Emerging challenges: Massive green algae blooms in the Yellow Sea

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The massive green algae (*Enteromorpha prolifera*) bloom in a coastal area of Qingdao between May and July 2008 prior to the sailing competition of the 29th Olympic Games has raised great concerns in local and regional communities and governmental agencies on environmental deterioration, causes and mitigation of such massive algal blooms. Results from field and laboratory studies during the bloom and post-bloom periods revealed that the bloom was originated from an offshore area 150 km south of Qingdao, and caused by complex coupled land-ocean and natural-human processes associated with increases in nutrient and organic matter loadings to the coastal ocean due to rapid expansions of agriculture, aquaculture and urbanization, behavior of algae, seasonal wind and coastal currents, and transport of nutrients and biota. This environmental disaster has brought us emerging challenges on how to integrate monitoring, analysis and prediction of complex coupled natural and human processes, environmental regulations, and management in land-ocean uses for the sustainable socioeconomic development in China.

The massive green algae bloom in the coastal region of Qingdao China between May and July 2008 brought the world attention because the algae bloom covered an area of approximately 13,000-30,000 km^2 including the sailing venue for the 29th Olympic Games (Fig. 1). To avoid any anoxia and harmful algal blooms due to potential decomposition of organic matters during the post algal bloom period, a heroic effort was made to remove the green algae by more than 16,000 people using more than 1,000 transportation vehicles and 1,600 fishing and transportation vessels. Approximate 1 million fresh weight (FW) tons of algae were removed from beaches and nearby coastal waters while an estimate of another 2 million FW tons settled into deep waters.

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A green algae bloom at a much smaller scale occurred for the first time in July-August 2007 around the coastal region of Qingdao. The reoccurrence of the green algae bloom in May-July 2008 within the same region has raised great concerns on coastal environmental change associated with human impacts and climate change, and serious questions about where these green algae came from and where the nutrients came from to support these algal blooms. A number of rapid-responding studies including remote sensing, shipboard surveys, field collections and laboratory experiments were conducted during the bloom and post-bloom periods in both 2007 and 2008 by Chinese marine scientists.

The green algae species blooming in both 2007 and 2008 has been identified as *Enteromorpha prolifera (Müller) J. Agardh (other name, Ulva prolifera O.F. Müller)* from both morphological and genetic studies of samples collected by scientists at the Institute of Oceanology Chinese Academy of Sciences (IOCAS) (Figure 2)[1], and is in the same genus as *Ulva procera and Ulva linza*[2]. *E. prolifera* is a benthic species and widely distributed in intertidal zones of most global oceans. It is often harvested as edible seaweed in China, Japan, Korea and Southeast Asian countries. A 2007 *E. prolifera* habitat survey with a grid resolution of approximately 15 km covering most the western Yellow Sea and northern East China Sea by the scientists from IOCAS did not find any *E. prolifera* habitat in offshore areas.

The results from the Terra-Moderate Resolution Imaging Spectroradiometer (MODIS) analysis have revealed the development and trajectory of the *Enteromorpha prolifera* bloom between May and July 2008 in the southwestern Yellow Sea (Figure 3). *E. prolifera* patches were first seen in a shelf area 100 km off the northern Jiangsu coast 150 km south of Qingdao on May 15, 2008. The number and sizes of *E. prolifera* patches increased and expanded as they moved northward. The patches covering an area of approximately 13,000 km^2 reached Qingdao around June 11, 2008. The history of this green algae bloom suggests the existence of a northward current transporting those green algae patches northward, which was also indicated by many bamboo poles found within drifting *E. prolifera* patches near Qingdao. Such bamboo poles are widely used in Porphyra farming facilities in northern Jiangsu intertidal zones which provide the informative evidence for the origin of *E. prolifera*.

The previous oceanographic studies have indicated a southward Yellow Sea Coastal Current (YSCC) in the spring season along the shelf region of Shangdong and Jiangsu Provinces which is driven by both freshwater runoff and the basin-scale cyclonic circulation[3]. Some numerical modeling studies argued that in spring and summer months, a weak mean northward coastal current driven by predominated southerly wind exits[4-5]. The northward surface coastal current was observed at a mooring (35°N and 121°E) deployed by IOCAS. To further investigate the physical and biogeochemical processes, a field study onboard the RV Science III was conducted by the IOCAS in the *E. prolifera* bloom area between July 21 and 31, 2008.

