The Variability of Spring Sand-Dust Storm Frequency in Northeast Asia from 1980 to 2011

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ABSTRACT

The characteristic distributions of regional sand-dust storm (SDS) weather processes over Northeast Asia from 1980 to 2011 were investigated using the shared WMO surface station meteorological data, atmospheric sounding data, China high density weather data, NCEP/NCAR reanalysis data, as well as the archived original weather maps of China. The concentration-weighted trajectory (CWT) method was used to calculate the SDS frequency from the discrete station data and to track the large-scale regional SDS weather processes in Northeast Asia. A spline trend analysis method was employed to investigate the variability of the SDS weather systems. The results show that during 1980–2011, the SDS weather processes exhibit both a historical persistence and abrupt transitions with an approximate 10-yr high-low occurrence oscillation. Through composite analysis of atmospheric circulation during high and low SDS years, it is found that the SDS occurrences are closely related to the anomalies of arctic vortex and midlatitude westerly, and the circulation patterns around the Lake Baikal. During the high frequency years, the meridianal flows in the upper and mid troposphere above the high SDS corridor in East Asia (from the Lake Balkhash along Northwest and North China, Korean Peninsula, and Japan Islands) are apparently stronger than the meridianal flows during the low SDS frequency years, favoring the development and transport of SDSs in the midlatitude regions.

Key words: sand-dust storm weather processes, arctic vortex, midlatitude westerly, concentration-weighted trajectory method

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1. Introduction

Under the background of global climate change, there is a growing trend of large areas of drought and desertification that threatens the environment of human survival. Among them, the sand-dust storm (SDS) associated with certain atmospheric weather systems exerts a significant impact on both regional and global weather and climate and has caused great concern of scientists. On 5 July 2011, the SDS "Habub" rushed through Phoenix, Arizona, USA; on 17 April 2006, a strong SDS struck the large area of North China and brought serious dust pollution to Beijing, which had rarely been seen in the past 50 years. In early April 2007, a large area of "muddy rain" ocurred in Shanghai, Ningbo, and Hangzhou of China.

Since the last century, a large number of studies have been carried out both internationally and domestically on the SDS monitoring, spatial/temporal dist-

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ributions, mechanisms of emission and transport, as well as SDS impacts on climate and weather. Using the combined remote sensing and surface observation techniques, scientists have tracked and investigated the SDS weathers over long distance in West North America, North Europe, Sahara in Africa, and Asia (Emilio et al., 2007: Franzen, 1995; Joseph et al., 1980; Iwasaka, 1983). Brazel and Nicking (1986) analyzed the relationship between the dust occurrence and the weather types in Arizona of Southwest US. Zhao et al. (2008) studied the correlation between the North American aerosols and the Asian dust processes, and pointed out that the intercontinental transports of dust among North American, North African, and Asian continents exert a huge impact on the global climate change.

China is a country with high occurrences of SDSs and has always paid attention to the SDS related severe weather studies, such as in the SDS generation mechanisms and numerical simulations of SDSs (Ye et al., 2000; Zhou et al., 2002; Sun and Li, 2001; Gong et al. 2003; Wang Jinsong, 2004; Zhu and Zhang, 2010). Recent studies on the SDS physiochemical properties indicated that mineral dust aerosol particles can produce important climate forcing through the scattering and absorption of solar short wave and earth long wave radiations (Shi and Zhao, 2003; Zhu et al., 2003; Zhang et al., 2005). In terms of SDS climate effects and SDS forecasts, a dust forecasting system with data assimilation ability CUACE (China Unified Atmospheric Chemistry Environment for aerosols)/Dust was developed (Zhang, 2006; Gong and Zhang, 2008; Niu et al., 2008; Zhou et al., 2008). Yang et al. (2008) studied the characteristics of three-dimensional structure of the circulations during the winter/spring transitional period and their impact on the SDS activities, and Yang et al. (2011) developed the SDS seasonal forecast model. The spatial and temporal distributions of SDSs in northern China were also investigated by many researchers in China (Gong et al., 2003; Jiang and Chen, 2008; Kang and Wang, 2005; Li et al., 2003; Song et al., 2007; Zhu et al., 2003).

