SCIENCE CHINA
Earth Sciences

• RESEARCH PAPER •

February 2013 Vol.56 No.2: 301–310
doi: 10.1007/s11430-012-4460-x

Numerical analysis for contribution of the Tibetan Plateau to dust aerosols in the atmosphere over the East Asia

MAO Rui[1,2*], GONG DaoYi[1], SHAO YaPing[3], WU GuangJian[4] & BAO JingDong[2]

[1] *State Key Laboratory of Earth Surface Processes and Resource Ecology, Beijing Normal University, Beijing 100875, China;*
[2] *Department of Physics, Beijing Normal University, Beijing 100875, China;*
[3] *Institute of Geophysics and Meteorology, University of Cologne, Cologne D-50923, Germany;*
[4] *Institute of Tibetan Plateau Research, Chinese Academy of Sciences, Beijing 100085, China*

Received November 15, 2011; accepted April 5, 2012; published online July 18, 2012

Although the Tibetan Plateau is widely thought as a potential dust source to the atmosphere over East Asia, little is known about the temporal changes of Tibetan dust activities and Tibetan dust source strength. In this study, we address these two issues by analyzing dust storm frequencies and aerosol index through remote sensing data and by means of numerical simulation. The findings indicate that monthly dust profiles over the Tibetan Plateau vary significantly with time. Near the surface, dust concentration increases from October, reaches its maximum in February–March, and then decreases. In the middle to upper troposphere, dust concentration increases from January, reaches its maximum in May–June, and decreases thereafter. Although Tibetan dust sources are important contributors to dust in the atmosphere over the Tibetan Plateau, their contribution to dust in the troposphere over eastern China is weaker. The contribution of Tibetan dust sources to dust in the atmosphere over the Tibetan Plateau decreases sharply with height, from 69% at the surface, 40% in the lower troposphere, and 5% in the middle troposphere. Furthermore, the contribution shows seasonal changes, with dust sources at the surface at approximately 80% between November and May and 45% between June and September; in the middle and upper troposphere, dust sources are between 21% from February to March and less than 5% in the other months. Overall, dust aerosols originating from the Tibetan Plateau contribute to less than 10% of dust in East Asia.

Tibetan Plateau, dust aerosol, aerosol index, numerical dust modeling, dust sources

Citation: Mao R, Gong D Y, Shao Y P, et al. Numerical analysis for contribution of the Tibetan Plateau to dust aerosols in the atmosphere over the East Asia. Science China: Earth Sciences, 2013, 56: 301–310, doi: 10.1007/s11430-012-4460-x

The direct and indirect effects of dust aerosols on climate change in East Asia are important to climate research [1–3]. Dust aerosols directly influence radiative balance by modifying the reflection, scattering, and absorption of solar and terrestrial radiation [4]. Moreover, dust aerosols interact with clouds and indirectly influence precipitation and the meteorological processes that affect the occurrence and magnitude of storms in the middle troposphere [5–7]. In North East Asia, there are vast areas of deserts and sandy regions. Recently, modeling and observational studies have indicated that dust from East Asia can be transported more than once around the globe by the westerly winds and hence may potentially impact the global climate [7, 8]. As the amount of dust in the troposphere over East Asia is controlled largely by local sources, it is important to estimate the relative importance of these sources.

The Tibetan Plateau is considered an important source of Asian dust. On the plateau, there exists a vast tract of sand dunes and desert lands. For example, an area of approximately 2000 km^2 of desert land (with moving sand dunes in winter) exists in the valleys of the Yarlung Zangbo River

*Corresponding author (email: mr@bnu.edu.cn)

and its tributaries, with an average altitude of approximately 3600 m. Between the Gangdese and Kunlun Mountain are a series of near west-east glaciated mountains and a vast area of planation surface (Plateau Surface) on which there are many wind-blown sand dunes and lakes of various sizes. The aeolian surfaces occupy approximately 400 km^2, most of which is moving sand dunes. Moreover, deserted meadow and grassy soils occupy a much wider area than the sand dunes and include almost the entire source areas of the Yellow River and the Yangtze River. These areas provide ample materials for dust storm occurrence [9].

The contribution of the Tibetan Plateau to dust aerosols in the troposphere over East Asia shows seasonal variations. Over the plateau, dust transport activities occur frequently in winter, spring, and summer [10–12], which implies that the Tibetan Plateau provides more dust to the atmosphere in these seasons than in autumn. Moreover, the relative importance of Tibetan dust aerosols also varies with height. Huang et al. [13] detected summertime Tibetan dust plumes using the CALIPSO data (Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations). They found that for lower layers (at altitudes from 3 to 5 km), the depolarization ratio for 64% of the pixels exceeded 20%. However, between 7 and 10 km, the depolarization ratio for 47% of the dust pixels was less than 10%. The larger depolarization ratio indicates the presence of highly concentrated desert dust; that is, the higher the dust concentration, the greater the volume depolarization ratio. These results suggest that there is more dust closer to the surface relative to the middle to upper troposphere over the Tibetan Plateau.

Data regarding dust originating from the Tibetan Plateau are unfortunately scarce, and this lack of empirical data is the primary reason for the dearth of detailed investigations. Observational data suitable for dust research include meteorological and geological records as well as remote sensing data. The meteorological records involve current weather reports and visibility measurements [5, 13]; geological records include ice cores, sea sediment records, and loess records [10, 14]; remote sensing data are collected primarily by satellite-borne instruments, such as the Ozone Monitoring Instrument (OMI), CALIPSO, and Moderate Resolution Imaging Spectroradiometer [11, 15]. Weather stations and geological records are rare on the Tibetan Plateau, and their locations are sporadic. Therefore, few dust observations are available for the Tibetan Plateau, and these data cannot adequately represent the dust activities in this region. Remote sensing data provide a good overview of dust distribution but cannot easily be used to quantify dust amount. Thus, observational data alone are insufficient to meet the research needs.

