

**Eutrophication  
behind the  
world-largest floating  
macroalgal blooms**

Q. Xing

# Progressive eutrophication behind the world-largest super floating macroalgal blooms in the Yellow Sea

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## Abstract

World-largest super floating macroalgal blooms of *Ulva prolifera* have lasted 7 years by now in every summer in the Yellow Sea, the outer part of a semi-enclosed coastal sea. Evaluation of the inter-annual variability in the trophic status is one of fundamental tasks for prediction and management of the blooms. We show the new findings of a progressive eutrophication in the large Yellow Sea basin behind the super floating macroalgal blooms. The inter-annual variability in human-induced nutrient pollution from 2001 to 2012 was assessed by a nutrient pollution index weighted by area (AWCPI-NP), and a significant increase in the trophic status was found in the macroalgal bloom (MAB) phase (2007–2012): the average AWCPI-NP was higher than that in the pre-MAB phase (2001–2006) by about 45 %; meanwhile, in the Jiangsu Shoal, origin place of the drifting macroalgae, the annual in-situ nutrient concentrations increased rapidly from 2000 to 2011. Chlorophyll *a* concentration (Chl *a*), an indicator of eutrophication, increased by about 15 % in the bloom region from the pre-MAB to MAB phase. This progressive eutrophication might lead to the non-linear outburst in the growth of macroalgae, i.e., green tides, in the Yellow Sea since 2007.

## 1 Introduction

Satellite image records revealed that large scale of macroalgae blooms (MAB) started from 2007 in the Yellow Sea (Hu et al., 2010; Xing et al., 2011a; Keesing et al., 2011); these floating macroalgal blooms have seriously impacted the Yellow Sea by covering hundreds of square kilometers of ocean surface in every summer (Liu et al., 2009; Xing et al., 2011a; SOA, 2013). In the early May, i.e., at the early stages of bloom, the patches of floating algae *Ulva prolifera* from the turbid waters of Jiangsu Shoal usually drift southward along with the Jiangsu Coastal Current, and enter the East China Sea; as the Northeast Asia monsoon becomes stronger, most of the floating macroalgae

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drift northwardly and reach the southern coast of Shandong peninsula in June and July; and they disappear in August (Fig. 1) (Xing et al., 2011a).

The super macroalgal blooms brought adverse impacts on local coastal tourism, marine transportation, fisheries, and the aquatic systems; the blooms aroused a global concern on coastal marine environment (Sun et al., 2008; LOICZ, 2008; Hu and He, 2008; Smetacek and Zingone, 2013), especially on eutrophication. The dynamics of phytoplankton is usually controlled by nutrients in aquatic ecosystem (Tilman et al., 1982; Hecky et al., 1988; Egge and Aksnes, 1992; Gao and Song, 2005); similarly for macroalgae, growth of *Ulva* ssp. and *Enteromorpha* spp. was highly related to the enrichment of nutrient (especially the nitrogen) as shown by experimental and numerical studies (Menesguen et al., 2006).

Eutrophication, a process of nutrient enrichment of water (Lund, 1967; Ferreira et al., 2011), is a significant problem for coastal marine system (Turner and Rabalais, 1994; Cai et al., 2011), and nitrogen and phosphorus are recognized as the major pollutants causing eutrophication (García-Pintado et al., 2007; Kauffman et al., 2010). In China, Coastal water quality levels (WQLs) and their spatial distribution are annually presented in Marine Environmental Quality Bulletin, and the WQLs have been dominated by the nutrient pollution, i.e. the total inorganic nitrogen (TIN-N) and the active phosphorus (PO<sub>4</sub>-P) (SOA, 2010, 2011, 2013). So, the eutrophication may be reason of macroalgal blooms in the China coastal waters.

However, to our knowledge, there is neither long-term data nor effective approaches for evaluation of macroalgae related nutrient enrichment in the entire semi-enclosed region of the Large Yellow Sea basin which includes the Yellow Sea and the Bohai Sea. Chlorophyll *a* (Chl *a*), a pigment in phytoplankton, is extensively used as an indicator in eutrophication assessment (Carlson, 1977; Ferreira et al., 2011). However, the long-term records of in situ Chl *a* are scarce because it is not a compulsory parameter in the marine environmental monitoring system in China (Qu et al., 2006). Alternatively, satellite remote sensing data in archive has the potential in providing historical records of Chl *a*, and can be used for long-term assessment (Bot and Colijin, 1996).

