Correlation of Dust Storms in China with Chlorophyll *a* Concentration in the Yellow Sea between 1997–2007

TAN Sai-Chun[1, 2] and SHI Guang-Yu[1]

[1] *State Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing 100029, China*
[2] *Key Laboratory of Meteorological Disaster of Ministry of Education, Nanjing University of Information Science and Technology, Nanjing 210044, China*

Received 26 September 2011; revised 8 November 2011; accepted 14 November 2011; published 16 March 2012

Abstract Based on daily observation data at 222 meteorological stations in China, the characteristics of dust storms between 1997 and 2007 were examined. Next, the relationship between dust events and chlorophyll (Chl) *a* concentration in the Yellow Sea was investigated. There were six regions with high annual frequencies of dust storms. The seasonal distribution of dust storms showed spatiotemporal variation. The six regions with highest annual frequencies also exhibited high frequencies of dust storms in spring. Dust storms in most regions occurred in spring. Of all dust storms in China, sixty-five percent of all dust storms occurred during the spring. The area and frequency of dust storms were smaller in fall and winter than in spring and summer. A significant correlation was found between dust events and Chl *a* concentration in the Yellow Sea. High correlation regions included Qinghai-Xizang region, part of the Hexi Corridor, the western Inner Mongolia and Hetao Regions, and the Hunshandake Desert. The high correlation may be induced by the high ratio of dust storms in the abovementioned regions that arrive over the Yellow Sea, as inferred through a forward trajectory analysis; especially notable is dust transported at a lower altitude (< 3 km).

Keywords: dust storm, spatial distribution, seasonal variation, chlorophyll, Yellow Sea

Citation: Tan, S.-C., and G.-Y. Shi, 2012: Correlation of dust storms in China with chlorophyll *a* concentration in the Yellow Sea between 1997–2007, *Atmos. Oceanic Sci. Lett.*, **5**, 140–144.

1 Introduction

Both observations and simulations show that northern China is one of the most important source regions for Asian dust (Zhang et al., 2003; Wang et al., 2005; Qian et al., 2006; Wang et al., 2010). The dust aerosols carried by dust storms play not only an important role in the radiative forcing of climate via scattering and absorbing shortwave and longwave radiation directly (Sokolik et al., 2001), but also may affect cloud cover and precipitation patterns indirectly by affecting cloud microphysics (Levin et al., 1996). Moreover, much research suggests that nutrients contained in the dust particles, especially Fe, could affect ocean primary production through atmospheric deposition, causing feedback effects on climate (Martin and Fitzwater, 1988; Duce and Tindale, 1991; Bishop et al., 2002; Uematsu et al., 2003; Jickells et al., 2005; Yuan and Zhang, 2006; Han et al., 2011). Consequently, understanding the spatiotemporal characteristics of dust storm events is very important.

Many studies have investigated the characteristics of dust storms in China during the second half of the 20th century based on the data from meteorological stations (Li et al., 2003; Zhou and Zhang, 2003; Tang and Chao, 2005; Wang et al., 2005; Qian et al., 2006), but few studies have addressed the situation of the last decade. Li et al. (2003) reported five areas in China with high frequencies of dust storms using data from 185 conventional meteorological stations between 1964 and 1998. Based on data from 681 meteorological stations, Zhou and Zhang (2003) reported 223 typical severe dust storms in northern China from 1954 to 2002, and 82.5% of all severe dust storms occurred in the spring. Wang et al. (2005) found that the South Xinjiang Region and the Hexi Corridor were the two areas with most frequent dust storms in China based on 701 meteorological stations from 1954 to 2000.

It is believed that the deposition of dust aerosols could exert a significant influence on the biogeochemical cycles of the ocean. Yuan and Zhang (2006) reported a high correlation between dust events and biological productivity at the KNOT station (44°N, 155°E) in the western North Pacific. Jo et al. (2007) reported that dust storm episodes were significant in the initiation of spring blooms in the Sea of Japan (also known as the East Sea), especially those associated with precipitation. However, few studies have addressed the direct link between the observational dust storm records and ocean responses for long periods, especially in the past eleven years and in marginal seas (Jo et al., 2007; Tan et al., 2011).