Dust models have been developed to simulate regional dust processes and to provide quantitative dust estimates. For example, Uno et al. [7] used a dust model combined with CALIPSO measurements to simulate the global transport of dust generated from the Taklimakan Desert during May 2007. Using the Northern Aerosol Regional Climate Model (NARCM), Zhao et al. [16] constructed the 44-year (1960–2003) climatology of spring Asian dust emissions, loads, depositions, trans-Pacific transport routes, and budgets. The inter-annual variability in Asian dust and its climate connections have been analyzed [17]. Zhang et al. [18] highlighted the different contributions of various dust sources using the NARCM. In sum, estimating the contribution of the Tibetan Plateau to dust aerosol levels in the atmosphere over East Asia using dust modeling is interesting and important. In this study, an Integrated Wind Erosion Modeling System (IWEMS) will be employed to simulate dust processes on the Tibetan Plateau and its margin area. Based on the simulations, monthly changes in the amount of dust aerosols over the Tibetan Plateau and the contribution of the Tibetan Plateau to dust aerosols in the atmosphere over East Asia will be measured. This work will enhance our understanding of the Tibetan Plateau's contribution to dust aerosols in the atmosphere over East Asia.

1 Data and methods

1.1 Data

In this study, dust storm frequency (DSF) was used to reflect changes in the amount of dust aerosols at the near-surface. The frequency of dust storms is defined as the total number of days with dust storm occurrence. Because dust storms increase dust aerosols at the surface, the frequency of dust storms may reflect variations in the amount of dust aerosols at the surface with an in-phase relationship. The dust storm records are provided by the China Meteorology Administration and include information about station heights, start times and end times of dust storm events, wind speeds, and wind directions from 1954–2007. The DSF of the Tibetan Plateau was obtained by averaging the DSF of each station. To better represent the frequency of dust storms over the Tibetan Plateau, we selected stations whose heights are larger than or equal to 3000 m above sea level (a.s.l.) (The reason will be clarified in Section 2.3 for station selection). These selected stations are located in the middle and eastern regions of the Tibetan Plateau (Figure 1).

In addition, the sum of the aerosol index (AI) derived by the Total Ozone Mapping Spectrometer (TOMS) was used to describe changes in the amount of dust aerosols in the middle to high troposphere over the Tibetan Plateau. The AI is obtained via the Internet (ftp://toms.gsfc.nasa.gov/pub/version8/aerosol/) between the years 1979 and 2005. AI is widely used in dust aerosol research [11]. To retrieve the sum of the AI over the Tibetan Plateau, we first computed the daily sum of AI over the Tibetan Plateau, and then the daily AI sum was averaged for each month, which yielded a monthly AI sum over the Tibetan Plateau. Because there is a gap in the AI data between May 1993 and July 1996, the data are divided into two parts: before 1993 and after 1996.

These two time-windows cannot be concatenated. Therefore, we analyzed two time-windows of the monthly AI sum: from 1979 to 1992 and from 1997 to 2005.

DSF could indirectly reflect the amount of dust aerosols in the middle to high troposphere because frequent dust storms could lift more dust aerosols into the troposphere. However, we used AI instead of DSF to reveal the changes in the amount of dust aerosols in the middle to high troposphere in this study because in addition to the Tibetan dust source, many remote dust sources also could transport dust aerosols into the middle to high troposphere over the Tibetan Plateau, such as the Taklimakan Desert, the Thar Desert, or the Arabian desert. Using the frequency of dust storms over the Tibetan Plateau or other dust sources to reflect the dust aerosol amount in the middle to high troposphere over the Tibetan Plateau is not sufficiently precise.

Although the sum of AI could reveal the dust aerosol amount in the atmosphere over the Tibetan Plateau, there are some uncertainties involved with the AI data, including (1) the effect of clouds on aerosols, (2) the types of aerosols, and (3) the numerical relationship between AI and the amount of dust aerosols. First, clouds are common over the southern and southeastern regions of the Tibetan Plateau, especially during summertime. The existence of clouds may contaminate the retrieval of aerosols. However, in this study, the effect of clouds on the aerosols is minimized. AI values are positive for ultraviolent (UV) absorbing aerosols, near zero for clouds, and negative for scattering aerosols. The AI data used only include positive values and are therefore less contaminated by clouds [19]. Second, in addition to dust aerosols, black carbon and some UV absorbing aerosols also produce significant AI signals, especially with high concentrations or altitudes. However, dust aerosols are the main components of aerosols in the troposphere over the Tibetan Plateau [12]. The sum of AI over the Tibetan Plateau may predominantly represent the amount of dust aerosols in the middle to high troposphere. Third, several studies have indicated that high AI is accompanied by high dust concentrations in the middle to high troposphere [19]. Thus, a positive correlation may occur between the AI and the amount of dust aerosols, although there is no precise numerical relationship between them.

1.2 Model description

The IWEMS is widely employed in dust simulations in East Asia [20, 21]. Mao et al. [22, 23] has implemented this model to study northeastern Asian dust between 1982–2006, and based on these simulations, the authors analyzed the effects of the Arctic Oscillation on dust over East Asia. In this study, we used IWEMS to simulate aeolian dust processes over the Tibetan Plateau and its margin area. The IWEMS consists of modeling, monitoring, database and data assimilation components. The modeling component comprises an atmospheric model and modules for land-surface processes and dust emission, transport and deposition. The atmospheric model–either global, regional or meso-scale-serves as a host for the other modules. The atmospheric models have advanced numerics for atmospheric dynamics and physical processes, e.g. radiation, clouds, convection, and turbulent diffusion. A land-surface scheme simulates the energy, momentum and mass exchanges between atmosphere, soil and vegetation. For dust modeling, the land-surface scheme produces friction velocity and soil moisture as outputs. Given three dust emission mechanisms (aerodynamic entrainment, saltation bombardment, and aggregates disintegration), the dust emission scheme obtains friction velocity and soil moisture from the land-surface scheme and other spatially distributed parameters from the geographical information system (GIS) database and calculates dust-emission rates for different particle size groups. To predict dust motion, the transport and deposition model obtains wind, turbulence and precipitation data from the atmospheric model and dust emission rate and particle-size information from the dust-emission model [24].

In this study, the initial field and the boundary field of the atmospheric model, which is updated every six hours, is provided by the National Centers for Environmental Prediction and National Center for Atmospheric Research (NCEP/NCAR) Reanalysis dataset. Atmospheric changes over the Tibetan Plateau and its margins during the simulation are similar to real atmospheric changes. In addition, the land-surface data are required for land-surface, dust-emission and dust-deposition schemes in the IWEMS. The dust source is obtained through the Environmental and Ecological Science Data Center for West China, National Natural Science Foundation of China (http://westdc.westgis.ac.cn) [25]. The leaf area index (LAI) is provided by Boston University [26]. The vegetation cover (VC) is transferred from normalized deviation vegetation index (NDVI) [27], derived by Gutman and Ignatov [28]. The vegetation data, including LAI and VC, are updated each month.

