

# Can Asian dust trigger phytoplankton blooms in the oligotrophic northern South China Sea?

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[1] Satellite data estimate a high dust deposition flux ( $\sim 18 \text{ g m}^{-2} \text{ a}^{-1}$ ) into the northern South China Sea (SCS). However, observational evidence concerning any biological response to dust fertilization is sparse. In this study, we combined long-term aerosol and chlorophyll-a (Chl-a) measurements from satellite sensors (MODIS and SeaWiFS) with a 16-year record of dust events from surface  $\text{PM}_{10}$  observations to investigate dust transport, flux, and the changes in Chl-a concentration over the northern SCS. Our result revealed that readily identifiable strong dust events over this region, although relatively rare (6 cases since 1994) and accounting for only a small proportion of the total dust deposition ( $\sim 0.28 \text{ g m}^{-2} \text{ a}^{-1}$ ), do occur and could significantly enhance phytoplankton blooms. Following such events, the Chl-a concentration increased up to 4-fold, and generally doubled the springtime background value ( $0.15 \text{ mg m}^{-3}$ ). We suggest these heavy dust events contain readily bioavailable iron and enhance the phytoplankton growth in the oligotrophic northern SCS. **Citation:** Wang, S.-H., N. C. Hsu, S.-C. Tsay, N.-H. Lin, A. M. Sayer, S.-J. Huang, and W. K. M. Lau (2012), Can Asian dust trigger phytoplankton blooms in the oligotrophic northern South China Sea?, *Geophys. Res. Lett.*, 39, L05811, doi:10.1029/2011GL050415.

## 1. Introduction

[2] For years, the northern South China Sea (SCS) has been known as a region which receives significant atmospheric inputs of minerals [e.g., Duce *et al.*, 1991]. These inputs have been considered a major external forcing of the oceanic ecosystem in the region [e.g., Wong *et al.*, 2007; Liu *et al.*, 2010]. Although Wu *et al.* [2003] first speculated that the region is limited by bioavailable iron, the role of dust inputs for the ecosystem in the northern SCS is still being debated. More recently, atmospheric measurements revealed that long-range transported dust being deposited into the northern SCS is possible [Wang *et al.*, 2011]; however, the frequency and deposition flux of such events are not well-known. In addition, the biological response to dust deposition needs to be examined to fill critical gaps in the existing knowledge.

[3] In this study, we present a satellite perspective on the dust flux and dust-triggered biogeochemical response over the northern South China Sea (SCS). The northern SCS is characterized as a sink area of Asian dust [e.g., Lin *et al.*, 2007; Wang *et al.*, 2011], and has oligotrophic (i.e., nutrient-poor) surface waters [e.g., Wong *et al.*, 2007], during the springtime. Long-term chlorophyll-a (Chl-a) concentration from Sea-viewing Wide Field-of-View Sensor (SeaWiFS) measurements since 1997, in conjunction with  $\text{PM}_{10}$  (particulate matter with aerodynamic diameter  $< 10 \mu\text{m}$ ) observations over this region are applied in the study. Multi-year composites of Chl-a imagery were utilized to overcome the insufficient spatial coverage of Chl-a retrievals in the region due to the cloudy environment. They provided a first look at the Chl-a distribution for heavy dust events and the background during March and April in this region. Satellite retrievals of Fluorescence Level Height (FLH) were used to confirm the increase in satellite Chl-a retrieval is not due to nonliving particles in the surface water [e.g., Claustre *et al.*, 2002; Lin *et al.*, 2011]. Ancillary ocean current, sea-surface height anomaly (SSHA), and sea-surface temperature data were used to elucidate the deeper-ocean nutrient supply via upwelling. The dust flux was estimated using eleven years (2000–2010) of Moderate Resolution Imaging Spectroradiometer (MODIS) data, which provided critical information to support our findings. This study is the first one to demonstrate that the oceanic biogeochemistry in the northern SCS can respond significantly to the atmospheric input of Asian dust.

