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Key Points:
- There were three different transport pathways for spring Asian dust events in the study area
- Ocean primary productivity was significantly increased by the spring Asian dust events
- There has been a recent decrease in spring Asian dust events in the western North Pacific Ocean

Supporting Information:
- Supporting Information S1

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Spatial and temporal variabilities of spring Asian dust events and their impacts on chlorophyll-*a* concentrations in the western North Pacific Ocean

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Abstract As the western North Pacific Ocean is located downwind of the source regions for spring Asian dust, it is an ideal location for determining the response of open waters to these events. Spatial analysis of spring Asian dust events from source regions to the western North Pacific, using long-term daily aerosol index data, revealed three different transport pathways supported by the westerly wind system: one passing across the northern East/Japan Sea (40°N–50°N), a second moving over the entire East/Japan Sea (35°N–55°N), and a third flowing predominantly over the Siberian continent (>50°N). Our results indicate that strong spring Asian dust events can increase ocean primary productivity by more than 70% (>2-fold increase in chlorophyll-*a* concentrations) compared to weak/nondust conditions. Therefore, attention should be paid to the recent downturn in the number of spring Asian dust events and to the response of primary production in the western North Pacific to this change.

1. Introduction

Over the last two and half decades, input of aeolian dust into the ocean environment has been regarded as an important research topic due to its potential effects on ocean primary productivity (OPP), carbon cycling, and climate change [*Martin*, 1990; *Bopp et al.*, 2003; *Jickells et al.*, 2005]. Global dust emission rate estimates range from ~1000 to 2200 Tg yr^{-1} [*Zender et al.*, 2004]. The most intense dust sources are the desert areas of the North Africa (i.e., Saharan dust) and the central Asia (i.e., Asian dust) [*Mahowald et al.*, 2005]. Asian dust, originating in Taklimakan and Gobi Deserts, accounts for ~10–25% of global dust emission and is the second largest dust source globally [*Tanaka and Chiba*, 2006; *Tegen and Schepanski*, 2009].

As the western North Pacific Ocean (WNP) is located downwind from the source regions of Asian dust (Figure 1a), it is an ideal location for determining the response of open waters to these events. Supported by the westerly wind system, the supply of Asian dust to the WNP mainly occurs in spring (March–May) [*Duce et al.*, 1980; *Uematsu et al.*, 1983; *Takemura et al.*, 2002]. The month of April, alone, is responsible for more than 50% of spring Asian dust events (Figure S1 in the supporting information) [*Sun et al.*, 2001; *Tan et al.*, 2012]. Modeling studies and short-term observations suggest that spring Asian dust is rapidly transported from its source regions across the WNP to North America by westerly winds [*Duce et al.*, 1980; *Uematsu et al.*, 1983; *Husar et al.*, 2001; *Logan et al.*, 2010]. However, the lack of large-scale and long-term observations means that little is known about the spatial and temporal variability of the transport pathways of spring Asian dust events.

Previous studies reported that concentrations of deposited iron observed during Asian dust events were much higher than those observed during the nondust periods, while the difference between dust and nondust events in deposited nitrate and total phosphorus concentrations was not nearly as dramatic [*Kang et al.*, 2009; *Kim et al.*, 2009; *Furutani et al.*, 2010; *Onishi et al.*, 2015]. Therefore, in the WNP ecosystem (colimited by iron and nitrogen [*Moore et al.*, 2002; *Liu et al.*, 2004; *Krishnamurthy et al.*, 2009]), it is expected that, along the transport pathways of spring Asian dust, OPP is temporarily enhanced through relief of iron stress that acts as a limiting factor for the phytoplankton growth under nondust conditions [*Duce and Tindale*, 1991; *Moore et al.*, 2002]. Recently, studies have reported a significant correlation between spring Asian dust events and

