Physical-biological sources for dense algal blooms near the Changjiang River

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[1] Harmful algal blooms ("red tides") occur primarily in a confined region on the inner shelf off the Changjiang River in the East China Sea during May–August. The areal extent of these blooms has increased dramatically in the last decade, and is thought to be associated with the rapid increase in nutrient supply via the Changjiang River. An interdisciplinary survey conducted in August 2000 identified three areas of high chlorophyll-*a* concentration in this region: the near-surface Changjiang River plume with high dissolved oxygen and pH, the thermocline above Taiwan Warm Current (TWC) water, and near the bottom north of the Zhoushan Island complex, an area of strong sediment deposition from the Changjiang River with low dissolved oxygen and pH. These results imply that the formation of phytoplankton blooms is controlled by a complex interplay of physical, geological, biological, and chemical processes associated with the Changjiang River discharge, sediment deposition, and TWC intrusions. The predicted increase in nutrient loading in the Changjiang River due to further economic development of Shanghai and reduction in sediment discharge due to the Three Gorges dam suggest that this part of the East China Sea could become an ecosystem disaster, with possible downstream contamination of Korea and Japan, unless the nutrient loading from Shanghai and surrounding cities and aquaculture activities along the coast are reduced. *INDEX TERMS:* 4815 Oceanography: Biological and Chemical: Ecosystems, structure and dynamics; 4845 Oceanography: Biological and Chemical: Nutrients and nutrient cycling; 4546 Oceanography: Physical: Nearshore processes; 4568 Oceanography: Physical: Turbulence, diffusion, and mixing processes; 4235 Oceanography: General: Estuarine processes. **Citation:** Chen, C., J. Zhu, R. C. Beardsley, and P. J. S. Franks, Physical-biological sources for dense algal blooms near the Changjiang River, *Geophys. Res. Lett.*, *30*(10), 1515, doi:10.1029/2002GL016391, 2003.

1. Introduction

[2] Phytoplankton blooms can color the water when concentrations reach >20 μg chl/l, forming a harmful algal bloom (HAB) (or "red tide"). Even when these HABs are formed by species that are not toxic, they can be harmful if their dissipation and senescence depletes the oxygen in the water, leading to massive mortality of fish and other important species. HABs frequently occur in a region bounded by 29°–32.5°N and 122°–123°20′E (with 70% of the blooms located in an area of 30°30′–32°N and 122°15′–123°15′E) over the western inner shelf of the East China Sea (Figure 1). During April through November 1986–98, 102 HAB events were reported by surface-monitoring, with the highest frequency in May through August [*EICE*, 2000]. On average, HABs were observed on 60 days each year, with each event lasting 2–4 visible days. The longest event occurred on June 30 through July 14, 1989, a period of 15 days. The spatial extent of these blooms has increased over the last decade: the average size of a bloom was <=2000 km^2 in 1987–88, up to 7000 km^2 in 1990, and >7000 km^2 in 2000 [*TGDPWG*, 1987]. The dominant algal species has recently shifted from the diatom (*Skeletonema costatum*) to the dinoflagellates (*Prorocentrum dentatum*, *Noctiluca scintillans*, and *Alexandrium spp.*). *Alexandrium tamarense* is toxic, and is a major source of paralytic shellfish poisoning. Recent studies have reported that bacteria contained in *Noctiluca scintillans* may produce toxins or change the toxic level of the algae in the China Sea [*Kirchner et al.*, 2000]. Most of the HAB species are nontoxic, however, blooms of these algae result in massive mortality of many wild and farmed fishes, shrimps, and shellfishes though oxygen depletion.

