INTERNATIONAL JOURNAL OF CLIMATOLOGY
Int. J. Climatol. **26**: 1379–1396 (2006)
Published online 29 March 2006 in Wiley InterScience (www.interscience.wiley.com). DOI: 10.1002/joc.1324

EAST ASIAN DUST STORM AND WEATHER DISTURBANCE: POSSIBLE LINKS TO THE ARCTIC OSCILLATION

DAO-YI GONG,[a]* RUI MAO[a] and YI-DA FAN[b]
[a] *Key Laboratory of Environmental Change and Natural Disaster, College of Resources Science and Technology, Beijing Normal University, Beijing 100875, China*
[b] *Division of Satellite Remote Sensing, Chinese Disaster Reduction Center, Beijing, 100053, China*

Received 12 April 2005
Revised 17 January 2006
Accepted 1 February 2006

ABSTRACT

In this work, the authors investigated the spring dust storm frequency variations in northern China and its relationship with weather disturbances, cold high, eddy kinetic energy (EKE), as well as the impact of the Arctic Oscillation (AO) on the dust storm frequency variations. It is found that there is a significantly decreasing trend of −26%/10 years in the dust storm frequency variations. In addition, the year-to-year variations are also remarkable, which account for 58.3% of the total variance of the dust storm frequency variations. The synoptic variance of 850 hPa height, EKE, and near-surface cold highs are highly correlated with the dust storm frequency variations. During the last 40 years or so, there have been significant trends in synoptic variance, cold-high frequency, and kinetic energy over northern China and Mongolia, which are −3.2, −4.0, and −5.0%/10 years, respectively. The trends are fairly consistent with long-term variations of dust storm frequency. The AO shows good correlation with the interannual variations of the dust storm frequency. This out-of-phase relation is supported by the significantly negative correlations between AO index and eddy growth rate between 850/700 hPa in midlatitude East Asia, implying that AO can modulate weather disturbances and dust storm activities through influencing the atmospheric instability. It is found, however, that the spring AO index shows no evident long-term trend. Land cover changes, global warming, and other climate teleconnections may, at least partly, be responsible for the secular decreasing of dust storm frequency over northern China. Copyright © 2006 Royal Meteorological Society.

KEY WORDS: dust storm; Arctic Oscillation; weather disturbance; East Asia

1. INTRODUCTION

The dust storm is studied as a global phenomenon taking place frequently in semiarid and arid areas over the globe (Goudie, 1983; Littmann, 1991; Goudie and Middleton, 1992, 2001). During the recent decades there have been rapidly increasing concerns about dust storm activity and its influence in East Asia as the population and economy grow remarkably (Wang *et al*., 2004). Although documented as a recurrent natural phenomenon in historical and geological records (Zhang, 1984; Zhang *et al*., 1997), the dust storm is now regarded as one of the severest disasters in northern China. To understand its variability and causes is of practical and scientific significance. A variety of factors is suggested to account for the dust storm changes, including large-scale atmospheric circulation variations, local to regional climate conditions, teleconnections, and so on. For example, Zhang *et al*. (1997), Qian *et al*. (2002), and Zhao *et al*. (2004) indicated that the changes in atmospheric circulation background are closely related to dust storm frequency in northern China. Some authors (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) found that the regional climate variables play important roles in influencing dust storm activities. Higher land-surface air temperature, less precipitation, and strong wind are favorable conditions

* Correspondence to: Dao-Yi Gong, College of Resources Science and Technology, Beijing Normal University, 100875, China; e-mail: gdy@bnu.edu.cn

for dust storm occurrence and intensity. Teleconnection factors such as El Niño/Southern Oscillation (ENSO) are supposed to play a role through influencing East Asian winter monsoon. It was found that frequent dust storms tend to take place when La Niña is at its peak (Mu and Li, 1999; Ye *et al*., 2000; Gao *et al*., 2003). Li *et al*. (2003) reported that sensible heat from the land surface in the Tibetan Plateau may exert an influence on middle-high troposphere circulation and, consequently, influence the dust storm weather with an out-of-phase relationship between them. In addition, the local land cover changes resulting from human activities is often blamed for the origin and enhancement of dust storms (Ye *et al*., 2000).

It is a well-known notion that the direct cause of dust storms is the weather disturbance (referred to as the high-frequency variations in the meteorological variables with typical synoptic timescale in this manuscript). Continental to planetary scale circulations in middle and/or high latitudes can exert great influence on weather conditions and, consequently, affect dust storm activities. For example, Zhao *et al*. (2004) indicated that the large-scale cold air activities, as represented by Asian polar intensity index and northern hemispheric polar vortex area index, are in good relationship with the storm frequency in North China. As a dominant mode in extratropic atmospheric circulation, Arctic Oscillation (AO) plays an essential role in influencing the background circulation and also in modulating the weather variability (e.g. Thompson and Wallace, 2001; Wettstein and Mearns, 2002; Gong and Drange, 2005). Gong and Ho (2004) and Gong *et al*. (2004a) found that the high frequency variance of temperature in East Asia is significantly connected to the AO in winter, daily temperature variance tending to be smaller during positive-AO years.

Given the importance of weather disturbances with regard to dust storms and the fact that AOs play a role in modulating synoptic activities, this study aims to address the relationship between the synoptic disturbances and dust storm activity in northern China, and their possible links to the AO. The season of analysis is confined to spring (March, April, and May), a season when there is maximum occurrence of dust storms. In Section 2 we describe the atmospheric circulation data, dust storm data, AO index, and method of rank correlation. In Section 3 we examine the relationship between dust storm frequency and synoptic disturbances. Their relations to the AO are investigated in Section 4. A discussion on the long-term trends is presented in Section 5. Finally, the paper is summarized in Section 6.

2. DATA AND METHOD

2.1. Dust storm and gale data

According to the China Meteorological Administration (CMA) regulation, a dust storm day is counted as one when there is a huge amount of dust and sand blowing from the ground and the horizontal visibility becomes falls below 1 km, as observed once or more within a period of 24 hours (20:00 through next 20:00, Beijing local time).

We confined our target region to northern China, where very frequent dust storms are observed. The western portion of this region is also known to be a key area for the maximum frequency of dust storms in China (CMA, 2002; Zhou, 2001). Within this region we selected 26 stations. Zhou and Zhang (2003) checked the dust storm data sets for the whole of northern China on the basis of daily synoptic charts and station observations. They did not count the number of dust storm days at each station and instead identified each single dust event. A single dust event may cover many stations and persist for a couple of days. We compared the number of dust storm events and number of dust storm days, and found that the variation is fairly consistent after the 1960s, but there are remarkable differences in the early periods. In the 1950s, the number of dust storm days are abnormally high compared to the number of dust storm events. To avoid the possibility for data discontinuity, our analysis is set to the period 1962–2002. The locations of these stations are shown in Figure 1. We used the mean number of dust storm days averaged from all 26 stations as the dust storm frequency (hereafter referred to as F_{Dust}).

Many authors indicated that most dust storms take place in spring in East Asia, although they can actually occur in any season (cf Zhou, 2001). In northern China too, spring dust storms have the highest occurrence. The mean frequency as estimated from the 26 stations for the period 1962–2002 is 4.6 days, accounting for more than 60% of the annual number of about 7.6 days (Figure 2).

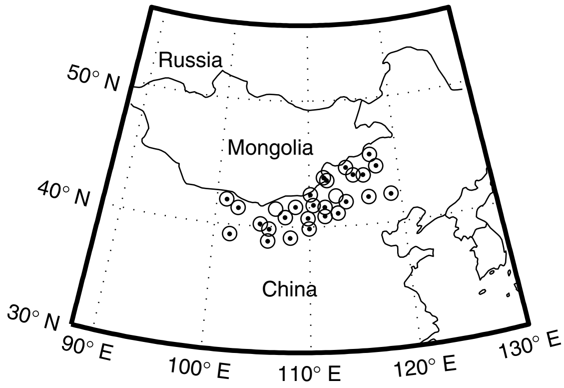

Figure 1. Target region and locations of stations used in the present study. "•": dust storm stations; "◯": gale data stations

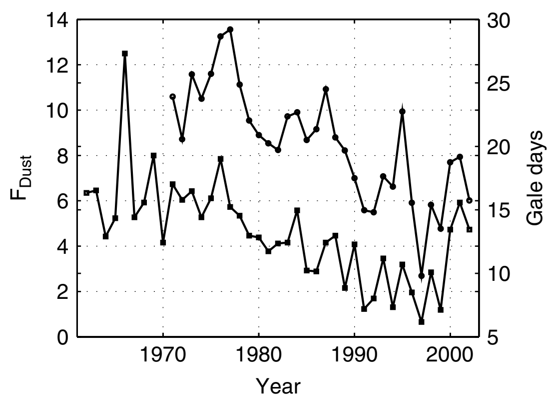

Figure 2. Time series of the number of dust storm days averaged from 26 stations for the period 1962–2002(lower curve), and mean number of gale days from 28 stations for the period 1971–2002 (upper curve)

The number of gale days are available for 28 stations within the study region. Gale days are defined as those with a wind speed in excess of 17.2 ms^{-1} (i.e. wind force scale ≥ 8). The target region is one of the centers that has the maximum number of gale days in China (see CMA, 2002, p211). Gale data of all 28 stations are available for the period 1971–2002.