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In order to understand the causes of macroalgal blooms in the Yellow Sea, it is essential to know the status and trend of nutrient enrichment before and after the large-scale macroalgal blooms. In this paper, we use Chl *a* to analyze the change and trend of eutrophication as well as an index combining the area of nutrient-polluted marine waters and their corresponding level to evaluate the entire regional trophic status of coastal waters, and explore the process of eutrophication behind the super macroalgal blooms.

## 2 Data and methods

### 2.1 Studied area and field work

The Yellow Sea (Fig. 1) is a semi-enclosed coastal sea with an area of 380 000 km<sup>2</sup> connecting the Bohai Sea with open waters – the East China Sea; the Bohai Sea with an area of about 77 000 km<sup>2</sup>, may be also considered to be part of the large Yellow Sea ecosystem (UNDP, 2007). The surrounding areas of the large Yellow Sea have experienced strong disturbance from human activities, e.g., urbanization, industry, agriculture and aquaculture, with the rapid economic development of China in the past decades. Coastal anthropization caused that large amounts of nitrogen and phosphorus as well as other pollutants have been discharged into the basin, and the aquatic ecological system has been facing a serious problem of degradation (SOA, 2010; Wang et al., 2011). Field work was carried out to investigate the macroalgal blooms at the coast of Yantai, Qingdao and the Northern Jiangsu Shoal, and in the Yellow Sea in 2007, 2008, 2009, 2010 and 2014.

### 2.2 Area-weighted water quality level

Eutrophication index or composite pollution index – CPI can be used to evaluate the pollution status of a given water body, especially with the issue of eutrophication (SOA, 2011; Zou, 1985; Xiao et al., 2007; Chen et al., 2007). As coastal water quality in China

have been dominated by nutrient pollution (SOA, 2010, 2011, 2013), an area-weighted nutrient pollution index (AWCPI-NP) was proposed (Xing et al., 2011b) to evaluate the overall water quality status in regional waters which can be classified as different water bodies with different water quality levels, see Eq. (1):

$$5 \quad \text{AWCPI-NP} = \sum_{i=2}^5 N_i \cdot P_i \cdot A_i \quad (1)$$

where  $i$  is the water quality level of polluted waters,  $N_i$  is the lower limit of TIN-N concentration ( $\text{mgL}^{-1}$ ) at the level  $i$ , and the same with  $P_i$ , the lower limit of  $\text{PO}_4\text{-P}$  concentration ( $\text{mgL}^{-1}$ ) at this level (Table 1).  $A_i$  is the corresponding area of water body at this level ( $\text{km}^2$ ).

The yearly AWCPI-NP was calculated using Eq. (1). As data before 2001 was not available, only the data of water quality level ( $i$ ) and its area ( $A_i$ ) since 2001 were collected from the annual reports of SOA, China. For the Yellow Sea, we have no water quality data about the coastal waters near Korean Peninsula, and so the AWCPI-NP was calculated based on the water quality data from China. Taking the population, watershed and other factors into account, it is safe to hypothesize that the AWCPI-NP at the western Korean coastal waters will not decrease, which will not influence the results of time series analysis in AWCPI-NP.

### 2.3 Mapping floating macro-algae

Floating macroalgae has the similar spectral characteristics to vegetations, and so the widely used normalized difference vegetation index (NDVI) can be applied to extract the macroalgae patches, or other similar indices (Hu et al., 2009) can be used. In this work, Moderate-Resolution Imaging Spectroradiometer (MODIS terra/aqua) reflectance products with a resolution of 500 m were used. After MODIS imageries were georeferenced, the band 1# (840–875 nm) and 2# (620–670 nm) were used to generate the NDVI images. The NDVI was calculated as Eq. (2). A threshold value of NDVI

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was set to identify the floating macroalgae patches; due to the impacts from clouds, haze, sun glints, water background, a strategy of dynamic NDVI threshold was used to extract macroalgae patches (Xing et al., 2011a; Cui et al., 2013). Finally the maximum MODIS-derived daily distributions of macroalgae from 2007 to 2013 were calculated.