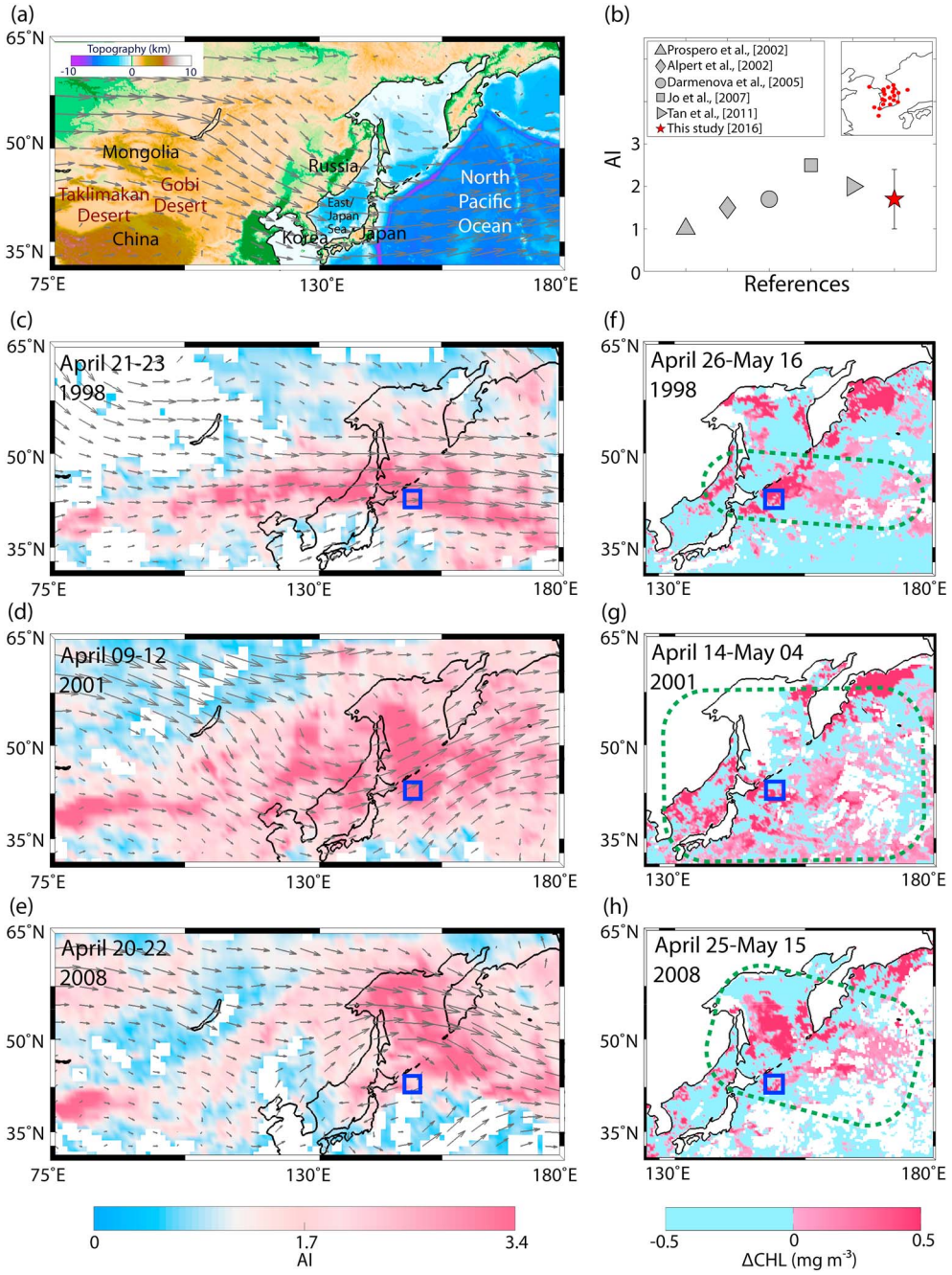

Figure 1. (a) Map illustrating the area of interest from central Asia to the western North Pacific Ocean (WNP) (30°N–65°N and 75°E–180°E). The color scale represents 2-Minute Gridded Global Relief Data (ETOPO2) topography (http://rda.ucar.edu/datasets/ds759.3/) [*Bezděk and Sebera*, 2013]. The grey arrows represent mean (1998–2014) spring winds at 700 hPa. (b) Published threshold aerosol index (AI) values used to determine the occurrence of dust events. The error bar used here (red star) indicates standard deviation from mean. The inset shows the location (red circles) of the 21 land-based KMA stations whose data were used in our analysis. Spatial distributions of AI for (c) 21–23 April 1998, (d) 9–12 April 2001, and (e) 20–22 April 2008, in the WNP, based on NASA's Total Ozone Mapping Spectrometer (TOMS) (1998 and 2001) and Ozone Monitoring Instrument (OMI) (2008) satellite observations. The grey arrows represent mean National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) wind velocities at 700 hPa averaged over 5–6 days spanning dust events. Spatial distributions of ΔCHL (mg m^{-3}) for (f) 26 April to 16 May 1998, (g) 14 April to 4 May 2001, and (h) 25 April to 15 May 2008. The green dotted lines indicate the area in which the AI values exceeded the 1.7 threshold. The blue square (42°N–44°N and 148°E–150°E) indicates 2° × 2° region in which AI exceeded the 1.7 threshold value more than three times, during each of the April timeframes. Data from this area were used for Figure 2.

OPP at the Kyodo North Pacific Ocean Time-series station in the WNP (44°N, 155°E) [*Yuan and Zhang*, 2006; *Han et al.*, 2011]. WNP spring blooms are strongly influenced by surface mixed layer dynamics and availability of sunlight and occur over the same general season as the springtime dust events [*Sverdrup*, 1953; *Yoshimori et al.*, 1995; *Obata et al.*, 1996]. However, because the Asian dust events are episodic within the spring timeframe, until now, the relationship between these short-lived dust events and OPP has not been confirmed across the broader expanse of the WNP.