2.2. Atmospheric circulation variables

In the present study the atmospheric circulation variables we used are obtained from the European Centre for Medium-Range Weather Forecast's (ECMWF) 40-year reanalysis (ERA40, http://data.ecmwf.int/data/d/era40_daily). The ERA40 data sets are available for the period 1957–2002, with a spatial resolution of $2.5^{\circ} \times 2.5^{\circ}$. The original data were recorded six-hourly. In order to save for data downloading and processing time, we used only those data taken at 0000 UTC (local time being 8:00 AM). In fact we tested data for 0600 UTC and found very similar results. Using the data from a different observational time did not change our conclusion. Since we are interested in the lower troposphere weather disturbances associated with the dust storm activities and AO, we focused our analysis on the lower troposphere in the Northern Hemisphere. The circulation variables include geopotential heights (Φ), and wind velocities at 925, 850 and 700 hPa levels. In order to get the transient components we applied a high-pass filter, which retains the high frequency shorter than 7 days, to the daily time-series at each grid for all these variables. Monthly mean is obtained by averaging the daily values for the respective month.

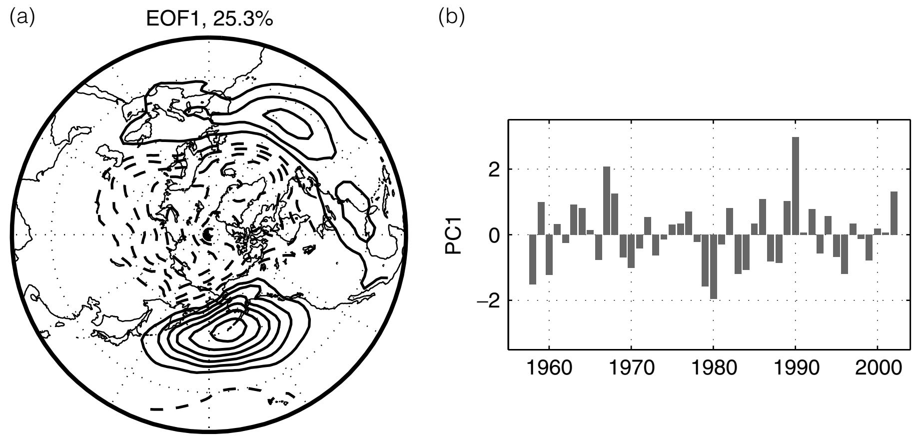

Figure 3. EOF1 of covariance of March–May SLP anomalies (a), and the corresponding time coefficients (b). ECMWF reanalysis data, 1958–2002. Units are arbitrary

There are observed seasonalities in AO, its structure and significance vary with the seasons (e.g. Rogers and McHugh, 2002; Ogi *et al*., 2004). Since we are concerned with the simultaneous-linkage between AO and dust storm frequency in spring, it seems more reasonable to employ the AO index derived from the sea level pressure (SLP) of March–May or the geopotential height field. Following Thompson and Wallace (1998), we defined the AO as the first empirical orthogonal function (EOF) of March–May ERA40 SLP anomalies within the domain that is poleward of 20 °N. Here the EOF is performed on the covariance matrix. SLP anomalies are multiplied by the square root of the cosine of the latitude in order to account for the area factor. This mode accounts for 25.3% of the total variance. The corresponding time coefficients are taken as the AO index (Figure 3).

2.3. Rank correlation

In the present study, we used the Spearman rank correlation to investigate the relations among the variables. Given two variables, their rank correlation (r_s) is defined as

$$r_s = 1 - \frac{6\Sigma_{i=1}^{n} D_i^2}{n(n^2 - 1)} \quad (1)$$

where D_i is the difference in ranks between the ith pair of data values and n is the length of the time series. Equation (1) is a derived form of rank correlation. Number 6 appears because these deal with the summation of successive numbers (ranks). The rank correlation is a more robust and resistant method than the ordinary Pearson correlation coefficient (Wilks, 1995). This kind of correlation is particularly suitable when there are outliers or a nonlinear relationship.

3. DUST STORM AND WEATHER DISTURBANCE

3.1. Changes of dust storm frequency

The mean time-series of F_{Dust} is shown in Figure 2. The mean for the whole period is 4.6 days. Clearly, there are strong year-to-year fluctuations with a large standard deviation of 2.2 days (48.3% of the mean). Another overwhelming feature is the rapidly decreasing trend. The linear trend estimated for the whole period by using the least-squares method is −26.0%/10 years, which is statistically significant at the 99% confidence level. Thus, the East Asian dust storm activity has experienced remarkable interannual fluctuations as well as a long-term decreasing trend. Of the total variance of F_{Dust} time series, secular trend and interannual variations account for 41.8% and 58.3%, respectively, which is consistent with the previous studies. For example, Gao *et al*. (2003) reported a similar change in the dust storm frequency over Inner Mongolia. Analysis for northern China and the whole of China showed similar decreasing trends in the number of dust storm days (Zhou, 2001; Qian *et al*., 2002). The evident increase in 2000–2002 as shown in Figure 2 is also found in many other stations over midlatitude East Asia (Gao *et al*., 2003; Kurosaki and Mikami, 2003). An increase in the recent couple of years will not change the long-term trend. The decreasing trend is dominant over the last several decades.

It should be mentioned that most of these analysis are based on the number of dust storm days. The changes in the F_{Dust} may be related to the occurrence of dust storm events and their life times. Interestingly, Zhou and Zhang (2003) analyzed the changes in single dust storm events in northern China (approximately north of 35 °N) since the 1950s. Their results showed similar and consistent temporal features. Correlation between F_{Dust} and the number of dust events is 0.4 for the period 1962–2002. Particularly, the year-to-year variations are almost identical, and the correlation between the interannual components is 0.6. In addition, the number of typical dust storm events in spring displays a moderate trend of −7.9%/10 years since the 1950s, significant at the 90% level. The life time of the events has a slight but discernable tendency of shortening. Therefore, decrease in the F_{Dust} is most likely due to the decrease in the number of dust storm events and the shortening of event life time. These changes are not local phenomena but common features over the whole of northern China.

3.2. *Weather disturbance*

Northern China is known to be a typical arid to semiarid region; in such a dry environment the weather activity is the direct cause of the dust storm. To get a better understanding of the association of F_{Dust} with weather disturbances, we computed the synoptic variance of atmospheric circulation. The geopotential heights(Φ), meridional winds (v), and zonal winds (u) are often used in the analysis of transient eddies in atmospheric circulations. The amplitude of their transient components can be represented in the forms of $\overline{\Phi'^2}^{1/2}$, $\overline{u'^2}^{1/2}$, and $\overline{v'^2}^{1/2}$ (cf Nakamura and Wallace, 1990; James, 1994, and many other authors), where the prime indicates the anomalies resulting from high-pass filtering or from removal of stationary components, and the bar indicates the time mean over one period. These quantities are often used as indices of synoptic variance. In middle latitudes the typical timescale of synoptic activity is about 7 days; therefore, in order to get Φ', u', and v' we applied a high-pass filter to remove the components longer than 7 days. Then the synoptic-scale variance is calculated locally for each spring (March 1 through May 31). Here we focused on $\overline{\Phi'^2}^{1/2}$ of 850 hPa.

Figure 4 shows the simultaneous Spearman rank correlations between F_{Dust} and high variance of 850 hPa heights in spring. Generally, there is an in-phase relationship between height variance and F_{Dust} in East Asia. Greater variance is linked to an increasing number of dust storm days. Apparently, the correlation center slightly shifts westward to the target region, suggesting the importance of the nonlocal weather systems. Significant regions are located in Mongolia and parts of northern China, suggesting that most weather systems associated with dust storms are seen in neighboring Mongolia and its vicinities. As a center of correlation the region of 40–50 °N and 95–110 °E is a key area for monitoring and understanding weather disturbances (c.f. Figure 4). To check the details we chose this relatively small center to make the regional mean time-series of high variance. A smaller region may provide a more sensitive signature that would be helpful for the detection of relationships. In fact a broader domain would not evidently change the results. The F_{Dust} is highly correlated with the synoptic variance of the key region. Rank correlation between them is +0.43, significant at the 99% level. The ordinary Pearson's correlation is even higher and is at +0.47. We also repeated the computation using 925 and 1000 hPa heights and found that the main features remain almost the same as for 850 hPa. The slight difference is that the significant regions cover a broader area in the lower levels (925 and 1000 hPa, figures not shown).

