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Impact of Dust Aerosol on Glacial–Interglacial Climate

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ABSTRACT

The temperature anomaly and dust concentrations recorded from central Antarctic ice core records display a strong negative correlation. The dust concentration recorded from an ice core in central Antarctica is 50–70 times higher during glacial periods than interglacial periods. This study investigated the impact of dust aerosol on glacial–interglacial climate, using a zonal energy balance model and dust concentration data from an Antarctica ice core. Two important effects of dust, the direct radiative effect and dust-albedo feedback, were considered. On the one hand, the direct radiative effect of dust significantly cooled the climate during the glacial period, with cooling during the last glacial maximum being as much as 2.05°C in Antarctica. On the other hand, dust deposition onto the ice decreased the surface albedo over Antarctica, leading to increased absorption of solar radiation, inducing a positive feedback that warmed the region by as much as about 0.9°C during the glacial period. However, cooling by the direct dust effect was found to be the controlling effect for the glacial climate and may be the major influence on the strong negative correlation between temperature and dust concentration during glacial periods.

Key words: dust aerosol, glacial interglacial, energy balance model

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1. Introduction

During the Late Quaternary, dust concentrations recorded from central Antarctic ice cores fluctuated substantially and were 50–70 times higher during glacials and stadials than during interglacials and interstadials (Imbrie et al., 1989; Petit et al., 1999; Fischer et al., 2007; Petit and Delmonte, 2009). The relationship between the glacial–interglacial climate and dust has been studied previously (Lambert et al., 2008; Harrison and Goñi, 2010) and a tight coupling between Antarctic atmospheric dust aerosol and climate has been corroborated (Lambert et al., 2008; Röthlisberger et al., 2008). Wang et al. (2006) found a strong negative correlation between the frequency of dust events and air temperature over the northern Tibetan Plateau of China, reflected in the Malan ice core record. The loess record also shows a similar relationship between dust and air temperature (Zhang et al., 1997).

Dust may affect the glacial–interglacial climate directly by scattering and absorbing both solar and terrestrial radiation (Charlson et al., 1992; Aoki et al., 2005; Hayasaka et al., 2006; Wang et al., 2010; Liu et al., 2011), which is termed the “dust direct effect”. However, dust also has indirect and semi-direct effects on cloud properties (Ackerman et al., 2000; Ramanathan and Crutzen, 2003; Nakajima et al., 2003; Huang et al., 2006a, b, c, 2007; Stith et al., 2009; Huang et al., 2008, 2009, 2010). With the fluctuation in the glacial–interglacial climate, two further important effects may occur. Firstly, dust from the lower and higher latitudes (Prospero et al., 2002; Crucius et al., 2011) contains iron (Fe), which in its soluble form is an essential micronutrient for marine biota. Consequently, dust nutrient inputs to the oceans could in-

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*Corresponding author: LIU Yuzhi, liuyzh@lzu.edu.cn crease the drawdown of CO_2 from the atmosphere to the ocean, which could cool the atmosphere (Ridgwell and Watson, 2002; Zeng, 2007). And secondly, the dust deposited on the surface of glaciers absorbs solar radiation, which changes the ice albedo, thereby increasing the rates of glacial melting (Warren and Wiscombe, 1980; Peltier and Marshall, 1995; Calov et al., 2005; Bar-Or et al., 2008; Xu et al., 2009).

Many studies have attempted to identify the direct effect of dust on the glacial–interglacial climate (Harvey, 1988; Kiehl and Briegleb, 1993; Overpeck et al., 1996; Andersen and Ditlevsen, 1998; Claquin et al., 2003). Mahowald et al. (2006) suggested that globally averaged dust loadings changed by +88% during the last glacial maximum (LGM), which generated globally averaged dust radiative forcing at the top of atmosphere of –1 W m^{-2} and decreased global mean surface temperature by approximately 0.85°C relative to the current climate. Estimates of glacial dust radiative forcing vary from –3 to +0.1 W m^{-2}. Schneider von Deimling et al. (2006a, b) reported that a failure to account for the impact of glacial dust and vegetation cover generates an underestimation of global cooling during the LGM of about 1.5°C. Harvey (1988) also used an energy balance climate model to show that plausible increases in the atmospheric aerosol optical depth during the LGM could have created a further global mean cooling of 2°C–3°C. Simultaneously, many concerns regarding the albedo effect of dust deposition have been raised, with Peltier and Marshall (1995) describing the dust effect on snow albedo during glacial periods as a multiplicative constant that accelerates the ablation rate of ice sheets. However, major uncertainties still remain in the detailed understanding of past and future dust-albedo feedbacks (Ridgwell and Watson, 2002; Mahowald et al., 2006).

