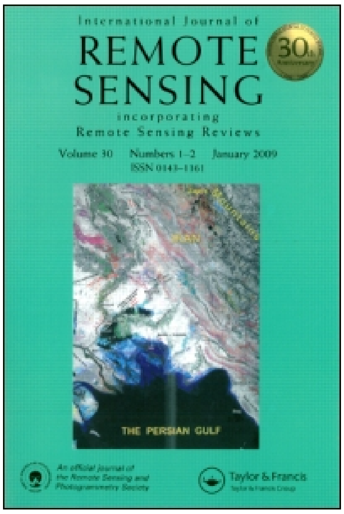

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Remote sensing of day/night sea surface temperature difference related to phytoplankton blooms

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The diurnal sea surface temperature (D-SST, which is the daytime SST minus the night-time SST) and its relationship with heavy phytoplankton blooms were observed using satellite and *in situ* data. Two phytoplankton bloom events covering large areas in the East China Sea (ECS) were analysed to investigate the reactions among D-SST, chlorophyll-*a* (chl-*a*) concentration, suspended sediment (SS), coloured dissolved organic matter (CDOM), wind speed (WS) and solar radiation (SR). The results showed a positive relationship between D-SST and chl-*a* concentration in phytoplankton bloom areas. Further analyses of 12 major phytoplankton bloom events (total area >1000 km^2) occurring between 2000 and 2005 in the ECS, accompanied by *in situ* observation data in Daya Bay, confirmed a positive correlation between chl-*a* concentration and D-SST. These results showed that an increase in D-SST may be found in heavy phytoplankton bloom areas. The present study represents an important step for understanding the influence of phytoplankton on ocean conditions.

1. Introduction

It is well known that sea surface temperature (SST) is one of the most important factors for phytoplankton blooms (Bricaud *et al.* 2002). Studies on chlorophyll-*a* (chl-*a*) and SST in the South China Sea (SCS) showed that nutrients in cold water (low SST) associated with upwelling can induce phytoplankton blooms (Tang *et al.* 2004). Phytoplankton blooms are now able to be monitored (directly) either through their influence on water colour or (indirectly) correlating with algal bloom and associated water masses that can be checked out with the characteristics of SST (Tester *et al.* 1991, Keafer and Anderson 1993, Suh *et al.* 2004). Some *in situ* experiments indicate an increase in SST during the daytime period of algal blooms (Qi *et al.* 1994), while various studies utilizing satellite images show an increase in SST at the location of algal blooms. This has significantly stimulated research efforts among ocean scientists to investigate and clarify the influence of algal bloom on sea surface temperature and diurnal sea surface temperature (D-SST, which is the daytime SST minus the night-time SST).

D-SST is important for ocean–atmosphere convection and the net transport of heat by the ocean as a whole (Kawai and Wada 2007). D-SST variation can be caused by solar heating (Stramma and Cornllon 1986), wind stress, air–sea heat flux (Price *et al.* 1987) and precipitation rate (Webster *et al.* 1996). Much research has been conducted to understand the reasons for the changes in D-SST (Soloviev and Lukas 1997, Casey 2002, Kawai and Kawamura 2002). Previous studies have shown high D-SST during

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periods of weak wind speed and strong insolation (Gentemann and Donlon 2003, Kawai and Kawamura 2005). The daily peak in diurnal warming is related directly to the minimum wind speed during the day; D-SST was attributed to low wind speeds and strong insolation (Cornillon *et al.* 1993).

Phytoplankton blooms appear to be an increasingly common phenomenon on a world-wide scale and are sometimes considered to be harmful either because of their potential threat to human health through the consumption of contaminated seafood, as in the case of many toxic phytoplankton blooms, or through the changes in species abundance and distribution (Anderson 1997, Tester and Stumpf 1998, Wang *et al.* 2008). Spatial and temporal variability in phytoplankton blooms is controlled largely by various factors, such as nutrition, temperature and wind mixing (Cloern 1996, Beman *et al.* 2005, Heisler *et al.* 2008). Research on Hong Kong's worst 'red tide' showed that the increase in sea surface temperature and the high concentrations of PO_4-P, NH_4-N and TKN (total Kjeldahl nitrogen) are the important factors for the bloom's occurrence (Yang and Hodgkiss 2004). Kim *et al.* (2007) studied the relationship between phytoplankton bloom and wind stress; the results showed that seasonal wind played an important role in controlling the spring and autumn blooms.

