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Preliminary remote sensing observation of sea surface temperature increase during *Ulva prolifera* blooms

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A massive bloom of green macroalgae Ulva prolifera *occurred in June 2008 in the Yellow Sea, resulting in perhaps the largest "green tide" event in the history of bloom research. The covered area is about 1,200 km^2 and the impacted area reached 40,000 km^2 on 31 May. This also occurred in the following two years, 2009 and 2010. We analyzed the satellite data from MODIS and the results showed that sea surface temperature increased 1–3°C in* U. prolifera *bloom locations. The macroalgae in the water may have been the cause of the increase of sea surface temperatures. Rapid increases of* U. prolifera *biomass during the blooms may have increased radiation absorption of the water, and thus enhanced the rate of heating at the sea surface. The present study represents a preliminary observation, which is an important step for understanding influences of macroalgae on ocean surface conditions.*

Keywords: green algae, marine ecology

Introduction

It is well known that the sea surface temperature (SST) is an important factor for the formation of algal blooms (Baicaud et al., 2002). Variations in sea surface temperature can be caused by solar heating (Stramma et al., 1986), wind stress (Price et al., 1987) and precipitation rate (Webster et al., 1996). Many researchers have studied the relationship between the sea temperature and the formation of algal blooms. Some in situ experiments note an increase of SST in the area of algal blooms (Qi et al., 1994), while various studies utilizing satellite images show an increase of SST at the location of algal blooms. This has significantly stimulated research efforts among ocean scientists to investigate and clarify the influence of algal blooms on sea surface temperature.

The excessive growth of some green algae species such as *Ulva, Enteromorpha, Chaetomorpha* and *Cladophora*, have been reported in the formation of macroalgae blooms or green-tide events in many parts of the world including Europe, North America, South America, Japan and Australia (Morand and Briand, 1996; Hiraoka et al., 2004; Morand and Merceron, 2005; Merceron et al., 2007). These green algae species are able to respond rapidly to excess nutrients, particularly when water temperature conditions are favorable to their growth (Valiela et al., 1997; Raffaelli et al., 1998). Typically, green-tides are characterized by the choking of waterways in the immediate area of the bloom and subsequent local wind and tide driven local deposition on the shore. This deposition can be destructive to coastal marine habitats (e.g. Seagrass) and cause economic losses

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to marine industries (e.g. fisheries and tourism) (Nelson et al., 2008).

In June 2008, the world's largest green-tide event ever, covering about 600 km^2, occurred along the coast of the Yellow Sea near Qingdao in China, threatening the 2008 Olympic Games sailing regatta (Liu et al., 2009; Qiao et al., 2009). In the two years that followed, 2009 and 2010, the green-tide recurred again in the Yellow Sea, most notably in 2009 (Hu et al., 2010), the covered area reached 2,100 km^{2}and the affected area reached early 60,000 km^2. These green-tide events provided the foundation for us to study the effect of macroalgae blooms on the sea surface temperature in the Yellow Sea.

In previous research, using satellite data and in situ data, we found that sea surface temperature could be affected by microalgae blooms (Wang and Tang, 2010). The diurnal sea surface temperatures can increase by 2–4°C at the bloom location. When macroalgae form blooms, do they also affect the sea surface temperature? A massive bloom of green macroalgae *U. prolifera* occurred in 2008, 2009 and 2010 in the Yellow Sea, providing us a good chance to investigate changes of SST related with the macroalgae bloom.

Remote sensing has become an indispensable tool for the monitoring of algal blooms over larger regions and over shorter/longer time scales than could be otherwise workable with ship based samplings (Tang et al., 2003). Here we used satellite data to analyze SST changes at macroalgae blooms location.

Materials and methods

Study area

The Yellow Sea is a semi-enclosed marginal sea of the northwestern Pacific, with an average depth of about 50 m and maximum depth of 100 m. It connects with the Bohai Sea in the north, and to the East China Sea in the south (Figure 1a). It has a rather smooth topography in its central region and steep slope topographies on both its western and eastern sides. In its western region, the depth is less than 20 m, where the China Continent Coastal Water, including Lubei and Subei Coastal Waters, is located. In the central region, there is a water mass with characteristic low temperature, called Yellow Sea Cold Water. In the eastern region there is a warm and saline water flowing from southeast to northwest, called the Yellow Sea Warm Current. At the confluence of warm and cold waters, the nutrient concentrations are very high, resulting in high primary production and important fishing areas. It therefore has been recognized that fisheries resources in the Yellow Sea are among the most abundant in the China Seas. The Yelllow Sea is also characterized by the seasonal variability of monsoons. The present study is focused on sea surface temperature changes at the location of *U. prolifera* blooms in the Yellow Sea.

