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Sand/dust storms over Northeast Asia and associated large-scale circulations in spring 2006

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Abstract

This paper presents a study on the meteorological conditions that accompany the sand/dust storms (SDS) of East Asia in spring 2006, based on the SDS data collected both by WMO during 2000–2006 and by 2456 Chinese surface stations, and on the meteorological reanalysis data from NCEP-NCAR . The evolution of 3-D structures of the general circulations prevailed in both winter and spring as well as their annual anomalies were investigated by comparing the years having most and least occurrences of SDS between 2000 and 2006. It is found that spring 2006 featured a noticeably increased occurrence of SDS, compared with previous years. The general circulations prevailed through both winter and spring, especially the 3-D structure of the polar circulation, show the significant anomalies compared to a normal year. This produced a range of corresponding weather phenomena, including circumpolar vortices at the upper troposphere, mid-level westerly jets, and lower zonal winds, which all favored the SDS production and transport in 2006. The study also reveals a fact that comparing with a normal year, the transitional period from the winter of 2005 to the spring of 2006 has witnessed a fast-developed high center at the upper troposphere of the northern hemisphere and the circumpolar vortex area, which pushes the area dominated by the circumpolar vortices further to mid-latitudes. The circumpolar vortices shifted southwards, and prevailed over an extensive area across the northeast hemisphere for a sustained period. The mid-high latitude areas that sit in the south of the circumpolar vortices in Asia have experienced significantly abnormal westerly jets at the mid-level of troposphere. Zonal winds prevailed at the mid and lower levels of troposphere. Sea level pressure registered an abnormal high at 4–10 hPa, compared with a normal year. The above-mentioned 3-D structures of general circulation have created thermal and dynamic conditions that favor the repeated genesis and momentous development of the Mongolian cyclones, which in turn contributes to the frequent occurrences and long distance transport of SDS.

1 Introduction

Spring 2006 was regarded as one of the most frequent sand/dust storms (SDS) seasons in the last 10 years in northeast Asia with 31 dust storm processes recorded, 19 of which happened in China. The dust fall in Beijing on 17 April 2006 was estimated to be 330 k tons which translated correspondingly into 20 kg per person in Beijing. Damages were also reported in Mongolia, China, Korea and Japan (Yang et al., 2006; Zhang, 2006).

SDS episode is influenced by synoptic circulation patterns of both regional and global scales (Franzen, 1995; Wang et al., 2006; Xu, 1997; Zhao, 1993). In the latitude band of 35–40° N where arid and semiarid areas are located, westerly jet stream carries the wind-blown dust particles and transports them into other parts of the globe (Zhang et al., 1999). Recent researches indicate that the frequent occurrence of the dust storm is one of the characteristics of global climate changes. There are complex interactions and influences between dust storm and climate (Zhang et al., 2002). It is found that Asian dust originated from the desert area by surface wind in Northern China is transported through westerly jet stream aloft to a long distance that includes North Pacific and North America. Although changes in atmospheric dust concentrations may trigger large-scale climate responses, as suggested by Zhang et al. (2002), the feedback between dust and climate can also be viewed as a mechanism by which the monsoon climate can be modulated by the dusts' radiative effects, including any attendant effects on the hydrological cycle. That is, the climatic conditions governing dust transport may be sensitive to the dusts' effects on atmospheric circulation and precipitation that result from dust-induced changes to the land/ocean temperature structure.

Locally, the surface conditions in the desert areas such as the vegetation and snow covers and soil moisture govern the frequency of dust occurrence (Gong et al., 2003). However, the synoptic patterns of global or regional circulations control the production and transport of dust storms (Qian et al., 2002a; Yang et al., 2006). It is very important to establish a relationship between the dust storms and weather patterns in order to improve our understanding of the dust storm processes and enhance our ability to forecast the dust storm. Wang et al. (2003, 1995) analyzed the spatial and temporal distributions of dust storm weathers in Northern China and showed the characteristics of them. Using the network monitoring data, the dust storm and floating dust weathers in China and the trends and inter-annual variations of the dust storm weathers were also obtained (Qian et al., 2002b; Zhou, 2001). Nevertheless, the analysis of large-scale circulations such as the westerly jet, northern oscillation and polar vortex and their relationship to the dust storm occurrence is not well understood.