1.3 Methodology

Two model experiments are conducted in this study: one using all dust sources, including the Tibetan dust sources (OBS), and the other using all dust sources without the Tibetan dust source (CTRL). All other input variables to the model, including soil characteristics and atmospheric boundary conditions, are equal in both experiments. The OBS simulates real-time dust weather processes, and variations in dust aerosols during simulation are caused by the contributions of all dust sources; in contrast, the CTRL only simulates dust aerosol changes that are caused by dust sources independent of the Tibetan dust source. The difference between these two experiments (i.e. OBS minus CTRL) reflects the influence of the Tibetan dust source on dust in the atmosphere over the East Asia.

To highlight the contribution of the Tibetan dust source to dust in the atmosphere over East Asia, we selected extreme years and special dust sources for simulation. The selected years were 1972, 1974, 1976, 1979, and 1984. These years had frequent dust storms and may contribute to more dust in the atmosphere over East Asia (Figure 2). In each year, the twelve months starting from 1 January to 31 December are simulated individually, and the initial dust concentration of 1 January in each year is set as zero. In addition, only the Tibetan dust sources with heights greater than 3000 m a.s.l. are considered. These sources could easily transport dust to the middle to high troposphere over the Tibetan Plateau and eastern China.

To create a reasonable simulation, two points are considered in this study: (1) the contribution ratio other than the contribution amount is computed; and (2) vegetation change on the inter-annual timescale is not considered. Clearly, the simulations are rarely consistent with observations during modeling. The Tibetan Plateau has a vast area and diverse land surface conditions. However, there are relatively few observations of land surface collected, which are useful for accurate modeling. The lack of observational data makes it difficult for the IWEMS to accurately simulate dust processes over the Tibetan Plateau and its margins. To better estimate the contribution of the Tibetan dust source to atmospheric dust, a contribution ratio other than the contribution amount is calculated. The difference of contribution amounts between observation and simulation is substantially larger than that of the contribution ratio between observation and simulation. In addition, to reduce the vegetation impact on dust emission, the vegetation change on the inter-annual timescale is not taken into consideration. For a given month and a given grid point, vegetation data that were averaged over the years between 1982 and 2006 are implemented.

2 Dust concentration changes in the atmosphere over the Tibetan Plateau

2.1 Monthly changes derived by observations

In this study, we used DSF and the sum of AI to represent dust concentrations in the atmosphere over the Tibetan Plateau. The DSF presents dust concentrations at the surface, and the sum of daily AI provides dust concentrations in the middle to high troposphere. As there is a gap in the AI data between May 1993 and July 1996, the AI data are divided into two periods: 1979–1992 and 1997- 2005. We calculated the monthly AI sum during these two periods independently. To maintain consistency across datasets, monthly DSF were calculated twice for different periods. In addition, monthly DSF calculations during the period from 1961 to 2007 were also calculated.

Figure 3(a) shows the monthly changes in the Tibetan DSF. As seen in the figure, during different periods, the DSF shows similar monthly changes, increasing from October, reaching its peak during February to March, and then decreasing. The high DSF occurs in December and lasts until the following April. For instance, compared with the annual average of DSF of 7.0 days during 1961–2007, the DSF from December to the following April accounts for 5.5 days, which is 82% of the annual average of DSF. In addition to the DSF, Figure 3(b) shows monthly changes in the AI sum over the Tibetan Plateau. During both periods, i.e. 1979–1992 and 1997–2005, the monthly changes in the sum of AI show similar variation. The sum of AI increases from January and reaches its peak between April and June, after which it declines. Clearly, the sum of AI between April and June is higher compared to the other months. For instance, during 1979–1992, the sum of AI from April to June ac-

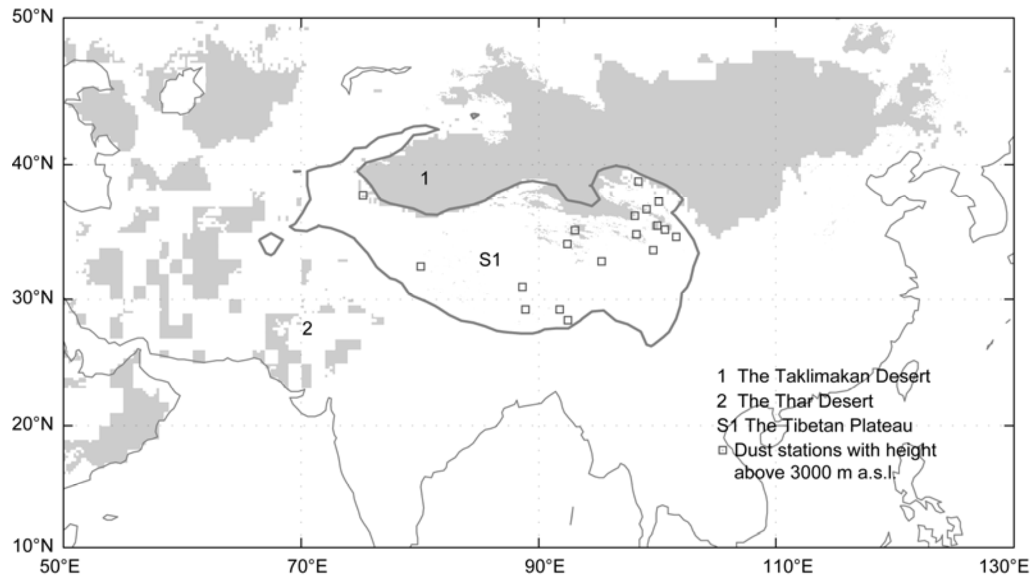

Figure 1 Research area and location of dust storm stations. The shaded area is the dust source used in the dust simulation. The contour line is to enclose the region that has height ⩾3000 m a.s.l. The rectangles represent stations over the Tibetan Plateau.

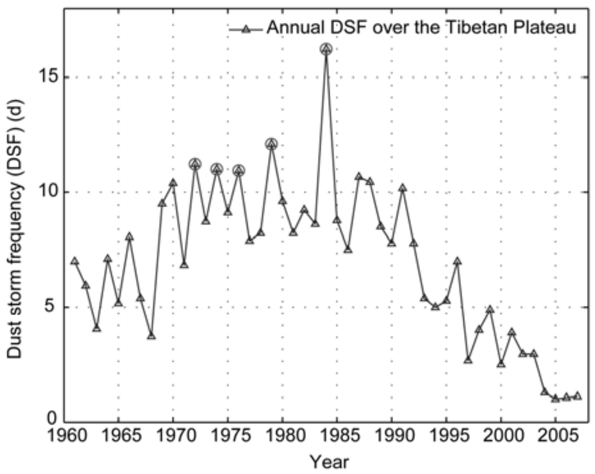

Figure 2 The annual variations in the frequency of dust storms over the Tibetan Plateau. The circles represent the simulation years, that is, 1972, 1974, 1976, 1979, and 1984.

counts for 38% of the sum of AI in a year. This monthly AI sum distribution is consistent with the results of Xia et al. [29], who found that the aerosol optical depth over the Tibetan Plateau is high during late spring and early summer and peaks during May and June.

