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On the Recurrent *Ulva prolifera* Blooms in the Yellow Sea and East China Sea

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On the recurrent *Ulva prolifera* blooms in the Yellow Sea and East China Sea

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[1] A massive bloom of the green macroalgae *Ulva prolifera* (previously known as *Enteromorpha prolifera*) occurred in June 2008 in the Yellow Sea (YS), resulting in perhaps the largest "green tide" event in history. Using a novel index (Floating Algae Index) and multiresolution remote sensing data from MODIS and Landsat, we show that *U. prolifera* patches appeared nearly every year between April and July 2000–2009 in the YS and/or East China Sea (ECS), which all originated from the nearshore Subei Bank. A finite volume numerical circulation model, driven by realistic forcing and boundary conditions, confirmed this finding. Analysis of meteorological/environmental data and information related to local aquaculture activities strongly supports the hypothesis that the recurrent *U. prolifera* in the YS and ECS resulted from aquaculture of the seaweed *Porphyra yezoensis* (or *nori*) conducted along the 200 km shoreline of the Subei Bank north of the Changjiang (Yangtze) River mouth. Given the continuous growth in aquaculture efforts in the region, similar macroalgae bloom events, such as the summer 2008 event, are likely to occur in the future, particularly between May and July. This was confirmed by the 2009 bloom event in the same regions and the same period. The profit of the local *P. yezoensis* aquaculture industry (~16,000 Ha in 2007) is estimated as U.S. $53 million, yet the cost to manage the impact of the summer 2008 *U. prolifera* bloom exceeded U.S. $100 million. Therefore, better strategies are required to balance the economic benefit of seaweed aquaculture and the costs of environmental impacts.

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1. Introduction

[2] Coastal eutrophication is a serious environmental problem caused by excessive nutrients and other pollutants derived from agriculture, urbanization, and industries. In the Gulf of California, recurrent phytoplankton blooms are linked to agriculture irrigation and runoff [*Beman et al.*, 2005]. On the west Florida shelf, the frequency of toxic *Karenia brevis* blooms appears to have increased over 10 fold between the 1950s and the 2000s, in part due to increased nutrient inputs from coastal runoff [*Brand and Compton*, 2007]. In Chinese coastal waters of the Yellow Sea (YS), East China Sea (ECS), and the Bohai Sea, the number and size of toxic algae blooms also have increased since 1998 [*Zhou and Zhu*, 2006].

[3] Green macroalgae blooms have also been reported in the world's oceans [e.g., *Fletcher*, 1996; *Blomster et al.*, 2002; *Nelson et al.*, 2003; *Merceron et al.*, 2007]. These are typically small blooms restricted to coastal areas. However, between May and July 2008, an extensive bloom of the green macroalgae *Ulva prolifera* (previously known as *Enteromorpha prolifera* [see *Hayden et al.*, 2003]) occurred in coastal and offshore waters of the YS (Figure 1a). By late June 2008 this bloom had covered 2400 km^2 of water as estimated from satellite imagery collected with the NASA Moderate Resolution Imaging Spectroradiometer (MODIS), and thought to be one of the largest in recorded history (see section 3 and Table 1 [*Hu and He*, 2008]). Various methods were employed to maintain an algae-free water area near Qingdao for the Olympic sailing games, at a cost exceeding U.S. $100 million (Text S1) [*Wang et al.*, 2009].[1]

[4] Using MODIS observations and other means, several studies have examined the summer 2008 bloom and possible

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[1]Auxiliary materials are available in the HTML. doi:10.1029/2009JC005561.

