Abstract  Partial pressure of CO₂ (pCO₂) was investigated in the Changjiang (Yangtze River) Estuary, Hangzhou Bay and their adjacent areas during a cruise in August 2004, China. The data show that pCO₂ in surface waters of the studied area was higher than that in the atmosphere with only exception of a patch east of Zhoushan Archipelago. The pCO₂ varied from 168 to 2264 μatm, which fell in the low range compared with those of other estuaries in the world. The calculated sea-air CO₂ fluxes decreased offshore and varied from −10.0 to 88.1 mmol m⁻² d⁻¹ in average of 24.4 ± 16.5 mmol m⁻² d⁻¹. Although the area studied was estimated only 2 × 10⁴ km², it emitted (5.9 ± 4.0) × 10³ tons of carbon to the atmosphere every day. The estuaries and their plumes must be further studied for better understanding the role of coastal seas playing in the global oceanic carbon cycle.

Keyword: partial pressure of carbon dioxide; spatial distribution; sea-air exchange; Changjiang Estuary; Hangzhou Bay

1 INTRODUCTION

Increasing in carbon dioxide (CO₂) level in the atmosphere has become a concern in many scientists as perhaps a serious global environmental problem to the human beings (Haugan, 1997). The carbon transport by rivers has been well-documented as a part of the global carbon cycle (Meybeck, 1993; Abril et al., 2000). Estuaries are important transitional zones between land and sea. With rapid development of industry and agriculture in recent decades, huge amounts of nutrients with inorganic and organic carbon from both natural and anthropogenic sources have been introduced into ocean via shallow coastal waters every year, especially estuaries (Wu, 1999; Schlünz and Schneider, 2000). It was found over 30 years ago in pioneering studies by Park et al. (1969), Kelley and Hood (1971), and Kelley et al. (1971) that some coastal ecosystems, such as estuaries and upwelling systems, act (at least temporally) as strong sources of CO₂ to the atmosphere.

The Changjiang (Yangtze River) Estuary, about 120 km long and over 90 km wide at its outer limit, is a mesotidal estuary and characterized by the complexity of morphology associated multi-order bifurcations (Li and Zhang, 1998; Yang et al., 2003). Hangzhou Bay, the estuary of the Qiantang River, is dominated by macrotides. The sedimentary dynamic process in the bay is characterized with the alternation of rapid erosion and deposition in tidal cycles. Both the Changjiang Estuary and Hangzhou Bay are within the Changjiang Delta Region and near the metropolis Shanghai, the most important economic development zone in China.

The areas surrounding the Changjiang Estuary and Hangzhou Bay have been the focus of element biogeochemical research for many years. In recent years, environmental changes in the Changjiang Estuary and Hangzhou Bay resulted from rapid development in the surroundings have caught public
attention. However, information for clear understanding of dissolved inorganic carbon behaviors in these areas remains insufficient. The main objective of this paper is to describe the $pCO_2$ spatial distribution in surface waters of the Changjiang Estuary, the Hangzhou Bay, and their adjacent areas, estimate the air-sea fluxes of CO$_2$, and discuss the main factors impacting them.

2 MATERIALS AND METHODS

The field investigation was carried out from August 5 to 10, 2004, on board of R/V Zhe Hai Huan Jian. 37 stations were set in the areas of the Changjiang Estuary, Hangzhou Bay and nearby regions and covered almost entire salinity gradient (Fig.1). Water samples were collected with Go-Flo sampler just below the sea surface.

Fig.1 The study area and the sites deployment

Salinity (S), temperature (T), pH and total alkalinity (TA) of the samples were measured in situ. S and T were measured using a Sea-Bird SBE 19plus CTD probe. For pH measurements, an ORION Ross type combination electrode was used and calibrated on the NBS scale. Precision for pH measurements was 0.03 pH units. Samples for total alkalinity (TA) were collected in 500-ml glass bottles according to the DOE (Department of Energy, USA) procedures (Dickson and Goyet, 1994) and analyzed onboard as quickly as possible by Gran titration with the precision of approximately 0.1%–0.3%.

Values of carbon dioxide partial pressure ($pCO_2$) and total inorganic carbon (T$CO_2$) in the water column were calculated from TA and pH measurements, with the dissociation constants of carbonic acid from Mehrbach et al. (1973). The CO$_2$ solubility was calculated according to Weiss (1974).

The flux of $CO_2$ across the air-sea interface ($F$) was calculated from the difference of $CO_2$ partial pressure between the water surface and the air ($\Delta pCO_2$), and the $CO_2$ transfer velocity ($k$) using the equation:

$$F = k \times \alpha \times \Delta pCO_2$$

where $\alpha$ is the $CO_2$ solubility at in situ temperature and salinity (Weiss, 1974). The magnitude of the flux is mainly imposed by the value of $k$, which is a function of various parameters and processes such as wind speed, turbulence at the interface, air bubbles, and surface organic films, etc (Borges et al., 2004). The direct measurements of the physical component of gas exchange in rivers and estuaries were fewer than those in streams, lakes and marine systems (Raymond and Cole, 2001). Raymond and Cole (2001) suggested that under a lack of direct estuarine $k$ measurements condition, $k_{600}$, i.e. the $k$ for $CO_2$ at 20°C in freshwater, that is, $k$ at a Schmidt number of 600, should be in the range of 3–7 at average wind speeds ($4.6\pm0.28$ m s$^{-1}$), tidal velocity ($0.34\pm0.28$ m s$^{-1}$), and estuary depth (>10 m). Therefore, as an attempt, a $k$ value of 7 cm h$^{-1}$ should cover the average physical mixing condition in the studied area considering the Changjiang Estuary and Hangzhou Bay as a mesotidal and macrotidal region respectively, and should be adequate for the purpose of tracing biogeochemical processes in this work. $\Delta pCO_2$ imposes the direction of the flux and mainly depends on the $pCO_2$ in surface water since atmospheric $pCO_2$ is relatively homogeneous and much less variable. Tan et al. (2004) measured the atmospheric $pCO_2$ in the west East China Sea (ECS) near the investigated spot of this study in the summer of 2001, and gained an average value of 375 μatm. Considering the rise in atmospheric CO$_2$ concentration with time, an atmospheric $pCO_2$ of 380 μatm was used to estimate the CO$_2$ flux across sea-air interface. A positive flux value indicates a transfer of CO$_2$ from surface water to the atmosphere, while a negative one represents the reverse.

3 RESULTS AND DISCUSSION

3.1 Spatial distribution of $pCO_2$