Based on the above analysis, one could conclude that the monthly distribution of DSF is not similar to that of the sum of AI. The DSF is high from February to March, but the sum of AI shows high values from April to June. The high DSF from February to March implies that near-surface dust concentration on the Tibetan Plateau is high during this period. This finding also suggests that the contribution of the Tibetan dust source to dust in the atmosphere over East Asia is concentrated during February and March because high near-surface dust concentrations could cause considerable dust to be lifted from the surface to the middle to high troposphere. Additionally, the large AI sum during April and June indicates that dust concentrations in the middle to high troposphere over the Tibetan Plateau are high during April and June. This inconsistency in the monthly distributions of DSF and AI sum implies that the Tibetan dust source contributes less to dust in the atmosphere over the Tibetan Plateau between April and June. The high dust concentration over the Tibetan Plateau from April to June may be caused by a combination of dust sources, including the Thar Desert and the Taklimakan Desert. These dust sources could transport dust to the high troposphere over the Tibetan Plateau between May and June.

2.2 Monthly changes derived by simulations

Figure 4 shows the simulated monthly dust concentrations over the Tibetan Plateau. As seen in the figure, near-surface dust concentrations are high relative to concentrations in the high troposphere. The dust concentrations are 92, 16, and 5

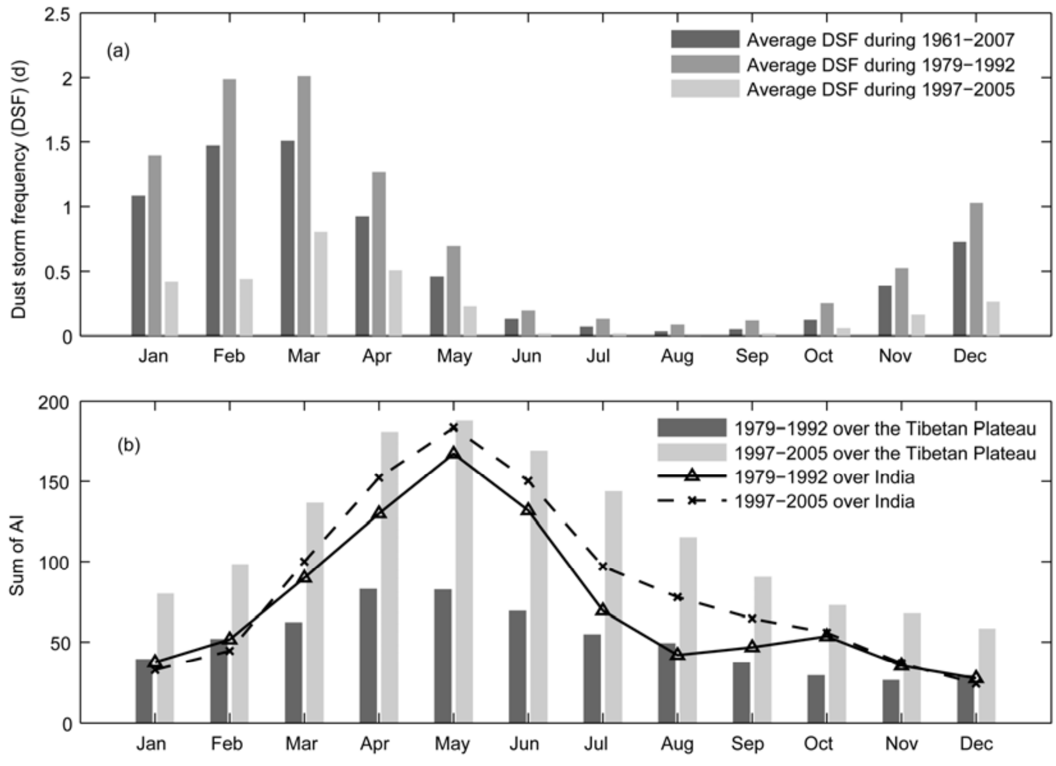

Figure 3 The dust storm frequency (a) and the total sum of aerosol index (b) over the Tibetan Plateau. The bar and solid line in (b) indicate the monthly sum of AI over the Tibetan Plateau and the Thar Desert, respectively. The extent of the Thar Desert is 70°–80°E and 20°–30°N.