The purpose of this study is (1) to investigate the spatial and temporal variability of spring Asian dust events beginning at their source regions and extending into the WNP and (2) to determine their impacts on OPP in the WNP.

2. Methods

2.1. Data

The analysis of spring Asian dust event transport pathways presented here covers a 16 year period from 1998 to 2014 (note that the period of 2002–2004 was totally excluded from our analysis due to the lack of reliable observations; see Text S1 in the supporting information) and is based on a variety of parameters associated with satellite observations (e.g., aerosol index, wind velocity, chlorophyll-*a*, isolume depth, and precipitation) as well as the ocean temperature record from a reanalysis model. Aerosol index (AI) values that provide a measure of the magnitude of dust loading in the atmosphere [*Herman et al.*, 1997; *Torres et al.*, 2007] were used to investigate the transport pathways of spring Asian dust event. The 700 hPa (i.e., ~3 km above the Earth's surface) winds were used to represent the pathway for the active connection between dust sources in the atmosphere and the WNP [*Husar et al.*, 2001; *Satake et al.*, 2004]. Chlorophyll-*a* concentrations, indicating phytoplankton biomass [*Steele*, 1962; *Cullen*, 1982], were obtained for the study period from the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) and Moderate Resolution Imaging Spectroradiometer (MODIS) Aqua satellites [*O'Reilly et al.*, 2000; *McClain*, 2009]. Isolume depth, which defines the layer within which photosynthesis can occur in the upper water column, was estimated from the relationship between surface photosynthetically active radiation (PAR) and chlorophyll-*a* concentrations [*Morel et al.*, 2007; *Boss and Behrenfeld*, 2010]. Isolume depth, corresponding to PAR = 0.054 mol quanta m^{-2} d^{-1}, was recently determined in the North Pacific Subtropical Gyre [*Laws et al.*, 2014] and is typically expressed as $Z_{0.054}$. We use $Z_{0.054}$ to estimate the photosynthetic depth (i.e., isolume depth > mixed layer depth (MLD)) in our analysis. Precipitation (i.e., rain) was classified into four types based on magnitude [*Liu*, 2015]: (1) no rain, (2) light rain (<2.5 mm h^{-1}), (3) moderate rain (2.5–10 mm h^{-1}), and (4) heavy rain (>10 mm h^{-1}). MLD was estimated as the depth at which temperature is 0.2°C less than the temperature at 3 m (i.e., $T_{\text{at 3 m}} - T_{\text{a depth}} = 0.2$°C) [*Thompson*, 1976].

To investigate the impact of spring Asian dust events on OPP in the WNP, we used chlorophyll-*a*, isolume depth, precipitation, and MLD data. The OPP discussion in section 3.2 is based on OPP estimated from satellite-based chlorophyll-*a* concentrations by using an appropriate OPP algorithm, which was redeveloped by adding primary productivity data set measured by the ^{13}C method in the WNP [*Kameda and Ishizaka*, 2005]. Further details are provided in Text S1.

2.2. Definition of Spring Asian Dust Events Based on Aerosol Index

Satellite-based AI estimates have been widely used as a key parameter in spatial and temporal analyses of dust events [*Herman et al.*, 1997; *Prospero et al.*, 2002]. AI estimates act as indicators to determine whether dust events occur in particular source regions and to trace the pathway along which they are transported. A threshold value is set, and AI values greater than the threshold are generally regarded as occurrence of dust events. Previous studies have suggested threshold values from 1.0 to 2.5 based on the spatial distribution of AI values in various particular dust source regions (see Figure 1b) [*Alpert et al.*, 2002; *Prospero et al.*, 2002; *Darmenova et al.*, 2005; *Jo et al.*, 2007; *Tan et al.*, 2011]. To find an optimal AI threshold associated with the occurrence of spring Asian dust events in our study area, we used reports from the 21 land-based Korea Meteorological Administration (KMA) stations on the spring Asian dust that occurred between 1998 and 2014, as there are no ocean-based stations providing in situ observations on Asian dust to determine its onset and duration. In addition, the station locations are downwind of Asian dust source regions (Figure 1a), representing that the KMA stations are directly influenced by the Asian dust events due to geographic proximity to