Remote sensing of phytoplankton blooms has become an indispensable tool for monitoring these algal blooms over larger regions and shorter/longer time-scales than would be practicable with ship-based samplings (Tang *et al.* 2003). In particular, remotely sensed SST has been used to trace the transport of algal blooms (Tester *et al.* 1991) and, thus, offers great promise as a tool to provide early warning of conditions conducive to phytoplankton bloom development and transport (Keafer and Anderson 1993). In the currently available literature, there are few *in situ* observations of D-SST in algal bloom-impacted areas because of the difficulty of observing ocean conditions at night. Now we can use satellite data to analyse D-SST changes at algal bloom locations.

The variation in D-SST could also be highly useful in Korean waters, in helping to identify potentially predictive signals likely to be indicative of impending algal bloom events (Suh *et al.* 2004). However, additional and more comprehensive information is needed to validate more conclusively the degree in variation and to what extent the variation differential in diurnal SST can be attributed to algal blooms.

In the majority of cases for Chinese coastal waters, algal bloom events can sometimes cover more than 1000 km^2. Moreover, in recent years, the algal bloom frequency has increased, especially in the East China Sea (ECS) (Zhou *et al.* 2003, Tang *et al.* 2006). In 2003 alone, 119 algal bloom events, with a cumulative area of 14 550 km^2, were reported over Chinese coastal areas. Seventy-two percent of these events, covering 89% of the total affected Chinese coastal areas during that year, were observed in the ECS (SOA 2004). While examining SST in algal blooms during 2002 to 2005 in the ECS, we noticed significant variations in D-SST at the algal bloom-impacted areas. This resulted in the present study – to investigate the relationships between blooms/chl-*a* concentration and D-SST using both remote sensing and *in situ* data, and also to analyse the influence of suspended sediment (SS), coloured dissolved organic matter (CDOM), solar radiation (SR) and wind speed (WS) on the D-SST variation.

2. Materials and methods

2.1 *Study area*

The ECS is an important marginal sea of China (1 249 200 km^2), with an average depth of 370 m. The present study is focused on the area that has proximity to algal

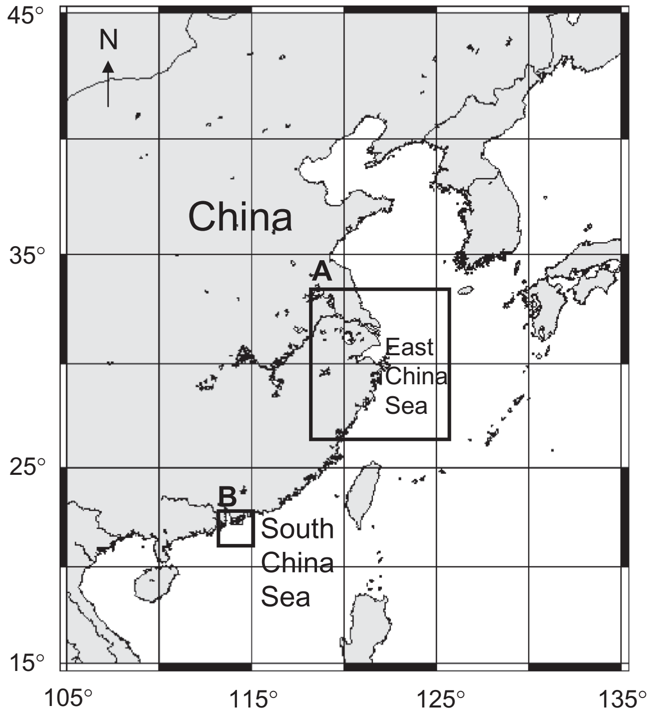

Figure 1. Location of the study area: Box A, the East China Sea; Box B, Daya Bay.

blooms (Latitude, N: 120–128° and Longitude, E: 26–34°) on its western boundary (figure 1, box A). The Yangtze River, discharging into the ECS, is the largest and third-longest (6300 km) in the world. Initially, we were able to collect the referenced data (e.g. previous studies and publications, including news from the internet on the locations, species compositions and cell concentrations) for about 28 major/minor algal bloom events in the ECS between 2000 and 2005. Twelve of these major incidents are considered in the present investigation. Daya Bay is located at 22.5–22.9°N, 114.5–114.9°E, in the northern South China Sea (figure 1, box B), where some *in situ* experiments were carried out.

