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Long-term trends of dust events over Tibetan Plateau during 1961–2010

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HIGHLIGHTS

- Tibetan Plateau Dust Index (TPDI) were defined based on dust events records.
- The occurrence of dust events over Tibetan Plateau has decreased since 1970s.
- The decreasing trend was possibly an abrupt change in 1990s.
- Weakened surface wind speed and westerly jet and increased vegetation are possible causes.

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ABSTRACT

In this study we analyzed dust events records of surface meteorological stations on Tibetan Plateau (TP) during 1961–2010 and provided the spatial and temporal distribution of dust events. The occurrence of dust events has significantly decreased since the 1970s. We defined the Tibetan Plateau Dust Index (TPDI) for the most dust active periods, spring and winter, to characterize the large scale variability of dust events over TP. Mann–Kendall test suggested the decreasing trend was possibly an abrupt change in the 1990s. The decline of surface wind speeds could partly explain the decrease of dust events over TP. TPDI is positively correlated to the surface winds, with correlation coefficients of 0.42 for spring and 0.46 for winter, respectively. The averaged number days with strong winds (wind speed greater than 6.5 ms^{-1}) for the 4 selected stations, which were chosen to define TPDI, are significantly correlated with TPDI for both spring (correlation coefficient = 0.69) and winter (correlation coefficient = 0.76) and also showed a deceasing trend. The upward trend of vegetation cover was indicated by the normalized difference vegetation index (NDVI), which can be attributed as another factor driving the decrease of dust events over TP. TPDI is negatively correlated to the NDVI, with correlation coefficients of −0.48 for spring and −0.29 for winter. Additionally, analysis of geopotential height fields and wind fields indicate an enhanced ridge in the north of TP and weakened westerly jet in the low-frequency years of dust events, which also drive the decline of dust events over TP.

1. Introduction

Tibetan Plateau (TP), covering 2.5×10^6 km^2 with an average elevation ranging from 4000 to 5000 m, has a remarkable impact on the regional and even global climate, which can be seen in monsoon system (Yanai et al., 1992; Wu et al., 2012), atmospheric circulation (Ye and Wu, 1998; Duan and Wu, 2005), water cycle (Lu et al., 2005; X. D. Xu et al., 2008a,b), snow (Lau et al., 2010; Huang et al., 2011) and many other aspects of climate system. Like many other regions over the world, TP also experienced significant climate change in the past few decades. For instance, significant warming trend over TP seemed to be more intense comparing with its adjacent areas or the same latitudinal zone (Liu and Chen, 2000). Undergoing rapid change of cryosphere in TP is also noticeable, including the glacier retreat, inconsistent snow cover change and permafrost degradation (Kang et al., 2010). Both remarkable climate impact and sensitivity make TP an essential region to be studied from different angles in the context of climate change.

Dust aerosol, as one of the major contributors to aerosol mass loading (Boucher et al., 2013), plays an important role in the

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radiation budget of the climate system. Dust aerosol can impact radiation balance via absorbing and scattering solar radiation (i.e. direct effects) (Tegen, 2003; Haywood et al., 2003; Huang et al., 2009; Zhao et al., 2013; Chen et al., 2014a). Dust aerosol can also alter cloud property (i.e., indirect and semi-direct effect) and thereby affecting radiation balance (Twomey et al., 1984; Huang et al., 2006a, 2006b, 2010, 2014). Dust aerosol over the TP originates from either local sources or remote sources (Zhang et al., 2001). Numerical modeling indicates most of dust over TP, especially on the surface level, is contributed by the local dust emission in the winter and early spring, while distant sources contribute more in summer and autumn (Chen et al., 2013, 2014b; Mao et al., 2013), which is consistent with satellite observation results (e.g. Huang et al., 2007a; Xia et al., 2008). Comparing with other dust sources in the arid and semiarid regions of China, TP shows a great potential in the vertical transport of dust aerosol to a high altitude because of its distinctive terrain. Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) detected the dust layer over TP could vertically extend to altitudes of 11–12 km (Liu et al., 2008). Owing to the high elevation and the unique location of TP, dust aerosol can be further transported by the mid-latitude westerly jet to Korea, Japan (Ono et al., 1998) and even to the Pacific Ocean (Duce et al., 1980). Recent studies showed that dust aerosol in the TP has profound climate effect. Lau et al. (2006) and Lau and Kim (2006) found that dust aerosol along with black carbon may advance and intensify Indian summer monsoon and proposed a mechanism called "Elevated-Heat-Pump" (EHP) effect, which is driven by heating of the elevated surface air over northern and southern slopes of the TP via absorption of radiation by dust and black carbon. Additionally, numerical simulation results show that heating effect of dust and black carbon can enhance warming and accelerate snow melting in the TP and Himalayas (Lau et al., 2010; Lee et al., 2013).

In the past, most studies on dust loading and events over TP were based on the ice core records, among them are some valuable results (e.g. Kang et al., 2000; Wang et al., 2006), but the temporal resolution and spatial coverage of ice records is relatively limited. Satellite observation greatly facilitates the detection of the dust (e.g. Huang et al., 2007b; Chen et al., 2010) and provides unprecedented view of the dust aerosol over TP (e.g. Huang et al., 2007a), while the relatively short time spans of datasets incapacitate it to provide a continuous observation record describing variability of dust aerosol in the past few decades. Dust events observation of Chinese meteorological stations has relative good temporal resolution (daily), spatial coverage (multiple stations) and long-time record of observation (several decades). Dust events are closely related to the dust emission, transport and deposition and have been studied by many researchers especially focusing on Taklimakan, Inner Mongolia and other regions (e.g. Sun et al., 2001; Qian et al., 2002; Wang et al., 2005, 2010; Huang et al., 2008; Pu et al., 2015), while TP has received less attention. In terms of strong climate impact of dust over TP, it is necessary to investigate the change of dust events over TP in order to understand its response to the undergoing climate change. An objective of this paper is to define a Tibetan Plateau dust index (TPDI) using the dust events records from surface meteorological stations, which characterize the statistical nature of the dust events over TP in the past few decades, and use this index to study the variability of dust events over TP and investigate the possible cause for it.

This paper is organized as follows. Section 2 provides a general description of dataset used in this study and describes the method to obtain the dust index. In Section 3, the spatial and temporal distribution of dust events over TP alone with the TPDI will be presented. Section 4 analyses possible causes for the variability of dust events. Conclusions are given in Section 5.

2. Data and method

2.1. Surface dust events records

The spatial and temporal characteristics of dust events was studied using the data of dust storm, blowing dust and floating dust from 47 observation stations over TP (see Fig. 1) during the period between 1961 and 2010, which is provided by the National Meteorological Center of the China Meteorological Administration (CMA). In order to ensure the integrity and reliability of data, only the stations that have at least 45-year data records were selected for the research. Most of the stations are located at the eastern TP, because of the harsh climate on the north western TP. Surface wind speed data of these stations was obtained from China National Meteorological Information Center.

2.2. Reanalysis datasets

Three different reanalysis datasets are employed in this study, as described below.