the source regions, and the transport of Asian dust via westerly winds is quite fast, suggesting that the gradient in the AI values from the source regions to the 21 KMA stations is not large. We focused the analysis particularly on those reports dealing with severe dust events—PM_{10} (particulate matter less than 10 μm in diameter)>400 $\mu g\, m^{-3}$ for at least 2 h in a dust day (http://www.kma.go.kr). Based on these criteria, the AI values from 21 KMA land-based observation stations (see the inset in Figure 1b), suggesting the occurrence of severe dust events, were identified, sorted, and averaged. The mean AI value, to be employed as the threshold for recognition of dust events in our analysis, was estimated to be 1.7 with a standard deviation of 0.7 ($n = 98$). This threshold AI value is comparable with the published estimates for various other regions [*Alpert et al.*, 2002; *Prospero et al.*, 2002; *Darmenova et al.*, 2005; *Jo et al.*, 2007; *Tan et al.*, 2011] (Figure 1b). The AI values were classified into three types based on their magnitude: (1) nondust event (AI < 1.7), (2) weak dust event (AI 1.7–2.5), and (3) strong dust event (AI > 2.5). In the study area, about 8% of all AI values reported between 1998 and 2014 were identified as spring Asian dust events (i.e., AI > 1.7) (Figure S2), where the term "spring" is defined as March through May.

3. Results and Discussion

3.1. Spatial and Temporal Variability

To analyze the spatial distribution of the spring Asian dust events between 1998 and 2014, we mapped the number of dust event days (i.e., those with AI > 1.7) over an area from central Asia to the WNP (30°N, 75°E to 65°N, 180°E) (Figure S3). Overall, the dust event day totals were greatest (>30 spring days) in the source regions (i.e., Gobi and Taklimakan Deserts) and lower over the WNP (<~10 days). This pattern of eastward decrease in dust days from the source regions to the WNP is consistent with a simulation of dust deposition [*Uematsu et al.*, 2003].

By using the daily AI values with each 1° × 1° pixel in the WNP (Figure S4a) for each spring day, it was determined that the individual Asian dust events were sporadic (i.e., episodic), showing no discernible pattern over the study period (Figures S4b–S4o). However, AI values greater than 1.7 were concentrated in the month of April (pixel number: ~20,000) (Figure S5a), which had nearly as many dust days as March (pixel number: ~11,000) and May (pixel number: ~12,000) combined. In addition, the distribution of April AI values greater than 1.7 was spread over a much larger geographical area than the March and May distributions (Figures S5b–S5d), suggesting that April is a crucial time for spring Asian dust event research not only because of the number events [*Sun et al.*, 2001; *Lee et al.*, 2006; *Tan et al.*, 2012] but also because of the broad geographical reach of April events. Only in 1998 (21–23 April, 5 May, and 16–17 May), 2000 (8–9 May), 2001 (9–12 April), and 2008 (20–22 April) did the mean AI value averaged over the entire study area exceed the 1.7 threshold (solid red lines in Figures S4b–S4o). These 2 to 3 day periods are interpreted as particularly strong and significant spring Asian dust events.

To determine specific transport pathways from the source regions to and across the WNP, we focused on the April 1998, 2001, and 2008 dust events as they were substantially stronger and had broader impact than the others (Figures S6 and S7). Based on the geographical AI distributions for these events, three different spatial patterns were discerned (Figures 1c–1e): the first passed across the northern East/Japan Sea (40°N–50°N; April 1998), the second covered the entire East/Japan Sea (35°N–55°N; April 2001), and the third flowed predominantly over the Siberian continent (>50°N; April 2008). Not surprisingly, these patterns appear to be correlated with variations of westerly wind direction (Figures 1c–1e). For example, strong westerly winds in April 1998 developed in a narrow band leading to an Asian dust event (AI > 1.7) that moved eastward, passing over the East/Japan Sea and the WNP, also along a narrow band (40°N–50°N; Figure 1c) [*Husar et al.*, 2001]. In April 2001, strong westerly winds developed over a somewhat broader band, which led to an Asian dust event that moved into the WNP affecting the entire East/Japan Sea (Figure 1d). A pattern similar to this observed event was described in a numerical experiment modeling the transport of this April 2001 Asian dust event [*Zhao et al.*, 2003]. The westerly winds in April 2008 blew predominantly over northeastern Asia before extending into the WNP through the Okhotsk Sea. The Asian dust event resulting from these winds was transported over Siberia from the source regions and then spread into the WNP (Figure 1e). In summary, the month of April appears to be the best time for determining transport pathways for the major spring Asian dust events, and wind patterns are key factor for determining the geographical spread of dust both over the continent and the WNP.