## 2. Environmental Background in the Northern SCS

[4] In the past decade, the environmental background of the northern SCS has been well studied by the South-East Asia Time-series Station (SEATS;  $18^\circ\text{N}$ ,  $116^\circ\text{E}$ ), research cruises, and ocean models [e.g., Chen *et al.*, 2004; Tseng *et al.*, 2005; Wong *et al.*, 2007; Liu *et al.*, 2010, and references therein]. Conditions of the surface water in the northern SCS are generally warm ( $\sim 22$ – $29^\circ\text{C}$ ), with a shallow nutricline depth ( $\sim 60 \text{ m}$ ), a persistently deep photic zone ( $\sim 85 \text{ m}$ ), and oligotrophic. Liu *et al.* [2002] suggested that the East Asian monsoon, with its seasonal changes in wind and temperature, is the major driving force of ocean current dynamics, mixed layer depth, and upwelling, which in turn influence the chlorophyll distribution in the region. Seasonal variability of surface Chl-a concentration ( $0.3 \text{ mg m}^{-3}$  in winter and  $0.03 \text{ mg m}^{-3}$  in summer), related to the mixed layer depth (up to  $\sim 100 \text{ m}$  in winter and  $20 \text{ m}$  in summer), is supported by observations at SEATS [Tseng *et al.*, 2005]. The high surface Chl-a concentration during

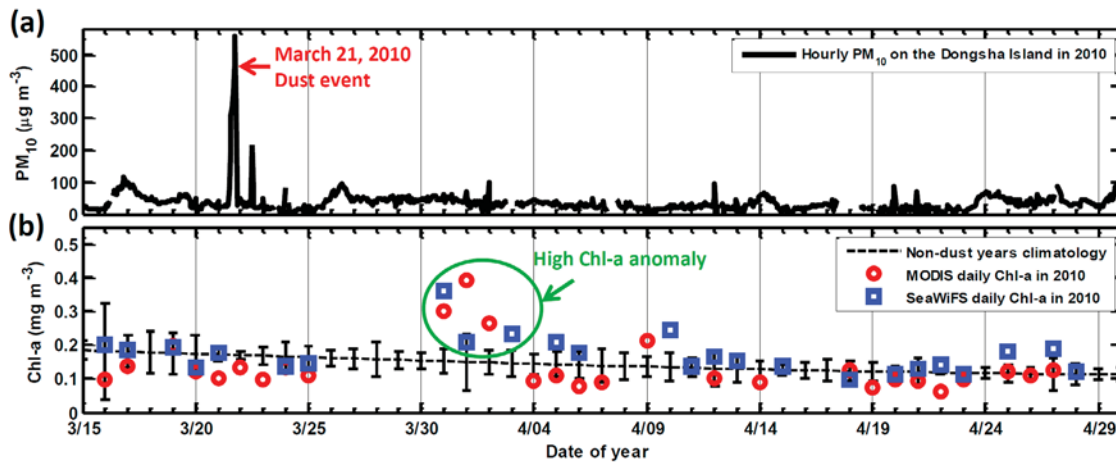
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**Figure 1.** Time series of (a) hourly PM<sub>10</sub> mass concentrations at the Dongsha Island, and (b) daily-averaged Chl-a concentration for open ocean pixels in the northern SCS derived from Aqua/MODIS and SeaWiFS observations during 15 March 2010–30 April 2010. We defined the open ocean as a region between 17–22°N and 110–121°E with depths deeper than 1000 m, including the slope and basin areas of the northern SCS. The PM<sub>10</sub> concentrations were measured with a TEOM (Model 1400ab; R&P Co.). The raw Chl-a data with Level 3 Standard Mapped Image in 9 km resolution were obtained from the NASA/OceanColor website (<http://oceancolor.gsfc.nasa.gov/>). The climatology of the daily-averaged Chl-a concentration within one standard deviation for background years are indicated by a dashed line and error bars.

the wintertime is attributed to relatively high levels of nutrients being supplied by deeper-ocean waters via a deeper mixed layer. Even during winter, the observed concentrations of dissolved inorganic nitrogen, phosphorus, and Chl-a are  $\sim 0.3 \mu\text{M}$ ,  $\sim 0.06 \mu\text{M}$ , and  $0.3 \text{ mg m}^{-3}$ , respectively [Tseng *et al.*, 2005]. Compared to other marginal seas (e.g., the northern Arabian Sea [Singh *et al.*, 2008]), the northern SCS has been considered a low-nutrient and low-chlorophyll region (a so-called ‘biological desert’). Hence, atmospheric inputs have been suggested to being a major external forcing of the biogeochemistry in the northern SCS, and remain to be studied [Wong *et al.*, 2007; Liu *et al.*, 2010].