This paper presents a study for the 2006 spring SDS and its synoptic weather analysis. Comprehensive data sets are used in the study that include the surface dust concentration monitoring net work, FY-2C satellite retrieval, weather data from 2456 CMA (the China Meteorological Administration) weather monitoring stations, WMO data and NCEP re-analysis data. It is aimed to link the anomalies of the major synoptic circulations to the dust occurrence in spring 2006 and investigate the role of these anomalies in the processes of dust production and transports.

2 SDS processes across the northeast Asia in 2006

2.1 Criteria for defining and classifying a SDS event and process

A SDS event is usually defined in terms of visibility and wind speed at a location (Chen et al., 2004). According to the meteorological observation standard defined by CMA (CMA, 1979), the weather phenomenon of a general SDS can be classified into four levels for reporting purpose, i.e. floating dust, blowing dust, sand/dust storm (SDS), and severe sand/dust storm. A floating dust event is defined, when dust and fine sands floating in the air can be observed in an evenly distributed manner, with light breeze, or windless near the surface of the premises where the observation is made with a horizontal visibility less than 10 km. For blowing dust, winds blow up dust or sand from the ground, with a horizontal visibility between 1 km and 10 km. When a SDS occurs, strong winds stir up a turbid air by blowing up dust or sand from the ground, left a horizontal visibility of 500 m–1000 m. A severe SDS blows up dust or sand particles from the ground in an aggressive manner, causing a heavily contaminated air with a horizontal visibility less than 500 m.

To give a nicety defenetion of SDS process and making a comparative and relative standard of SDS is very important. Certain number of SDS events forms a SDS process. In an attempt to classify the SDS events as a process or episode, the concept of "affected areas with SDS features", or σ (Wang et al., 2006), and the approach to define the intensity, have been used. Objective means is used to analyze the SDS processes, with due consideration to both WMO's standard for observation density and the practical standards applied to intensive observations at major sand-dust monitoring sites. International synoptic data exchanged via WMO's GTS at 00:00, 06:00, 12:00, 18:00 UTC, and domestic synoptic data collected at 00:00, 03:00, 06:00, 09:00, 12:00, 15:00, 18:00, 21:00 UTC, are used as major evidences for classifying the SDS processes affecting the northeast Asia. No separate efforts have been made to characterize the floating dust weather process. The criteria for classifying a SDS process are defined as follows:

1. Based on the distribution of existing regular weather stations across the northeast Asia, the number of observing stations that can spot the sand-dust phenomenon under a defined resolution is used to determine the sphere of influence. A blowing dust process is made up of five or more observed blowing dust phenomena over an area, at a given observing hour, under the same weather pattern. The ending time of a blowing dust process is mainly determined by the variation of intensity of the weather system, and the genesis and dying-out of the phenomenon.

2. The definition of a sand/dust storm process, or a severe SDS process, is made based on the same principle above-mentioned. The only difference is a SDS process, or a severe SDS process is registered as onset, only when or more SDS phenomena are observed at a given observing hour. The ending time of such

ACPD
7, 9259–9281, 2007

processes is also mainly determined by the variation of intensity of the weather system, and the genesis and dying-out of the storms.

3. The most severe SDS process is recorded if both i) and ii) conditions are met in the same day.

2.2 2.2 Frequency of spring SDS across the northeast Asia

Based on the above definition and classification, an analysis has been made to the origins of the SDS processes across the northeast Asia in spring 2006. The study shows that the northeast Asia had 31 SDS processes in the spring of 2006, 26 of which, or 84% of the total, originated from the deserts of Mongolia and15 transferred to the lower reach areas, affecting a number of parts of the region, including China, Korean Peninsula, and Japan. During the same period, only four of the total 31 processes were originated from China and one from the Republic of Korea (Table 1). However, China was affected by 15 SDS processes that had an origin from Mongolia and got reinforced in the course of the lower reach transportation, by the sand sources across the desert areas of north China. In this context, China had altogether 19 SDS processes, under the combined influence of long range transport and local origin. Of them, 15 were rated as severe SDS, 8 SDS, and 6 blowing dust processes. This makes the year 2006 having most sand/dust storms since 2000, or 39% higher than the average of the preceding seven years.