Remote sensing data–SST and ocean color products

The SST and sea surface chlorophyll *a* (chl *a*) concentration data were acquired from MODIS (NASA data distribution system). The images are processed by using the SeaWiFS Data Analysis System (SeaDAS) (Baith et al., 2001).

Sea surface wind

Ocean vector wind was obtained using Sea-Windsscatterometer (Remote Sensing Systems in Santa Rosa, California, USA, http://www.ssmi.com/qscat/) for calculating the weekly average.

Results

Ulva prolifera blooms in 2009

The pathway of blooms

In June, 2009, macroalgae blooms occurred in southern Yellow Sea, China. The observations by satellite data, aircraft and ships show the pathway of macroalgae bloom formation (Figure 1a). It was first reported near the east ocean area of Yancheng, Jiangsu province on 3 June 2009 and occupied more than 7,000 km^2. The period of 4 June to 24 July showed an evolving algae bloom as numerous large green patches and demonstrated the time course in growth of algal biomass as well as the direction of movement of the patches (Figure 1a). The largest area of coverage reached 60,000 km^2 on 3 July (Table 1). On 3 June (Figure 1a), some small green patches which covered about 42 km^2 (Table 1) were evident in the east area of Yancheng, Jiangsu province. About one month

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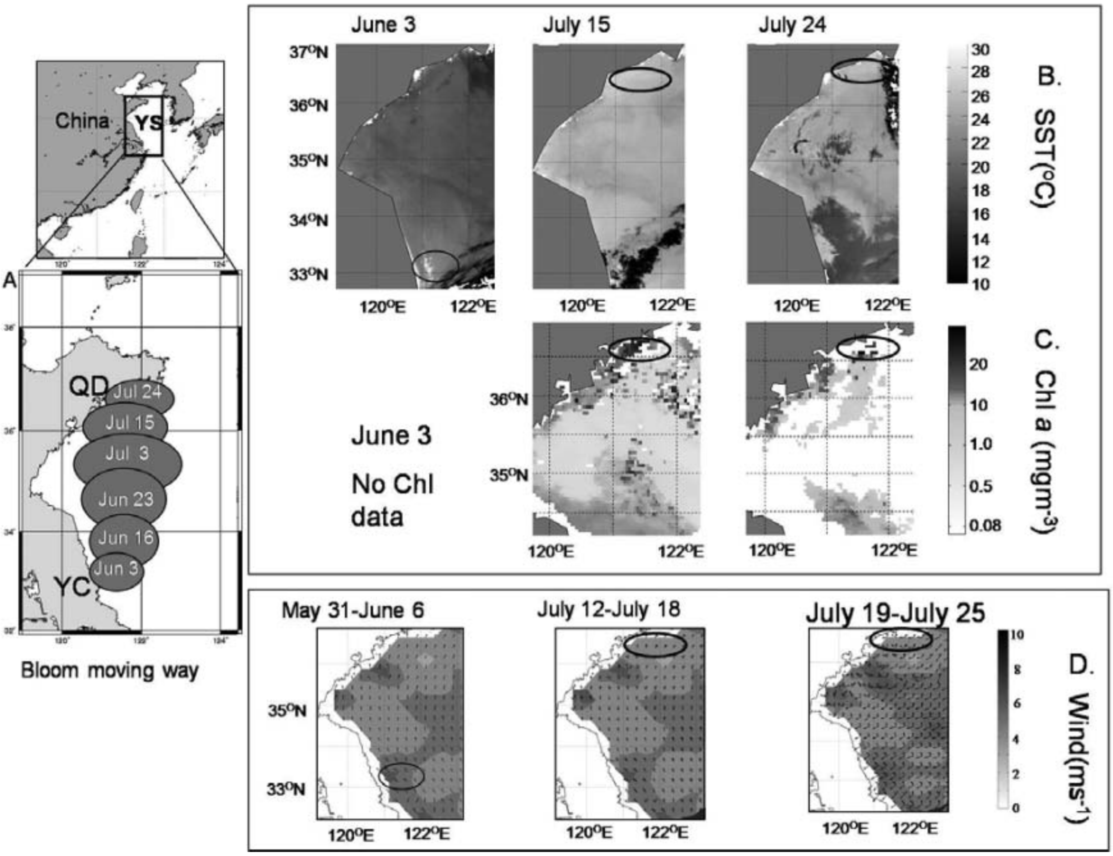