[5] The main limitation to phytoplankton growth in the upper water column in the northern SCS is the availability of nutrients. Nitrogen and phosphorus are known as macronutrients, and are the main nutrients supporting the growth of phytoplankton. Iron is required for numerous processes within the cell, including photosynthesis, respiration, nutrient uptake, and nitrogen fixation. Because iron is required in relatively small amounts, it is known as a micronutrient. Results from nutrient enrichment experiments and seawater bottle samplings indicate that the ecosystem in the northern SCS is limited by the lack of bio-available nitrogen and iron [e.g., Wu *et al.*, 2003; Chen *et al.*, 2004], despite the fact that the dust input into the region is high [Duce *et al.*, 1991].

[6] The high aerosol loading of the Asian springtime, attributed to substantial and varied emissions (e.g., anthropogenic, biomass burning, and dust) from the Asian continent, has an extensive impact on the ecosystem [e.g., Tsay *et al.*, 2009, and references therein]. Recently, the link between high aerosol optical thickness (AOT) and the Chl-a response in the northern SCS has been studied based on a satellite assessment [Lin *et al.*, 2009]. According to their analysis of monthly datasets, the low correlation between AOT and Chl-a during springtime suggests that atmospheric aerosols may not play a major role in the biogeochemistry in the northern SCS. Despite data issues associated with sampling of satellite retrievals, the quantification of dust

deposition into open oceans from satellite observations has been proven to be difficult, especially in regions with complex vertical distribution of aerosols [e.g., Hsu *et al.*, 2003]. Surface PM<sub>10</sub> measurements can facilitate the identification of dust transport and depositions, which help us to elucidate the relationship between dust deposition and biological response more robustly.

### 3. Long-Range Transported Dust and Flux Estimate Over the Northern SCS

[7] On 19–21 March 2010, a significant Asian dust storm affected large areas from the Gobi deserts to the West Pacific, including Taiwan [Wang *et al.*, 2011] and southern China [Zhao *et al.*, 2011]. For the first time, detailed characteristics of long-range transported dust aerosols were acquired by a comprehensive set of ground-based instruments deployed at Dongsha Island (20°42′52″N, 116°43′51″E; <http://aerosol.atm.ncu.edu.tw/DongSha/>) in the northern SCS during a pilot campaign for the 7-SEAS (Seven South East Asian Studies, <http://7-seas.gsfc.nasa.gov/>) project [Wang *et al.*, 2011]. Figure 1a shows the PM<sub>10</sub> mass concentration during the field campaign. The unique high PM<sub>10</sub> concentration (reaching  $\sim 570 \mu\text{g m}^{-3}$ ) on 21 March 2010 suggests that long-range transported dust over this region is easily identified compared to the oceanic background.

[8] Dust deposition into the northern SCS can be estimated as the dry deposition flux of dust ( $F$ ), which is expressed as:

$$F = C \times V_d \quad (1)$$

where  $C$  is the dust concentration and  $V_d$  the dry deposition velocity. In the case of 21 March 2010, the dust concentration was calculated as the product of the observed PM<sub>10</sub> concentration (Figure 1) and the derived dust fraction suggested by Wang *et al.* [2011]. The dry deposition velocity was assumed to be  $2.0 \text{ cm s}^{-1}$ , which is consistent with

Hsu *et al.* [2009] for Asian dust observed in the East China Sea (ECS). As a result, during the dust event, the hourly dry deposition flux of dust increased from 1 to 34 mg m<sup>-2</sup>. The dust flux integrated for the entire dust event period (about 8 hours) was estimated to be ~0.14 g m<sup>-2</sup>, accounting for only a small fraction of the annual dust flux (>10 g m<sup>-2</sup> as suggested by Duce *et al.* [1991]). Furthermore, the total dust loading for the northern SCS (between 17–22°N and 110–121°E) for this particular event was suggested to be ~0.09 million ton (Mt). Compared with the annual deposition of Asian dust to the western North Pacific (around 64–300 Mt [Prospero *et al.*, 1989; Uematsu *et al.*, 2003]), this event contributed only a relatively small amount, although it appears to be possible to stimulate phytoplankton growth in iron-limited regions [e.g., Crusius *et al.*, 2011].