3.2. Impacts on Chlorophyll-*a* Concentrations

As a form of "natural iron fertilization" capable of increasing OPP, dust events have been frequently linked to climate change both on glacial-interglacial time scales and in modern times [*Martin*, 1990; *Kohfeld and Harrison*, 2001; *Bopp et al.*, 2003]. *Bishop et al.* [2002] reported that production of particulate organic carbon increased sharply 5 days after an Asian dust event reached the eastern North Pacific Ocean near Station Papa. It continued to increase for 2 weeks beyond the arrival of the dust event. Another study conducted in the East/Japan Sea (Figure 1a) linked spring bloom in this marginal sea with Asian dust events occurring between 1998 and 2002 [*Jo et al.*, 2007]. As the WNP region of study presented here is located directly downwind and lies in closer proximity to the source regions of Asian dust than Station Papa in the far eastern Pacific, it is reasonable to hypothesize that WNP OPP can also be correlated with the dust events. It is the link that we seek to confirm. As in iron-stressed systems the addition of iron may lead to an increase in chlorophyll-*a* concentrations only, without an associated increase in OPP [*Behrenfeld et al.*, 2009], here we assume that surface chlorophyll-*a* concentrations can be used to represent surface OPP and therefore to estimate changes in OPP due to dust events.

To investigate the response of OPP to spring Asian dust events in the WNP, we first examined the spatial distribution of chlorophyll-*a* anomalies within ~5–10 days after the onset of the 1998, 2001, and 2008 spring Asian dust events. Chlorophyll-*a* anomalies (ΔCHL) assumed to represent the chlorophyll-*a* response to dust events were defined as $\Delta CHL_{<year>} = CHL_{<year>} - CHL_{mean}$, where $CHL_{<year>}$ is the concentration for a particular year (here 1998, 2001, or 2008) defined as the composite over a 3 week period beginning with a lag of 5 days after the onset of the Asian dust event (e.g., for the 21–23 April 1998 event, CHL_{1998} is the composite from 26 April to 16 May 1998); CHL_{mean} is the temporal average chlorophyll-*a* concentration calculated over the same period from all years (e.g., the 1998 CHL_{mean} is based on all 26 April to 16 May periods between 1998 and 2014). Specific dates are provided in the legends of Figures 1f–1h. The 5 day lag time was derived from previous studies that reported North Pacific OPP stimulated by dust within ~5–10 days of particular dust events [*Young et al.*, 1991; *Bishop et al.*, 2002; *Shi et al.*, 2012]. In spite of some obscuration due to cloud interference, the overall spatial distribution of positive ΔCHL in 1998, 2001, and 2008 was generally consistent with the distribution of AI values$>$1.7 (Figures 1c–1h), broadly implying a probable cause-and-effect relationship (Figure S8).

The second step in the investigation involved an intensive temporal analysis in a smaller area to elucidate this relationship (42°N–44°N and 148°E–150°E; blue square in Figures 1c–1h). This particular area was selected because here not only did the April AI values collectively exceed the threshold 1.7 in 1998, 2001, and 2008 but also there was greater availability of data as chlorophyll-*a* images were less influenced by cloud interference compared to other areas (Figures S9 and S10). In addition, it is known that there is a dearth of cloud cover compared to the south of the Kuroshio Extension where clouds form in the unstable atmosphere that lies above the warmer Kuroshio waters [*Tomita et al.*, 2013]. In this area, the temporal variability of springtime AI and chlorophyll-*a* was compared in strong dust and weak/nondust years (Figure 2). Examining the structure of MLD and $Z_{0.054}$ (see the insets in Figures 2a and 2c), representing the conditions (i.e., nutrient supply, stratification, and irradiance) that drive a typical spring bloom [*Sverdrup*, 1953; *Obata et al.*, 1996], we identified two distinguishable sets of springtime conditions: one in which the MLD shoals with time, e.g., 1998 (strong dust year) and 2010 (weak dust year [*Tan et al.*, 2016, 2017]), and a second in which the MLD fluctuates, e.g., 2001 (strong dust year) and 2014 (nondust year).

The water column structures of MLD and $Z_{0.054}$ were identical in the spring of 1998 and 2010 (see Figure 2a inset), indicating that the conditions for typical spring blooming were similar. However, it is evident that the chlorophyll-*a* pattern in these two years was different (Figures 2a and 2b). In the spring of 2010, a weak dust year, the concentrations of chlorophyll-*a* were quite constant with time and were relatively low ($<2\,mg\,m^{-3}$) compared to the mean values averaged for the 1998–2014 spring (Figure 2a). On the other hand, the concentrations of chlorophyll-*a* in the spring of 1998, a strong dust year, rapidly increased to $>2\,mg\,m^{-3}$ (mean chlorophyll-*a* ~$1.4\,mg\,m^{-3}$) with a lag time of ~10 days after a strong dust event (AI > 2.5) on approximately April 20 and then peaked at a maximum of $5.3\,mg\,m^{-3}$ (Figure 2b). The increasing trend was maintained for ~15 days (see a shadow zone in Figure 2b).