This paper examines the reason for the negative relationship between the temperature anomaly and dust concentration and investigates two major dust effects: the direct radiative effect, and dust-albedo feedback. We report upon work using a one-dimensional energy balance model and dust concentration records from the Vostok ice core in central Antarctica. The contribution of dust to the Antarctic climate during the last glacial–interglacial cycle was then compared with the effects of other forcings such as orbital changes and variation in the emission of greenhouse gases (GHGs).

2. Model and experimental design

The energy balance model (EBM) used here is a typical zonally averaged energy balance model. The climate calculations can be executed for only one hemisphere given the antisymmetric seasons in the Northern and Southern Hemispheres. The fundamental assumptions of the EBM are that the atmospheric state can be summarized entirely by the surface temperature and that all energy fluxes can be computed on the basis of surface temperature. Latitude is the only spatial variable presented in the model, and thus, heat is transferred poleward within the atmosphere, but not longitudinally or vertically. The basic equation of the EBM is as follows:

$$Q(x)[1-\alpha(x)]-I(x)=D(x)\ , \tag{1}$$

where $x=\sin\varphi$, φ is latitude, $Q(x)$ is insolation, $\alpha(x)$ is the albedo of the surface, $I(x)$ is the infrared emission from the Earth, and $D(x)$ is horizontal (meridional) heat transport.

2.1 *The dust direct effect*

According to the parameterization scheme of the dust direct effect (Charlson et al., 1992; Penner et al., 1992; Sokolik and Toon, 1996; Diaz et al., 2001), the forcing due to dust (F_{dust}) is considered. By neglecting the effect on thermal radiation due to dust, F_{dust} can be merged into the term of insolation, $Q(x)$, giving

$$Q(x)=Q'(x)+F_{\text{dust}}\ , \tag{2}$$

in which $Q'(x)$ is defined as (Budyko, 1969; Berger, 1978; North, 1975; North et al., 1981, 1983)

$$Q'(x)=S_0 f(e,o,p)/4\ , \tag{3}$$

where S_0 is the solar constant (assumed to be 1367 W m^{-2} in this study), and $f(e,o,p)$ is the factor of latitude distribution for insolation and is a function of eccentricity (e), obliquity (o), and the precession of perihelion (p).

The direct forcing due to dust, F_{dust}, can be calculated as

$$F_{\text{dust}}\cong-\frac{1}{2}Q'(x)\tau_r^2(1-A_{\text{c}})[1-\alpha(x)]\beta\sigma_{\text{d}}\ , \tag{4}$$

where τ_r is the atmospheric transmission (0.76 was used here); A_{c} is the global averaged cloud fraction (0.5); σ_{d} is the areal mean dust optical depth, which is determined by the mass concentration (g m^{-2}) and the specific cross extinction cross (m^2 g^{-1}); and β is the fraction of radiation scattered upward by dust (0.29).

2.2 *Dust-albedo feedback*

Dust deposition is considered to lead to a decrease in the surface albedo and to absorb more solar radiation, inducing positive feedback. In this study, we included dust-albedo feedback in the parameterization of surface albedo, $\alpha(x)$.

Firstly, we parameterized $\alpha(x)$ as

$$\alpha(x)=\begin{cases}0.62 & T(x)\geqslant T_{\text{c}}\\ 0.303+0.0779P_2(x) & T(x)<T_{\text{c}}\end{cases}\ , \tag{5}$$

Table 1. Experimental design.

Experiment (Exp.)	Forcing factor(s)
I	Solar radiation change
II	Factors in Exp. I + GHGs + WaterV
III	Factors in Exp. II + Aerosol
IV	Factors in Exp. III + Dust-albedo feedback

where T_c is the temperature of the snowline and $P_2(x)$ is the second Legendre polynomial, $(3x^2 - 1)/2$.