To further illustrate the severity of SDS in spring 2006, a compared analysis of the sand/dust storm processes affecting China since 2000 was given in Table 2. Five SDS processes occurred in March, or 21% more than the average. April was visited by 8 processes or 27% up over the seven-year average. The month of May had 6 SDS processes, or 82% more than the seven-year average (Table 2). Table 2 also separates the SDS frequencies from 2000–2006 into three categories: blowing dust storm (BLDS), sand/dust storm (SDS), and severe SDS (SSDS).

ACPD

7, 9259–9281, 2007

Northeast Asia SDS and 3-D large-scale circulations

Y. Q. Yang et al.

EGU

2.3 Synoptic footprints of SDS processes in spring 2006

An analysis comparing the genesis and dying out of SDS processes in the springs since the year from 2000 shows that the sand/dust storms affecting China in the spring of 2006 have the following footprints:

Earlier onset for severe SDS

Table 2 shows that two severe SDS processes occurred in March 2006, with an increased frequency of 182%, compared with the average of the past seven years. Under the influence of the Mongolian cyclone, the first severe SDS process took shape over the west part of Mongolia at 14 h, 8 March 2006. 21 h later (1100, 9 March) it made its impacts on the west part of Inner Mongolia, and the mid-part of Gansu Province in China. It furthered its course in the following hours to affect ten provinces and one city, including northern Ningxia, northwest Shan'xi, Shanxi, northern Hebei, Beijing, northern Henan, Shandong, Liaoning, and Jilin. After that, it made an eastward transportation, and reached the Republic of Korea in 30 h (1700, 10 March). The episode became the earliest severe SDS process in the spring of 2006, with an extensive affected area. It also makes the earliest severe SDS process with a widest coverage since the years from 2000.

Most sand/dust in April

China had 8 SDS processes in April 2006, of which 3 were rated as severe SDS processes, 2 SDS processes, and 3 blowing dust process. In the past years since 2000, it was rare to see 2 severe SDS and 1 SDS occur in a short period of 7 days from 5 April to 11 April. This leads to a sharply raised frequency of 110% for the occurrence of severe SDS processes over the average of the past years.

Serious damages

All 19 SDS processes affecting China were accompanied by floating dust. This is especially true to the severe SDS process affecting Beijing area on 16–18 April 2006. According to incomplete figures, Beijing was covered with 330 000 tons of sand-dust, which resulted in a seriously contaminated air marked by grade-5 for air quality.

3 Variation of 3-D structures of general circulation over the northeast Asia in the winter to spring transitional period of 2006

Studies indicated that SDS phenomena usually occurred under the conditions of complicated atmosphere activities in dynamical and thermodynamical process, but the weather circulation in multi-scale interaction can push emission of SDS and offer an organized system for SDS form and its transportation in a long distance. An analysis of the evolution of boundary layer weather systems, and variation of 3-D structures of large-scale circulation over the lower and middle level of troposphere, from the winter of 2005 to the spring of 2006, was done using NCEP-NCAR reanalysis data to link their roles in and contributions to the raising frequency of SDS across the northeast Asia in the spring of 2006.

3.1 Evolution of circumpolar vortices over the northern hemisphere

A circumpolar vortex in the northern hemisphere is a seasonal-scale circulation system, playing an important modulator role in the seasonal transitional period (Zhang and Wang, 1995; Zhu and Lin, 1981). Its scope and intensity variations impose a larger impact on the cold air activities across the Eurasian continents, especially for the transitional period from winter to spring.

A 100 hPa field comparison between 2006 having most sand/dust episodes, and 2003 enjoying least sand/dust episodes (Fig. 1) shows that:

1. There is a strong circumpolar vortex over 100 hPa in the February of both 2006 and 2003, with a similar sphere of influence. However, there is a noticeable high center in the 100 hPa circumpolar vortices of 2006 (small oval in Fig. 1a).
2. A comparison between February and March of 2006 (small oval in Fig. 1a) shows that the high-value center gains a substantial development across the 100 hPa circumpolar vortices from February through March, with an extensive coverage (large oval in the lower chart of Fig. 1a). This makes a significant difference against the 100 hPa circumpolar vortices of 2003. There is no high-value center in the circumpolar vortices of 2003.
3. There is a fast developing high-value center in the circumpolar vortices of 2006, which pushes the prevailing circumpolar vortices further to an area close to 52 N. The circumpolar vortices travel southwards, and dominate a large area across the northeast hemisphere, for a long duration. The circumpolar vortices of 2003 keep up a stable status with limited motion. There are no noticeable variations from February to March, in terms of dominating areas.

