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A linkage between Asian dust, dissolved iron and marine export production in the deep ocean

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ABSTRACT

Iron-addition experiments have revealed that iron supply exerts controls on biogeochemical cycles in the ocean and ultimately influences the Earth's climate system. The iron hypothesis in its broad outlines has been proved to be correct. However, the hypothesis needs to be verified with an observable biological response to specific dust deposition events. Plankton growth following the Asian dust storm over Ocean Station PAPA (50°N, 145°W) in the North Pacific Ocean in April 2001 was the first supportive evidence of natural aeolian iron inputs to ocean; The data were obtained through the SeaWiFS satellite and robot carbon explorers by Bishop et al. Using the NARCM modeling results in this study, the calculated total dust deposition flux was 35 mg m^{-2} per day in PAPA region from the dust storm of 11–13 April, 2001 into 0.0615 mg m^{-2} d^{-1} (about 1100 nM) soluble iron in the surface layer at Station PAPA. It was enough for about 1100 nM to enhance the efficiency of the marine biological pump and trigger the rapid increase of POC and chlorophyll. The iron fertilization hypothesis therefore is plausible. However, even if this specific dust event can support the iron fertilization hypothesis, long-term observation data are lacking in marine export production and continental dust. In this paper, we also conducted a simple correlation analysis between the diatoms and foraminifera at about 3000 m and 4000 m at two subarctic Pacific stations and the dust aerosol production from China's mainland. The correlation coefficient between marine export production and dust storm frequency in the core area of the dust storms was significantly high, suggesting that aerosols generated by Asian dust storm are the source of iron for organic matter fixation in the North Pacific Ocean. These results suggest that there could be an interlocking chain for the change of atmospheric dust aerosol–soluble iron–marine export production.

1. Introduction

The work of John Martin (Martin and Fitzwater, 1988; Martin, 1990) sharply focused attention on the role of iron (Fe) in ocean productivity, biogeochemical cycles, and global climate with proposing "that phytoplankton growth in major nutrient-rich waters is limited by iron deficiency". To prove the iron fertilization hypothesis, 12 small-scale iron-addition experiments (FeAXs) have been conducted since 1993. The findings of these 12 FeAXs revealed that iron supply exerts control on the dynamics of plankton blooms, which in turn affect the biogeochemical cycles of carbon, nitrogen, silicon, and sulfur, and ultimately influence the Earth's climate system (Coale et al., 1996, 2004; Watson et al., 2000; Bishop et al., 2002; Boyd et al., 2007; Cassar et al., 2007; Buesseler et al., 2008). The iron hypothesis in its broad outlines has been thoroughly tested and shown to be correct, but it has not yet been tested with the hypothesis that there is an observable biological response to specific dust deposition 'events'. Only two papers claimed to demonstrate such a response (Bishop et al., 2002; Young et al., 1991), but both presented the evidences that are equivocal at best. Few data are available to study natural inputs of iron to the oceans via continental dust storms. The differences between natural and artificial fertilization are very subtle. Blain et al. (2007) reported that natural fertilization was 10–100 times more efficient at removing carbon from the surface of the ocean than any artificial

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experiments. However, this result observed by Blain et al. (2007) is partially contradicted by the recent observations from Pollard et al. (2009), who described a natural bloom with higher sequestration efficiency than artificial ones but much lower than work of Blain et al. Bioavailable dissolved iron is an important factor controlling upper ocean productivity, and iron limitation is a principle reason for the existence of HNLC regions. Dissolved iron sources for the ocean include dissolution of iron from mineral dust particles deposited from atmosphere, diffusion from continental margin sediments, fluvial and hydrothermal (Berelson et al., 1996, 2003; de Baar and de Jong, 2001; Poulton and Raiswell, 2002; Johnson et al., 2003, 2005; Jickells et al., 2005; Moore and Braucher, 2008). In open ocean regions, atmospheric dust deposition may be the dominant sources of dissolved iron, while sedimentary sources are dominant in regions near the continental margins (Moore and Braucher, 2008). Hence, it has generally been assumed that dissolution from mineral dust was the main source of dissolved iron to the surface of the open ocean (Jickells et al., 2005), particularly in the development of ocean biogeochemical models, most of which include only a dust source for dissolved iron (Archer and Johnson, 2000; Aumont et al., 2003; Gregg et al., 2003; Parekh et al., 2004, 2005). During specific dust deposition 'events' from East Asian dust storm episodes, the aeolian deposition is the most important iron source of open ocean waters in the north Pacific, where there is a significant long range transport from Asian deserts to the open ocean.

The arid and semi-arid area in Northern China is the second largest dust source in the world, inferior only to the Sahara Desert (Han et al., 2008a). About 800 Tg dust aerosols are emitted into the atmosphere every year from the Chinese desert area, and approximately 400 Tg transport for a long rang resulting deposition into the North Pacific Ocean, where it is the HNLC region (Zhang et al., 2003). The supply of iron-rich dust to the North Pacific Ocean is very important in maintaining oceanic primary production and CO_2 uptake. Buesseler et al. (2007) showed that the biological pump was both stronger and more efficient in the North Pacific Ocean compared with Hawaii in the center of the Pacific Rim.

In April 2001, Bishop et al. found the first supportive evidence of natural iron inputs to the ocean (Bishop et al., 2002). Plankton growth over Ocean Station PAPA in the North Pacific Ocean following the dust storm was confirmed when NASA's SeaWiFS satellite glimpsed the sea surface turning greener with chlorophyll. These satellite observations further supported the supposition that iron and other micronutrients from the Asian dust storm could fertilize the phytoplankton (Bishop et al., 2002). However, robot carbon explorers could not collect dust samples, and the satellite images of dust could not reflect dust inputs to the oceans (Han et al., 2006). Therefore, the study of direct continental dust processes, such as the atmospheric dust deposition flux and the soluble iron flux at Ocean Station PAPA following the dust storm is required to confirm in the respect of natural iron fertilization.