NCEP-NCAR Reanalysis 1 (NCEP R1) is the most widely used reanalysis data produced by the National Centers for Environmental Prediction/National Center for Atmospheric research (NCEP/NCAR) using three-dimensional variational (3DVAR) data assimilation scheme (Kalnay et al., 1996), with 2.5° × 2.5° horizontal resolution and 28 vertical levels.

The Modern Era Retrospective-Analysis for Research and Applications (MERRA), as the most recent reanalysis dataset, is produced by NASA Global Modeling and Assimilation Office using the GEOS data assimilation system (Rienecker et al., 2011), with 0.5° × 0.667° horizontal resolution and 72 vertical levels.

ERA-Interim, which is produced by the European Centre for Medium-Range Weather Forecasts (ECMWF) using a much improved atmospheric model and assimilation system comparing with ERA-40, has improved several inaccuracies exhibited in the ERA-40 (Dee et al., 2013). The spatial resolution of this dataset is 0.75° × 0.75° with 60 vertical levels.

NCEP R1 data over 50 years (1961–2010) are utilized in this study, which fully covers the research period. MERRA and ERA-Interim data in the period of 1979–2010 are used, since these two dataset are only available since 1979.

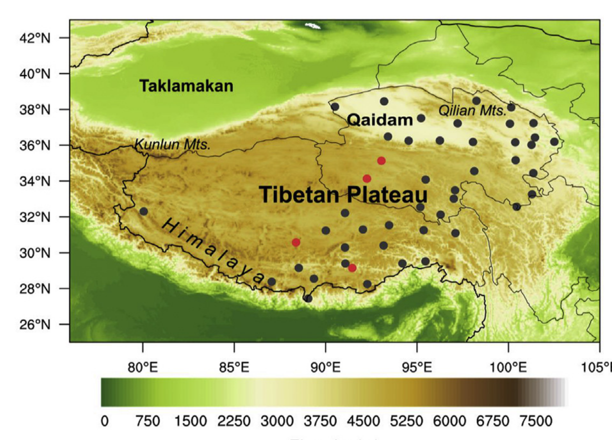

Fig. 1. Locations of surface observation stations for dust events and spatial distribution of the topography over TP. Dots indicate the location of the surface observation stations. Red dots represent four stations that are selected to define the TPDI and contours represent the elevation. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2.3. Satellite-based vegetation index

Normalized Difference Vegetation Index (NDVI) remote sensing data is used in this paper, which is derived from the Advanced Very High Resolution Radiometer (AVHRR) carried aboard the National Oceanic and Atmospheric Administration (NOAA) polar-orbiting weather satellite. The sensor provides one of the longest series of NDVI observation product which is still active. NDVI data used in this study covers the period from 1982 to 2010.

2.4. Method to define TPDI

In general, dust events are classified into three types (i.e. dust storm, blowing dust and floating dust) primarily according to the visibility and wind speed (Wang et al., 2005). Dust storm is associated with strong winds, which could efficiently uplift and transport dust aerosol, and horizontal visibility lower than 1 km. Blowing dust is weaker compared to dust storm, with visibility typically ranging from 1 km to 10 km. Floating dust usually occurs under calm weather condition with weak winds and visibility less than 10 km. Using observation data of 15 dust events during 1995–1998, Niu et al. (2001) found that the dust concentration during a dust storm, blowing dust and floating dust process is proportional to each other. Dust storm has a dust concentration 3 times higher than that of blowing dust and 9 times higher than that of floating dust. According to this relationship, Wang et al. (2008) defined dust index for Taklimakan Desert and Gobi Desert independently utilizing data from selected stations to describe the statistical characters of the dust events over these regions. These indexes were validated and well correlated with Total Ozone Mapping Spectrometer (TOMS) Absorbing Aerosol Index (AAI). Using a similar approach, TPDI is defined as follows:

1) Four stations are selected via calculating the correlations of the frequency of monthly dust storm days between each station and choosing the first four stations with the highest correlation coefficients with other stations so that the TPDI could properly capture the regional character of dust events over TP. These four stations are described in Table 1 and marked in Fig. 1. The correlation coefficients of these four stations are above 0.43 with an average about 0.53 (self-correlation are excluded), being statistically significant at the 99% level.
2) Based on the observation of Niu et al. (2001) and formula of Wang et al. (2008), the formula for the TPDI is given by

$$TPDI = FD + BD \times 3 + DS \times 9$$

where FD, BD and DS are number of days for floating dust, blowing dust and dust storm, respectively.

3) The average number of days for different dust events at selected four stations is substituted in the formula to provide the TPDI.

3. Spatial and temporal characteristics

Fig. 2 demonstrates the annual mean number of dust storm, blowing dust and floating dust over TP. In general, dust storm is more frequent in the middle part of TP comparing with eastern part of TP according to Fig. 2a. Wang et al. (2005) pointed out that the areas where annual mean occurrence days of dust storm are greater than 10 days are three areas: Xinjiang Basin, Hexi region and northeastern TP. It suggests that TP is also a region suffer from the frequent dust storms, although the frequency is lower comparing with the other two regions. The spatial distribution pattern of blowing dust (Fig. 2b) is basically similar to the dust storm, with greater values. The spatial distribution of floating dust is quite different from dust storm and blowing dust, as illustrated in Fig. 2c. Floating dust occurs frequently at Qaidam Basin and Qilian Mountain region in the northern TP and happens relatively rare the rest part of TP. Strong winds over TP make it difficult to maintain floating dust and favor the occurrence of dust storm and blowing dust. Based on the analysis above, it is evident that the dominant type of dust event over TP is blowing dust and dust storm.

Table 1
List of stations used to define the Tibetan Plateau Dust Index (TPDI).

Name	Province	Latitude (°)	Longitude (°)	Height (m)
Tuotuohe	Qing Hai	34.13	92.26	4533.1
Wudaoliang	Qing Hai	35.13	93.05	4612.2
Shenza	Tibet	30.57	88.38	4672.0
Zedang	Tibet	29.15	91.46	3551.7