Another pair of years, 2001 (strong dust year) versus 2014 (nondust year), illustrates a different MLD tendency (i.e., fluctuation with time; Figure 2c inset) as compared to shoaling with time just discussed for 1998 and 2010

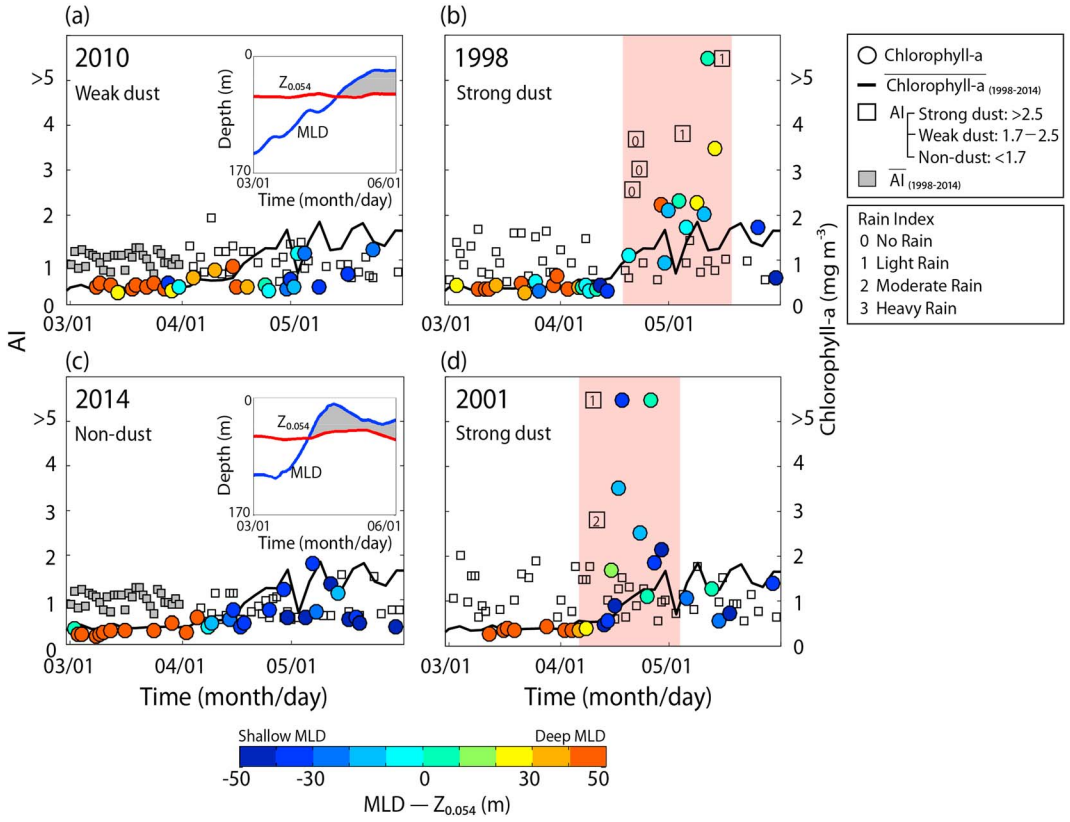

Figure 2. Daily AI values (black squares) and daily chlorophyll-*a* concentrations (mg m^{-3}, circles) during the spring of (a) 2010 (weak dust event), (b) 1998 (strong dust event), (c) 2014 (nondust event), and (d) 2001 (strong dust event) in the WNP (blue square in Figures 1c–1h). The filled black squares indicate AI values replaced with average 1998–2014 March values (Figures 2a and 2c). The black solid line indicates springtime trend in 1998–2014 mean chlorophyll-*a* concentrations (3 day composite). The pink shading highlights enhanced chlorophyll-*a* feature driven by strong spring Asian dust. The color scale represents difference between mixed layer depth (MLD) and isolume depth ($Z_{0.054}$): the negative values and grey zones in the insets indicate favorable conditions for active photosynthesis. The numbers in AI squares indicate the magnitude of precipitation during strong dust events.

(Figure 2a inset). As shown above, the spring of 2001 developed a shaped-peak of chlorophyll-*a* (maximum 6.3 mg m^{-3}) with a lag time of ~5 days after the strong dust event (AI > 2.5) on approximately April 10 (Figure 2d), whereas such a dramatic increase is not seen in the spring of 2014 (Figure 2c). The patterns of temporal interplay between MLD and $Z_{0.054}$ associated with the 2008 and 1998 dust events were similar. However, the earlier event has been chosen for illustration here because there were relatively more satellite-based chlorophyll-*a* data available (Figure S10). Nevertheless, although their increase was not quite as dramatic, the 2008 chlorophyll-*a* concentrations increased to >2.0 mg m^{-3} (i.e., compared to mean value 1.6 mg m^{-3}) after the strong dust event (Figure S11). We also identified a significant relationship between dust events and chlorophyll-*a* in the East/Japan Sea through a comparison of strong dust year (2006) versus nondust year (2014) (see Text S2 and Figure S12). The lag times (~5–10 days) were consistent with the results from the previous natural/artificial iron studies [*Bishop et al.*, 2002; *Tsuda et al.*, 2005].