[9] Even such a small amount of mineral dust, containing bioavailable micronutrients (e.g., dissolvable iron) deposited into surface waters will enhance phytoplankton blooms. Meskhidze *et al.* [2005] investigated iron solubilization in deliquesced Asian dust aerosols during springtime outflow conditions. They established the relationship between the amount of bioavailable iron and initial acid species (e.g., SO<sub>2</sub>) in plumes, and found that the initial SO<sub>2</sub>-to-dust ratios play an important role. Smaller dust plumes generally have a higher fraction of dissolved iron because they require a lower amount of SO<sub>2</sub>. When compared with dust events reported in the western North Pacific, it was found that Asian dust transported to the SCS occurs rarely and that events are weaker. In addition, Asian dust over the northern SCS is transported within a shallow boundary layer and typically encounters the densely-populated and industrialized Chinese coast and downstream Taiwan. Meanwhile, the dust plume can mix with enriched SO<sub>2</sub> from dimethylsulfide (DMS) oxidation in the marine atmosphere [Wang *et al.*, 2011]. With intense acid modification, the small fraction of iron contained in the dust-laden plume is easily transformed into a form that is readily soluble in the waters of the northern SCS.

[10] The frequency of Asian dust transports over the northern SCS was further explored, based on an analysis of the spatiotemporal evolution of PM<sub>10</sub> concentration over Taiwan for 59 dust events since 1994 (<http://dust.epa.gov.tw>). This identified six dust events (24 March 2000, 13 April 2001, 18 March 2005, 19 March 2006, 26 April 2009, and 21 March 2010) of sufficient strength to transport dust from northern Taiwan to southern Taiwan in springtime. These dust events featured similar synoptic weather conditions and transport characteristics over Taiwan (see Figure S1 in the auxiliary material), suggesting possible influence over the

**Table 1a.** Annual and Seasonal Dust Flux Estimates for the Northern SCS

Ocean	Annual Dust Flux Reported <sup>a</sup> (g m <sup>-2</sup> )	Annual Dust Loading From MODIS (g m <sup>-2</sup> )	Annual Dust Flux Estimates for Northern SCS <sup>b</sup> (g m <sup>-2</sup> )
Yellow Sea	53.7	66.75 (±22.81)	18.54
Northern ECS	27.0	35.50 (±8.13)	17.53
Southern ECS	21.4	29.06 (±4.81)	16.97
Northern SCS <sup>b</sup>		23.05 (±3.86)	17.68

<sup>a</sup>Reported by Hsu *et al.* [2009, and references therein].

<sup>b</sup>Region includes only the slope and basin area.

**Table 1b.** Seasonal and Heavy Dust Fluxes over the Northern SCS

	MAM	JJA	SON	DJF
seasonal dust flux <sup>a</sup>	6.14	2.75	4.37	4.42
heavy dust flux <sup>b</sup>	0.28	0.00	0.00	0.00

<sup>a</sup>Breakdown from the annual dust flux.

<sup>b</sup>With definition of daily AOT > 0.6 and fine mode fraction (FMF) < 0.4.

northern SCS region.<sup>1</sup> It should be noted that the case of 21 March 2010 appears to be the largest dust event, and is the only one characterized with *in situ* measurements in the northern SCS [Wang *et al.*, 2011].