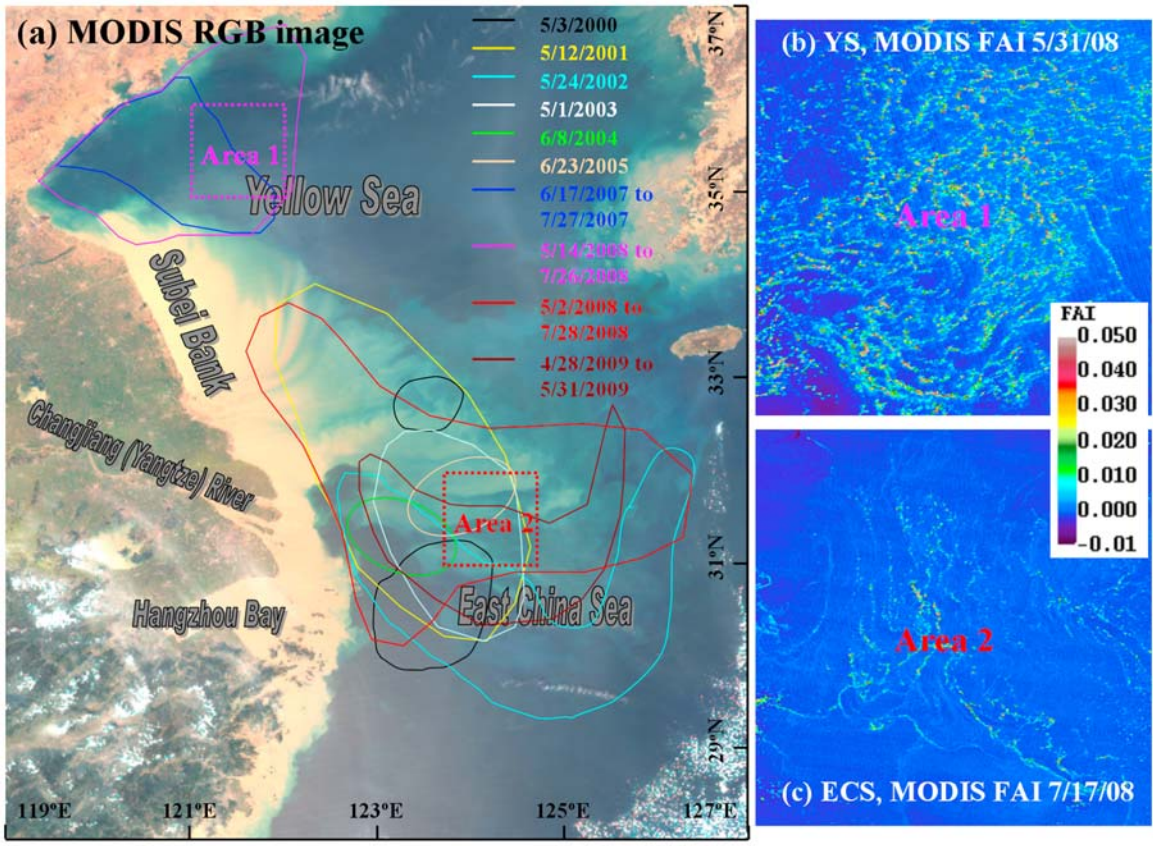

Figure 1. (a) Approximate location and distribution of *U. prolifera* identified from MODIS FAI imagery between April 2000 and May 2009. The background MODIS RGB image on 5 April 2003 shows the extensive sediment plume from the Subei Shallow Bank to the ECS. Nearly all *U. prolifera* algae slicks in the ECS were found in the downstream portion of this plume, which occurs every year between fall and spring following cross-shelf currents between the Subei Bank and the ECS [*Yuan et al.*, 2008]. (b and c) MODIS FAI images tracing *U. prolifera* blooms in 1 × 1° areas in the YS and ECS on 31 May 2008 and 17 July 2008, respectively. More examples of the full-resolution MODIS FAI imagery showing the algae slicks, including those after May 2009, are provided in the auxiliary material. Algae coverage statistics are provided in Table 1.

causes, including the speculation that there was a high rate of nutrient delivery to coastal waters, and the linkage with seaweed aquaculture [*Hu and He*, 2008; *Li et al.*, 2008; *Liang et al.*, 2008; *Lü and Qiao*, 2008; *Qiao et al.*, 2008; *Sun et al.*, 2008; *Liu et al.*, 2009]. However, the 250 m resolution MODIS data could not be used to trace the bloom initiation when the *U. prolifera* patches are much smaller, and the method to detect *U. prolifera* suffered from the interference of changing environmental and observing conditions (aerosol type and thickness, solar/viewing geometry). Also, there is great interest in understanding whether this event was restricted to the YS only, whether it was the result of local eutrophication similar to the recurrent phytoplankton blooms in coastal waters worldwide [*Beman et al.*, 2005; *Zhou and Zhu*, 2006; *Brand and Compton*, 2007], and whether it was a historically recurring problem that might continue in the future.

[5] Here, by combining multiresolution remote sensing data from Landsat (30 m) and MODIS (250 m), numerical circulation modeling with realistic forcing, meteorological/environmental data, and information related to local aqua-

Table 1. Ten Year Record of the Green Macroalgae *U. prolifera* in the Three Adjacent Regions, as Revealed by MODIS and Landsat Imagery[a]

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Region 1	1	1	0	0	1	0	0	1	1	1
Region 2	0	0	0	0	0	0	0	1	1	1
Region 3	1	1	1	1	1	1	0	0	1	1
Algae area (km^2)	<10	15	57	<10	<10	<10	0	21	1940	1600

[a]The 10 year record is from April 2000 to August 2009. Here "1" means *U. prolifera* appears in at least one satellite image, while "0" means no *U. prolifera* is found in any available satellite images. The three regions are defined as follows: Region 1 is the Subei Bank (sediment-rich waters north of the Changjiang River mouth; Figure 1a), Region 2 is the Yellow Sea-waters north of the Subei Bank, and Region 3 is the East China Sea. Most information for Region 1 was derived from Landsat, and for Region 2 and Region 3 most information was derived from MODIS. Note that of the 10 years examined, only 2006 showed no *U. prolifera* for any of the three regions. The maximum algae area for the entire study region estimated using a linear unmixing model with MODIS FAI data is also shown. These crude estimates without ground-truth validation may contain ±20% uncertainties. Assuming 1 kg algae m^{-2} (wet weight), 1.9 and 1.6 million metric tons of algae biomass were estimated for 2008 and 2009, respectively.