Figure 1. Study area (map A is the enlarged area of the black line box) and track of *Ulva prolifera* blooms in Yellow Sea during 3 June to 24 July in 2009 (gray ellipse in A) and satellite images (YS: Yellow Sea; YC: YanCheng; QD: QingDao).

later (1 July), the bloom patches had grown rapidly and covered about 1,200 km^2 impacting 40,000 km^2 (Table 1). At this time, they crossed out of the Jiangsu province and moved into the middle of the Yellow Sea near to Qingdao, Shandong province. On 3 July, the large green patches began to move towards the coast of Qingdao and Weihai, and began depositing on shore on 15 July (Figure 1a).

Increase of sea surface temperature and chl *a* concentration during the blooms

During the period in which the blooms were moving, a patch of increased SST was found in the same area as the bloom's location (Figure 1). In the beginning of this bloom event, 3 June, the SST

Table 1. The area of green-tide during the transport in Yellow Sea in 2009.

Date (DD-MM-YYYY)	Area covered (km^2)	Area impacted (km^2)	Increased SST (°C)
03-06-2009	42	6550	3–4 (Figure 1b)
16-06-2009	48	9300	
01-07-2009	1100	38,000	
02-07-2009	2100	58,000	
04-07-2009	1300	43,000	
06-07-2009	108	24,000	
15-07-2009	40	7000	1–2 (Figure 1b)

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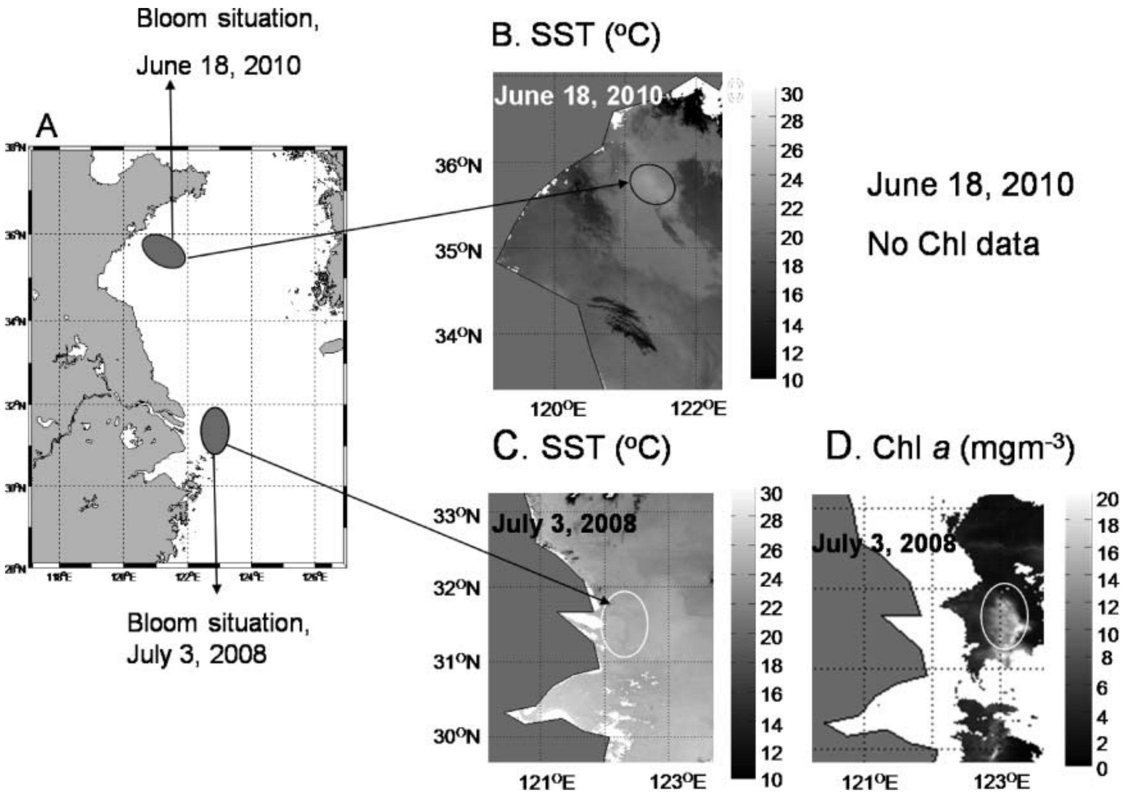