[11] We then wondered whether the dust flux over the northern SCS from these rare (i.e., only six times during 1994–2010) Asian dust events agrees with the estimate by Duce *et al.* [1991]. We further calculated the dust mass loading from MODIS aerosol data (see auxiliary material for details on methodology), and compared it with the measured dust flux over the Yellow Sea and the East China Sea (ECS) [Hsu *et al.*, 2009, and references therein], and from that estimated the dust flux for the northern SCS ( $F_{SCS}$ ) as follows,

$$F_{SCS} = \frac{F_a}{(\tau \cdot Q_{ext})_a} \times (\tau \cdot Q_{ext})_{SCS} \quad (2)$$

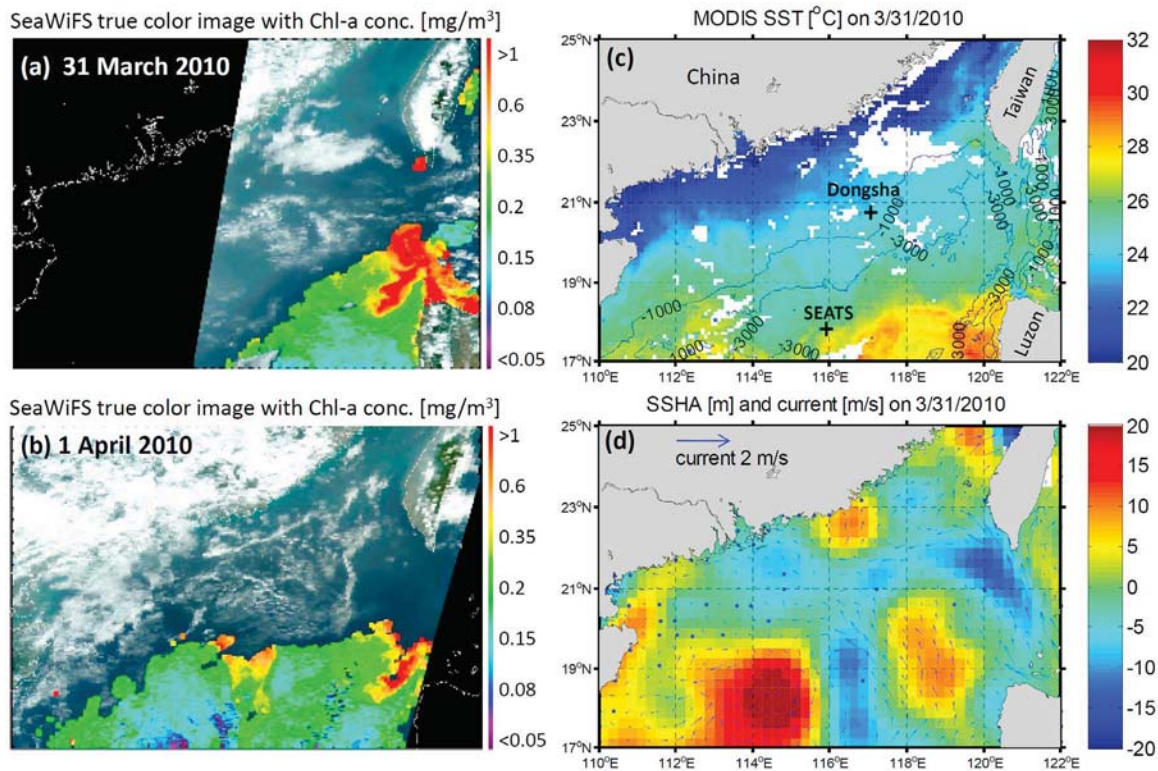
where  $\tau$  is coarse mode AOT at 550 nm (after subtracting an estimation contribution from marine sea-spray aerosol), and  $Q_{ext}$  is the mass extinction efficiency for Asian dust. The subscript  $a$  denotes the region of the Yellow Sea or the ECS.

