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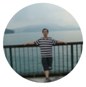

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Variation of Riverine Material Loads and Environmental Consequences on the Changjiang (Yangtze) Estuary in Recent Decades (1955−2008)[†]

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With intense anthropogenic perturbations in the Changjiang (Yangtze) River basin, the riverine loads and compositions of materials into the Changjiang Estuary have greatly changed, resulting in dramatic deterioration in the Changjiang Estuary and adjacent sea environments. Based on a long-term data set of the material loads into the Changjiang Estuary, changing trends and associated impacted factors were presented. The results showed downward trends concentrations and loads of dissolved silicate (DSi) over the past 50 years due to dam constructions in the Changjiang River. However, dissolved nitrogen (DIN) and dissolved inorganic phosphate (DIP) exhibited remarkable upward trends due to the increase of the population and the use of large-scale chemical fertilizer in the Changjiang River basin. The sharp decrease in the ratio of DSi/DIN and the increase in the ratio of DIN/DIP could cause increased Red tide bloom and decreased dissolved oxygen in the Changjiang Estuary. In addition, even though water discharge has remained almost constant, the suspended sediment discharge was shown to be sharply decreased due to the construction of dams.

Introduction

The transport of fluvial materials to the oceans represents a vital pathway within the global geochemical cycle (*1*). However, rapid changes in land use and vegetation cover by intense anthropogenic interference have resulted in massive modifications of materials to estuarine systems (*2, 3*), which may significantly alter the estuarine environment (*3*−*5*). Accordingly, analyses of the changes of riverine material loads and their associated potentially negative environmental impacts on large estuaries have received particular attention (*6*−*10*).

The Changjiang (Yangtze) River is the largest river in the Eurasian continent, with a length of 6300 km, a catchment area of 1.8 × 10^6 km^2 and a human population of over 4 × 10^8 (*11*) (Figure 1). The annual water discharge and suspended sediment discharge (SSD) of the Changjiang River into the estuary are relatively high, at ca. 0.9 × 10^{12} m^3 and 4.18 × 10^8 t (*11*). The abundant fresh water and SSD of the Changjiang River contains high nutrient loads transported into the estuary and adjacent sea. It has been reported that loaded materials from the Changjiang River could produce important impacts not only on the estuary and adjacent sea but also on the West Pacific coastal seas environment (*12, 13*). Since the 1950s, the changing trends of these material loads into the Changjiang Estuary have been determined because of concern about dam construction, fertilizer use and other influences (i.e., human population increase). The consequences of the Changjiang Estuary have included significant changes of the environment, including accelerating eutrophication, frequent Red tide occurrences and extensive hypoxia. Although some preliminary research has indicated that material loads into the Changjiang Estuary have changed (*8, 12*−*15*), there have been only a few quantified studies of variations of material, including nutrient loads. The recent large scale anthropogenic and climate perturbations in the Changjiang River basin, including impounding of dams, extreme drought of 2006, and the first 172.8 m impounding of Three Gorges Dam (TGD) of 2008, are likely to have a heavy impact on the material loads and estuarine environment. Thus, based on the newly available observation data, the aim of the present work is to conduct a comprehensive analysis of the riverine material loads and environmental response of the Changjiang Estuary since the 1950s.