To consider the effect of dust deposition on the surface, we quantified ice-albedo feedback in a simplified manner by determining the average clear-sky reflected shortwave radiation at the surface and then further parameterized the albedo as follows (Calov et al., 2005):

$$\alpha_n(x) = \alpha(x) - 0.4\lambda_\alpha(x)[1 - \alpha(x)] , \quad (6)$$

where $\alpha_n(x)$ is the new albedo after considering the deposition of dust, and $\lambda_\alpha(x)$ is the function of averaged zenith angle and dust concentration, which was taken from ice core records in this study. The effect of the dust-albedo feedback can have a greater impact on ice surfaces than on ice-free surface, which is reflected in the factor $\lambda_\alpha(x)$.

2.3 *Experimental design*

In addition to the quantitative contribution of the dust to the Antarctic glacial–interglacial climate, we computed the impact of orbital forcing according to Milankovich theory. We also simulated radiative forcing due to GHGs (Shi, 1992) by using the CO_2 and CH_4 concentrations from the Vostok ice core record in central Antarctica. The feedback process caused by water vapor was also included. We calculated the temperature anomaly during the period 0–10 kyr B.P. and compared it with present conditions. The reference temperature anomaly used in this study was taken from the Vostok ice core data. In the description below, we briefly present results simulated by the EBM, and the temperature anomaly from the Vostok ice core data, to represent the simulated and observed temperature anomalies, respectively. We designed four experiments, as listed in Table 1. In experiment I, the only driver was the change in solar radiation due to orbital forcing. In experiment II, the model was driven by orbital forcing, radiative forcing due to GHGs, and water-vapor feedback. On the basis of experiment II, dust direct radiative forcing was included in experiment III (dust-albedo feedback was not included). In experiment IV, dust-albedo feedback was included.

3. Results

First, we confirmed the performance of the model by simulating the present state of the climate over Antarctica. Figure 1 shows the zonal mean temperature distribution in the Southern Hemisphere simulated by the EBM in this study (solid line). In Fig. 1, the observed zonal mean temperature (dashed line) was calculated from European Centre for Medium-Range Weather Forecasts (ECMWF) 40-Year Reanalysis (ERA-40) data for the period 1958–2000. The ERA-40 dataset contains temperature values at a resolution of 2.5°×2.5°. Figure 1 shows that the simulation for the present climate corresponds well to the observed temperature (dotted line). The simulation is good for the Antarctica region.

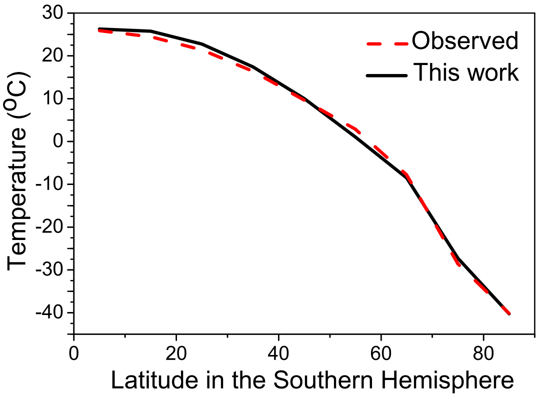

Fig. 1. Simulated and observed present-day surface temperatures in the Southern Hemisphere.

Insolation due to orbital forcing is the basic driver for modeling the glacial–interglacial climate and was included in each experiment (see Table 1). The impact of dust on the Antarctic glacial–interglacial climate was computed according to the difference in the simulated temperature anomalies simulated under experiments III and II. Figure 2 shows the temperature anomalies in central Antarctica in experiments I, II, and III.