3.2 Westerly jets at the mid-level troposphere

In the transitional period from winter to spring, the evolution of mid-latitude westerly is a common concern for SDS weather production and transport. An analysis shows that there was a prevailing easterly jet at the lower and mid-level of troposphere over an extensive area ranging from the Baikal Lake to most part of north China, during the period of December 2005–January 2006. The above-mentioned area was dominated by northwesterly jets, rather than by the easterly as in February 2006.

Figure 2a shows a 500 hPa wind field anomaly for April (upper chart) and May (lower chart) 2006. It indicates that there is a significant cyclone circulation at the mid-level troposphere, from the Baikal Lake to north China, prevailed by a stronger northwest jet across the northeast Asia, compared with a normal year. The axis of the jet sits over an area notorious for desertification, including Kazakhstan, Mongolia, and northern part of China. An area running from north China to the Hexi Corridor stands at the opening of the jet (Fig. 2a). The horizontal divergence radiated from the jet opening at the mid-level troposphere creates a large-scale circulation desirable for boosting the unstable energy at the lower and mid-level of troposphere. Once sands are stirred and blown up from ground, the mid-level northwesterly jets become a powerhouse energizing the long distance transport of sand and dust.

As it was mentioned earlier, the radiating opening of westerly jets sit right over a lower reach area made up of the mid and east parts of Mongolia, and an array of deserts in north China, including the Badain Juran Desert, the Kubuqi (Hobq) Desert, and the Onqin Daga sandy land that are sensitive to the sand-dust processes. In this context, the area at the opening of radiating jets, from north China to the Hexi Corridor, is put under the influence of lower troposphere, which is desirable for an ascending turbulence and blowing sand/dust up from ground. The genesis and development of the jets at the mid-level troposphere, together with strong jet bands, and a wide opening in front of jets, have created an extremely ideal pattern for the genesis and development of a SDS, and for its subsequent transportation.

The circulation for 2003 (Fig. 2b) presents a completely different distribution pattern of 500 hPa field anomaly: 1) the centre of cyclone circulation at the mid-level troposphere is located in the Far East region, with a noticeable eastward axis for the northwesterly jets appeared in the rear. It mainly affects the east part of East Asia; 2) the mid and west parts of Mongolia, a major desertification area in the northeast Asia, sits on a U-shape field. A belt running from the east part of Mongolia to the northern part of China is under the domination of weak southerly jets. All these are not in a position to create a condition favorable for the long distance transport as it was in 2006. In this context, the axis of northwesterly jets at the mid-level troposphere, which departs slight from the major sand-dust sources of the northeast Asia, makes another reason behind the reduced frequency of sand/dust episodes in 2003.

3.3 Evolution of momentum field at the lower troposphere

The perturbation vorticity field of lower large-scale circulation is very important to the blowing dust process, after the onset of a SDS (Sun and Yao, 2002). The footprints of jet fields at the mid-level troposphere have been discussed in Sect. 3.2, indicating that the large scale anti-cyclone jets at the mid-level troposphere across the northeast Asia, and its loudspeaker like radiation in front, together with a corresponding lower complex jet fields, create a powerhouse for stirring up a SDS process at the lower atmosphere, through the shift from the mid-level troposphere to the lower wind fields. These dynamic features can find expressions in zonal winds, and in the climatic features of wind anomaly. The large-value area of annual zonal wind anomaly not only reflects the momentum of large scale westerly streams, but also constitutes a major factor that triggers up the onset of blowing dust process at the boundary layer.

Figure 3a shows the 850 hPa zonal wind anomaly for the spring of 2006. It can be seen from the figure that a vast area, ranging from Mongolia to most part of China's Xinjiang, Inner Mongolia, Gansu, Ningxia, Shan'xi, Shanxi, Beijing, Tianjin, Shandong, and Henan, has recorded a strong westerly at the lower troposphere, compared with a normal year. A northwest-southeasterly zonal wind belt of strong positive anomaly, with an unusually strong wind speed of 1–2 m/s, dominates an extensive area covering the southwest of the Baikal Lake, west of Mongolia, Gansu, west of Inner Mongolia, Ningxia, Shan'xi, Shanxi, Henan, Shandong, Korean Peninsula, and southern part of Japan. There is also a corresponding zonal wind belt of strong positive anomaly at the mid-level troposphere, with a wind speed anomaly as strong as 3 m/s at 500 hPa, covering a zonal wind area running from the southwest of the Baikal Lake, to the mid-south of Mongolia, and further to the mid and west part of China's Inner Mongolia. This implies that the large scale westerly in the spring of 2006 has a deep vertical structure due to its high momentum area.