The measured sea surface temperature distribution shows that the offshore surface waters were warmer approximately 25.5°C due to spring-summer solar heating, and the offshore deep waters were cooler varying from 18°C at thermocline to 8°C in the deep Yellow Sea Cold Water (YSCW) due to thermal isolation (Fig. 4). The warmest surface water was found approximately 26.5°C near the northern Jiangsu coast associated with freshwater runoff and shallow water column. A cold water tongue extended from 21°C at 32°N northward to 24°C at 34°30'N off the northern Jiangsu coast, and another cold water of 22°C occurred off the Qingdao coast, both of which were a clear indication of coastal upwelling consistent with the predominant southerly wind observed at the Qingdao Olympic sailing site in May-July (Fig. 5). These temperature and wind data suggest: a southerly wind drives an eastward Ekman transport and in turn produces coastal upwelling of the deep cold water; as the coastal water is driven offshore, the sea surface level along the coast is reduced which leads to a downhill sea surface slope higher offshore and lower at the coast; and then this surface slope and the earth rotation produce an along-coast barotropic geostrophic current in the right-hand direction perpendicular to the downhill slope, which in our case was northward.

The macronutrients provide the linkage between the runoff in the northern Jiangsu coast and the *Enteromorpha prolifera* bloom area (Fig. 4). Microbes decompose organic matter producing ammonia, which is quickly oxidized to nitrite and nitrate. Nitrite concentration in ocean is typically low because of the easy oxidation from nitrite to nitrate. In coastal runoff and aquaculture areas, the nitrite level can be highly elevated due to heavy use of fertilizers, high organic matter content and microbial activities. Therefore, nitrite concentration becomes a tracer of the coastal water affected by runoff and aquaculture. The highest nitrite concentration of greater than 1.1 μmol L^{-1} was found off the coast of Sheyang, northern Jiangsu Province within the warmest coastal water while the lowest nitrite concentrations of less than 0.1 μmol L^{-1} in the surface waters were found off Qingdao coast and in offshelf regions. The northern extension of this nitrite plume co-occurred with the *E. prolifera* bloom origin found on May 15, 2008. The high nitrite concentration off Sheyang directly indicates the anthropogenic source of nutrients.

The Huai River watershed of 174,000 km^2 in northern Jiangsu and Anhui Provinces has experienced significant agriculture, aquaculture and urban-industrial expansions in the last 2 decades. In northern Jiangsu regions, the urban area has been expanded at an annual rate over 7%[6]. The aquaculture area in Jiangsu Province has been increased from 302,000 ha in 2001 to 813,000 ha in 2006 at an annual rate of 17%[7]. In the last decade the aquaculture has been moved from inland ponds to coastal zones. Up to 2005, the saltwater aquaculture area in intertidal zones had reached approximately 160,000 ha in northern Jiangsu Province, approximately 10% of China's total saltwater aquaculture area[7]. The estimated annual total nitrogen loading into northern Jiangsu coastal areas was approximately 15,000 ton in 2001-2003 including agriculture fertilizers, aquaculture waters and human-industrial waste water discharges[6]. We expect a significant increase in nutrient loading during recent years due to the continuous expansion of aquaculture in the coastal zone. Especially in June 2008, the eastern Huai River watershed received 15-30 cm of rain, 2-3 times more than the normal based on data from Jiangsu Provincial Meteorological Bureau (JPMB). Stormwater runoff from flooded agriculture lands and sewer-industrial waste water ponds led to increases in both nutrient and organic matter loadings into the coastal regions and inland lakes. The nitrite plume observed during our cruise is a clear evidence of these anthropogenic nutrient and organic matter loadings into the coastal waters which fueled the green algae blooms.

Enteromorpha prolifera growth in the intertidal zone off northern Jiangsu Province is usually light limited because the light attenuates below the minimum light level of 9 μmol m^{-2} s^{-1} for *E. prolifera* to grow within a meter in coastal highly turbid waters[8]. During the *E. prolifera* reproduction cycle, reproduction cells are released into water column, which usually drift and form new colonies[9]. The reproduction has been enhanced during the Porphyra harvest season in March-May by discarding live debris of co-growing *E. prolifera* directly into coastal waters off northern Jiangsu Province, which were further transported offshore with nutrient-rich coastal waters by wind-driven Ekman transport. The offshore waters are much less turbid, and the compensation depth can easily reach 10-20 m[8].

