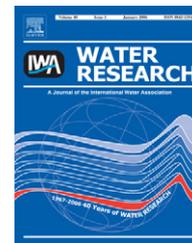


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Ecological anomalies in the East China Sea: Impacts of the Three Gorges Dam?

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ABSTRACT

In this study, we examined possible impacts of the Yangtze River Three Gorges Dam (TGD), the world largest hydroelectric construction, on the adjacent marine ecosystem of the East China Sea (ECS) during its initial water storage period. The TGD filled the first one-third of its storage capacity of 39 billion m³ in 10 days in June 2003, causing an abrupt reduction in the river flow into the ECS. Noticeable changes in the microbial community structure including pico-sized autotrophs, heterotrophic bacteria and microbial diversity in the estuary and the ECS were observed 2 months later. Although causes for these changes could be multiple, the sudden decrease of river runoff and an ensuing intrusion of ECS ocean currents were postulated to be among the major ones.

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1. Introduction

The East China Sea (ECS) is the largest continental marginal sea in the Western Pacific (Wong et al., 2000), which is characterized by dynamic interactions among water systems including nutrient enriched freshwater input from the Yangtze River (Gong et al., 1996), and the warm and oligotrophic Kuroshio Current and Taiwan Strait Current

(Miao and Yu, 1991). Located 1800 km upstream from the Yangtze River estuary of the ECS is the Three Gorges Dam (TGD) (Fig. 1). Being 185 m high and 2300 m long, TGD is the largest hydroelectric construction in the world, which covers 1080 km² of drainage area and will have a total water storage capacity of 39.3 billion m³. The filling of the TGD reservoir at a water level of 175 m will be completed in 2009. An initial TGD water storage of 12.4 billion m³ was completed within 10 days

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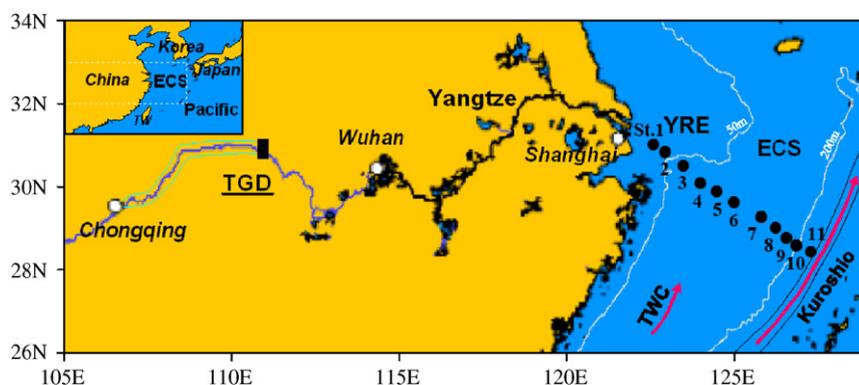


Fig. 1 – Map of the Yangtze River and the East China Sea (ECS) showing locations of the Three Gorges Dam (TGD) and our investigation stations in the ECS. YRE: Yangtze River estuary; TWC: Taiwan Warm Current; Kuroshio: Kuroshio Current.

in June 2003, which was about 2% of the averaged annual discharge but caused a 27% reduction in flow rate at the Yangtze River mouth in late June (Cao et al., 2005). Could this event have any impact on the ECS ecosystem?

It has been suggested that the effects of freshwater input from the Yangtze River on the ECS might be phase-lagged by a few months (Delcroix and Murtugudde, 2002). In the present study, we collected environmental and biological data including remote-sensing patterns of macroscale distribution of temperature, salinity, chlorophyll *a* (Chl. *a*), and particulate organic carbon (POC), and as seen from *in situ* observations of microscale structure of the community, including pico-sized autotrophs and bacteria, and microbial diversity in the ECS in September of 2003 as well as September of 2002 (as reference). We here examine the data to check the possible influences of the abrupt reduction of runoff due to the TGD initial water storage on the ECS ecosystem.

