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Why do dust storms decrease in northern China concurrently with the recent global warming?

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[1] Recent studies have shown that the spring dust storm frequency (DSF) in northern China exhibits an obvious downward trend over the past 50 years concurrently with the recent global warming. We found that the decline of DSF is significantly correlated with the increase of the surface air temperature (SAT) in the region of 70°E–130°E, 45°N–65°N around Lake Baikal, where anthropogenic forcing induces prominent warming in the recent decades. Corresponding to the SAT rise in this region, an anomalous dipole circulation pattern is found in the troposphere that consists of a warm anti-cyclone centered at 55°N and a cold cyclone centered around 30°N. The DSF is positively correlated to the activity of Mongolian cyclones. The warming trend around Lake Baikal possibly induces a weakening of the westerly jet stream and the atmospheric baroclinicity in northern China and Mongolian regions, which suppress the frequency of occurrence and the intensity of the Mongolian cyclones and result in the decreasing DSF in North China. This mechanism will likely further reduce the spring DSF in the future global warming scenario. **Citation:** Zhu, C., B. Wang, and W. Qian (2008), Why do dust storms decrease in northern China concurrently with the recent global warming?, *Geophys. Res. Lett.*, *35*, L18702, doi:10.1029/2008GL034886.

1. Introduction

[2] Changes in occurrences of natural disasters, which are possibly associated with global warming, have been receiving ever-increasing attention worldwide. Dust storm is one of the severe disastrous weather in China, especially during spring when more than 85% of annual dust storms occur. A number of studies have shown that the spring dust storm frequency (DSF) bears a negative correlation with the local surface air temperature (SAT), and exhibits a downward trend over the past 50 years [*Qian et al.*, 2002; *Zhou and Zhang*, 2003; *Zhai and Li*, 2003; *Zhao et al.*, 2004; *Fan et al.*, 2006; *Gong et al.*, 2006, 2007]. Why does dust storm decrease in the northern China concurrently with the recent global warming? What does this decrease imply for its future change? This paper aims at addressing these questions.

[3] Past studies suggested that regional climate variables play an important role in influencing dust storm activities [e.g., *Qian et al.*, 2002; *Gao et al.*, 2003; *Zhang and Ren*, 2003; *Kurosaki and Mikami*, 2003; *Liu et al.*, 2004; *Ding et al.*, 2005]. The downward trend in DSF was linked to the changes in the Northern polar vortex and Siberian high through their impacts on the cold surges in East Asia [*Zhao et al.*, 2004; *Gong et al.*, 2006], and to the decreasing meridional temperature gradient between Mongolia and northern China [*Qian et al.*, 2002]. The spring DSF bears a significant negative and positive correlation to spring Arctic Oscillation (AO) and Pacific/North American (PNA) pattern on interannual time scale, suggesting that the variation of DSF is likely affected by the activities of AO and PNA [*Gong et al.*, 2006, 2007]. The latter provides us with understanding of the variation of DSF via changes of large-scale circulations. However, both the spring AO and PNA indices show no evident long-term trends, and the linkage between the trends of spring DSF and the SAT was not directly discussed in the previous studies.

[4] In this study, we explore the long-term variation of Chinese DSF in spring (March to May), and its possible linkage with the global warming and it related circulation changes in the Northern Hemisphere. The data we used include the DSF (days per month) observed over 258 stations which are provided by the Chinese Meteorological Administration (CMA), the GISS (Goddard Institute for Space Study, NASA) global land SAT data [*Hansen et al.*, 1999, 2006], as well as the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis data [*Kalnay et al.*, 1996; *Kanamitsu et al.*, 2002]. The study period is from 1954 to 2007 (54 years). A dust storm day is counted when a huge amount of dust and sand blowing from the ground to sky and the horizontal visibility falls below 1 km, as observed at least once in four observations within a day as it was described in the previous works [*Qian et al.*, 2002; *Gong et al.*, 2006]. In the present study, the spring DSF is defined as the seasonal average of monthly dust storm days in spring (March–May). The t-test is applied to our statistical analysis.