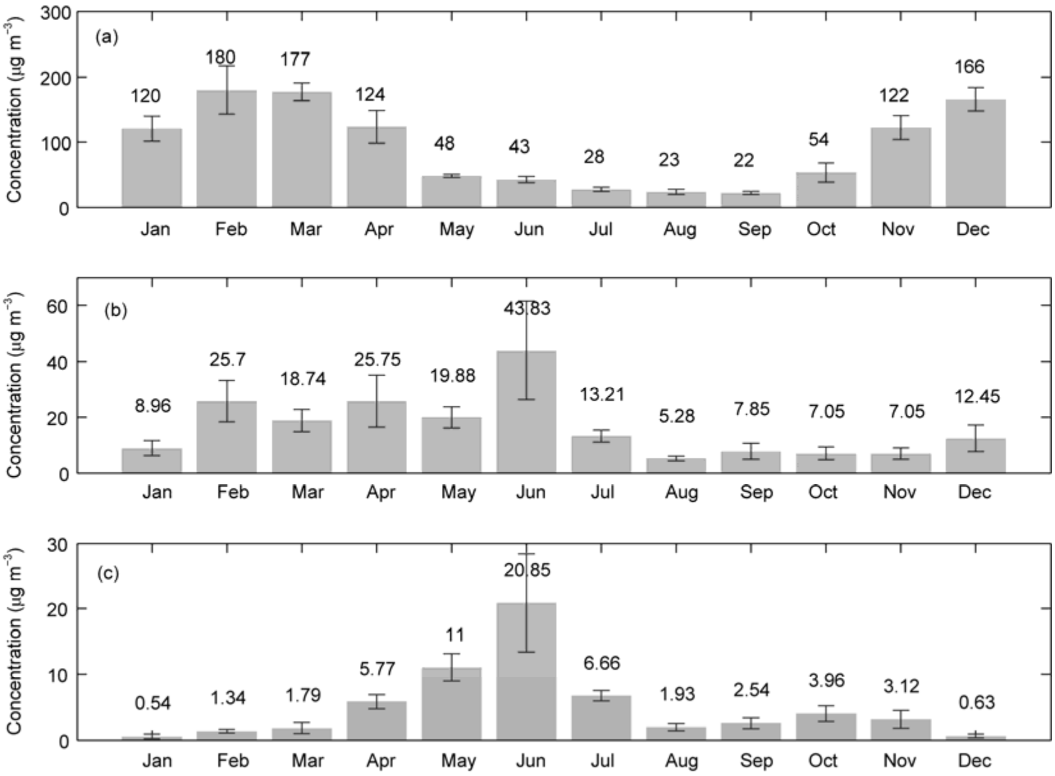

Figure 4 The simulated dust concentration at surface (a), at 0.975 Sigma level (b), and at 0.850 Sigma level (c). Solid lines are ±1 standard error of mean about the mean dust concentration.

μg m^{-3} for the surface, the 0.975 Sigma level (250 m above ground level), and the 0.850 Sigma level (1500 m above ground level), respectively. The monthly distributions of dust concentrations vary vertically over the Tibetan Plateau. At the surface, the dust concentration is high during winter and spring, peaking in November and remaining large until the next April; the average dust concentration from November to the following April is 153 μg m^{-3}, but is only 36 μg m^{-3} in other months. At the 0.850 Sigma level, dust concentrations appear to be high during late spring and early summer with a peak from April to July, when the dust concentrations average 11 μg m^{-3}, relative to only 2 μg m^{-3} in the other months. At the level between the surface and the 0.850 Sigma level, i.e. the 0.975 Sigma level, dust concentration is affected by concentrations at the surface and at the 0.850 Sigma level. Dust concentration is high from November to the following July, with an average of 21 μg m^{-3}; in other months, it is low, with an average of 6.8 μg m^{-3}.

A comparison between Figure 3 and Figure 4 indicates that the simulations appear to be roughly consistent with observations. The simulated near-surface dust concentration over the Tibetan Plateau is high from November to the following April, during which time the DSF of the Tibetan Plateau is also high. Similarly, at the 0.850 Sigma level, the simulated dust concentration over the Tibetan Plateau is high from April to July, which is consistent with the high sum of AI from April to June.

3 Contribution of the Tibetan dust source to dust in the atmosphere over the East Asia

Both observational data and computational simulations suggest that near-surface dust concentrations over the Tibetan Plateau are high from November to the following April in each year. Therefore, we hypothesized that the contribution of the Tibetan dust source to dust in the atmosphere over East Asia is concentrated in the months between November and April, particularly during February and March. In the current section, we will estimate the contribution of the Tibetan dust source to dust in the atmosphere over East Asia by analyzing the simulations.

3.1 Contribution to dust in the atmosphere over the Tibetan Plateau

We first examined the contribution ratio of the Tibetan dust source to dust in the atmosphere over the Tibetan Plateau. The contribution ratio is determined as follows: for a given level, the difference in dust concentration over the Tibetan Plateau is obtained between OBS and CTRL (OBS minus CTRL). Thereafter, the ratio of this difference to the dust concentration of OBS is computed, which is used to measure the contribution of the Tibetan dust source to dust in the atmosphere over the Tibetan Plateau at the given level. Following this procedure, contribution ratios of the Tibetan dust source for different levels in the troposphere are computed.

Figure 5 shows contribution ratio of the Tibetan dust source to dust in the atmosphere over the Tibetan Plateau. As seen in the figure, when the height of the levels increases, the contribution ratio averaged among all months drops sharply. The contribution ratios are 69%, 40%, and 5% for the surface, the 0.975 Sigma level, and the 0.850 Sigma level, respectively. The average contribution ratio of 69% at the surface is supported by Zhang et al. [30]. Zhang et al. [30] collected aerosols at Wudaoliang station on the Tibetan Plateau from September 1993 to May 1994 and found that the Tibetan Plateau's aerosol contribution accounts for 70% of the aerosols in the atmosphere.

In addition to the average contribution ratio across all months, the monthly distribution of the contribution ratio varies. Near the surface, the monthly contribution ratio is high from October to May; during this period, the average contribution ratio is 80%, which is larger than the 45% found in other months. At the 0.975 Sigma level, the contribution ratio peaks from November to April with an average of 72% and then decreases from May to September, during which its average is only 9%. At the 0.850 Sigma level, the contribution ratio is large from February to March; during this period, the average of contribution ratios is 21%, compared to less than 5% in other months.

Based on the above analysis, two points can be concluded: (1) The Tibetan dust source contributes more to near-surface dust over the Tibetan Plateau, primarily the surface level and the 0.975 Sigma level, and (2) in the middle to high troposphere over the Tibetan Plateau, the contribution of the Tibetan dust source is much less pronounced, but the contribution of other potential dust sources is prominent. Even between February and March, when the Tibetan dust source contributes more atmospheric dust, other dust sources may provide nearly 80% of dust in the middle to high troposphere over the Tibetan Plateau.

3.2 Contribution to dust in the atmosphere over the Eastern China

Dust aerosol produced by the Tibetan dust source can drift to the middle to high troposphere over the Tibetan Plateau and thereafter move to eastern China via zonal winds and even as far as South Korea and Japan. Investigations on the contribution of the Tibetan dust source to dust in the troposphere over Eastern China are critical. As previously mentioned, from February to March, the Tibetan dust source contributes more to dust in the troposphere over the Tibetan Plateau; therefore, we primarily analyzed the contribution of the Tibetan dust source to dust in the troposphere over Eastern China during the months of February and March. It is worth noting that dust load (dust in atmospheric column),

