Yangtze River floods enhance coastal ocean phytoplankton biomass and potential fish production

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[1] The occurrence of extreme weather conditions appears on the rise under current climate change conditions, resulting in more frequent and severe floods. The devastating floods in southern China in 2010 and eastern Australia 2010–2011, serve as a solemn testimony to that notion. Accompanying the excess runoffs, elevated amount of terrigenous materials, including nutrients for microalgae, are discharged to the coastal ocean. However, how these floods and the materials they carry affect the coastal ocean ecosystem is still poorly understood. Yangtze River (aka Changjiang), which is the largest river in the Eurasian continent, flows eastward and empties into the East China Sea. Since the early twentieth century, serious overflows of the Changjiang have occurred four times. During the two most recent ones in July 1998 and 2010, we found total primary production in the East China Sea reaching 147×10^3 tons carbon per day, which may support fisheries catch as high as 410×10^3 tons per month, about triple the amount during non-flooding periods based on direct field oceanographic observations. As the frequencies of floods increase world wide as a result of climate change, the flood-induced biological production could be a silver lining to the hydrological hazards and human and property losses inflicted by excessive precipitations. **Citation:** Gong, G.-C., et al. (2011), Yangtze River floods enhance coastal ocean phytoplankton biomass and potential fish production, *Geophys. Res. Lett.*, *38*, L13603, doi:10.1029/2011GL047519.

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1. Introduction

[2] Rivers are the lifelines for sustaining human livelihood as they provide freshwater and other resources to human societies. The materials delivered by rivers, especially the large ones, have strong impacts on the adjacent continental shelves by enhancing primary productivity, which in turn serves as the energy source to the food chains in continental margins, where fish stocks are considerably more abundant than those in the neighboring open ocean [*Watson and Pauly*, 2001]. Therefore, river discharges conceivably play a critical role in sustaining the continental shelf fisheries resources. On the other hand, river discharges are directly related to the likelihood of flood hazards. The higher the discharge is, the more likely flooding of the river basin occurs, resulting in losses of human lives and properties [*Zong and Chen*, 2000]. Huge amounts of terrigenous materials along with runoff waters are discharged to the coastal ocean during floods [*Turner et al.*, 2006]. As global warming causes shifts in the climate system and induces more frequent occurrences of extreme weather conditions, such as tropical cyclones, the chances of excessive rainfalls that result in floods increase throughout the world [*Knox*, 1993; *Palmer and Raisanen*, 2002; *Milly et al.*, 2002; *Christensen and Christensen*, 2003]. It is warranted to investigate how the increasing river runoffs associated with more frequent floods may impact the coastal ocean ecosystems.

[3] The Yangtze River (aka Changjiang) is the largest river in China as well as on the Eurasian continent and the fifth largest in the world. With a total length of 6300 km, it originates from heights reaching 6600 m in the Qinghai-Tibetan Plateau (see Figure 1a). It flows eastward and empties into the East China Sea, which is a vast continental shelf sea and renowned for its rich fishery resources [*Watson and Pauly*, 2001]. The long-term average discharge rate is 956 $km^3\ yr^{-1}$, which accounts for more than three quarters of the total amount of river runoffs discharged to the contiguous continental shelves of the East China, Yellow and Bohai Seas [*Liu et al.*, 2010]. The highest monthly discharge occurs in July [*Xu and Milliman*, 2009] with a mean discharge of about 46000 $m^3\ s^{-1}$ as recorded at the Datong Gauge Station (at the lower reach of Changjiang, see Figure 1a for station location). This is the month of the year, when floods happened most frequently in the past. According to hydrological records, widespread flooding over the Changjiang drainage basin has occurred four times since the beginning of the 20th century. The most recent one occurred from June to August in 2010