3.3. *Strong cold highs*

Correlations in Figure 4 show interesting spatial features. In particular, contour lines display discernable orientations. One is in the north–south direction spanning Russia and Mongolia in the north to southeast

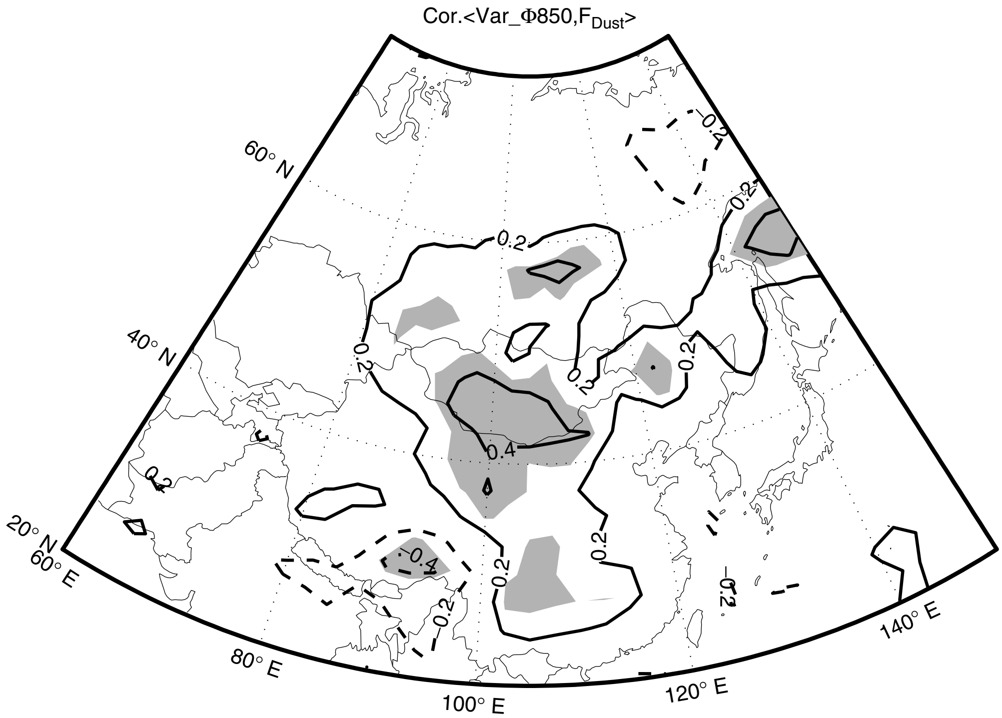

Figure 4. Spearman rank correlation coefficients between geopotential height variance of 850 hPa level and the number of dust storm days. Contour interval is 0.2. Zero contours are omitted for simplicity. Values in excess of the 95% confidence level are shaded

China, and the other is in the west–east direction along about 45–50 °N over northern China and Mongolia. Apparently, the west–east distributed correlations would be related to the prevailing cyclonic activities since most cyclones sweep from west to east along midlatitude East Asia (Zhang and Lin, 1992). Quan *et al*. (2001) and Qian *et al*. (2002) found that the activity of cyclones tends to be in phase with the dust storm frequency. The temperate cyclones account for a large portion of the variance in dust storm frequency, and the decreasing frequency of cyclones should play an essential role in the decreasing occurrence of dust storms in northern China (Qian *et al*., 2002; Wang and Li, 2003).

High pressures and the associated cold surges are important components of the East Asian winter monsoon. In this manuscript, the cold high denotes the strong surface high pressures in the daily SLP field. It should be indicated that in some circumstances the dust storms might result from the cold highs near the surface (Zhang and Chen, 1999). A rapidly moving cold high can cause considerable pressure and temperature fluctuations within a short time period when the cold air mass passes by (Ding, 1990). As a result of the passage of a typical cold high, the SLP would rise by 8–14 hPa within 24 h. This can bring strong gales and easily blow dust from the land surface into dry air in circumstances such as those found in the arid and semiarid Gobi and the deserts of East Asia. Clearly, cyclones alone cannot account for all of the dust storm conditions. To get a better understanding of dust storm related weather disturbances, we should also take into account the cold highs. Interestingly, the north–south distributed high correlations in Figure 4 are fairly consistent with the prevailing track of winter-month cold surges. Compared to the climatological tracks of the cold surge, there are very similar spatial features. The high correlation center of high variance is almost identical to the location of maximum occurrence of cold highs in East Asia in the cold seasons (Zhang and Chen, 1999; CMA, 2002, p156).

We investigated the relation between the frequency of cold highs and dust storm activities. In order to quantify the rapidly moving cold highs, we defined a cold-high frequency index (F_{High}) as the number of days with Δ SLP $\geq$ 9 hPa between two consecutive days (i.e. a day when the SLP is 9 hPa or higher than the

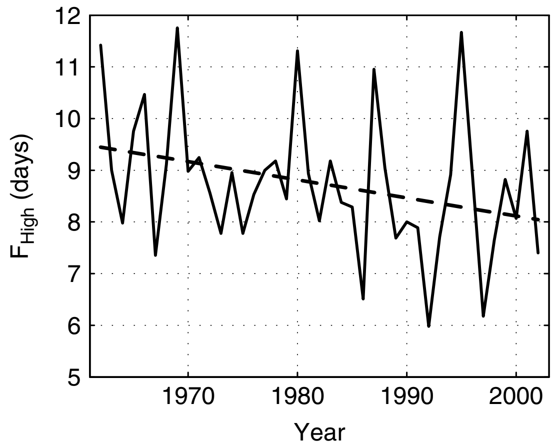

Figure 5. Frequency of cold highs averaged over the region of 37.5–45 °N and 100–120 °E. Dashed line gives the linear trend (−4.0%/10 year, significant at 95%)

previous day). Here 9 hPa is chosen because this is approximately the 90th percentile of Δ SLP in northern China. Therefore, the F_{High} is a measure of the extremely strong cold highs.

We computed the correlation between the high variance of 850 hPa heights and F_{High}. The correlation distribution shows well defined features. High positive correlations appear in northern China and Mongolia, and extend to southern China (figure not shown). This pattern is very similar to Figure 4. Figure 5 shows the time series of the mean frequency of cold highs in northern China and vicinities (37.5–45 °N, 100–120 °E). For comparison, its linear trend is also shown. Here the domain is about 3–5 degrees south of the first target region analyzed in the previous sections and is chosen with the purpose of monitoring the cold highs that pass the dust storm station area. Its temporal variation is highly correlated with F_{Dust} at a value of $r_s = +0.43$(almost identical to the ordinary Pearson's correlation of +0.44, both significant at the 99% level). The F_{High} also displays a significant (at the 95% level) linear trend of −4.0%/10 years, which is comparable to the synoptic variance trend of −3.2%/10 years (see Table 2). This implies that, in addition to the cyclones, the surface cold highs are also important factors that exert notable influence on dust storm frequency.

3.4. Eddy kinetic energy

It is the wind that blows dust into air. Stronger wind means greater kinetic energy. Greater kinetic energy provides more power for blowing and carrying dust. Not surprisingly, the F_{Dust} is correlated with the number of gale days at a rather high value of $r_s = +0.76$ (ordinary Pearson correlation is even higher at $r = +0.79$) for the period 1971–2002 (see Table 1 and Figure 2). Kurosaki and Mikami (2003) emphasized that frequent strong winds are the primary cause for the rise of dust events in East Asia in the period 2000–2002. Strong winds may be related to the monthly or seasonal mean wind speed (e.g. in case the prevailing wind gets stronger), and may also be related to the weather activities. The former is associated with large-scale atmospheric circulation background, while the latter is related to local or regional weather fluctuations. It is important to note that in the lower troposphere the eddy kinetic energy (EKE) accounts for more than half the total kinetic energy. In midlatitude East Asia, the average portion that EKE accounts for is about 51% and 53% at 850 and 925 hPa pressure levels, respectively.

We calculated the EKE in terms of $\overline{(u'^2 + v'^2)}/2$. The correlations between F_{Dust} and EKE at the lower troposphere are displayed in Figure 6. The high correlation region spans northern China from west to east. The relations are also evident in parts of Russia and central China. This kind of pattern is generally consistent with the changes in synoptic variance in the lower troposphere geopotential heights. Mean EKE at the 850 hPa level averaged in the areas from 37.5–45 °N and 100–120 °E is highly correlated with F_{Dust}. The Spearman

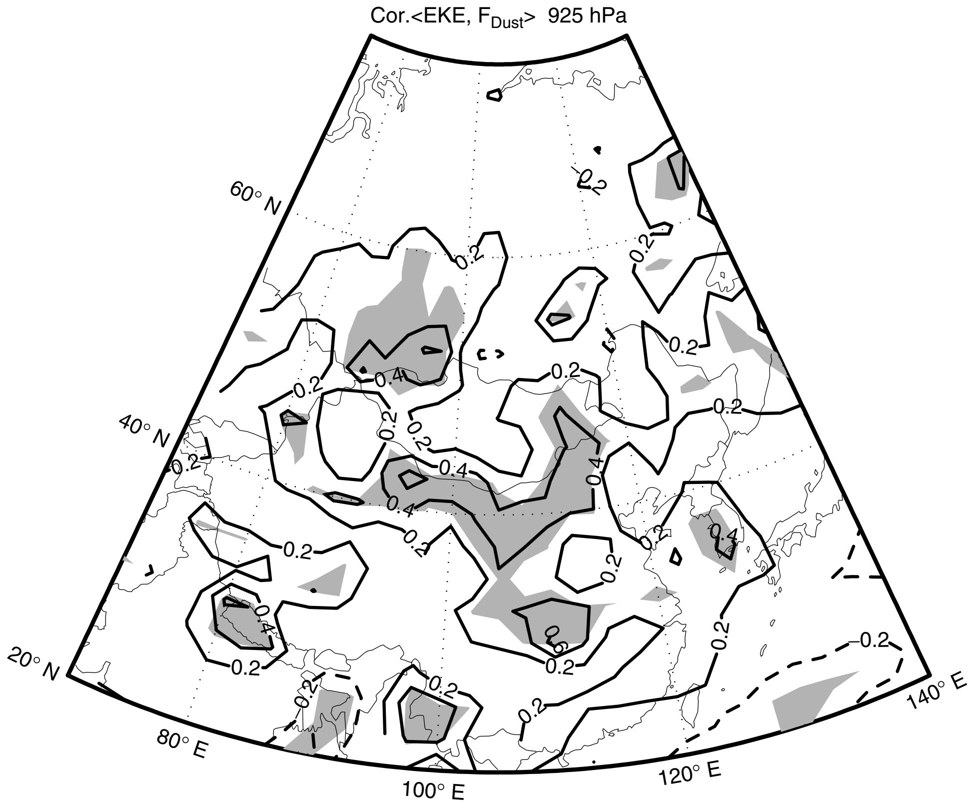

Figure 6. Spearman rank correlation coefficients between F_{Dust} and eddy kinetic energy at 925 hPa level. Contour interval is 0.2. Zero contours are omitted for simplicity. Values in excess of the 95% confidence level are shaded