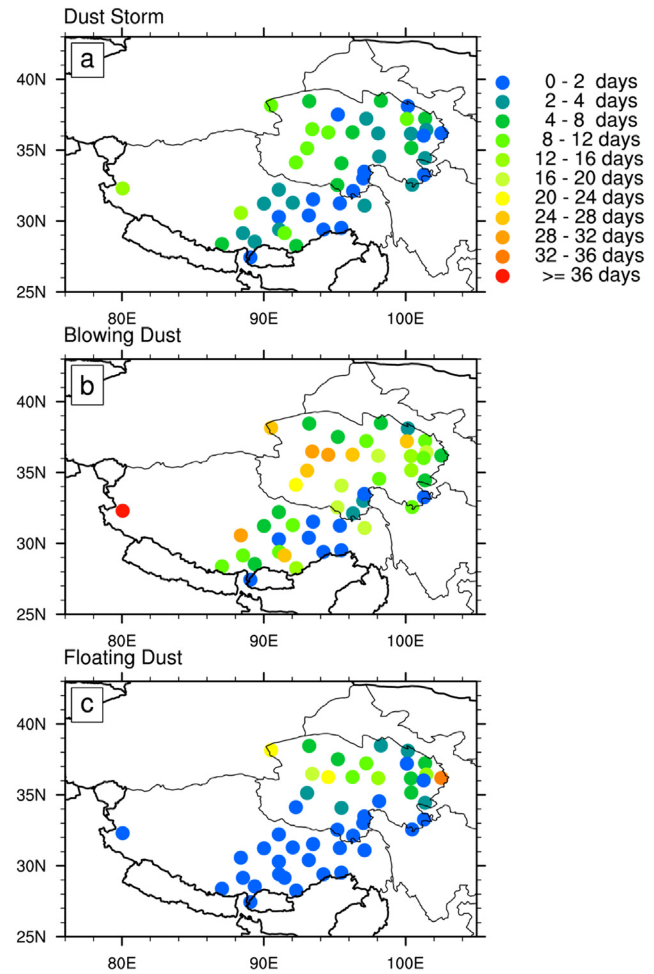

Fig. 2. Spatial distribution of annual mean occurrence days of (a) dust storm, (b) blowing dust and (c) floating dust in Tibetan Plateau during 1961–2010.

Fig. 3 shows the statistical results of monthly averaged dust events over all the TP stations for each decade. It can be seen that the peak period of dust events is from December to May, when the TP is under the control of the westerly jet. Fang et al. (2004) found that the high value center of dust events will move northwards along with the moving of the westerly jet core during this period. It is worth to point out that the monthly distribution of surface observed dust events is not fully consistent with the satellite observation results. Using The Multiangle Imaging Spectro Radiometer (MISR) observation data, Xia et al. (2008) found that the monthly aerosol optical depth (AOD) over entire TP in-

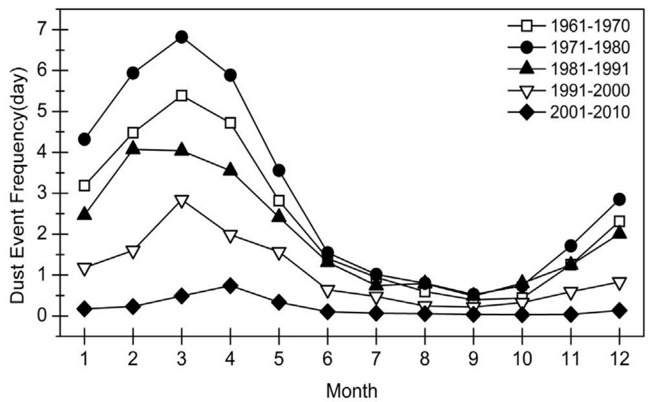

Fig. 3. Monthly averaged dust events (sum of dust storm, blowing dust and floating dust) over Tibetan Plateau for the period of 1961–1970(open square), 1971–1980(solid circle), 1981–1990(solid triangle), 1991–2000(open inverted triangle) and 2001–2010 (solid diamond).

crease gradually from January to May or June and then decreases in the rest of the year, in other words peak period of AOD differ from that of the surface observed dust events. The similar results were also provided by Mao et al. (2013) using Total Ozone Mapping Spectrometer (TOMS) Aerosol Index. However, there are three aspects need to be take into consideration to explain the difference of monthly distribution between surface observed dust events and satellite observation. Firstly, this inconsistency in the monthly distributions can partly be attributed to the different dust contribution rate from dust sources. By simulating the dust budget with WRF-Chem model, Chen et al. (2014b) pointed out that local dust emission is dominant for TP in winter and spring, while transported dust from remote sources contributes more in summer, which can be illustrated by case studies about TP dust transport from Taklimakan in summer (Chen et al., 2013; Liu et al., 2015) along with satellite observation results (Xia et al., 2008). Local dust emission is ruling especially near the surface level, while remote sources contribute more at the middle to high troposphere as indicated by Mao et al. (2013). Secondly, the spatial distribution should be taken into account when a regional mean value is given. According to Xia et al. (2008), although the average AOD over TP is high in summer, the areas with highest AOD are generally northern slope of TP, while eastern TP, where most of stations are located, has low AOD which close to 0.1. The detailed monthly AOD distributions over TP given by Xu et al. (2015) also indicate the similar pattern in summer. Thirdly, although dust is account for a large portion of the aerosol loading over TP, the contribution of other aerosols should also be considered, especially in summer. Aerosol samples collected in TP during summer and corresponding backward air-mass trajectories indicate that anthropogenic aerosols could be traced back to South Asia (Cong et al., 2007, 2015), which can be illustrated by a modeling study given by Liu et al. (2015). As for the interdecadal variation, dust events increased about 1 day from the 1960s to the 1970s for winter and spring and occurs frequently during the 1970s. After that, dust events experienced a downward trend in the next 30 years. The 2000s is the period with the lowest occurrence of dust events in the past 50 years, which is lower than 1day, and without apparent monthly variation.

An overall decreasing trend of dust events since the 1970s is depicted by Fig. 3, which makes it necessary to investigate the trend for each station individually so as to reveal the spatial feature of this change. Fig. 4 shows a dominant downward trend over TP for all three kinds of dust event, although a few of stations saw a slight increase. Southern TP witnessed a significant decrease of dust storm (Fig. 4a) which approximately deceased by 2 days per

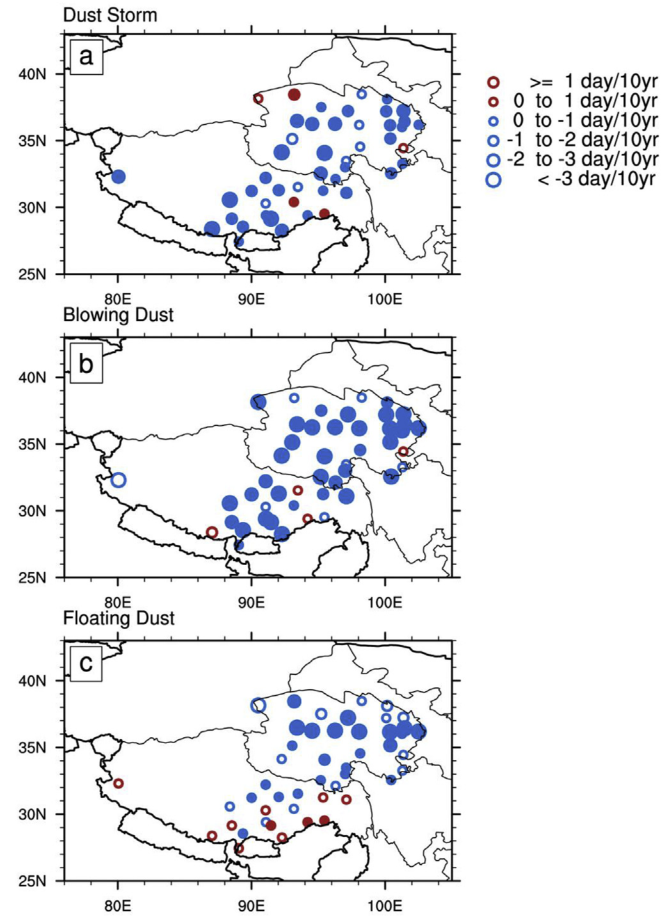

Fig. 4. Spatial distribution of the linear trends of decadal occurrence days of (a) dust storm, (b) blowing dust and (c) floating dust on Tibetan Plateau over 1961–2010. The positive (negative) trends are marked with red (blue) circles. The solid circles indicate that the linear trend at this station is statistically significant ($P < 0.05$). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

decade, while Northern TP (i.e. Qaidam Basin and Qilian Mountain region) experienced remarkable decrease of floating dust (Fig. 4c) which roughly deceased by 3 days per decade. In comparison with dust storm and floating dust, spatial feature of change for blowing dust (Fig. 4b) is consistent throughout of TP that most of trend coefficients are lower than - 3 days per decade which are statistically significant at the 99% level.