Most of the SDS weather processes in East Asia originate from Mongolia and they influence China, Korea, Japan and beyond (Yang et al., 2008). This study aims to investigate the variability in the distribution of the moving SDS processes associated with the activity of large-scale weather systems in the recent 30 years (1980–2011). Using composite analysis, the difference in the three-dimensional structure and evolution of the large-scale circulations such as the westerlies and arctic vortex during high and low SDS years was investigated, and the variability of SDS weather processes is emphasized.

2. Data and methods

2.1 Data sources

This paper makes use of the reorganized and quality-controlled data archive in the China National Meteorological Information Center from 1980 to 2011. This data archive contains the original weather charts of China, the World Meteorological Organization (WMO) exchangeable surface weather observations, the upper atmospheric sounding data, China high density weather observations, and the NCEP/NCAR reanalysis data.

2.2 Method

The China Meteorological Administration (CMA) classifies the SDS into four categories: floating dust, blowing dust, SDS, and severe SDS. The last three categories are investigated in this paper.

In view of the lack of quantitative data for SDS compositions, previous investigations have used the number of SDS days and hours to search for the historical SDS trends. As a result of the recent advancement in the monitoring techniques of SDS as well as the establishment of the SDS surface monitoring network of the CMA and the SDS retrieval from the FY-2C satellite, a more quantitative measurement of SDSs in China has become available (Che et al., 2005: Wang Yaqiang et al., 2008). Based on the recent development of the concentration-weighted trajectory (CWT) method, the relationship between the SDS processes and the total observed SDS concentrations along the moving path in a unit grid and time has been established to quantitatively and objectively define the strength of the SDS process (Wang et al., 2006). This has provided an alternative to investigate the strength of the SDS weather.

Using the CWT method, this paper digitalized the network observed SDS data from 1980 to 2011. By analyzing and choosing the area impacted by SDS processes under the large-scale weather system, the "characteristic impacted domain" (σ) was introduced (Yang et al., 2008). The CWT equation is defined as:

$$c_{ij} = \frac{\sum_{l=1}^{m} c_l \tau_{ijl}}{\sum_{i=1}^{m} \tau_{ijl}}, \tag{1}$$

where c_{ij} is the SDS strength at grid (i, j), l is the SDS path index, m is the total number of SDS paths, c_l is the category code of the observed SDS along path l, and τ_{ijl} is the time spend at grid (i, j) by the path l. Within the grid-based "impacted domain," Eq. (1) combines the tracking search of the SDS process strength with the observed SDS (i.e., SDS category code) as well as with the time and space of a moving grid.

3. Variation characteristics of SDS processes

3.1 Decadal variations

Figure 1 presents the trend of total SDS process number in spring (March–May) from 1980 to 2011 computed from Eq. (1). The 1980–2007 results were checked for consistency with the the archived Chinese original weather maps (Wang Jizhi et al., 2008) and the published "Yearbook of Dust Weather".

The main results for the SDS process number distribution in spring are summarized as follows.

(1) There is a clear interannual variation and the 32-yr average value between 1980 and 2011 is 15.0 (Table 1).

(2) In terms of the decadal variation, there is no clear trend for the first 20 years but a decreasing trend for the last 12 years. From 1980 to 1989, the total number is 161 with an average of 16.1 yr^{-1}; from 1990 to 1999, the total is 165 with an average of 16.5 yr^{-1}; from 2000 to 2009, the total is 131 with an average of 13.1 yr^{-1} (Table 1).

(3) There are 9 yr (1981, 1983, 1984, 1992, 1993, 1995, 1999, 2001, and 2006) with SDS process number $\geqslant$ 18, accounting for 28% of the total occurrences, with a maximum of 25 in 1984. In contrast, each of the years of 1988, 1989, 2003, 2005, 2009, and 2011 has a SDS process number $\leqslant$ 9, accounting for 19% on average of the total. The minimum number is 7 in 2003 and 2009.

(4) High SDS years occur 3 times in the 1980s or 9.4% of the total years; 4 times in the 1990s or 12.57% of the total years; twice in the 2010s or 6.25% of the total years.