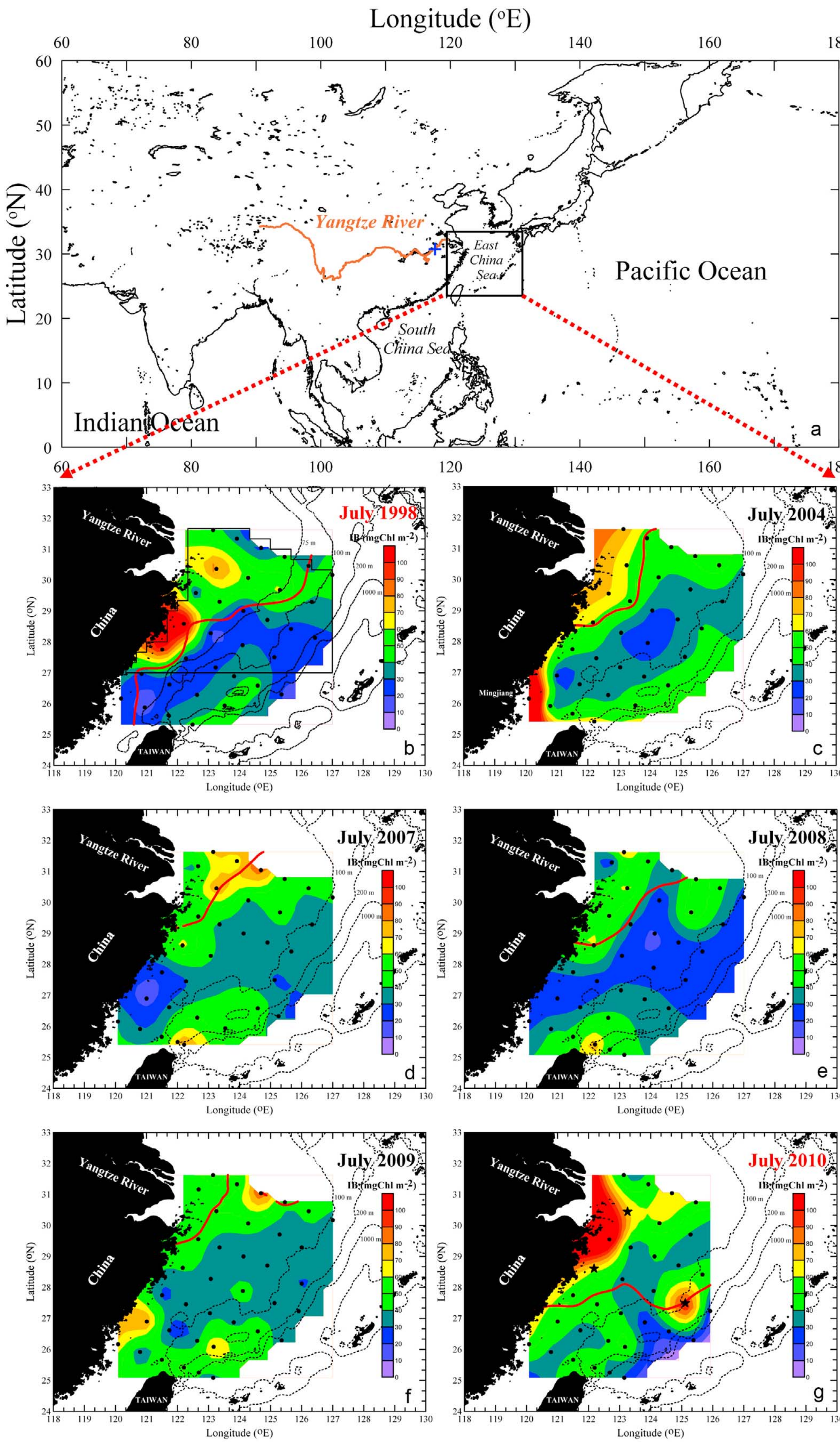
Longitude (°E)
Latitude (°N)
Yangtze River
East China Sea
Pacific Ocean
South China Sea
Indian Ocean
a
July 1998
July 2004
July 2007
July 2008
July 2009
July 2010
Yangtze River
China
TAIWAN
Mingjiang
Longitude (°E)
Latitude (°N)
b
c
d
e
f
g

Figure 1

with the record high water discharge occurring in the middle reach of Changjiang in July as gauged in the Three Gorges Dam (see http://en.wikipedia.org/wiki/2010_China_floods). The three previous events occurred, respectively, in 1931, 1954 and 1998. The total deaths caused by these floods amounted to tens of thousands, economic losses to billions of dollars and number of people affected to millions [*Zong and Chen*, 2000] (see also http://en.wikipedia.org/wiki/2010_China_floods).

[4] In this study, our repeated oceanographic observations of the East China Sea in the past decade (1998–2010) caught two of the most devastating floods of the Changjiang River in China, and allow us to examine the consequences of the floods in the coastal ocean. We found the average carbon fixation rate during the flooding periods was about three times that during the non-flooding periods.