High-resolution records indicate that millennial-scale cold periods during the last glacial period and deglaciation were marked by abrupt dust flux increases (Fischer et al., 2007; Tjallingii et al., 2008; David et al., 2010). As shown in Fig. 2, the abrupt increase in dust aerosol during glacial periods simulated a significant cooling effect. During the period from 72 to 57 kyr B.P., atmospheric dust generated an obvious radiative

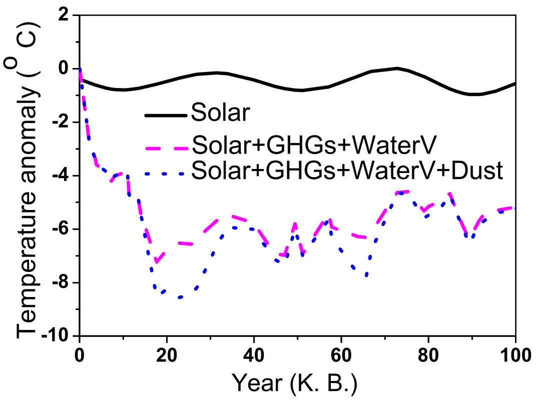

Fig. 2. Antarctic temperature anomalies in experiments I (solid line), II (dashed line) and III (dotted line).

effect, which induced a considerable cooling. Similar circumstances occurred during the period from 33 to 13 kyr B.P. The direct effect due to dust aerosol may have reached -3.32 W m^{-2} and made a pronounced contribution to cooling, by as much as 2.05°C during the LGM. Harvey (1988) also showed that plausible increases in the atmospheric aerosol (including dust and sea salt) optical depth during the LGM could have caused a further global mean cooling of 2°C–3°C. The result of this study is almost in accordance with Harvey's result. Chylek and Lohmann (2008) found that dust radiative forcing generated a 3.10 W m^{-2} cooling in the LGM, with the climate sensitivity ranging from 0.36°C (W m^{-2})$^{-1}$ to 0.69°C (W m^{-2})$^{-1}$. In the present study, the radiative forcing of dust aerosol in the LGM is close to Chylek and Lohmann's result, and the climate sensitivity [0.61°C (W m^{-2})$^{-1}$] is also in the range of the values reported by Chylek and Lohmann (2008). Yue et al. (2010) estimated that LGM dust aerosol exerted a global annual-mean shortwave radiative forcing of -4.69 W m^{-2} at the surface and would have reduced the global annual mean surface air temperature by 0.18°C. The radiative forcing of LGM dust in this study is comparable with that of Yue et al. (2010), except that we simulated greater climate sensitivity.

Figure 2 also shows that the contribution of solar radiation change due to orbital forcing was less than 10% of the total temperature anomaly and accounted for only a small part of the temperature anomaly. The radiative forcing of GHGs was estimated to be about 4.45 W m^{-2} in the present study.

The simulated result, containing the dust direct effect (experiment III), displayed periods where it did not fit well with the central Antarctic temperature anomaly from Vostok ice core data (solid line in Fig. 3) In particular, for cold periods when dust aerosol deposited abruptly, there were variations of about 0°C–1°C. Considering that the simulation result in experiment III does not agree well with the temperature anomalies from the Vostok ice core record, we postulate that some important factor that has an influence on the glacial climate was omitted in experiment III. As we know, in addition to the dust direct effect, the presence of dust on the ice/snow surface could have decreased the surface albedo (Warren and Wiscombe, 1980; Peltier and Marshall, 1995; Calov et al., 2005; Bar-Or et al., 2008), inducing positive feedback that could have increased the atmospheric temperature. In experiment IV (Table 1), we added another possible effect of dust, the feedback of dust-albedo. The effect

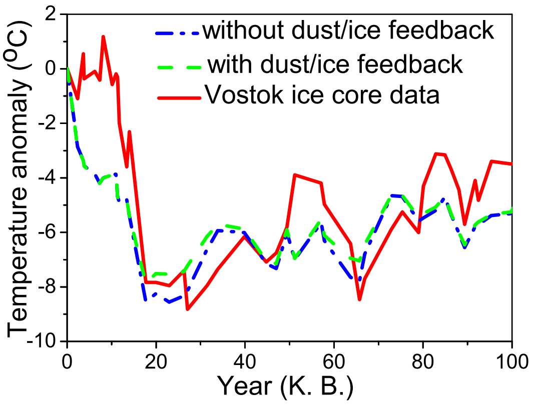

Fig. 3. Temperature anomaly in central Antarctica simulated (dot-dashed line: experiment III, without dust-albedo feedback; dashed line: experiment IV, with dust-albedo feedback) and derived from an ice core record of the last glacial–interglacial period (solid line).