Data and Methods. Most of the environmental data were collected and monitored monthly/seasonally from 1955 to 2008 at the Datong gauging station, which can represent the riverine materials flowing into the Changjiang Estuary (*11, 16*) (Figure 1). Monthly water discharge, suspended sediment concentration (SSC) (1955−2008), and nutrient data (1962−1999) were obtained from the Changjiang Water Resources Commission (CWRC). Seasonal monitoring data for nutrient loads were measured along the section near the Xuliujing station (Figure 1) during 2002−2008 (data from the East China Sea environment monitoring center of China and the dissolved silicate include years 2004, 2006, 2008). However, nutrient data, including dissolved silicate (DSi) from 1987 to 1999 (except for 1998), dissolved inorganic phosphate (DIP) from 1991 to 1997, and dissolved ammonium, nitrite, and nitrate were not obtained from CWRC since they have not yet been released. Here, the monitored DSi is in the form of silicate (SiO_3^{2-}); DIN (dissolved inorganic nitrogen) is the sum of ammonium (NH_4^+), nitrite (NO_2^-) and nitrate (NO_3^-); DIP is dissolved inorganic phosphate (PO_4^{3-}). Data on the annual population and chemical fertilizer use in the Changjiang River basin during 1955−2008 were collected from statistical yearbooks of the People's Republic of China (statistical yearbooks of the National Bureau of Statistics of China, 1955−2008). Dissolved oxygen (DO) and Red tide data were obtained from the East China Sea environment monitoring center of China (http://www.dhjczx.org/) and from the previous publications (*17*−*21*). The details for data monitoring and/or measurements can be found in Supporting Information (SI) Table S1.

Results

Changes in Runoff and SSD. Although running mean of 5 years analysis of temporal water discharge indicated a minor increase in runoff, there was no obvious evidence of statistically significant trends for variation in this time series (Figure 2a). The decennial runoff discharge has mainly fluctuated around a mean of 900 × 10^9 m^3/yr over the past 50 years (Figure 2b).

Similarly, simple trend analyses of SSC and SSD time series from 1955−2008 showed clear evidence indicating interannual SSC and SSD decreases (Figure 2c and e), which is in

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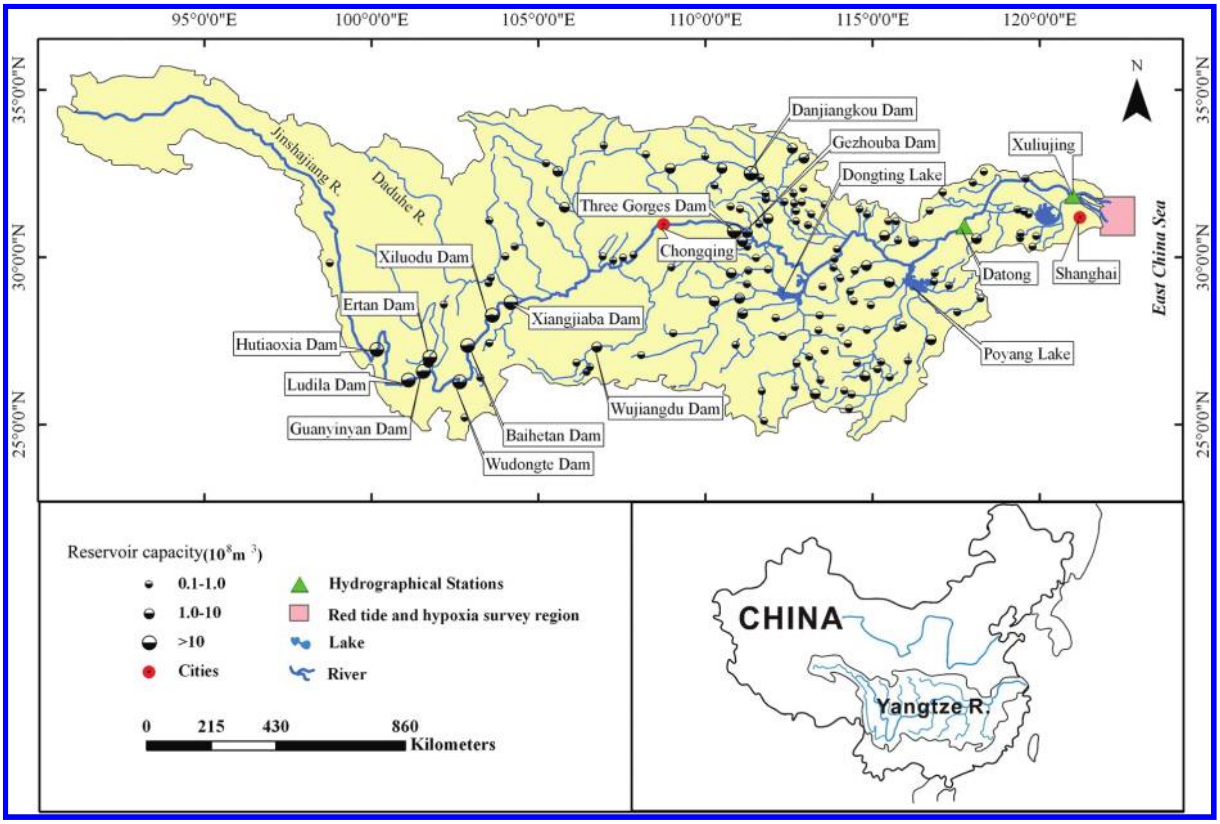