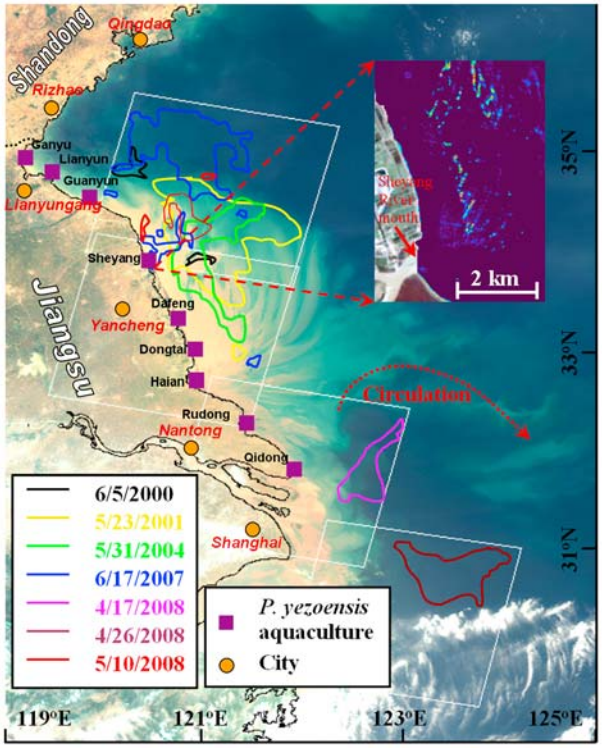

Figure 2. Approximate location and distribution of *U. prolifera* identified from Landsat FAI imagery between April 2000 and August 2008. The coverage of the 140 Landsat scenes is outlined by white boxes. The background MODIS RGB image on 23 May 2004 shows the recurrent sediment plume from the Subei Bank to the ECS. The approximate locations of coastal *P. yezoensis* aquaculture are annotated in purple. The inset shows a Landsat FAI image (17 June 2007) showing *U. prolifera* algae slicks within 2 km of the Sheyang River mouth. More examples of the full-resolution Landsat FAI imagery showing the algae slicks are provided in the auxiliary material.

culture activities, we examined all macroalgae events in the YS and ECS between 2000 and 2009 to address the questions posed above on of algae bloom origin, occurrence frequency, and potential causes.

2. Data and Methods

[6] MODIS and Landsat data from 2000 to date were obtained from the U.S. NASA and USGS, respectively, and processed to generate RGB and Floating Algae Index (FAI) imagery using the methods described by *Hu* [2009]. The index was defined as the reflectance difference between a near-infrared wavelength and a baseline. Specifically, Rayleigh-corrected reflectance (R_{rc}) was first obtained

$$R_{rc,\lambda}(\theta_0, \theta, \Delta\phi) = \pi L_{t,\lambda}{}^*(\theta_0, \theta, \Delta\phi)/(F_{0,\lambda} \times \cos\theta_0) - R_{r,\lambda}(\theta_0, \theta, \Delta\phi), \qquad (1)$$

where λ is the wavelength, L_t^* is the calibrated sensor radiance after correction for gaseous absorption, F_0 is the extraterrestrial solar irradiance, θ_0 is the solar zenith angle, θ is the sensor (viewing) zenith angle, $\Delta\phi$ is the relative azimuth, and R_r is the reflectance due to Rayleigh (molecular) scattering. For simplicity, the dependence of R_{rc} on the solar-viewing geometry (θ_0, θ, $\Delta\phi$) will be omitted. FAI was then derived as

$$\begin{aligned} \mathrm{FAI} &= R_{rc,NIR} - R_{rc,NIR}{}', \\ R_{rc,NIR}{}' &= R_{rc,RED} + (R_{rc,SWIR} - R_{rc,RED}) \\ &\quad \times (\lambda_{NIR} - \lambda_{RED})/(\lambda_{SWIR} - \lambda_{RED}), \end{aligned} \qquad (2)$$

where $R_{rc,NIR}{}'$ is the baseline reflectance in the NIR band derived from a linear interpolation between the red and short-wave IR (SWIR) bands. For MODIS, λ_{RED} = 645 nm, λ_{NIR} = 859 nm, λ_{SWIR} = 1240 nm. For Landsat, λ_{RED} = 660 nm, λ_{NIR} = 825 nm, λ_{SWIR} = 1650 nm.

[7] Model simulations and image comparisons showed that the index was more effective in detecting floating macroalgae than other methods primarily because most of the aerosol effects are removed by the baseline subtraction, and FAI is less sensitive to changes in solar/viewing geometry [*Hu*, 2009]. Floating macroalgae appears as outstanding slicks or patches over near-homogenous water background on the FAI imagery, which can be easily delineated. Further, because of the linear design (equation (2)), FAI is more suitable than other nonlinear indexes (e.g., Normalized Difference Vegetation Index, NDVI) when used for algae area estimates, where pixels with partial algae coverage can be estimated with linear unmixing [e.g., *Hu et al.*, 2010]. For any cloud-free ocean pixel, FAI ≥ 0.02 was assumed to correspond to 100% algae coverage while FAI ≈ 0.0 was assumed to represent 0% algae coverage [*Hu et al.*, 2010]. The lower bound threshold actually varied between −0.001 and 0.001 after calibration through trial and error with careful visual inspection.

[8] The FAI method was implemented to derive MODIS and Landsat FAI imagery between 2000 and 2009. Due to frequent cloud cover, of the 4580 MODIS scenes (or 5 min image granules) covering the YS and ECS (28°N – 37°N and 119°E – 127°E, Figure 1a) between April and July 2000–2008 and between April and May 2009, only ~400 images containing cloud cover were processed and analyzed. Similarly, about 140 Landsat scenes covering coastal waters of the Subei Bank and near the Changjiang (Yangtze) River mouth (Figure 2) for the same periods were processed and analyzed.

[9] A particle tracking experiment was designed and implemented using a high-resolution, unstructured grid ECS Finite-Volume Coastal Ocean Model [*Chen et al.*, 2008]. The model was driven by realistic wind stress and heat flux at the surface, freshwater discharges from the Changjiang River, and eight major astronomical tidal constituents (M_2, S_2, N_2, K_2, K_1, O_1, P_1, Q_1) on open boundaries. The Kuroshio and Taiwan Warm Currents were simulated by specifying the water transport on the inflow and outflow boundaries under the April climatological fields of temperature and salinity. The model was run for a period of 1 April to 31 May 2008. Two groups of particles were released on the sea surface on 17 April 2008 near the Changjiang River mouth (where and when initial *U. prolifera* were identified from Landsat FAI imagery) and in nearshore waters of the Subei Bank, respectively, to trace their movements through

10 May 2008 when algae slicks in the YS first appeared in Landsat FAI imagery (see section 3).

[10] The data of annual culture area and production of *Porphyra yezoensis* were obtained from multiple sources, including statistics from the Jiangsu Statistics Bureau and local news media (Text S2). For years when area data were not available, they were estimated using annual production data because they were approximately proportional to each other.