Table I. Correlation matrix including F_{Dust}, gale days, eddy kinetic energy (EKE) and regional mean height variance of the 850 hPa surface (40–50 °N, 95–110 °E). Correlation coefficients are calculated for spring (March–May) over the period 1962–2002

	F_{Dust}	$\overline{\Phi'^2}^{1/2}$	EKE	Gale days[c]
F_{Dust}	/	0.43[a]	0.46[a]	0.76[a]
$\overline{\Phi'^2}^{1/2}$	0.43[a]	/	0.41[a]	0.60[a]
EKE	0.46[a]	0.41[a]	/	0.32[b]
Gale days[c]	0.76[a]	0.60[a]	0.32[b]	/
Trend(%/10 year)	−26.0[a]	−3.2[a]	−5.0[a]	−17.5[a]

[a] : significant at the 95% level,
[b] : at 90%,
[c] : 1971–2002

correlation is $r_s = +0.42$, which is almost identical to Pearson's r of $+0.40$. We compared the levels of 925 and 850 hPa and found that the local EKE in 925 hPa shows more evidence of relation with the dust storm frequency, while at the 850 hPa the high correlation regions shift a little to the west of the target region. However, the main features are very similar. These results strongly support the theory that, in association with weather disturbances, the transient components of winds in the lower troposphere play very important roles in influencing dust storm activities.

4. RELATIONS TO AO

4.1. Correlations with AO index

Previous studies have found that AO strongly influences the East Asian winter monsoon and climate on seasonal to decadal time scales (Wu and Huang, 1999; Gong *et al*., 2001; Wu and Wang, 2002), and also has an influence on the daily variance in circulation and temperature in winter (Gong and Ho, 2004; Gong *et al*., 2004a; Gong and Drange, 2005; Jeong and Ho, 2005). A large portion of the trends of high variance in winter temperatures and SLP can be accounted for by the simultaneous AO index. For spring, however, the condition may be different since the spring AO index shows no evident trend.

In this section we address the association of AO with dust storm and weather disturbances in the boreal spring. In order to get an idea of whether the East Asian weather disturbances are related to the AO, we checked their correlations. Figure 7 displays the simultaneous correlation between AO index and high-pass filtered height variance at 850 hPa level in spring over the Northern Hemisphere. Clearly, the AO-related changes in high variance at 850 hPa height shows a well-defined pattern over the Northern Hemisphere, and the anomaly signals are of large-scale, implying that the signals do not take place randomly and are unlikely to be noise. The spatial features are similar to those described in the previous studies. Even the out-of-phase changes in the northern Pacific and northern Atlantic regions are similar to the results from the National Centers for Environmental Prediction/National Center for Atmospheric Research reanalysis data set (e.g. Chang and Fu, 2002).

Noteworthily, in East Asia (including our study region) there is a vast area that displays significant changes in association with AO variations. During the high-AO springs the synoptic variance tends to be weaker, while in the low-AO years it becomes stronger. The influence of AO on weather variance is also supported by other evidence. Besides the 850 hPa height variance, we also computed the correlations between AO index

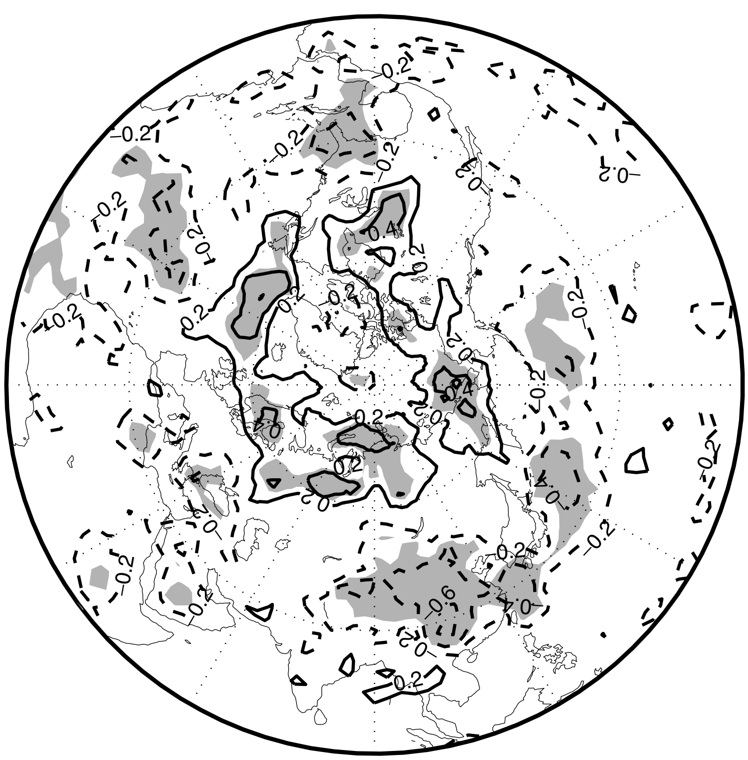

Figure 7. Correlation coefficients (r_s) between geopotential height variance of 850 hPa level and AO index. Contour interval is 0.2. Zero contours are omitted for simplicity. Values in excess of the 95% confidence level are shaded

Table II. Correlation of the AO index with the atmospheric variables, as calculated for the area 37.5–45 °N, 100–120 °E, over the period 1962–2002. All correlations are significant at 95%

	850 hPa $\overline{\Phi'^2}^{1/2}$	925 hPa EKE	F_{High}
Spearman's r_s	−0.59	−0.33	−0.46
Pearson's r	−0.52	−0.31	−0.46

and EKE and the frequency of cold highs, and got fairly consistent results (figures not shown). The regional mean time-series of these indices that were averaged over the study region were also compared with the AO index. As shown in Table 2 all of them show significant correlations to the AO index, suggesting that the AO can influence or modulate East Asian weather variability. Consequently, it could easily be inferred that during high-AO years there would be smaller F_{Dust} in northern China, and vice versa.

Gong *et al*. (2004c) investigated the connections of dust emission in northern China and neighboring regions (a total of ten sub-regions) to a variety of climate indices based on the simulated dust emission during the past several decades. They found that there is almost negligible correlation between AO and dust emission in three sub-regions that are covered by our research region or are close to it. The correlations are −0.044, 0.138, and 0.035 for the regions of S6, S7, and S8, respectively. No notable relations are found for the other seven regions too. The lack of AO-dust storm links in numerical simulations might arise from the low capability of climate models in simulating the high-frequency components of regional phenomena. We computed the correlation between the AO index and F_{Dust} using the nonfiltered data. These correlations are also small. Spearman rank correlation r_s is −0.03, and the ordinary correlation r is −0.08, neither of which is significant. These obviously disagree with the results of the close connection between AO and weather disturbances. This discrepancy is most likely due to the predominant long-term variations of dust storm frequency. As seen from Figure 3, the spring AO index shows no evident trend. Instead, the year-to-year fluctuations are dominant. The timescale concerning its occurrence is of importance with respect to the AO-dust storm connection. After the removal of long-term changes, we compared the year-to-year variations of dust storm frequency with the AO index (Figure 8). Clearly, the notable connection between AO index and interannual variations of F_{Dust} shows up. Two time series are significantly correlated at a value of $r_s = -0.304$. Although spring AO experiences no long-term changes, it exerts a remarkable influence on interannual variations of weather disturbances and, consequently, impacts the dust storm activities.

4.2. *Eddy growth rate*

Weather disturbances are closely related to the atmospheric instability. As the leading mode in the extratropic northern hemispheric circulation, the monthly mean AO index provides us with an understanding of the

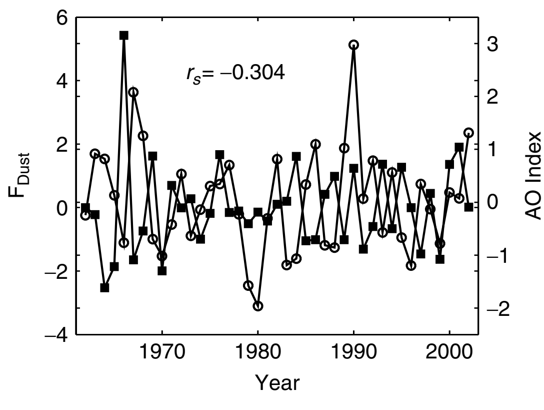

Figure 8. Time series of interannual components of F_{Dust}(square), compared with AO index(open circle)

background of westerly air-flow (Wallace, 2000; Li and Wang, 2003). Its association with the transient components has been addressed by many theoretical analyses and modeling studies (e.g. Yu and Hartmann, 1993; Limpasuvan and Hartmann, 2000; Wittman *et al.*, 2004, and many other authors). Local eddies may be related to the local baroclinicity and wave activities (Chang and Orlanski, 1993). To get an idea of the dynamic links with AO, we simply considered the local baroclinicity. Here, we computed the eddy growth rate (σ) as defined by the following equation.

$$\sigma = 0.31\frac{f}{N}\frac{\partial|V|}{\partial z} \qquad (2)$$

where f is the Coriolis parameter, N is the Brunt-Väisälä frequency and $\frac{\partial|V|}{\partial z}$ is the vertical shear. In principle, N may vary with height. Here we suppose that N is a constant for simplicity. We computed these parameters between 850 and 700 hPa pressure levels.