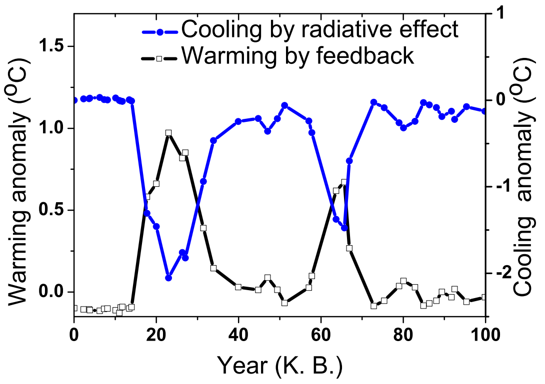

Fig. 4. Contributions of the direct radiative effect due to dust aerosol and dust-albedo feedback to the climate anomaly over the last glacial–interglacial cycle.

Table 2. Explained variance and correlation coefficients in each experiment.

Experiment	Explained variance	Correlation coefficient
I	5.44%	0.09
II	75.71%	0.78
III	86.2%	0.83
IV	86.5%	0.83

of dust-albedo feedback is postulated to increase the ice albedo and warm the climate, especially during glacial periods.

Figure 4 shows the warming by such dust-albedo feedback, and also presents a comparison with the cooling caused by the dust direct effect. As shown in Fig. 4, warming by dust-albedo feedback ranged from about 0 to 0.91°C. The radiation flux change was from 0 to 1.54 W m^{-2}. The effect of such feedback could almost be neglected during interglacial periods, but was significant during glacial and deglaciation periods. The dust-albedo feedback may have induced a temperature increase of as much as 0.91°C and a radiation flux change of 1.54 W m^{-2} during the LGM. As the results of Prospero et al. (2012) showed, dust may decrease the albedo of glacial area and accelerate glacial melting. The positive feedback due to the dust and ice surface albedo may increase glacial melting and bring about the transition from a cold glacial to a deglaciation period.

As shown in Fig. 3, after considering dust-albedo feedback in experiment IV, the variation between the observed (Vostok ice core data) and simulated Antarctic temperature was reduced. Our results demonstrate that dust aerosol plays an important role in glacial climate change. However, large discrepancies still occurred during the period from 0 to 20 kyr B.P. because of the coarse temporal resolution of the GHG record in the Vostok ice core data.

Table 2 lists the explained variances and correlation coefficients between simulated and observed (ice core data) temperature anomalies in the experiments (shown in Table 1). The results presented in Table 2 also suggest that the dust direct effect and dust-albedo feedback are very important factors in glacial climate simulation. Although a consideration of dust-albedo feedback may not improve correlation results, it can enhance the explained variance (i.e., improve the simulation).

4. Conclusions

Using an improved energy balance model, this study explained the relationships between dust aerosol and the Antarctic temperature anomaly during the last glacial–interglacial cycle. The results show that dust aerosol could have cooled the climate by the direct effect during the last glacial–interglacial cycle, with a huge decrease of up to 2.05°C identified during the extremely cold glacial period. The direct effect of dust aerosol may have contributed to abrupt climate change with the rapid emission of dust aerosol during the cold glacial period and stadial epoch. At the same time, dust deposition on the ice could have decreased the surface albedo in the Antarctic, inducing an obvious positive feedback that could have increased the atmospheric temperature during the glacial–interglacial cycle. Dust-albedo feedback was predicted to be as much as about 0.9°C during the LGM, inducing an obvious warming, which may have increased glacial melting. However, although both of these opposite dust effects have played important roles in the glacial climate, cooling by the dust direct effect is the controlling factor for the glacial climate and may be the major reason for the strong negative correlation between temperature and dust concentrations during glacial periods.

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REFERENCES

Ackerman, A. S., O. B. Toon, J. P. Taylor, D. W. Johnson, V. H. Peter, and J. F. Ronald, 2000: Effects of aerosols on cloud albedo: Evaluation of twomey's parameterization of cloud susceptibility using measurements of ship racks. *J. Atmos. Sci.*, **57**, 2684–2695.

Andersen, K. K., and P. D. Ditlevsen, 1998: Glacial/interglacial variations of meridional transport and washout of dust: A 1-dimensional model. *J. Geophys. Res.*, **103**, 8955–8962.