$$5 \quad \text{NDVI} = (\text{band1} - \text{band2}) / (\text{band1} + \text{band2}) \quad (2)$$

## 2.4 Satellite-derived Chl *a* data

The annual Chl *a* concentration with a 9 km × 9 km spatial resolution was obtained from the satellite imaging products of Sea-viewing Wide Field-of-view Sensor (SeaWiFS) and MODIS aqua (data available: <http://oceancolor.gsfc.nasa.gov>). The Chl *a* data were derived from SeaWiFS and MODIS aqua imageries on the basis of the algorithm developed by O'Reilly et al. (1998). To avoid the uncertainties in satellite-derived Chl- *a* products in the turbid waters, we extracted the average of Chl *a* at the middle of the Yellow Sea (123–125° E, 34–36° N) as well as the Bohai Sea (120–120.5° E, 38.25–38.75° E) during the 1998–2012 period (Fig. 1): (a) MODIS data: 2002–2012; (b) SeaWiFS: 1998–2010. The systematic bias between the SeaWiFS Chl *a* and the MODIS Chl *a* was corrected through Eq. (3), and then, the corrected SeaWiFS Chl *a* from 1998 to 2002 and the MODIS Chl *a* from 2003 to 2012 were used to generate a yearly time series of satellite-derived Chl *a*.

$$20 \quad \text{SeaWiFS Chl } a, \mu\text{g L}^{-1} = 1.0772 \times \text{MODIS Chl } a + 0.0961 \quad (3)$$

## 2.5 Other data

Monthly Sea Surface Temperature (SST), and Photosynthesis Active Radiation (PAR) of detected by MODIS terra were used for investigating the water temperature and solar radiation (data available: <http://oceancolor.gsfc.nasa.gov>). To investigate the impacts of runoff on the Yellow Sea and the Bohai Sea, precipitation data from 1998 to 2009 in the two coastal regions were extracted from the Tropical Rainfall Measuring

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Mission (TRMM) Microwave Imager precipitation products: (a) the west coastal region of the Yellow Sea (117–122° E, 32–37° N); (b) the Bohai coastal region (115–123° E, 36–42° N), which had been calibrated and rescaled to monthly data (3B43) on the  $0.25^\circ \times 0.25^\circ$  grid (Huffman, 2007). To analyze the trends in precipitation, a 12-point running average was used to remove the impacts of seasonal fluctuations.

### 3 Results

#### 3.1 World-largest super floating macroalgal blooms

The maximum daily covered areas from 2007 to 2013, derived from satellite imageries, show that floating macroalgae mainly occurred in the west of the Yellow Sea and to the north of the Jianguo Shoal (Fig. 1). The Jianguo Shoal was the source of macroalgae and its waters was highly eutrophicated due to the nutrient input discharge of anthropogenic activities (Liu et al., 2012), but the turbid water conditions with the lowest Secchi depth of 0.1 m, limited the rapid growth of macroalgae (Xing et al., 2011a).

Especially from 2008, the bloom scale increased by several to ten folds. In the summer of 2008, the world-largest macroalgal blooms of *Ulva prolifera* drifted from the middle of southern part of the Yellow Sea and hit the Qingdao City (Xing et al., 2009; Liu et al., 2009; Zheng et al., 2011), covering an area of 1200 km<sup>2</sup> in total (Table 2) and impacting as many as 40 000 km<sup>2</sup> of sea surface; and, only from a part of the coast of Qingdao, more than 1 000 000 tons of biomass were collected (Xing et al., 2011a). This bloom scale is much larger than any other places in the world, e.g., Italy, France, Australia (Menesguen, 2006; Morand and Briand, 1996); and the conservatively collected biomass of green algae in 2008 is also larger than that of floating sargassum in a recent large scale bloom (Gower and King, 2011; Smetacek and Zingone, 2013).

## 3.2 Progressive nutrient pollution behind the MAB

In the semi-enclosed region of the Yellow Sea and the Bohai Sea, the polluted areas characterized by different water quality levels fluctuated yearly without a significant trend during the 2001–2012 period (Fig. 2): in the Yellow Sea, the area of relatively clean waters (Level II) decreased by about 50% while the Level V (heavily polluted waters) increased sharply, and there were no significant trends in the polluted (Level III) and slightly polluted waters (Level II); and from this information, it is difficult to assess the overall trophic status. The application of the area-weighted eutrophication index or nutrient pollution index (AWCPI-NP) overcomes the method previously used (Xing et al., 2011b); Fig. 2c and d show the AWCPI-NP changed in the Yellow Sea and the Bohai Sea. Both the Yellow Sea and the Bohai Sea experienced an increase in nutrient pollution, especially the latter increased by one fold from 2001 to 2007.