However, even if this particular case can support the iron fertilization hypothesis, long-term observation data are lacking in marine export production and continental dust. Long-term data about the export production (e.g., diatoms and plankton foraminifera) in the central subarctic Pacific at water depth between 3000 and 4800 m (Onodera et al., 2005; Asahi and Takahashi, 2007) might allow us to study the relationship between continental dust and its effects on the marine biological system. These data might provide an opportunity to trace the temporal evolution and spatial distribution of the dust concentration in the dust sources, its intermediate transport, and its deposition regions in understanding a linkage among terrestrial dusts, marine productivity, and sequestered carbon in the deep ocean.

2. Study area, data sources, and the model

The study area lies in Northern China and the North Pacific Ocean. The dust source regions cover the deserts in Northern China between 40° and 50°N and 75° and 115°E including Taklimakan, Gurbantunggut, Kumtag, Badain Jaran, Tengger, Ulan Buh, Hobq, Mu Us, Onqin Daga, and Horqin, forming an E–W oriented mid-latitude desert belt (Fig. 1). The area of deserts is 1.5×10^6 km^2, nearly 15.9% of the total area of China (Sun et al., 1998). Except for the Gurbantunggut Desert, the high frequency centers of dust storms are located in the deserts and their surrounding regions in Northern China. When dust storms break out, dust aerosols in dust source regions are raised into the atmosphere and transported from west to east or northwest to southeast driven by atmospheric circulation (Han et al., 2008b). A dominant dust aerosol transport pathway exists from Tarim Basin–Hexi Corridor (or Inner Mongolia)–middle eastern China–Korean Peninsula–Japan–northwestern Pacific Ocean (Zhao et al., 2006).

The North Pacific Ocean is characterized with High-Nitrate, Low-Chlorophyll, where dissolved iron is a main limiting factor for plankton growth (Ridgwell, 2003). The marine export production data from Stations 50N (165°01′E, 50°01′N) and SA (174°E, 49°N) are taken from the papers of Onodera et al. (2005) and Asahi and Takahashi (2007), respectively. The time-series sediment traps with 21 collecting cups (Honjo and Doherty, 1988) were installed on a mooring system at water depths of approximately 1000, 3000, and 5000 m at each station. For the station 50N observation from December 1997 through May 2000, sample collection intervals were either 15.03 or 17.375 days, deployment depth was 3260 m, and diatoms fluxes (as a representative of marine export production) data were in domain of the study (Onodera et al., 2005). In order to correlate with the monthly dust aerosol data, diatoms fluxes data were averaged over natural month producing 30 monthly diatoms fluxes data. For the time-series data of station SA from August 1990 to July 1999, sample collection intervals were either 20 or 56 days, deployment depth was 4812 m, and the

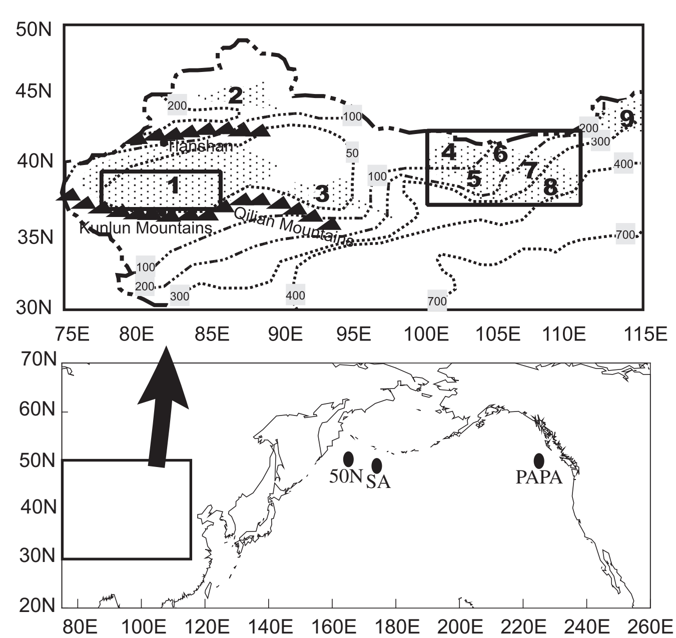

Fig. 1. Distribution of deserts and precipitation in Northern China (top): 1. Taklimakan; 2. Gurbantunggut; 3. Kumtag; 4. Badain Jaran; 5. Tengger; 6. Ulan Buh; 7. Hobq; 8. Mu Us; 9. Onqin Daga. The panes represent the high frequency centers of dust storms. The station locations in North Pacific (bottom).

planktonic foraminifera data were analyzed as the representative of marine export production (Asahi and Takahashi, 2007).

The dusty weather data of 681 stations were obtained from the National Climate Center of the Chinese Meteorological Administration (CMA) with an index defining the days of dust storm and blowing dust based on visibility (Yang et al., 2008).

The Northern Aerosol Regional Climate Model (NARCM) used in this study has been used extensively in simulating Asian dust storms during ACE-Asia (Gong et al., 2003; Zhao et al., 2003) and 44-year climatology of Asian dust aerosol and trans-Pacific transport (Gong et al., 2006; Zhao et al., 2006). The NARCM captured most of the Asian dust mobilization and produced reasonable distributions of the dust concentrations over source regions and downwind areas from East Asia to the North Pacific Ocean to western North America. The NARCM contains all of the atmospheric aerosol processes: production, transport, growth, coagulation, dry and wet deposition, and an explicit microphysical cloud module to treat aerosol–cloud interactions. The detailed method is provided in the literatures (Gong et al., 2003, 2006; Zhao et al., 2006).

For this study, we conducted a 44-year (1960–2003) simulation of every spring from February to May using the National Centers for Environmental Prediction (NCEP) reanalyzed meteorology data as the lateral boundary conditions with fully nudged wind in the whole field every 6 h. This nudge setup resulted in meteorological fields being forced to observations of the NCEP reanalysis meteorology with 6-h forecast segments, which could ensure a realistic meteorological force on dust aerosol emission and transport. The integration time step was 20 min. 12 diameter classes from 0.01 to 40.96 μm were used to represent the size distribution of all aerosols (Zhao et al., 2006). The daily dry and wet deposition fluxes of dust aerosol simulated by NARCM are discussed together with the observation data.