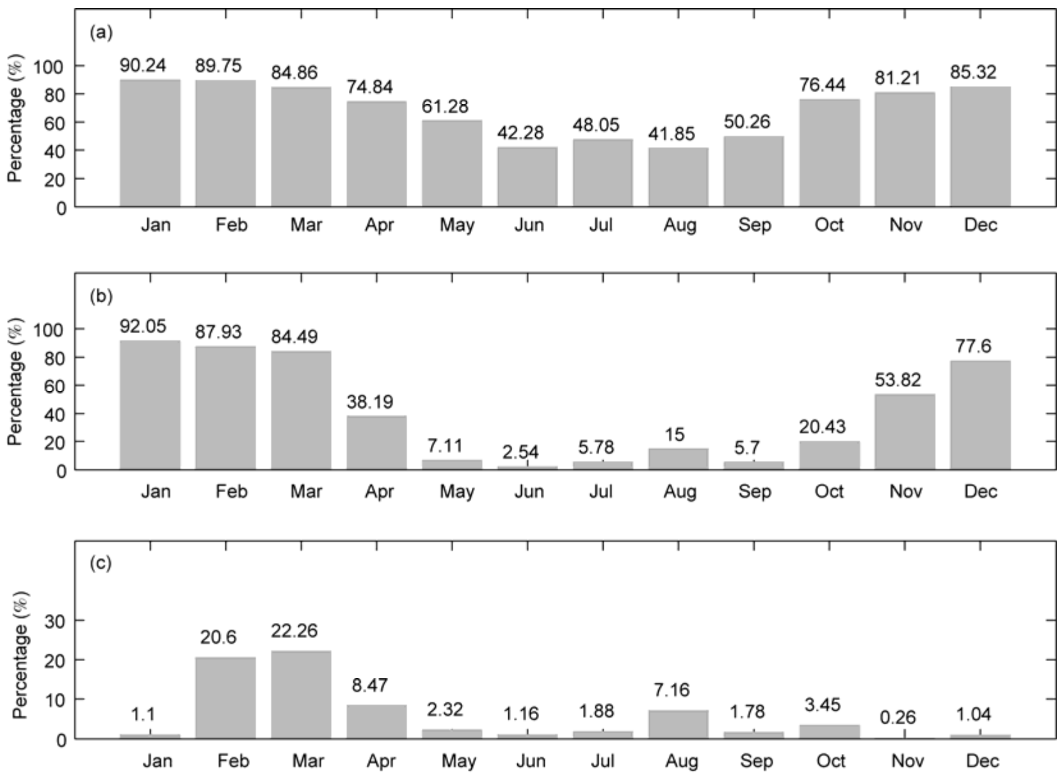

Figure 5 Contribution of dust source on the Tibetan Plateau to dust aerosols in the atmosphere over the Tibetan Plateau. (a) Surface level; (b) 0.975 Sigma level; (c) 0.85 Sigma level.

in lieu of other dust concentrations, is used to estimate the contribution ratio because during the process of dust transportation from the Tibetan Plateau to eastern China, dust deposition and dust updraft occur. Dust concentrations at each level in the troposphere cannot fully represent the amount of dust in the troposphere over eastern Asia. Therefore, we examined changes in dust in the atmospheric column to estimate the contribution of the Tibetan dust source. For a given grid point, we first calculated the difference of dust load between OBS and CTRL (OBS minus CTRL) and then computed a ratio of this difference to the dust load of OBS, which is considered to be the contribution ratio of the Tibetan dust source to dust in the troposphere.

Figure 6 shows the spatial distribution of the contribution ratio of the Tibetan dust source to dust in the atmosphere over East Asia. The contribution of the Tibetan dust source is confined primarily to the Tibetan Plateau and eastern China. The contribution ratio over the Tibetan Plateau is larger and equal to 50% and is nearly 70% in the north and northwestern regions of the Tibetan Plateau. However, the contribution ratio over eastern China is less than 10%. Therefore, the contribution of the Tibetan dust sources primarily occurs over the Tibetan Plateau and has only minor effects on the dust in the troposphere over eastern China.

4 Discussion

The above analyses show that dust concentrations in the middle to high troposphere over the Tibetan Plateau reach their peaks during May and June, and the peak of near-surface dust concentration on the Tibetan Plateau occurs during February and March. This finding implies that the Tibetan dust source contributes less to dust in the middle to high troposphere over the Tibetan Plateau during May and June. Moreover, with the exception of the Tibetan dust source, other potentially important dust sources may play a role in the amount of dust in the middle to high troposphere over the Tibetan Plateau during May and June. Some authors have indicated that these potential dust sources include the Taklimakan Desert [13], the Thar Desert [31], and the Middle Asia and the Arabian deserts [32]. Dust drifts upward from these dust sources and is transported to the slope and top of the Tibetan Plateau via zonal winds in the troposphere.

To investigate which source contributes more to dust in the middle to high troposphere over the Tibetan Plateau from May to June, a composite analysis was applied on dust concentration in the middle troposphere between May and June and February and March (May to June minus February to March). Furthermore, horizontal wind anomalies associated with dust concentration anomalies were also analyzed. The horizontal wind is retrieved from the ECMWF reanalysis data (EAR–40) from the years between 1958 and 2002.

As shown in Figure 7, at the 0.850 sigma level, dust concentration anomalies are centered primarily over the Thar Desert, the Tibetan Plateau, and northeastern China. Compared to dust concentrations during February and March, dust concentrations during May and June are relatively higher, with 5–10 μg m^{-3} over the Thar Desert, 1 μg m^{-3} over the Tibetan Plateau, and 1–2 μg m^{-3} over northeastern China. Among these anomalies, the anomaly over the Thar Desert is prominent, implying that the Thar Desert may be an important dust source for dust in the middle to high troposphere over the Tibetan Plateau during summer. In addition, we examined the monthly distribution of dust aerosols in the troposphere over the Thar Desert. The sum of AI averaged over the Thar Desert (70°–80°E and 20°–30°N) is computed monthly (Figure 2). Figure 2 shows that the AI sum over the Thar Desert increases after January, reaches its peak during April and June, and gradually decreases afterwards. The monthly distribution of the sum of AI over the Thar Desert is similar to that over the Tibetan Plateau. Therefore, the Thar Desert may contribute to the