2. Material and Methods

[5] Since 1997, Taiwanese oceanographers have conducted oceanographic expeditions in the East China Sea surveying the biogeochemical conditions to establish a long-term observational database. A special emphasis of the observations has been to explore the effects of Changjiang River discharges on the East China Sea. The currently ongoing project, Long-term Observation and Research of the East China Sea (LORECS), is closely related to two large international cooperative projects, namely, the Surface Ocean Lower Atmosphere Study (SOLAS) and the International Biogeochemical and Ecosystem Research (IMBER). Extensive surveys in the East China Sea between 25°N and 32°N had been carried out in July of 1998, 2004, 2007, 2008, 2009 and 2010. The timing of those in 1998 and 2010 coincided with the flooding periods of Changjiang.

[6] For this report, data were taken from six July cruises on board the *R/V* Ocean Researcher I, Taiwan. Hydrographic data and water samples for nutrients, chlorophyll *a* and primary productivity measurements were taken by the CTD (SBE9/11 plus, Seabird Inc., USA) and Rosette (Model 1015, General Oceanics Inc., USA) assembly. Nutrient samples were collected with Teflon coated Go-Flo bottles (20L, General Oceanics Inc., USA) mounted on a rosette sampler and stored under liquid nitrogen until analysis. Analytic methods for the determination of nutrients (nitrate, phosphate and silicate), chlorophyll *a* and primary productivity are described elsewhere [*Parsons et al.*, 1984; *Gong et al.*, 2000; *Welschmeyer*, 1994]. Abundances and species composition of microplankton were identified and counted using an inverted epifluorescence microscope (Nikon-Tmd 300) at 200X or 400X. The depth of the euphotic zone was defined as the depth of 1% surface light penetration. Discharge data at the Datong hydrological gauge station (117.62°E, 30.76°N; at the lower reach of Changjiang) taken from the Chinese Bureau of Hydrology were used to represent the discharge of the Changjiang River. Changjiang discharge data between 2004 and 2010 were taken from Chinese Bureau of Hydrology with the help of Su Jilan at State Key Laboratory of Satellite Ocean Environment Dynamics, Second Institute of Oceanography and Yang S.L. at State Key Laboratory of Estuarine and Coastal Research, East China Normal University, China.

3. Results and Discussion

[7] The mean monthly Changjiang River discharge of July in the non-flooding years varied between 33955 and 40943 $m^3 s^{-1}$, while those for 1998 and 2010 were 74000 and 60527 $m^3 s^{-1}$, respectively [*Yu et al.*, 2009] (see also Chinese Bureau of Hydrology, http://www.cjh.com.cn/). The average of the discharge values under flooding conditions was 1.8 times that under non-flooding conditions. The distributions of vertically integrated chlorophyll *a* inventories (IB) observed on the six July cruises are presented in Figure 1. The IB value, which serves as an index of the total algal biomass, was always quite high near the Changjiang river mouth and decreased seaward toward the east or southeast. Also plotted in Figures 1b–1g are the isohalines of salinity 31, which mark the outer boundary of the Changjiang Diluted Water (CDW). The CDW coverage represents the expansion of the surface water directly influenced by the Changjiang discharge [*Gong et al.*, 1996, 2003, 2006]. In five among the six cases, the maximum IB occurred within or near the 31 isohaline, indicating the strong correlation between high algal biomass and river discharge. For the one exception of the 2004 cruise, the highest IB was observed near the river mouth of Mingjiang (Figure 1c). This also testified to the importance of river discharges. While the river discharged nutrients contribute directly to the elevated algal growth, other indirect effects could also be important. The freshwater enhanced stratification and the shelf circulation driven by river discharge leading to shoreward intrusion of nutrient-replete subsurface seawater may further boost algal blooms.

[8] It is apparent that the CDW coverage during the two flooding periods in 1998 and 2010 (Figures 1b and 1g) was larger than those under non-flooding conditions (Figures 1c–1f). The CDW reached as far as the 75 m isobath during the 1998 flood and dispersed even farther during the 2010 flood reaching the 100 m isobath. It is shown in Figure 2 that the total carbon fixation rate followed closely the variation of the CDW coverage in the six cases. The mean area of CDW coverage (141.5×10^3 km^3) and the mean total observed chlorophyll *a* inventory (8.3×10^6 tons) during the flooding periods were nearly four times those during the non-flooding periods (Table 1). Analysis of the microplankton species composition of samples collected from three stations on the 2010 cruise (sites marked with asterisk in Figure 1g) revealed that diatoms were dominant, and the three species,

[1] Auxiliary materials are available in the HTML. doi:10.1029/2011GL047519.