[11] Air temperature data were obtained from the Jiangsu Meteorological Bureau. Nutrient and pollutant discharge data of coastal rivers were from the State Oceanic Administration (SOA) of China. Pollution index data using a combination of Chinese national water quality standards (GB3097-1997) were obtained from SOA and the Ministry of Environmental Protection (MEP) of China. Because of lack of long-term nutrient concentration data in the YS, annual statistics of pollution level index was used as a surrogate for nutrient availability. Other environmental data were also obtained from various sources and analyzed. These include satellite-estimated sea surface temperature (SST), surface wind, and surface radiation.

3. Results

[12] Figure 1 shows the multiyear sequence of the *U. prolifera* locations observed from MODIS imagery between April 2000 and May 2009 (more recent imagery are shown in the auxiliary material). Because of the frequent cloud cover, it was difficult to construct a complete time series for every year to show bloom evolution over time. However, it is clear that the summer 2008 *U. prolifera* bloom event in the YS (pink color in Figure 1a, also see Figure 1b) is only an extreme case of the recurrent blooms between April 2000 and May 2009. Indeed, excluding the year of 2006, *U. prolifera* slicks were identified in MODIS imagery every year, mostly in the ECS rather than in the YS.

[13] Due to the space limit, the full-resolution MODIS FAI imagery and the temporal evolution of *U. prolifera* cannot be shown here, but some examples are provided in the Auxiliary materials (Figures S1–S8). The algae slicks identified from the MODIS imagery are typically from April to July, with the earliest on 3 April (2002) at about 370 km east of the Hangzhou Bay. In other years, the first appearance of the algae slicks ranged from mid-April to mid-June, with most slicks found in the ECS, some of which extended to at least 400 km offshore from the Changjiang River mouth. Although the algae slicks in the ECS are much thinner than those in the YS (Figure 1c versus Figure 1b), the surface water area containing the multiyear algae slicks is much higher in the ECS (about 130,000 km^2) than in the YS (about 40,000 km^2).

[14] The MODIS time series imagery suggests that the algae slicks in the YS followed the northward coastal current and those in the ECS followed the cross-shelf current during the spring. The effect of this latter current can be clearly visualized from the extensive sediment plume from the Subei Bank to the offshore areas in the southeast (Figure 1a [also see *Yuan et al.*, 2008]). Algae slicks in both the YS and ECS can be traced to the very turbid and shallow Subei Bank. However, the 250 m MODIS imagery is limited in detecting small algae patches that might be present in the nearshore bank. The exact detection limit is difficult to determine without field data. However, the linear unmixing of FAI to determine partial pixel coverage may help estimate this limit. The linear unmixing model resulted in ~2%/pixel coverage for several thin slicks that were visible in the MODIS FAI imagery, corresponding to 2% × 250 m = 5 m for the slick width. For small algae patches that do not form continuous slicks, 2%/pixel coverage corresponds to about 35 × 35 m in algae size. Thus, an algae slick <5 m in width cannot be detected by the 250 m MODIS FAI imagery.

[15] The Landsat image series at 30 m resolution extended the MODIS findings to the nearshore waters, even if their coverage was limited due to cloud cover and due to the 16 day satellite orbit cycle. Figure 2 shows the multiyear sequence of the *U. prolifera* locations identified from the Landsat FAI imagery. The high-resolution FAI images revealed much smaller *U. prolifera* slicks or patches near the coast of the Subei Bank, at one time only 2 km from the Sheyang River mouth in June 2007 (Figure 2 inset). In 2008, Landsat FAI imagery showed small algae slicks near the Changjiang River mouth on 17 and 26 April 2008, nearly a month earlier than reported previously using MODIS for the YS [*Hu and He*, 2008]. Because of the small size, most of the *U. prolifera* slicks were not observable in MODIS imagery. Although there is no ground-truth data, the thin filaments of 1–2 Landsat pixels (30–60 m) showed a spectral shape featuring a distinctive reflectance peak at 825 nm, which is characteristic of floating macroalgae. On 10 May 2008, extensive slicks of *U. prolifera* were found in the north of the Subei Bank. Landsat FAI images also showed recurrent slicks in the same locations in May and/or June of 2000, 2001, 2004, 2007, and 2008. Most of the slicks in the shallow bank were oriented in the N-S or NE-SW direction, following the direction of the Yellow Sea Coastal Current (YSCC, see *Yuan et al.* [2008]).

[16] Although a complete statistics of *U. prolifera* occurrence is difficult to achieve due to the frequent cloud cover, Table 1 lists whether or not the algae slicks/patches were found from the available near-cloud-free satellite images in each of the three adjacent regions: Region 1 for the Subei Bank, Region 2 for the YS excluding the Subei Bank, and Region 3 for the ECS. *U. prolifera* was found in Region 3 in every year except 2006 and 2007, and found in Region 1 in 6 years in the 10 year record through August 2009. For Region 2, only in 2007, 2008, and 2009 were *U. prolifera* found during the summer.

[17] The total algae coverage for each year was estimated as the maximum coverage during that year using one or more FAI images and the linear unmixing scheme. Results are listed in the last row of Table 1. Although the algae areas between 2000 and 2007 (except 2006) are negligible as compared with those found in 2008 and 2009, the surface water areas containing the algae slicks are extensive (Figures 1 and 2). This suggests that the algae slicks were thinner and more diluted between 2000 and 2007. Assuming a conservative 1 kg algae m^{-2} (wet weight), approximately 1.9 and 1.6 million metric tons of algae biomass were estimated for 2008 and 2009, respectively. These figures are significantly lower than those reported earlier [*Hu and He*, 2008] because of the linear unmixing method used with FAI data.