Spring (i.e. March, April and May) and winter (i.e. December, January and February) have a high occurrence of dust event as showed in Fig. 3. Therefore, TPDI for spring and winter are defined by following the method described in Section 2 and are presented in Fig. 5. TPDI describes the large scale variability of dust events over the TP and is a combination of dust storm, blowing dust and floating dust with corresponding weight coefficient. In spite of some fluctuations, both of spring and winter TPDI rose gradually since the 1960s and saw a downward trend after the 1970s. This is consistent with the result in Fig. 3. More specifically, linear fitting of TPDI indicate a decline with coefficient $-1.77\ yr^{-1}$ and $-3.15\ yr^{-1}$ for spring and winter, respectively. Similar declining trend was also observed in ice core data (e.g. Wang, 2005).

Mann–Kendall test (Mann, 1945; Kendall, 1948) is a nonparametric method which can be used to objectively detect the climate abrupt change. This method was utilized in this study for TPDI to determine whether the reduction of dust events over TP is an abrupt change and the results of spring and winter are given in

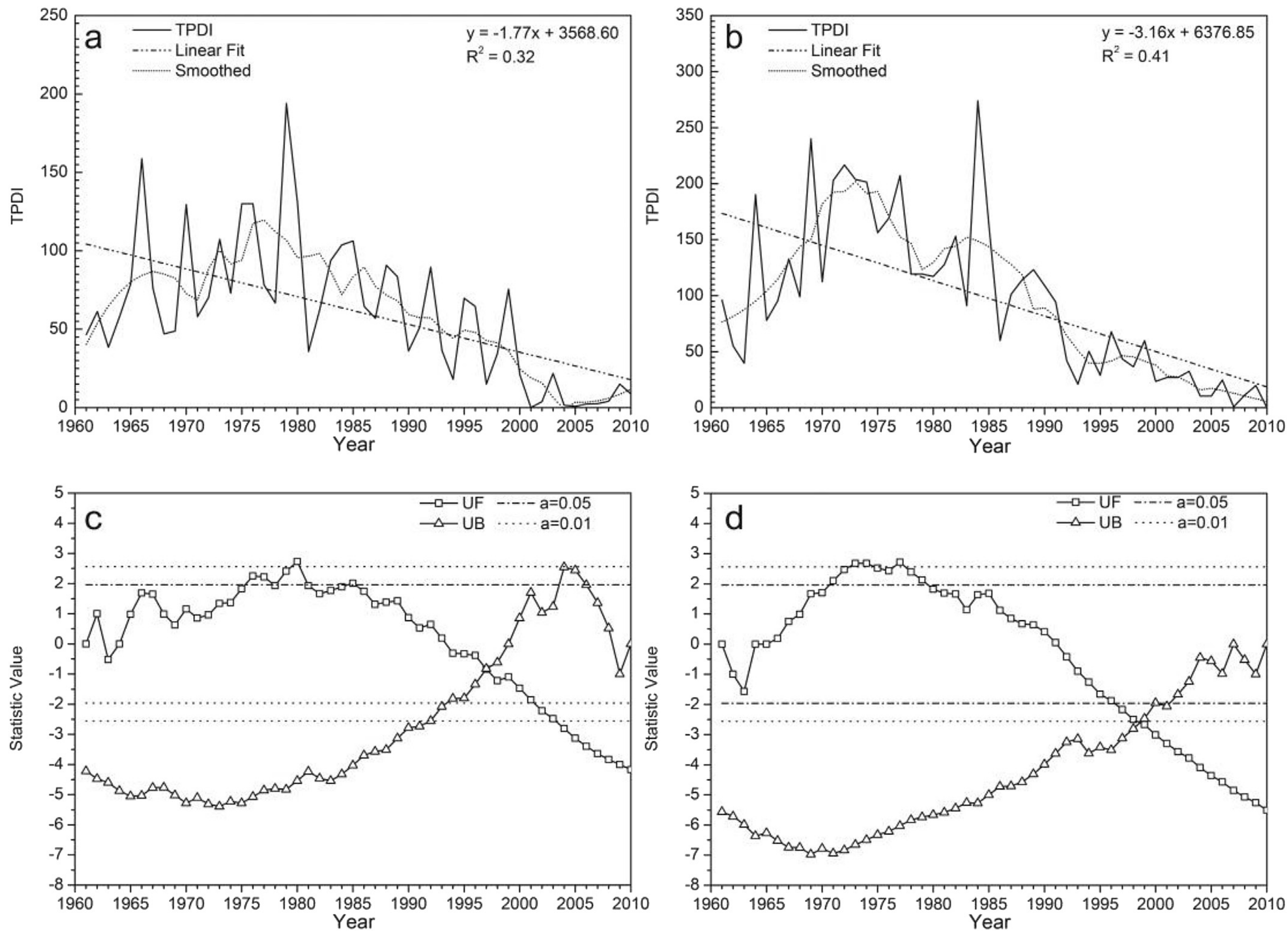

Fig. 5. Variations of the TPDI for (a) spring and (b) winter and their corresponding Man-Kendell statistical quantity curve in (c) spring and (d) winter. UF (squares) and UB (triangles) represent the statistical indicator for Mann Kendall test.

Fig. 5c and d, respectively. The decreasing trends of spring TPDI are statistically significant ($P < 0.05$) during the 2000s. The intersection point of UF and UB curve is located between two positive or negative critical lines, indicating this downward trend is an abrupt change, and its corresponding year 1997 is the year when this abrupt change happened. The result of winter TPDI is basically similar to the spring. A substantial declining trend of winter TPDI are depicted since 1995 ($P < 0.05$) and intersection point located in 1997 which is not between two positive or negative critical lines.