The improvements in remote sensing of ocean color during the past decade could make it possible to understand the impacts of dust storms on ocean biological activity during the past eleven years. Our previous study (Tan et al., 2011) showed a significant positive correlation between Chl *a* concentration in the Yellow Sea and the frequencies of severe and very severe spring dust storms in China during 1998–2008. However, that study did not show which dust source areas contributed to Chl *a* concentrations in the Yellow Sea. In the present study, based on the dust storm records at 222 meteorological stations

Corresponding author: TAN Sai-Chun, sctan@mail.iap.ac.cn

in China, we first investigated the characteristics of dust storms during 1997–2007. We then examined the possible link between dust storms at different dust source areas and Chl *a* concentration in the Yellow Sea. The Yellow Sea is one of the important marginal seas of the Pacific Ocean. Zhang and Gao (2007) reported that during 2000–02, the probability of Asian dust aerosol deposition to the Yellow Sea was the largest among the coastal seas in the western Pacific.

2 Data and methods

The occurrence dates of dust storms at 222 meteorological stations in China with continuous records from 1997 to 2007 with at least one day of observed dust storms were obtained from the National Meteorological Information Center/China Meteorological Administration (NMIC/CMA). At each station, a dust storm is defined as a storm with a minimum visibility of $\leqslant$ 1 km and an instantaneous maximum wind speed of $\geqslant$ 10 m s^{-1} (Qian et al., 1997).

Daily mean surface air temperature (°C), wind speed (m s^{-1}), relative humidity (%), air pressure (hPa), and rainfall (mm) at the same 222 meteorological stations were used to analyze environmental conditions when dust storms occurred. These data were also provided by NMIC/CMA.

Chl *a* concentration data came from the SeaWiFS Level-3 Standard Mapped Image (SMI) products and were provided by the Ocean Biology Processing Group/Goddard Space Flight Center/National Aeronautics and Space Administration (OBPG/GSFC/NASA). The spatial resolution of SeaWiFS Chl *a* concentration is 9 × 9 km. Our previous work showed a high correlation between satellite data and *in situ* Chl *a* concentration (correlation coefficient R^2=0.78) for the coastal seas of China (Tan et al., 2011), suggesting that satellite data reflect *in situ* variation of Chl *a* concentration. Chl *a* concentration in regions shallower than 20 m was excluded because terrestrial processes have dominant impacts on phytoplankton growth in coastal regions.

To understand the impacts of dust storms from different source areas on the China seas, a forward trajectory analysis was performed using the Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) model (Draxler and Rolph, 2010) with inputs from the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) global reanalysis of meteorological data.

3 Results and analysis

3.1 The characteristics of dust storms in China during 1997–2007

Figure 1b shows the frequency of occurrence of dust storms (days y^{-1}) in China between 1997 and 2007. There were six high-dust-storm-frequency regions (Fig. 1a). These are the Taklimakan Desert (labeled as region A), the west of Inner Mongolia (region B, including Badain