Figure 9 shows the changes in eddy baroclinic growth rates in association with the AO index. The strongest negative relations span the area from Yangtze River to southern Japan, and this belt is apparently the location of the East Asian jet stream. Ambaum *et al.* (2001) and Chen *et al.* (2003) indicated that the AO-related jet stream in East Asia tends to weaken in high-AO phases in winter, which is consistent with our results from the lower troposphere for spring. Interestingly, a significant region appears in northern China and southern Mongolia. This implies that during the high-AO springs there is a smaller eddy growth rate in the target region and its vicinities, resulting in weaker eddy activities. Consequently, it would give rise to less dust storms. For comparison, we also computed the correlation between eddy growth rate and the interannual components of F_{Dust} (see Figure 10). In association with greater dust storm frequency, there is a larger eddy growth rate in northern China and vast areas of Mongolia. The spatial patterns in Figures 9 and 10 are fairly consistent. In order to suppress the local noise, we also checked the regional mean time-series of σ over the high

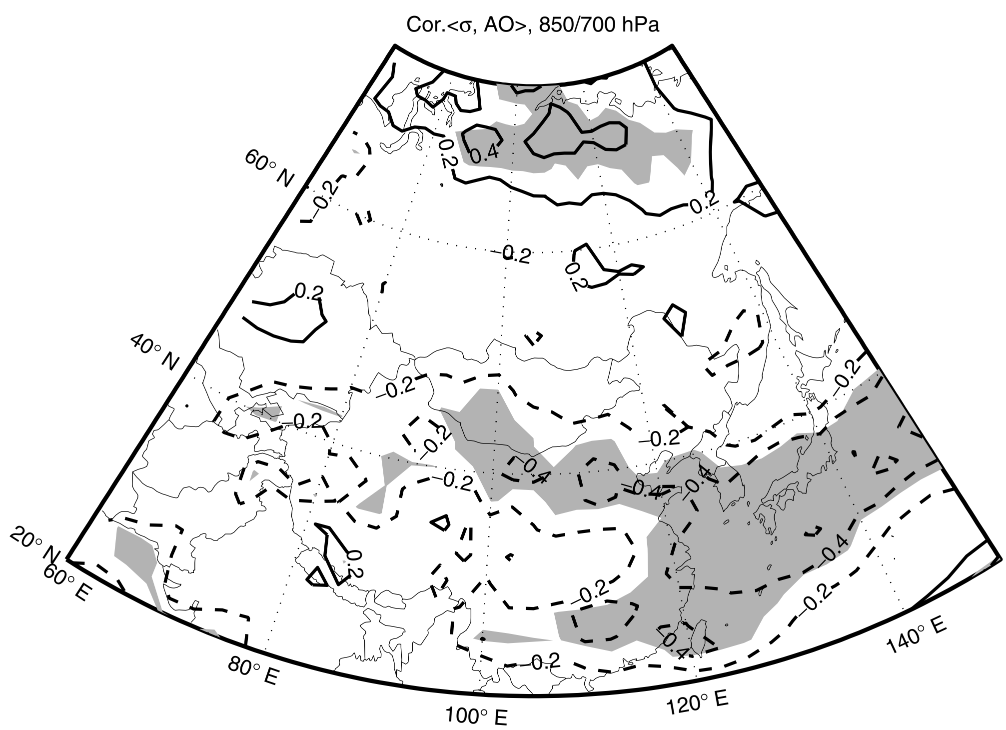

Figure 9. Spearman rank correlation coefficients between AO index and eddy growth rate (σ). Values in excess of the 95% confidence level are shaded

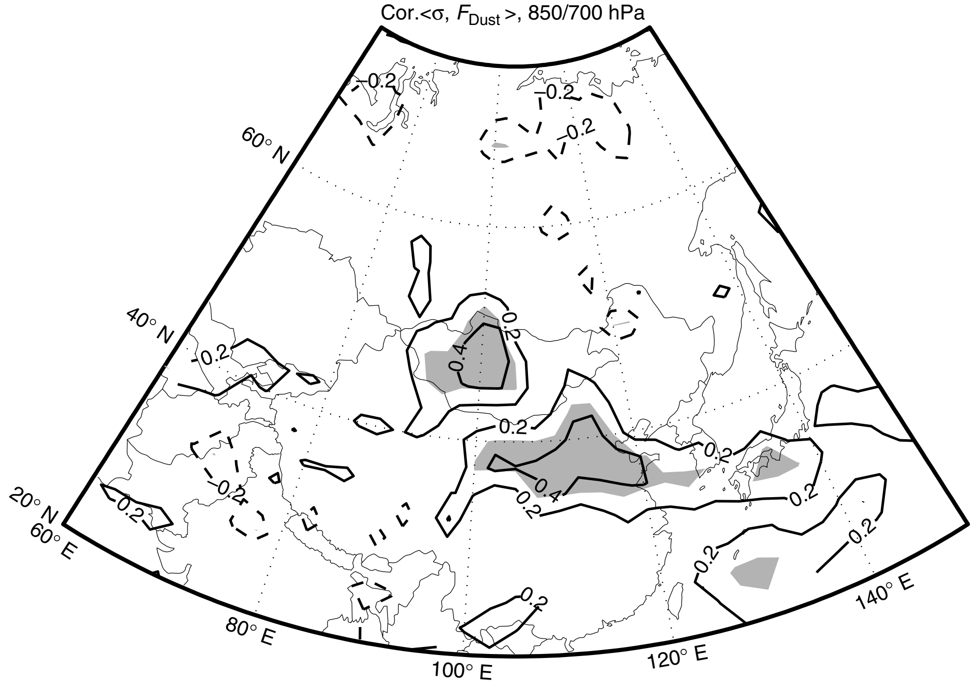

Figure 10. Spearman correlation between eddy growth rate (σ) and interannual components of F_{Dust}. Contour interval is 0.2. Zero contours are omitted for simplicity. Values in excess of the 95% confidence level are shaded

correlation center of 35–45 °N and 100–120 °E. Mean σ correlates with the AO index at −0.47. Meanwhile, the correlation between σ and F_{Dust} is +0.44, both significant at the 99% level. Therefore, we concluded that the AO can modulate weather disturbances and dust storm activities by influencing local baroclinicity. Their connection is substantial on the interannual timescale.

5. SECULAR TRENDS

The above analysis shows that there is a significant secular trend in F_{Dust}. Consistent long-term changes can also be found in weather disturbances, including synoptic variance, EKE, and cold-high frequency. For example, the strong decreasing tendency in synoptic variance and EKE at 850 hPa are observed in northern China and Mongolia (see Figures 11 and 12). Averaged over the target region, their linear trends are −3.2% and −5.0%/10 years, respectively (see also Table 1). The trend of −4.0%/10 years for the frequency of cold highs is also significant. These values are quite consistent and comparable in magnitude. Evidently, the most direct and important cause of dust storm is the weather disturbance, which plays an essential role in the dust storm trend.

The increasing trend of winter AO during the last few decades is remarkable, and explains a considerable portion of the concurrent decrease in day-to-day variance of lower troposphere circulation and temperature over East Asia (Gong and Ho, 2004; Gong *et al*., 2004a). However, in spring the situation changes greatly. The ERA40 AO index clearly lacks any significant trend (Figure 3). For confirmation, we also checked the AO index derived from the National Centers for Environmental Prediction/National Center for Atmospheric Research reanalysis data set (Kalnay *et al*., 1996), and found that it too shows no clear trend. Therefore, the lack of a secular trend in the spring AO index is likely to be true. We computed the trends of eddy growth rate between 850 and 700 hPa pressure levels, and found that there is also no consistent and significant trend in northern China and Mongolia. Thus, spring AO and local eddy growth rate cannot explain the observed

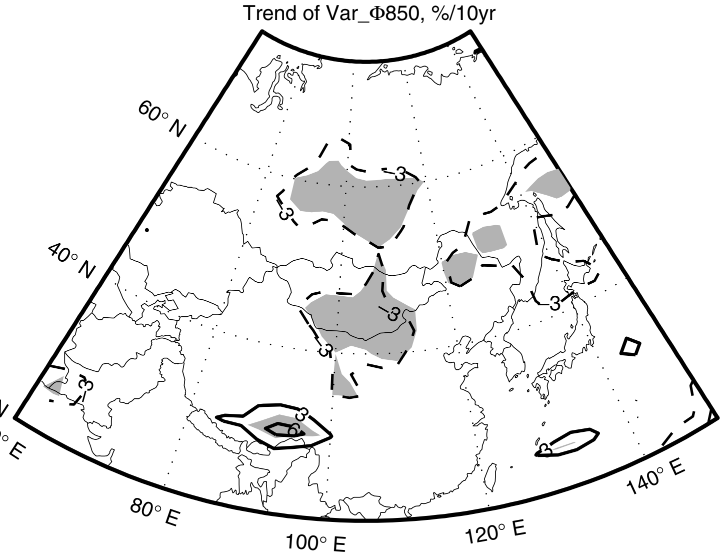

Figure 11. Trend of geopotential height variance, $\overline{\Phi'^2}^{1/2}$, 850 hPa level. Contour interval is 3%/10 year. Zero contours are omitted for simplicity. Values in excess of the 95% confidence level are shaded

