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Nutrient dynamics from the Changjiang (Yangtze River) estuary to the East China Sea

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ABSTRACT

Water and sediment samples were collected from the Changjiang (Yangtze River) estuary and the adjacent East China Sea during impoundment of the river at the Three Gorges Dam. The concentrations of dissolved inorganic and organic nutrients, and particulate inorganic phosphorus and particulate organic phosphorus in the water column (PIP and POP, respectively) and sediments (SIP and SOP, respectively) were analyzed. The nutrient dynamics in salt marshes associated with the Changjiang estuary were also considered. In addition, river water samples were collected bimonthly in the lower reaches of the Changjiang. The concentrations of dissolved inorganic nutrients, PIP and POP showed temporal and spatial variations, which decreased from the coast to offshore areas. The dissolved organic nitrogen and phosphorus (P) concentrations showed patchy distributions, but were consistent with the distribution of phytoplankton biomass. Phosphorus is the major limiting element for phytoplankton growth. Among the various P forms, particulate P represented 38–52% of total P. The PIP and POP concentrations showed clear seasonal variations corresponding to the occurrence of the levels of suspended particulate matter. The P accumulation rates showed a decreasing trend from the coast to offshore areas, and high P burial efficiencies were found; the latter were related to a low benthic PO_4^{3-} flux and high sediment accumulation rates. The potential bioavailable P was estimated to be 65–70% of total P, of which more than two-thirds was regenerated in the water column. The salt marsh in the Changjiang estuary plays an important ecological role in nutrient transport from the river to offshore areas, and increased P limitation.

1. Introduction

Riverine transport is a major pathway for the transfer of particulate matter and dissolved elements from land to sea. Globally, large rivers may play an important role in this terrestrial–marine linkage. Excessive nutrient discharges and changes in nutrient ratios caused by land use transformation and anthropogenic emissions result in eutrophication, leading to modification of aquatic food webs and the occurrence of severe hypoxic events in coastal environments (Turner, 2002; Turner and Rabalais, 1994; Sundareshwar et al., 2003; Whitney et al., 2005). Natural wetlands are filtering areas for sediment, nutrients and contaminants from runoff and wastewater, with the efficiency of such filtering depending on the loading rate and the specific ecological and hydrological characteristics of the system (Delaune et al., 1981; Nixon, 1980; Sanders et al., 2014; Woltemade, 2000).

Approximately 20% of the world's population live in East Asia (Hong et al., 2002), a region where ocean processes are strongly influenced by riverine inputs. In East Asia, recent technological innovations, economic development and population increases have resulted in substantial stress on adjacent coastal waters due to human perturbations (including changes in land use, increased pollution drainage, and aquaculture), in addition to the stress already imposed on marine ecosystems by climate change (Zhang et al., 2007). This has greatly modified the coastal ecosystem; for example, frequent harmful algal blooms (HABs) and seasonal hypoxia have been observed off the Changjiang (Yangtze River) estuary (Zhang et al., 2007; Zhou et al., 2008; Zhu et al., 2011) and the Zhujiang (Pearl River) estuary (Yin and Harrison, 2007).

One of the major rivers in East Asia is the Changjiang. The damming of this river through the construction of the Three Gorges Dam (TGD) and impoundment in 2003 reduced nutrient and sediment loads to the East China Sea (ECS), with the potential for far-reaching environmental and human health effects (Chen, 2000; Duan et al., 2008; Gong et al., 2006; Liu et al., 2003; Zhang et al., 1999). The TGD-induced shift in nutrient composition and transport from the river to the outer sea is expected to lead to greater phosphorus (P) limitation

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in the Changjiang estuary and the ECS. In this study we report data on nutrient concentrations in the Changjiang estuary and the adjacent ECS based on observations made in the period 2001–2003. Water and seabed sediment samples were analyzed to estimate the P bioavailability in suspended particulate matter (SPM) and sediments. The aims of the study were to investigate the effect of estuarine wetlands on nutrient transport from the river to offshore areas, and to identify the major factors affecting nutrient dynamics in this system. The results of this study enhance understanding of nutrient dynamics and its relationship to the sustainability of ecosystems in the Changjiang estuary and adjacent ECS during impoundment of the Changjiang at the TGD.