2.2 *Remote sensing data*

2.2.1 SST and ocean colour products. The SST data were acquired from the Advanced Very High Resolution Radiometer (AVHRR) (spatial resolution, 4 km/daily) on the National Oceanic and Atmospheric Administration's (NOAA's) Polar Orbiting Environmental Satellites (POES) (http://rs.gso.uri.edu/amy/avhrr.html). D-SST data were obtained by using the daytime SST minus the night-time SST. Ocean colour products were derived from Sea-viewing Wide Field-of-view Sensor (SeaWiFS). We processed three products to compare the relative amount of phytoplankton, CDOM (including detrital material) and SS in sea water: (1) the absorption coefficient of phytoplankton at 443 nm; (2) the absorption coefficient of CDOM at 412 nm; (3) the particulate backscatter coefficient at 555 nm to denote SS. Data were obtained from standard level-2 products of SeaWiFS (OC4v4 algorithm, 4 km × 4 km). SeaWiFS data were provided by the National Aeronautics & Space Administration (NASA)'s Ocean Color Working Group (http://oceancolor.gsfc.nasa.gov/) and processed using the SeaWiFS Data Analysis System (SeaDAS).

2.2.2 Solar radiation and sea surface wind. Solar radiation images were obtained from the National Center for Environmental Prediction (NCEP) reanalysis data provided by National Oceanic and Atmospheric Administration (NOAA)/Office of Oceanic and Atmospheric Research (OAR)/Earth System Research Laboratory (ESRL) Physical Sciences Division (PSD), Boulder, Colorado, USA (http://www.cdc.noaa.gov/). Wind vector images (QuikScat data) were produced by Remote Sensing Systems, sponsored by the NASA Ocean Vector Winds Science Team. Data were processed using MATLAB 6.0 and GrADS (Grid Analysis and Display System)

2.3 *Phytoplankton bloom data and analysis*

Phytoplankton bloom information from 2000 to 2005 in the ECS were collected from various sources, including government statistics reports, research journals, conferences and other reports and newspapers. Twelve main algal bloom cases (area > 1000 km^2) were selected (table 1) while remote sensing data were available and relatively good. Two large areas (> 7000 km^2) of algal blooms were selected to process remote sensing data of D-SST, chl-*a* concentration, SS, CDOM and WS for detailed analysis. In all 12 algal events, we selected 100 km^2 for data sampling and a total of 212 sampling boxes were analysed.

3. Results

There were 28 major/minor phytoplankton bloom events in the ECS between 2000 and 2005. Of these, two large affected regions (area > 7000 km^2) were selected as examples to analyse. These reflected both offshore and coastal algal bloom occurrences. In addition, for detailed analyses, 12 examples were collected utilizing remote sensing data.

3.1 *Analysis of two cases*

3.1.1 Case in 2000. During 3–24 May 2000, there were two large algal bloom events in the Zhongjielie Island and Taizhou Island areas (table 1), where *Prorocentrum dentatum* was the dominant species (SOA 2000). The toxic algal cell concentrations reached $6 \times 10^9 m^{-3}$. Elevated D-SST was evident at the location of algal blooms (figure 2(*a*), 'a' and 'b'), where D-SST reached 2–4°C. Chl-*a* concentration was observed to be higher than 5 mg m^{-3} (figure 2(*b*)) at both bloom areas; some areas reached 16 mg m^{-3},obviously higher than in the surrounding waters, but SS and CDOM did not show significant increases in either algal bloom event areas (figures 2(*c*) and (*d*)). The SR was about 320 W m^{-2} – the same as the surrounding areas (figure 2(*e*)). The daytime WS (figure 2(*f*)) in the algal bloom area did not show significantly different characteristics. In summary, high chl-*a* concentration may be associated with high D-SST in algal bloom regions.

3.1.2 Case in 2005. In 2005, several algal bloom events occurred in the ECS region. The most severe and widespread of these was the algal bloom event occurring at the Yangtze and Qiantang River estuary, in which the affected area reached 7000 km^2. The D-SST in the algal bloom region was clearly higher than that in the surrounding

Table 1. Twelve algal bloom cases in the East China Sea.