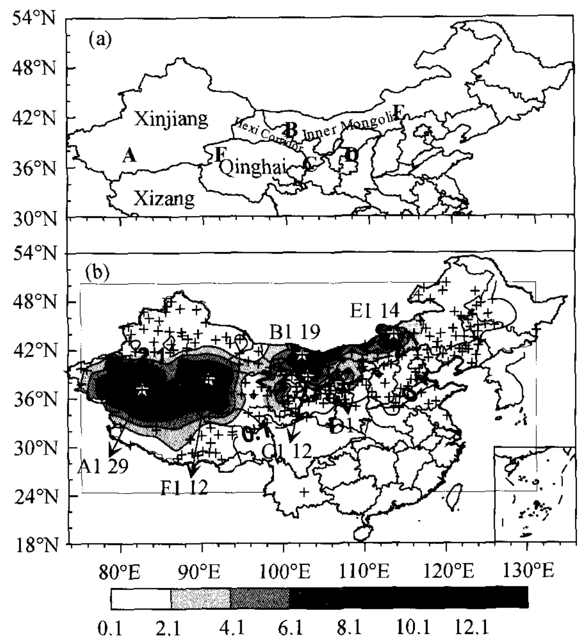

Figure 1 (a) The locations of regions A, B, C, D, E, and F. A: Taklimakan Desert, B: the west of Inner Mongolia, C: Hexi Corridor, D: Hetao Region, E: Hunshandake Desert, and F: the southeastern Xinjiang and Qinghai-Xizang region. (b) The contours of average annual frequency of dust storms (days y^{-1}) in China for 1997–2007 and the location of 222 meteorological stations (plus signs) used in this analysis. A1, B1, C1, D1, E1, and F1 are the stations of Minfeng, Guaizihu, Minqin, Yanchi, Sunitezuoqi, and Mangya, respectively.

Jaran Desert, Ulanbuh Desert, and Tengger Desert), the Hunshandake Desert (region E), the Hexi Corridor (region C), the southeastern Xinjiang and Qinghai-Xizang regions (region F, including the Kumtag and Qaidam Basin Deserts), and the Hetao Region (region D, including the Ordos and Loess Plateaus) in order of descending dust storm frequency. The stations with the highest dust storm frequency for the above six regions were Minfeng (A1 shown in Fig. 1b, 29 days y^{-1}), Guaizihu (B1, 19 days y^{-1}), Sunitezuoqi (E1, 14 days y^{-1}), Minqin (C1, 12 days y^{-1}), Mangya (F1, 12 days y^{-1}), and Yanchi (D1, 7 days y^{-1}).

The abovementioned five high-dust-storm-frequency regions (A through E) were the same areas with a high frequency of dust storms during 1964–98 (Li et al., 2003) and 1964–2000 (Qian et al., 2006). However, there was not a center showing at region F during the decades before 2000. In addition, region A was the area with the maximum frequency in both the period of 1997–2007 and decades before 2000.

The spatial distribution of dust storms showed a clear seasonal variation (Fig. 2). The six regions with the highest frequencies of dust storms in spring (Fig. 2a) and the corresponding stations with the highest frequencies were the same locations that showed the highest annual mean rate of dust storms. However, the value of frequencies was smaller. In summer (Fig. 2b), the area with high dust storm frequency was smaller than that in spring. High summer frequencies of dust storms only occurred in regions A and B, and the summer frequency at most stations was lower than in spring except for some stations in re-

