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Possible influence of Arctic Oscillation on dust storm frequency in North China

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Abstract: This study has investigated the influence of Arctic Oscillation (AO) on dust storm frequency in North China in spring seasons during 1961–2007. There is a significant linkage between dust storm frequency and AO; a negative (positive) AO phase is related to an increased (decreased) dust storm frequency in North China. This relationship is closely related to changes in the cold air activity in Mongolia. The cold air activity exerts large impacts on the dust storm frequency; the frequency of cold air activity over Mongolia not only positively correlates with the dust storm frequency in North China, but also shows a long-term decreasing trend that is an important reason for the long-term decreasing of dust storm frequency in North China. The AO has large influence on the frequency of cold air activity over Mongolia; a negative (positive) AO phase is highly related to an increased (decreased) frequency of cold air activity over Mongolia, which results in an increased (decreased) dust storm frequency in North China.

Keywords: dust storm frequency; cold air activity frequency; Arctic Oscillation

1 Introduction

Dust storms frequently occur in northern China in the spring (Zhou and Zhang, 2003), which not only cause severe damage to human lives and properties in northern China, but also exert impacts on regional and global climate change by huge amount dust transport in atmospheric troposphere (Tegen *et al.*, 1996; Uno *et al.*, 2009). Recently, some studies indicated that dust storm related losses vary from region to region over East Asia. Larger potential losses and destructions were observed in areas where they experienced more dust storms and had more developed economic conditions. For example, North China (35°N–45°N and 105°E–120°E, specified in Figure 1) suffered more losses from dust storms due to the higher occurrence of the dust storms, the large population, and the relatively developed economy, even compared

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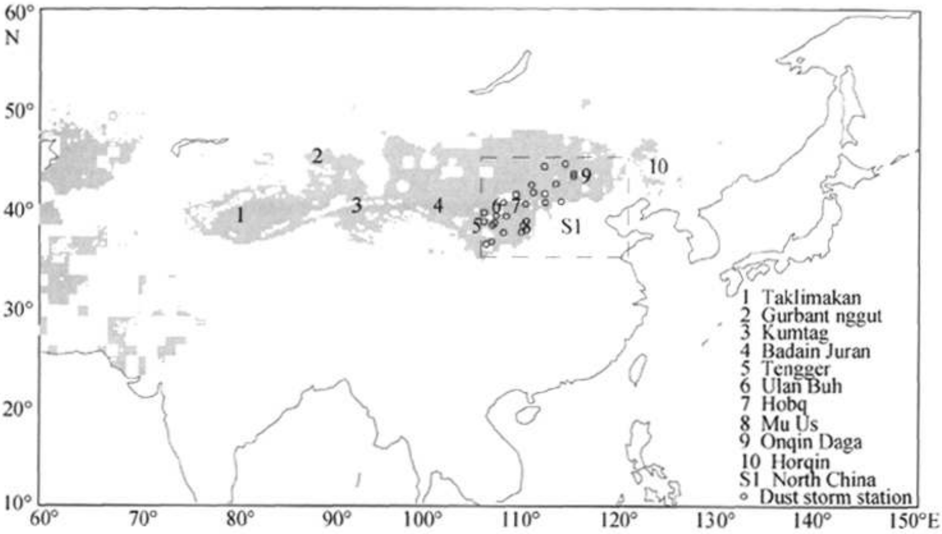

Figure 1 Research region and locations of dust storm stations used in the present study. The shaded area represents the potential dust source area in northeast Asia

with the deserts and Gobi desert in China (Wang *et al.*, 2001). Thus, it is interesting to study the variability of dust storm frequency (DSF) in North China and its causes.

The DSF in North China has evident multi-timescale variability (Zhou and Zhang, 2003). Previous studies suggested that the variations in DSF in northeast Asia were believed to be connected by changes in planetary-scale atmospheric circulations (Gong *et al.*, 2006b). Planetary-scale atmospheric circulations are often related to the passage of cold surge and cyclone that can directly influence the occurrence of dust storm weather. Arctic Oscillation (AO), which is a dominant mode of atmosphere circulation in the middle to high latitude of the Northern Hemisphere, has a significant influence on Asian climate (Gong *et al.*, 2001; Gong and Ho, 2003). When AO is in a positive (negative) phase, less (more) cold surges are observed over North China (Gong *et al.*, 2009). It is thus appropriate to assume that AO has the ability to influence the variability of DSF in North China by modulating the cold air activities in northeast Asia. For example, based on the observations Gong *et al.* (2006a) reported that AO was negatively correlated with the DSF and suggested a possible linkage between AO and DSF in North China.