Figure 1. (a–g) Distribution of vertically integrated algal chlorophyll *a* inventory (IB) in the East China Sea observed on six July cruises between 1998 and 2010. The first and last of the six cruises (Figures 1b and 1g) were conducted during periods of serious flooding in the Changjiang drainage basin. The red curve in each plot represents the isohaline of salinity 31, indicating the outer boundary of the Changjiang Diluted Water (auxiliary material, Figure S1).[1] The black dashed curves are isobaths for 75, 100, 200 and 1000 m depths. The polygon of solid black lines in Figure 1b indicates the domain of the integrations conducted for Table 1 and Figure 2. For volume integrations the maximum depth is the bottom depth or 100 m whichever is smaller. The cross symbol in Figure 1a indicates the location of the Datong hydrological gauge station.

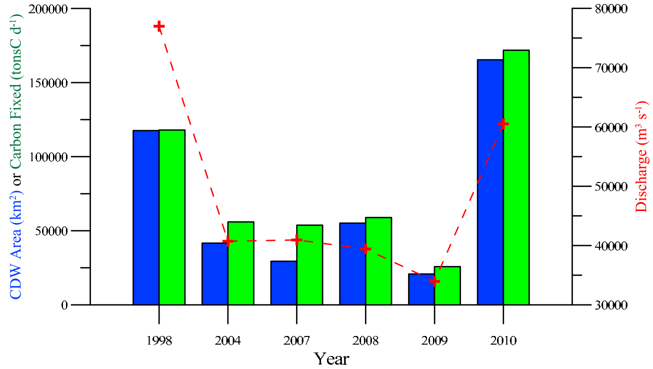

Figure 2. The areas of Changjiang Diluted Water coverage (blue) and total primary production (green) in the integration domain shown in Figure 1b observed on the six July cruises between 1998 and 2010. The corresponding mean monthly discharges of Changjiang are also shown as the red crosses.

Chaetoceros spp., *Rhizosolenia* spp. *and Nitzschia* spp., comprised 80% or more of the total diatom concentration. The diatom abundance attained was as high as 1×10^5 cells L^{-1} (Table 2) near the river mouth, suggesting diatoms accounted for most of the biomass observed.

[9] The total algal photosynthesis rate, namely, the primary production, estimated for the area of CDW coverage observed on the 1998 cruise was 117.9×10^3 tons C d^{-1} and that observed on the 2010 cruise was 176.0×10^3 tons C d^{-1}. The average carbon fixation rate during the flooding periods was about three times that during the non-flooding periods (Table 1). Based on the observed primary production and mean tropic level of 3, the fisheries catches that may be sustained were calculated [*Pauly and Christensen*, 1995] and are listed in Table 1. The mean sustainable catch for the flooding periods was 410×10^3 tons month^{-1}, which was three times that during non-flooding periods. Aside from the high biomass inventory near the coast, a patch of relatively highstanding stock of phytoplankton was always present along the shelf break northeast of Taiwan (Figure 1), resulting from Kuroshio upwelling [*Liu et al.*, 1992a, 1992b; *Gong et al.*, 1995]. It is interesting to note that this patch appeared to be less developed during the flooding periods than during the non-flooding periods. The apparent anti-correlation with the CDW coverage warrants further investigation.

[10] It is worth mentioning that increasing riverine loads of nutrients are often associated with environmental quality deterioration in the coastal ocean resulting from harmful algal blooms (HABs) and benthic layer hypoxia [e.g., *Cloern*, 2001; *Heisler et al.*, 2008; *Rabouille et al.*, 2008; *Zhang et al.*, 2010]. Periodical occurrences of HABs in the ECS, excessive growth of green macroalgae *Ulva prolifera* in the Yellow Sea (YS) and significant expanse of hypoxia in the bottom water off the Changjiang River mouth have been observed in recent years [*Chen et al.*, 2007; *Hu et al.*, 2010; *Wang and Wu*, 2009]. However, the observed peaks of HABs in the ECS occurred in May and June, prior to the peak flows of the Changjiang River in July and August [*Wang and Wu*, 2009]. The notorious 2008 massive algal bloom in the YS that started in late May and vanished in mid- July [*Wang et al.*, 2009] has been linked to coastal aquaculture. The observations do not suggest Changjiang floods as a direct cause of HABs or other disruptive algal blooms. In fact, the dominance of diatoms in the flood-induced algal blooms could make the blooming algae a high quality food source for the upper trophic levels in the ECS ecosystem. On the other hand, the flood-enhanced productivity and stratification could favor the development of seasonal hypoxia in the ECS in late summer. Close monitoring of the environmental conditions in the flood seasons should be conducted to discern any adversary effects that may be caused by Changjiang floods.