3. Results

The Asian dust storm of 6–9 April, 2001 is the strongest one during the last 20 years; its intensity and affected area were even greater than those of the well-studied strong dust storm in April, 1998 (Jaffe et al., 2003). The dust storm swept Northern China and Midwestern Mongolia, passed Korea, Japan, and the North Pacific Ocean, and finally reached North America during 16–18 April (Han et al., 2006). This trans-Pacific transport resulted in a remarkable increase in dust aerosol concentration over about 80–90% of North America (Jaffe et al., 2003). This dust storm event and its long distance transport had been well researched (Gong et al., 2003; Jaffe et al., 2003; Zhao et al., 2003; Han et al., 2006). On 10 April, 2001, using robotic carbon explorers, Bishop et al. (2002) began to measure the particulate organic carbon (POC) and chlorophyll of the marine mixed layer in the PAPA region in the North Pacific Ocean; these measurement data make it possible to study how the strongest dust storm affected the POC and chlorophyll in the marine mixed layer (Bishop et al., 2002). Because there were no ocean surface observation data of dust deposition into the North Pacific region (Bishop et al., 2002), and TOMS (Total Ozone Mapping Spectrometer) measured well but only for aerosols above 2 km from the surface (Herman et al., 1997), the surface spatial distribution of dust deposition fluxes can only be estimated in other ways. This dust storm event was observed with the simultaneous monitoring of surface PM10 or TSP in China, Korea, and Japan. In addition, the POC and chlorophyll proxies were also measured in the ocean mixture layer in the PAPA region (Bishop et al., 2002). According to Fig. 2, the surface PM10 reached the peak values in Northern China during April 6 and 9 and in Seoul (Korea) on April 10 and 11. The NARCM model simulated the daily dry and wet dust deposition flux in the PAPA region (45°N–55°N, 150°W–140°W)

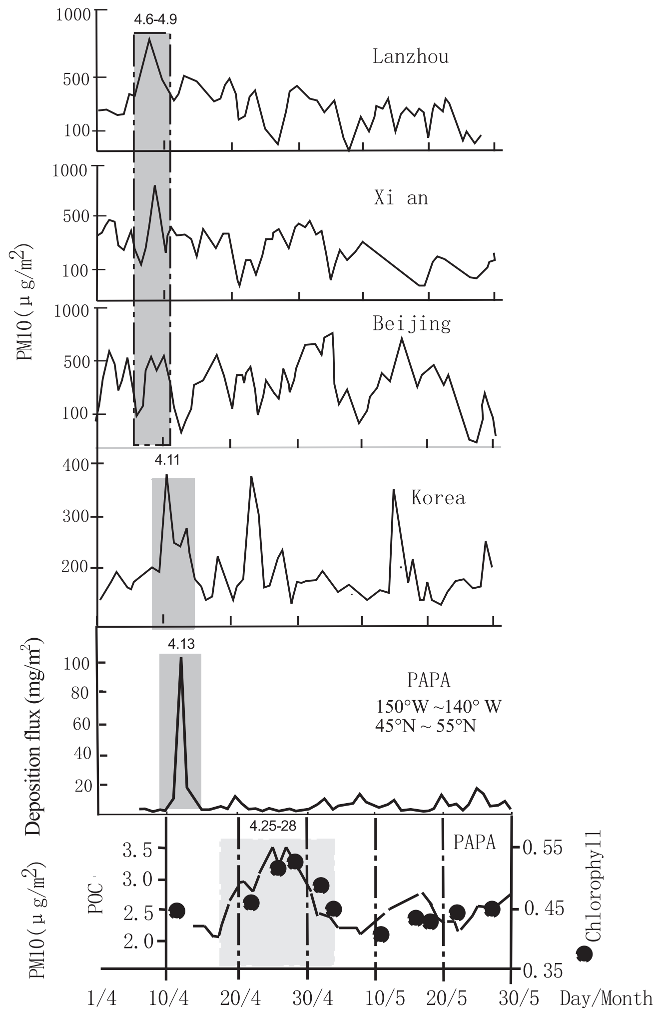

Fig. 2. Time-series of PM10 values in different terrestrial regions, dust deposition flux at Station PAPA during the dust storm and POC and chlorophyll in the North Pacific Ocean in April and May 2001.

from 6 April to 31 May, 2001. The total dust deposition flux (dry and wet) increased dramatically after from 11 April, reached the maximum on April 13, and returned rapidly the original level on 14 April (Fig. 2). The calculated total dust deposition flux was 35 mg m^{-2} per day for 11–13 April in PAPA region. However, in a biogeochemical context, the key flux to the oceans is not directly for dust aerosol, but for soluble or bioavailable iron. Using the most commonly accepted iron/dust ratio of 3.5% in a dust storm (Gao et al., 2003), we converted the deposited 35 mg m^{-2} d^{-1} of dust into 1.225 mg m^{-2} d^{-1} of iron. Then, using 5% as the ratio of soluble iron to total aeolian iron according to Cassar et al. (2008), we converted the total aeolian iron into 0.0615 mg m^{-2} d^{-1} (about 1100 nM) soluble iron in the surface layer at Station PAPA. Only 2 nM increase in iron concentrations can stimulate massive phytoplankton blooms in an iron-limited (HNLC) oceanic area (Wells, 2003). It was enough for about 1100 nM to enhance the efficiency of the marine biological pump and trigger the rapid increase of POC and chlorophyll. Comparison of the variation of POC and chlorophyll in the North Pacific Ocean with different terrestrial regions and the simulated total dust deposition flux in PAPA from the dust storm in April, 2001, it clearly shows that the POC and chlorophyll of the marine mixed layer began to increase rapidly on 18 April, reached their peaks on 25–28 April, and then declined (Fig. 2). The variations of POC and chlorophyll lagged about 2 weeks behind the changes of atmospheric dust concentrations. During this two-week period in the mixed layer, POC almost doubled and chlorophyll increased by ~20% compared to that before the dust storm, causing a measurable ocean biological response. Based on the above discussion, the iron hypothesis is plausible. We could also confirm that atmospheric dust–soluble iron–POC and chlorophyll in marine mixed layer is a related logical chain in natural states.