While previous studies established statistical linkage between the AO and the DSF in North China, the physical process by which AO influences the DSF has not well understood and need to be clarified. A key physical mechanism as suggested by previous studies is that AO triggers the synoptic-scale disturbances in the lower troposphere, which results in the DSF variation in North China (Gong *et al.*, 2006a). This is because the synoptic-scale disturbances could reflect the weather activities that directly control the occurrence of dust storm. The synoptic-scale variance is often computed as the variance of high-frequency components in geopotential heights, meridional winds, and zonal winds. Note that the high-frequency fluctuation of meteorological variables is a statistical variable obtained from the high-pass filtered atmospheric circulation data and measures the day-to-day variance of the circulation during the spring. The synoptic-scale variance itself, however, does not identify which actual weather system (such as the front, anticyclone or cyclone) is associated with the DSF. As well-known, the most impressing atmospheric condition relating to dust storm in northeast Asia is characterized by cold air activity, which is mostly caused by Mongolian cyclonic depression and frontal systems sweeping across the deserts in Mongolia and China (Sun *et al.*, 2001). Hence, the analysis of the relationship between AO and cold air activity frequency (CAAF) could help elucidate how DSF is linked to AO. In addition, previous studies only used statistical technique to describe the connection between AO and DSF (e.g., Gong *et al.*, 2006a). Few studies have demonstrated the AO impact on DSF by using model simulation. In this study we will investigate the influence of AO on DSF in North China, by analyzing observation data and by employing numerical simulation using dust model. The season of analysis is confined to boreal spring (March, April, and May), a season when there is maximum occurrence of dust storms.

Because the linear correlations between two time series largely depend on the low-frequency variations, for example, the decadal changes and trends in AO and the dust storms may result in quite high values of correlation coefficients even though their long-term changes might be caused by different reasons. In such situation, the high correlation does not imply any physical linkage between them. While, the links between AO and DSF derived on interannual timescale would be more robust and convincing (Gong *et al.*, 2007). Therefore, to highlight the possible influence of AO on variables investigated (including DSF and CAAF) in the present study, we performed all analysis with focus on interannual timescale variations. We also simulated dust storms and checked the simulated climatology of the northeast Asian DSF and spatial distribution in the context of AO-DSF relationship.

The rest of this paper is structured as follows. Section 2 briefly describes data and method used. In Section 3, the relationship between DSF in North China and CAAF in northeast Asia is described. In Section 4, the variations in the DSF related to AO changes and the possible mechanism are outlined. Finally, the summary is given in Section 5.

2 Data and analysis method

2.1 Data

The data used in this study consist of National Centers for Environmental Prediction and National Center for Atmospheric Research (NCEP/NCAR) reanalysis data, observational dust storm records, and the simulated climatology of northeast Asian dust storms obtained by dust model. The analyzed variables of the NCEP/NCAR reanalysis data involve geopotential height and sea level pressure (SLP), which are available for the period 1961 through 2007 and with a spatial resolution of 2.5° × 2.5°. The time series of AO, the synoptic-scale disturbance, and the CAAF in spring are all computed using the NCEP/NCAR data sets. Here we followed the definition of Thompson and Wallace (1998) to construct the original springtime AO time series, i.e., the time coefficients of the first empirical orthogonal function (EOF) of the SLP field northward of 20°N is used as the AO index (Gong *et al.*, 2006a). To quantitatively measure the synoptic-scale disturbance, we used the method of Wallace *et al.* (1988) to define the high-frequency fluctuations in the geopotential height (HFFGH) as the index of synoptic-scale variance. The HFFGH was computed as the variance of highpass-filtered daily height in spring. The highpass-filtered heights were obtained using a highpass filter with a cut-frequency near 0.15 day^{-1}, thus only components of high-frequency shorter than about 6.7 days were maintained and used for analysis. Before filtering, the geopotential height was converted to an approximation of the geopotential stream function by a weighting factor (sin45°/sinφ, where φ is latitude). This small adjustment made the statistics based on geopotential height more directly comparable with those based on wind and vorticity. We defined the CAAF based on the degree of SLP fluctuation in consecutive days, namely the difference of SLP between consecutive days (ΔSLP). Accompanying a typical cold air event, the absolute value of ΔSLP at a specific station would change as large as 8–14 hPa within 24 hours (Gou, 2003). In the present study we identified all events where ΔSLP $\geqslant$ 10 hPa over the spring season at a given point of grid, then the sum of the event frequency was defined as the CAAF index.