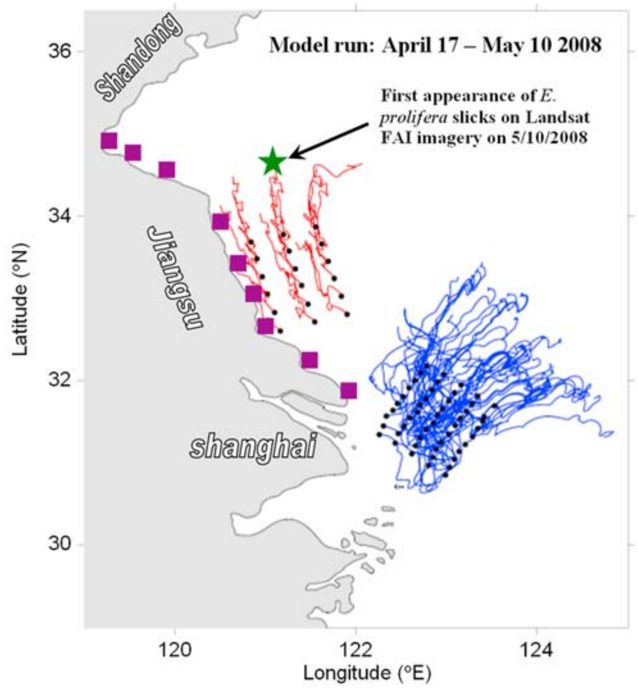

Figure 3. Trajectory of surface particles from 17 April to 10 May 2008 from a numerical model [*Chen et al.*, 2008]. The approximate locations of coastal *P. yezoensis* aquaculture are annotated in purple. The first appearance of *U. prolifera* slicks in the north of Subei Bank on the 10 May 2008 Landsat FAI image is annotated with a star.

[18] In summary, *U. prolifera* was found from satellite imagery every year between 2000 and 2009 except 2006. The sequence of patterns observed in the MODIS and Landsat imagery (Figures 1, 2, and S1–S8 in the Auxiliary materials) suggest that the 2008 *U. prolifera* blooms in the YS and ECS as well as the recurrent *U. prolifera* slicks/patches in other years all originated in nearshore waters of the Subei Bank.

[19] The numerical circulation experiment confirmed this finding. Simulated surface particles released on 17 April 2008 in nearshore waters of the Subei Bank (red traces in Figure 3) were advected alongshore to the north, following the pattern of *U. prolifera* slicks seen in the Landsat FAI imagery of 10 May 2008 (red outlines in Figure 2). In the ECS, particles released near the river mouth moved offshore to the northeast and then to the east (blue traces in Figure 3). The experimental results showed that although algae patches in both locations (north of the Subei Bank in the YS and around the Changjiang River mouth) originated from the Subei Bank, the latter could not be transported to the YS, but were rather advected offshore in the ECS following the water movement. This tendency is consistent with the clockwise low-frequency circulation of the low-salinity plume originated from the Changjiang River [*Chen et al.*, 2008]. In this region, *U. prolifera* was found farther offshore (as seen in the MODIS FAI image of July 2008; Figures 1a and 1c), a result of advection of the nearshore *U. prolifera* following the cross-shelf current. These circulation patterns also agree with the recurrent sediment plume patterns observed in typical MODIS RGB imagery collected in this region, for example on 5 April 2003 (Figure 1a) and 23 May 2004 (Figure 2). The circulation patterns are driven by the cross-shelf current from the Subei Bank to the ECS, as revealed by the MODIS image sequence of normalized water-leaving radiance [*Yuan et al.*, 2008]. Clearly, the combination of multisensor remote sensing and high-resolution numerical circulation modeling revealed the nearshore origin for *U. prolifera* in nearly all years between 2000 and 2009.

[20] What would cause the initial accumulation of *U. prolifera* in nearshore waters? Local news media reported that *U. prolifera* was often found to accompany the cultured seaweed in coastal waters. Therefore, we speculated that there might be a connection with seaweed aquaculture [*Hu*, 2009]. *Liu et al.* [2009] also hypothesized that aquaculture of the seaweed *P. yezoensis* in coastal waters of Jiangsu Province could account for the 2008 *U. prolifera* bloom in the YS. The independent study here strongly supports this hypothesis.

[21] Coastal aquaculture in Jiangsu Province provides 95% of the nation's *P. yezoensis* product. This industry has grown to occupy at least 44,000 Ha in 2008 compared to about 5700 Ha in 1999 (Figure 4 and Text S2). *P. yezoensis* are cultured using bamboo rafts and rope nets, which are known to be accompanied by *U. prolifera* as a nuisance species (Text S3 [*Wang et al.*, 2007]). *U. prolifera* can grow over *P. yezoensis* on the aquaculture rafts, causing poor harvests. Common techniques to remove *U. prolifera* from *P. yezoensis* include lifting the rafts out of the water and suspending them in air or storing them in cold compartments, as *U. prolifera* quickly dies in air or cold temperature (Text S3). During or before harvesting in May, the cleaning of the culturing rafts or severe storms can release considerable amounts of *U. prolifera* to the water. Although *U. prolifera* is known to grow well in sewage waters (D. Bronk, Virginia Institute of Marine Science, personal communication, 2008; B. Lapointe, Harbor Branch Oceanographic Institution, personal communication, 2009), the dramatic increase in cultured *U. prolifera* area in 2008 strongly suggests the bloom's connection with an increase in aquaculture biomass of *P. yezoensis*, since nutrients and