However, this is only a single case. Long-term observation data about marine export production and continental dust are lacking. Furthermore, this case cannot explain how carbon might be sequestered in the deep ocean.

The Southern Ocean experiment demonstrated that phytoplankton responds directly to iron-addition by increasing primary production and biomass, with a corresponding reduction in pCO_2 and nitrate concentrations (Coale et al., 2004). This result suggests that in certain areas iron could more efficiently pump carbon into the deep ocean and sequester it from the atmosphere. The biological pump was stronger and more efficient than other regions in the North Pacific Ocean; 50% of the carbon from a plankton bloom such as diatoms was pumped into the deep ocean (Buesseler et al., 2007). Diatom and planktonic foraminifera fluxes as two important indicators of marine export production were studied in the central subarctic Pacific (Station 50N at a depth of 3260 m and Station SA at 4812 m) over December 1997–May 2000 and in years 1990–1999, respectively (Onodera et al., 2005; Asahi and Takahashi, 2007). These long-term data sets provide us an opportunity to study the relationship between mainland dust and its affect on marine biological systems.

In the NARCM, the total depositions include particle dry deposition and wet deposition with below-cloud and in-cloud scavenging (Gong et al., 2003). Fig. 3 shows the geographic distribution of the simulated total dust aerosol depositions of all 12 size bins for 1 March to 31 May from 1990 to 1999. The total dust mass deposition ranged between 0.05 and 500 tons km^2 over the Asian continent and the North Pacific Ocean. This range is of the same order of magnitude as that modeled by Tegen and Fung (1994) and is almost similar to the 44-year pattern over the North Pacific from 1960 to 2003 (Zhao et al., 2006). These results indicate that the Stations 50N, SA, and PAPA lie on the main transport pathway of Asian dust storms (Fig. 3). Iron-containing dust is transported from Asian deserts through the atmosphere to the North Pacific Ocean, affecting the ocean's biogeochemistry and improving the efficiency of the biological pump.

The correlation coefficients were calculated between the days of dust storms at 681 weather stations in mainland China and diatom fluxes at Station 50N with same time, 1-month and 2- month lags from December 1997 to June 2000. The results show that the correlation coefficients with a 1-month lag are best with the biggest areas of significant correlations. It is seen from the spatial distribution of correlation coefficients in Fig. 4. Significant positive correlation areas passing the 95% confidence level of *t*-test are respectively the Taklimakan Desert, the headwater region of the Yangtze and Yellow Rivers in the center of the Tibetan Plateau, the Hexi Corridor, the Inner Mongolia Plateau, and the North China Plain. Except for the headwater region of the Yangtze and Yellow Rivers and the North China Plain, the significant positive correlation areas are exactly consistent with the high frequency centers of dust storm in Northern China. However, Fang et al. (2004) also considered the headwater region of the Yangtze and Yellow Rivers to be an important dust source region; dust storms in this region occur with high frequency mostly in winter and spring, as observed with visibility from surface meteorological stations (Han et al., 2008b). The North China Plain could also be a main source region of blowing dust in China (Zhou et al., 2002).

Most of the peaks of diatom fluxes with a 1-month log matched the peaks of dusty days at Minqin (103.05°E, 38.38°N), a representative station in Hexi Corridor and Taklimakan desert, and the rest of the peaks of diatom fluxes with a 1-month lag matched the peaks of dusty days at Zurihe (112.54°E, 42.24°N), a representative station of the Inner Mongolia Plateau and North China Plain (Fig. 5). This result can be explained by the fact that the deposited dust at Station 50N likely originated from various dust source regions.

Fig. 6 shows the spatial distribution of the correlation between the days of dust storm at 781 weather stations in mainland China and the planktonic foraminifera fluxes at Station SA with a 1-month lag from August 1990 to July 1999. The patterns of significant positive correlation are similar with Station 50N, but the areas are smaller than Station 50N. The shadow areas reaching 95% confidence level of *t*-test in Fig. 6 also were concentrated in dust source areas in Northern China, similarly to the result for Station 50N. Most of the peaks of planktonic foraminifers fluxes with a 1-month lag at Station SA matched the peaks of dusty days at Hetian (79.56°E, 37.08°N), which is a representative station in the south margin of Taklimakan Desert (Fig. 7a), and the rest of the peaks matched the peaks of dusty days at Tuole (98.25°E, 38.48°N), which is a representative station in the Tibetan Plateau (Fig. 7b). The dust deposition at Station SA could also be originated from different dust source areas. Furthermore, the number of samples from Station SA is 108 records, which is 3.7 times as many as the number for Station

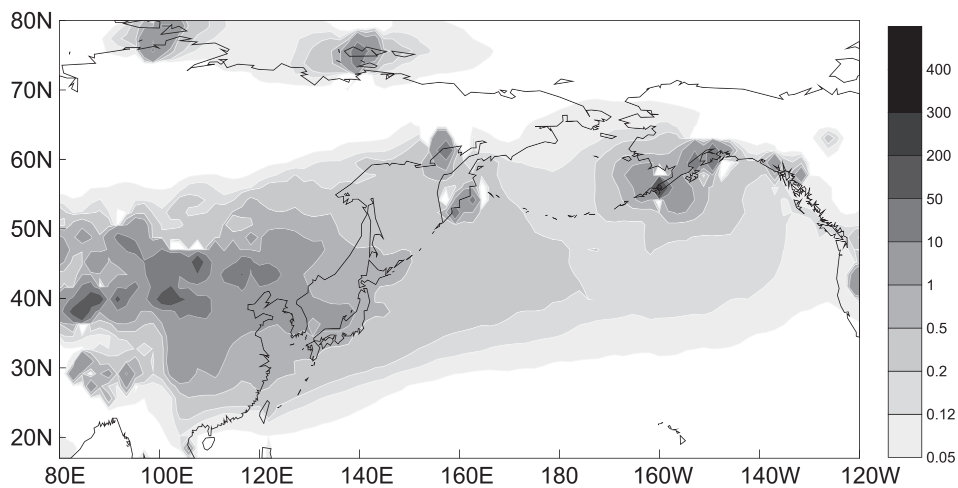

Fig. 3. Geographic distribution of the simulated total dust deposition in spring from 1990 to 1999.