Aoki, Te., T. Tanaka, A. Uchiyama, M. Chiba, M. Mikami, and J. Key, 2005: Sensitivity tests of direct radiative forcing by mineral dust using spectrally detailed radiative transfer model. *J. Meteor. Soc. Japan*, **83A**, 315–331.

Bar-Or, R., C. Erlick, and H. Gildor, 2008: The role of dust in glacial-interglacial cycles. *Quaternary Science Reviews*, **27**, 201–208.

Berger, A., 1978: Long-term variations of daily insolation and Quaternary climatic change. *J. Atmos. Sci.*, **35**, 2362–2367.

Budyko, M. I., 1969: The effect of solar radiation variations on the climate of the Earth. *Tellus*, **21**, 611–

619.

Calov, R., A. Ganopolski, M. Claussen, V. Peoukhov, and R. Greve, 2005: Transient simulation of the last glacial inception. Part I: Glacial inception as a bifurcation in the climate system. *Climate Dyn.*, **24**, 545–561.

Charlson, R. J., S. E. Schwartz, J. M. Hales, R. D. Cess, J. A. Coakley, Jr., J. E. Hansen, and D. J. Hofmann, 1992: Climate forcing by anthropogenic aerosols. *Science*, **255**, 422–430.

Chylek, P., and U. Lohmann, 2008: Aerosol radiative forcing and climate sensitivitydeduced from the Last Glacial Maximum to Holocene transition. *Geophys. Res. Lett.*, **35**, L04804, doi:10.1029/2007GL032759.

Claquin, T., C., and Coauthors, 2003: Radiative forcing of climate by ice-age atmospheric dust. *Climate Dyn.*, **20**, 193–202.

Crusius, J., A. W. Schroth, S. Gassó, C. M. Moy, R. C. Levy, and M. Gatica, 2011: Glacial flour dust storms in the Gulf of Alaska: Hydrologic and meteorological controls and their importance as a source of bioavailable iron. *Geophys. Res. Lett.*, **38**, L06602, doi: 10.1029/2010GL046573.

David, M., S. B. Wallace, and W. Gisela, 2010: Gustiness: The driver of glacial dustiness? *Quaternary Science Reviews*, doi: 10.1016/j.quascirev.2010.06.009.

Diaz, J., F. Exposito, C. Torres, F. Herrera, J. Prospero, and M. Romero, 2001: Radiative properties of aerosols in Saharan dust outbreaks using ground-based and satellite data: Applications to radiative forcing. *J. Geophys. Res.*, **106**, 18403–18416.

Fischer, H., M. Siggaard-Andersen, U. Ruth, R. Röthlisberger, and E. Wolff, 2007: Glacial/interglacial changes in mineral dust and sea-salt records in polar ice cores: Sources, transport, and deposition. *Rev. Geophys.*, **45**(1), doi: 10.1029/2005RG000192.

Harrison, S. P., and M. F. S. Goñi, 2010: Global patterns of vegetation response to millennial-scale variability and rapid climate change during the last glacial period. *Quaternary Science Reviews*, **29**, 2957–2980.

Harvey, L. D. D., 1988: Climatic impact of ice-age aerosols. *Nature*, **334**, 333–335.

Hayasaka, T., K. Kawamoto, G. Shi, and A. Ohmura, 2006: Importance of aerosols in satellite-derived estimates of surface shortwave irradiance over China. *Geophys. Res. Lett.*, **33**, L06802, doi: 10.1029/2005GL025093.

Huang, J. P., B. Lin, P. Minnis, T. Wang, X. Wang, Y. Hu, Y. Yi, and J. K. Ayers, 2006a: Satellite-based assessment of possible dust aerosols semi-direct effect on cloud water path over East Asia. *Geophys. Res. Lett.*, **33**, doi: 10.1029/2006GL026561.

Huang, J. P., P. Minnis, B. Lin, T. Wang, Y. Yi, Y. Hu, S. Sun-Mack, and K. Ayers, 2006b: Possible influences of Asian dust aerosols on cloud properties and radiative forcing observed from MODIS and CERES. *Geophys. Res. Lett.*, **33**, L06824, doi: 10.1029/2005GL024724.