4. Potential cause for the trends of TP dust events

It is clear that the dust events over TP are characterized with an overall declining trend since the 1960s, accompany with interannual fluctuations and an abrupt change at the 1990s as indicated by Mann–Kendall test. The downward trend of dust events in TP is consistent with the recent dust trend in many parts of the world. Shao et al. (2013) indicated that the global mean near-surface dust concentration has decreased by 1.2% yr^{-1} during 1984–2012, which can be mainly attributed to the decrease of dust activities in North Africa, Northeast China, South America and South Africa. There are also some areas have increasing trend of dust events in recent years such as Iceland (Dagsson-Waldhauserova et al., 2013) and Mongolia regions (Lee and Sohn, 2011). To explain the trend of dust events in different regions, various controlling factors has been considered and investigated, including wind (e.g. Kurosaki and Mikami, 2003), precipitation (e.g. Guan et al., 2014), temperature (e.g. Guan et al., 2014), vegetation (e.g. Lee and Sohn, 2011) and modes of variability, such as the Atlantic Multidecadal Oscillation and the Antarctic Oscillation (e.g. Shao et al., 2013; Gong et al., 2006). In this paper, the relationship between wind speed, vegetation, large scale circulation and the dust index have been investigated attempting to identify potential causes for the trends of TP dust events controls the changes of the dust events over TP.

4.1. Surface wind speed

It has been wildly recognized that wind is a curial factor controlling not only emission but also transport of dust during a dust event. For instance, Kurosaki and Mikami (2003) found a good correlation between the frequencies of strong winds and dust outbreaks, which means that increases of strong winds lead to more dust outbreaks and vice versa. Since TPDI is a representative for regional scale and describes the statistical characters of the dust events, wind speeds should also be presented with regional feature. Averaged surface wind speeds of spring and winter for a selected area (30°–35°N, 85°–95°E) since 1961 are calculated using NCEP reanalysis data and showed in Fig. 6. Generally, there is a good one-to-one relationship between variations and peaks of TPDI and wind speeds. It indirectly implies the reliability and representativeness of TPDI, as TPDI and wind speeds

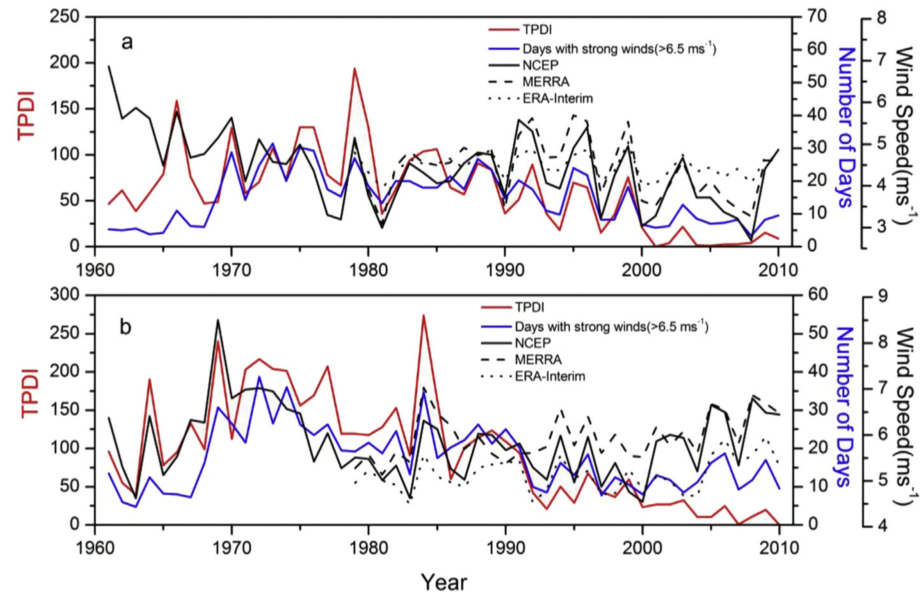

Fig. 6. Variations of the TPDI, averaged number of days with strong winds and the averaged surface wind speed using three different dataset for (a) spring and (b) winter over 1961–2010. Solid red line indicates TPDI. Solid blue line indicates the number of days with strong winds. The averaged surface wind are calculated over 30°–35°N, 85°–95°E using NCEP (solid), MERRA (dash) and ERA-Interim (dot) dataset. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

are obtained independently to demonstrate the regional characteristic. The correlation of two time series is 0.42 for spring and 0.46 for winter. Comparing with the apparent decline trend of TPDI, wind speed did not persistently decrease. Linear trend of wind speeds is -0.032 ms^{-1} yr^{-1} for spring and -0.008 ms^{-1} yr^{-1}for winter during 1961–2010. The linear trend of the average wind speeds for the four selected stations is -0.018 ms^{-1} yr^{-1} for spring and -0.031 ms^{-1} yr^{-1} for winter during 1961–2010 according to surface observation data (not shown on the plot). This result is accord with the linear trend in annual mean surface wind speed using surface meteorological data given by previous studies, which is -0.006 ± 0.002 ms^{-1} yr^{-1} during 1960–2009 given by Lin et al. (2013) and -0.02 ms^{-1} yr^{-1} during 1984–2006 given by Yang et al. (2011), respectively. In general, the linear trends are in accord with each other qualitatively, although negligible difference existed due to different time periods and datasets. This decline of surface speed over TP is in agreement with the decreasing trend over other part of China since the beginning of the 1970s (Xu et al., 2006; Jiang et al., 2010), whereas it is more significant over TP (Yang et al., 2011), which can be partly attributed to the elevation dependence of change in surface winds (Lin et al., 2013; McVicar et al., 2008). It is noticeable that surface wind speed start to recover since the 2000s, especially during winter, similar to the results of Lin et al. (2013). Despite this recovery, TPDI still remain at a low level. Since the average surface wind speed could smooth the instantaneous wind speed fluctuation, the averaged number days with strong winds for the 4 selected stations, which were used to define TPDI, were calculated. The days with strong winds at the station are defined as the days with daily averaged wind speed greater than 6.5 ms^{-1}. This criterion was chosen as it is the conventional threshold for dust emission in numerical models (Tegen and Fung, 1994; Kurosaki and Mikami, 2003). The TPDI and the number of days with strong winds are significantly correlated to each other for both spring (correlation coefficient = 0.69) and winter (correlation coefficient = 0.76). In addition, the number of days with high winds decreased by 0.98 days per decade for spring and by 1.36 days per decade for winter. In brief, analysis above suggests that the decline of surface wind could partly explain the decrease of dust events in the past few decades.

Due to the complex terrain of TP, the reliability of the surface wind speed of the NCEP should be considered. You et al. (2010) indicated that wind speed of NCEP dataset over TP were generally well correlated with the surface observation records at the annual scale and also capture the significant decreasing trends of wind speeds during 1980–2005. As suggested by Wang and Zeng (2012), multiple reanalysis products should be included in the study of weather and climate over the TP. Therefore, averaged wind speed of the other two reanalysis data, MERRA and ERA-Interim, are also calculated for the same area and depicted in Fig. 6. Due to the different time span of dataset, MERRA and ERA Interim data are only available since 1979. The wind speed of NCEP is generally lower than MERRA and higher than ERA-Interim. Time series of different reanalysis are all well correlated to each other. The correlation coefficients of wind speed between the NCEP and MERRA (ERA-Interim) are 0.90 (0.91) in spring and 0.78 (0.72) in winter during their overlapping period (1979–2010), with $P < 0.01$. According to the evaluation of multiple reanalysis dataset over TP given by Wang and Zeng (2012), the performance of the NCEP and ERA-Interim are about the same for wind speed, and the MERRA show the best performance among these three datasets.