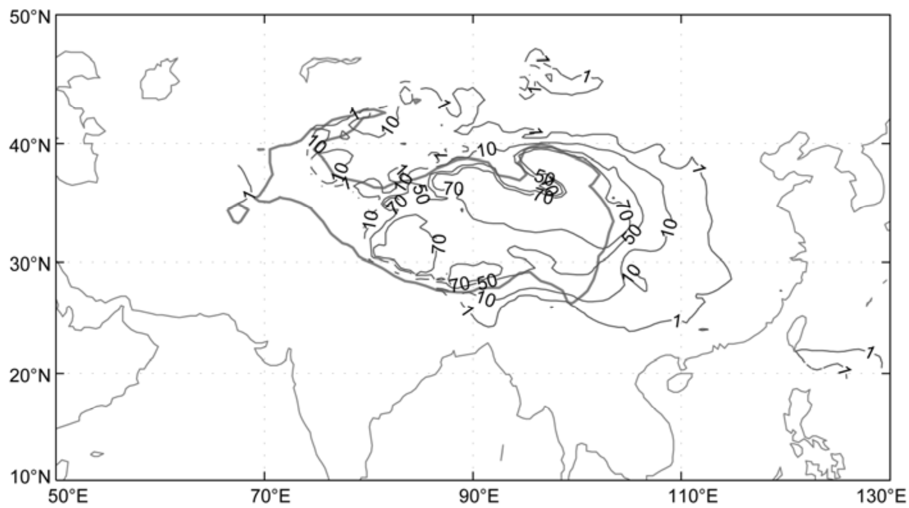

Figure 6 Contribution of dust source on the Tibetan Plateau to dust load over East Asia during February to March. Unit: %.

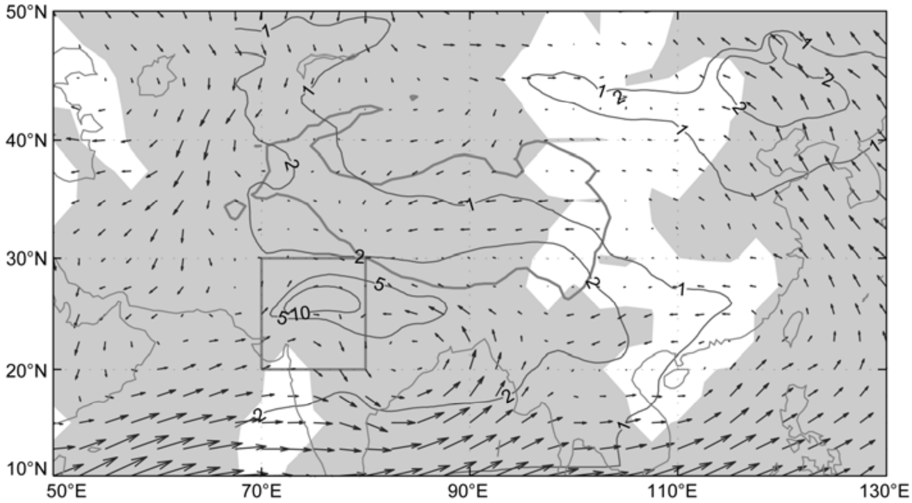

Figure 7 Composite difference of dust concentration (contour lines) at the 0.85 Sigma level and horizontal winds (vectors) averaged between 775 and 925 hPa (May to June minus February to March). Shading areas represent the horizontal winds that are significant beyond the 99% confidence level. The maximum vector is equal to 6.20 m s^{-1}.

high amounts of dust in the middle to high troposphere over the Tibetan Plateau during May and June.

In addition, we analyzed horizontal wind anomalies associated with dust concentration anomalies. A composite analysis of horizontal winds between May and June and February and March was analyzed. Sikka [33] indicated that dust weather events reach their maximum before monsoon onset, and dust is transported by southwestern winds. Therefore, we focused our analyses on the horizontal wind anomalies in the low troposphere. The mean wind field averaged between 925 and 775 hPa represents the wind field in the low troposphere. As seen in Figure 7, compared to horizontal winds from February to March, a cyclonic anomaly of atmospheric circulation occurred over eastern India, which facilitated the transport of dust from the Thar Desert, which was transported to the middle and eastern part of the Tibetan Plateau.

5 Conclusions

In this study, dust storm frequency, the sum of AI derived from TOMS, and numerical simulation were used to reveal (1) the monthly distribution of dust concentrations in the troposphere over the Tibetan Plateau and (2) the contribution of the Tibetan dust source to dust in the atmosphere over East Asia. The monthly distribution of dust concentrations varied over the Tibetan Plateau. Near the surface, dust concentration was high from November to April of the following year, reaching a peak in February and March. At the 0.850 Sigma level, dust concentration was high between April and July, and its peak occurred in May and June. The dust concentration at the 0.975 Sigma level was affected by the surface level and the 0.850 Sigma level. The dust concentration at the 0.975 Sigma level was high from November to the following July.

Although the Tibetan dust sources are important to dust in the atmosphere over the Tibetan Plateau, they only contribute weakly to dust in the troposphere over eastern China. The contribution of the Tibetan dust sources to dust in the atmosphere over the Plateau decreases sharply with height, from 69% at the surface, 40% at the 0.975 sigma level, and 5% at the 0.85 Sigma level. Furthermore, the contribution shows seasonal changes: at the surface, the contribution varies between 80% from November to May and 45% from June to September; at the 0.975 sigma level, the contribution varies between 72% from November to April and 9% from May to October; at the 0.850 sigma level, the contribution varies between 21% from February to March and less than 5% in the other months. Overall, dust aerosols originating from the Tibetan Plateau contribute less than 10% of dust in Eastern China.

The Thar Desert may be an important source of dust in the troposphere over the Tibetan Plateau. The monthly distribution of the sum of AI over the Thar Desert is consistent with that over the Tibetan Plateau; it increases from January to May/June and then begins to decrease. During May/June, a cyclonic anomaly of atmospheric circulation occurs in the low troposphere over the Thar Desert, which could transport dust from the Thar Desert to the eastern Tibetan Plateau.

It is worth noting that there are some uncertainties in this study. (1) The contribution of dust sources in the Chaidam Basin, which is located in the northeast region of the Tibetan Plateau, has not been considered. Zhang et al. [18] indicated that the contribution of the Chaidam Basin to dust emission in East Asia is less than 5%; therefore, the contribution of the dust source in the Chaidam Basin to dust in the atmosphere over the Tibetan Plateau is minimal. In addition, the Chaidam Basin is located in the northeast area of the Tibetan Plateau, and its dust can be easily transported away from the Tibetan Plateau. Thus, the contribution of the dust source in the Chaidam Basin has a weak effect on our conclusion. (2) We have not considered background aerosols in our simulation, and a sample of only five years cannot provide an exact estimation. We will consider these factors in a future study.

This work was supported by National Basic Research Program of China (Grant No. 2012CB955301), National Natural Science Foundation of China (Grant No. 41101075), China Postdoctoral Science Foundation (Grant Nos. 20090460222, 201104060), and State Key Laboratory of Earth Surface Processes and Resource Ecology (Grant No. 2011-RC-01).