S. no.	Date	Location	Area (km^2)	D-SST (°C) of the area without HAB	D-SST (°C) of the area with HAB	References
1 (Case I)	3–21 May 2000	Zhongjielie Island (sea area) (*Prorocentrum dentatum*)	7000	0–2	1–4	SOA
2 (Case I)	12–24 May 2000	Taizhou Island (sea area) (*Prorocentrum dentatum*)	5800	0–2	2–3	SOA
3	10–17 May 2001	Yangtze River estuary (sea area) (*Prorocentrum triestinum*; *Prorocentrum dentatum)*	3400	0–2	2–4	SOA
4	12–16 June 2002	Taizhou (sea area) (*Prorocentrum dentatum*)	1300	0–2	2–4	SOA
5	20 August 2002	Zhoushan (sea area)	1200	0–1	2–5	SOA
6	22 August 2002	Zhoushan (sea area)	1500	0–1	2–3	SOA
7	1 May 2003	Yangtze River estuary (sea area)	1200	0–1	2–3	SOA
8	19 May 2003	Yangtze and Qiantang Riverine estuaries (*Prorocentrum dentate*)	1000	0–1	3–5	SOA
9	28–30 June 2003	Yangtze River estuary and offshore (sea area) (*Skeletonema costatum*)	1000	0–1	3–4	SOA
10	10 May 2004	Zhoushan (sea area) (*Prorocentrum donghaiense*)	8000	0–2	1–2	SOA
11	4 April 2005	East china Sea (sea area)	3000	0–1	5–6	SOA
12 (Case II)	31 May–12 June 2005	Taizhou Yangtze and Qiantang River estuaries (*Prorocentrum dentatum*)	7000	–1–0	2–4	SOA

HAB, harmful algal bloom

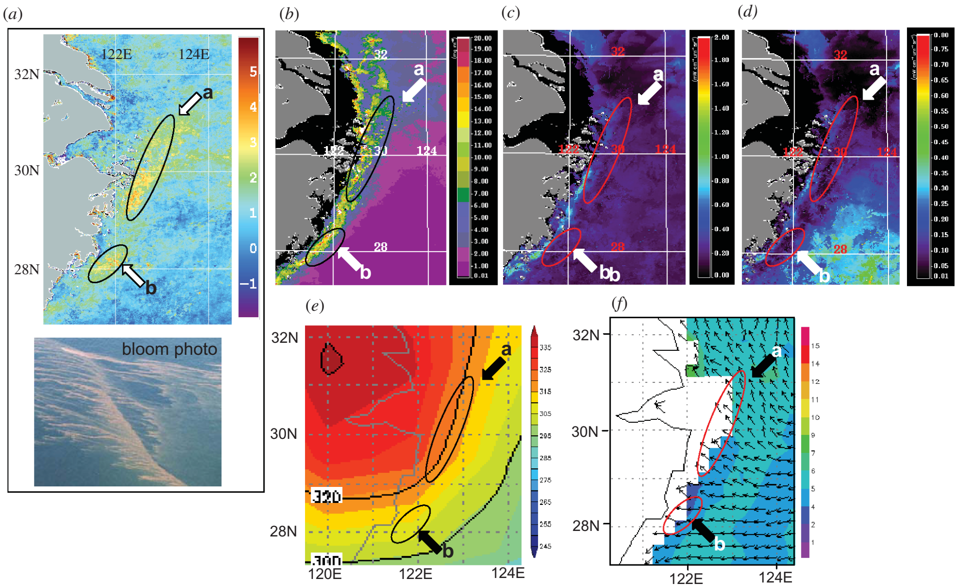

Figure 2. Satellite images and *in situ* photo of blooms (case I) during 3–24 May 2000: (*a*) D-SST (°C) and bloom photo; (*b*) chl-*a* (mg m^{-3}); (*c*) SS (mW cm^{-2} µm^{-1} sr^{-1}); (*d*) CDOM (mW cm^{-2} µm^{-1} sr^{-1}); (*e*) SR (W m^{-2}); (*f*) DWS (m s^{-1}). Points 'a' and 'b' indicate the algal bloom reports in the Zhongjielie and Taizhou Island sea areas, respectively.