2. Materials and methods

2.1. Study area

The Changjiang is the largest river in the Euro-Asian continent. It has a freshwater discharge of 924.8×10^9 m^3 yr^{-1} and a sediment load of 0.5×10^9 tons yr^{-1}, and empties into the ECS. The ECS is one of the largest marginal seas in the western North Pacific Ocean, and is noted for its high levels of primary productivity and for the tremendous extent of river runoff into the sea, notably from the Changjiang. The circulation system of the ECS is complicated. The Changjiang diluted water (CDW) extends to the northeast towards the Tsushima/Korea Straits during summer, but in winter it flows southwest within a narrow band adjacent to the Chinese coast (Beardsley et al., 1985; Mao et al., 1963; Zhao, 1991; Zhu et al., 1997). The Kuroshio Current flows northeast along the margin of the continental shelf. Extensive exchange of water and nutrients occurs between the ECS and the Kuroshio Current across the shelf break region, driven by upwelling and frontal processes (Gong et al., 1996; Su, 1998). The Taiwan Warm Current is composed of waters originating from northward flow through the Taiwan Strait and shelf-intrusion from the Kuroshio Current in the area north of Taiwan (Chen and Wang, 1999; Liu et al., 2000; Zhang et al., 2007).

The extremely high water volumes and sediment loads of the Changjiang directly influence the circulation, nutrient dynamics, phytoplankton community and trophic structure in the adjacent ECS (Zhang and Su, 2006). The Changjiang water is enriched with high concentrations of NO_3^- and $Si(OH)_4$ (~100 μM), but is depleted of PO_4^{3-} (~1 μM) (Liu et al., 2003, 2009). The long-term annual average $Si(OH)_4$ concentration and flux in the Changjiang have slightly decreased or have been stable since the 1950s. However, the NO_3^- and PO_4^{3-} concentrations and fluxes have increased, especially since the 1980s (Jiang et al., 2014; Li et al., 2007). In recent years these changes have led to the increased occurrence of blooms of non-siliceous algae (*Prorocentrum dentatum*) rather than siliceous algae (*Skeletonema costatum*), and to frequent HABs and seasonal hypoxia in near-bottom waters in the ECS adjacent to the Changjiang estuary (Zhang et al., 2007; Zhou et al., 2008; Zhu et al., 2011).

Chongming Island (482 km^2), located at the mouth of the Changjiang, is the largest estuarine alluvial island in the world (Wu et al., 2005). The Dongtan wetland is an intertidal wetland located seaward to the east of Chongming Island, and is the most extensive tidal flat in the Changjiang estuary. This wetland is particularly important as it provides a biogeochemical and ecological buffer between the terrestrial areas and the ECS. More than one-third of the wetland area is colonized by marsh vegetation, providing crucial habitat for a wide variety of birds and wildlife (Xu et al., 2001). The Dongtan wetland of Chongming Island is typically several kilometers in width with an average slope of 0.02-0.04%, mean tidal range of about 2.70 m and average salinity of 1–3 (Yuan et al., 2002). On the basis of tidal level, the Dongtan wetland can be subdivided into high marsh, low marsh and bare flat. The high marsh is located above the mean high tide level (3.11 m), the bare flat below the mean low tide level (0 m), and the low marsh is the intermediate zone (Yang, 1997). The high marsh is dominated by two pioneer plant species, *Scirpus mariqueter* and *S. triqueter*, although *Carex scabrifolia* and *S. tabernaemontani* also occur in the high marsh. *S. mariqueter* also occurs in the low marsh area, and there is no vegetation on the bare flat (Zhou et al., 2007). The biomass of *S. mariqueter* is 745 g m^{-2} in the high marsh and 295 g m^{-2} in the low marsh (Yuan et al., 2002). Benthic fauna is abundant in both the high and low marsh zones. Tidal creek systems are well developed in the study area, especially in the low marsh. Human activities have led to a substantial reduction in natural wetland area, through reclamation of a 49,000 ha area (Yuan et al., 2002).