4.2. Vegetation

Another crucial factor controlling the dust events is vegetation (Tegen et al., 2002; Engelstaedter et al., 2003), which could directly control dust emission, since dust emission usually occurs at the bare surface, and indirectly affects dust emission via changing surface roughness. Dust aerosol over the TP originates from either local sources or remote sources (Zhang et al., 2001), while the local dust emission is dominant in the spring and winter especially on the surface level (Mao et al., 2013; Chen et al., 2014b). The vegetation coverage of TP has evident seasonal feature, which usually start to rise in spring and peak at summer (Zhang et al., 2013; Ding et al., 2007). Following the similar approach like previous studies (e.g. Zou, 2004), the relationship between dust events and vegetation condition over TP is examined using TPDI and AVHRR NDVI data in this study. Fig. 7 illustrates the averaged NDVI in spring and winter during 1982 and 2010 and TPDI in the corresponding

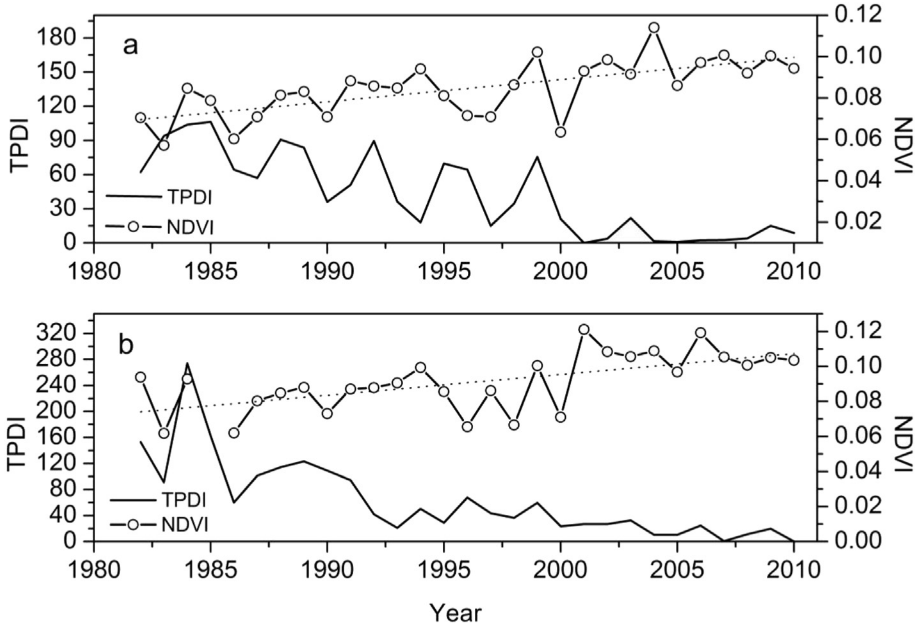

Fig. 7. Variations of the TPDI and the averaged NDVI in (a) spring and (b) winter over 1982–2010. Solid lines indicate the TPDI and line with circles indicate the NDVI. The averaged NDVI are calculated over 30°–35°N, 85°–95°E based on AVHRR data.

period. A negative correlation between TPDI and NDVI is identified. The correlation between TPDI and NDVI is −0.48 for spring and −0.29 for winter, and only the former correlation coefficient is statistically significant at the 99% level. It is noteworthy that TPDI and NDVI are changing almost synchronously during 1982 and 1990. In contrast, the negative correlation became more manifest since the 1990s. This might be one of the possible reasons to explain the persistent decrease of TPDI even though the wind speeds start to recover (see Fig. 6). The positive trend of NDVI reveal the improvement of vegetation in the selected area with the slope equals 0.001 yr^{-1} for both spring and winter during 1982 and 2010, which is similar to the linear trend 0.001 yr^{-1} spring NDVI during 1999–2008 given by Wang and Han (2012).

The overall improvement of vegetation over TP has been indicated by several studies using various datasets and different time span in recent years. For example, Zhou et al. (2007) found that TP experienced a significant vegetation enhancement over the most area of the TP by using GIMMS NDVI data during 1982–2002, with as much as 86.9% of region saw an increasing trend. This overall upward trend of vegetation was also depicted by Shen et al. (2011), X. K. Xu et al. (2008a,b), Zhang et al. (2013),etc. The change of vegetation of TP can be attributed to the profound climate change over TP such the change of temperature and precipitation (Zhou et al., 2007; Wang et al., 2010). As indicated by Gao et al. (2015), most stations which located in the arid and semi-arid area of the TP have became much wetter during 1979–2011.

In short, the overall improvement of the vegetation over TP is depicted by various studies and suggested to be another factor that associated with the decline of the dust events in TP, especially for spring.

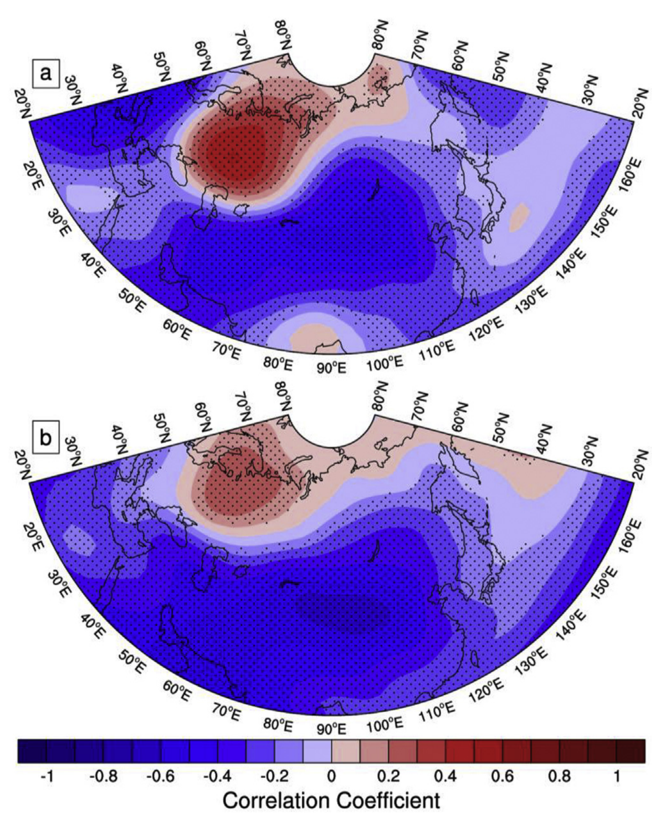

Fig. 8. Correlation coefficients between TPDI and 500 hPa geopotential height for (a) spring and (b) winter.

4.3. Atmospheric circulation

The occurrence of dust events in TP is greatly affected by the middle latitude westerly jet (Fang et al., 2004). The northward shift of the westerly jet over the TP through winter to spring result to the movement of the dust events activity centre (Han et al., 2008), which make the dust events over TP are of the "westerly jet type".