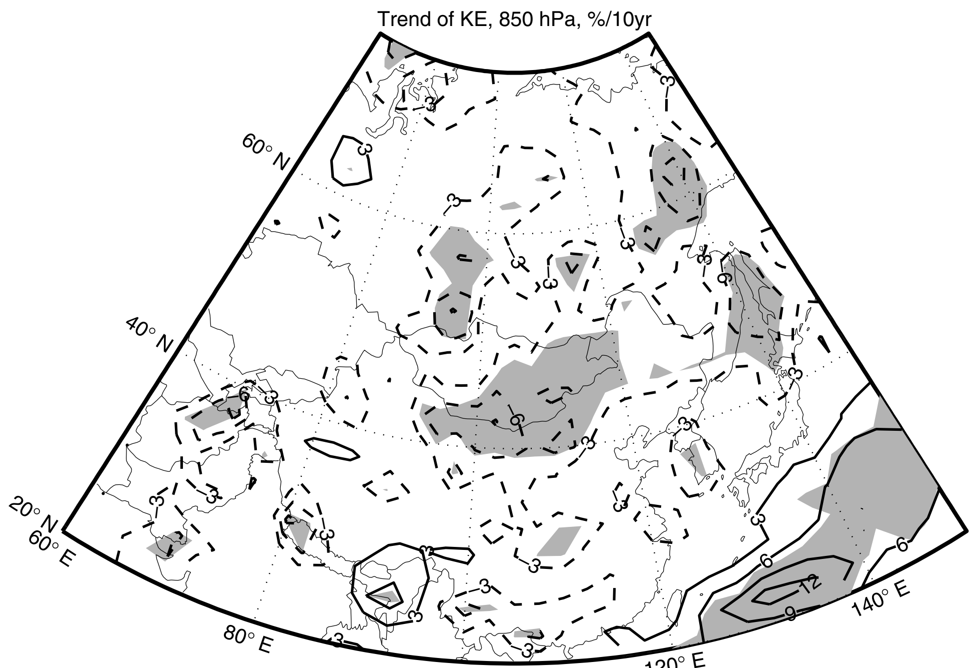

Figure 12. Trend of high-frequency kinetic energy at 850 hPa, shown as percent per 10 years. Zero contours are omitted for simplicity. Areas above the 95% confidence level are shaded

secular changes in the synoptic variance of the lower troposphere and the decreasing trend in dust storm days, though they have good correlation on the interannual timescale.

It should be pointed out that the weather disturbances directly change the wind and kinetic energy, not the dust itself. Only when there is plenty of dust blowing into the airstream can it become a dust storm. Obviously, the atmospheric dynamic condition provides only the possibility for a dust storm. Although climatic factors play important roles in dust emission (Tegen *et al*., 2004; Zhang *et al*., 2003), the contributions by other factors (such as land use, soil moisture, precipitation, desertification, and so on) may also be important (Liu *et al*., 2004; Zhang *et al*., 2003; Gong *et al*., 2004b). Land surface vegetation can influence the dust flux into the air. Observations show that different vegetation conditions have different potential for releasing dust (Gu *et al*., 2002; Liu *et al*., 2003). Vegetation can also change the land surface kinetic energy. In a well vegetated area the possibility of dust storms would be much lower than in poorly vegetated areas. Satellite observations show that vegetation coverage and vegetation health index such as the normalized difference vegetation index (NDVI) in the target region and its vicinities have been increasing during the last two decades or so, indicating a tendency toward greener conditions and better vegetation coverage in spring (Fan, 2003; Zou and Zhai, 2004). Using a new global NDVI data (Tucker *et al*., 2005) we checked the trend of NDVI (averaged from area 38–45 °N, 100–120 °E). As shown in Figure 13, spring NDVI in the target region is increasing at a rate of 3.758%/ 10 years, significant at the 99% level. This is in good agreement with the long-term changes in dust storm activities. Therefore, land cover changes are responsible (at least partly) for the secular decreasing of dust storm frequency over northern China during the last 20 years or so. This supports well the previous findings. The long-term trend and its relation to F_{Dust} in the last 40 years, however, are not clear since no reliable land cover and land management records are available prior to the 1980s.

In Figure 13 we plot the regional mean temperature and precipitation time-series averaged from the 26 stations. The spring temperature is rising at a rate of 0.371 °C/ 10 years, significant at the 99% level (see Tables 3 and 4). It correlates with F_{Dust} at −0.32. However, after the trends are excluded, the correlation drops to −0.17. On the interannual timescale, correlation between F_{Dust} and precipitation is −0.26, about the 90% significance level, while the unfiltered time-series are correlated at only −0.11. This is mainly due to the lack of significant secular trends in precipitation. Generally, the relationship between F_{Dust} and local climate (temperature and precipitation) is moderate and consistent with the previous studies. However, they can only explain a small part of the secular variations of F_{Dust}. Most of the weather systems (such as the cyclones

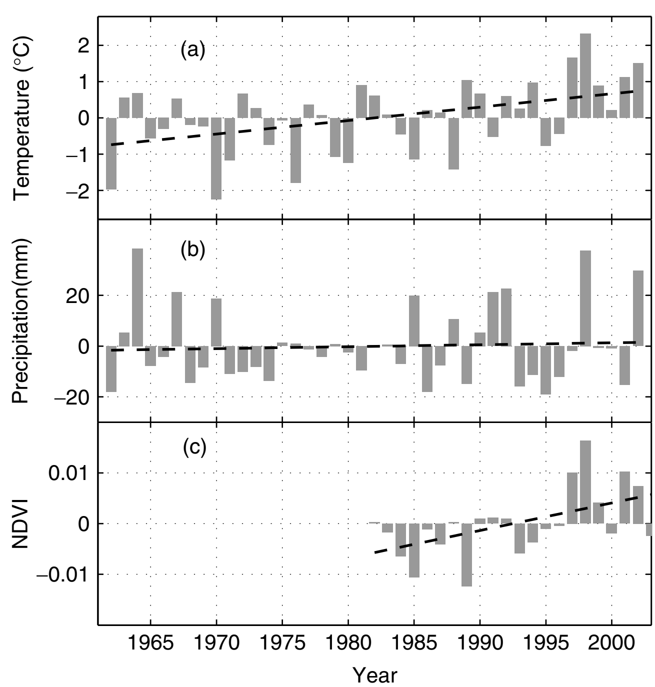

Figure 13. Time series of (a) temperature, (b) precipitation, and (c) NDVI. All are shown as anomalies with respect to the whole time-series. Temperature and precipitation are the means from 26 stations. NDVI is averaged over all the pixels within a rectangular area of (38–45 °N, 100–120 °E). Dashed lines are linear trends. For the statistics of their trends see Table 3

and anticyclones) originate in remote areas west/north to the target region. The local temperature and rainfall anomalies probably exert a slight influence on the activity of the large-scale weather system. The long-term trend in local temperature might also be due to the hemispheric climate change. Some studies indicate that the global warming signal is very clear in the observed seasonal (spring, winter, and autumn) climate variations in East Asia (for example, Hu *et al*., 2000, 2003), and the role of global warming on the secular trend of the dust storm cannot be ruled out. The significant trend in the mean temperature from 26 stations and its consistency with the F_{Dust} trend might imply a global warming signal. Global warming seems to exert an influence on F_{Dust} through atmospheric circulation rather than through changing the local temperature in the target region.

It is interesting to note that the trends in the changes in dust storm occurrence are particularly apparent around 1976/77 and 1999/00, resembling the temporal features in some large-scale climate signals such as the Pacific Decadal Oscillation (PDO). Here we also checked the possible roles of five identified teleconnection climate signals, including PDO, Nino 3.4 sea-surface temperature (SST), Eurasian teleconnection pattern (EU), northern circumpolar vortex, and Asian circumpolar vortex. The PDO index here is kindly provided by Mantua *et al*. (1997). Nino 3.4 SST time-series is taken from Climate Prediction Center (via www.cpc.ncep.noaa.gov/data/indices). The northern hemisphere circumpolar vortex area index is computed as the area encompassed by a specific contour line, which is defined by the strongest meridional height gradient at the 500 hPa level (Burnett, 1993). The Asian polar vortex is defined in the same form as the northern hemisphere circumpolar vortex but confined to the Asian sector (60–150 °E). Both vortex indices are derived from ERA-40 data. The EU index is as the definition of Wallace and Gutzler (1981) but re-computed using ERA-40 500 hPa heights. Their secular trends and correlations with F_{Dust} are listed in Tables 3 and 4. The two circumpolar vortex area indices are important on the interannual variations, their correlation with F_{Dust} are 0.29 and 0.28 for northern hemisphere circumpolar vortex and Asian polar vortex, respectively. ENSO signals are moderate, with a correlation of 0.25, but not significant. Influence of EU and PDO on the year-to-year variations of F_{Dust} are almost negligible (r_s is 0.03 and 0.09, respectively). However, when the long-term variations are considered, the correlations of PDO, Nino 3.4 SST and EU all become negative, contrary to that for the interannual timescale. Among the five climate teleconnections, only PDO shows a significant trend. This leads to a significant correlation with F_{Dust} ($r_s = -0.45$). A careful comparison shows that the PDO trend change in 1988/89 is remarkable, but there is no comparable change in F_{Dust}. The contribution of PDO to the secular trend of F_{Dust} needs careful analysis. Interestingly, both Nino 3.4 SST and PDO show moderate

Table III. Trends of several climate indices. Data periods are 1962–2002, except for NDVI, which is 1982–2002. Units: Per Decade

	Temperature	Rainfall	NDVI	PDO	Nino 3.4 SST	EU	N. H. vortex area index	Asian vortex area index
Trends	0.37 °C[a]	0.76 mm	3.76%[a]	0.35[a]	0.07 °C	0.02	0.09%	0.18%

[a] : significant at the 95% level.