(5) Low SDS years occur twice in the 1980s or 6.25% of the total years and 4 times in the 2010s or 12.5% of the total years, with no obvious low SDS in

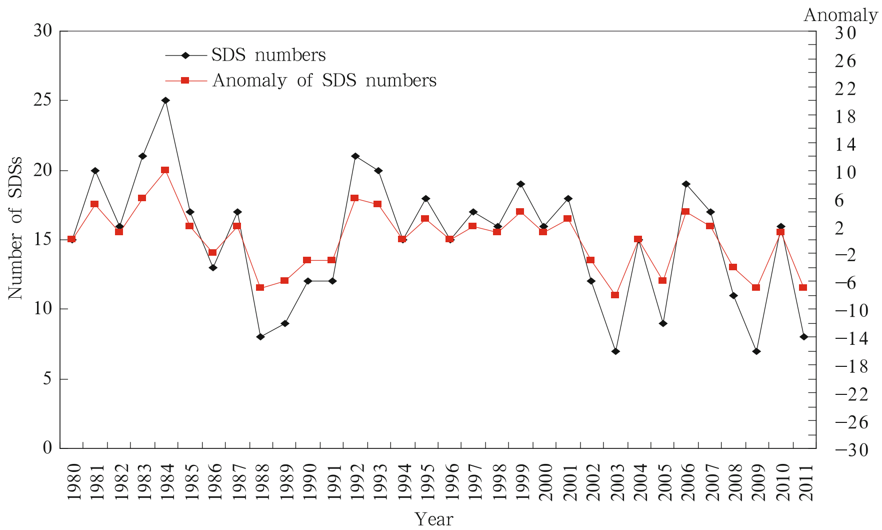

Fig. 1. Annual variations of the SDS process number in spring (March–May) in China from 1980 to 2011 (black line) and its anomaly (red line).

Table 1. Interdecadal characteristics of spring sand-dust weather frequency in China during 1980–2011

Year	Total number of SDS processes	Average frequency of SDS processes	Number of high SDS year (percentage)	Number of low SDS year (percentage)
1980–2011	481	15.0	9(28.1%)	6(18.8%)
1980–1989	161	16.1	3(9.4%)	2(6.3%)
1990–1999	165	16.5	4(9.4%)	0(0%)
2000–2009	131	13.1	2(6.3%)	4(12.5%)

Note: High SDS year is defined as the year with the number of SDS occurrences $\geqslant 18$; low SDS year is with the number of yearly occurrences $\leqslant 9$.

the 1990s.

3.2 Anomaly of SDS process frequency

Figure 1 also presents the time series of the anomaly of spring (March–May) SDS process numbers. It is shown that:

(1) During 1980–1991, there is a positive anomaly of SDS total numbers in the first 6 years and a negative anomaly in the later 6 years.

(2) From 1992 to 2011, there is a significant change in the anomaly with an increased timescale of persistency. The first 10 years (1992–2001) have a positive anomaly while the last 10 years (2002–2011) have a negative anomaly, with a close magnitude for both.

It can be seen that there is a complexity of the SDS interannual and decadal variabilities and further study is needed.

4. Analysis of the SDS evolution trend

4.1 Cubic spline analysis

In order to reveal the historical trend of the long time series, an assumption is made that any time series can be separated into two components, i.e., historical persistency and historical fluctuation. Therefore, during any historial "turning point", a variation in the time series reflects comprehensively the coexistence of the persistency and fluctuation (Wang et al., 2010). Zhang et al. (1995) and Wei (1999) examined the 100-yr historical tropical cyclone (TC) data by a cubic spline method and found that the method could realistically uncover the climatic trend of TCs in Northwest Pacific. Therefore, we adopted this method in this study to investigate the SDS trend.