[11] From more than a decade (1998–2010) field expeditions in the East China Sea, we captured the rare scenes of wide-spread healthy algal blooms during the two most recent devastating floods in China's largest river basin, revealing

Table 1. The Area of Coverage by the Changjiang Diluted Water Observed on July Cruises Between 1998 and 2010 and the Corresponding Monthly Mean Discharges of Changjiang[a]

	Discharge[b] (m^3 s^{-1})	Area[c] ($x10^3$ km^2)	IB[d] ($mgChl$ m^{-2}) Mean	Standard Deviation	IP[e] (mgC m^{-2} d^{-1}) Mean	Standard Deviation	Total Chl *a* ($x10^6$ tons)	Carbon Fixed ($x10^3$ tons C d^{-1})	Catches[f] ($x10^3$ tons mon^{-1})
29 June-4 July 1998	74000	117.6	60.3	33.4	1003	686(11,6)	7.10	117.9	329.1
12–15 July 2004	40720	41.7	65.4	8.9	1343	473(5,2)	2.72	55.9	156.1
5–8 July 2007	40943	29.4	59.9	20.0	1829	909(5,3)	1.76	53.8	150.0
5–8 July 2008	39427	55.1	50.2	20.2	1069	826(7,4)	2.77	58.9	164.4
2–6 July 2009	33955	20.8	64.9	28.6	1237	636(4,0)	1.35	25.8	71.9
9–15 July 2010	60527	165.4	57.4	26.9	1039	412(18,8)	9.48	176.0	490.9
Non-flood[g]	38761	36.8	60.1	19.4	1370	711	2.15	48.6	135.6
Flood[h]	67264	141.5	58.8	30.2	1021	549	8.29	147.0	410.0

[a]Also listed are the mean values of vertically integrated chlorophyll *a* inventory (IB) and averaged primary production (IP) and their total values within the area of CDW coverage. The fisheries catches that may be sustained by the observed primary productions are provided. Dates are when CDW was observed.

[b]The monthly mean discharge rate of Changjiang of the corresponding July.

[c]The area of CDW coverage as observed within the black polygon shown in Figure 1b.

[d]Mean of vertically integrated inventory of Chl *a* down to bottom depth or 100 m. "std" (standard deviation) shows the variability within the CDW.

[e]Mean of vertically integrated primary production. The numbers in parenthesis in the std column represent the number of stations within CDW and that for primary productivity (PP) measurements. For stations without PP measurements PP is calculated by the relationship between IP and IC ($IP = 3.377*IC^{1.556}$, $R^2 = 0.907$; see auxiliary material, Figure S2).

[f]Calculated using the relationship [Carbon fixed] = [Catches/9]x10$^{(TL-1)}$, where TL is Trophic Level, which is assumed to be 3 [*Pauly and Christensen*, 1995].

[g]Mean values calculated for non- periods.

[h]Mean values calculated for flooding periods.

Table 2. Chlorophyll *a* concentrations (Chl *a*) and Diatom abundances in surface water observed on the 2010 cruise at two inner shelf stations (29 and 30) and an outer shelf station (12) (Sites marked with asterisk in Figure 1F).

Station No.	Longitude (°E)	Latitude (°N)	Chl *a* (mg m^{-3})	Diatom (cells L^{-1})	*Chaetoceros* spp. (cells L^{-1})	*Rhizosolenia* spp. (cells L^{-1})	*Nitzschia* spp. (cells L^{-1})	*Chaetoceros* spp. (%)	*Rhizosolenia* spp. (%)	*Nitzschia* spp. (%)	Subtotal (%)
12	125.126	27.499	0.70	1921	384	0	1153	20	0	60	80
29	123.253	30.459	3.36	102615	11923	25692	53077	12	25	52	88
30	122.166	28.616	4.67	183268	125000	192	25000	68	0	14	82

the benefits to the coastal ocean ecosystem by the flood waters. It has been recently recognized that the global water cycle derived from the satellite data indicates that the sum of world-wide river runoffs has shown a mean annual increase of 540 km^3 yr^{-1} in the last 13 years [*Syed et al.*, 2010]. While the potential losses and damages caused by floods associated with the increasing runoffs are being assessed [*Parry et al.*, 2007], it may bring some solace to the global community considering the potential benefits the floods may generate in the form of fisheries resources in continental margins adjacent to large rivers. A careful assessment of the fishery resources in the ECS is warranted to verify the potential benefits implied from our observations.