FIGURE 1. Gauging stations and research area.

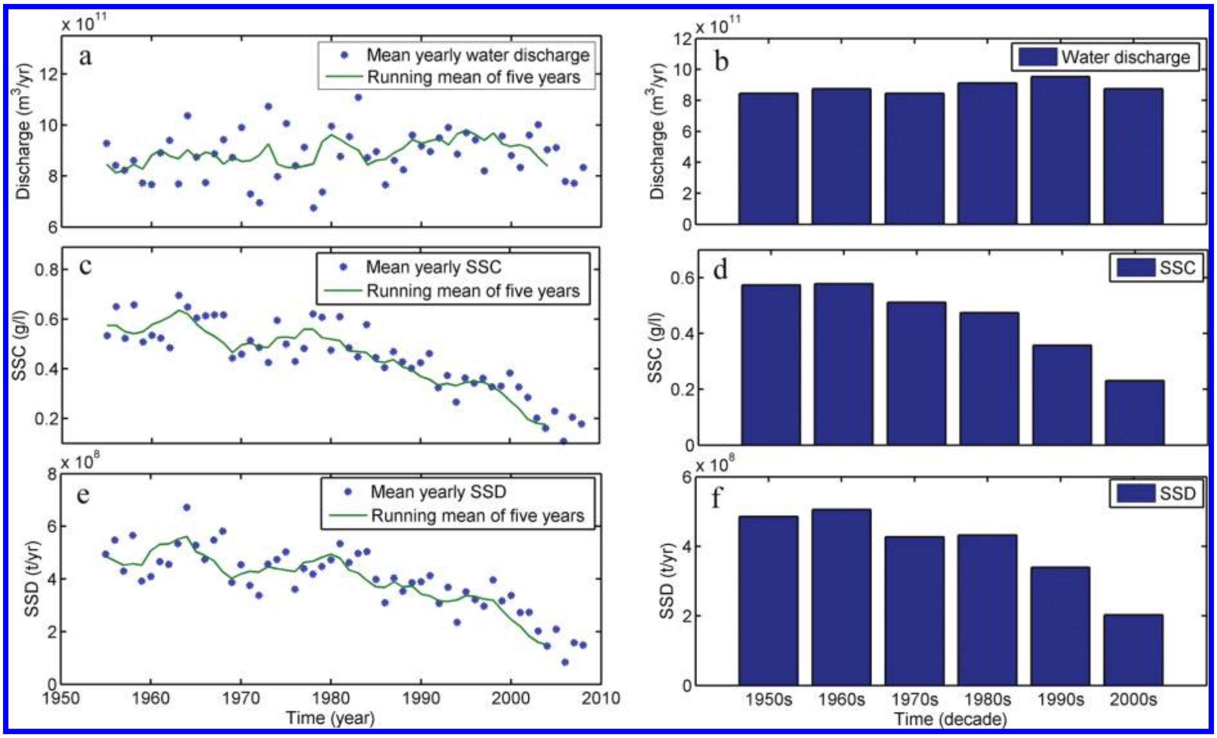

FIGURE 2. Interannual and decennial variation of runoff, SSD and SSC at Datong.

agreement with the previously published results (*13*, *15*). However, using more recent data (2000s) in the present work, it is evident that the decrease of SSC and SSD was more sharply after the 2000s.