The results from our incubation experiments indicate that under the optimal temperature, salinity and light of 25°C, 24 and 72 μmol $m^{-2}s^{-1}$, respectively, *E. prolifera* can grow at a rate between 0.1 and 0.35 day^{-1}. These conditions were found in the initial *E. prolifera* bloom area (Figs. 3 and 4). In 45 days between May 15 2008 when the *E. prolifera* bloom was first sighted and July 1 when the *E. prolifera* bloom arrived at Qingdao, the bloom increased 90-300 times at this growth rate range. As *E. prolifera* grew at the optimal condition, the oxygen produced due to photosynthesis would fill the inner tubes of *E. prolifera* to keep them buoyant, preventing them from sinking out of euphotic zone. *E. prolifera* usually aggregates by attaching to the bottom in intertidal zones forming colonies. Unusually, during both the 2007 and 2008 blooms, *E. prolifera* formed floating colonies by tangling each other.

These evidences have suggested that the *Enteromorpha prolifera* bloom in the coastal area near Qingdao was caused by a series of complex coupled physical-biogeochemical-biological processes: the high nutrient and organic matter loadings into the northern Jiangsu coastal area were associated with rapid expansions of agriculture, aquaculture and urbanization; large amount of *E. prolifera* live debris were discarded into coastal waters during porphyra harvesting; the predominant southerly wind in May-July produced an offshore Ekman transport which also setup a sea surface slope inducing a northward coastal current; these nutrients, organic matters and *E. prolifera* were transported offshore by the surface Ekman currents and then northward by the coastal current; and as the light field was improved, *E. prolifera* reached its optimal growth, formed floating aggregates as colonies, and bloomed. These processes would potentially repeat every year in northern Jiangsu Province if we do not reduce the nutrient and organic matter loadings into the coastal zone.

This *Enteromorpha prolifera* bloom is similar to the harmful algal blooms (HAB) in the Gulf of Maine and hypoxia zone in the Gulf of Mexico[10-12]. The common feature of these disaster events in coastal areas is the coupling between land and ocean and transport-retention of nutrients and biota by coastal currents. The costs of these events were high. In 2005, the *Alexandrium* bloom in Massachusetts Bay cost the shellfish industry 100 millions of US dollars. Though the total cost of the 2008 *E. prolifera* bloom in Qingdao is still unknown, the cost of cleanup efforts reached billions of Chinese Yuans.

The pressing environmental challenges have been emerging in China as the aquaculture, industries and urbanization have been growing at fast speeds. The 2007-2008 *E. prolifera* blooms in the coastal regions of Qingdao provide an excellent example of the coupled human and natural processes that led to an environmental disaster. The magnitude and complexity of the blooms far exceeded the capability and capacity of any individual local or regional monitoring and management offices to understand and to manage. During the event, an ad hoc management team was formed by scientists from different disciplines and managers from regional and city offices which provided invaluable capability and capacity for identifying algal species, natural and human causes leading to the blooms, potential consequences during blooms and post blooms and methods to mitigate blooms. The study of *E. prolifera* blooms needs to go broader and deeper from understanding individual natural and human processes to integrative solution of environmental protection, land-ocean uses and sustainable socioeconomic development. This study suggests that there is an urgent need of integrated environmental and socioeconomic services to provide optimal solutions to communities, industries and management offices for environmental protection, land-ocean uses and management.

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Figure captions

Fig. 1. *Enteromorpha prolifera* bloom in the coastal area of Qingdao in June 2008.

Fig. 2. Morphology of green algae (*Enteromorpha prolifera*) from samples obtained during the bloom in June 2008.

Fig. 3. Bathymetry of the Yellow Sea and Jiangshu–Shandoing coastal area. The black lines indicate the coasts, and blue lines are depth contours in m. Inserted boxes indicate the green algae (*Enteromorpha prolifera*) bloom areas on May 15 (blue box), May 20 (green box), May 30 (yellow box), and June 20 (red box). The inserted image is the remote sensing data from MODIS – Terra product on May 30 2008, and the green color is enhanced to highlight the green algae bloom in the yellow box.

Fig. 4. Temperature in °C (left panel) and nitrite in μmol L^{-1} (right panel) at 5 m observed between July 21 and 31, 2008.

Fig. 5. Wind rose with a mean wind speed of 8 knots at the Qingdao Olympic sailing site between May and July in 2007–2008.