Fig. 4. Spatial distribution of correlation coefficients between the days of dust storm and diatom fluxes at Station 50N with a 1-month lag in China. The contouring method is Ordinary Kriging Interpolation. The shadow areas show reaching 95% confidence level of *t*-test. The dark spots show 681 dusty weather stations in China.

50N. It implied that Asian continental dust is closely related to marine export production on a long-term time scale.

However, from Figs. 4 and 6 shows Visual inspection of the productivity data indicates that two flux peaks of the marine export productivity occurred annually, one in spring and another in autumn. About these autumn productivity peaks, many factors affect marine primary production, such as surface sea temperature, solar radiation, upwelling, and icebergs besides the dust aerosols. Therefore, we think the other factors could play the dominant role in the autumn productivity peaks, especially related with the seasonal variations in precipitation over Asian continents.

Due to the seasonality of Asian dust storm, we selected Asian dust storm in spring in this study. It is found that the significant positive correlation between the Asian dust storm occurrences in spring and the marine primary productivity with a 1-month lag implied that Asian continental dust has a close relationship with the oceanic biological pump in the North Pacific Ocean.

4. Discussion and conclusions

In April, 2001 Bishop et al. (2002) made the first direct continuous observations of the ocean's biological response to natural inputs of dust iron. However, there is an absent chain with dust deposition and aeolian iron fluxes at PAPA. In our study, the modeled dust deposition flux increased rapidly from 11 April, 2001, reached the maximum on 13 April, and returned the normal value on 14 April. The calculated soluble iron peaked at 0.0615 mg m^{-2} d^{-1} (about 1100 nM) during heavy dust deposition in the surface layer at Station PAPA, enhancing the efficiency of the marine biological pump and trigger the rapid increase of POC and chlorophyll. Subsequently, the observation showed that the POC and chlorophyll of the marine mixed layer began to increase rapidly on 18 April, reached the peaks on 25–28 April, and then declined in PAPA region (Bishop et al., 2002). The variations of POC and chlorophyll lagged behind the atmospheric dust variation by about 2 weeks. The timing of the POC increase was similar to that in FeAXs in southern ocean waters (Coale et al., 2004; Jickells et al., 2005). Our complementary dust deposition with the soluble iron data from Station PAPA made Bishop's logical chains more perfectly to support the iron hypothesis in nature states.

Due to the seasonality of Asian dust storm, a case study on dust storm in spring is selected from the modeling results. Even if this case supports the iron fertilization hypothesis, long-term observational data about the effects of continental dust on marine export production are lacking. A correlative comparison with 1984–1989 records of carbon sedimentation at 3800 m at Station PAPA established a very loose "link" between delivery of dust from the atmosphere and enhanced carbon export to the deep sea (Bishop et al., 2002). However, the previous researches showed that strong dust events are highly episodic and affect the HNLC water of the North Pacific Ocean near Station PAPA for a few days once every several years (Boyd et al., 1998; Bishop et al., 2002). The locations of Stations 50N and SA are on the typical dust transport passway from the Asian continent. Therefore, the marine export production at those stations might be more easily affected by the frequent Asian continental dust storms. The significant positive correlation between marine export productivity with a 1-month lag and the days of dust storms in mainland China can be well explained by the

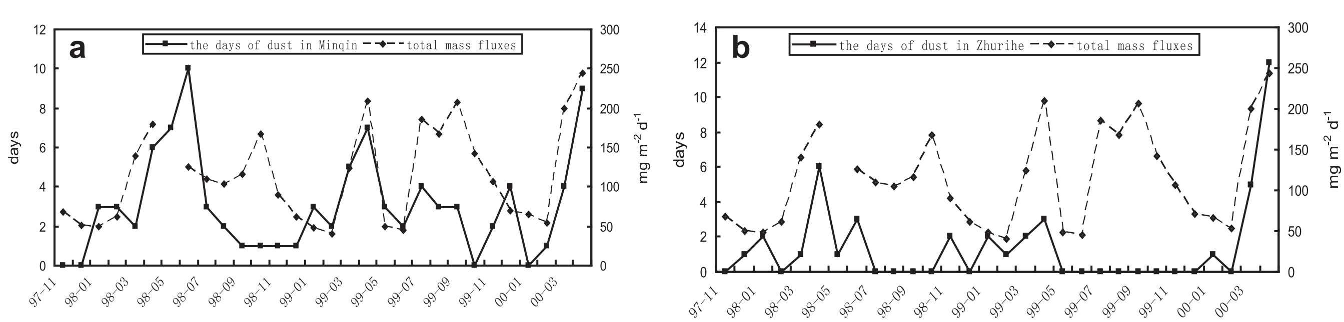

Fig. 5. The changes of the dusty days at representative stations in Northern China and marine product with a 1-month lag at Station 50N.

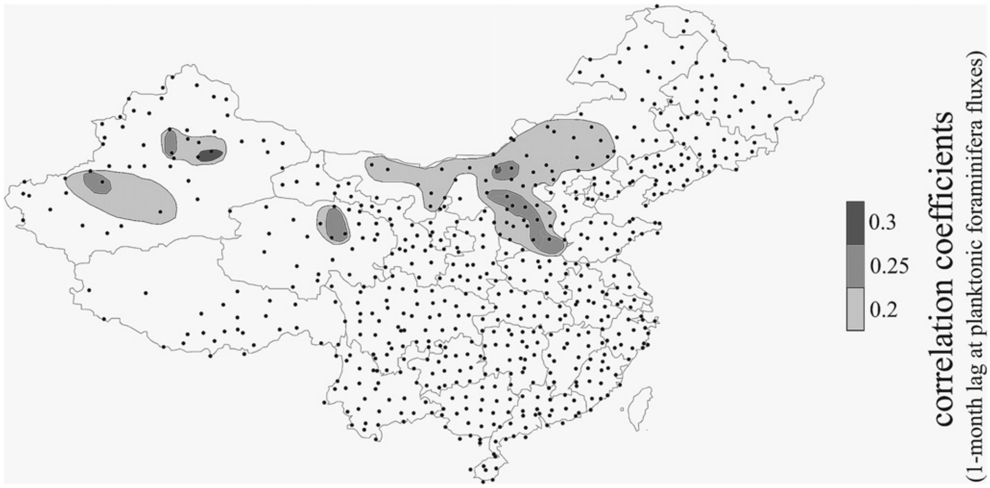

Fig. 6. Spatial distribution of correlation coefficients between the days of dust storm and planktonic foraminifera fluxes at Station SA with a 1-month lag in China. The contouring method is Ordinary Kriging Interpolation. The shadow areas show reaching 95% confidence level of *t*-test. The dark spots show 681 dusty weather stations in China.