4.2 Trend of the SDS precess frequency during 1980–2011

As shown in Fig. 2, the 1980–2011 time series of the SDSs have the characteristics of both historical persistency and transitional fluctuation. Compared with Fig. 1, it can be seen that a negative and a positive anomaly occurred in 1986 and 1987, respectively. However, in Fig. 2, a kind of reduced historical persistency can be seen during the 10-yr period from 1980 to 1989. No sudden change in signals of SDS events was found from 1989 to 2008 but two transitional signals for SDS events occurred in 1996 and 2003, respectively. From the spline fitted curve, the wave-like trends are identified, and the details are given below:

(1) The first wave occurred during 1980–1989 with

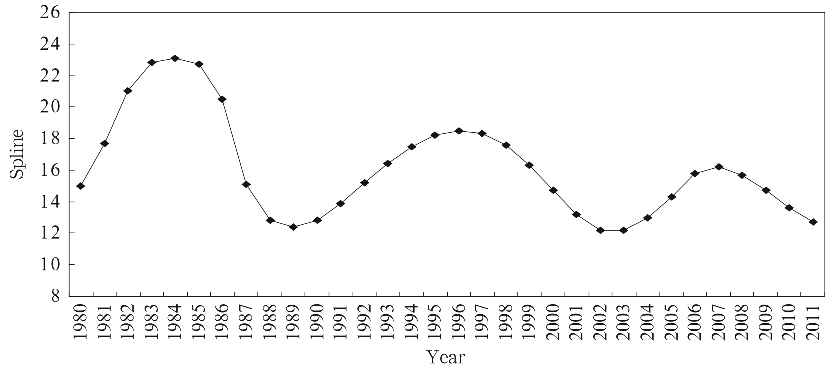

Fig. 2. Cubic spline analysis of SDS over Northeast Asia for 1980–2011.

a peak value of 23 in 1984 and a trough value of 12 in 1989.

(2) The second wave occurred during 1990–2002 with a peak value of 18 and a trough value of 12.

(3) The third wave was from 2003 to 2011, with a peak value of 16 and a trough value of 12.

Analysis of long time-series data for understanding the response to climate change of the interdecadal change of sandstorms are meaningful. Kang and Wang (2005) utilized power spectral analysis to study the 1954–1999 sand-dust weather frequency (number of days) and found that sand-dust weather frequency has three spectral peaks of over 95% reliability at 1, 10, and 20 yr or so in North China. The study on severe dust storms using the data during 1952–2000 in North China and Northwest China (Qian et al., 2002) showed that fluctuation of dust storm activity is rising during 1960–1970, reduced in 1980–1990, and rising again sharply after 2000; and it is possible that a new round of active SDS activity will come in association with the decadal change of the atmospheric circulation in East Asia. Thus, a wave like variation characteristics of SDS changes can be found. Comparing this study with previous long time sequence analyses finds that:

1) Because of limited data availability, most frequency analyses of dust occurrence were based on the dust days observed in the past studies. In this study, analyses of frequency changes of SDSs are based on the analysis of accompanying midlatitude weather systems (such as the Mongolian cyclone) moving together with the sand-dust storms.

2) In the period 1980–2011, low frequency and fluctuation characteristics of SDS events can still be identified. Our result is consistent with the study of Kang and Wang (2005) in that the fluctuation of SDSs has a period of around 10 yr. It is also found that in different historical periods, fluctuation and superposition of different scale circulation patterns and SDS activities reflect the complexity of the SDS climate trend.

5. Composite analysis of circulation patterns in the Northern Hemisphere during the high and low SDS years

5.1 Upper-level circulation features

In order to identify the characteristic difference of atmospheric circulation during the high and low SDS years from 1980 to 2011, the NCEP/NCAR reanalysis data were used for the composite analysis of the high SDS occurrence years (1984, 1992, 1999, 2001, and 2006) and the low SDS occurrence years (1988, 1989, 2003, 2005, and 2009). Figure 3 shows the difference of the wind vector in the upper troposphere (200 hPa) between high and low SDS years. Figure 3 indicates that the difference lies in the anticyclonic circulation in the polar area. The key points are as follows:

(1) During the high SDS years, the atmosphere is obviously controlled by an anticyclonic circulation, reflecting a strongly developed high pressure system in the Arctic.