The annual values of AWCPI-NP from 2001 to 2012 (Fig. 2c) show a significant high level of nutrient status since 2004 in the semi-enclosed region ( $p < 0.01$ ,  $F$  test). The large-scale floating macroalgal blooms, happened every summer since 2007, and the averaged AWCPI-NP in 2007–2012 (MAB phase) is larger by about 45% than that in 2001–2006 (pre-MAB phase), and nearly three times of that in 2001–2003. These results supports that the eutrophication process in the Yellow Sea might lead to the macroalgal blooms. When the AWCPI-NP is normalized by the enclosed area, we can find that the Bohai Sea has a higher trophic status than the Yellow Sea (Fig. 2d). We can expect that the net nutrients flux are generally from the polluted nearshore waters to clean offshore waters and from the inner semi-enclosed region (the Bohai Sea) to outer part (the southern Yellow Sea).

Records (SOA, 2013; JSOF, 2012) show that polluted sea water in Jiangshu province (coastal water along the Jiangsu Shoal, Fig. 1c) increased rapidly by more than one fold from 2003 to 2011, and its contribution to the pollution in the Yellow Sea also increased, e.g., more than 60% in 2007 (Fig. 3a). Meanwhile, the nitrogen and phosphorus concentration increased significantly from 2000 to 2011 (Fig. 3b); especially, the

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fluctuations in nutrients and temperature in the center of the Yellow Sea (Box A in Fig. 1); and (c) macroalgal blooms may affect phytoplankton in the ways of nutrient-competitions and so on. At the center of the Yellow Sea, the Chl *a* lower than  $1.5 \mu\text{gL}^{-1}$  had a high correlation with the AWCPI-NP ( $p < 0.01$ ) (Fig. 3b), which might imply that the less eutrophicated waters were sensitive to the nutrient input.

The floating macroalgae could cause false values in the satellite-derived Chl *a* (Xing et al., 2014). The annual Chl *a* concentration in the MAB phase was higher than that in the pre-MAB phase by 16%; when the months (June, July, August) with possible impact of floating algae were excluded, a rise of 15% in Chl *a* was still observed from the pre-MAB to MAB phase. These results suggest that a progressive eutrophication existed behind the super MAB and that the MAB did not change the eutrophication trend. Satellite-derived optical indices in addition to Chl *a*, also suggested an increase in the portion of phytoplankton particles in the southern Yellow Sea (Xing et al., 2012).

As indicated by Chl *a*, trophic status both in the middle southern Yellow Sea (Box A) and the offshore waters in the East China Sea (Box ECS in Fig. 1c), were lower than that in southwest of Yellow Sea (Box C), especially by 50% in the summer season. Macroalgae from the Jiangsu shoal visited the two regions (Hu et al., 2010; Xing et al., 2011a), but the bloom scales were very small, which also suggests that trophic status regulated the scale of macroalgal blooms in China coastal waters.

#### 4 Discussion and concluding remarks

The eutrophication trend indexed by the Chl *a* was consistent with the contemporary increasing trend in the AWCPI-NP and the fact of the continuous super macroalgal blooms in the Yellow Sea. The increase in Chl *a* in the Yellow Sea and the Bohai Sea in the 1998–2006 period was opposite of the decreasing trend at the low-latitude zone of global open oceans where the nutrients were reduced because of the enhanced seawater stratification driven by climate event – El Niño/Southern Oscillation (ENSO) (Behrenfeld et al., 2006). The increase in Chl *a* in coastal waters was most likely to be

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driven by the local eutrophication due to the input of excess nutrient because of human activities (Morand and Briand, 1996; Seitzinger et al., 2005).