2.2. Sampling

Field sampling was conducted at sampling stations in the Changjiang estuary and the ECS in the period 2001–2003, including during four cruises in the period 2002–2003: August 2002 (R/V Jin Xing 2); November 2002 (R/V Ke Xue 1); February 2003 (R/V Zhe Hai Huan Jian); and April–May 2003 (R/V China Hai Jian 47). A total of 28 stations in 7 sections were sampled during the summer, fall and winter cruises, and 42 stations in 10 sections were sampled during the spring cruise (Fig. 1). At each sampling, water samples were collected at three depths (surface, intermediate and near-bottom) using 20-L Niskin bottles; the depth of the intermediate sample depended on the water depth. Following collection the water samples were filtered through preweighed 0.45 μm cellulose acetate filters that had been precleaned with 10% hydrochloric acid (pH = 2) followed by rinsing with Milli-Q water. The filtrates were fixed with saturated $HgCl_2$ and stored in the dark. On return to the laboratory the filters were dried at 50°C and reweighed to determine the mass of SPM. The samples were analyzed for particulate inorganic P (PIP) and particulate total P (PTP).

A total of 12 core sediment samples were carefully collected (see Fig. 1 for locations) to avoid resuspension of bottom sediments. This was achieved using a multi-corer with 4 sub-tubes of inner diameter 9 cm and length 61 cm. The sediment cores were sectioned at 0.5-cm intervals in the upper 2 cm and at 1-cm intervals for greater depths. The sediment samples were stored at −20°C, and were later freeze-dried prior to analysis for sediment inorganic P (SIP) and sediment total P (STP).

In the period September 2001–September 2003, river water samples were collected bimonthly at Nantong in the major reach of the Changjiang. Water samples were collected in the river course in 2-L polyethylene bottles attached to a glass-fiber reinforced fishing pole. The samples were filtered through 0.45 μm filters, and the filtrates were fixed using saturated $HgCl_2$.

Field sampling in the Dongtan wetland was conducted on six occasions during the period 2001–2002 (18 April 2001, 16 June 2001, 11 September 2001, 24 October 2001, 12 December 2001 and 22 March 2002). Both creek water and groundwater were collected for chemical analysis from the high marsh, low marsh and bare flat areas (Fig. 1). Following collection the water samples were immediately filtered through precleaned 0.45 μm pore-size acetate cellulose filters, and the filtrates were preserved by the addition of $HgCl_2$.

2.3. Chemical analyses

Concentrations of nutrients (NO_3^-, NO_2^-, NH_4^+, PO_4^{3-} and $Si(OH)_4$) were analyzed using an autoanalyzer (Skalar SAN^{plus}) (Liu et al., 2005). The total dissolved nitrogen (TDN) and total dissolved P (TDP) were measured according to the methods of Grassholf et al. (1999). The analytical precision was 0.06 μM for NO_3^-, 0.01 μM for NO_2^-, 0.09 μM for NH_4^+, 0.03 μM for PO_4^{3-}, 0.15 μM for $Si(OH)_4$, 0.68 μM for TDN, and 0.02 μM for TDP. The dissolved inorganic nitrogen (DIN) concentration was calculated as the sum of the concentrations of NO_3^-, NO_2^- and NH_4^+. The concentrations of dissolved organic nitrogen (DON) and dissolved organic P (DOP) were calculated as the differences between TDN and DIN, and between TDP and the concentration of PO_4^{3-}, respectively.

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