In the spring of 2006, the high momentum area, represented by the positive anomaly of zonal winds at the lower troposphere, had a good coverage of Mongolia and north-

ACPD

7, 9259–9281, 2007

EGU

west China, a major sand source in the northeast Asia. High momentum gathered energy across the area, and sent a downward transport that triggered up the turbulence movement at the boundary layer, which led to sand blowing. This makes an important footprint explaining the increased outbursts of sand/dust storms in 2006.

Figure 3b shows the distribution of 850 hPa zonal wind anomaly in the spring of 2003. It can be seen that major sand sources of the northeast Asia, including Mongolia, northwest China, north China, the southern part of northeast China, Korea, the Republic of Korea, and Japan, have been well covered by the negative zonal wind anomaly. In the meantime, the high momentum area, represented by the positive zonal wind anomaly at the lower troposphere, is far away from major sand sources of the northeast Asia. It is worth mentioning that of 10 sand/dust processes occurred in 2003, 7 were originated from or affected the Nanjiang Basin, northern part of Tibet, Qinghai, and Gansu. This is associated with the existence of a higher positive zonal wind anomaly over the areas.

3.4 Abnormal sea level pressure of northeast hemisphere

Figure 4a shows the distribution of sea level pressure anomaly for the winter of 2005 (upper), and the spring of 2006 (lower). The distribution of sea level pressure anomaly for the winter of 2002 (upper) and for the spring of 2003 (lower) is given in Fig. 4b. A comparison between Fig. 4a and Fig. 4b indicates that:

1. In the winter of 2005, the northern hemisphere had a strong polar high with an extensive coverage, from Greenland to offshore areas of northern Europe, further to the Eurasian continents where Russia sits, and then eastwards to the Bering Strait. There is a quite opposite picture for the winter of 2002, where the polar high affected a limited part of the northwest Europe, with a weak intensity.

   (a) In the winter of 2005, an area from the Tamil Peninsular to Siberia on the northern hemisphere was affected by an extremely strong polar high, with an annual positive anomaly as high as 6–12 hPa, with a large coverage. It is well known that the Tamil Peninsular is a key source of cold air for the northeast

ACPD

7, 9259–9281, 2007

Asia. The positive anomaly area in 2003 only affected a limited part of the northwest Europe, with a weak intensity.

(b) In the spring of 2006, the northern hemisphere had a polar high that moved in a counter-clockwise manner at 8090 degree (Fig. 4a). The positive anomaly high center, originally located at the Tamil Peninsular, was shifted to the Bering Strait. At the same time, another positive anomaly high center, originally sat at the Greenland area, moved in a counter-clockwise manner to the Tamil Peninsular. On the contrary, in the transitional period from winter to spring of 2003, the northern hemisphere had a polar high that did not show an apparent shift, with a noticeably weak positive anomaly center, and limited sphere of influence. Meanwhile, the negative anomaly of the Tamil Peninsular got reinforced.

4 Conclusions

Through the analysis of the synoptic circulation patterns and the occurrences of the SDS between 2000 and 2006, some conclusions can be drawn:

1. The spring of 2006 witnessed a noticeably increased frequency of SDS, compared with previous years after 2000.

2. In 2006, the 3-D structures of polar circulations over the northern hemisphere are noticeably different, compared with a normal year, especially the year enjoying a reduced frequency of SDS. The distribution and variation of circumpolar vortices at the upper troposphere carries the following fingerprints. During the transitional period from winter to spring of 2005–2006, there was a fast developing high center across the upper troposphere and circumpolar vortices, which pushed the prevailing area of circumpolar vortices further to mid-latitudes. It energizes a southward shift of circumpolar vortices, with a large coverage of the

ACPD
7, 9259–9281, 2007
Northeast Asia SDS and 3-D large-scale circulations
Y. Q. Yang et al.