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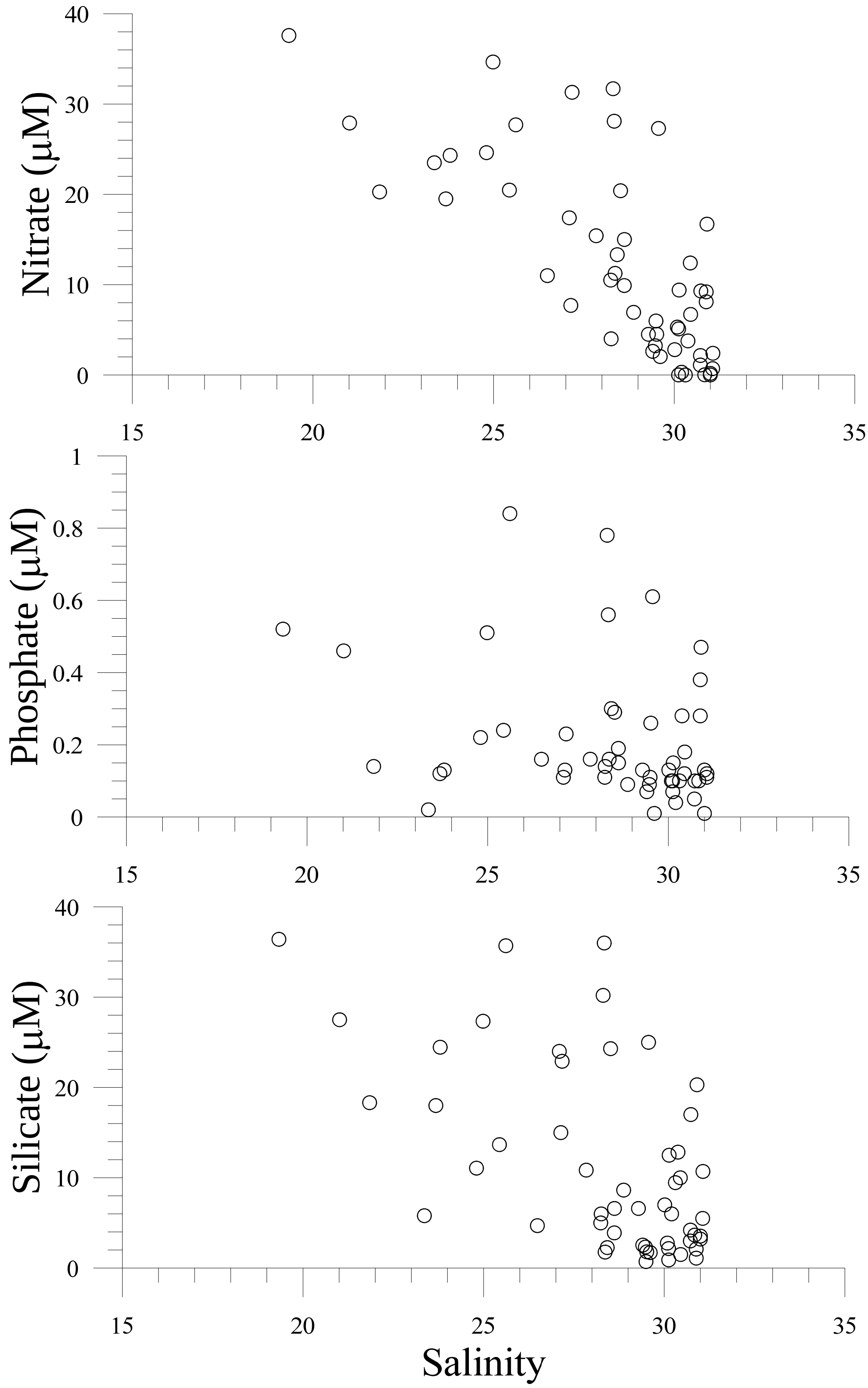

Figure S1. Relationships between salinity and inorganic nutrients in surface water at stations within the coverage of the Changjiang Dilute Water as observed on the six cruises between 1998 and 2010. The relationships indicate that the presence of riverine nutrients is evident in the waters with salinity less than 31.