Fig. 1

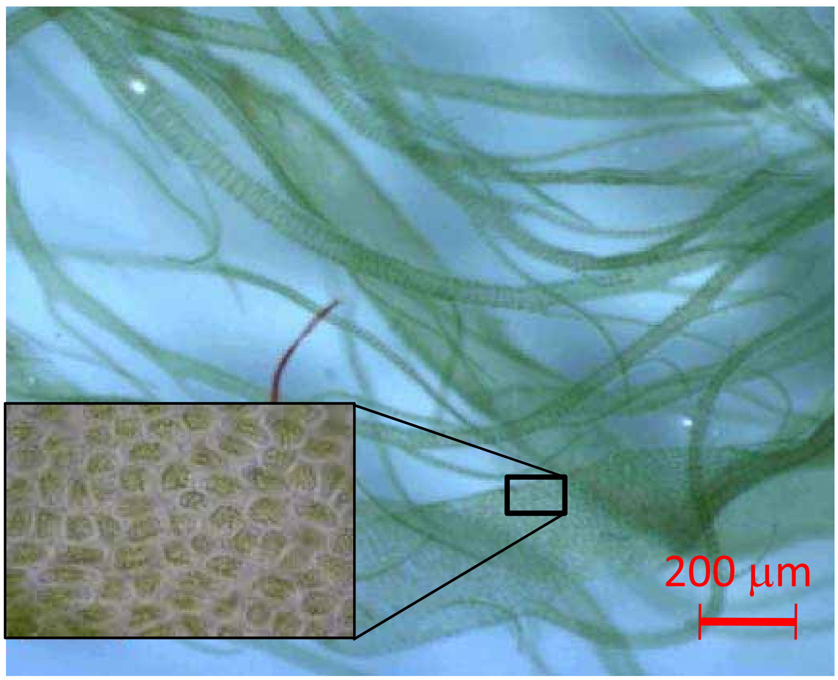

Fig. 2

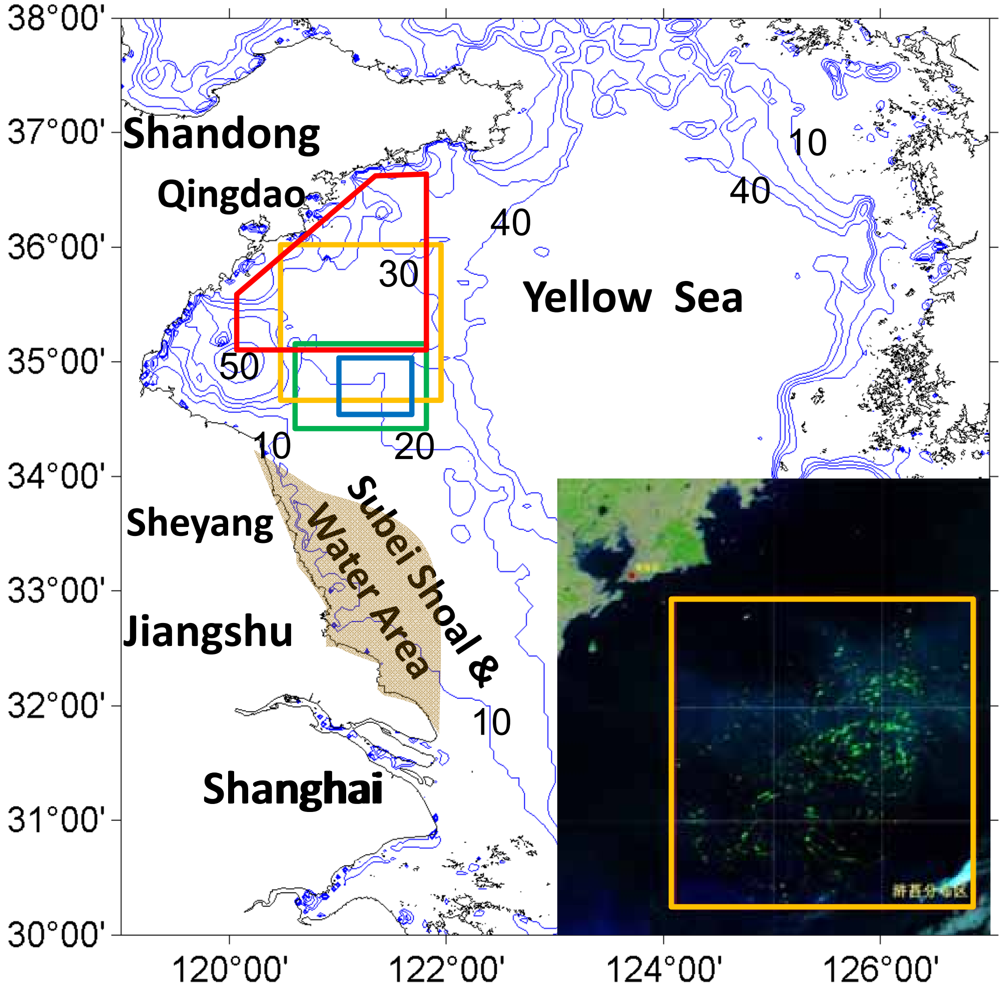
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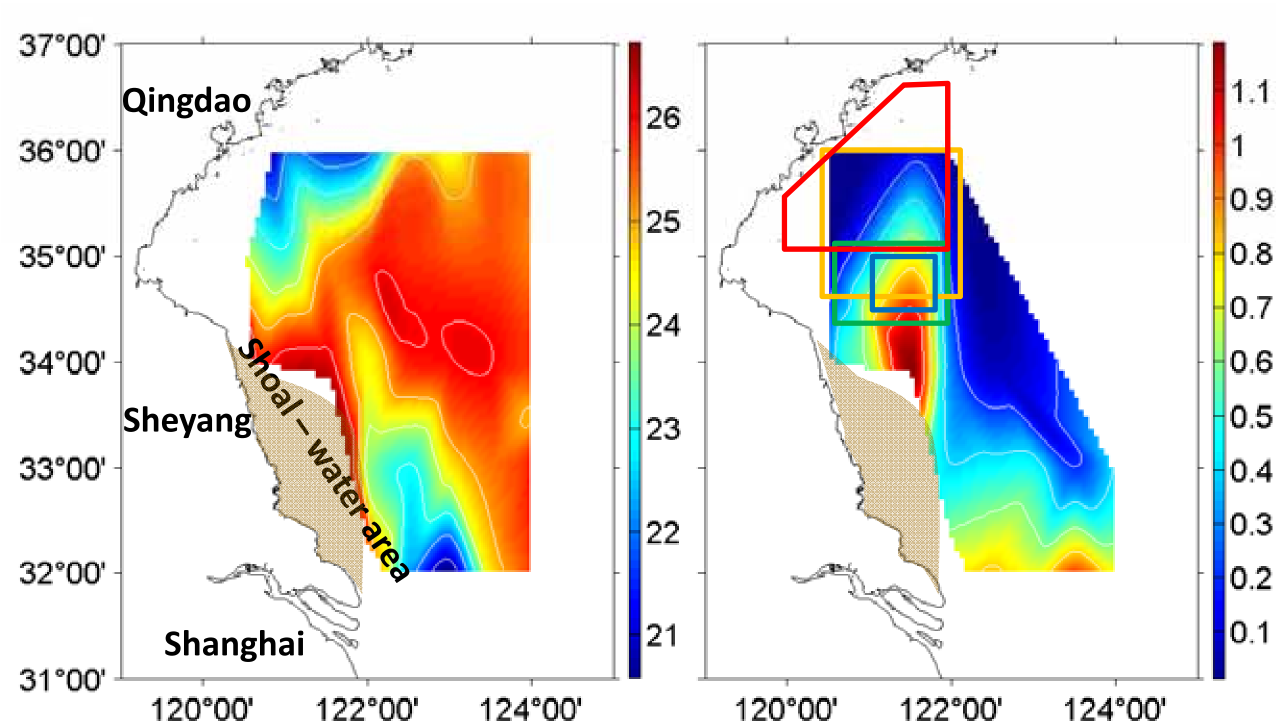
Fig.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Sheyang
Shanghai
Shoal – water area
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122°00'
124°00'
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Fig.

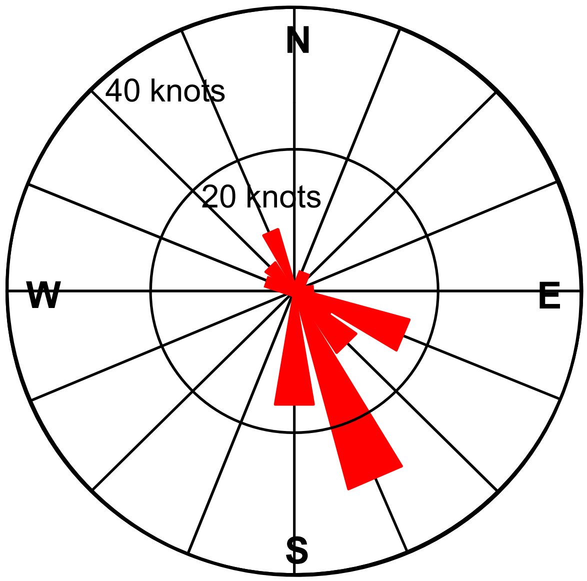

Fig.