[12] The results are shown in Tables 1a and 1b. The estimates of the dust flux for the northern SCS based on the data from three oceans are similar, with an average of 17.68 g m<sup>-2</sup> a<sup>-1</sup>, which is in a good agreement with Duce *et al.*'s [1991] estimate (>10 g m<sup>-2</sup> a<sup>-1</sup>). However, dust flux in the northern SCS reveals a strong seasonal variability. Spring has the highest dust flux (6.14 g m<sup>-2</sup>) and a remarkably high contribution (0.28 g m<sup>-2</sup>, ~5%) from heavy dust events, compared to other seasons. Similar values of dust flux (~4.4 g m<sup>-2</sup>) in the autumn and winter were estimated. The dust flux in summer showed the lowest value, but, surprisingly, still with a significant amount (2.75 g m<sup>-2</sup>). Because southwesterly winds prevail in the summer, dust from the Gobi deserts can be considered negligible, whereas the densely-populated and industrialized areas in the vicinity of the northern SCS are more likely to be the origin [e.g., Lin *et al.*, 2007]. The annual dust flux from local sources was estimated at around 11 g m<sup>-2</sup> a<sup>-1</sup> (four times the summertime dust flux, and 62% of the annual dust flux). This result has the important implication that much of the iron embedded in the mineral dust might not be transformed to a bioavailable form if it was only transported over a short distance when reaching the oligotrophic northern SCS. This supports the contention of Wu *et al.* [2003] that this region is limited by the availability of bioavailable iron.

[13] The dust flux of heavy dust episodes only happened in the spring and contributed only a small amount, measuring 0.28 g m<sup>-2</sup> (i.e., 2% of the annual dust flux). This amount is twice that of our previous estimate of 0.14 g m<sup>-2</sup> based on PM<sub>10</sub> observation, and appears to be reasonable. The small proportion of heavy dust flux also confirms our

<sup>1</sup>Auxiliary materials are available in the HTML. doi:10.1029/2011GL050415.





**Figure 2.** (a, b) Maps of Chl-a concentration, (c) sea surface temperature ( $^{\circ}\text{C}$ ), and (d) surface current and sea-surface height anomaly (SSHA) for high Chl-a anomaly days corresponding to the 2010 dust event. The surface current data was obtained from the hybrid coordinate ocean model (HYCOM) output with spatial resolution of  $1/12^{\circ} \times 1/12^{\circ}$ . The SSHA is based on satellite altimetry data with spatial resolution of  $1/3^{\circ} \times 1/3^{\circ}$  obtained from AVISO (Archiving, Validation and Interpretation of Satellite Oceanographic data). The bathymetry (in m) of the study area is denoted by contour lines in Figure 2c.

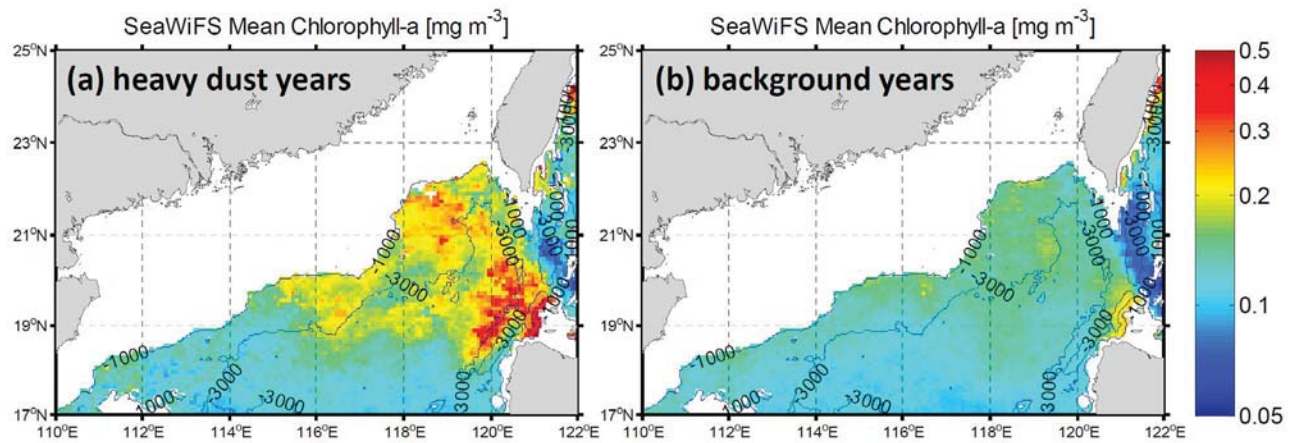
finding that heavily dust-laden air masses may not be able to reach the SCS region easily (i.e., only 6 out of 59 historical dust events reached the SCS region). Consequently, although the northern SCS receives substantial dust from the Asian continent, it is the small proportion transported by the springtime heavy dust events, transported over long distances from the Gobi deserts, with a higher possibility of having micronutrients available in a bioavailable form, which leads to a positive Chl-a anomaly.