[3] Eutrophication has been thought to be a leading cause of HABs around the western inner shelf of the East China Sea. Nutrient loading from the Changjiang River has increased dramatically in the last decade with rapid economic development in Shanghai and other adjacent coastal cities. Annual averaged concentrations of dissolved inorganic nitrogen (DIN) in the Changjiang River jumped from about 9 μmol N/l in 1986 to 56 μmol N/l in 1992 and was greater than 106 μmol N/l in 1997. During this same period, dissolved inorganic phosphorus (DIP) increased from 0.58 μmol N/l in 1986 to 0.65 μmol N/l in 1992, to greater than 0.91 μmol N/l in 1997 [*EICE*, 2000; *TGDPWG*, 1987]. The ratio of DIN to DIP jumped from 16 in 1986 to 117 in 1997, with a maximum exceeding 450, 7–28 times larger than the Redfield ratio. Similar trends were also found in silicate, dissolved iron, and dissolved organic nitrogen and phosphorus. This rapid rise in nutrient supply to the inner shelf off the Changjiang River is due to increased sewage collection and export from Shanghai, overuse of agriculture fertilizers around the coast, and uncontrolled aquaculture activities around island complexes off the coast [*EICE*, 2000]. Although the concentration of DIP is still less than 1% of that of DIN, it is much higher than the level at which the growth of phytoplankton is limited. As a result, the inner shelf off the Changjiang River has become a highly eutrophic area in which nutrients are not longer factors limiting the growth of phytoplankton.

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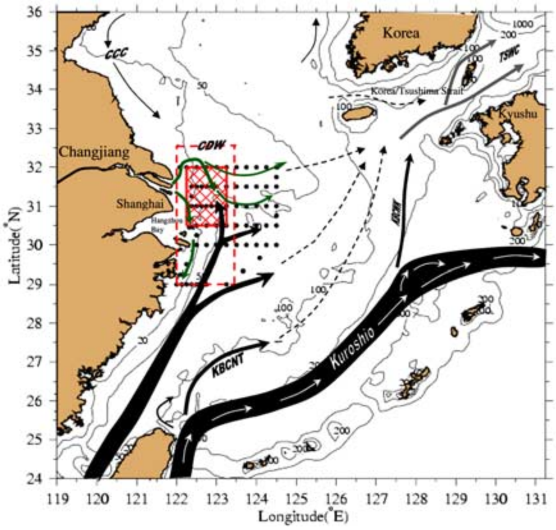

Figure 1. Schematic of the summer surface circulation in the East China Sea. TWC: the Taiwan Warm Current; CDW: Changjiang Diluted Water; KBCNT: Kuroshio branch current north of Taiwan; KBCWK: Kuroshio branch current west of Kyushu; TSWC: Tsushima Strait Warm Current, and CCC: China Coastal Current. Heavy green arrows show the general direction of CDW flow during the summer high discharge period. The heavy-solid red box: the primary red tide formation area containing 70% of the HAB events; the larger heavy-dashed line box: the area containing all the HAB events reported in the last 15 years. Islands off Hangzhou Bay are part of the Zhousan Island complex. Dashed line arrows: the possible water sources flowing into the Tsushima Strait. This figure is a modified version of Figure 10 in *Ichikawa and Beardsley* [2002]. The 50-, 100-, 200-, and 1000-m isobaths are shown.

[4] The East China Sea is a typical subtropical ocean. With sufficient light intensity, HABs could occur at any time and location that had an adequate nutrient supply. The fact that HABs occur primarily in the region off Shanghai shown in Figure 1 implies that there must be some specific processes that lead to enhanced phytoplankton growth in that region. To investigate these processes, we conducted an interdisciplinary field survey in the Changjiang River and western inner shelf of the East China Sea in August 3–22, 2000 (Figure 1). Water column measurements of temperature, salinity, suspended sediment concentration, chlorophyll-*a* (Chl-a), dissolved oxygen (DO), and pH were made with a Seabird CTD and Multi-Parameter Environmental Monitoring System-YSI6600 along east-west transects through the study area, with closer station spacing in the primary HAB formation (HAB) region. This was the first well-organized, comprehensive interdisciplinary survey in China designed to identify the physical and biological processes that lead to enhanced algal blooms in this critical HAB region.