2. Long-Term Trends of Spring DSF and SAT

[5] We applied the Empirical Orthogonal Function (EOF) analysis to the spring DSF data to explore its long-term trend. Figure 1 shows the two leading modes (EOF1 and EOF2) and the corresponding principal components (PC1 and PC2). In the EOF analysis, only 98 stations were used to warrant data continuity and uniformity. The EOF1 and EOF2 account for 44.6% and 11.5% of the total variance, respectively. The PC1 shows a remarkable long-term downward trend, while PC2 shows prominent interannual variations. The spatial pattern of the EOF1 displays nearly uniform distribution of DSF anomalies with large values

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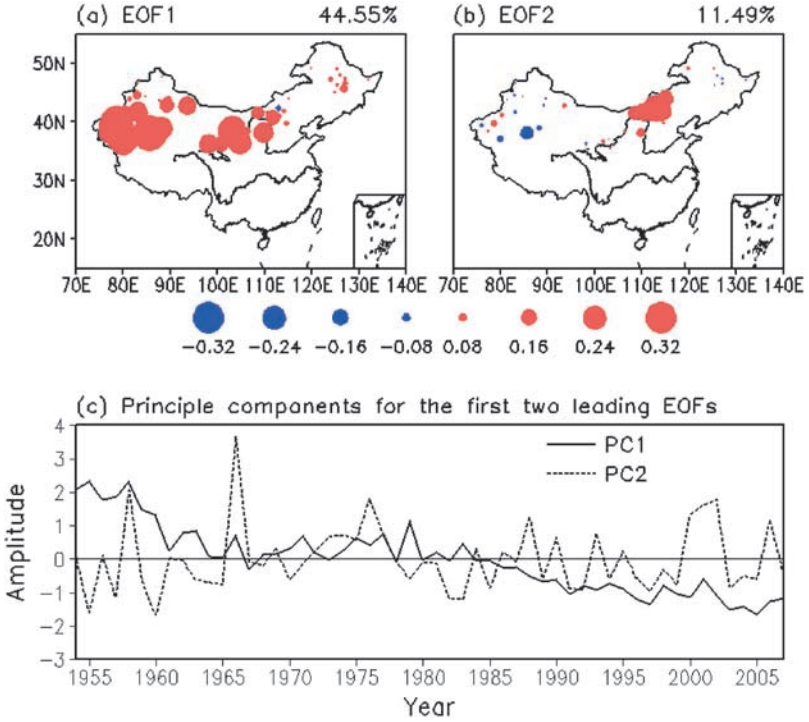

Figure 1. Empirical orthogonal function (EOF) analysis of spring (March to May) dust storm frequency (DSF, days per month) in China. (a) EOF1, (b) EOF2, and (c) PC1 (solid line) and PC2 (dotted line) during 1954–2007.

cover the deserts of Taklimakan, Gurbantunggut, Badain Jaran, Tengger and Mu Us in North China [*Zou and Zhai*, 2004]. In the EOF2, the positive values appear in Horqin and Hunshandake Desert, near eastern Inner Mongolia, and weak negative DSF anomalies exist in the western and the eastern China, respectively. While the EOF1 has decreasing trend, the EOF2 is not. The spatial pattern of the EOF2 has a maximum loading in the eastern Inner Mongolia, suggesting that there is no decreasing trend in the Inner Mongolia dust storm. We also note that the source region of eastern Inner Mongolia may link closely to the dust storm appearances in Japan and Korea, that may partially explain why the dust storm frequency appears increasing in Japan and Korea [*Yoshino*, 2002; *Kurosaki and Mikami*, 2003; *Tian et al.*, 2007]. However, the spring DSF in China mainly exhibits an obvious long-term declining trend suggested by EOF1 and PC1, and the interannual signal mainly appears in the region studied by Gong et al. [*Gong et al.*, 2007]. PC1 suggests the DSF occurs most frequently in the 1950s and least frequently after 1980s with a steady downward tendency as pointed by the previous study [*Zhou and Zhang*, 2003]. To identify the linkage between spring DSF and global warming, we defined the PC1 as the DSF index (DSFI) in the present study.

[6] We computed correlation coefficients between DSFI and the land SAT in the Northern Hemisphere. Figure 2 indicates that the DSFI bears a simultaneous, significant negative correlation with the SAT over Eurasian continent, and the large negative correlation coefficients (below −0.8 and significant at 0.01 confidence level) are found in the region around Lake Baikal, where the SAT exhibits a remarkably warming trend over the past 50 years [*Hansen et al.*, 1999, 2006]. As such, the DSFI is significantly correlated to the SAT index (SATI), which is defined by the SAT averaged over the region of 45°N–65°N, 70°E–120°E, with a negative correlation coefficient of −0.63 and −0.33, respectively, with and without the trends. This result suggests that the negative correlations are primarily coming from the trends. Therefore, the change of SAT over the Lake Baikal is likely related to the long-term variation of DSF.