(2) Average flow in the low SDS composite years

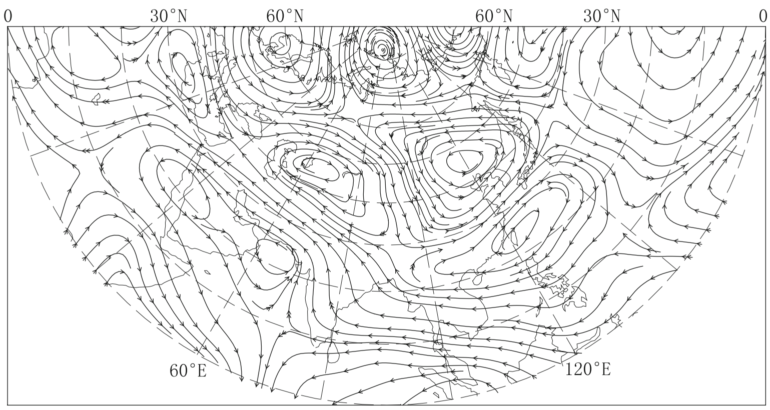

Fig. 3. Difference of the wind vector in the upper troposphere (200 hPa) between high and low SDS years for spring (March–May).

shows only a center point of the anticyclonic vortex located in the polar area (figure omitted). In addition to the polar anticyclone, there is a secondary center of the anticyclonic vortex south of the first one, which reflects the occurrence of a southward shifted component of the anticyclone, compared to the high SDS years.

(3) The difference field (Fig. 3) also shows that there exists a large-scale and strong cyclonic circulation from the Lake Baikal in Russia to North and Northeast China. On its south side from the Ural Mountains to North China, the flow vector difference reveals an obvious northwest flow, indicating that during high SDS years, the cold front tends to flow into the mid and low latitudes.

5.2 Mid-tropospheric circulation features

Under the background of the above upper-level large-scale circulation in the Northern Hemisphere, the key area for the SDS activity in the middle troposphere in Northeast Asia spans from the Arctic, the Lake Baikal to Northeast Asia. Figure 4 shows the difference of the flow vector in the middle troposphere (500 hPa) between high (1984, 1992, 1999, 2001, and 2006) and low (1988, 1989, 2003, 2005, and 2009) SDS composite years.

It is seen from Fig. 4 that there is a strong cyclonic circulation (centered around 50°–65°N, 70°–90°E) from the Lake Baikal, Lake Balkhash to the Mongolian Plateau, Northwest China, North China, the Korean Peninsula, and Japan Islands. Its south areas extending from the Lake Balkhash, Northwest China, North China, the Korean Peninsula, to the Japan Islands are dominated by large-scale northerly flow, indicating that the atmospheric circulation in the high SDS years is more favorable for the cold air to penetrate to the mid and low latitudes.

5.3 Mid-tropospheric circulation patterns for 2006 and 2003

Figure 5 shows the 500-hPa flow fields for a typical high SDS year 2006 (Fig. 6a) and a typical low SDS year 2003 (Fig. 6b). It is found that the center of the cyclonic circulation was around 65°N, 90°E for 2006 and around 75°N, 110°E for 2003, i.e., the center of the cyclonic circulation shifted northeastward. Compared to the low SDS year 2003, the streamlines for 2006 above the Lake Balkhash, Northwest China, North China, the Korean Peninsula, and to the Japan Islands are much denser and the meridional northwest flow is much stronger, with an obvious low pressure trough located from Northwest to North China.

This indicates that during the high SDS year 2006, northwestly flow was stronger, and it is easier for cold air to accumulate in Northwest and North China. Because of the stronger meridional circulation, cold air is more likely to be transported into the Korean Peninsula, Japan, and other low latitude regions. On the contrary, the typical low SDS year 2003 featured a northward-shifted center of lows, flat westerly in mid-high latitudes, and sparse streamlines. The meridional circulation from Northwest and North China to the Korean Peninsula and Japan is weaker, preventing high-latitude cold air to move southward. It is clearly seen that there is a significant difference in 500-hPa circulations between April 2006 and April 2003, suggesting different dynamic-driven conditions for high and low SDS years.