The observational dust record was reported through the meteorological network of the China Meteorological Administration during 1961–2007. Because the observational DSF was equal to the sum of the daily dust record in spring for each station, the unit of DSF was days. In order to highlighting the variability of DSF and removing the influence of stations that had minor DSF and missing records, two conditions were set: (1) the selected station had a climatological dust storm frequency in spring exceeding 1 day during the analysis period, and (2) the selected station had fewer than 5 years when no dust storm occurred in the spring (Zhou *et al.*, 2006). On the basis of these conditions, 163 stations were identified in northern China and 24 stations were selected within North China (marked as circles in Figure 1). The time series of domain-averaged DSF in North China for observations were determined by averaging the DSF of the selected stations over North China.

2.2 Simulation data

In the present study we used a regional climate model, the Integrated Wind Erosion Modeling System (IWEMS), to obtain the climatology of dust in northeast Asia during the period from 1982 to 2006. The IWEMS can reasonably reproduce the dust process in northeast Asia, including dust emission, dust concentration, and other dust variables (Shao *et al.*, 2003). The initial and boundary conditions used for IWEMS were taken from the 6-hourly NCEP-NCAR reanalysis data. During the whole simulation period, the atmospheric boundary conditions were updated every 6 hours, while the vegetation was updated monthly. The outputs of IWEMS simulation had a horizontal resolution of 50 km × 50 km and 25 vertical levels from ground to 0.1 sigma level. On the basis of these simulations, Mao *et al.* (2011) analyzed the relationships of AO with dust emission, dust transport, and other dust variables in northeast Asia. Therefore, we believe that to analyze the simulation would provide useful information for better understanding AO-East Asian dust storm connections.

We retrieved the simulated DSF from the IWEMS simulations. Because the IWEMS could not produce horizontal visibility as used for dust weather classification in observations, we referenced the technical guidelines for sand and dust storm monitoring (GB/T, 2006, the Standardization Administration of China), and alternatively chose the surface dust concentration of 2 mg m^{-3} as the threshold value for a dust storm to occur. For a given grid point, when the simulated daily dust concentration near the surface exceeded 2 mg m^{-3}, a dust storm event was set to have occurred at this grid point. Accordingly, the simulated DSF was equal to the sum of dust storm events occurring in spring for each grid point, and its unit was also days. All the datasets used in the study were confined to the period of 1961 through 2007 because this period overlapped with the observational dust storm records, except the simulated DSF which was available during 1982–2006.

2.3 Analysis method

The statistical methods used include Pearson's correlation and composites. Because we wanted to examine the AO–dust relation on interannual timescale, the correlations were employed based on the interannual components for all variables. The time series of each variable was first filtered using the Butterworth filter with a cutoff frequency of 1/10 $year^{-1}$, and then only the interannual components were retained for 1961 through 2007. Because the data period of simulated DSF (available from 1982 to 2006) was somewhat short, we derived composite difference for both observational and simulated DSF. Here the DSF composites were computed according to the typical high and low AO years, designed for verifying the influence of AO on DSF. The typical AO years were determined based on the interannual components of AO time series for 1982 through 2006. We selected five maximum AO years and five minimum AO years for the period. The typical positive AO years identified are 1982, 1986, 1990, 1994, and 1997, and the typical negative AO years are 1987, 1988, 1991, 1993, and 2005. We then used hypothesis testing to judge the significance of the difference between positive and negative AO conditions. Because it was uncertain whether the source population of dust variables would have a normal distribution, we used the non-parametric testing (i.e., the Wilcoxon rank sum test) to test the mean values of two samples from the positive and the negative AO phases. Any measured test value that falls outside the range bounded by 4 and 21 was considered statistically significant beyond the 90% confidence level for a non-directional test (see Dowdy *et al.*, 2004). It should be noted that because of the limited samples taken in extreme years, the composite analysis should be regarded as a collection of case studies, even though there were meaningful statistical tests carried out for the composite difference.