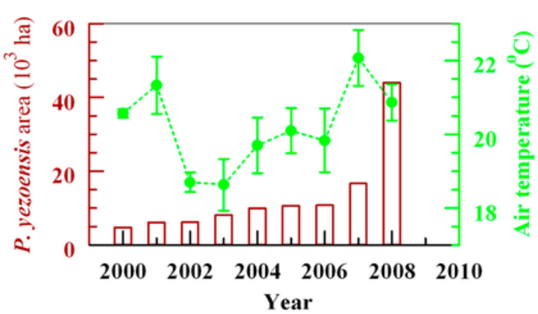

Figure 4. Aquaculture of the seaweed *P. yezoensis* in coastal areas of Jiangsu Province (in Ha). Also shown are the average air temperatures for the month of May from three coastal cities (Lianyungang, Yancheng, and Nantong) with *P. yezoensis* aquaculture.

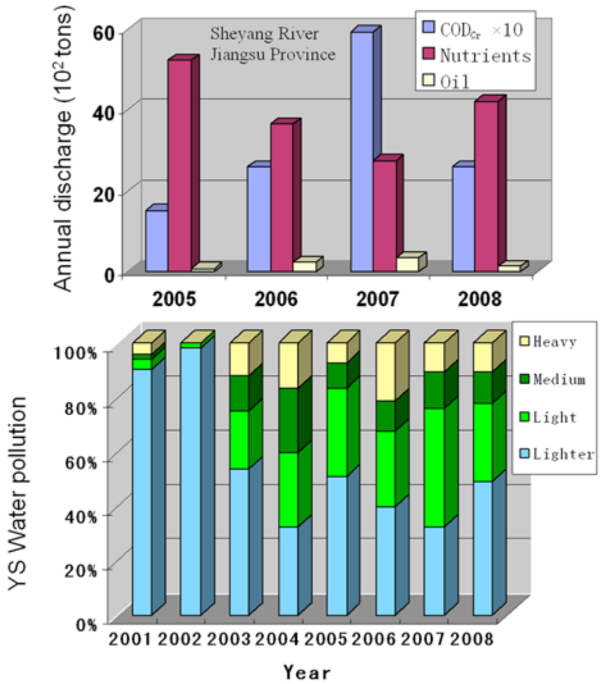

Figure 5. (top) Annual discharge of the three major pollutants from Sheyang River (location shown in Figure 1a inset) and (bottom) annual percentage area of polluted water, defined by a pollution level index (GB3097-1997), in the YS. The index was used as a surrogate for nutrient availability.

other pollutants discharged from local rivers to the YS did not show any apparent increase in 2008 relative to, for example, 2005, when the *U. prolifera* bloom was only found in the ECS (Figure 5).

4. Discussion

[22] In summary, four lines of evidence support the hypothesis that *U. prolifera* in the YS and ECS was connected to coastal aquaculture of *P. yezoensis* along the 200 km shoreline of the Subei Bank, specifically, (1) proximity (several kilometers) to shore of the first appearance of *U. prolifera* in Landsat imagery; (2) recurrent *U. prolifera* slicks between 2000 and 2009 all traced to the Subei Bank (the slicks may have occurred in other years before 2000 in nearshore waters, but this is unknown due to the lack of MODIS and Landsat data before 2000); (3) connectivity revealed by the particle tracing numerical experiment; and (4) *U. prolifera* growth with *P. yezoensis* aquaculture nets. For the same reasons, the summer 2008 bloom event in the YS resulted from the dramatic expansion of the *P. yezoensis* aquaculture (Figure 4).

[23] However, some questions still remain unanswered, such as why *U. prolifera* patches were not found in satellite imagery in 2006. Similarly, it is unclear why extensive blooms did not occur in the YS in 2000, 2001, and 2004, when small *U. prolifera* patches appeared in the north of the Subei Bank.

[24] Laboratory studies showed that *U. prolifera* preferred low-light environments, and optimal growth required temperatures between 15 and 25°C [*Taylor et al.*, 2001; *Wang et al.*, 2007]. We have examined all environment variables that can potentially affect *U. prolifera* growth, including air temperature recorded in several local cities, sea surface temperature (SST) from MODIS (2003 to present) and AVHRR (Advanced Very High Resolution Radiometer, 1985 to present), photosynthetically available radiation (PAR) estimated from SeaWiFS measurements (Sea-viewing Wide Field-of-view Sensor, 1997 to present), and surface wind patterns from QuikScat measurements (2000 to present). However, there was no conclusive interannual pattern that could explain why *U. prolifera* was not found in 2006. For example, air temperature in May 2006 was significantly higher than in May 2002 (Figure 4), yet extensive *U. prolifera* slicks were found in the ECS in 2002 while no *U. prolifera* was found in 2006. We speculate that the occurrence of *U. prolifera* in 2006 may have been missed in the satellite time series due to clouds. For 2005, only one MODIS image on 23 June 2005 showed some *U. prolifera* slicks about 200 km east of the Changjiang River mouth (Figure 1a). If clouds had covered the entire ECS on this day, our statistics would show no *U. prolifera* for 2005 either. The same argument also applies to the much less frequent Landsat imagery, which could have easily missed some *U. prolifera* slicks in the Subei Bank.