EGU

northeast hemisphere, and a long duration, which benefits the high frequency activities of SDS processes.

3. There is an apparent abnormal westerly jet at the mid-level of troposphere and right side of the circumpolar vortices, across the mid-high latitude areas of Asia. Zonal winds prevail at the mid and lower troposphere. This has played an important role in causing frequent attacks of cold air and SDS processes across the northeast Asia, the onset of blowing dust, and subsequent lower reach transport.

4. In the spring of 2006, the northern hemisphere had a polar high that moved in a counter-clockwise manner, which affected a long sustained strong positive anomaly across the Tamil Peninsular, a key cold air source in the northeast Asia.

5. A comparison between the years having most and least occurrences of SDS shows that the frequency of SDS bears a significant correlation with the maintenance and evolution of large-scale circulation structures at the lower, mid, and upper levels of troposphere. In this context, understanding and studying the footprints of global circulations that affect the SDS system is important to raise the operational capability of monitoring and early warning of SDS weathers. The effort also benefits an improved understanding of the genesis, development, and long distance transport of sand/dust storms.

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ACPD

7, 9259–9281, 2007

Northeast Asia SDS and 3-D large-scale circulations

Y. Q. Yang et al.

EGU

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Table 1. Sand and dust storm processes over the northeast Asia in the spring of 2006.

Origin	Affected areas	Frequency	Percentage	Notes
Mongolia	China, DPRK, Republic of Korea, Japan	26	84%	Lower reach areas
China	DPRK, Republic of Korea, Japan	4	13%	15 episodes originated from the upper reaches
Republic of Korea	Republic of Korea	1	3%	Korean Peninsula affected by 15 episodes originated from the upper reaches, Japan affected by 3 episodes originated from the upper reaches

Table 2. A frequency comparison of total SDS hit China during the period of 2000–2006.

Year	March	April	May	Subtotal
2000	3	8	5	16
2001	7	8	3	18
2002	6	6	0	12
2003	0	4	3	7
2004	7	4	4	15
2005	1	6	2	9
2006	5	8	6	19
Total	29	44	23	96
Averaged	4.14	6.29	3.29	13.71
Anomaly percentage for 2006	21%	27%	82%	39%

ACPD

7, 9259–9281, 2007

Title Page
Abstract Introduction
Conclusions References
Tables Figures
◀I ▶I
◀ ▶
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

EGU

Table 3. Comparison of SDS frequency in 2000–2006 for three types of SDS: blowing dust storm (BLDS), sand/dust storm (SDS), and severe SDS (SSDS).

Year Month		2000	2001	2002	2003	2004	2005	2006	Total	Annual means for 2000–2006	Anomaly (%) for 2006
March	BLDS	1	3	1	0	4	1	3	13	1.86	62%
	SDS	2	4	3	0	2	0	0	11	1.57	–100%
	SSDS	0	0	2	0	1	0	2	5	0.71	182%
April	BLDS	2	1	0	2	3	2	3	13	1.86	62%
	SDS	5	4	4	2	1	3	2	21	3.00	–33%
	SSDS	1	3	2	0	0	1	3	10	1.43	110%
May	BLDS	4	1	0	3	2	1	1	12	1.71	–42%
	SDS	0	2	0	0	2	1	5	10	1.43	250%
	SSDS	1	0	0	0	0	0	0	1	0.14	–100%
		16	18	12	7	15	9	19	96	13.71	39%

ACPD

7, 9259–9281, 2007

Northeast Asia SDS and 3-D large-scale circulations

Y. Q. Yang et al.

Title Page
Abstract Introduction
Conclusions References
Tables Figures
◀◀ ▶▶
◀ ▶
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

