (ECS) where a moderate or major sink of atmospheric CO_2 was observed (Zhang and Ma, 1997; Tsunogai et al., 1999; Zhai and Dai, 2009; Tseng et al., 2011; Qu et al., 2013). Carbon cycling in seas that located away from large river plumes (such as the South China Sea) is generally influenced by an exchange with adjacent oceans through horizontal intrusion and subsequent vertical mixing (Dai et al., 2013) as well as other factors involving temperature, air–sea CO_2 exchange, and biological activities (Chai et al., 2009; Lu et al., 2012). Thus, carbon cycling in continental margins with regional disparity is forced by an integrated effect of chemical, physical, and biological processes.

The Yellow and East China Seas (YECS) have a broad continental shelf shallower than 200 m and are strongly affected by a large

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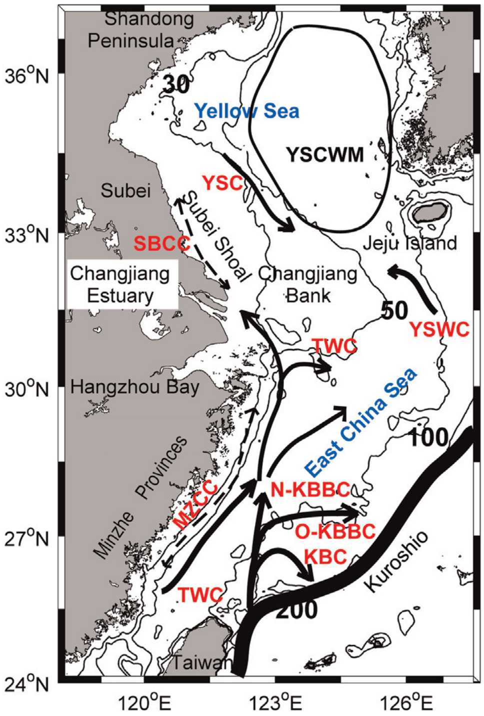

Fig. 1. Topography and schematic map of circulation in the Yellow and East China Seas (YECS). Black arrows denote circulation including Yellow Sea Current (YSC), Yellow Sea Warm Current (YSWC), Taiwan Warm Current (TWC), and Kuroshio intrusion (KBC: surface Kuroshio Branch Current; O-KBBC: offshore Kuroshio Bottom Branch Current; N-KBBC: Nearshore Kuroshio Bottom Branch Current, i.e. Kuroshio subsurface water). Double-arrow dotted curve indicates coastal current which direction changes with monsoon (SBCC: Subei Coastal Current; MZCC: Minzhe Coastal Current). The Yellow Sea Cold Water Mass (YSCWM) is indicated by a closed curve. Contours in black denote isobaths of 30, 50, 100, and 200 m.