3 Impact of cold air activity on dust storm frequency

In this section, the influence of CAAF on DSF in North China is investigated by applying correlation analysis, which is used as the reference for connecting variations in DSF in North China with AO changes, discussed in Section 4. We will check the linkage between DSF in North China and synoptic-scale disturbance, and then speculate on the relationship between DSF in North China and CAAF to provide an explanation for the linkage between synoptic-scale disturbance and DSF.

3.1 Change of dust storm frequency

Figure 2 shows the temporal variation of domain-averaged DSF in North China from observational records in the years 1961–2007. As shown in this figure, there were evident long-term changes, with a decreasing trend in the mid-1960s through the end of the 1990s and a slightly increasing trend thereafter. The long-term trend of DSF was 1.0d/10yr for the

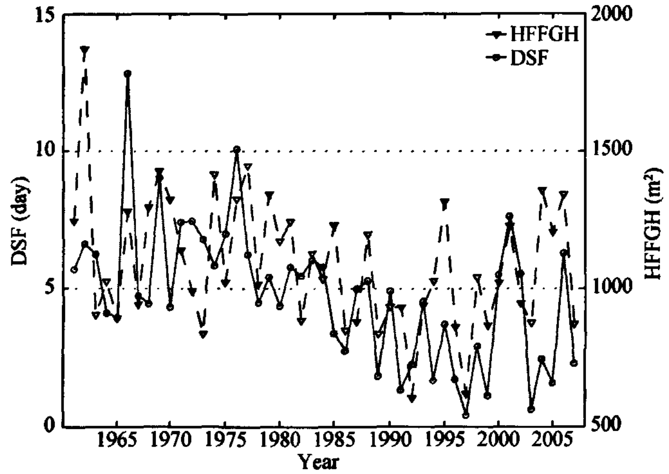

Figure 2 Time series of domain-averaged dust storm frequency in North China (solid line with circle), and high-frequency fluctuations in geopotential height (HFFGH) over Mongolia (90°E–105°E, 45°N–55°N) at 1000 hPa (dashed line with triangle). Unit: day for dust storm frequency, and m^2 for HFFGH.

years 1961 through 2007 (significant at 99% confidence level). The DSF occurrence had the maximum value in the mid-1960s with a value of 13 days per year, and in the late 1990s the DSF reached the lowest value of 2 days per year. In addition, the DSF has experienced remarkable interannual fluctuations as well as long-term changes. Of the total variance of DSF time series, the secular trend and interannual variation accounted for 42.4% and 58.6%, respectively. Thus, the variability of DSF on the interannual timescales might be more important and the analysis for interannual timescale could reveal the important physical mechanism for AO effect on dust storm.

3.2 Correlation between dust storm frequency and synoptic-scale disturbance

We then analyzed the relationship between the DSF in North China and the HFFGH at 1000 hPa in northeast Asia in spring. As seen in Figure 3a, there was a significant relationship between DSF and HFFGH; an increased (decreased) DSF in North China was associated with an intense (weak) HFFGH over Mongolia (significant at 95% confidence level). We also computed the correlation of DSF with the HFFGH at 500 hPa and 850 hPa (figure not shown), and found that there were positive correlation regions over Mongolia, where this type of anomalies was a nearly equivalent barotropic structure. In order to reduce the local noise, we constructed the time series of domain-averaged HFFGH over Mongolia (90°E–105°E, 45°N–55°N) at 1000 hPa as shown in Figure 2. The variations in the HFFGH over Mongolia at 1000 hPa were well consistent with the changes of DSF in North China. The correlation coefficient between them was 0.37, significant at 95% confidence level. In addition, the time series of domain-averaged HFFGH over Mongolia at 1000 hPa showed an evident decreasing trend in the years 1961 to 2007, which was –54 m^2/10a (significant at 95% confidence level). This suggested that the long-term weakening of HFFGH over Mongolia in the lower troposphere was an important reason for the long-term decreasing of DSF in North China. Summing up, the synoptic-scale disturbance over Mongolia can effectively indicate the viability of the DSF in North China. The significant regions in Figure 3a were