1 Zhang X Y. Aerosol over China and their climate effect (in Chinese). Adv Earth Sci, 2007, 22: 12–16
2 Shi G Y, Wang B, Zhang H, et al. The radiative and climatic effects of atmospheric aerosols (in Chinese). Chin J Atmos Sci, 2008, 32: 826–840
3 Yin Y, Chen L. The effects of heating by transported dust layers on cloud and precipitation: A numerical study. Atmos Chem Phys, 2007, 7: 3497–3505
4 Tegen I, Lacis A A, Fung I, et al. The influence on climate forcing of mineral aerosols from disturbed soils. Nature, 1996, 380: 419–422
5 Han Y, Fang X, Zhao T, et al. Suppression of precipitation by dust particles originated in the Tibetan Plateau. Atmos Environ, 2009, 43: 568–574
6 Gao H W, Qi J H, Shi J H, et al. Long-range transport ofAsian dust and its effects on ocean ecosystem (in Chinese). Adv Earth Sci, 2009, 24: 1–10
7 Uno I, Eguchi K, Yumimoto K, et al. Asian dust transported one full circuit around the globe. Nat Geosci, 2009, 2: 557–560
8 Yumimoto K, Eguchi K, Uno I, et al. An elevated large-scale dust veil from the Taklimakan Desert: Intercontinental transport and three-dimensional structure as captured by CALIPSO and regional and global models. Atmos Chem Phys, 2009, 9: 8545–8558
9 Fang X M, Han Y X, Ma J H, et al. Dust storms and loess accumulation on the Tibetan Plateau: A case study of dust event on 4 March 2003 in Lhasa. Chin Sci Bull, 2004, 49: 953–960
10 Han Y, Fang X, Kang S, et al. Shifts of dust source regions over central Asia and the Tibetan Plateau: Connections with the Arctic oscillation and the westerly jet. Atmos Environ, 2008, 42: 2358–2368
11 Liu Z, Liu D, Huang J, et al. Airborne dust distributions over the Tibetan Plateau and surrounding areas derived from the first year of CALIPSO lidar observations. Atmos Chem Phys, 2008, 8: 5045–5060
12 Zhang X Y, Arimoto R, Cao J J, et al. Atmospheric dust aerosol over the Tibetan Plateau. J Geophys Res, 2001, 106: 18471–18476
13 Huang J, Minnis P, Yi Y, et al. Summer dust aerosols detected from CALIPSO over the Tibetan Plateau. Geophys Res Lett, 2007, doi: 10.1029/2007GL029938
14 Wang N L, Yao T D, Yang X D, et al. Variations in dust event frequency over the past century reflected by ice-core and lacustrine records in north China. Sci China Ser D-Earth Sci, 2007, 50: 736–744
15 Qian S L, Li C C, Zhang Q H. Study on the distribution of upper air aerosols and the transport of dust over East Asia (in Chinese). Acta Sci Nat Univ Pekinensis, 2009, 3: 20–27
16 Zhao T L, Gong S L, Zhang XY, et al. A simulated climatology of Asian dust aerosol and its trans-Pacific transport. Part I: Mean climate and validation. J Clim, 2006, 19: 88–103
17 Gong S L, Zhang X Y, Zhao T L, et al. A simulated climatology of Asian dust aerosol and its trans-Pacific transport. Part II: Interannual variability and climate connections. J Clim, 2006, 19: 104–122
18 Zhang X Y, Gong S L, Zhao T L, et al. Sources of Asian dust and role of climate change versus desertification in Asian dust emission. Geophys Res Lett, 2003, doi: 10.1029/2003GL018206
19 Li J, Carlson B E, Lacis A A. A study on the temporal and spatial variability of absorbing aerosols using Total Ozone Mapping Sectrometer and Ozone Monitoring Instrument Aerosol Index data. J Geophys Res, 2009, 114: D09213
20 Shao Y, Jung E, Leslie L M. Numerical prediction of northeast Asian dust storms using an integrated wind erosion modeling system. J Geophys Res, 2002, doi: 10.1029/2001JD001493
21 Shao Y, Yang Y, Wang J J, et al. Northeast Asian dust storms: Real-time numerical prediction and validation. J Geophys Res, 2003, doi: 10.1029/2003JD003667
22 Mao R, Gong D Y, Bao J D, et al. Possible influence of Arctic Oscillation on dust storm frequency in North China. J Geogr Sci, 2011, 21: 207–218
23 Mao R, Ho C H, Shao Y, et al. Influence of Arctic Oscillation on dust activity over Northeast Asia. Atmos Environ, 2011, 45: 326–337
24 Shao Y. A model for mineral dust emission. J Geophys Res, 2001, 106: 20239–20254
25 Wang Y M, Wang J H, Qi Y, et al. China 1∶100000 Desert (Sand land) Map. Environmental and Ecological Science Data Center for West China (http://westdc.westgis.ac.cn), 2002
26 Ganguly S, Schull M A, Samanta A, et al. Generating vegetation leaf area index earth system data record from multiple sensors. Part 1: Theory. Remote Sens Environ, 2008, 112: 4333–4343
27 Tucker C J, Pinzon J E, Brown M E, et al. An extended AVHRR 8-km NDVI dataset compatible with MODIS and SPOT vegetation NDVI data. Int J Remote Sens, 2005, 26: 4485–4498
28 Gutman G, Ignatov A. The derivation of the green vegetation fraction from NOAA/AVHRR data for use in numerical weather prediction models. Int J Remote Sens, 1998, 19: 1533–1543
29 Xia X, Wang P, Wang Y, et al. Aerosol optical depth over the Tibetan Plateau and its relation to aerosols over the Taklimakan Desert. Geophys Res Lett, 2008, 35: L16804
30 Zhang X Y, Zhang G Y, Chen T, et al. Remote mineral aerosol in westerlies and their contributions to the Chinese Loess. Sci China Ser D-Earth Sci, 1996, 39: 67–76
31 Kuhlmann J, Quaas J. How can aerosols affect the Asian summer monsoon? Assessment during three consecutive pre-monsoon seasons from CALIPSO satellite data. Atmos Chem Phys, 2010, 10: 4673–4688
32 Xu J Z, Hou S G, Chen F K, et al. Tracing the sources of particles in the East Rongbuk ice core from Mt. Qomolangma. Chin Sci Bull, 2009, 54: 1781–1785
33 Sikka D R. Desert climate and its dynamics. Curr Sci, 1997, 72: 35–46