Figure 2. Situation of *Ulva prolifera* blooms (gray ellipse in A) in Yellow Sea on 3 July 2008 and 18 June 2010 and satellite images.

of water in the region with bloom reached 27–28°C, which is higher than the SST (24°C–25°C) around the affected area. There was no chl *a* data on this day. On 15 July, the degree of SST at the bloom location was 1–2°C higher than the surrounding area (Figure 1b). Chl *a* concentration of the bloom location reached 24 mg m^{-3}, considerably higher than the surrounding area without a bloom (Figure 1c). On 24 July, with more and more algae depositing on the shore, the degree of SST (25°C–26°C) along the coast became less than the SST (26°C–27°C) on 15 July, but is still higher than in surrounding regions (Figure 1b). The chl *a* concentration of the bloom location reached 22 mg m^{-3}.

Sea surface winds during the blooms

During the period from June to July, the pattern of south-west winds was consistent with the movement of *U. prolifera* blooms patches from near Yancheng to Qingdao and Weihai. Within the bloom regions, the wind speed did not show significantly different characteristics (Figure 1d, the

Table 2. Three *Ulva prolifera* bloom events occurred during 2008–2010.

Date (DD-MM-YYYY)	Area covered (km^2)	Area impacted (km^2)	Increased SST (°C)
03-07-2008	500	16,000	1–2 (Figure 2c)
15-07-2009	40	7000	1–2 (Figure 1b)
18-06-2010	350	12,400	2–3 (Figure 2b)

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area of black circle). During the bloom period, the wind is south-west with an average speed of 5.6 ms^{-1}. Sometimes the wind speed can reach 8.9 ms^{-1}.

Two more *Ulva prolifera* blooms in 2008 and 2010

Ulva prolifera blooms have also been reported in the Yellow Sea in the years of 2008 and 2010. Using satellite and aircraft observations, we can trace the travel of the blooms. The SST is higher at the bloom location area in 2008 and 2010. In 2008, the sea surface temperature of blooms region reached 27^{o} (Figure 2c). In 2010, the sea surface temperature of blooms region reached 23^{o} (Figure 2b). In 2008, the chl *a* concentration of the bloom region was much higher, reaching 16 mg m^{-3} (Figure 2d). The patch of higher chl *a* concentrations and SST coincided with the bloom in terms of location and timing (Figure 2).

Discussion

The satellite images showed high SST and a chl *a* patch in Yellow Sea in 2009, and this patch moved from the south to the north of Yellow Sea. This high SST and chl *a* patch coincided with the *U. prolifera* bloom in terms of location and timing. The same phenomena appeared in 2008 and 2010 (Table 2). High SST in *U. prolifera* bloom areas was observed (Figures 1b, 2b and 2c) in the present study, in agreement with previous findings which indicated that phytoplankton can increase the sea surface temperature (Wang and Tang, 2010; Sathyendranath et al., 1991).

Rapid increases of *U. prolifera* biomass during the blooms may increase radiation absorption of water, and thus increases the rate of heating at the sea surface. Light is both scattered and absorbed by algae, and the effects depend on their size distribution and biomass (Mazumder et al., 1990). Thus, the SST in areas of phytoplankton blooms may be different according to the different species and biomass of the algae making up the bloom.

Solar irradiance may be reflected at the surface, backscattered by algae to the atmosphere. Algae have a major influence on water clarity and attenuation of light in oceans (Baicaud et al., 1988). Usually, light penetration is largely a function of size distribution and biomass of algae (Mazumder et al., 1990). In bloom areas, the light penetration is reduced, and water causes rapid light attenuation with depth. As a result, the warming effect of solar radiation is restricted to sea surface temperature, causing it to increase.

Satellite images showed high chl *a* concentration in the *U. prolifera* bloom area. The macroalgae biomass increased during the blooms, which will increase chl *a* concentration. On the other hand, macroalgae blooms may change the phytoplankton population structure and biomass in the water, which can also alter the chl *a* concentration in the water.

Conclusions

We analyzed satellite data of three incidents of *U. prolifera* blooms in the Yellow Sea, and the results showed a sea surface temperature (SST) increase of 1–3°C in *U. prolifera* bloom locations. The macroalgae in the water may have increased the sea surface temperature. Rapid increases of *U. prolifera* biomass during the blooms may have increased radiation absorption of water, and thus enhanced the rate of heating at the sea surface.

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