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The impact of the winter North Atlantic Oscillation on the frequency of spring dust storms over Tarim Basin in northwest China in the past half-century

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Abstract
The relationship between the frequency of spring dust storms over Tarim Basin in northwest China and the winter North Atlantic Oscillation (NAO) is investigated by using the observed dust storm frequency (DSF) and the 10 m wind velocity at 36 stations in Tarim Basin and the National Centers for Environment Prediction/National Center for Atmospheric Research reanalysis data for the period 1961–2007. The spring DSF (winter NAO) index shows a clear decreasing (increasing) linear trend over 1961–2007. The winter NAO correlates well with the subsequent spring DSF over Tarim Basin on both interannual and interdecadal time scales and its interannual to interdecadal variation plays an important role in the spring DSF. Two possible physical mechanisms are identified. One is related to the large scale anomalous circulations in spring in the middle to high troposphere modulated by the winter NAO, providing the background of dynamical conditions for the dust storm occurrences. The other is related to the shifts in the local horizontal sea level pressure (SLP) gradients and 10 m wind speed, corresponding to changes in the large scale circulations in spring. The decrease in the local 10 m wind speed due to the reduced horizontal SLP gradients over Tarim Basin during the strong winter NAO years contributes to the decline of the DSF in the subsequent spring.

Keywords: North Atlantic Oscillation, dust storm, Tarim Basin

1. Introduction

A dust storm is a meteorological phenomenon common in arid and semi-arid regions. It has been argued that dust storm increases have recently been changing both the local and the global climate, and also impacting local economies. The deserts and the Loess Plateau in northwest China, dominated by arid and semi-arid climate, are among the main airborne dust sources in the Northern Hemisphere (Prospero *et al* 2002). The severe dust storms in northwest China can extend to Korea, Japan and the Pacific, and even reach the western coast of North America (Duce *et al* 1980, Husar *et al* 2001). Studies of the spatial and temporal distribution characteristics of the dust storms occurring over northwest China, including their sources and paths (Zhou and Wang

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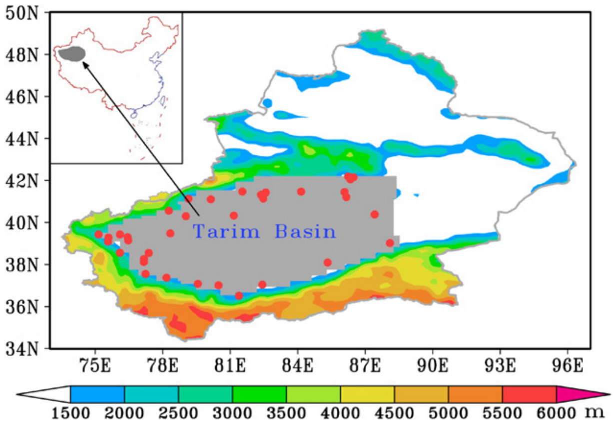

Figure 1. Tarim Basin location and the distribution of the 36 meteorological stations (red dots) for observation of the dust storms and 10 m wind speed over Tarim Basin during 1961–2007. Colored shaded areas show the terrain height. The gray shaded area shows the location of Tarim Basin.

2002, Wang *et al* 2003a, Qian *et al* 2002, Ding and Li 2005, Kang and Wang 2005), revealed that the Taklimakan desert, which is located in Tarim Basin and the largest desert in China, is one of the centers with particularly high dust storm frequency (DSF) in China, and the farthest distant and most important source area for dust deposits in the northern Pacific (Iwasaka *et al* 1988, Wang *et al* 2003b). Recent studies (Ma *et al* 2006, Li *et al* 2008a) have indicated a significant descending trend in the DSF over Tarim Basin, which is located in southern Xinjiang province in northwest China (as shown in figure 1), with an area of around 900 000 km^2, and is the largest basin in China. It is surrounded by the Tien Shan Mountains to the north, the Pamirs to the west, the Kunlun Mountains (the northern edge of the Tibetan Plateau) to the South and the Altun Mountains to the east. Because of the extremely dry and arid inland climate (Chen *et al* 2006b) and most of the basin being occupied by deserts, which are very important source areas for dust storms, spring dust storms occurred over Tarim Basin very frequently (Wang *et al* 2003b, 2003a). Understanding the mechanism of formation of the dust storms over Tarim Basin and predicting them has been one of the most important issues for regional climate and environment studies.

Many studies have shown that the occurrence of dust storms is strongly correlated with large scale anomalous atmospheric circulation patterns, such as the Antarctic Oscillation (AAO) (Fan and Wang 2004), the Arctic Oscillation (AO) (Gong *et al* 2006), and the Pacific/North American pattern (PNA) (Gong *et al* 2007); these large scale anomalous atmospheric circulation patterns can change the local climate factors like temperature, precipitation, wind, moisture etc. These climate factors are significantly associated with the DSF (Quan *et al* 2001, Zhai and Li 2003, Liu and Li 2004). A study by Ding and Li (2005) showed that the enhanced geopotential height over the Mongolian plateau and Middle Siberia and increased precipitation, as well as an anomalous shift in the phase and intensity of the stationary wave over Eurasia, contribute to the decreased DSF over northwest China. As the dominant mode of winter climate variability in the North Atlantic region, ranging from central North America to Europe and into much of Northern Asia, the North Atlantic Oscillation (NAO) plays an important role in affecting the precipitation, air temperature, wind etc in the Northern Hemisphere and China (Marshall *et al* 2001, Yu and Zhou 2004).