From the 1950s to the 1960s, SSC remained at an almost constant value of 0.57 g/L and both SSD and runoff increased by only 4%. However, the downward trend in SSD ranged from 5.06 × 10^8 t/yr in the 1960s to 3.39 × 10^8 t/yr in the 1990s. This is equivalent to a 10% decrease of SSD per decade. However, the sharpest decreases in SSD and SSC changed from 3.39 × 10^8 t/a and 0.36 g/L in the 1990s to 2.03 × 10^8 t/a and 0.23 g/L in the 2000s, respectively. This indicates a decrease rate of around 30% in the most recent decade, which is three times the rate of the previous 30 years (1960s−1990s) (Figure 2d and f). In addition, it should be noted that the highest and lowest annual runoff discharges occurred in the

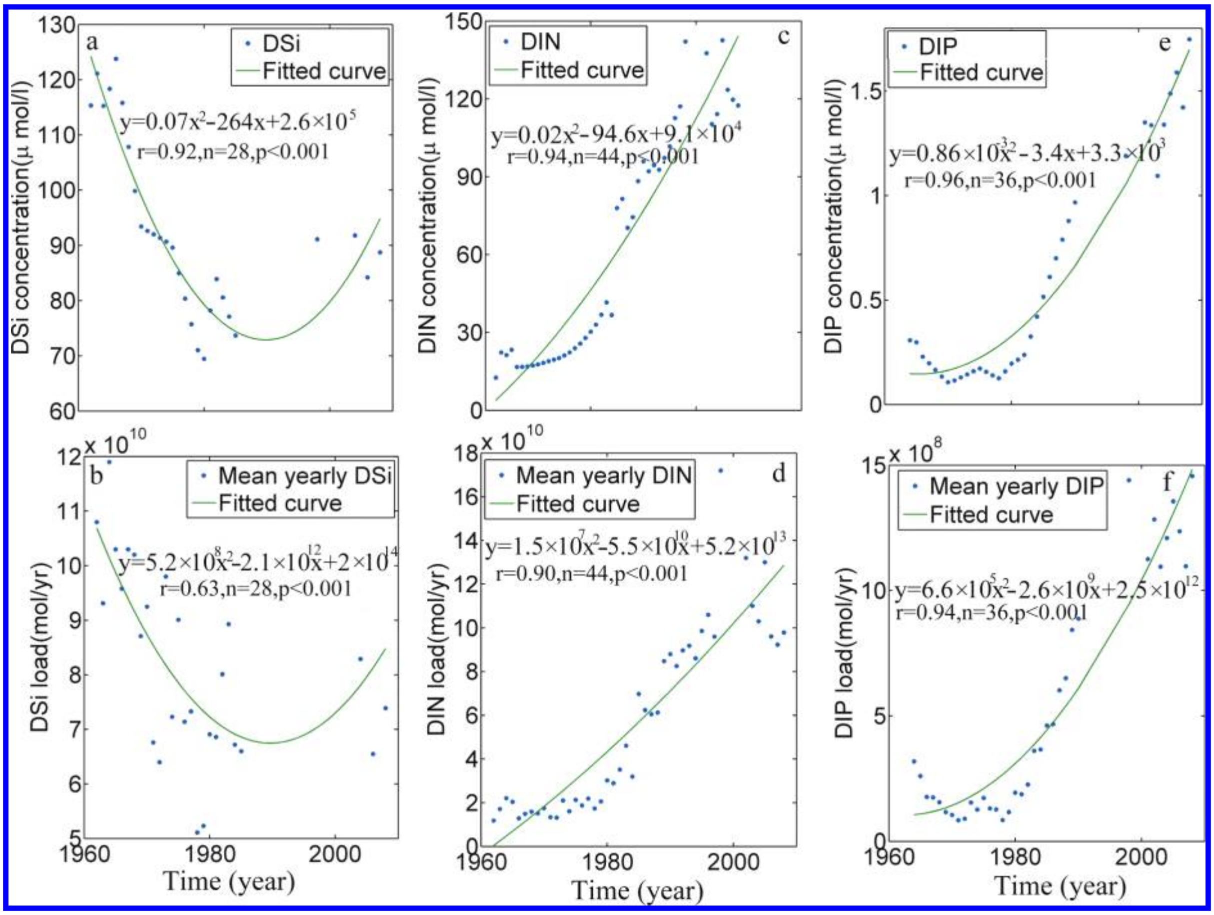

FIGURE 3. Interannual variation in the concentrations and loads of DSi, DIN, and DIP.

flood year of 1998 and the extreme drought year of 2006, at 1210×10^9 m^3/yr and 778×10^9 m^3/yr, respectively. However, the highest SSD was not observed in 1998, although the lowest annual SSD occurred in 2006 at only 0.84×10^8 t/a.

Changes in Nutrients. Although several studies assessed the loads of DSi, DIN and DIP into the Changjiang Estuary based on data collected before 1998 (*12, 13, 22*), the previous understanding of the nutrient loads cannot reflect recent environmental changes. Thus, it is crucial to assess the recent changes in material loads due to the intense anthropogenic perturbations that occurred in the Changjiang River basin.

Changes in Nutrient Concentrations. A polynomial regression method was applied to analyze changes in the concentrations of DSi, DIN, and DIP (Figure 3). It can be seen in Figure 3 that the concentrations of DIN and DIP both parabolically increased from 18.4 and 0.22 μmol/L in the 1960s to 124 and 1.42 μmol/L, respectively, in 2000s (Figure 3c and e). However, the DSi concentration parabolically decreased by 30% from 114.66 