Coastal zones in China have experienced a rapid process of urbanization and industrialization especially in the past thirty years since the beginning of opening-up economic policy in China (He et al., 2006). Magnitude of human disturbance in these areas have been increasing, and large amounts of anthropogenic pollutants (including nutrients) have been discharged into rivers and then into coastal waters. For example, the river nitrate flux in the Yangtze River basin increased about ten folds from 1968 to 1997 (Yan et al., 2003). The reports on China marine environment from 1992 to 2012 (SOA, 2010, 2011, 2013), also showed that the total area of unclean waters increased in the past 20 years, which were mainly due to nutrient pollution. The Yellow Sea and the Bohai Sea experienced a large amount of nutrients input due to human activities such as agriculture and aquaculture, especially at the Jiansu shoal. In addition to the anthropogenic perturbation in surrounded land regions with rapid economic development, the climatic variations of the precipitation increase in the coastal regions (Fig. 5) tended to bring more nutrients to coastal waters through runoff, wet precipitation and possible submarine groundwater discharge, and thus contribute to the increase in the AWCPI-NP.

Natural variations in water temperature, light conditions, can lead to the changes in the growth of phytoplankton, and, the increased Chl *a* in this way may not suggest an eutrophication process. With the comparison between the macroalgal bloom phase (2008–2013) and the pre-bloom phase (2001–2006), neither the Sea Surface Temperature (SST) nor the Photosynthesis Active Radiation (PAR) had significant shift (see Fig. 6). This fact suggests that SST and PAR were not likely the driving factors for the increase in phytoplankton or the outbreak of macroalgal blooms. Herbivorous zooplankton grazing can regulate the accumulation of phytoplankton (Behrenfeld and Boss, 2014), thus less grazing pressure rather than the eutrophication may lead to the increase in the biomass of phytoplankton (Chl *a*). However, the spatial contrast in Chl *a*, e.g., high Chl *a* in the Bohai Sea (Box B), moderate Chl *a* in southwest of Yellow Sea

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(Box C), and low Chl *a* in the middle of Yellow Sea (Box A) or East China Sea (Box ECS), suggests that the trophic status rather than zooplankton dominate the spatial distribution in Chl *a*; and, according to the reports of UNDP (United Nations Development Programme) (2007, 2011) on the Yellow Sea Large Marine System (YSLMS), no reports suggested a decrease in zooplankton biomass in this region.

Overall, twelve years of AWCPI-NP and Chl *a* data show that the Yellow Sea was facing a progressive eutrophication, and macroalgal blooms coincided with high levels of nutrient pollution. The expansion of *P. yezoensis* aquaculture were thought to lead to the world-largest macroalgal blooms in the Yellow Sea (Liu et al., 2009; Hu et al., 2010); in this view, there should be blooms before 2007 and their scales should be able to be predicted by the scale of aquaculture (e.g., the area) to which the seed population (Smetacek and Zingone, 2013) can be regarded to be linear proportional. However, there were no such floating macroalgal blooms observed in the Yellow Sea near Qingdao even with high spatial satellite images (Hu et al., 2010; Xing et al., 2011a). Increased aquaculture scale wouldn't likely dominate the non-linear outburst in the biomass of macroalgae, e.g., the green tides in 2008, but increased nutrient supply would by improving the growth rate (Smetacek and Zingone, 2013) when the nutrient level reaches the threshold for blooms, like the red tide of phytoplankton. We can speculate that the large scale macroalgal blooms since 2007 is the result of cumulative effect of eutrophication, i.e. over enrichment of nutrients.

As the current water trophic status is at a high level, if there is no significant change in the environmental conditions, we speculate that the large scale algal blooms in the Yellow Sea would not disappear unless the nutrients input can be effectively reduced. In fact, MODIS imagery show that a small scale of green tide was forming in the Souther Yellow Sea on 3 May, 2014, which covered about 50 km<sup>2</sup> of sea surface and was expected to increase in the coming summer. The averages of TIN and PO<sub>4</sub>-P in macroalgae-dominated waters (southwest of Yellow Sea) during the bloom of 2008 were 14.89 and 0.27 μmolL<sup>-1</sup>, respectively (Xia et al., 2009), which implied a limitation of phosphorus and general clean waters against China national marine quality criteria

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**Table 1.** TIN and PO<sub>4</sub>-P concentrations used for calculation of AWCPI-NP.