biological pump. Transport of dust aerosols from Asia to Stations 50N and SA in the North Pacific Ocean requires about 3–5 days (Han et al., 2005; Yuan et al., 2006). The timing of the ocean's biological response to natural dust iron is about 2 weeks according to the observation at Station PAPA (Bishop et al., 2002). During this 2-week period, this heavy-shelled plankton sinks fast before they can decompose back into dissolved carbon near the surface (Honda, 2003). In addition, the foraminifera ingest huge quantities of plankton, especially diatoms. When they die, they sink and thereby transport carbon toward the depths. Honda (2003) estimated the settling velocity of particles to be greater than 115 m d^{-1} in the North Pacific Ocean. When sediment traps captured diatoms and foraminifera at Stations 50N and SA, the settling times from the ocean's surface to depths of 3260 m and 4812 m were less than

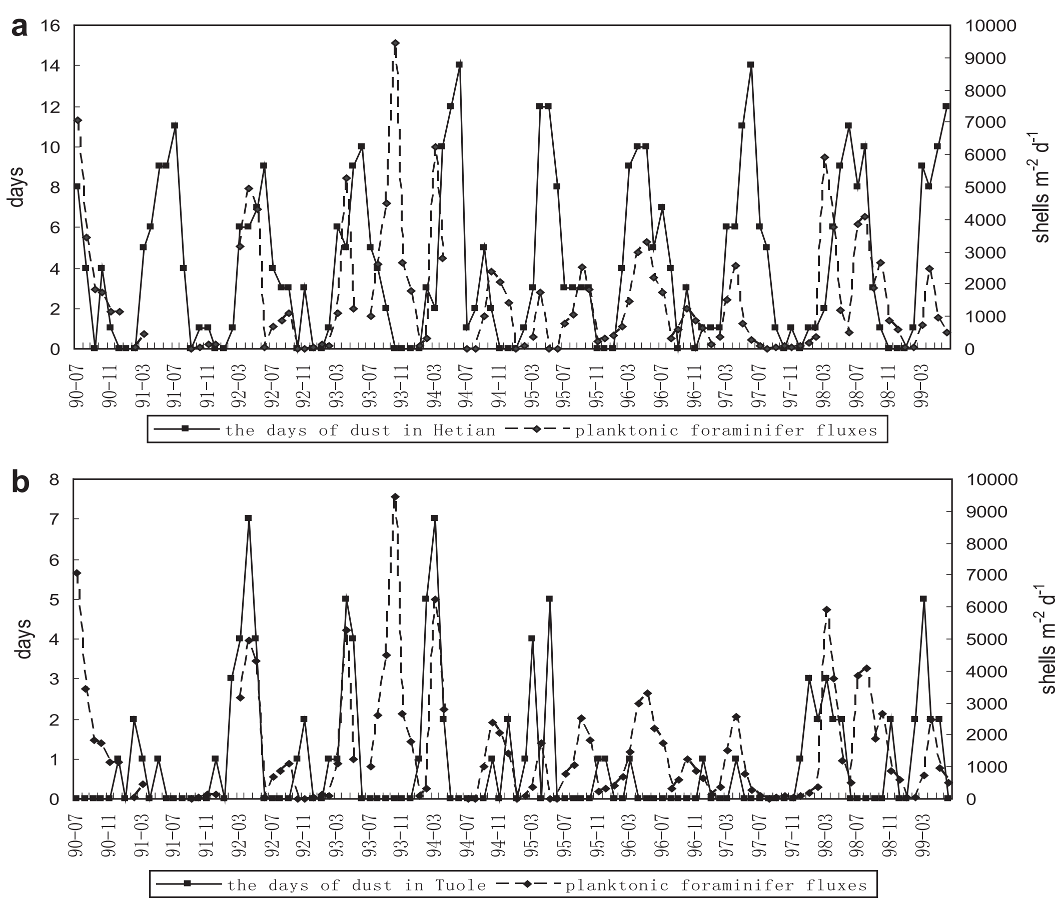

Fig. 7. Changes of dusty days in Hetian (a) and Tuole (b) of China and planktonic foraminifera fluxes with a 1-month lag at Station SA.

28 days and 40 days, respectively. Because the time of settling partly overlapped with the time of the ocean's biological response to the input of natural dust iron, we estimated the total time from the occurrence of the Asian continental dust storm to dust deposition into the deep ocean could be longer than one month. This interval of time is consistent with that of the biological pump. Although many other factors affect marine primary production, such as surface sea temperature, solar radiation, upwelling, and icebergs (Jickells et al., 2005), the significant positive correlation between the dust storm occurrences in the dust source region in China and the marine primary productivity with a 1-month lag implied that Asian continental dust has a close relationship with the oceanic biological pump in the North Pacific Ocean. Because both diatoms and foraminifera can sequester carbon from the atmosphere into the deep ocean, the significant positive correlation between delivery of dust from the atmosphere and diatoms or foraminifera in the deep ocean provides evidence that iron-rich dust increases marine export production. The study also revealed a high positive correlation between the changes in dust fluxes in Lingtai (107°39′E, 35°04′N) and the paleoproductivity of the North Pacific Ocean (159°07.70′E, 33°21.75′ N) during the past 250 ka (Wu et al., 2006). Vostok ice-core records show in the regularly, naturally occurring periods over the past 500,000 years, high levels of iron-rich dust in the atmosphere coincided with decreased atmospheric carbon dioxide levels of up to 100 ppm (Petit et al., 1999; Ridgwell, 2003). These results all suggest that there is an interlocking chain for the change of atmospheric dust aerosol–soluble iron–marine export production.