μmol/L in the 1960s to 88.25 μmol/L in the 2000s (Figure 3a; SI Table S2). Moreover, although these nutrient concentrations showed interannual changes with parabolic increases/decreases, the concentrations of DSi, DIN, and DIP between the flood season and dry season were not significantly different, even in the flood year of 1998 and the drought year of 2006 (SI Table S3).

The ratios of both DSi/DIN and DIN/DIP showed parabolic changes (SI Figure S1). The ratio of DSi/DIN was 6.23 in the 1960s and 0.74 in the 2000s (SI Table S2). In addition, the DIN/DIP ratio had obvious fluctuations, with an increase from 84 in the 1960s to 154 in the 1970s but with a decrease to 87 in the 2000s.

Changes in Nutrient Loads. The DSi load decreased by 40% from 101×10^9 mol/yr in the 1960s to 73×10^9 mol/yr in the 1970s. After that, it was relatively stable at a mean of about 74×10^9 mol/yr in the subsequent three decades although there were limited data available after 1985. (Figure 3b). However, the DIN and DIP loads remained at stable values from the 1960s to the 1970s. Substantial increases of DIN and DIP loads occurred from the 1970s to the 1980s (approximately 3-fold) and from the 1980s to the 1990s (2-fold) (Figure 3d and f). The mean annual loads in the 2000s were 108×10^9 mol/yr for DIN and 1232×10^6 mol/yr for DIP, which represent only 6% increases compared to the values in the 1990s. Furthermore, the nutrient loads also showed seasonal characteristics. Although DSi and DIN loads in the flood or drought years showed relatively high or low values due to the variable runoff, the DIP loads remained relatively stable both in the flood year of 1998 and in the drought year of 2006, which was reflected by the relatively high DIP concentration of 1.58 μmol/L in 2006 and the relatively low value of 1.19 μmol/L in 1998. Therefore, the DIP loading into the Changjiang River did not strictly follow water discharge.