3. Possible Linkage Between DSF and Global Warming

[7] The possible connection between spring DSF and global warming could be explained by the circulation anomalies over the Eurasian continent. To identify the possible connection between the spring DSF and the circulation changes associated with the SATI, we present four meridional cross-sections of various SATI-correlation fields with air temperature, GPH, wind, and wind speed along 100°E from 1000 hPa to 10 hPa (Figure 3). The air temperature exhibits a significantly reversed pattern at the lower and upper atmosphere and to the north and south of 40°N, corresponding to the change of SATI (Figure 3a). The significantly positive correlations with the warming trend in the air temperature occur in the lower troposphere below 300 hPa and between 40°N and 80°N, and corresponding negative correlations, the cooling trend occur at the upper levels and from 45°N to the North Pole. To the south of 40°N, however, the negative correlations, associated with the cooling appear in the lower troposphere below 200 hPa and between 20°N and 40°N, and the corresponding positive correlations, with respect to the warming occur in the upper atmosphere. Therefore, the anomalous air temperature exhibits a vertical ‘‘saddleback’’ pattern associated with the

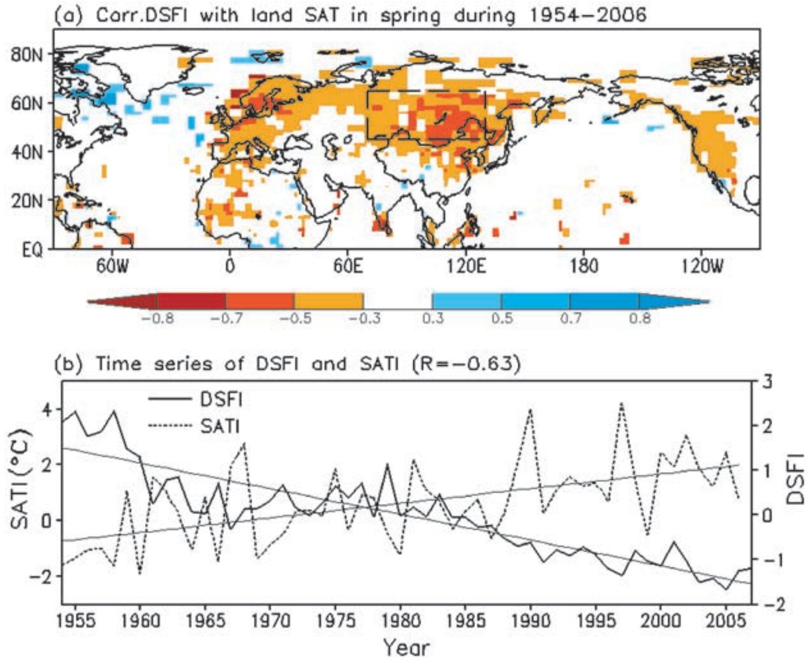

Figure 2. (a) Correlation coefficients between dust storm frequency index (DSFI) and spring land surface air temperature (SAT) in the Northern Hemisphere during 1954–2007. (b) Time series of DSFI (solid line) from Figure 1c and SAT index (SATI, dotted line) based on the averaged STA at the rectangle box in Figure 2a.

simultaneous change of SATI. A dipole of significantly positive and negative correlations in the GPH appears in the 55°N and 30°N, respectively, with the maximum center at 500 hPa and 300 hPa, which correspond to the maximum warming and cooling in the air temperature field (Figure 3b). Associated with the cooling trend in the higher latitude over the upper level atmosphere, the GPH anomalies exhibit a significant negative correlation to the SATI, which is possibly related to the enhanced polar vortex. Different from the case of air temperature, the anomalous wind field exhibits a "sandwich" pattern from north to south, with enhanced westerly anomalies in the regions of 60°–75°N, suppressed westerly jet stream in 30°–50N, and enhanced westerly south of 30°N in the troposphere below 200 hPa. The zonal wind speed shows a similar anomaly pattern (Figures 3c and 3d). Similar correlation patterns can also be