river (the Changjiang River) plume and ocean circulations including the Kuroshio intrusion (Kuroshio Surface Water intrusion and Kuroshio Subsurface Water (KSW) intrusion), Taiwan Warm Current (TWC), Yellow Sea Warm Current (YSWC), and coastal current system (Fig. 1) (Su, 2001; Yang, 2011). High primary production in the YECS could increase the capability to absorb CO_2 from the air. Sparse observations revealed that CO_2 source and sink pattern varies greatly on the seasonal scale together with large variations in different regions in the YECS. Zhang et al. (2010) and Xue et al. (2011) concluded that the southern Yellow Sea (YS) overall behaved as a net annual source of atmospheric CO_2, in which a permanent CO_2 source was observed in the nearshore area mainly induced by vertical mixing and terrestrial inputs as well as upwelling, while the only net sink was found during spring in the central YS because of the strong biological activities and the weak water stratification. However, underway measurements by the State Oceanic Administration of the People's Republic of China (SOA) reported in Bulletin of China's Marine Environmental Status 2013 showed that the YS absorbed atmospheric CO_2 during winter, spring and fall, whereas it emitted CO_2 to the atmosphere in summer, and thus the YS overall acted as a net sink of atmospheric CO_2 (http://www.coi.gov.cn/gongbao/nrhuanjing/nr2013/201403/t20140325_30704.html). On the basis of field surveys conducted in spring, summer, and fall in the southern YS, Qu et al. (2014) indicated that the central YS absorbed CO_2 from the atmosphere during these three seasons, whereas the Subei Shoal released CO_2 into the air, and then they concluded that the southern YS as a whole served as a weak CO_2 sink during April to October. The pattern of carbon source and sink in the ECS also exhibits substantial seasonal variation, and the ECS is generally considered as a sink of atmospheric CO_2 throughout the year except in fall (Shim et al., 2007; Zhai and Dai, 2009; Qu et al., 2013). In the ECS, the strongest carbon sinks were observed in winter, followed by spring and summer, and the carbon sources were found in fall (Zhai and Dai, 2009; Qu et al., 2013). Tseng et al. (2011) suggested that CO_2 absorption of the ECS was greater in spring than that in winter and detected that a CO_2 sink in the Changjiang Diluted Water (CDW) area was mainly due to the strong phytoplankton growth driven by riverine nutrients, while the southern part of the ECS characterized by warm and saline water might have equilibrated with the atmospheric partial pressure of CO_2 (pCO_2) or even behaved as a carbon source during summertime. CO_2 observations conducted on a moored buoy on the outer shelf of the ECS implied that this area served as a carbon source in summer and a carbon sink in fall and winter (Nemoto et al., 2009). Why do these conflicting results for CO_2 source and sink occur in the same area? What factors mainly influence the seasonal variability of CO_2 fluxes in different areas? Which one is more important to regulate CO_2 fluxes, the biological pump, solubility or the physical advection and mixing? To understand the controlling processes that result in these seasonal and regional variations, quantitative analysis using a numerical model is required.

In this paper, we focused on developing a coupled physical–ecological-carbon cycle model to study which process substantially influenced the seasonal sink and source patterns of atmospheric CO_2 in the YECS. According to the topographic features and the relationship between pCO_2 and temperature in the surface water, the YECS were divided into three subregions, namely the central YS, the Changjiang Bank, and the middle shelf of the ECS, to quantify the main processes' relative contributions to the total dissolved inorganic carbon (DIC) variations in the euphotic layer and find out the dominant factor of the spatiotemporal changes of FDIC in each subregion.

2. Methods

2.1. Model configuration

Three modules are included in our model, namely hydrodynamic, biological and inorganic carbon system modules. Water temperature, salinity, velocities, and diffusivity coefficients that the biological and carbonate modules required in each step were calculated from the hydrodynamic module; in other words, the three modules were run simultaneously.

By using a nesting method, a hydrodynamic module with high resolution (1/18°) for the YECS was derived from the Princeton Ocean Model (POM) (Mellor, 1998; Blumberg and Mellor, 1987), and additional details were presented in Guo et al. (2003). The biological module was reconstructed in the YECS based on the NORWegian ECOlogical Model (NORWECOM) and coupled with the hydrodynamic module (Zhao and Guo, 2011). Further details and parameters used in this model can be found in Zhao and Guo (2011). The model was run using climatological monthly forcing to obtain the seasonal patterns of analyzed variables, such as temperature, velocity, mixing coefficients, nutrient concentration and biomass of algae.

In the inorganic carbon system module, DIC and total alkalinity (TA) were designated as prognostic variables, and pCO_2 in the water was diagnostic variable. The governing equations of DIC and TA in sea water are as follows:

$$\frac{\partial[DIC]}{\partial t} = [\frac{\partial[DIC]}{\partial t}]_A + [\frac{\partial[DIC]}{\partial t}]_V + [\frac{\partial[DIC]}{\partial t}]_B + [\frac{\partial[DIC]}{\partial t}]_F + [\frac{\partial[DIC]}{\partial t}]_R \tag{1}$$

$$\frac{\partial[TA]}{\partial t} = [\frac{\partial[TA]}{\partial t}]_A + [\frac{\partial[TA]}{\partial t}]_V + [\frac{\partial[TA]}{\partial t}]_B \tag{2}$$