5.4 Zonal flow index during high and low SDS years

The zonal flow index is an important parameter in diagnosis of the meridional variability of westerly

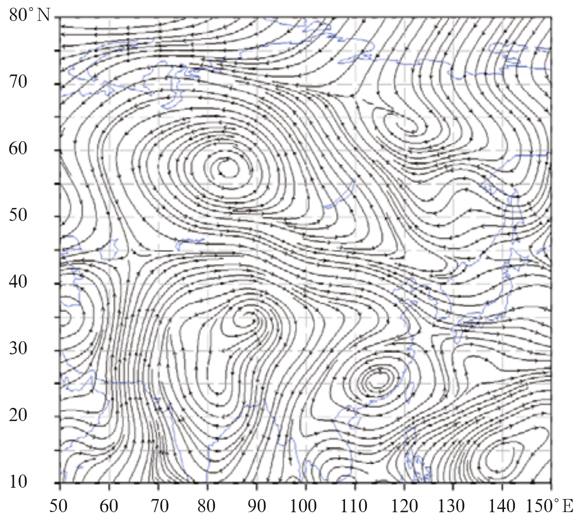

Fig. 4. Difference of the wind vector in the middle troposphere (500 hPa) between high and low SDS years.

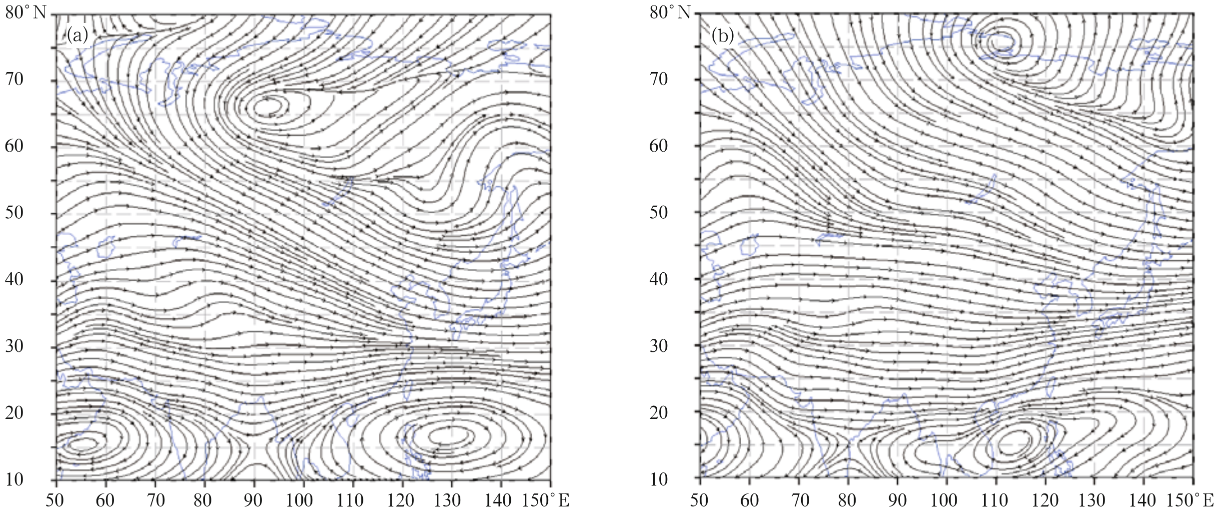

Fig. 5. 500-hPa streamline fields for typical high (a; 2006) and low (b; 2003) SDS years.

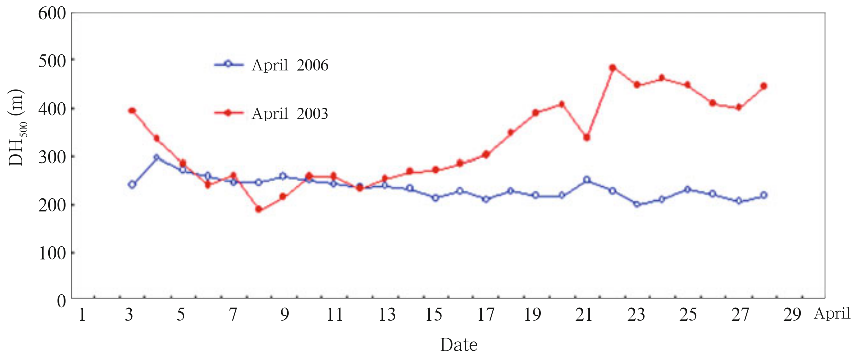

Fig. 6. The moving averaged zonal flow index for April 2006 (the line with solid dots) and 2003 (the line with hollow dots) at 500 hPa between 45° and 65°N.