2. Materials and methods

2.1. Remote-sensing images of SST, SSH, Chl. *a*, POC, and transparency

SST was calculated based on the moderate resolution imaging spectroradiometer (MODIS). Chl. *a* and normalized water-leaving radiation at 555 nm ($L_{WN}(555)$) were obtained from the sea-viewing wide field-of-view sensor (SeaWiFS). These data were acquired from Goddard Earth Sciences Data and Information Services Center, National Aeronautics and Space Administration (NASA). Ocean binned Level 3 products with 4-km spatial resolution for temperature (MODIS) and with 9-km spatial resolution for the Chl. *a* and $L_{WN}(555)$ (SeaWiFS) were contoured after Gaussian smoothing. The estuary contains terrigenous particles and colored dissolved organic matter which may cause an overestimate of Chl. *a*. Nighttime and daytime SST fields were averaged to generate an integrated field. Water transparency was calculated using an indirect inverting semi-analytic algorithm based on the relationship between water transparency and inherent optical properties (He et al., 2004). Salinity was estimated by a salt steric height approach (Yan et al., 2006). $L_{WN}(555)$ has been

shown to be a good quantitative proxy for POC in the open ocean (Mishonov et al., 2003), and is used here as an approximation of POC (see supporting methods for details).

2.2. Measurements of ecological parameters

Samples for picoplankton analysis were taken from surface water along the transect across the continental shelf on September 13–15, 2002 and September 9–14, 2003. Water temperature and salinity were measured with an SBE 9 plus underwater unit with sensors for conductivity, temperature, and pressure (SBE 9/11 plus CTD system, SeaBird Inc., USA). Abundance of total bacteria, *Synechococcus*, *Prochlorococcus*, and pico-sized eukaryotes were determined by flow cytometry (Marie et al., 1997; Jiao et al., 2002) using an Epics Altra II (Beckman Coulter, USA) flow cytometer. Chl. *a* was determined using an Agilent Technologies high-performance liquid chromatography (HPLC, Model 1100) equipped with an auto-sampler and a Hypersil octadecyl silano (ODS) C18 column (5 μ m, 4.0 \times 250 mm) and a diode array detector (DAD). Nutrients were determined according to the protocol from joint global ocean flux study (JGOFS, 1996).

2.3. Phylogenetic analysis by 16S rDNA clone library statistics

Samples were collected from surface water at St. 2 (estuary) and St. 5 (shelf). Prefiltered (through 10 μ m filters, Millipore, USA) water samples (1–3 l) were refiltered onto 0.22 μ m-pore-size filters (Millipore). Triplicate community DNA extracted from the same source were mixed for the construction of 16S rRNA gene clone library using eubacterial universal primer 27F and 1492R as described by Sekiguchi et al. (2002). A total of 300 clones from each clone library were sequenced using primer 27F. The affiliation of each sequence was determined at the phylum or class level by basic local alignment search tool (BLAST) in the National Center for Biotechnology Information (NCBI) (<http://www.ncbi.nlm.nih.gov/BLAST/>) and “sequence match” analysis in the ribosomal database project (RDP) website (<http://rdp.cme.msu.edu/>). Operational taxonomy units (OTUs) were measured by using the distance

level of 2% in the distance-based OTU and richness determination (DOTUR) program (Schloss and Handelsman, 2005). All OTUs were subjected to the construction of neighbor-joining trees using ClustalX version 1.81 (Thompson et al., 1997).

3. Results and discussion

Significant changes in environmental and ecological parameters were observed between September 2002 and 2003.

As can be seen from the images derived from remote-sensing data (Fig. 2a, b) and *in situ* measurements (Fig. 3a, b), in September, the freshwater plume was less extensive while the shoreward intrusion of the warm water was much greater in 2003 than in 2002. Since the long-term annual river discharge pattern showed that both 2002 and 2003 were normal years (Supporting data #1) and that the Kuroshio and the Taiwan Warm Currents were not stronger in 2003 than in 2002 (actually there was a weak El Niño event in 2002) (McPhaden, 2004), the observed greater shoreward intrusion of the warm water could possibly be attributed to compensation for the suddenly reduced outflow from the Yangtze River due to the water retention in the TGD reservoir in June 2003. A time-series observation (2000–2004) of salinity as indicated by salt steric height near the Yangtze River mouth also

showed an increase of salinity during summer 2003 compared with the previous and following years, providing additional evidence for the influence of decreased river discharge (Supporting data #2).