[25] Hence, we conclude that small patches of *U. prolifera* existed in the Subei Bank every year at some point between April and June, a result from the continuous *P. yezoensis* aquaculture. Indeed, MODIS SST data showed that the low bound threshold temperature (15°C) for optimal growth of *U. prolifera* occurred in the month of April when *P. yezoensis* was harvested. This also agrees with the MODIS/Landsat observations in Figures 1 and 2. Depending on the water movement directions, the *U. prolifera* patches can be transported to ECS and/or the YS north of the Subei Bank. Once in the sediment-poor YS, the initial amount of *U. prolifera* and nutrient availability collectively determine whether a massive bloom may occurs during subsequent months. For example, May 2000 and 2001, although some *U. prolifera* patches were found in the relatively clear waters north of the Subei Bank, low nutrient levels in this region (Figure 5 (bottom)) probably did not provide conditions for massive blooms during the following months. In contrast, during May 2008 when excessive amount of *U. prolifera* was transported from the Subei Bank to the sediment-poor YS, a massive bloom occurred even if available nutrients (inferred from the water pollution index for the region) were not significantly higher than previous years (2003–2007). Thus, *U. prolifera* blooms were not a result of increased nutrients, but very likely a result of expanded aquaculture. Other environmental factors may play a role, yet their interannual temporal patterns were not conclusive.

[26] Coastal aquaculture of *P. yezoensis* in nearshore waters of the Subei Bank started in the 1960s, and has expanded rapidly in the last decade (Figure 4). Although complete statistics for 2009 are not available, a recent news report suggests that in Yancheng City alone, about U.S. $17 million was invested to increase the aquaculture area by another 5400 Ha in 2009 (Text S2). It is therefore natural to ask whether a similar bloom event as in summer 2008 will occur in 2009.

[27] During preparation of this manuscript between late 2008 and early 2009, the most recent MODIS imagery in May 2009 showed extensive *U. prolifera* slicks in the ECS (Figure 1a). Landsat imagery on 29 May 2009 showed that the algae slicks in the Subei Bank were only 20 km south of the location where *U. prolifera* was initially found in May 2008 [*Hu and He*, 2008]. We predicted that once the algae slicks reached the sediment-poor waters in the north, a similar bloom to the summer 2008 case would occur. Indeed, at the time of this writing in October 2009, we have observed a bloom event in the YS that was nearly identical in dimensions to the 2008 bloom event, except that due to different wind directions the massive bloom did not end up in Qingdao. On 2 July 2009 when the bloom had reached its maximum extent, of the 39,000 km^2 waters containing the algae in the YS, about 1450 km^2 were covered by the algae. In comparison, during the 2008 bloom event, on 25 June 2008 (maximal bloom extent), of the 24,000 km^2 waters containing the algae in the YS, about 1840 km^2 were covered by the algae. The algae area coverage in the two years is similar, although some of the algae slicks in July 2009 drifted northeast and reached South Korea. These results suggest that with the continuous expansion of the coastal aquaculture of *P. yezoensis*, similar bloom events are likely to occur in the future, posing significant environmental concerns to local government and management agencies.

[28] Approximately 25% of the global human population resides in coastal zones [*Small and Nicholls*, 2003]. Correspondingly, coastal aquaculture of seaweed in many countries, especially in Asia but also including North America, supports the local economy and provides a significant portion of the global seafood. For example, a net profit of about U.S. $53 million was obtained from the *P. yezoensis* aquaculture in Jiangsu Province in 2007 (Text S2). However, the profit is completely compromised by the environmental management cost (>U.S. $100 million to manage the algae bloom in 2008; Text S1 [*Wang et al.*, 2009]). Proper management, with more efficient methods to suppress *U. prolifera* growth during both culturing and harvesting, is key to avoid future massive *U. prolifera* blooms in the YS. On the other hand, similar to the role of the brown macroalgae *Sargassum spp.* in the Gulf of Mexico and the South Atlantic Bight, recurrent *U. prolifera* in the ECS as a biproduct of the coastal aquaculture may serve as an important habitat (shade and food) for fish, shrimp, turtles, crabs, and other organisms [*South Atlantic Fishery Management Council*, 2002]. Whether or not this is true, however, deserves further investigations.

[29] In the global perspective, green macroalgae blooms have been reported in many coastal oceans. The effectiveness of the FAI and the free availability of MODIS and Landsat data have demonstrated great potentials in establishing a long-term record of the algae blooms for any coastal ocean region. Such a record can help understand local environmental changes in response to anthropogenic activities and global climate change.

5. Conclusion

[30] The summer 2008 *U. prolifera* bloom event in the YS stimulated several studies for the bloom's origin, cause, and ecological consequence. This multidisciplinary work resulted in several new findings. First, application of a novel index (FAI) to multiresolution remote sensing data showed that *U. prolifera* occurred not only in 2008, but also in almost every year between 2000 and 2009, although the area coverage of the macroalgae before 2008 was much smaller than those in 2008 and 2009. Combined with high-resolution numerical circulation modeling, the results revealed that the recurrent *U. prolifera* was all traced to the nearshore waters of the Subei Bank. Finally, analysis of local aquaculture data and other environmental data strongly suggests that the recurrent *U. prolifera* slicks/patches (including the massive blooms in summer 2008 and summer 2009) in both the YS and ECS were unlikely a result of coastal eutrophication but rather connected to coastal aquaculture of *P. yezoensis* in this region. Because of the continuous expansion in aquaculture, similar bloom events such as those in summer 2008 and summer 2009 may also occur in the future.

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References

Beman, J. M., K. R. Arrigo, and P. A. Matson (2005), Agricultural runoff fuels large phytoplankton blooms in vulnerable areas of the ocean, *Nature*, *434*, 211–214, doi:10.1038/nature03370.

Blomster, J., S. Back, P. D. Fewer, M. Kiirikki, A. Lehvo, A. C. Maggs, and M. J. Stanhope (2002), Novel morphology in *Enteromorpha* (*Ulvophyceae*) forming green tides, *Am. J. Bot.*, *89*(11), 1756–1763, doi:10.3732/ajb.89.11.1756.