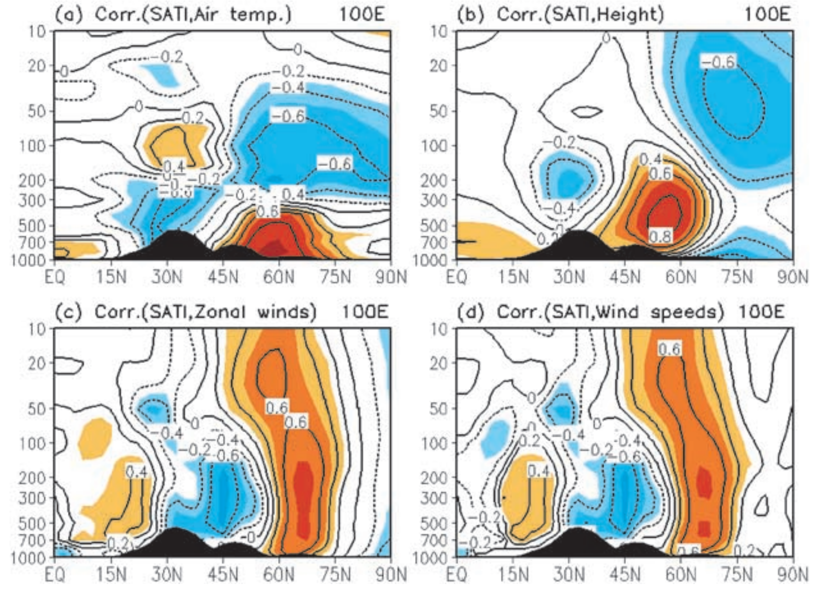

Figure 3. Height-latitude section of correlation coefficients between surface air temperature index (SATI) and (a) air temperature, (b) geopotentail height (GPH), (c) zonal wind, and (d) wind speeds along 100°E in spring during 1954–2006. The correlations that are at 95% confidence level are shaded. The black shading shows topography.

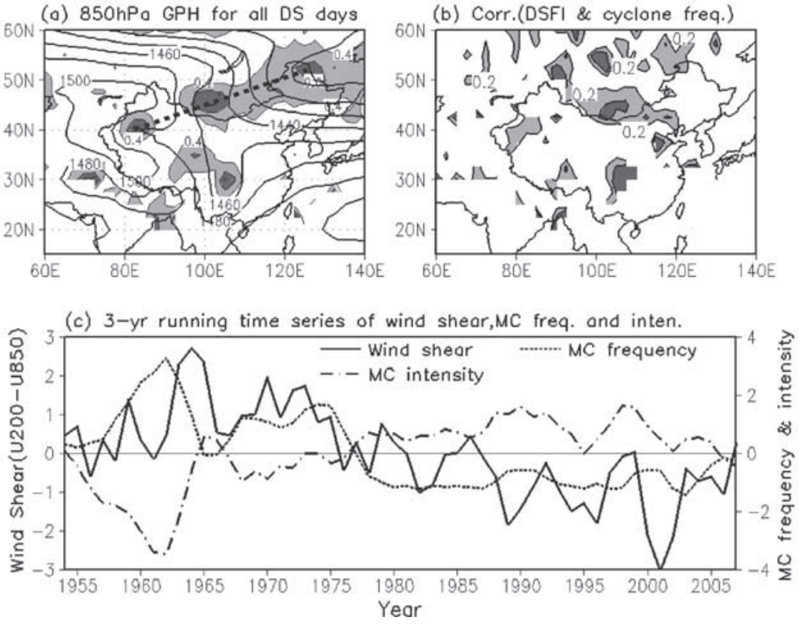

Figure 4. (a) Composite 850 hPa geopotential height (contours) for the 1,023 dust storm days and the climatological frequency of occurrence of cyclone centers (shading, counter interval is 0.2) in spring during 1954–2007, (b) the correlation coefficient between DSFI and the frequency of occurrence of the cyclones, the counter interval is 0.2, and the values lower than 0.2 are omitted, (c) the 3-yr running mean of anomalous zonal wind shear index between 200 and 850 hPa ($U_{200\ \mathrm{hPa}}-U_{850\ \mathrm{hPa}}$) over the region of 70°–130°E, 40°–55°N (solid line), 3-yr running means of Mongolian cyclone (MC) frequency (dotted line, right coordinate, unit: $0.1 \times \mathrm{day}^{-1}$), and the MC intensity index (dot-dashed line, unit: 10gpm), which is the geopotential height averaged over the region of 90°–115°E, 40°–50°N.

observed along 80°E and 120°E (figures are not shown). Therefore, the SATI-related atmospheric circulations exhibit in the whole troposphere, resulting in unfavorable atmospheric conditions for the dust storm weather.