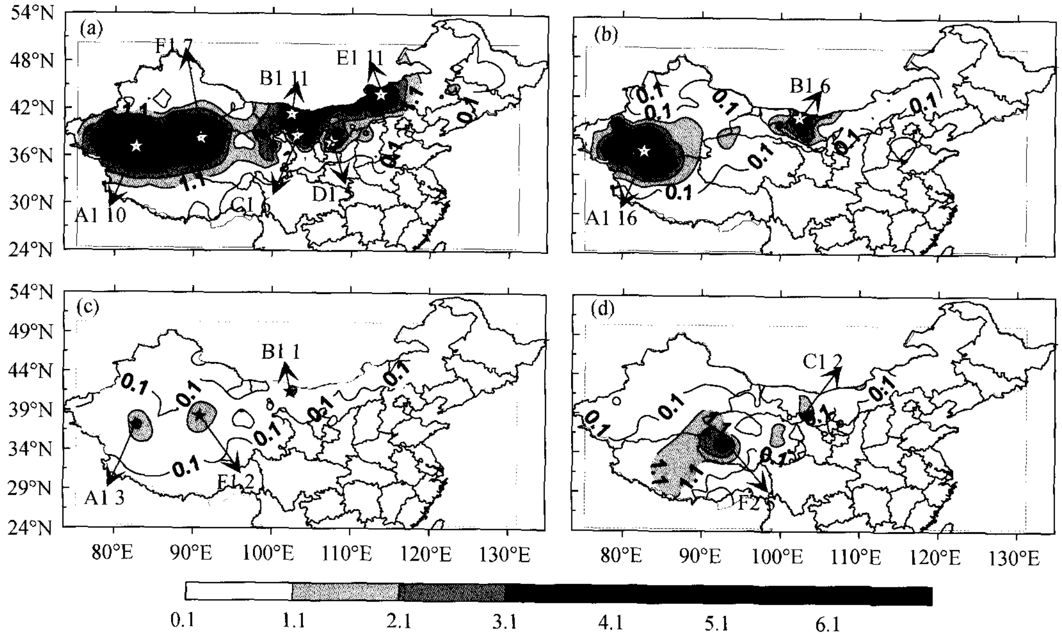

Figure 2 The contours of average dust storm frequency (days y^{-1}) for (a) spring, (b) summer, (c) fall, and (d) winter in China for 1997–2007. A1, B1, C1, D1, E1, and F1 are the same stations as in Fig. 1. F2 is Wudaoliang station.

gion A. The area and frequency of dust storms was smaller in fall (Fig. 2c) and winter (Fig. 2d) relative to spring and summer. High dust storm frequencies appeared in regions A, B, and F in the fall, and the highest frequency was just 1–3 days y^{-1}. In winter, dust storms occurred mainly in regions B and F at frequencies lower than 5 days y^{-1}.

The ratio of dust storm frequency in the spring to the annual frequency was approximately 65% on average. Wang et al. (2005) also reported that the occurrence of dust storms in spring in Hetao Region and the northeastern China Region amounted to 60%–70% of all storms for the period 1954–2000.

The occurrence of dust storms was closely related to environmental factors. The monthly occurrence of dust storms in China (days $month^{-1}$) was positively correlated to monthly mean wind speeds (correlation coefficient R = 0.85 at significance level $p < 0.01$) and temperature (R = 0.21 at $p < 0.05$), and negatively correlated to relative humidity ($R = -0.67$ at $p < 0.05$) and pressure ($R = -0.46$ at $p < 0.05$). There was no significant correlation between dust storms and rainfall over the whole of China. However, rainfall was reduced when dust storms occurred. This could be seen from the frequency of dust storms and the meteorological factors at the stations with high dust storm frequencies (> 7 days y^{-1}) (Table 1). The annual

Table 1 The occurrence frequency of dust storms and meteorological factors for the period of 1997–2007 at stations with dust storm occurrence frequencies > 7 days y^{-1}.

Station	Province/ autonomous region	Dust storm occurrence (days y^{-1})	Daily mean wind speed (m s^{-1})	Annual rainfall (mm)	Daily mean temperature (°C)	Daily mean relative humidity (%)	Daily mean pressure (hPa)
Guaizihu	Inner Mongolia	18.9	4.7	40.0	10.2	32.3	907.0
Mandula	Inner Mongolia	8.4	4.3	163.0	6.4	42.5	877.1
Sunitezuoqi	Inner Mongolia	13.6	4.0	171.1	4.3	50.0	896.7
Hailisu	Inner Mongolia	10.2	5.4	135.8	6.2	41.8	848.6
Zhurihe	Inner Mongolia	9.4	4.9	192.4	6.2	45.4	885.4
Keping	Xinjiang	13.2	1.3	108.6	12.0	48.6	884.9
Tieganlike	Xinjiang	7.4	1.6	31.1	11.8	46.7	918.7
Pishan	Xinjiang	8.9	1.7	54.2	13.2	42.6	862.5
Hotan	Xinjiang	11.4	2.1	42.3	13.8	39.9	862.3
Minfeng	Xinjiang	29.4	1.7	40.9	12.7	39.4	858.3
Mangya	Qinghai	11.8	2.4	42.9	4.4	29.6	713.1
Lenghu	Qinghai	8.3	3.5	16.7	3.6	30.1	727.9
Minqin	Gansu	11.7	1.3	61.7	4.7	22.3	431.8
Yanchi	Ningxia	7.1	2.6	281.4	9.1	50.3	865.7

rainfall at 8 out of 14 stations was less than 100 mm, and relative humidity was less than 50% at almost all of 14 stations. The correlation of wind speed, temperature, and pressure with dust storms was also clearly shown at the stations with highest dust storm frequencies. Daily mean wind speed at 12 out of 14 stations was larger than 1.5 m s^{-1}. Daily mean temperature at 10 stations was higher than 5°C, and daily mean pressure at 12 stations was lower than 900 hPa.