Water quality level	II	III	IV	V
TIN (mgL <sup>-1</sup> )	0.2	0.3	0.4	0.5
PO <sub>4</sub> -P (mgL <sup>-1</sup> )	0.015	0.030	0.030	0.045

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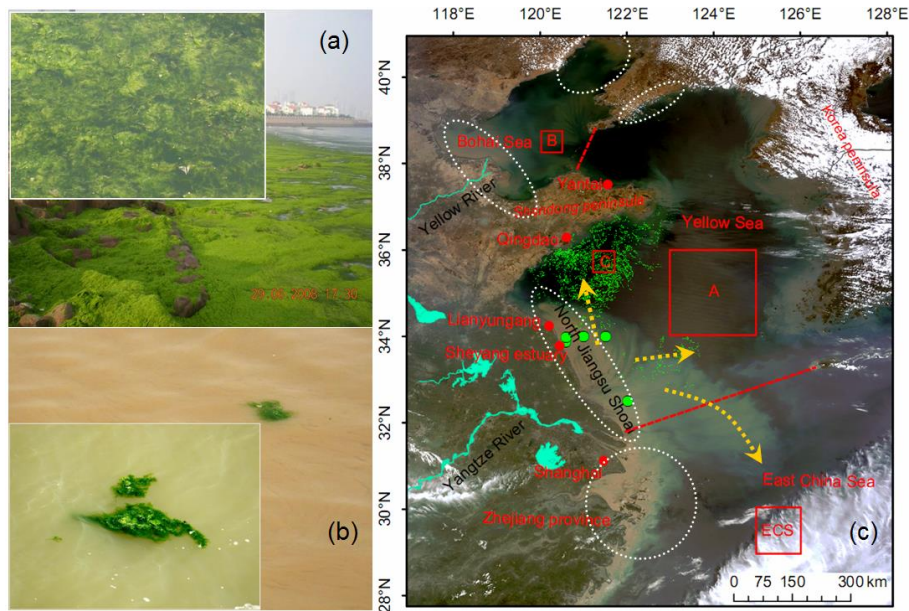
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**Table 2.** The satellite-derived annual maximum daily covering areas of floating macroalgae.

Year	Day-Month	Covering area, km <sup>2</sup>
2007	17 Jun	110
2008	31 May	1200
2009	22 Jul	860
2010	9 Jul	310*
2011	20 Jul	700
2012	21 Jun	300*
2013	29 Jun	1110

\* Due to the impact of clouds, the covering area is less estimated by about 50–150 %.



**Fig. 1.** In-situ photos of *Ulva prolifera* of green algae **(a)** covering the beaches in Qingdao on 29-June-2008 (photo by Qianguo Xing and Xianzheng Yuan) and **(b)** floating in the Northern Jiangsu Shoal (photo by Qianguo Xing and Yanju Hao). **(c)** Map of the spatial distribution of the green tide. Green patches are the sites of the annual maximum daily covering area of macroalgae from 2007 to 2013; green dots indicate the locations where macroalgae were validated in the cruise in the May of 2009; brown arrows show the major drifting pathways of floating macroalgae; the four red boxes show the locations where satellite-derived chlorophyll concentration was extracted; the red dash lines show the boundary of the Yellow Sea; the white-dot circles show the major polluted sites; the background image (generated by Qianguo Xing) is a true colour composite of bands 1(R), 4(G), 3(B) of MODIS acquired on 31 March 2010 (<http://ladsweb.nascom.nasa.gov/>).