[8] The warming rate is faster in the region around the Lake Baikal, and it is nearly double than the SAT in China and the Northern Hemisphere over the past 50 years (figure not shown). Therefore, our hypothesis is as follows. The warming trend around Lake Baikal might induce a meridional air temperature gradient, a weakening of the westerly jet stream, reduce the atmospheric baroclinicity and suppress the frequency and strength of Mongolian cyclone (MC) in North China, thus the DSF. To verify this hypothesis, we examined the daily 850 hPa weather systems that prevailed in 1,023 dust storm days in the spring seasons during 1954–2006. Following *Qian et al.* [2002], we identified the locations of the cyclone centers and the corresponding central values using 850 hPa 6-hr GPH. A critical value for selection of cyclone center is set to 1360 geopotential meters (gpm). The grid points lower than 1360 gpm are identified. The grid point with the lowest value relative to its surrounding points determines the central location of the cyclone. If these points have the same values, the central location is determined by the meridional and zonal arithmetic mean of these points. In the present study, we define the cyclone frequency as the total number of daily occurrence of cyclone at each grid averaged in one season. We also defined the cyclone intensity by the seasonal average of cyclone central GPH value at 850 hPa. The seasonal average of zonal wind shear of $\frac{\partial U}{\partial Z}$ between 200 and 850 hPa ($U_{200\ hPa}-U_{850\ hPa}$) was used to measure the atmospheric baroclinicity due to the meridional air temperature contrast in East Asia.

[9] Figure 4a shows the composite map of 850 hPa GPH for 1,023 dust storm days, where the shaded value indicates the climatological spring cyclone frequency. It shows that the dust storm often concurs when a cyclone is centered in the southern Mongolia, southwest Xinjiang province of China, and Northeast China. Downstream of the fronts associated with these cyclone centers are located the Gobi and Taklamakan Desert. The frequent occurrences of these major cyclones result in a composite trough at the 850 hPa GPH, which connects the three centers of maximum cyclone frequency (Figure 4a). Furthermore, the DSFI is well correlated with the frequency of Mongolian cyclone with a significant correlation coefficient of 0.40 in the southern Mongolia (Figure 4b).

[10] To elucidate the possible linkage between the trends of DSFI and SATI, we calculated three indices, they are the 3-yr running mean of vertical shear of the zonal wind anomaly averaged over the region of 70°–130°E, 40°–55°N, the Mongolian cyclone frequency and cyclone intensity index which is defined by the 850 hPa GPH averaged over the Mongolian region of 90°–115°E, 40°–50°N. The result suggests that the vertical shear index exhibits a significantly downward trend, corresponding to the warming around Lake Baikal during 1954–2006 (Figure 4c). The decreased vertical shear is accompanied by the decreasing MC frequency (the correlation coefficient is 0.57) and weakening of the MCs (correlation coefficient is –0.40). These correlation coefficients are statistically significance at 95% confidence level. And the correlation comes from

primarily their corresponding trends. Therefore, the warming trend around Lake Baikal induces a weakening of the westerly jet stream and the atmospheric baroclinicity in northern China and Mongolian region, which cause the decreases of the frequency and strength of the MC and the dust storm activity in North China. The simultaneous changes of DSF, SATI, and related atmospheric circulation patterns, appearing in the air temperature, GPH, and wind fields are manifestation of atmospheric response to the warming around Lake Baikal.

4. Summary

[11] The relationship between the spring dust storm frequency (DSF) in northern China, land surface air temperature (SAT), and the related atmospheric circulations in the Northern Hemisphere during 1954–2007 were examined. It is found that the downward trend of the spring DSF is negatively correlated to the SAT anomalies in North China and North Asia. The most significant correlation coefficients (< -0.8) appear around the Lake Baikal, where the SAT exhibits a significantly warming trend over the past decades in the recent global warming [*Hansen et al.*, 1999, 2006]. Our results suggest that the spring DSF in China is closely associated with the activity of Mongolian cyclone. The warming trend around Lake Baikal results in a decrease of the westerly jet stream and the atmospheric baroclinicity in midlatitude East Asia, thus reducing the frequency and strength of Mongolian cyclones. As a result, the frequency of the spring dust storm in North China has declined in the past 50 years. In the future global warming scenario, the SAT near the Lake Baikal will likely continue rising, and thus the spring dust storm frequency is anticipated to continuously drop.

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