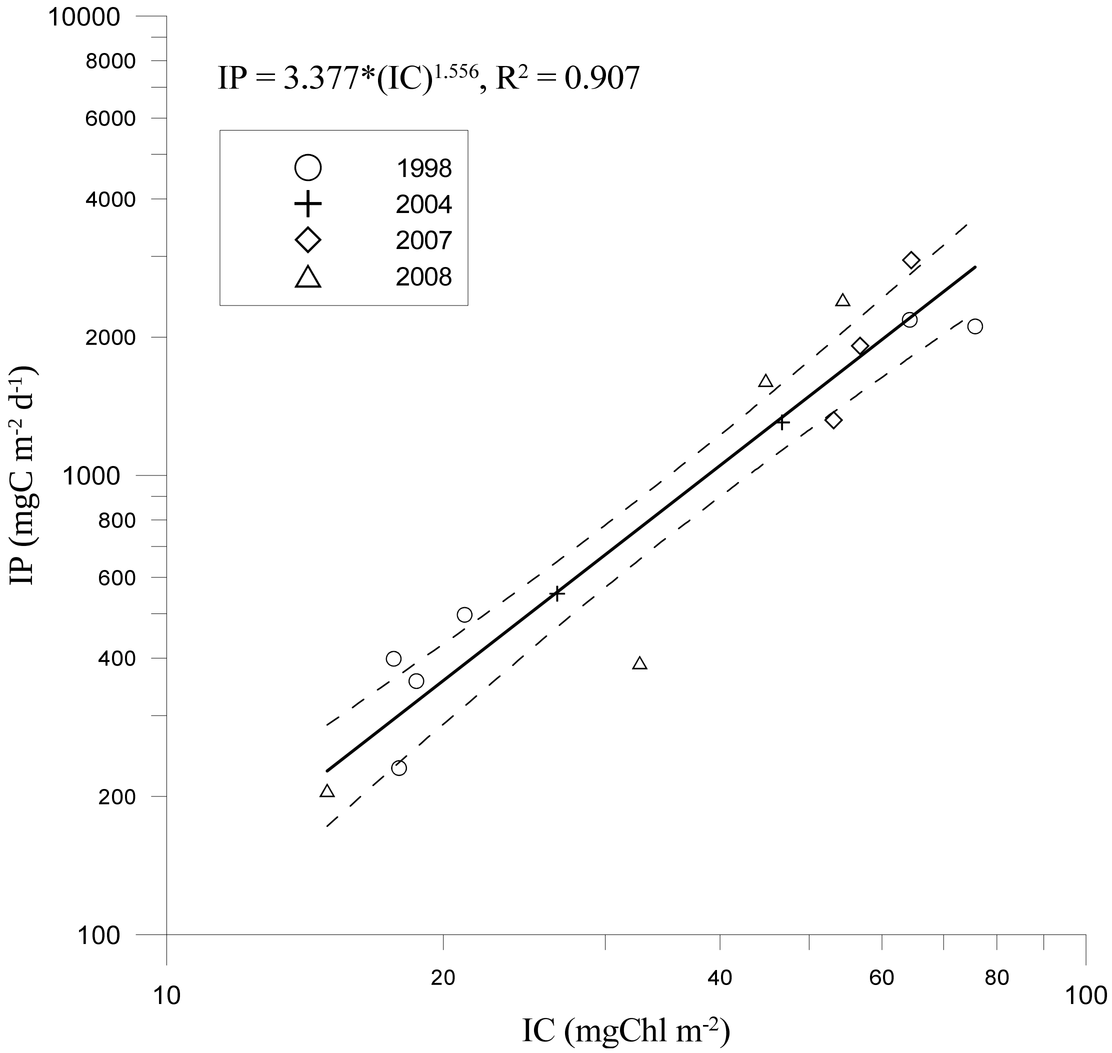

Figure S2. The relationship between euphotic zone integrated chlorophyll *a* concentration (IC) and primary production (IP) as observed on the four July cruises between 1998 and 2008. Dashed line indicated upper and lower level of 95% confidence.