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References

Archer, D.E., Johnson, K., 2000. A model of the iron cycle in the ocean. Global Biogeochem. Cy. 14, 269–279.

Asahi, H., Takahashi, K., 2007. A 9-year time-series of planktonic foraminifer fluxes and environmental change in the Bering sea and the central subarctic Pacific Ocean, 1990–1999. Prog. Oceanogr. 72, 343–363.

Aumont, O., Maier-Reimer, E., Blain, S., Monfray, P., 2003. An ecosystem model of the global ocean including Fe, Si, P co-limitations. Global Biogeochem. Cy. 17, 1060. doi:10.1029/2001GB001745.

Berelson, W., McManus, J., Coale, K., Johnson, K., Burdige, D., Kilgore, T., Burdige, T., Pilskaln, C., 1996. Biogenic matter diagenesis on the sea floor: a comparison between two continental margin transects. J. Mar. Res. 54, 731–762.

Berelson, W., McManus, J., Coale, K., Johnson, K., Burdige, D., Kilgore, T., Colodner, D., Chavez, F., Kudela, R., Boucher, J., 2003. A time series of benthic flux measurements from Monterey Bay, CA. Cont. Shelf Res. 23, 457–481.

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

Blain, S., et al., 2007. Effect of natural iron fertilization on carbon sequestration in the Southern Ocean. Nature 446, 1070–1074.

Boyd, P., John, A.B., Harrison, P.J., 1998. In vitro iron enrichment experiments at iron-rich and -poor sites in the NE subarctic Pacific. J. Exp. Mar. Biol. Ecol. l227, 133–151.

Boyd, P.W., Jickells, T., Law, C.S., Blain, S., Boyle, E.A., et al., 2007. Mesoscale iron enrichment experiments 1993–2005: synthesis and future directions. Science 315, 612–617.

Buesseler, K.O., et al., 2007. Revisiting carbon flux through the ocean's twilight zone. Science 316, 567–570.

Buesseler, K.O., et al., 2008. Ocean iron fertilization—moving forward in a sea of uncertainty. Science 319 (5860), 162. doi:10.1126/science.1154305.

Cassar, N., Bender, M.L., Barnett, B.A., Fan, S.M., Moxim, W.J., Hiram II, L., Tillbrook, B., 2008. Response to comment on "The Southern Ocean biological response to aeolian iron deposition". Science 319 (5860), 159. doi:10.1126/science.1150011.

Cassar, N., Bender, M.L., Barnett, B.A., Fan, S.M., Moxim, W.J., Hiram II, L., Tillbrook, B., 2007. The Southern Ocean biological response to aeolian iron deposition. Science 317 (5841), 1067. doi:10.1126/science.1144602.

Coale, K.H., Johnson, K.S., Fitzwater, S.E., Gordon, R.M., Tanner, S., et al., 1996. A massive phytoplankton bloom induced by an ecosystem-scale iron fertilization experiment in the equatorial Pacific Ocean. Nature 383, 495–501.

Coale, K.H., Johnson, K.S., Chavez, F.P., Buesseler, K.O., Barber, R.T., et al., 2004. Southern Ocean iron enrichment experiment: carbon cycling in high- and low-Si waters. Science 304, 408–414.

de Baar, H.J.W., de Jong, J.T.M., 2001. Distributions, sources and sinks of iron in seawater, in: biogeochemistry of iron in seawater. In: Turner, D., Hunter, K.A. (Eds.), IUPAC Book Series on Analytical and Physical Chemistry of Environmental Systems, 7, pp. 123–253.

Fang, X.M., Han, Y.X., Ma, J.H., Song, L.C., Yang, S.L., Zhang, X.Y., 2004. Dust storms and loess accumulation on the Tibetan Plateau: a case study of dust event on 4 March 2003 in Lhasa. Chin. Sci. Bull. 49, 953–960.

Gao, Y., Fan, S.M., Sarmiento, J.L., 2003. Aeolian iron input to the ocean through precipitation scavenging: a modeling perspective and its implication for natural iron fertilization in the ocean. J. Geophys. Res. 108 (D7), 4221. doi:10.1029/2002JD002420.

Gong, S.L., Zhang, X.Y., Zhao, T.L., McKendry, I.G., Jaffe, D.A., Lu, N.M., 2003. Characterization of soil dust aerosol in China and its transport/distribution during 2001 ACE-Asia 2. Model simulation and validation. J. Geophys. Res. 108 (D9), 4262. doi:10.1029/2002JD002633.

Gong, S.L., Zhang, X.Y., Zhao, T.L., Zhang, X.B., Barrie, L.A., Mckendry, I.G., Zhao, C.S., 2006. A simulated climatology of Asian dust aerosol and its trans-Pacific transport. Part II: interannual variability and climate connections. J. Clim. 19, 104–122.

Gregg, W., Ginoux, P., Schopf, PS., Casey, N.W., 2003. Phytoplankton and iron: validation of a global three-dimensional ocean biogeochemical model. Deep-Sea Res. II 50, 3143–3169.

Han, Y.X., Zhao, T.L., Song, L.C., Kang, F.Q., Xi, X.X., 2005. The dust spatial distribution characteristic in spring and Northern Pacific region – observation and simulation. China Environ. Sci. 25, 257–261.

Han, Y.X., Fang, X.M., Song, L.C., Xi, X.X., Yang, S.L., 2006. Dust storm in Asia continent and bio-environment effects in the North Pacific: a case study of the strongest dust event on April 2001 in Mid-Asia. Chin. Sci. Bull. 51, 723–730.

Han, Y.X., Cheng, Y.H., Fang, X.M., Zhao, T.L., 2008a. The possible influence of dust aerosol on precipitation in Tarim Basin. China Environ. Sci. 28, 102–106.

Han, Y.X., Fang, X.M., Kang, S.C., Wang, H.J., Kang, F.Q., 2008b. Shifts of dust source regions over central Asia and Tibetan Plateau: connections with the Arctic oscillation and the westerly jet. Atmos. Environ. 42, 2358–2368.