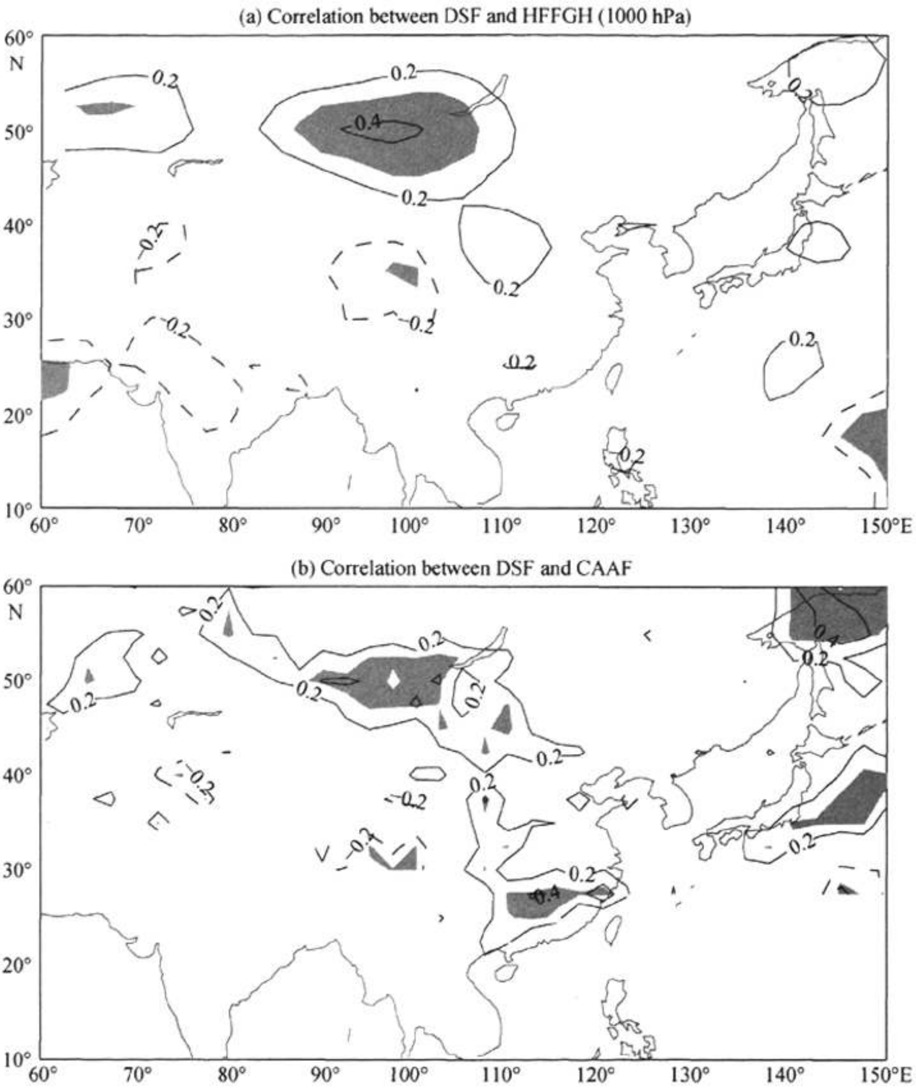

Figure 3 Correlation of domain-averaged dust storm frequency in North China with (a) high-frequency fluctuations in geopotential height at 1000 hPa and (b) cold air activity frequency. The correlations in excess 95% confidence level are shaded. Solid lines represent positive values and dashed lines represent negative values.

located in Mongolia, suggesting that most weather systems associated with dust storm in North China might be tracked back to Mongolia and its vicinities.

3.3 Correlation between dust storm frequency and cold air activity frequency

To get a better understanding of the relationship between the DSF in North China and the synoptic-scale disturbance over Mongolia, we further checked the correlation of DSF in North China with the CAAF in northeast Asia in spring (Figure 3b). As can be seen in this figure, there was a band of areas with positive correlations extending from Mongolia southward to southern China (where majority of grids were significant at the 95% confidence level). The domain-averaged CAAF over Mongolia (90°E–105°E, 45°N–55°N) was highly related to the DSF in North China with a correlation coefficient of 0.44 (significant at the 95% confidence level). We also employed a regression analysis for CAAF-DSF connection. It is found that when the CAAF over Mongolia increases (decreases) a standard value, the DSF in North China will increase (decrease) 1.13 day. All statistical relationship suggested that the cold air activity over Mongolia could exert important impacts on the formation of dust storm events in North China. In addition, the north–south distributed high correlations were fairly consistent with the prevailing track of winter-month cold surges (Figure 3b). Sun *et al.* (2001) indicated that the paths of the cold air outbreaks can be classified into two broad categories: the north path and northwest path. For the north path, the cold air masses are formed near Lake Baikal and move southward across central Mongolia and China. The cold air outbreaks along this route frequently cause dust storms in the southern Gobi Desert of Mongolia. For the northwest path, cold air outbreaks coming from the northwest result in dust storms that occur mainly in northwest China. The spatial distribution of positive correlations in Figure 3b was identical to the north route of cold air outbreaks, which move southward across central Mongolia and China. The above analysis suggested that most of the dust storm events in North China were associated with the north-path cold air activities.