2. Distributions of Water Properties and Chlorophyll-*a* Concentration

[5] Distributions of temperature and salinity clearly show that water in the study area have two primary sources: the Changjiang Diluted Water (CDW) (temperature of >22°C and salinity of <29 psu) and the Taiwan Warm Current (TWC) (temperature between 16°C and 29.5°C and salinity of >29 psu) (Figure 2) [*Beardsley et al.*, 1985; *Chen et al.*, 1994]. The Changjiang River discharge in August 2000 was 39,000 m^3/s, about 10% lower than the 40-year mean August value of 43,000 m^3/s. As usual, the CDW splits into two branches upon entering the shelf: one flowed northeastward first and then rotated clockwise east of 122.5°E and the other flowed southeastward along the coast. CDW carried suspended fine sands with sizes of about 0.025–0.035 mm. Most of the fine sands were deposited west of 122.5°E (Figures 3–5: thin red lines), indicating that the northeastward branch of CDW was characterized by clearer water with high nutrients, while the southwestward branch of CDW was generally highly turbid water. The TWC intruded into the study area along the 50-m isobath. This saline and warm water met with CDW just off the mouth of the Changjiang River, forming temperature and salinity fronts around 122.5°E.

[6] Corresponding to the distinct water masses, three distinct patterns of high chlorophyll-*a* concentration were found in the HAB area: (a) near the surface in the north (east of 122.5°E) in relatively clear CDW (Figures 2 and 3); (b) in the thermocline associated with the TWC (Figures 2 and 4); and (c) near the bottom north of the Zhoushan Island complex (Figure 5). The northern high Chl-a zone was the largest, concentrated in the upper 10 m, with high DO and pH. Based on these characteristics, it is quite likely that this bloom was caused by rapid in situ growth of phytoplankton with sufficient light and high nutrients. It is blooms in the HAB region that are commonly referred to when addressing eutrophication in this area.

[7] The other two areas of high Chl-a have not been recognized in previous studies. The northward intrusion of TWC along the 50-m isobath is a permanent feature of the East China Sea circulation in summer, which forms due to meanders of the Kuroshio either south or north of Taiwan [*Ichikawa and Beardsley*, 2002]. It is clear from the Chl-a-*T*-*S* correlation in Figure 2, the *T* and Chl-a contours in Figure

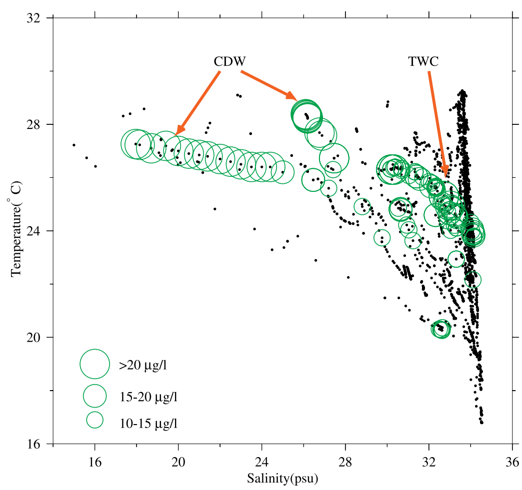

Figure 2. Chlorophyll-*a* vs temperature-salinity diagram. Each dot indicates a measurement point. Green circles are all Chl-a concentration values greater than 10 μg/l with a scale shown on the left-lower corner. This plot includes all CTD profiles taken during the cruise.

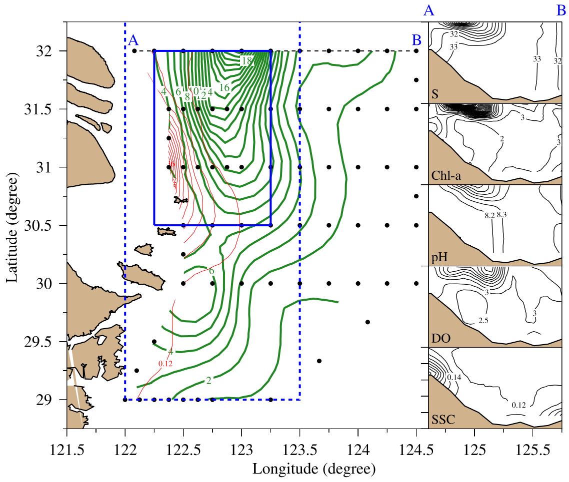

Figure 3. Distribution of Chl-a (heavy green lines) and suspended sediment concentrations (SSC) (thin red lines) at a depth of 3 m below the surface. The plots on the right side are vertical sections of salinity (PSU), Chl-a (μg/l), pH, DO (mg/l), and SSC (kg/m^3) along the northernmost transect labeled A–B. Depth is indicated by 10-m tick marks.