EGU

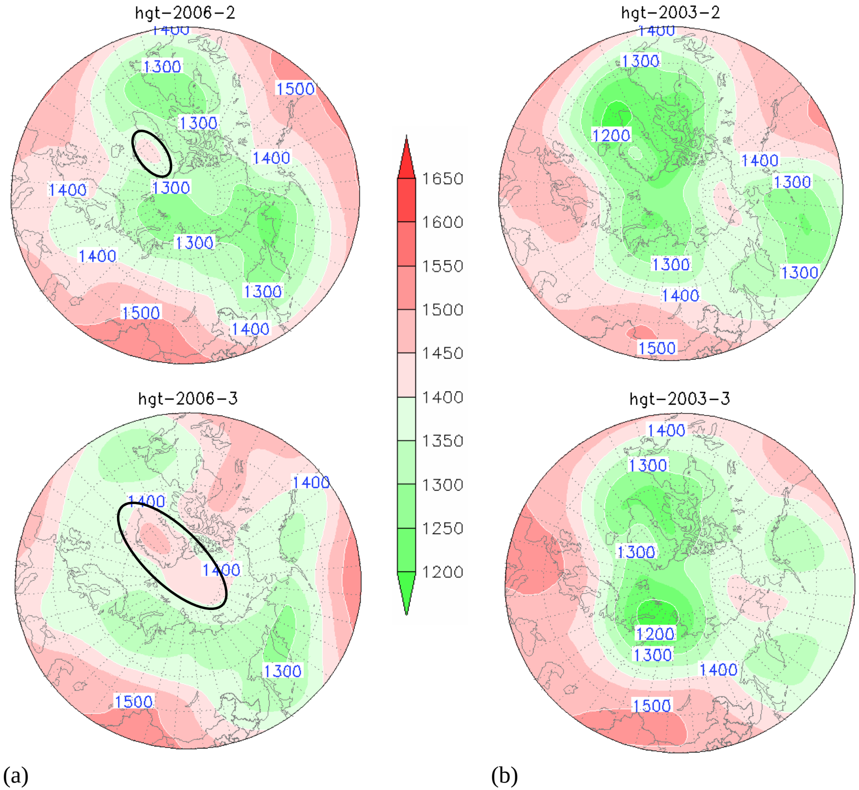
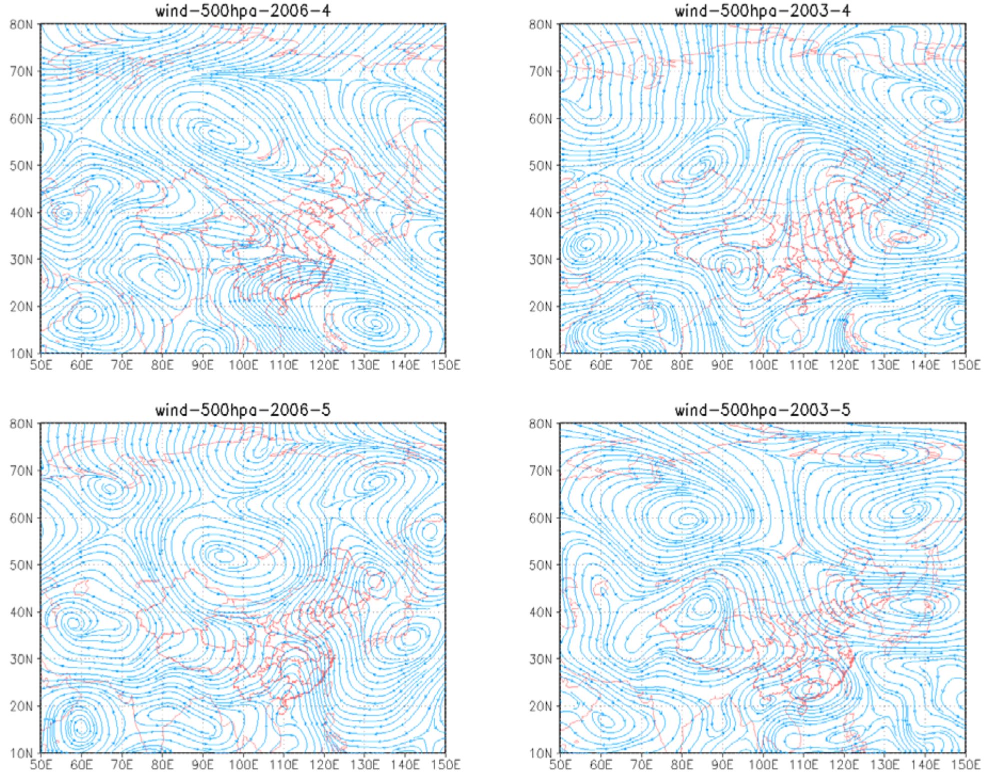


Fig. 1. 100 hPa geo-potential fields in February–March 2006 (left), and February–March 2003 (right).