Table IV. Spearman correlation of the dust storm frequency with the climate indices. Data periods are 1962–2002, except for NDVI which is 1982–2002

	Temperature	Rainfall	NDVI	PDO	Nino 3.4 SST	EU	N. H. vortex area index	Asian vortex area index
r_s with F_{Dust}, raw data	−0.33[a]	−0.11	−0.15	−0.45[a]	−0.13	−0.07	0.03	0.04
r_s with F_{Dust}, filtered data	−0.17	−0.26[b]	0.01	0.09	0.25	0.03	0.29[b]	0.28[b]

[a] : significant at the 95% level,
[b] : at 90%.

connections to AO index. Previous studies have found that there is a significant association between tropical Pacific SST and the AO (Quadrelli and Wallace, 2002). This implies that they could impact the dust storm frequency through influencing the AO, particularly on the interannual timescales. The long-term impacts of PDO and ENSO on dust storm through other mechanisms rather than through AO are not ruled out by this article.

To summarize, influence of the AO on dust storms are of interannual timescale. The observed long-term trends in the frequency of dust storm days should be related to a variety of factors ranging from regional vegetation conditions to climate teleconnections. However, the extent to which the secular trend of dust storms is connected to these factors and the mechanism connecting them are beyond the scope of the present article.

6. CONCLUSION

In northern China the spring dust storm frequency shows strong year-to-year variations as well as predominant long-term trends. During the period of 1962–2002 there is a significant rate of change of −26%/10 years. Some previous studies have also reported this significant decrease. However, our investigation of dust storm variations on the basis of synoptic activities is a new approach, and the discovery of their close connections to cold highs and AO is also new.

Our analysis shows that weather disturbances play essential roles in influencing the interannual fluctuations as well as the low frequency tendency of dust storm activities. The synoptic variance of 850 hPa heights in northern China and its vicinities is closely linked to dust storm frequency. Regional mean high variance from the target region correlates with the dust storm at a high correlation of $r_s = +0.43$, which is significant at the 99% level. Previous studies emphasized the importance of cyclones as the origin of dust storms. However, our analysis revealed that the rapidly moving cold highs near the surface also play significant roles. Mean frequency of cold highs significantly correlates with dust storms at a value of $r_s = +0.43$, which would result in remarkable changes in the EKE. The strong decreasing trends in synoptic variance, frequency of cold highs, and EKE at 850 hPa level are observed in northern China and Mongolia with change rates of −3.2, −4.0, and −5.0%/10 year, respectively, which is in good agreement with long-term variations of the dust storm frequency.

AO shows consistent relationship with different components of the East Asian winter monsoon circulations on a monthly seasonal mean timescale (Gong *et al.*, 2001; Wu and Wang, 2002) as well as on synoptic timescales. In positive-AO years, both the East Asian trough at 500 hPa and the Siberian High get weaker. Prevailing zonal circulation in the middle to upper troposphere would steer the weather disturbances more easily to move in the east–west direction, while a weaker East Asian winter monsoon in the lower troposphere gives rise to weaker and/or less frequent southward outbreak of the cold highs. At the same time, the local baroclinic instability in the middle latitudes of East Asia decreases. Previous studies (e.g. Ambaum *et al.*, 2001) have found that, in association with high AO conditions, the upper troposphere subtropical jet stream in the Pacific sector (including mid-high latitude East Asia) becomes weaker. Consequently, a weaker vertical wind shear provides an unfavorable dynamic situation for synoptic activities, as supported by the significant out-of-phase relation between AO index and eddy growth rate of 850/700 hPa in the midlatitude East Asia. All these are unfavorable for dust storm activities. Contrarily, the circumstances in negative-AO phases would enhance dust storm activities. The AO shows a good correlation with the interannual variations of the dust storm frequency at a value of −0.304.

However, for the low-frequency variations the spring AO index shows no evident long-term trend, nor does the AO-related eddy growth rate. Land cover changes may (at least partly) be responsible for the secular decrease in the dust storm frequency over northern China. However, whether and how the synoptic activities are related to the land cover changes, and whether there are other responsible factors (such as global warming and climate teleconnections), are still questions that need to be clarified. As a preliminary research, we present the observed connections using statistical analysis. More details and the mechanisms involving AO-dust storm connections can be obtained by employing skillful numerical models.

ACKNOWLEDGEMENTS

This study was supported by projects 2006CB400505, Huo Ying Dong Education Foundation-81014, and EYTP-1964. The ECWMF reanalysis data used in this study were obtained from the ECMWF server at http://data.ecmwf.int. The authors thank all anonymous reviewers for helpful comments and suggestions.

REFERENCES

Ambaum MHP, Hoskins BJ, Stephenson DB. 2001. Arctic oscillation or north atlantic oscillation? *Journal of Climate* **14**: 3495–3507.

Burnett AW. 1993. Size variations and long-wave circulation within the January northern hemisphere circumpolar vortex: 1946-89. *Journal of Climate* **6**: 1914–1920.

Chang EKM, Orlanski I. 1993. On the dynamics of a storm track. *Journal of the Atmospheric Sciences* **50**: 999–1015.

Chang KM, Fu YF. 2002. Interdecadal variations in northern hemisphere winter storm track intensity. *Journal of Climate* **15**: 642–658.

Chen W, Takahashi M, Graf HF. 2003. Interannual variations of stationary planetary wave activity in the northern winter troposphere and stratosphere and their relations to NAM and SST. *Journal of Geophysical Research* **108**(D24): 4797, DOI:10.1029/2003JD003834.

CMA. 2002. *Climatological Atlas of the People's Republic of China*. China Meteorological Press: Beijing; 250.

Ding YH. 1990. Buildup, air-mass transformation and propagation of Siberian high and its relations to cold surge in east asia. *Meteorology and Atmospheric Physics* **44**: 281–292.

Ding RQ, Li JP, Wang SG, Ren FM. 2005. Decadal change of the spring dust storm in northwest China and the associated atmospheric circulation. *Geophysical Research Letters* **32**: L02808, DOI:10.1029/2004GL021561.

Fan YD. 2003. Research on the remote sensing monitoring system of dust storm and its forming mechanism: case study on dust storms in north China, PhD thesis, Beijing Normal University, Beijing, (In Chinese).

Gao T, Su LJ, Ma QX, Li HY, Li X-C, Yu X. 2003. Climatic analysis on increasing dust storm frequency in the spring of 2000 and 2001 in inner Mongolia. *International Journal of Climatology* **23**: 1743–1755.

Gong DY, Ho CH. 2004. Intra-seasonal variability of wintertime temperature over East Asia. *International Journal of Climatology* **24**(2): 131–144.

Gong DY, Drange H. 2005. A preliminary study on the relationship between arctic oscillation and daily SLP variance in the northern hemisphere during wintertime. *Advances in Atmospheric Sciences* **22**(3): 313–327.

Gong DY, Wang SW, Zhu JH. 2001. East Asian winter monsoon and arctic oscillation. *Geophysical Research Letters* **28**: 2073–2076.

Gong DY, Wang SW, Zhu JH. 2004a. Arctic Oscillation influence on daily temperature variance in winter over China. *Chinese Science Bulletin* **49**(6): 637–642.

Gong SL, Zhang XY, Zhao TL, Barrie LA. 2004b. Sensitivity of Asian dust storm to natural and anthropogenic factors. *Geophysical Research Letters* **31**: L07210, DOI:10.1029/2004GL019502.

Gong SL, Zhang XY, Zhao TL, Zhang XB, McKendry IG, Zhao CS. 2004c. Climatology of Asian dust aerosol and its trans-pacific transport: interannual variability and climate connections. In WMO Sand and Dust Symposium, Beijing, 12–14 September, 2004.

Goudie AS. 1983. Dust storms in space and time. *Progress in Physical Geography* **7**: 502–530.

Goudie AS, Middleton NJ. 1992. The changing frequency of dust storms through time. *Climatic Change* **20**: 197–225.

Goudie AS, Middleton NJ. 2001. Sahara dust storms: nature and consequences. *Earth-Science Reviews* **56**: 179–204.

Gu W, Cai XP, Xie F, Li ZJ, Wu XH. 2002. Relationship between vegetation cover and distribution of days of sand storm: taking central and western inner Mongolia for example. *Advances in Earth Sciences* **17**(2): 273–277, (In Chinese).