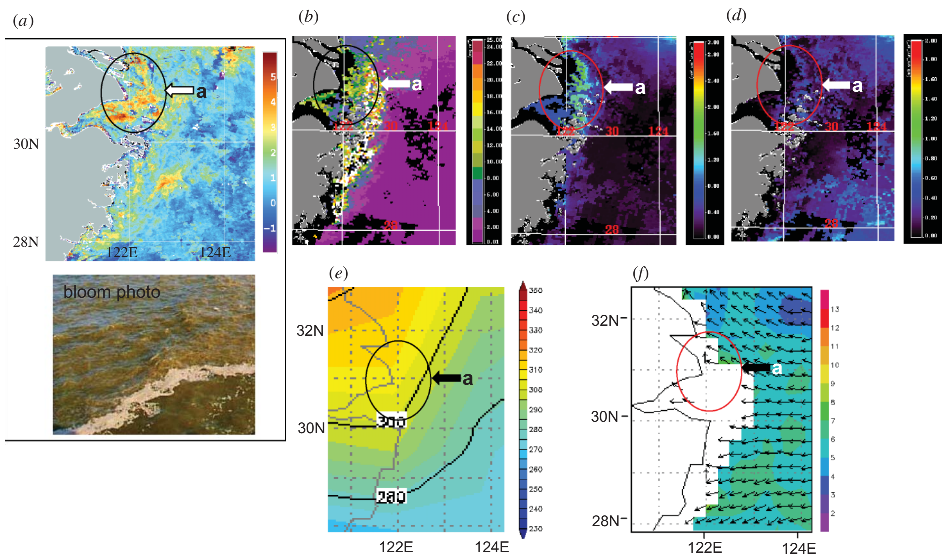

Figure 3. Satellite images and *in situ* photo of bloom (case II) during 31 May–12 June 2005. Point 'a' indicates the algal bloom report in the Yangtze and Qiantang River estuaries. (*a*) D-SST (°C) and bloom photo. (*b*) chl-*a* (mg m^{-3}). (*c*) SS (mW cm^{-2} µm^{-1} sr^{-1}). (*d*) CDOM (mW cm^{-2} µm^{-1} sr^{-1}). (*e*) SR (W m^{-2}). (*f*) DWS (m s^{-1}).

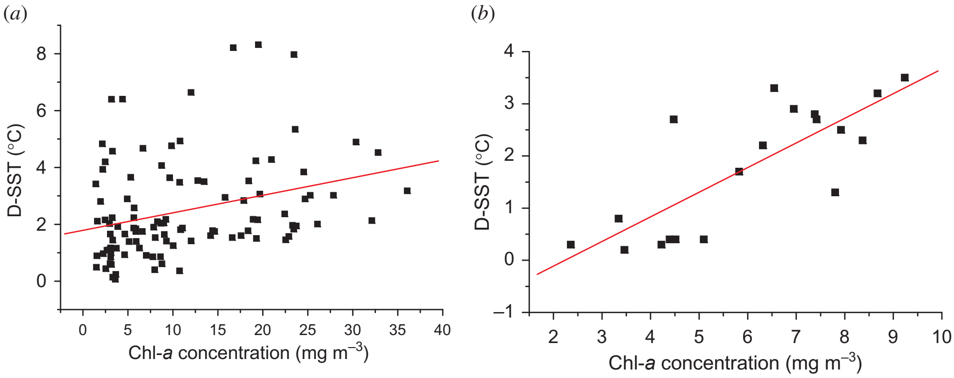

Figure 4. Correlation analysis of D-SST and chl-*a* concentration: (*a*) remote sensing data ($Y = 1.78712 + 0.06171$; $R = 0.30472$; $P = 0.00166$); (*b*) *in situ* measurements ($Y = -1.05755 + 0.47241X$; $R = 0.7926$; $P < 0.0001$).

area (figure 3(*a*), 'a'). The chl-*a* concentration was up to 10 mg m^{-3}; the highest concentration was 30mg m^{-3} (figure 3(*b*), 'a'). No significant high SS and CDOM were observed in the algal bloom waters (figures 3(*c*) and (*d*), 'a'). The same results were seen for the SR and WS in this large algal bloom region (figures 3(*e*) and (*f*), 'a'). The chl-*a* concentration was the main variable that affected the D-SST in the algal bloom region.