Brand, L., and A. Compton (2007), Long-term increase in Karenia brevis abundance along the southwest Florida Coast, *Harmful Algae*, *6*, 232–252, doi:10.1016/j.hal.2006.08.005.

Chen, C., et al. (2008), Physical mechanisms for the offshore detachment of the Chanjiang diluted water in the East China Sea, *J. Geophys. Res.*, *113*, C02002, doi:10.1029/2006JC003994.

Fletcher, R. L. (1996), The occurrence of "green tides": A review, in *Marine Benthic Vegetation: Recent Changes and the Effects of Eutrophication*, edited by W. Schramm and P. H. Nienhuis, pp. 7–43, Springer, Berlin.

Hayden, H. S., J. Blomster, C. A. Maggs, P. C. Silva, M. J. Stanhope, and J. R. Waaland (2003), Linnaeus was right all along: *Ulva* and *Enteromorpha* are not distinct genera, *Eur. J. Phycol. 38*, 277–294, doi:10.1080/1364253031000136321.

Hu, C. (2009), A novel ocean color index to detect floating algae in the global oceans, Remote Sens. *Environ.*, *113*, 2118–2129, doi:10.1016/j.rse.2009.05.012.

Hu, C., and M.-X. He (2008), Origin and offshore extent of floating algae in Olympic sailing area, *Eos Trans. AGU*, *89*(33), 302–303, doi:10.1029/2008EO330002.

Hu, C., Z. Lee, R. Ma, K. Yu, D. Li, and S. Shang (2010), Moderate Resolution Imaging Spectroradiometer (MODIS) observations of cyanobacteria blooms in Taihu Lake, China, *J. Geophys. Res.*, *115*, C04002, doi:10.1029/2009JC005511.

Li, D., S. He, Q. Yang, J. Lin, F. Yu, M.-X. He, and C. Hu (2008), Origin and distribution characteristics of *Enteromorpha Prolifera* in sea waters off Qingdao, China (in Chinese), *Environ. Prog.*, *402*(8B), 45–46.

Liang, Z., X. Lin, M. Ma, J. Zhang, X. Yan, and T. Liu (2008), A preliminary study of the *Enteromorpha prolifera* drift gathering causing the green tide phenomenon (in Chinese with English abstract), *J. Ocean Univ. China.*, *38*(4), 601–604.

Liu, D., J. K. Keesing, Q. Xing, and P. Shi (2009), World's largest macroalgal bloom caused by expansion of seaweed aquaculture in China, *Mar. Sci. Bulletin.*, *58*, 888–895, doi:10.1016/j.marpolbul.2009.01.013.

Lü, X., and F. Qiao (2008), Distribution of sunken macroalgae against the background of tidal circulation in the coastal waters of Qingdao, China, in summer 2008, *Geophys. Res. Lett.*, *35*, L23614, doi:10.1029/2008GL036084.

Merceron, M., V. Antoine, I. Auby, and P. Morand (2007), In situ growth potential of the subtidal part of green-tide forming Ulva spp. stocks, *Sci. Total Environ.*, *384*, 293–305, doi:10.1016/j.scitotenv.2007.05.007.

Nelson, T. A., A. V. Nelson, and M. Tjoelker (2003), Seasonal and spatial patterns of "green tides" (ulvoid algal blooms) and related water quality parameters in the coastal waters of Washington State, USA, *Bot. Mar.*, *46*, 263–275, doi:10.1515/BOT.2003.024.

Qiao, F., D. Ma, M. Zhu, R. Li, J. Zang, and H. Yu (2008), Characteristics and scientific response of the 2008 *Enteromorpha prolifera* bloom in the Yellow Sea (in Chinese), *Adv. Mar. Sci.*, *26*(3), 409–410.

Small, C., and R. Nicholls (2003), Global analysis of human settlements on coastal zones, *J. Coastal Res.*, *19*, 584–599.

South Atlantic Fishery Management Council (2002), Fishery management plan for pelagic *Sargassum* habitat of the South Atlantic region, report, Charleston, South Carolina. (Available at http://www.safmc.net/Portals/6/Library/FMP/Sargassum/SargFMP.pdf.)

Sun, S., et al. (2008), *Emerging challenges: Massive green algae blooms in the Yellow SeaNature Precedings*, hdl:10101/npre.2008.2266.1.

Taylor, R., R. L. Fletcher, and J. A. Raven (2001), Preliminary studies on the growth of selected green-tide algae in laboratory culture: Effects of irradiance, temperature, salinity and nutrients on growth rate, *Bot. Mar.*, *44*, 327–336, doi:10.1515/BOT.2001.042.

Wang, J., B. Yan, A. Lin, J. Hu, and S. Shen (2007), Ecological factor research on the growth and induction of spores release in *Enteromorpha Prolifera* (Chlorophyta), *Bull. Mar. Sci.*, *26*(2), 60–65.

Wang, X. H., L. Li, X. Bao, and L. D. Zhao (2009), Economic cost of an algae bloom cleanup in China's 2008 Olympic sailing venue, *Eos Trans. AGU*, *90*(28), 238–239, doi:10.1029/2009EO280002.

Yuan, D., J. Zhu, C. Li, and D. Hu (2008), Cross-shelf circulation in the Yellow and East China seas indicated by MODIS satellite observations, *J. Mar. Syst.*, *70*, 134–149, doi:10.1016/j.jmarsys.2007.04.002.

Zhou, M. J., and M. Y. Zhu (2006), Progress of the project "Ecology and Oceanography of Harmful Algal Blooms in China," *Adv. Earth Sci.*, *21*, 673–679.

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