Hu ZZ, Bengtsson L, Arpe K. 2000. Impact of global warming on the Asian winter monsoon in a coupled GCM. *Journal of Geophysical Research* **105**(D4): 4607–4624.

Hu ZZ, Yang S, Wu RG. 2003. Long-term climate variations in China and global warming signals. *Journal of Geophysical Research* **108**(D19): 4614, 10.1029/2003JD003651.

James IN. 1994. *Introduction to Circulating Atmospheres*. Cambridge Press: Cambridge, MA; 422.

Jeong JH, Ho CH. 2005. Changes in occurrence of cold surges over East Asia in association with arctic oscillation. *Geophysical Research Letters* **32**: L14704, DOI:10.1029/2005GL023024.

Kalnay E, Kanamitsu M, Kistler R, Collins W, Deaven D, Gandin L, Iredell M, Saha S, White G, Woollen J, Zhu Y, Chelliah M, Ebisuzaki W, Higgins W, Janowiak J, Mo KC, Ropelewski C, Wang J, Leetmaa A, Reynolds R, Jenne R, Joseph D. 1996. The NCEP/NCAR 40-year Reanalysis. *Bulletin of the American Meteorological Society* **77**: 437–431.

Kurosaki Y, Mikami M. 2003. Recent frequent dust events and their relation to surface wind in East Asia. *Geophysical Research Letters* **30**(14): 1736, DOI:10.1029/2003GL017261.

Li JP, Wang JXL. 2003. A modified zonal index and its physical sense. *Geophysical Research Letters* **30**(12): 1632, DOI:10.1029/2003GL017441.

Li DL, Zhong HL, Wei L, Lü LZ. 2003. Climatic characteristics of annual sand-dust storm days in northern China and its response to surface sensible heat in spring Qinghai-Xizang plateau. *Plateau Meteorology* **22**(4): 337–345, (In Chinese).

Limpasuvan V, Hartmann DL. 2000. Wave-maintained annular modes of climate variability. *Journal of Climate* **13**: 4414–4429.

Littmann T. 1991. Dust storm frequency in Asia: climatic control and variability. *International Journal of Climatology* **11**: 393–412.

Liu HY, Tian YH, Ding D. 2003. Contributions of different land cover types in Otindag sandy land and Bashang area of Hebei province to the material source of sand stormy weather in Beijing. *Chinese Science Bulletin* **48**(17): 1853–1856.

Liu XD, Yin ZY, Zhang XY, Yang XC. 2004. Analyses of the spring dust storm frequency of northern China in relation to antecedent and concurrent wind, precipitation, vegetation, and soil moisture conditions. *Journal of Geophysical Research* **109**(D16): D16210, DOI:10.1029/2004JD004615.

Mantua NJ, Hare SR, Zhang Y, Wallace JM, Francis RC. 1997. A Pacific interdecadal climate oscillation with impacts on salmon production. *Bulletin of the American Meteorological Society* **78**: 1069–1079.

Mu MQ, Li CY. 1999. ENSO signals in east Asian winter monsoon: observation analysis. *Chinese Journal of Atmospheric Sciences* **23**(3): 276–385, (In Chinese).

Nakamura H, Wallace JM. 1990. Observed changes in baroclinic wave activity during the life cycles of low-frequency circulation anomalies. *Journal of the Atmospheric Sciences* **47**: 1100–1116.

Ogi M, Yamazaki K, Tachibana Y. 2004. The summertime annular mode in the northern hemisphere and its linkage to the winter mode. *Journal of Geophysical Research* **109**(D20): D20144, DOI:10.1029/2004JD004514.

Qian WH, Quan LS, Shi SY. 2002. Variations of the dust storm in China and its climatic control. *Journal of Climate* **15**: 1216–1229.

Quadrelli R, Wallace JM. 2002. Dependence of the structure of the northern hemisphere annular mode on the polarity of ENSO. *Geophysical Research Letters* **29**(23): 2132, DOI:10.1029/2002GL015807.

Quan LS, Shi SY, Zhu YF, Qian WH. 2001. Temporal-spatial distribution characteristics and causes of dust-day in China. *Acta Geographica Sinica* **56**(4): 477–485, (In Chinese).

Rogers JC, McHugh MJ. 2002. On the separability of the North atlantic oscillation and arctic oscillation. *Climate Dynamics* **19**(7): 599–608.

Tegen I, Werner M, Harrison SP, Kohfeld KE. 2004. Relative importance of climate and land use in determining present and future global soil dust emission. *Geophysical Research Letters* **31**(5): L05105, DOI:10.1029/2003GL019216.

Thompson DWJ, Wallace JM. 1998. The arctic oscillation signature in the wintertime geopotential height and temperature fields. *Geophysical Research Letters* **25**: 1297–1300.

Thompson DWJ, Wallace JM. 2001. Regional climate impacts of the northern hemisphere annular mode. *Science* **293**: 85–89.

Tucker CJ, Pinzon JE, Brown ME, Slayback D, Pak EW, Mahoney R, Vermote E, Saleous NE. 2005. An extended AVHRR 8-km NDVI data set compatible with MODIS and SPOT vegetation NDVI data. *International Journal of Remote Sensing* (in press).

Wallace JM. 2000. North Atlantic oscillation/annular mode: two paradigms-one phenomenon. *Quarterly Journal of the Royal Meteorological Society* **126**: 791–805.

Wallace JM, Gutzler DS. 1981. Teleconnections in the geopotential height field during the northern hemisphere winter. *Monthly Weather Review* **109**(4): 784–812.

Wang SC, Li DL. 2003. Relationship between northern cyclones and climate change in northwest China. *Journal of Glaciology and Geocryology* **25**(5): 526–532, (In Chinese).

Wang XM, Dong ZB, Zhang JW, Liu LC. 2004. The modern dust storms in China: an overview. *Journal of Arid Environments* **58**(4): 559–574.

Wettstein JJ, Mearns LO. 2002. The influence of the north atlantic oscillation-arctic oscillation on mean, variance, and extremes of temperature in the northeastern United States and Canada. *Journal of Climate* **15**: 3586–3600.

Wilks DS. 1995. *Statistical Methods in the Atmospheric Sciences: An Introduction*. Academic Press: San Diego, California, U.S.A.; 467.

Wittman MAH, Polvani LM, Scott RK, Charlton AJ. 2004. Stratospheric influence on baroclinic lifecycles and its connection to the Arctic Oscillation. *Geophysical Research Letters* **31**: L16113, DOI:10.1029/2004GL020503.

Wu BY, Huang RH. 1999. Effects of the extremes in the North atlantic oscillation on east asian winter monsoon. *Chinese Journal of Atmospheric Sciences* **23**: 641–651, (In Chinese).

Wu BY, Wang J. 2002. Winter arctic oscillation, Siberian high and east asian winter monsoon. *Geophysical Research Letters* **29**: 1897, DOI:10.1029/2002GL015373.

Ye DZ, Chou JF, Liu JY, Zhang ZX, Wang YM, Zhou ZJ, Ju HB, Huang Q. 2000. Causes of sand-stormy weather in northern China and control measures. *Acta Geographica Sinica* **55**(5): 513–521, (In Chinese).

Yu JY, Hartmann DL. 1993. Zonal flow vacillation and eddy forcing in a simple GCM of the atmosphere. *Journal of the Atmospheric Sciences* **50**: 3244–3259.

Zhang DE. 1984. Climatic analysis of the dust storm weather in Chinese history. *Sciences in China (Series B)* **3**: 278–288, (In Chinese).

Zhang J-C, Lin Z-G. 1992. *Climate of China*. John Wiley and Sons, Shanghai Scientific and Technical Press: China, Shanghai; 376.

Zhang PZ, Chen GM. 1999. A statistical analysis of the cold wave high which influences on China. *Acta Meteorologica Sinica* **57**: 493–501, (In Chinese).

Zhang L, Ren GY. 2003. Change in dust storm frequency and the climatic controls in northern China. *Acta Meteorologica Sinica* **61**(6): 744–750, (In Chinese).

Zhang XY, Arimoto R, An ZS. 1997. Dust emission from Chinese desert sources linked to variations in atmospheric circulation. *Journal of Geophysical Research* **102**(D23): 28,041–28,047.

Zhang XY, Gong SL, Zhao TL, Arimoto R, Wang YQ, Zhou ZJ. 2003. Sources of Asian dust and role of climate change versus desertification in Asian dust emission. *Geophysical Research Letters* **30**(24): 2272, DOI:10.1029/2003GL018206.

Zhao C, Dabu X, Li Y. 2004. Relationship between climatic factors and dust storm frequency in inner Mongolia of China. *Geophysical Research Letters* **31**: L01103, DOI:10.1029/2003GL018351.

Zhou ZJ. 2001. Blowing-sand and sand storm in China in recent 45 years. *Quaternary Sciences* **21**(1): 9–17, (In Chinese).

Zhou ZJ, Zhang GC. 2003. Typical severe dust storms in northern China: 1954–2002. *Chinese Science Bulletin* **48**(11): 1224–1228, (In Chinese).

Zou XK, Zhai PM. 2004. Relationship between vegetation coverage and spring dust storms over northern China. *Journal of Geophysical Research* **109**: D03104, DOI:10.1029/2003JD003913.