circulation in the midlatitude. To quantify the difference in the midlatitude circulation between high and low SDS years, daily variation in the zonal flow index for April is analyzed for the typical high SDS (2006) and low SDS (2003) years.

On the isobaric surfaces at high altitude, the geostrophic wind can be calculated from the surface slope:

$$U_{\mathrm{g}} = \frac{g}{f}\left(\frac{\partial Z_{\mathrm{g}}}{\partial n}\right)_p, \qquad (2)$$

where n is the north direction in the Northern Hemisphere, Z_{g} is the geopotential height on the isobaric surface, f is the Coriolis parameter, and g is the gravitational constant. Since g/f is a constant, the isobaric surface slope $\left(\frac{\partial Z_{\mathrm{g}}}{\partial n}\right)_p$ can be used to quantify the geostrophic wind. The zonal flow index can be calculated directly from Eq. (2) minus a constant.

Figure 6 illustrates the results of the zonal flow index calculation using the slope $\left(\frac{\partial Z_{\mathrm{g}}}{\partial n}\right)_p$ at 45°–65°N of the Eastern Hemisphere (taking $\partial Z_{\mathrm{g}} = \mathrm{DH}_{500}$) and compares the daily zonal flow indices in April for high SDS (2006) and low SDS (2003) years. It is seen from Fig. 6 that the zonal flow index at 500 hPa during high SDS year (2006) is lower than that in the low SDS year (2003). Therefore, the meridional flow over the westerly belt in the midlatitude was enhanced to allow the spring Arctic cold air to penetrate into the warm region of the midlatitude and to favor the development of SDS weather in April 2006. Actually, 19 SDS weather processes occurred in spring 2006 with 5 strong SDS, which was the most frequent SDS year in the 21st century. On the other hand, only 7 SDS weather processes occurred in spring 2003 with no strong SDS occurrence, which was the least SDS year in the first 12 years of the 21st century (Table 2) (Yang et al., 2008). It can also be seen from Table 2 that, compared with the period of 1–15 April in 2003 with that of 2006, the gap of SDS frequency is quite small, but a notable discrepancy of SDS frequency is seen during the period of 16–30 April between 2003 and 2006. This is consistent with the daily variation of the zonal flow index in Fig. 6.

Table 2. Comparison of the frequency of SDS weather processes in 2006 and 2003

Year	Frequency of strong SDSs in spring	Frequency of SDSs in spring	Frequency of SDSs in 1–15 April	Frequency of SDSs in 16–30 April
2006	5	19	3	4
2003	0	7	2	0

6. Conclusions and discussion

In this study, based on the CWT method, the frequencies of the SDSs and associated weather process over Northeast Asia during 1980–2011 were calculated. The distribution of total moving SDS process numbers for 1980–2011 associated with the large-scale weather systems was obtained, and the anomaly characteristics of the distribution were revealed. Using a cubic spline analysis, the co-existence of historical persistence and transition variations with a wave-like behaviour was identified.

Composite analysis of the atmospheric circulations revealed that there was a sharp difference in the upper troposphere (200 hPa) and the middle troposphere (500 hPa) circulations between high and low SDS years over the areas from the Lake Balkhash, Northwest China, North China, the Korean Peninsula to the area around the Japan Islands. The circulations in high SDS years favor the transport of cold air to the mid-low latitudes, illustrating the reasonable response of SDS process strength to the change of weather and climate systems.

It should be noted that the climatic variation of SDS processes is not only a response to the climate change but also a feedback to the climate system, which should be further studied in the future.

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