#### 4. Dust-Triggered Chl-a Anomaly in the Northern SCS

[14] Satellite retrievals of Chl-a have often been applied to assess the behavior of oceanic biogeochemistry on a global scale [e.g., O'Reilly *et al.*, 1998]. However, the availability of Chl-a data over the SCS during spring is limited, as retrievals are not performed under cloudy conditions or in high-AOT cases. Bishop *et al.* [2002] reported that Chl-a responds to aeolian dust input with a time-lag: the Chl-a concentration in the mixed layer started to increase 5 days after the dust deposition, and peaked after 2 weeks. A shorter time-lag of chlorophyll blooming (e.g., 1–2 to up to 3–4 days) was observed by Singh *et al.* [2008]. Although the high Chl-a anomalies after the dust passage shows a good agreement with Bishop *et al.*'s [2002] results, poor temporal availability of Chl-a retrievals for the 2010 dust event (Figure 1b) hampered our ability to conclusively evaluate the entire

bloom cycle. Nevertheless, the high daily-averaged Chl-a concentrations on 31 March 2010 and 1 April 2010 showed about twice the climatology ( $0.18 \text{ mg m}^{-3}$ ) and were comparable to the wintertime Chl-a concentration of  $\sim 0.3 \text{ mg m}^{-3}$ , suggesting that the biological activities in the northern SCS can significantly respond to the aeolian dust input.

[15] Diagnostics of possible phytoplankton blooms associated with nutrient supply through upwelling were performed for the high Chl-a anomaly case in the spring of 2010. The presence of negative SSHA in the open ocean implies a possible upwelling due to cold-core cyclonic eddies [e.g., Chen *et al.*, 2007] or subsurface current convergence. By examining the satellite-derived SST and current on 31 March 2010 (Figures 2c and 2d), we found that there were no signs to support cold-core cyclonic eddy activity in the study domain. On the other hand, high Chl-a ( $>0.3 \text{ mg m}^{-3}$ , Figure 2a) off NW Luzon was observed in the area with a moderate upwelling to downwelling (the SSHA ranged from  $-5$  to  $10 \text{ m}$ ), which is attributed to the subsurface convergence of the northward flow just west of Luzon with the intruding Kuroshio current from the Luzon Strait [e.g., Liu *et al.*, 2010, and references therein]. The other elevated Chl-a near the north of SEATS (Figure 2b) was associated with a negative SSHA region, which was induced between two positive SSHA (i.e., downwelling) regions. We noticed that high Chl-a concentrations (up to  $1 \text{ mg m}^{-3}$ ) were observed mainly along the sloping topography, where the deeper-ocean nutrient supplies are more



**Figure 3.** The mean Chl-a concentration ( $\text{mg m}^{-3}$ ) maps based on the available composited SeaWiFS daily data sets for (a) heavy dust years and (b) background years.

sufficient (e.g., relatively rich sedimentary and potentially topographical upwelling). When aeolian dust is deposited into the nutrient-replete surface water, iron stimulates the phytoplankton growth by accelerating photosynthesis, respiration, and nutrient uptake within cells. At the same time, away from the slope areas, the elevated Chl-a concentration still reveals the effects of aeolian dust fertilization, even for the positive SSHA region. We therefore suggest that dinitrogen ( $\text{N}_2$ ) fixation, which involves iron, might play a relatively important role as a nutrient source in the area. However, understanding of the role of iron in governing an ecosystem is in its infancy, and more oceanic *in situ* measurements are required in order to fully understand the nutrient budget in the northern SCS.

[16] In addition to ocean upwelling influences, *Lin et al.* [2010] found that coastal nutrients and plankton of Vietnam could be brought to the northern SCS by a large ocean eddy, impacting the biogeochemistry in late spring. In contrast, our cases happened in early spring when the characteristic of eddy dynamics shows difference from late spring. More detailed studies, for instance, through numerical modeling, to identify the dynamic mechanism of eddy transport are needed.