Huang, J. P., Y. Wang, T. Wang, and Y. Yi, 2006c: Dusty cloud radiative forcing derived from satellite data for middle latitude region of East Asia. *Progress in Natural Science*, **10**, 1084–1089.

Huang, J., J. Ge, and F. Weng, 2007: Detection of Asia dust storms using multisensor satellite measurements. *Remote Sens. Environ.*, **110**, 186–191.

Huang, J., P. Minnis, B. Chen, Z. Huang, Z. Liu, Q. Zhao, Y. Yi, and J. K. Ayers, 2008: Long-range transport and vertical structure of Asian dust from CALIPSO and surface measurements during PACDEX, *J. Geophys. Res.*, **113**, D23212, doi: 10.1029/2008JD010620.

Huang, J., Q. Fu, J. Su, Q. Tang, P. Minnis, Y. Hu, Y. Yi, and Q. Zhao, 2009: Taklimakan dust aerosol radiative heating derived from CALIPSO observations using the Fu-Liou radiation model with CERES constraints. *Atmos. Chem. Phys.*, **9**, 4011–4021.

Huang, J., P. Minnis, H. Yan, Y. Yi, B. Chen, L. Zhang, and J. K. Ayers, 2010: Dust aerosol effect on semi-arid climate over Northwest China detected from A-Train satellite measurements. *Atmos. Chem. Phys.*, **10**, 6863–6872.

Imbrie, J., A. McIntyre, and A. Mix, 1989: Oceanic response to orbital forcing in the late Quaternary: observational and experimental strategies. *Climate and Geosciences: A Challenge for Science and Society in the 21th Century*, Berger et al., Eds., Kluwer Academic, Boston, 121–164.

Kiehl, J. T., and B. P. Briegleb, 1993: The relative roles of sulfate aerosols and greenhouse gases in climate forcing. *Science*, **260**, 311–314.

Lambert, F., and Coauthors, 2008: Dust-climate couplings over the past 800,000 years from the EPICA Dome C ice core. *Nature*, **452**, 616–619.

Liu, Y., and Coauthors, 2011: Aerosol optical properties and radiative effect determined from sky-radiometer over Loess Plateau of Northwest China. *Atmos. Chem. Phys.*, **11**, 11455–11463, doi: 10.5194/acp-11-11455-2011.

Mahowald, N. M., M. Yoshioka, W. D. Collins, A. J. Conley, D. W. Fillmore, and D. B. Coleman, 2006: Climate response and radiative forcing from mineral aerosols during the last glacial maximum, pre-industrial, current and doubled-carbon dioxide climates. *Geophys. Res. Lett.*, **33**, L20705, doi: 10.1029/2006GL026126

Nakajima, T., and Coauthors, 2003: Significance of direct and indirect radiative forcings of aerosols in the East China Sea region. *J. Geophys. Res.*, **108**, 8658, doi: 10.1029/2002JD003261

North, G. R., 1975: Theory of energy-balance climate models. *J. Geophys. Res.*, **32**, 2033–2043.

North, G. R., R. F. Cahalan, and J. A. Coakley, 1981: Energy-balance climate models. *Rev. Geophys. Space. Phys.*, **19**, 91–121.

North, G. R., J. G. Mengel, D. A. Short, 1983: Simple energy balance model resolving the seasons and the continents: Application to the astronomical theory of the Ice Age. *J. Geophys. Res.*, **88**, C11, 6576–6586.

Overpeck, J., R. David, L. Andrew, and H. Richard, 1996: Possible role of dust-induced regional warming in abrupt climate change during the last glacial period. *Nature*, **384**, 447–449.

Peltier, W. R., and S. Marshall, 1995: Coupled energy-balance/ice-sheet model simulations of the glacial cycle: A possible connection between terminations and terrigenous dust. *J. Geophys. Res.*, **100**, 14269–14289.

Penner, J. E., R. E. Dickinson, and C. A. O'Neill, 1992: Effects of aerosols from biomass burning on the global radiation budget. *Science*, **256**, 1432–1433.

Petit, J. R., and B. Delmonte, 2009: A model for large glacial–interglacial climate-induced changes in dust and sea salt 39 concentrations in deep ice cores (central Antarctica): Palaeoclimatic implications and prospects for refining ice 40 core chronologies. *Tellus*, **61**B, 768–790.