Discussion

Anthropogenic Impacts on Material Loads. Annual water discharge changes of the Changjiang River basin are mainly influenced by climatic (including rainfall) variability (*23*). Thus, the relatively low discharges occurred in the extreme drought year of 1978 and 2006 in recent 50 years were due to declines in precipitation. However, the environmental changes in the Changjiang River basin are also heavily impacted by the population of over 400 million. From the 1950s to the present, the population in the Changjiang River basin has continuously increased (SI Figure S2a). Almost one-third of China's population resides within this region. Therefore, large increases in pollutant discharge are strongly influenced by rapid urbanization and industrial development (*15*). A simple linear regression analyses of relation between DIN/DIP loads and total population showed that there is a close correlation with statistical significance (SI Figure S2b and S2c). The increased population in the Changjiang River basin may increase DIN and DIP loads in several ways, including increases in industrial and municipal wastewater drainage and fertilizer use.

Global increases in the total fertilizer use in recent decades have been well documented (*24*), and there is obvious evidence of the effects of DIN and DIP increases on aquatic eutrophication (*13*). As seen in SI Figure S3a and S3c, it is possible to distinguish changes in fertilizer nitrogen and phosphorus in the Changjiang river between two different periods: the 1960s−1980s period is characterized by relative stability, and the 1980s−2000s period is characterized by a intense upward trend (SI Figure S3a and S3c). The variations in the amount of consumed fertilizer in both periods cooccurred with the riverine loads of DIN and DIP (SI Figure S3b and S3d), indicating that riverine nutrient (DIN, DIP) loads were likely dominated by chemical fertilizer usage in the Changjiang River basin.

In comparison with those in other rivers, although the total nutrient loads in the Changjiang River are much larger, annual nutrient fluxes per square kilometer in the river basin are comparable (SI Table S4). Another intense anthropogenic influence of the Changjiang River basin on material loads, especially for SSC and SSD, is dam construction (SI Table S5, Figure 1, and SI Figure S4), which has played a key role in reducing material loads into the Changjiang Estuary. The slowdown of the flow behind dams will intensify suspended matter settling and decrease turbulent mixing when rivers were dammed (*25*). The current number of dams in the Changjiang River basin is over 48,000 (SI Table S5, Figure 1, and SI Figure S4). This can result in a large-scale particle settlement in reservoirs and SSD decreased downstream of dams along the Changjiang River. For example, since the TGD began operation in 2003, the measured SSD at Datong had sharply decreased to 2.06×10^8, 1.47×10^8 and 2.16×10^8 t in 2003, 2004, and 2005, respectively, in comparison with over 4.2×10^8 t/a before the 1970s.

The statistical significance of the correlation analysis between SSD and DSi indicates that the decreasing trend of the DSi is likely facilitated by the decreased SSD in the Changjiang River (SI Figure S5). However, additional measurements are needed. In addition, even though 48 000 dams have been built in the streams of the Changjiang River and the stored water magnitude has reached 142 km^3, the volume of water annually stored in the reservoirs is less than 10 km^3, which is about 1% of the annual discharge (*26*). Thus, the total annual water discharge has not significantly changed over the last of 50 years. However, interannual SSC and SSD downward drops and the lowest annual SSD occurred in 2006. Although DSi showed a decreasing trend in the 1960s, and was stable in the most recent three decades, the changes in both DIN and DIP had increased trends, mostly from a rapid rise in chemical fertilizer usage in the Changjiang River basin.

Impact of Material Loads on the Estuarine Environment. Although water discharge into the Changjiang Estuary has remained relatively stable, other materials, such as SSD and nutrients, have greatly decreased and increased, respectively. This phenomenon has definitely affected the environment of the Changjiang Estuary and adjacent seas (*8*). As a direct and quick response to the sharp decreases of SSD into the Changjiang Estuary, in comparison with that of 1958, the area of tidal-flat (>−5 m) was sharply increased in 1996, but slightly increased in 2004 and decreased in 2006. However, in one of typical tidal-flat−Nanhui shoal, it was even obviously erosion (SI Figure S6). It means that the present delta evolution has changed from rapid accretion to slow advancement, and even the local regions have had erosion. Therefore, the Changjiang delta is considered to be one of the world's great deltas currently threatened (*27*), which is a reflection of rapidly changing Changjiang Estuary environment.