[17] We composited daily Chl-a imagery with respect to the phase of individual phytoplankton bloom periods (i.e., 3–14 days after dust deposition as suggested by *Bishop et al.* [2002] and *Singh et al.* [2008]) for five of the six heavy dust events (the 2009 dust event was omitted as no measurements were available from SeaWiFS during that time). The mean concentrations of daily Chl-a over northern SCS are shown in Figure 3a. As contrast to the dust scenario, the mean Chl-a maps for the background years (i.e., those years from 1998–2010 without heavy dust events, over the same period of March 21–April 26) are shown in Figure 3b. The data in the shelf area (bathymetry  $> -1000$  m) of the northern SCS have been removed because Chl-a concentration in the area can be strongly affected by coastline upwelling, river discharge, island effects, and nutrients from the sediments of the continental shelf. Restricting the study area to the northern SCS basin and slope allows for a better elucidation of the role of atmospheric dust forcing in the region.

[18] Figure 3 shows that the dust deposition associated with heavy dust events can substantially influence the

oceanic biogeochemistry in the northern SCS, especially in the region north of  $18^\circ\text{N}$  and west of  $121^\circ\text{E}$ . In the study domain, elevated Chl-a concentrations about four times the background value were found off NW Luzon. The averaged Chl-a over the regions  $120\text{--}121^\circ\text{E}$  by  $19\text{--}20^\circ\text{N}$ , and  $118\text{--}119^\circ\text{E}$  by  $21\text{--}22^\circ\text{N}$  for heavy dust years (Figure 3a) were  $0.29$  and  $0.23 \text{ mg m}^{-3}$ , respectively, compared to the background value of  $0.15 \text{ mg m}^{-3}$  in these regions. Although the composited Chl-a map provides an incomplete picture of its spatial distribution due to frequent cloud coverage, it is an important step toward understanding the impact of airborne dust on the biogeochemistry in the SCS region. In addition, the evidence from the satellite observations can greatly aid in planning future scientific activities and deployment logistics.

## 5. Conclusion

[19] The long-range transport of Asian dust and its biogeochemical impacts on the northern South China Sea (SCS) were investigated based on the synergy of satellite and ground  $\text{PM}_{10}$  observations during the springtime. Over the past decade, six heavy Asian dust events reaching the region have been identified. These dust-laden air masses traveling through densely-populated and industrialized areas are characterized by intensified acidic modifications and by containing a large fraction of bioavailable iron. The analysis of the changes in SeaWiFS-retrieved Chl-a concentration between heavy dust and background years revealed that the Chl-a concentration was significantly enhanced (up to 4-fold) in the northern SCS in response to the passage of airborne dust plumes. The slope area was more susceptible to dust fertilization. However, such favorable conditions for phytoplankton blooms occur only rarely and their dust flux only accounts for a small portion ( $0.28 \text{ g m}^{-2}$ ,  $\sim 2\%$ ) of the annual dust flux ( $17.68 \text{ g m}^{-2}$ ).

[20] The present study provided a satellite perspective on the topic of the biogeochemical impact of Asian dust over the northern SCS. However, there is much we do not clearly know about the impact from climate variability (e.g., monsoon, ENSO), oceanography, and other atmospheric inputs, as well as their feedbacks. These issues are complex and interactive, which may rely on more detailed investigations and modeling studies. We suggest that (1) continuous



atmospheric measurements in the northern SCS should be conducted. Dongsha Island may be sufficient for monitoring the long-range transported Asian dust, if trace element measurements (e.g., iron, aluminum), which can help to identify the form of iron before it is deposited into the surface waters, are added; (2) a comprehensive investigation of the surface water conditions, i.e., nutrient dynamics and biological community structures for the region that is biologically sensitive to dust deposition (as shown in Figure 3a), should be performed; and (3) to deal with the cloudy conditions in the region, boundary-layer unmanned aerial vehicles or light-aircraft equipped with ocean-color imagers should be deployed in order to provide effective measurements of chlorophyll content during dust events.

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