Dust deposition can alter the water clarity and change the attenuation of light by increasing the concentration of suspended materials at ocean surfaces [*Claustre et al.*, 2002; *Stramski et al.*, 2004; *Ohde*, 2016], so Asian dust events may affect satellite-based chlorophyll-*a* concentrations. However, our results showed that the response of chlorophyll-*a* to strong Asian dust events was delayed with the lag times of 5–10 days (Figure 2). We are not sure if this delay (i.e., lag time) is due to the lack of light availability. A future study based on in situ observations is needed to accurately explain this delay phenomenon.

Dust deposition to the ocean occurs under both wet and dry conditions. In general, iron solubility through dry deposition is <0.8–2.1% in typical seawaters (pH = ~8.0) [*Jickells and Spokes*, 2001]. However, iron is more soluble (~14%) under wet deposition (i.e., precipitation with pH = ~4–7). For this reason, wet deposition has

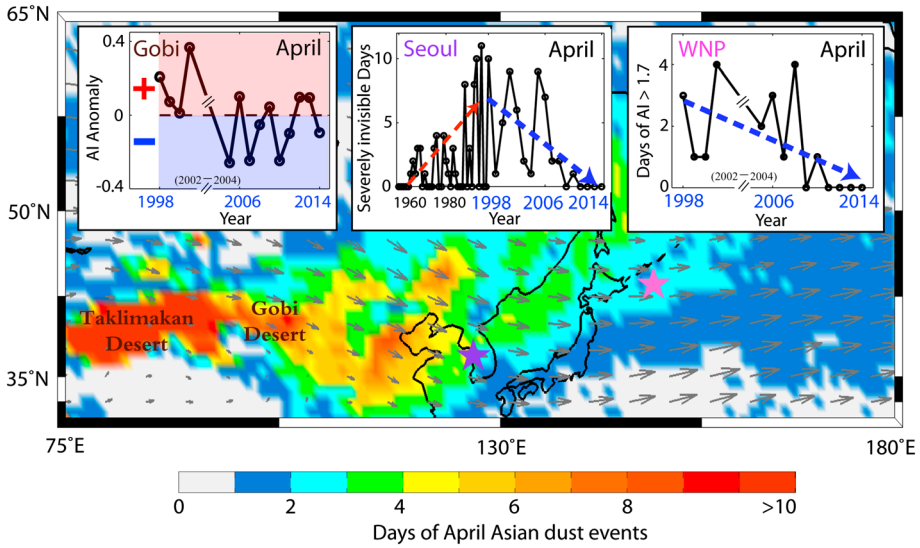

Figure 3. Recent decreasing trend of the spring Asian dust events. The first inset shows AI anomaly in the Gobi Desert during the month of April for the years of the study. AI anomalies were calculated as the difference between the individual April and the mean April values. The red plus and blue minus signs indicate AI anomaly >0 and AI anomaly <0, respectively. The second inset shows April severely invisible days (traditional method used to define dust events), observed in Seoul station (purple star) of KMA during April 1960–2014 where linear regression analysis ($r^2 = 0.44$, P value < 0.05) suggests a decreasing trend for April 1998–2014. The third inset shows the days with AI >1.7 in the WNP area 42°N–44°N, 148°E–150°E (pink star; same as the blue square in Figures 1c–1h) where linear regression analysis ($r^2 = 0.32$, P value < 0.05) again suggests decreasing trend for April 1998–2014. The color scale indicates the days of April Asian dust events (i.e., AI > 1.7) averaged during April 1998–2014 (except for 2002–2004). The grey arrows represent the mean wind vectors at 700 hPa during April 1998–2014.

been associated with an increased number of bioavailable iron forms [*Sunda*, 2001; *Jickells and Spokes*, 2001], which can be more effective at increasing chlorophyll-*a* concentrations [*Gao et al.*, 2003; *Jo et al.*, 2007]. During the strong spring Asian dust events in 1998 and 2001, little-to-no ($<2.5\ mm\ h^{-1}$) precipitation occurred, except for a moderate rain ($2.5–10\ mm\ h^{-1}$) in April 2001 (Figures 2b and 2d). Our results do not suggest any significant difference in OPP associated with wet dust events. However, there is a need for multiple in situ studies for confirmation, as satellite-based rain data do not provide the necessary detail.