4 Influence of AO on dust storm frequency and cold air activity

In this section, the possible mechanism by which AO influences DSF in North China will be investigated. We check the composite difference of DSF between the positive and negative AO years, here both the observation and the IWEMS simulations during 1982–2006 are analyzed. In order to reveal more physical details of AO-dust storm connection, we also analyze the associated changes in CAAF and synoptic-scale disturbance.

4.1 Influence of AO on dust storm frequency

Figure 4a shows the composite difference of observational DSF in spring between the negative and positive AO phases during 1982 to 2006. Generally, the DSF in North China tended to increase during negative AO phase conditions. This kind of change was also consistent with the results of statistical correlations (for example, Gong *et al.*, 2006a). The negative AO phases often were accompanied by a decreased DSF in both northwest China and central northern China (mainly the Taklimakan Desert, the Badain Jaran Desert, and the Tengger Desert). The composite difference of the simulated DSF shows similar results as for observations (Figure 4b). When AO was in a negative phase, there were positive anomalies of DSF in both southern Mongolia and North China. Simultaneously, there were negative anomalies of DSF in both northwest China and central northern China. We also computed the correlation between domain-averaged observational DSF and AO index during 1961–2007 and found that AO was negatively related with DSF in North China, with a correlation coefficient of –0.20 (significant at 85% confidence level). To test the dependence of AO-dust storm relation on the different timescale components, we tried to check their correlation using different cut-frequency filters. It is clear that the correlation between the AO and the DSF in North China was insignificant when the cutoff frequency of 1/10 year^{-1} was employed. However, the correlation between them was significant at 95% confidence level with a correlation coefficient of –0.35 when a cutoff frequency of 1/8 year^{-1} was used. This is