The correlation between TPDI and 500 hPa geopotential height in spring (Fig. 8 a) shows a significant negative centre located in the Mongolia and Northwest of China, with a correlation coefficient lower than −0.5. A positive centre lies in the East European Plain. This suggests that the above normal occurrence of dust events in spring over TP is closely associated with the negative 500 hPa geopotential height anomalies and positive 500 hPa

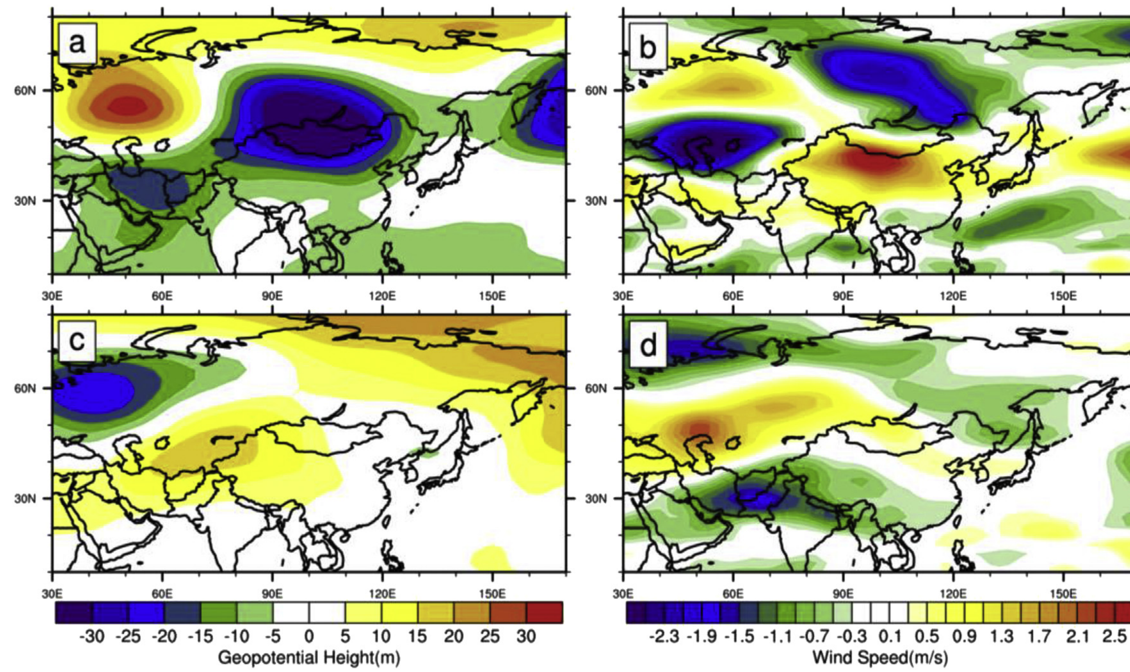

Fig. 9. Composites of springtime 500 hPa anomaly fields for (a) high-frequency year's geopotential height anomaly, (b) high-frequency year's wind speed anomaly, (c) low-frequency year's geopotential height anomaly and (d) low-frequency year's wind speed anomaly.

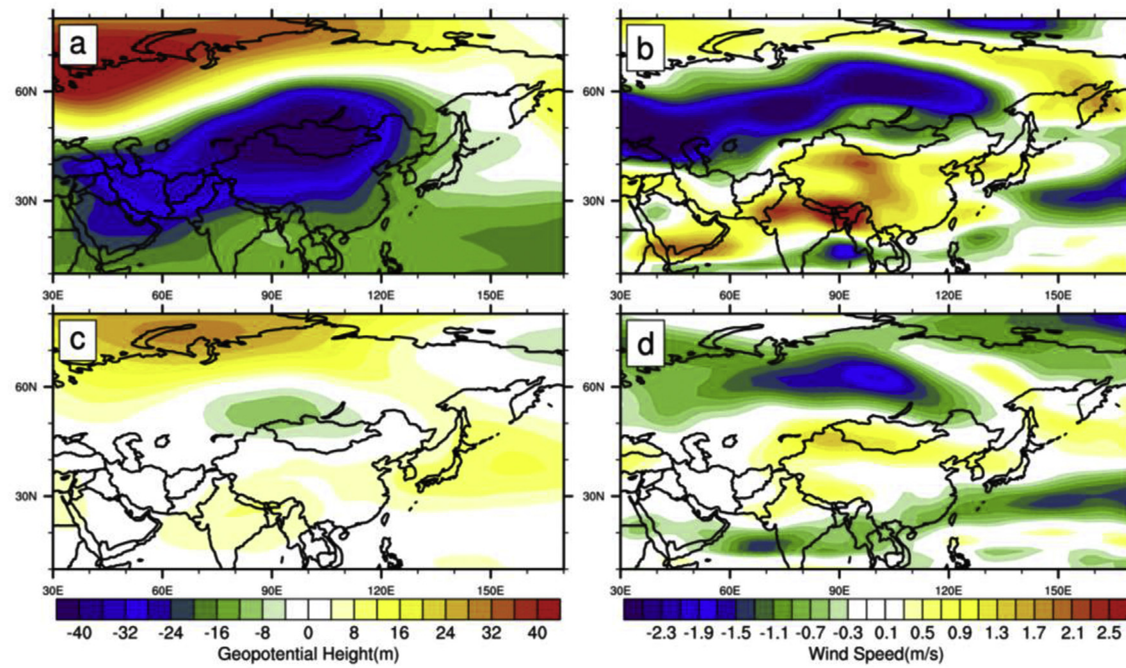

Fig. 10. Composites of wintertime 500 hPa anomaly fields for (a) high-frequency year's geopotential height anomaly, (b) high-frequency year's wind speed anomaly, (c) low-frequency year's geopotential height anomaly and (d) low-frequency year's wind speed anomaly.

Table 2
Composites years with high and low TPDI.

Spring	High-frequency years	1966, 1970, 1973, 1975, 1976, 1979, 1980, 1983, 1984, 1985
	Low-frequency years	1997, 2001, 2002, 2004, 2005, 2006, 2007, 2008, 2009, 2010
Winter	High-frequency years	1964, 1969, 1971, 1972, 1973, 1974, 1976, 1977, 1984, 1985
	Low-frequency years	1993, 2000, 2002, 2004, 2005, 2006, 2007, 2008, 2009, 2010