Corresponding to the hydrographic changes, satellite-derived Chl. *a* concentrations were higher in September 2003 than in September 2002 seaward of the Yangtze River estuary (Fig. 2c, d). Since nutrients were almost always replete (Supporting data #3—Table S1), but turbidity was lower in 2003 (Supporting data #4), the increase of Chl. *a* was possibly due to higher light availability resulting from much of the suspended load of sediments being retained by the dam in 2003, not just for the 10-day flow reduction, but also from that time forward since the reservoir acts as a holding pond where sediment can settle out (Fig. 2e, f). In neither year was the concentration of nutrients below the limiting values for primary production. L_{WN} (555) values, a POC proxy, were higher in 2003 than in 2002 (Fig. 2g, h). The observed increases of Chl. *a* and POC in 2003 in the estuarine area might be due to lower discharge caused by the water storage of the TGD reservoir which resulted in higher transparency, given nutrients were still replete in 2003 (Fig. 2e, f).

In situ measurements of the biological variables along a transect across the continental shelf from the Yangtze River mouth to the Kuroshio Current (Fig. 1) in September 2003 and

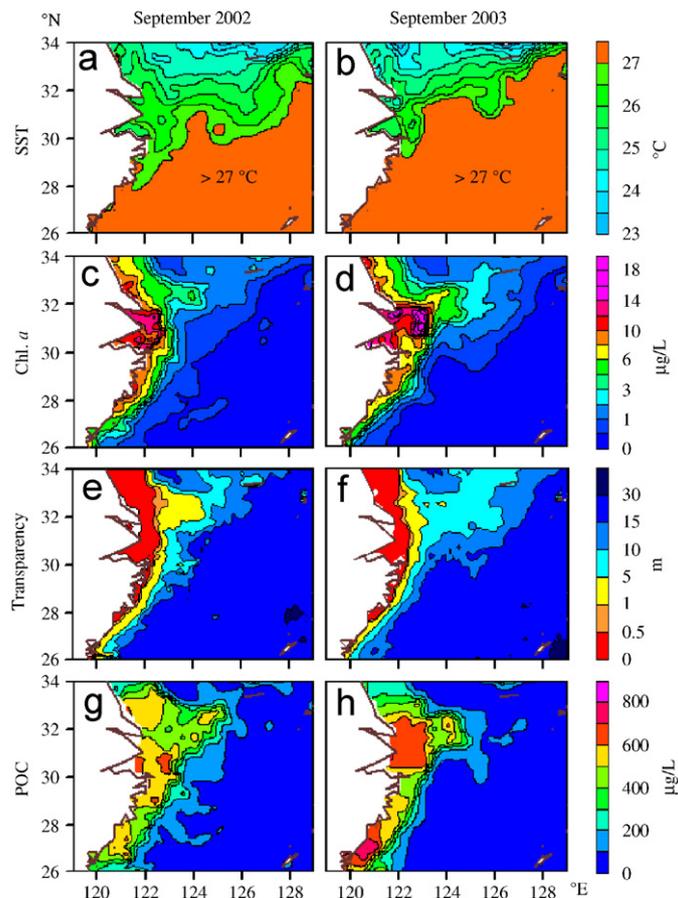


Fig. 2 – Remote-sensing data-derived distribution patterns of SST (a, b), Chl. *a* (c, d), transparency (e, f), and POC (g, h) in the East China Sea (left column: September 2002; right column: September 2003).