Our analysis suggests that spring Asian dust events were episodic and chlorophyll-*a* concentrations in the WNP increased dramatically after dust events. Assuming that increases in chlorophyll-*a* concentrations are significantly correlated to the increases in phytoplankton biomass, we estimated OPP in the WNP (42°N–44°N and 148°E–150°E; blue square in Figures 1c–1h) (see Text S1). It was found that OPP increased by more than 70% (>2-fold increase in chlorophyll-*a* concentrations) under strong dust event conditions (OPP_{1998}: $740 \pm 220\ mg\ C\ m^{-2}\ d^{-1}$, OPP_{2001}: $670 \pm 210\ mg\ C\ m^{-2}\ d^{-1}$) as compared to the weak/nondust conditions (OPP_{2010}: $430 \pm 100\ mg\ C\ m^{-2}\ d^{-1}$, OPP_{2014}: $340 \pm 80\ mg\ C\ m^{-2}\ d^{-1}$) (Table S1 in the supporting information). Recent studies report that occurrence of the spring Asian dusts declined in the source regions [*Hara et al.*, 2006; *Zhu et al.*, 2008] owing to disturbance of the westerly wind pattern due to climate change. Accordingly, April AI anomalies have decreased in the Gobi Desert, April severely invisible days observed at the KMA Seoul station have decreased since the late 1990s, and simultaneously, days in the WNP with April AI exceeding the 1.7 criterion have decreased over the 1998–2014 study period (see Figure 3). Meanwhile, a recent study reports that atmospheric nitrogen deposition has significantly increased in the North Pacific Ocean for the last three decades [*Kim et al.*, 2014], relieving nitrogen limitation. All this suggests that future study in the WNP investigating the effect on the OPP of the contrasting behavior of iron (i.e., decreasing trend) and nitrogen (i.e., increasing trend) inputs is needed.

4. Conclusions

We investigated the spatial and temporal dynamics of spring Asian dust events in the WNP and their impacts on OPP during the period of 1998–2014 (except for 2002–2004) in the WNP. We found three different transport pathways: one passing across the northern East/Japan Sea (40°N–50°N), a second moving over the entire

East/Japan Sea (35°N–55°N), and a third moving predominantly over the Siberia continent (>50°N). The spatial patterns appear to be mainly determined by the westerly wind system. OPP (estimated from chlorophyll-*a* concentrations) increased by more than 70% (>2-fold increase in chlorophyll-*a* concentrations) following strong spring Asian dust events compared to weak/nondust times in the WNP. Although the dust events are episodic, their potential for sequestering atmospheric CO_2 via the "biological pump" may be considerable. The OPP response to the recent decreasing trend in spring Asian dust events is contrasted by its response to increasing atmospheric nitrogen deposition, as both inputs are required to revive this nitrogen/iron colimited ocean environment. It therefore behooves us to pay attention to possible future changes in OPP in the WNP.

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Erratum

In the originally published version of this article, Figures 1c-1e were marked with longitude "75°E to 180°E", but the images represented "80°E to 180°E". The images have been corrected to represent longitude "75°E to 180°E" as they are labeled.

In the original Acknowledgments, the KOPRI project funding number was incorrectly labeled as PP10610 and has been corrected to PE17030.

In the originally published version of the supporting information, we mistakenly used the Western North Pacific-estimated $Z_{0.054}$ (blue square shown in Figure 1; Lat: 42°N–44°N and Long: 148°E–150°E) instead of the East/Japan Sea-estimated $Z_{0.054}$ (red star; Lat: 43°N–45°N and Long: 138°E–140°E) for the calculation of **'MLD – $Z_{0.054}$'** in Figure S12. However, this mistake does not affect our conclusions. We recalculated **'MLD – $Z_{0.054}$'** with the East/Japan Sea-estimated $Z_{0.054}$, and then reproduced corrected Figure S12.

In Figure S12, color information indicates the magnitude of **'MLD – $Z_{0.054}$'**. Here, $Z_{0.054}$ is estimated as follows [*Laws et al.*, 2014]:

$$Z_{0.054} = \log\left(\frac{0.054}{0.98\times \mathrm{PAR}}\right)\left(\frac{Z_{eu}}{\log(0.01)}\right), \qquad \text{(Supporting Information S2)}$$

where PAR is surface photosynthetically available radiation (mol quanta m^{-2} d^{-1}), Z_{eu} is the euphotic zone depth where the photon flux reaches to 1% of the surface photon flux (m) [*Ryther*, 1956], and is calculated as [*Morel et al.*, 2007]:

$$\log_{10} Z_{eu} = 1.524 - 0.436 \times \mathrm{CHL} - 0.0145 \times \mathrm{CHL}^2 + 0.0186 \times \mathrm{CHL}^3, \qquad \text{(Supporting Information S3)}$$

where CHL represents surface chlorophyll-a concentrations (mg m^{-3}).

These errors have been corrected, and the present version may be considered the authoritative version of record.