Herman, J.R., Bhartia, P.K., Torres, O., Hsu, C., Seftor, C., Celarier, E., 1997. Global distribution of UV-absorbing aerosols from Nimbus 7/TOMS data. J. Geophys. Res. 102, 16911–16922.

Honda, M.C., 2003. Biological pump in the northwestern Pacific. J. Oceanogr. 59, 671–684.

Honjo, S., Doherty, K.W., 1988. Large aperture time-series sediment traps: design objectives, construction and application. Deep-Sea Res. 35, 53–97.

Jaffe, D., Snow, J., Cooper, O., 2003. The 2001 Asian dust events: transport and impact on surface aerosol concentrations in the US. EOS 84, 501–516.

Jickells, T.D., et al., 2005. Global iron connections between desert dust, ocean biogeochemistry, and climate. Science 308, 67–71.

Johnson, K.S., Elrod, V.A., Fitzwater, S.E., Plant, J.N., Chavez, F.P., et al., 2003. Surface ocean-lower atmosphere interactions in the Northeast Pacific Ocean Gyre: aerosols, iron, and the ecosystem response. Global Biogeochem. Cy. 17, 1063. doi:10.1029/2002GB002004.

Johnson, W.K., Miller, L.A., Sutherland, N.D., Wong, C.S., 2005. Iron transport by mesoscale Haida eddies in the Gulf of Alaska. Deep-Sea Res. II 52, 933–953. 2005.

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

Martin, J.H., 1990. Glacial-interglacial CO_2 change: the iron hypothesis. Paleoceanography 5, 1–13.

Moore, J.K., Braucher, O., 2008. Sedimentary and mineral dust sources of dissolved iron to the world ocean. Biogeosciences 5, 631–656.

Onodera, J., Takahashi, K., Honda, M.C., 2005. Pelagic and coastal diatom fluxes and the environmental changes in the northwestern North Pacific during December 1997–May 2000. Deep-Sea Res. II 52, 2218–2239.

Parekh, P., Follows, M.J., Boyle, E.A., 2004. Modeling the global ocean iron cycle. Global Biogeochem. Cy. 18, GB1002. doi:10.1029/2003GB002061.

Parekh, P., Follows, M.J., Boyle, E.A., 2005. Decoupling of iron and phosphate in the global ocean. Global Biogeochem. Cy. 19, GB2020. doi:10.1029/2004GB002280.

Petit, J.R., Jouzel, J., Raynaud, D., Barkov, N.I., Barnola, J.-M., et al., 1999. Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica. Nature 339, 429–436.

Pollard, R.T., Salter, I., Sanders, R.J., Lucas, M.I., Moore, C.M., et al., 2009. Southern Ocean deep-water carbon export enhanced by natural iron fertilization. Nature 457 (7229), 577. doi:10.1038/nature07716.

Poulton, S.W., Raiswell, R., 2002. The low-temperature geochemical cycle of iron: from continental fluxes to marine sediment deposition. Am. J. Sci. 302, 774–805.

Ridgwell, A.J., 2003. Implications of the global CO_2 "iron hypothesis" for quaternary climate change. Geochem. Geophys. Geosyst. 4 (9), 1076. doi:10.1029/2003GC000563.

Sun, J.M., Ding, Z.L., Liu, T.S., 1998. Desert distributions during the glacial maximum and climatic optimum: example of China. Episodes 21, 28–31.

Tegen, I., Fung, I., 1994. Modeling of mineral dust in the atmosphere: sources, transport, and optical thickness. J. Geophys. Res. 99, 22897–22914.
Watson, A.J., Bakker, D.C.E., Ridgwell, A.J., Boyd, P.W., Law, C.S., 2000. Effect of iron supply on Southern Ocean CO_2 uptake and implications for glacial atmospheric CO_2. Nature 407, 730–733.
Wells, M.L., 2003. The level of iron enrichment required to initiate diatom blooms in HNLC waters. Mar. Chem. 82, 101–114.
Wu, F., Cao, J.J., An, Z.S., Song, Q.L., 2006. Correlation of Asian dust, paleo-productivity in North Pacific and CO_2 in the atmosphere during the past 25,000 years. Chin. J. Process Eng. 6, 75–80.
Yang, Y.Q., Hou, Q., Zhou, C.H., Liu, H.L., Wang, Y.Q., Niu, T., 2008. Sand/dust storm processes in Northeast Asia and associated large-scale circulations. Atmos. Chem. Phys. 8, 25–33.
Young, R.W., Carder, K.L., Betzer, P.R., 1991. Atmospheric iron inputs and primary productivity: phytoplankton responses in the North Pacific. Global Biogeochem. Cy. 52, 119–134.
Yuan, W., Wang, S.G., Zhang, J., Shang, K.Z., 2006. A preliminary study of relationship between the dust events in China continent and oceanic environment in Western North Pacific. Plateau Meteor. 25, 128–135.
Zhang, X.Y., Gong, S.L., Shen, Z.X., Mei, F.M., Xi, X.X., Liu, L.C., Zhou, Z.J., Wang, D., Wang, Y.Q., Chen, Y., 2003. Characterization of soil dust aerosol in China and its transport and distribution during 2001 ACE-Asia: 1.Network observations. J. Geophys. Res. 108 (D9), 4261. doi:10.1029/ 2002 JD002632.
Zhao, T.L., Gong, S.L., Zhang, X.Y., Blanchet, J.P., Mckendry, I.G., Zhou, Z.J., 2006. A simulated climatology of Asian dust aerosol and its trans-Pacific transport. Part I: mean climate and validation. J. Clim. 19, 88–103.
Zhao, T.L., Gong, S.L., Zhang, X.Y., McKendry, I.G., 2003. Modeled size-segregated wet and dry deposition budgets of soil dust aerosol during ACE- Asia, 2001: implications for trans-Pacific transport. J. Geophys. Res. 108 (D23), 8665. doi:10.1029/ 2002J D0 03363.
Zhou, Z.J., Wang, X.W., Niu, R.Y., 2002. Climate characteristics of sandstorm in China in recent 47 years. J.Appl. Meteor. Sci. 13, 193–200.