3.2 Relationship between chlorophyll *a* concentration and dust events

Figure 3 shows the spatial distribution of the correlation coefficient between monthly frequency of dust storms (days $month^{-1}$) at 222 meteorological stations and monthly area-averaged Chl *a* concentration (mg m^{-3}) in the Yellow Sea during the period from September 1997 to December 2007 (124 months in total). The significance level is less than 0.05. The contouring method is Ordinary Kriging Interpolation.

There were three main areas with a significant correlation coefficient: region F; parts of regions B, C, and D; and region E. The stations with the highest correlation coefficients at F, B-C-D, and E were located at Xinghai (F3, R = 0.41), Dingbian (D2, R = 0.44), and Damaoqi (E2, R = 0.42), respectively.

The regions with high correlation coefficients were consistent with the main dust sources affecting the Yellow Sea in 2000–02 observed by Zhang et al. (2005). They found that dust storms coming from or passing through the east of Qinghai province (part of region F), the west of Inner Mongolia (region B), the Loess Plateau (part of region D), and the Hunshandake Desert (region E) could affect the Yellow Sea.

Dust storms longer than five hours at the six stations (A1, B1, C1, D1, E1, and F1 shown in Fig. 1) were used to analyze the percentage of dust storms affecting the Yellow Sea. During the period from 1997 to 2007, the number of dust storms with durations of over five hours at A1, B1, C1, D1, E1, and F1 was 66, 43, 12, 12, 37, and 6, respectively. The percentage of dust storms impacting the Yellow Sea shown in Table 2 was defined as the ratio of dust storms arriving over the sea obtained using a trajectory analysis to the total number of dust storms.

According to the trajectories, although 71% of dust storms from station A1 could arrive over the Yellow Sea, they were mainly transported and arrived at high altitude (> 3 km). However, dust storms from the other five stations were mostly transported and arrived at lower altitudes (< 3 km). This result was consistent with previous observation and simulation results, which show that the elevated dust layer comes from the Taklimakan Desert, whereas the lower dust layer in the boundary layer originates from the Gobi Desert (Iwasaka et al., 1983; Mikami et al., 2006; Uno et al., 2009). Dust storms affecting the Yellow Sea transported at lower altitudes may be the reason for better correlation of Chl *a* concentration in the Yellow Sea with dust storms in the five regions other than region A. First, low-layer dust particles may interact and mix with anthropogenic materials easily while high-layer particles may mix little or not at all with anthropogenic materials when passing over megacities (Arimoto et al., 2006). Second, the surface water in the Yellow Sea may be more influenced by the dust particles arriving at low altitude than those that arrive at high altitude because the dust particles transported at the higher levels may just pass over without landing on the ocean surface.

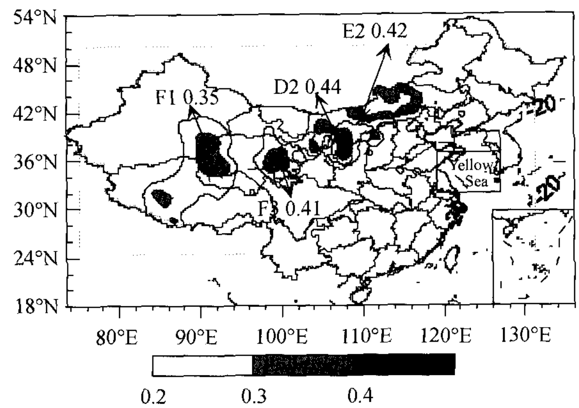

Figure 3 The correlation coefficient between monthly occurrence frequency of dust storms (days $month^{-1}$) at 222 meteorological stations and monthly area-averaged Chl *a* concentration (mg m^{-3}) in the Yellow Sea between September 1997 and December 2007. The contouring method is Ordinary Kriging Interpolation. The minimum contour is 0.2. D2, E2, F1, and F3 are the stations of Dingbian, Damaoqi, Mangya, and Xinghai. The rectangles show the location of the Yellow Sea. The isobaths are in meters.