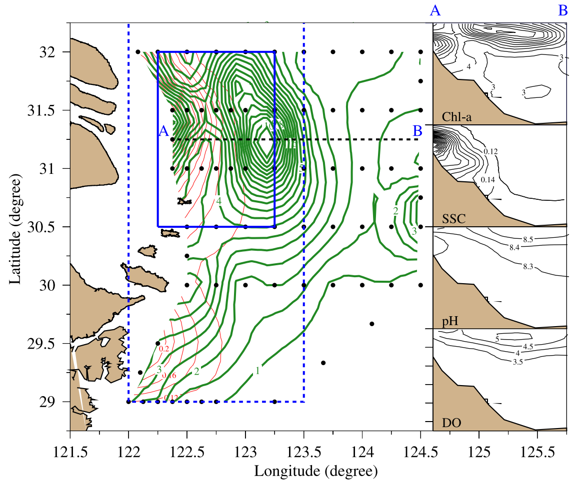

Figure 5. Distribution of Chl-a (solid green lines) and SSC (solid red lines) at a depth of 10 m below the surface. The plots on the right side are vertical sections of Chl-a, SSC, pH and DO on the transect labeled A-B. Mean values of observed data on sections 2 and 3 (counted from the north) are used for this plot. A linear interpolation method with a search radius of 5 points is adopted in drawing this figure.

4, and lack of high DO and pH that the subsurface core of high Chl-a observed in the southern HAB area is a result of northward advection by the TWC.

[8] The high Chl-a zone observed near the bottom in the southeast of the study area is thought to be real (as opposed to an instrument artifact) for two reasons: the first is the inherent accuracy of the YSI 6600 Chl-a probe in turbid water, and the second is based on results from recent mesocosm experiments. The YSI6600 Chl-a probe uses optical fluorescence with mechanical cleaning to determine the Chl-a concentration in the water column. This probe has been well tested and calibrated in turbid coastal waters, and exhibits little influence of turbidity on the accuracy of the measured Chl-a concentration. Mesocosm experiments were conducted by *Qiao et al.* [2000] in a vertically well mixed, high turbid area at 122°36.67′E, 30°50.46′N during October 10–17, 1997, the same area where we found high near-bottom Chl-a. Their results show that even in water with a euphotic depth as shallow as 0.25 m due to heavy suspended sediment, flagellates could photosynthesize and grow as a result of their upward swimming during the day. Field measurement samples indicate that dominant bloom species in the western inner shelf of the East China Sea have shifted from diatoms to flagellates over the last 10 years [*Qiao et al.*, 2000]. The measurement data are consistent with a suppression of diatom growth through turbidity caused by sediments from the CDW. This evidence also supports our argument that the bottom could be a third source of nutrients to fuel HAB's formation. The Changjiang River is characterized by strong semi-diurnal tidal currents with amplitudes of about 50 cm/s. Sediment re-suspension is energetic in the deposition area as a result of near-bottom current fluctuation driven by winds, surface waves, and large tides. If the above argument is true, then re-suspended sediment, which is generally believed to be a key factor restricting the growth of phytoplankton around the mouth of the Changjiang River, can become a cause of the phytoplankton bloom.

[9] No peaks of DO and pH were found in the patch of the high Chl-a in the area of heavy sediment deposition. One potential explanation is that the deposited sediment contained high organic matter which consumed DO as it was respired. Previous chemical measurements undertaken in the Changjiang River show that total organic carbon in the highest discharge month in 1986 was 3.71 mg/l, but exceeded 7.23 mg/l six years later [*EICE*, 2000]. A similar rapid increase was also reported for total organic nitrogen, etc.