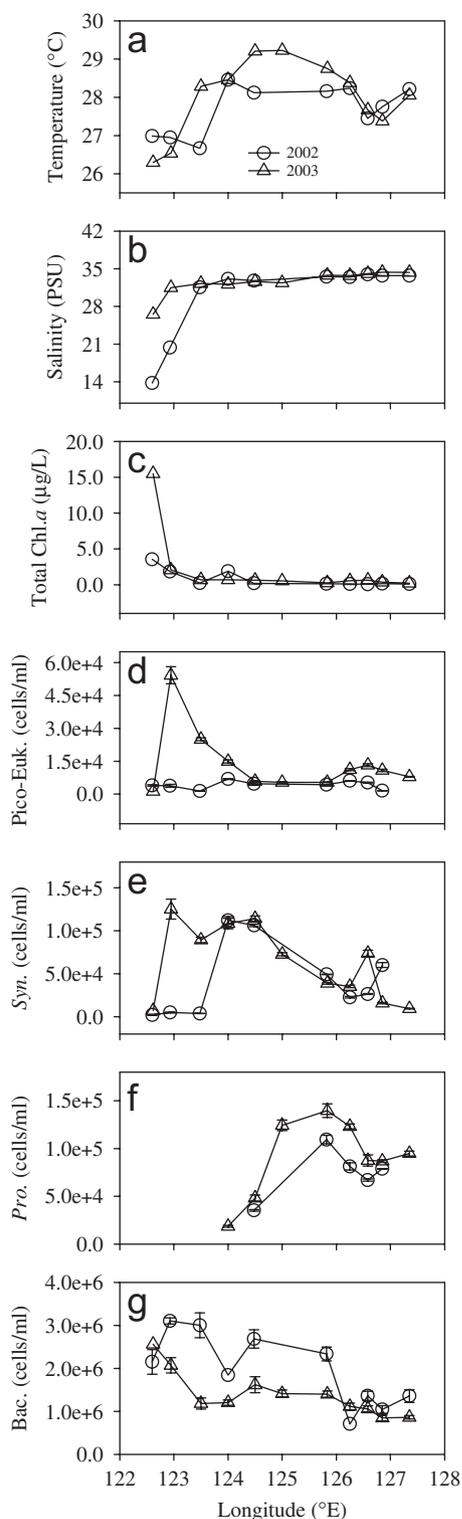


Fig. 3 – Distribution of water temperature (a), salinity (b), total Chl. *a* (c), pico-eukaryotes (d), *Synechococcus* (e), *Prochlorococcus* (f), and total bacteria (g) along a transect from the Yangtze River estuary to the Kuroshio Current (from left to right: St. 1–11, refer to Fig. 1). Circles: September 2002; triangles: September 2003.

2002 also showed evidence of significant changes between these 2 years. At the station close to the river mouth (St. 1), total Chl. *a* increased abruptly from 3.55 µg/L in 2002 to

15.51 µg/L in 2003 (Fig. 3c). Although silicate decreased from 58.92 to 13.40 µM (Supporting data #3), diatoms were still the major component of large phytoplankton. However, the species composition of diatoms changed, presumably due to changes in nutrient structure (Supporting data #3). The dominant diatom species was *Skeletonema costatum* (dominance 70%) in 2002, but were *Chaetoceros* spp. (30%) and *Pseudo-nitzschia* spp. (8%) in 2003. Size-fractionated measurements showed that Chl. *a* in >20 µm fraction increased from 0.71 to 7.64 µg/L, and thus large phytoplankton was responsible for the majority of the huge increase of total Chl. *a* in 2003. In contrast, on the continental shelf (St. 3–11), although the total Chl. *a* did not change much (Fig. 3c), the proportion of the smaller fractions (<20 µm) in the total increased from 50% to 72% in 2003 (Table 1).