4 Conclusions

In this study, the characteristics of dust storms in China between 1997 and 2007 were analyzed using daily meteorological data, and the correlation between dust storms and Chl *a* concentration in the Yellow Sea was examined.

Six regions with high dust storm frequencies appeared in China. In descending order, they are the Taklimakan Desert, the west of Inner Mongolia, the Hunshandake Desert, the Hexi Corridor, the southeastern Xinjiang and Qinghai-Xizang region, and the Hetao Region. The occurrence of dust storms was closely related to environmental factors. Dust storms were positively correlated to wind speed and temperature, and they were negatively correlated to relative humidity and air pressure.

Table 2 The percentage of dust storms arriving over the Yellow Sea during 1997–2007 as assessed using the HYSPLIT model for six representative stations.

Stations	A1: Minfeng	B1: Guaizihu	C1: Minqin	D1: Yanchi	E1: Sunitezuoqi	F1: Mangya
Affecting the Yellow Sea	71%	84%	100%	92%	30%	83%
Affecting the Yellow Sea through < 3 km layer	6%	63%	42%	67%	30%	67%

The seasonal distribution of dust storms showed spatial and temporal variation. The spatial distribution of dust storms in spring was very close to the annual mean distribution because in most regions, dust storms occurred in spring; of all dust storms, 65% occurred in spring.

Monthly Chl *a* concentration in the Yellow Sea exhibited a high correlation with the monthly occurrence of dust storms in some regions of China. The main high correlation regions included the southeastern Xinjiang and Qinghai-Xizang region, part of the west of Inner Mongolia, the Hexi Corridor, the Hetao Region, and the Hunshandake Desert. Forward trajectory analysis indicated that the ratio of dust storms at five stations with the highest storm frequencies from the abovementioned five regions arriving over the Yellow Sea, especially those transported at lower altitudes (< 3 km), was very large, resulting in a significant correlation between dust events in those regions and Chl *a* concentration in the Yellow Sea.

Acknowledgements. This work was supported by the National Natural Science Foundation of China (Grant Nos. 41005080 and 41130104) and Open Research Program of the Key Laboratory of Meteorological Disaster of the Ministry of Education, Nanjing University of Information Science and Technology (Grant No. KLME1110).

References

Arimoto, R., Y. J. Kim, Y. P. Kim, et al., 2006: Characterization of Asian dust during ACE-Asia, *Glob. Plan. Change*, **52**, 23–56.

Bishop, J. K. B., R. E. Davis, and J. T. Sherman, 2002: Robotic observations of dust storm enhancement of carbon biomass in the North Pacific, *Science*, **298**, 817–821.

Draxler, R. R., and G. D. Rolph, 2010: *HYSPLIT (HYbrid Single-Particle Lagrangian Integrated Trajectory) Model*, NOAA Air Resources Laboratory, Silver Spring, MD, available at http://ready.arl.noaa.gov/HYSPLIT.php.

Duce, R. A., and N. W. Tindale, 1991: Atmospheric transport of iron and its deposition in the ocean, *Limnol. Oceanogr.*, **36**, 1715–1726.

Han, Y., T. Zhao, L. Song, et al., 2011: A linkage between Asian dust, dissolved iron and marine export production in the deep ocean, *Atmos. Environ.*, **45**, 4291–4298.

Iwasaka, Y., H. Minoura, and K. Nagaya, 1983: The transport and spacial scale of Asian dust-storm clouds: A case study of the dust-storm event of April 1979, *Tellus*, **35B**, 189–196.

Jickells, T. D., Z. S. An, K. K. Andersen, et al., 2005: Global iron connections between desert dust, ocean biogeochemistry, and climate, *Science*, **308**, 67–71.

Jo, C. O., J.-Y. Lee, K.-A. Park, et al., 2007: Asian dust initiated early spring bloom in the northern East/Japan Sea, *Geophys. Res. Lett.*, **34**, L05602, doi:05610.01029/02006GL027395.