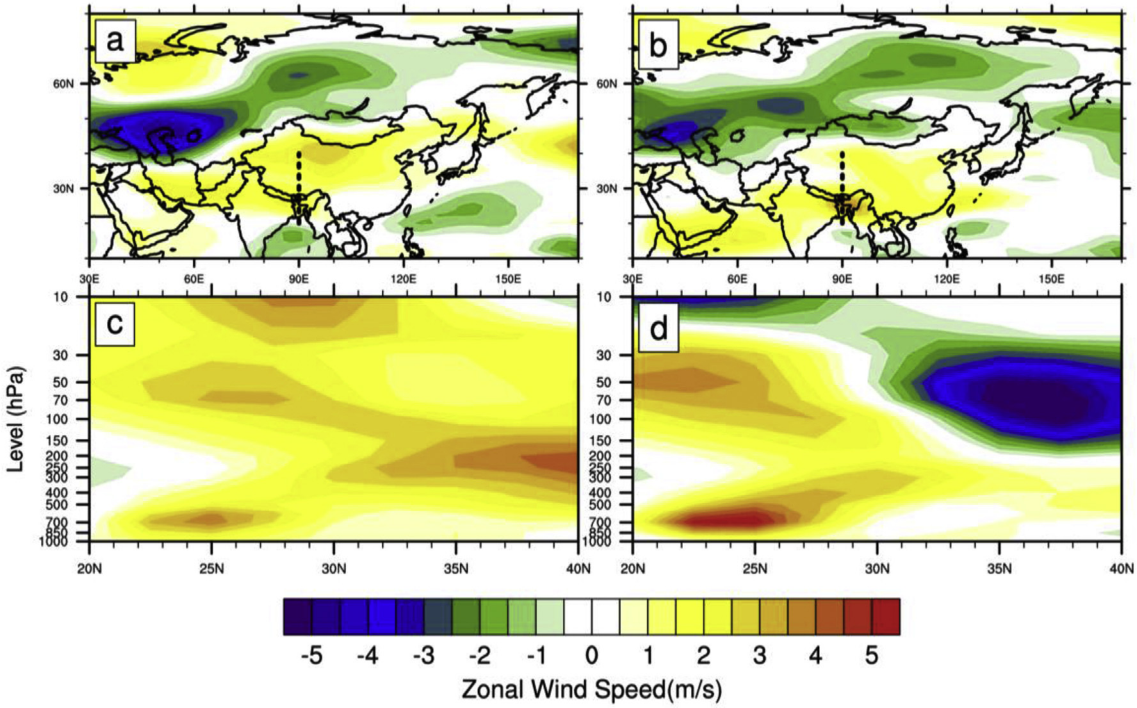

Fig. 11. Difference of 500 hPa zonal wind speed between high- and low-frequency years for (a) spring and (b)winter and cross-sections of zonal wind difference at 90.0°E for (c)spring and (d)winter.The dash line on the (a) and (b) indicate the location of the cross-section.

geopotential height anomalies over these regions, and vice versa. The correlation pattern of TPDI and 500 hPa geopotential height in winter (Fig. 8b) is generally similar to that for spring, with a relatively weaker positive centre and a stronger (correlation coefficient −0.7) and wider negative centre, which extends to the Arabian Sea. Comparing with spring, above normal occurrence of dust events in winter is mainly related to the negative 500 hPa geopotential height anomalies.

To further investigate the atmospheric circulation pattern in the high- and low-frequency years, 10-year composites of 500 hPa geopotential height and wind speed anomaly fields for spring and winter are provided in Fig. 9 and Fig. 10, respectively, and the difference of 500 hPa zonal wind speed between high- and low-frequency years are given in Fig. 11. High- and low-frequency years are chosen based on the ranking of TPDI, as listed in the Table 2. High-frequency years are mainly distributed before the 1990s, especially during the 1970s. Low-frequency years of springtime dust events are all distributed after 1997, which is identified to be the likely point for the abrupt change (Fig. 5a), while the wintertime dust events has only one year (i.e. 1993) is exceptional. These selected years make it possible to investigate the atmospheric circulation not only in the different situation of high-and low-frequency years, but also the change of it in the inter-decadal scale.

In the high-frequency years of springtime dust events, the negative geopotential height anomaly over Mongolia Plateau leads to a weaker ridge in the north of TP (Fig. 10a). The corresponding composite of 500 hPa wind speeds (Fig. 10b) shows the strengthened wind over TP, along with northern China. The increase of 500 hPa wind speeds over TP is mainly contributed by the enhanced zonal wind rather than meridional wind suggested by the composites of zonal wind and meridional wind (not shown). In other words, the high-frequency of springtime dust events is linked to the intensified westerly jet over TP. In contrast, the low-frequency year of springtime dust events is related to the stronger ridge in the north of TP and the reduction of 500 hPa wind speed over TP. Fig. 11a shows that the springtime westerly jet over TP at 500 hPa has became weaker for about 1.5 ms^{-1} during low-frequency years compared to high-frequency years. Cross-section of zonal wind difference at 90.0°E (Fig. 11c) indicates that this weakening trend of westerly jet is coherent at different height level. A similar analysis procedure has been carried out for the winter. The anomalies of 500 hPa geopotential height (see Fig. 10a and c) influencing TP have the same sign as the anomalies in spring, with much broader coverage. The enhancement of wind speeds is also evident over TP and become more significant at western TP in the high-frequency years (Fig. 10b). Interestingly, a weak positive anomaly of wind speed can also be found in the low-frequency years over TP (Fig. 10d). It is possibly related to the wind recovery since the 2000s as discussed above, since the low-frequency years are mostly from the 2000s. Nevertheless, the difference of 500 hPa zonal wind (Fig. 11b) shows that the westerly jet is weaker in the low-frequency years and the cross-section (Fig. 11d) illustrates that westerly jet is strengthened over TP up to 200 hPa in the high-frequency years, with an isolated centre that is weakened in the stratosphere, which is beyond the scope of this paper.

5. Conclusions

This study revealed that the dust events over TP are characterized with a dominant declining trend since the 1960s, accompany with annual and decadal fluctuations. Dust Index for the Tibetan Plateau in spring and winter was defined, as a combination of dust storm, blowing dust and floating dust with corresponding weight coefficient. TPDI characterize the large scale variability of dust events over TP. The results show that both spring and winter TPDI rose gradually since the 1960s and declined after the 1970s. The decreasing trend possibly was an abrupt change at the 1990s indicated by the Mann–Kendall test. Further possible causes for the trend were investigated. The decline of surface wind speeds could partly explain the decrease of dust events over TP, while there is the recovery of wind speeds since the 2000s, when the TPDI are continuing to decline. TPDI positively correlates to the time series of surface wind speeds, with correlation coefficients of 0.42 for spring and 0.46 for winter. The averaged number days with high winds for the 4 selected stations also show a declining trend and are significantly correlated with TPDI for spring (correlation coefficient = 0.69) and winter (correlation coefficient = 0.76). The increasing of vegetation cover is another factor driving the decrease of dust events over TP, especially in spring. TPDI is negatively correlated to the time series of NDVI, with correlation coefficients of −0.48 for spring and −0.29 for winter. Moreover, analysis of geopotential height and wind fields suggests that changed atmospheric pattern is another contributor. An enhanced ridge in the north of TP and weakened westerly jet are observed in the low-frequency years, which are mostly from the 2000s. Considering the important role of middle latitude westerly jet on the occurrence of dust events, weaker westerly jet associated with change in the atmospheric pattern is also influential to the activities of dust events.

It is worth noting that the analysis of dust events in this study was based on the surface observation records, which lack sufficient data over the remote northwestern TP. Satellite observation (e.g. CALIPSO) will be a good ancillary support to utilize in the future study. In addition, the attribution of the trend did not give the contribution rate for the each factor, which disenables this study to identify the major cause quantitatively. Furthermore, the implications of the decreased dust events over TP in the past few decades is still an open question, which may be worth study because of the profound climate effect of dust aerosol in the TP.

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