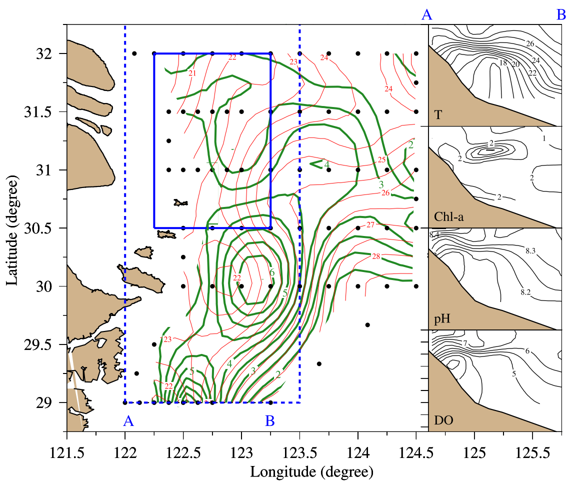

Figure 4. Distribution of Chl-a (solid green line) and temperature (solid red line) at a depth of 20 m below the surface. The plots on the right side are vertical sections of temperature (°C), Chl-a, pH, and DO on the southernmost transect labeled A–B.

3. Discussion and Conclusion

[10] Our analysis of the field data from the bloom area of the East China Sea suggests three new findings. First, the

three distinct sources for phytoplankton blooms implies that these blooms are controlled by a complex interplay of physical, biological, geological, and chemical processes. The near-surface high Chl-a zone, due to photosynthesis in the high-nutrient clear CDW, should be easily detected and tracked by aircraft and satellite remote sensing techniques. The thermocline and near-bottom high Chl-a zones are invisible to satellite remote sensing. Such blooms could exist in the water column for weeks or months and appear as "sudden" events without early warning. Second, the inference of a bloom having been advected northward by the TWC suggests a remote source for HABs in the bloom area, so that the Changjiang River discharge is not the only source as previously suspected. Since the Taiwan Strait has become a common area of HAB occurrence, bacteria and viruses associated with the phytoplankton could be transported northward to influence the ecosystem of the inner shelf off the Changjiang River's mouth. Third, we infer from the bloom location that the suspended sediment from the Chiangjiang River has become a new bloom source near the bottom. The ability of flagellates to migrate vertically, combined with increased nutrient loading and turbidity, has led to a shift from a diatom to a flagellate-dominated phytoplankton community.

[11] The Changjiang Three Gorges Project (TGP) is the largest hydroelectric project in the world, designed to generate power and improve flood control and navigation [*TGDPWG*, 1987]. It has, however, been criticized for its potential influence on the marine ecosystem in the East China Sea. Studies in the Black Sea report that a reduction of dissolved silicate due to diatom growth behind new dams in the Danube River has caused a dramatic shift in phytoplankton species composition from diatoms to flagellates downstream of the dams [*Humborg et al.*, 1997]. The concentration of the sands and muds in the river discharge to the ocean would be significantly reduced after the TGP power station begins operation [*TGDPWG*, 1987]. While improving navigation by decreasing the deposition of suspended sediment around the mouth of the Changjiang River, it would also provide a deeper euphotic zone for the growth of phytoplankton over the shallow shelf connected to the Changjiang River. Power generation will regulate the river discharge, with a reduction in October but increase in January through April [*TGDPWG*, 1987]. Since nutrients are no longer factors limiting the growth of phytoplankton, under improved light conditions HABs would become more frequent and intense around the mouth of the Changjiang River and on the inner shelf of the western East China Sea, possibly extending upstream into the Changjiang River. Blooms might even occur in winter and cover a much larger area than they presently do. With continued nutrient loading from Shanghai and other surrounding cities, and continued aquaculture activities around the Zhoushan island complex, the planktonic community of the western East China Sea could become permanently altered after the TGP power generation station begins operation.

[12] Many observations have demonstrated that CDW can be carried into the surface Kuroshio and even reach the Korea/Tsushima Strait and enter the Japan/East Sea [*Beardsley et al.*, 1985, 1992; *Chen et al.*, 1994]. In mean summer conditions, it would take about one month for CDW to reach either the Korea/Tsushima Strait or Kuroshio. If a HAB that began in the red tidal formation region lasted 3 to 4 weeks, the harmful algae could be transported to the Japanese or Korean coast by either the Kuroshio or via the Korea/Tsushima Strait. If this were to happen, then a local environmental problem caused by China could affect the ecosystem health downstream in the area of Korea and Japan. Such environmental impacts could affect the economic and societal wellbeing in these areas, and could exacerbate conflicts among countries of the coastal western Pacific Ocean if nothing is done to alleviate the situation.

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