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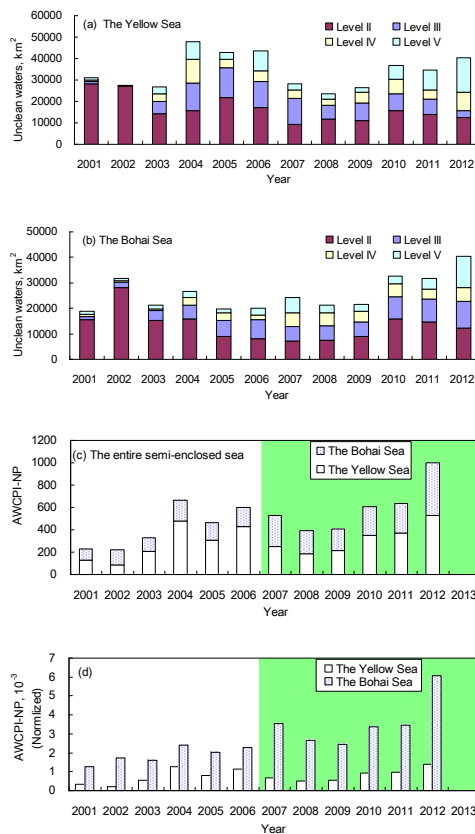
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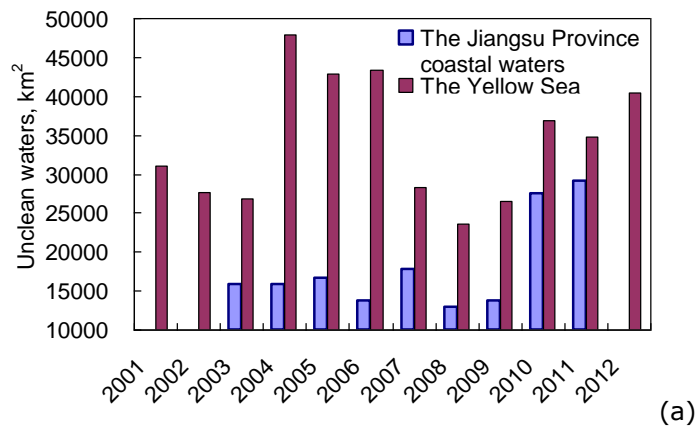
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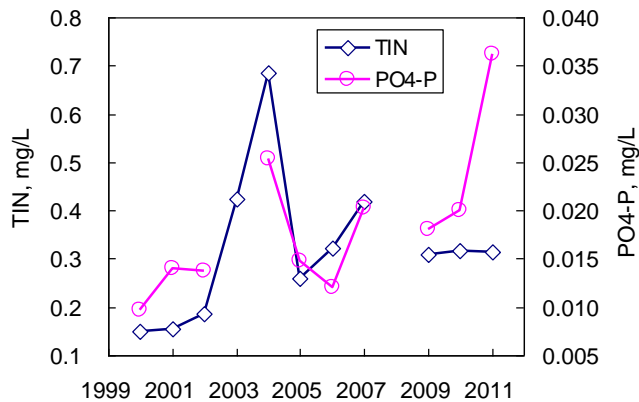
**Fig. 2.** (a) and (b) changes in nutrient quality levels in the Yellow Sea and the Bohai Sea, respectively, (c) the AWCPi-NP in the entire semi-enclosed sea, and (d) the AWCPi-NP normalized by the areas of the Yellow Sea (380 000 km<sup>2</sup>) and the Bohai Sea (77 000 km<sup>2</sup>). The green colour indicates the time span of super floating macroalgal blooms since 2007.

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(a)

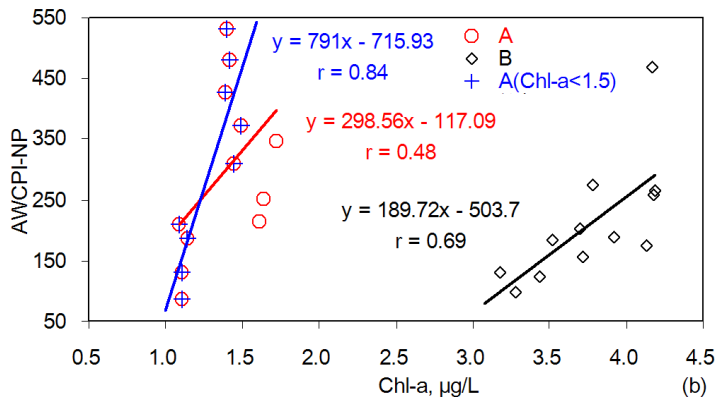
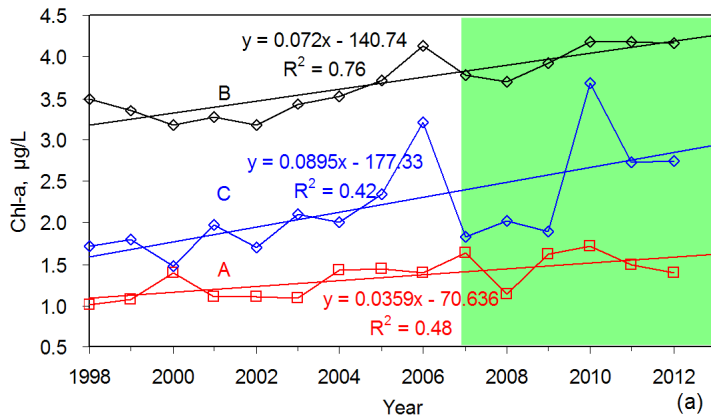


(b)

**Fig. 3.** Increasing trends in polluted area **(a)** and nutrient concentrations **(b)** in the Jiangsu Shoal behind the macroalgal blooms.