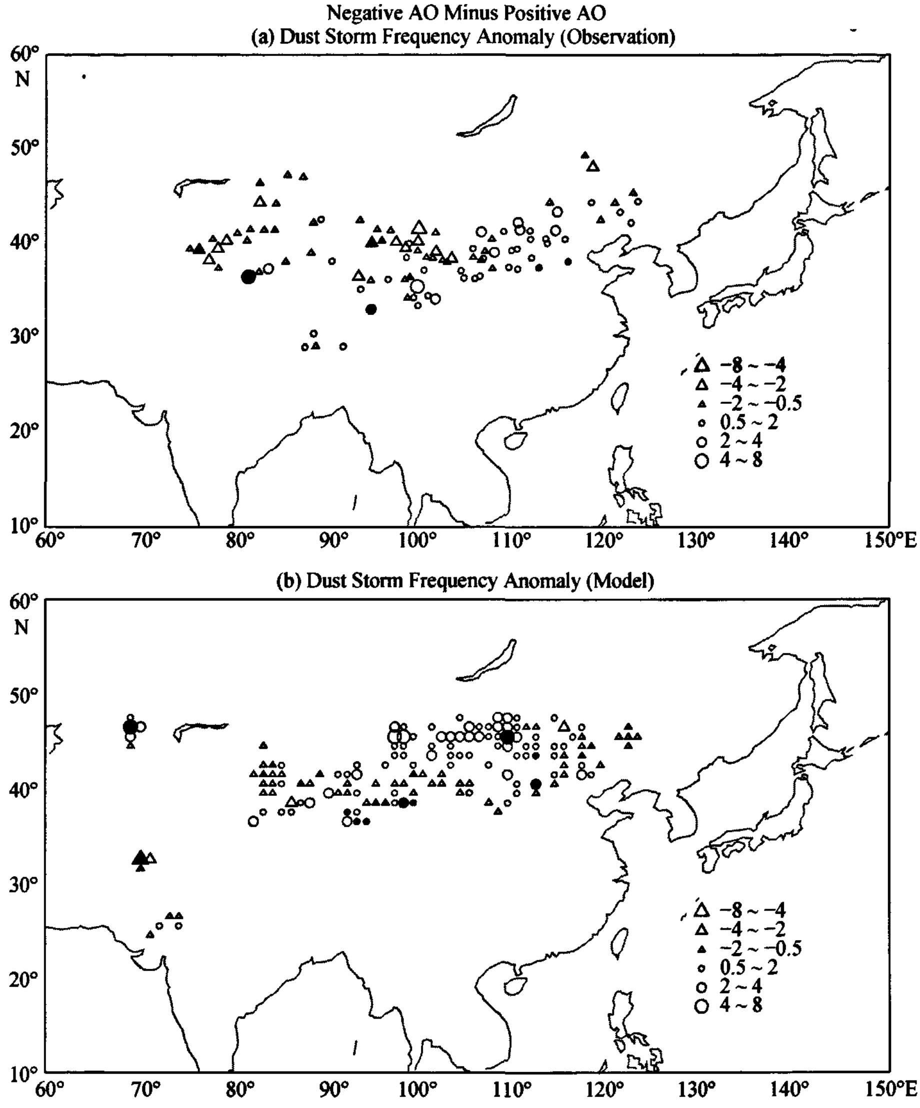

Figure 4 Composite difference of (a) observational dust storm frequency in China and (b) simulated dust storm frequency in spring over northeast Asia between the negative AO phase and the positive AO phase (value of the variable from the negative AO years minus that from the positive AO years). The difference in excess of the 90% confidence level is shaded. Triangles represent negative values and circles represent positive values. Unit: day for both (a) and (b).

because the AO time series has a significant period of quasi-8 years. Power spectrum analysis identifies that this ~8-year periodicity of AO is significant at the 95% confidence level. To sum up, AO was negatively correlated with DSF in North China on the interannual timescale. The dust storm frequency in southern Mongolia and North China tended to increase during negative AO springs.

4.2 Influence of AO on cold air activity frequency

Figure 5a shows the spatial distributions of correlation between AO and HFFGH at 1000 hPa in spring. As shown in this figure, AO was negatively related with HFFGH over Mongolia,