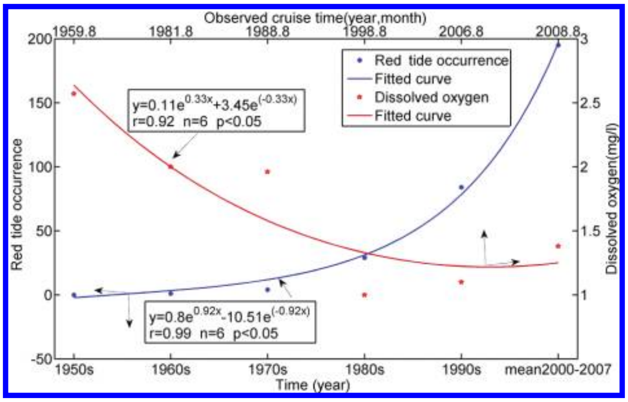

FIGURE 4. Variations in the frequency of Red tide and the lowest values of dissolved oxygen for each observed cruise in the Changjiang estuary (dissolved oxygen survey data from the East China Sea environment monitoring center of China and the previous published references (*13, 17*−*19, 21*).

In addition, the riverine DSi/DIN and DIN/DIP ratios into the Changjiang Estuary have changed substantially. As a result, the estuary and adjacent seas are likely to become more eutrophic, with completely shifted compositions of nutrients and phytoplankton. There was a sharp decrease in DSi/DIN, DSi/DIP, from 6.23, 523 in the 1960s to 0.71, 61.8 in the 2000s, respectively. Meanwhile, the ratio of DIN/DIP into the Changjiang Estuary was continuously higher. As a result, growth of nonsiliceous algae was observed in the Changjiang Estuary (*13*). For example, previous results showed that the ratio of *Skeletonema costatum* (siliceous alga) to the total predominant species has continuously decreased, from 33% in the 1980s to 31% in the 1990s and then to only 24% during 2000−2002. In contrast, the ratio of *Prorocentrum dentatum* (nonsiliceous alga) to the total predominant species has increased, from 12.5% in the 1980s to 14.3% in the 1990s and then to 36% during 2000−2002 (*13*). Similar trends have been observed in the Danube River of Spain (*28*). Moreover, expansions of the Red tide in the Changjiang Estuary and adjacent sea has also been observed (Figure 4). The occurrences of Red tide in the Changjiang Estuary had rapidly increased from 29 in the 1980s to 195 during 2000−2007. In addition, as another important environmental response, the high nutrient loads into the estuary could also be a threat to estuarine ecosystems through the alteration of hypoxia in the bottom waters (*29*). This could result in benthic fauna suffering from stress or death due to oxygen depletion (*30*), as well as the decrease in the diversity of the creatures living in the Changjiang estuary (SI Table S6) (*31*). The results of a most recent cruise in the Changjiang Estuary indicated that minimum dissolved oxygen (MIDO) levels were 1.38 mg/L in August 2008 (Figures 1 and 4). Multiyear observations showed that the MIDO time series were also decreased: MIDO values taken during the summer (e.g., August) were 2.57, 2.0, and 1.96 mg/L in 1959, 1981, and 1988, respectively. However, the summertime MIDO values had greatly changed from 1.96 mg/L in 1988 to 1.00, 1.10, and 1.38 mg/L in 1999, 2006, and 2008, respectively. These were exceptions to the general decrease of summer time MIDO values from 1988 to the 1990s and 2000s. Since large changes in the ratios of DSi/DIN and DIN/DIP have occurred with intensifying trends, the frequency of Red tide in the Changjiang Estuary has risen. As a reflection of hypoxia, the MIDO values have been decreasing.

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Supporting Information Available

Additional information including six tables and six figures. This material is available free of charge via the Internet at http://pubs.acs.org.

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