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**Fig. 4. (a)** Increases in the satellite-derived Chl *a* from 1998 to 2012 (the green colour indicates the time span of super macroalgal blooms), **(b)** relation between Chl *a* and the AWCPI-NP of the Yellow Sea (A) and the Bohai Sea (B) in 2001–2012.

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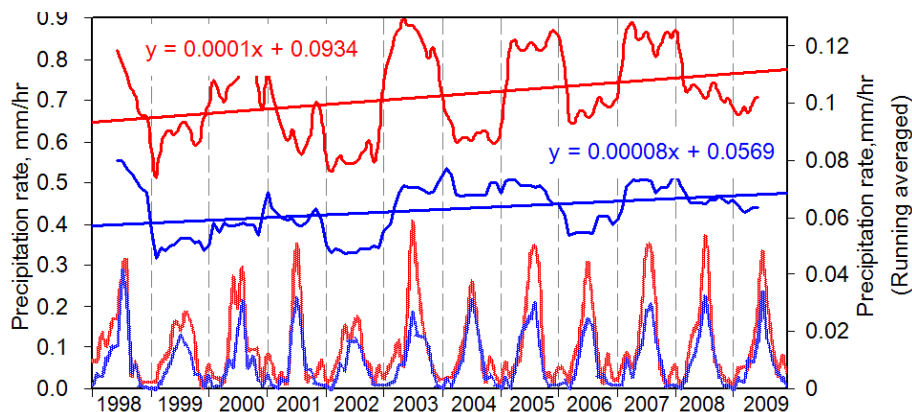
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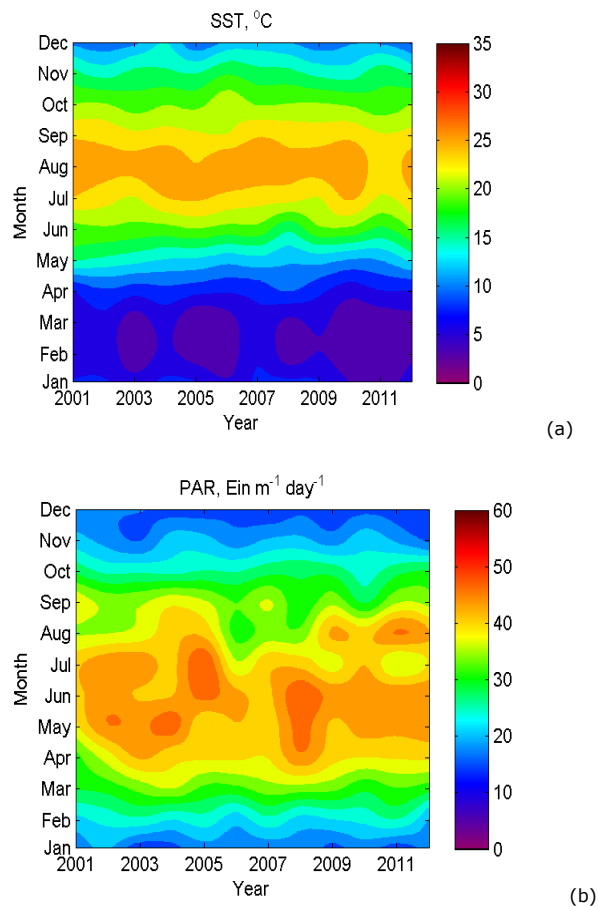


**Fig. 5.** Increasing trends in precipitation in the coastal regions of the Yellow Sea (red lines) and the Bohai Sea (blue lines). The solid lines show the 12-point running averaged precipitation rates.

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**Fig. 6.** Monthly SST and PAR in the period of 2001–2012 in the area with frequent occurrence of macroalgae (Box C).