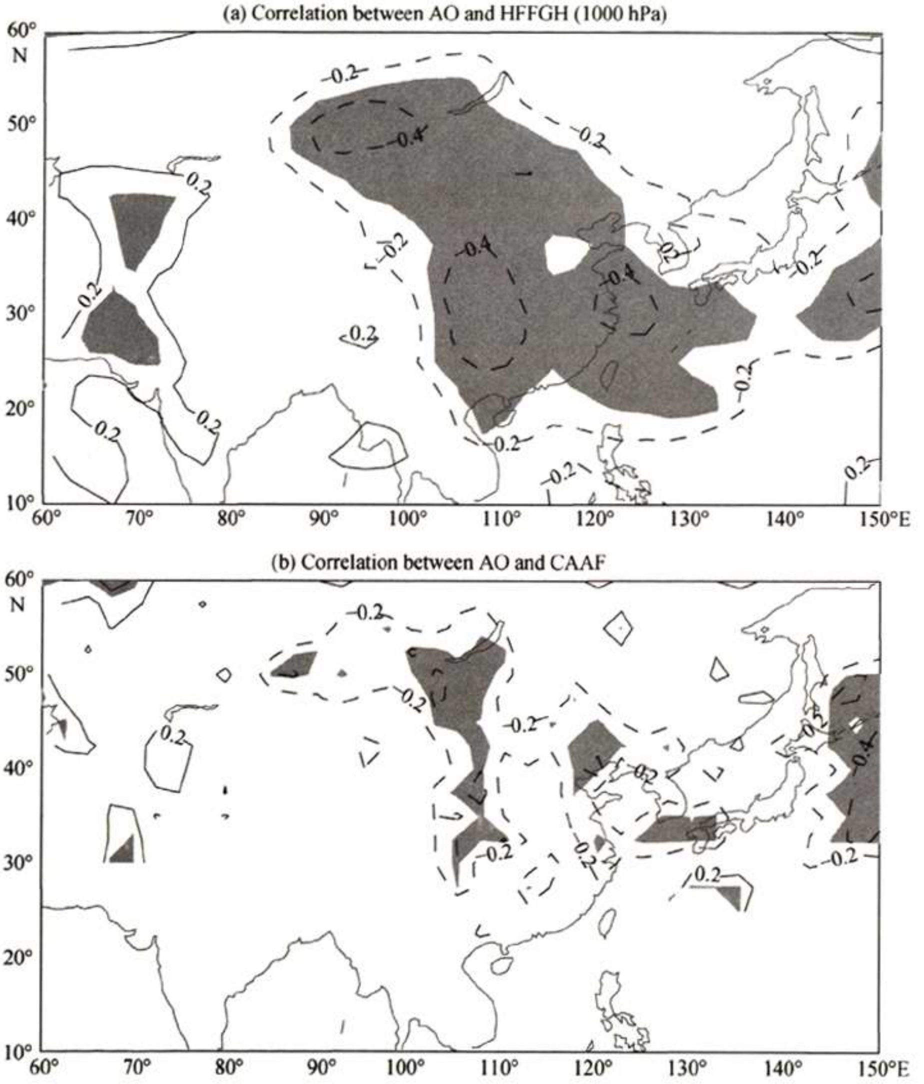

Figure 5 Correlation of AO with (a) high-frequency fluctuations in geopotential height at 1000 hPa and (b) cold air activity frequency. The correlations in excess 95% confidence level are shaded. Solid lines represent positive values and dashed lines represent negative values.

North China, and southern China (significant at the 95% confidence level). It suggested that a negative AO phase was connected with intense HFFGH from Mongolia through North China toward southern China. We also computed the correlation between AO and the HFFGH at 850 hPa level, and found that the negative correlation at the 850hPa level also appeared over Mongolia, North China, and southern China (significant at the 95% confidence level, figure not shown). The influence of AO on synoptic-scale disturbance is also supported by other evidence. The domain-averaged HFFGH over Mongolia (90°E–105°E, 45°N–55°N) and the AO were correlated at –0.42 (significant at the 95% confidence level). The significant correlation between AO and HFFGH in the lower troposphere demonstrated that negative AO can exert stronger influence on synoptic-scale disturbance, which in turn resulted in the increase of DSF in North China. In addition, the north–south oriented spatial distribution of negative correlations implied that the variability of synoptic-scale disturbance induced by AO was linked to the cold air activities which often move from Mongolia through Inner Mongolia to southern China.

To check the associated changes in cold air activities and their consistence with high frequency disturbance, we analyzed the correlation between AO and CAAF in spring. As shown in Figure 5b, there was a band of negative correlation covering Mongolia and North China. It implied that a negative AO phase in spring was connected with an increased CAAF over Mongolia and North China. This feature is consistent with the intense HFFGH over Mongolia and North China in Figure 5a. We also checked the correlation between the time series of domain-averaged CAAF over Mongolia (90°E–105°E, 45°N–55°N) and AO index. The correlation between them was –0.35, significant above the 95% confidence level. As above analysis displayed, the CAAF over Mongolia was positively correlated with the dust storm frequency in North China, thus during negative AO springs we would expect an increasing of the cold air activities over Mongolia and more dust storm events in North China.

5 Conclusions

In this study by analyzing the dust storm data from observations and simulations and the associated features in atmospheric circulation and synoptical disturbance, we have documented the relationships among DSF in North China, CAAF, synoptic-scale disturbance, and AO on interannual timescale in spring seasons during 1961–2007. Our major conclusions were summarized as follows:

(1) There were evident long-term changes in DSF in North China, with a decreasing trend in the mid-1960s through the end of the 1990s and a slightly increasing trend thereafter. The DSF has experienced remarkable interannual fluctuations as well as long-term changes. Of the total variance of DSF time series, secular trend and interannual variation accounted for 42.4% and 58.6%, respectively.

(2) The CAAF over Mongolia and North China can effectively influence the DSF in North China. On the interannual timescale, there was a significant linkage between DSF and CAAF; an increased (decreased) CAAF over Mongolia was associated with an intense (weak) synoptic-scale disturbance over Mongolia and an increased (decreased) DSF in North China. In addition, DSF in North China was tightly related to the north-path cold air activity that moved across from Mongolia southward to northern and southern China.

(3) AO had evident influence on CAAF, and thus had great potential impacts on DSF in North China. The negative (positive) AO phase was usually accompanied by an increased (decreased) CAAF over Mongolia and North China, and an intense (weak) synoptic-scale disturbance and more (less) dust storm events in Mongolia and North China.

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