ACPD
7, 9259–9281, 2007



(a) (b)

Fig. 2. Wind field Anomalies in April–May 2006 **(a)**, and April–May 2003 **(b)**.

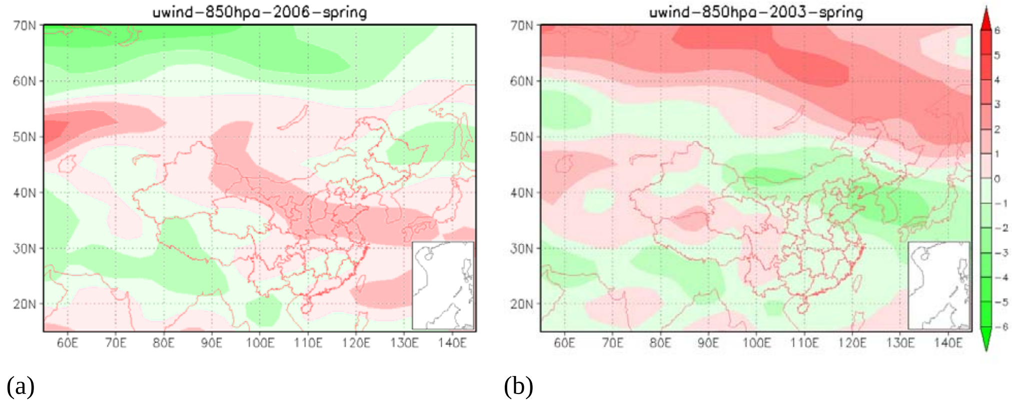


Fig. 3. Zonal wind anomalies at 850 hPa for spring 2006 **(a)** and spring 2003 **(b)**.

ACPD
7, 9259–9281, 2007

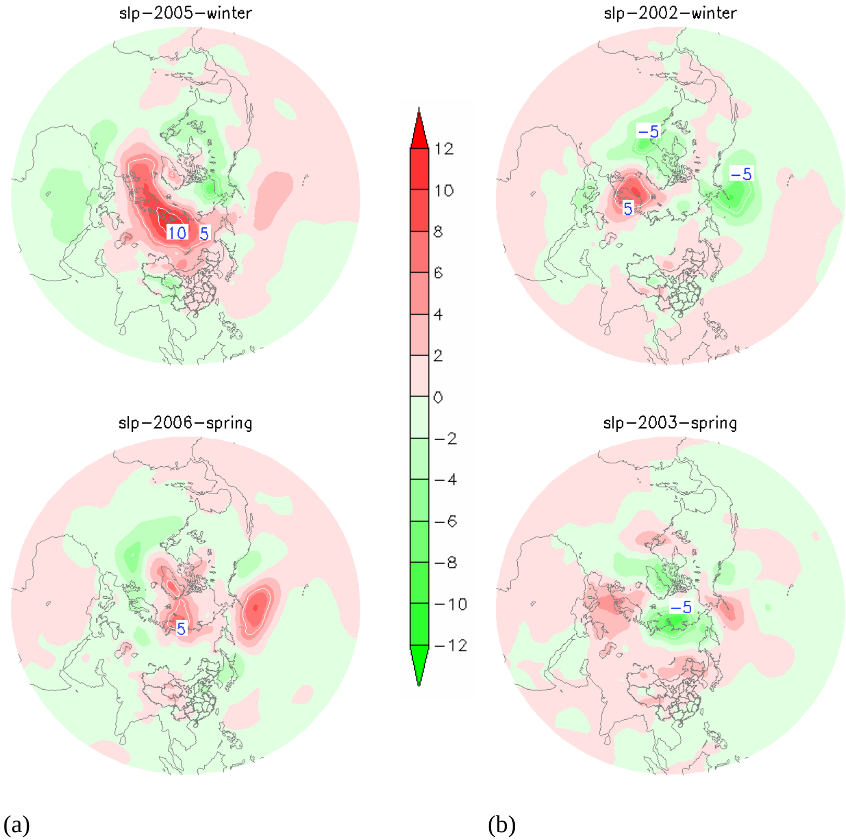


Fig. 4. Sea level pressure anomalies. **(a)** for Winter 2005 (upper) and Spring 2006 (lower) and **(b)** for Winter 2002 (upper) and Spring 2003 (lower).