3.2 *Relationship between chl-*a* concentration and D-SST*

Twelve major algal bloom events occurring between 2000 and 2005 in the ECS (table 1) were analysed with respect to the relationship of D-SST to chl-*a* concentration. The D-SST in the algal bloom areas is usually higher than that in the areas without algal blooms (table 1).

A total of 212 samples (area of 100 km^2) taken from 12 algal bloom events were analysed. The results show a positive correlation between D-SST and chl-*a* concentration (figure 4(*a*)). *In situ* data in Daya Bay also indicate this positive correlation (figure 4(*b*)). *In situ* data were obtained at the same location and season for one event. Satellite data were taken from many algal bloom events (from 2000 to 2005), which were at different locations and seasons. The correlation coefficient is different between the *in situ* and satellite data. It is possible that the correlation between D-SST and chl-*a* concentration was influenced by the algal blooms which occurred at different regions and seasons; more research is needed. However, both *in situ* and satellite results showed this positive correlation.

4. Discussion

4.1 *Diurnal SST with phytoplankton*

Phytoplankton require sunlight, water and nutrients for growth. Phytoplankton remain at or near the surface in the daytime because that is where sunlight is most abundant. As a result of stratification, nutrients can often become more enriched in bottom waters and often more depleted in surface waters. Phytoplankton generally undergo a diurnal vertical migration (DVM) (Kamykowski *et al.* 1998, Townsend *et al.* 2005), in which surface aggregations during the day and subsurface dispersal or aggregation at night are observed. In general, phytoplankton blooms stay at deeper layers at night and return to the surface layer (between 0 and 5 m) during the day to perform photosynthesis (Kamykowski *et al.* 1998).

High D-SST in algal bloom areas were observed (figures 2 and 3) in the present study, in agreement with previous findings that phytoplankton can increase the sea surface temperature (Sathyendranath *et al.* 1991). Rapid increases in algal cells during the blooms may increase absorption of radiation and, thus, enhance the rate of heating at the sea surface temperature. Bloom areas have more algae that can absorb more solar radiation and heat the surface temperature in the daytime. At night, there is no solar radiation, so there is no solar energy absorption. Meanwhile algal cells move to the deeper layers, bringing heat with them, which will in turn decrease the surface temperature. Therefore, diurnal SST is higher in the phytoplankton bloom areas.

Light is both scattered and absorbed by algae, and the effects depend on their size distribution and biomass. Smaller algae have greater absorption and scattering per unit mass than larger algae because their surface area per unit mass is larger (Mazumder *et al.* 1990). Thus, the diurnal SST in areas of phytoplankton blooms may be different according to the different species in the algal blooms. These relationships require much further study.

4.2 *The effect of water colour on the diurnal surface temperature*

Solar irradiance may be reflected at the surface, backscattered by planktonic particles to the atmosphere and absorbed as heat by water. Algae have a major influence on water clarity and attenuation of light in oceans (Bricaud *et al.* 1988). High D-SST observed in the phytoplankton bloom areas may be due to the discoloration of the water, resulting from the high density of pigmented cells. Chl-*a* concentration has a direct relationship with water colour.

When phytoplankton form blooms, the rapid increase in algal cells causes discoloration of water. 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 the sea surface temperature. The increased rate of light attenuation in the more deeply coloured areas results in more light energy being absorbed by the sea surface water, resulting in higher sea surface temperatures during the day. This, in turn, facilitates heat loss from the surface to the atmosphere during the evenings. The effect of water colour on light penetration provides mechanisms through which water colour may affect the sea surface temperature. Coloured water has a significantly lower sea surface temperature during the night compared with clear water (Houser 2006).

5. Summary

Using satellite data of D-SST, chl-*a* concentration, SS, CDOM, WS and SR in two phytoplankton bloom events in the ECS, we have analysed the effects of phytoplankton blooms on D-SST. The results show that phytoplankton blooms have positive effects on increasing D-SST due to diurnal vertical migration of phytoplankton and changes in water colour in the bloom events during phytoplankton bloom. Both satellite and *in situ* data reveal a positive relationship between chl-*a* concentration and D-SST in phytoplankton bloom events. High chl-*a* concentration may have positive effects on increases in D-SST.

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