Levin, Z., E. Ganor, and V. Gladstein, 1996: The effects of desert particles coated with sulfate on rain formation in the eastern Mediterranean, *J. Appl. Meteor.*, **35**, 1511–1523.

Li, D.-L., H.-L. Zhong, L. Wei, et al., 2003: Climatic characteristics of annual sand-dust storm days in northern China and its response to surface sensible heat in spring of Qinghai-Xizang Platea, *Plateau Meteor.* (in Chinese), **22**, 337–345.

Martin, J. H., and S. E. Fitzwater, 1988: Iron deficiency limits phytoplankton growth in the north-east Pacific subarctic, *Nature*, **331**, 341–343.

Mikami, M., G. Y. Shi, I. Uno, et al., 2006: Aeolian dust experiment on climate impact: An overview of Japan-China joint project ADEC, *Glob. Plan. Change*, **52**, 142–172.

Qian, Z.-A., Y. Cai, J.-T. Liu, et al., 2006: Some advances in dust storm research over China-Mongolia areas, *Chinese J. Geophys.* (in Chinese), **49**, 83–92.

Qian, Z.-A., H.-X. He, Z. Qu, et al., 1997: Classification criterion of duststorm in Northwest China, case list and their statistical features, *China Duststorm Res.* (in Chinese), Z.-Y. Fang et al. (Eds.), China Meteorological Press, Beijing, 1–10.

Sokolik, I. N., D. M. Winker, G. Bergametti, et al., 2001: Introduction to special section: Outstanding problems in quantifying the radiative impacts of mineral dust, *J. Geophys. Res.*, **106**, 18015–18027.

Tan, S.-C., G.-Y. Shi, J.-H. Shi, et al., 2011: Correlation of Asian dust with chlorophyll and primary productivity in the coastal seas of China during the period from 1998 to 2008, *J. Geophys. Res.*, **116**, G02029, doi:02010.01029/02010JG001456.

Tang, G.-L., and Q.-C. Chao, 2005: The spatiotemporal characteristics and variation of dust storms in China over 48 years, *J. Appl. Meteor. Sci.* (in Chinese), **16**, 128–132.

Uematsu, M., Z. Wang, and I. Uno, 2003: Atmospheric input of mineral dust to the western North Pacific region based on direct measurements and a regional chemical transport model, *Geophys. Res. Lett.*, **30**, 1342, doi:1310.1029/2002GL016645.

Uno, I., K. Eguchi, K. Yumimoto, et al., 2009: Asian dust transported one full circuit around the globe, *Nature Geosci.*, **2**, 557–560.

Wang, H., S.-L. Gong, H.-L. Zhang, et al., 2010: A new-generation sand and dust storm forecasting system GRAPES_CUACE/Dust: Model development, verification and numerical simulation, *Chinese Sci. Bull.*, **55**, 635–649.

Wang, S.-G., J.-Y. Wang, Z.-J. Zhou, et al., 2005: Regional characteristics of three kinds of dust storm events in China, *Atmos. Environ.*, **39**, 509–520.

Yuan, W., and J. Zhang, 2006: High correlations between Asian dust events and biological productivity in the western North Pacific, *Geophys. Res. Lett.*, **33**, L07603, doi:07610.01029/02005GL025174.

Zhang, K., and H.-W. Gao, 2007: The characteristics of Asian-dust storms during 2000–2002: From the source to the sea, *Atmos. Environ.*, **41**, 9136–9145.

Zhang, K., H.-W. Gao, R.-J. Zhang, et al., 2005: Sources and movement routes of sand-dust aerosols and their impact probabilities on China Seas in 2000–2002, *Adv. Earth Sci.* (in Chinese), **20**, 627–636.

Zhang, X.-Y., S.-L. Gong, T.-L. Zhao, et al., 2003: Sources of Asian dust and role of climate change versus desertification in Asian dust emission, *Geophys. Res. Lett.*, **30**, 2272, doi:2210.1029/2003GL018206.

Zhou, Z.-J., and G.-C. Zhang, 2003: Typical severe dust storms in northern China during 1954–2002, *Chinese Sci. Bull.*, **48**, 2366–2370.