More detailed examination of small plankton by flow cytometry showed that big changes occurred in the abundance of pico-sized eukaryotic autotrophic plankton (pico-eukaryotes). Except at the station close to the river mouth where large cells bloomed, pico-eukaryotes increased at all stations, especially in the outer region of the estuary probably due to higher light availability (Fig. 3d). Besides the eukaryotes, the two groups of prokaryotic autotrophs *Synechococcus* and *Prochlorococcus* also showed great changes. The former is ubiquitous in marine environments, contributing a substantial amount of total biomass. The latter is a typical oligotrophic species. It is extremely abundant in oligotrophic warm waters and is very sensitive to changes in environmental conditions (Partensky et al., 1999; Jiao et al., 2005). The key limiting factor for the coastward distribution of *Prochlorococcus* in the ECS was considered to be the movements of the warm water currents, the Kuroshio and the Taiwan Warm Water Currents (Jiao et al., 2002, 2005). *Synechococcus* are relatively more nutrient dependent and light dependent (Olson et al., 1990; Blanchot et al., 1992; Campbell and Vaultot, 1993; Campbell et al., 1997; Michele et al., 2001). Along the transect from the estuary to the Kuroshio Current, the abundance of *Synechococcus* was very low at the river mouth (7.2×10^3 cells/ml), and reached a maximum (1.3×10^5 cells/ml) in the outer region of the estuary where light availability become high and nutrient availability is still enough. The maximum abundance of *Synechococcus* extended about 130 km further towards the inner estuary in 2003 (Fig. 3e). Although *Prochlorococcus* were absent in the estuary, they were present further inshore with much higher abundance in 2003 than in 2002 throughout the transect in correspondence with the higher water temperature (Partensky et al., 1999; Jiao et al., 2002, 2005). The relatively lower abundance near the slope area, corresponding to relatively lower temperature, was most likely caused by shelf-break upwelling (Wong et al., 2004). Different from the autotrophic picoplankton, the distribution patterns of total bacteria showed a remarkable decrease across the continental shelf in 2003 (Fig. 3g, except for the station in the river mouth where the abundance of total bacteria increased, corresponding most likely to the bloom of large phytoplankton). The overall decrease of heterotrophic bacteria in 2003 was likely related to less terrestrial organic carbon being transported to the shelf from the river due to water storage by the dam.

Examination of microbial diversity using 16S rDNA analysis showed further details in the changes at the microbial community structure level. The overall diversity was lower in 2003 than in 2002 (Fig. 4). In the estuary, the occurrence frequency of clones affiliated to β -proteobacteria, which is a typical freshwater class (Zwart et al., 2002) and rarely found in marine environments (Nold and Zwart, 1998), declined substantially corresponding to the reduction of freshwater input. That of *Cytophaga-Flavobacterium-Bacteroides* (CFB) group also decreased somewhat. Some minor groups were even not detected. In contrast, the diversity of α -proteobacteria and cyanobacteria increased (Fig. 4 left). On the continental shelf, along with the freshwater decrease and further intrusion of high salinity water in 2003, β -proteobac-

teria fell out of detection, and the portion of cyanobacteria increased (Fig. 4 right).

As demonstrated by the above ecological and molecular evidence, changes at the base level of the ECS ecosystem between these 2 years were substantial. Although the causes for these observed changes could be multiple and complex, disturbance beyond the natural range of interannual variability like the TGD activity should no doubt be taken into consideration of the possible causes. And the sudden 27% decrease in river outflow and the accompanying warm water intrusion appears to be a likely cause, as also noted by Gong et al. (2006).

Since the 2003 water storage of the TGD reservoir was only about one-third of the designed total storage capacity, such changes will likely occur with further TGD water storage,

Table 1 – Changes in total and size-fractionated Chl. *a* concentrations in the estuary and shelf waters of the ECS between 2002 and 2003

	Total Chl. <i>a</i> ($\mu\text{g/L}$)		$>20\mu\text{m}$ Chl. <i>a</i> ($\mu\text{g/L}$)		$<20\mu\text{m}$ Chl. <i>a</i> ($\mu\text{g/L}$)		$>20\mu\text{m}$ Chl. <i>a</i> (%)		$<20\mu\text{m}$ Chl. <i>a</i> (%)	
	2002	2003	2002	2003	2002	2003	2002	2003	2002	2003
Estuary (St. 1 and 2) mean \pm SD	2.69 \pm 1.21	8.79 \pm 6.72	0.71 \pm 0.61	7.64 \pm 7.13	1.99 \pm 0.34	1.15 \pm 0.57	26	87	74	13
Shelf (St. 3–11) mean \pm SD	0.37 \pm 0.22	0.51 \pm 0.18	0.19 \pm 0.15	0.14 \pm 0.06	0.18 \pm 0.07	0.37 \pm 0.19	50	28	50	72