Petit, J. R., and Coauthors, 1999: Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica. *Nature*, **399**, 429–436.

Prospero, J. M., P. Ginoux, O. Torres, S. E. Nicholson, and T. E. Gill, 2002: Environmental characterization of global sources of atmospheric soil dust identified with the nimbus 7 total ozone mapping spectrometer (TOMS) absorbing aerosol product. *Rev. Geophys.*, **40**(1), 1002, doi: 10.1029/2000RG000095.

Prospero, J. M., J. E. Bullard, and H. Richard, 2012: High-latitude dust over the North Atlantic: Inputs from Icelandic proglacial dust storms. *Science*, **335**, 1078–1082.

Ramanathan, V., and P. J. Crutzen, 2003: New directions: Atmospheric brown "clouds". *Atmos. Environ.*, **37**, 4033–4035.

Ridgwell, A. J., and A. Watson, 2002: Feedback between aeolian dust, climate, and atmospheric CO2 in glacial time. *Paleoceanography*, **17**(4), 1059, doi. 10.1029/2001PA000729.

Röthlisberger, R., and Coauthors, 2008: The southern hemisphere at glacial terminations: Insights from the dome C ice core. *Climate of the Past*, **4**, 345–356.

Schneider, von Deimling, T., H. Held, A. Ganopolski, and S. Rahmstorf, 2006a: Climate sensitivity estimated from ensemble simulations of glacial climate. *Climate. Dyn.*, **27**, 149–163.

Schneider, von Deimling, T., A. Ganopolski, H. Held, and S. Rahmstorf, 2006b: How cold was the last glacial maximum? *Geophys. Res. Lett.*, **33**, L14709, doi: 10.1029/2006GL026484. .

Shi, G. Y., 1992: Radiative forcing and greenhouse effect due to the atmospheric trace gases. *Sci. China* (B), **35**, 217–229.

Sokolik, I. N., and O. B. Toon, 1996: Direct radiative forcing by anthropogenic airborne mineral aerosols. *Nature*, **381**, 681–683.

Stith, J. L., and Coauthors, 2009: An overview of aircraft observations from the Pacific Dust Experiment campaign. *J. Geophys. Res.*, **114**, D05207, doi: 10.1029/2008jd010924.

Tjallingii, R., M. Claussen, J.-B.W. Stuut, J. Fohlmeister, A. Jahn, T. Bickert, F. Lamy, and U. Röhl, 2008: Coherent high- and low-latitude control of the northwest African hydrological balance. *Nature Geoscience*, **1**(10), 670–675.

Wang, N., T. Yao, L. G. Thompson, and M. Davis, 2006: Strong negative correlation between dust event frequency and air temperature over the northern Tibetan Plateau reflected by the Malan ice core record. *Annals of Glaciology*, **43**, 29–33.

Wang, X., J. Huang, R. Zhang, B. Chen, and J. Bi, 2010: Surface measurements of aerosol properties over northwest China during ARM China 2008 deployment. *J. Geophys. Res.*, **115**, D00K27, doi: 10.1029/2009JD013467.

Warren, S. G., and W. J. Wiscombe, 1980: A model for the spectral albedo of snow. II: Snow containing atmospheric aerosols. *J. Atmos. Sci.*, **37**, 2734–2745.

Xu, B., M. Wang, D. R. Joswiak, J. J. Cao, T. D. Yao, G. J. Wu, W. Yang, and H. B. Zhao, 2009: Deposition of anthropogenic aerosols in a southeastern Tibetan glacier. *J. Geophys. Res.*, doi: 10.1029/2008JD011-510.

Yue, X., H. Wang, H. Liao, and D. Jiang, 2010: Simulation of the direct radiative effect of mineral dust aerosol on the climate at the Last Glacial Maximum. *J. Climate*, **24**, 843–858.

Zeng, N., 2007: Quasi-100 ky glacial-interglacial cycles triggered by subglacial burial carbon release. *Climate of the Past*, **3**, 135–153, doi: 10.5194/cp-3-135-2007.

Zhang, X. Y., R. Arimoto, and Z. S. An, 1997: Dust emission from Chinese desert sources linked to variations in atmospheric circulation. *J. Geophys. Res.*, **102**, 28041–28047.