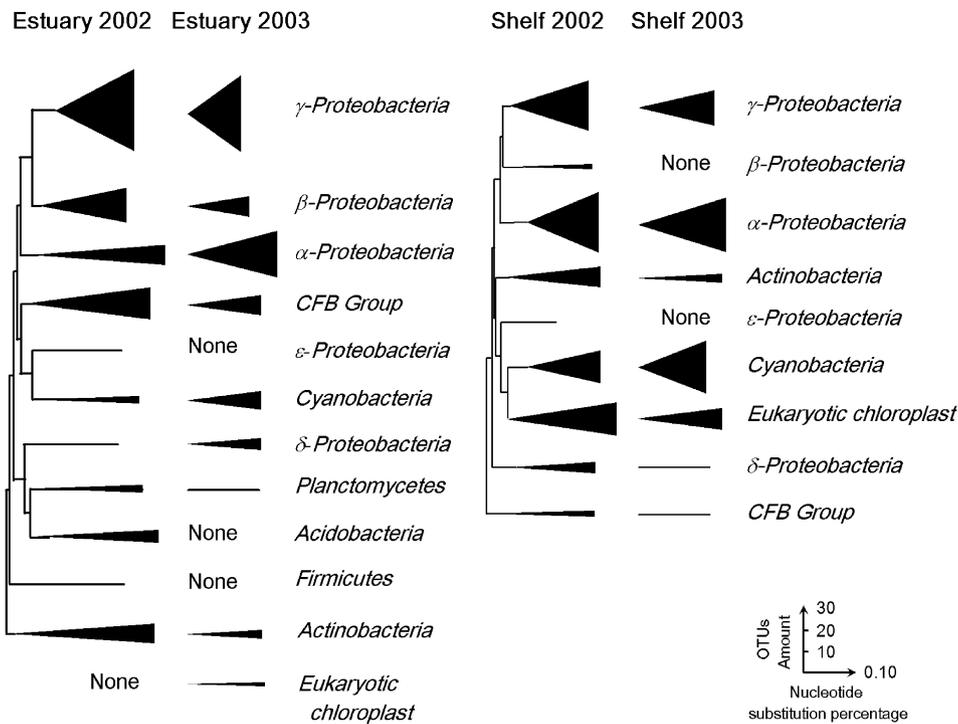


Fig. 4 – Changes in microbial community structure in the estuary and shelf of the ECS between 2002 and 2003. The phylogenetic trees were constructed using the neighbor-joining algorithm. Evolutionary distances for the 16S rDNA sequences were determined from an alignment of > 1000 nucleotide positions. Scale bars represent the nucleotide substitution percentage and amount of operational taxonomy units (OTUs).

depending on when and how drastically the flow is reduced. Compared with such episodic events as these short-term flow reductions, a significant permanent reduction of the river outflow could be more influential to the coastal ecosystem. There is an underway massive water conservancy project, China's South-to-North water diversion project, which will remove water (about 48 billion tons) seasonally from the Yangtze River to Northern China to mitigate floods in the South and droughts in the North by the year 2050 (Xu, 2003). More environmental and ecological data need to be collected in field studies along with simultaneous collection of remote-sensing parameters before and after major alterations to river flow to better assess, through measurements and modeling, the impact on coastal and ECS waters.

Although the sharp decrease of the river outflow was followed by an increase of Chl. *a* in the vicinity of the river mouth probably due to enhanced transparency, in the long run, less river discharge would cause less nutrient input to the estuary, less offshore transport of diluted Yangtze River water, and less cross-shelf water exchange. Meanwhile the Taiwan Warm Current and Kuroshio warm waters (relatively oligotrophic) might intrude further inshore on the shelf, ultimately causing reduction in primary production, and even changes in food web structure and function of the ecosystem (Xian et al., 2005).

4. Conclusions

Abrupt changes in river discharge by manipulation beyond natural cycles appear to trigger significant ecological responses in coastal waters. Therefore, future manipulation of natural systems should be very carefully considered and monitored.

Not only river discharge but also the ensuing intrusion of ocean currents should be taken into consideration. It appears that interactions between river outflow and ocean currents determined the ecological consequences in the ECS. Picoplankton and microbial diversity are good indicators for the consequent changes.

Further studies and monitoring are needed of potential long-term shifts of the coastal ecosystem that might be caused by human activities such as the future massive South-to-North water diversion of the Yangtze River.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.watres.2006.11.053.

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