The climate over Tarim Basin is significantly affected by the NAO (Nan *et al* 2006, Yang and Zhang 2008, Hao *et al* 2011). The changing climate over Tarim Basin should further affect the DSF over this region. However, little work has been done on revealing the relationship between the NAO and the DSF over Tarim Basin and possible underlying physical mechanisms. The aim of this paper is to investigate the relationship between the winter NAO and the spring DSF over Tarim Basin and further explore the possible mechanisms.

2. The data and method

The data on the DSF and 10 m wind speed used in this study are derived from the records from 36 meteorological stations over Tarim Basin (figure 1) obtained during 1961–2007 (Ma *et al* 2006). Dust storms are usually considered as the outcome from strong turbulent wind systems entraining particles of dust into the air with the visibility below 1000 m, in the daily observations in China (Qian *et al* 2002). The DSF indicates the days of dust storms that happen in one month or one year. The National Centers for Environment Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis data (Kalnay *et al* 1996) are also used to reveal the large scale atmospheric circulations. The daily NAO index (NAOI) data for the period 1961–2007 are available from the website www.cpc.ncep.noaa.gov/data/teledoc/nao.shtml. The winter NAOI derived from the daily NAO index data is averaged over boreal winter months (December, January and February, or DJF). The spring DSF index (DSFI) is derived from the regional means of the DSF records at the 36 meteorological stations, which are averaged over boreal spring months (March, April and May, or MAM).

We used an 11-point binomial smoothing algorithm (Hou and Wang 2004) to get the 11 year running means with the interannual variations removed. The smoothed time series Y_i $(i = 1, \ldots, N)$ can be derived from the original time series X_i $(i = 1, \ldots, N)$ according to the following formulas:

$$
\begin{aligned}
Y_j &= \sum_{i=1}^{kk} \alpha_i X_k \Big/ \sum_{i=1}^{kk} \alpha_i, && j > L \quad \text{and} \quad j \le N - L \\
Y_j &= \left(\sum_{i=a}^{kk} \alpha_i X_k \right) \Big/ \sum_{i=a}^{kk} \alpha_i, && j \le L \\
Y_j &= \left(\sum_{i=1}^{b} \alpha_i X_k \right) \Big/ \sum_{i=1}^{b} \alpha_i, && j > N - L
\end{aligned}
\qquad (1)
$$

where $m = kk - 1$, and $kk = 11$ in this study. $L = m/2$ is the moving window. $\alpha_i = \frac{m!}{(i-1)!(m-i+1)!}$ $(i = 1, \ldots, kk)$ is the binomial coefficient. $k = j - L - 1 + i$, $a = 2 + L - j$, $b = kk - j + N - L$. It is obvious that the smoothed time series Y_i $(i = 1, \ldots, N)$ have the same sample size as the original

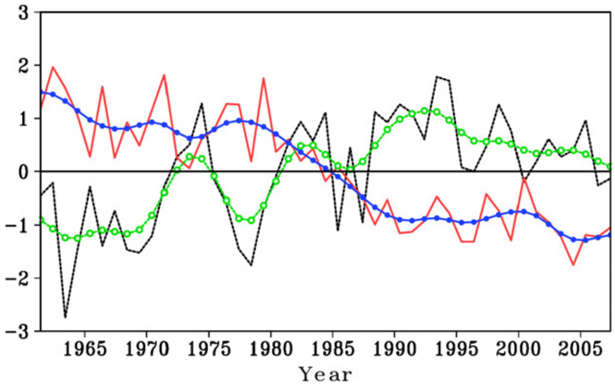

Figure 2. Normalized time series of the spring DSFI (solid line in red) and the winter NAOI (dashed line in black). Their 11 year running mean series are indicated by the closed circle line in blue and the open circle line in green, respectively.

time series X_i ($i = 1, \ldots, N$); this is different from the case for traditional moving averages, which shorten the sample size of the smoothed time series.

3. Results

The dust storms over Tarim Basin mainly occur in spring (Qian 1991), so only the relationships between the winter NAO and the spring DSF are discussed in this study. Figure 2 shows the normalized time series of the spring DSFI over Tarim Basin and the winter NAOI and their 11 year running mean. Both the winter NAOI and the spring DSFI present a distinct decadal change. The spring DSFI is in positive (negative) phase during 1961–1984 (1985–2007) and shows a clear decreasing linear trend during 1961–2007. In contrast, the winter NAOI is in negative (positive) phase during 1961–1980 (1981–2007) with a significant increasing linear trend during 1961–2007. The smoothed winter NAOI (green open circle line in figure 2) and the spring DSFI (blue closed circle line in figure 2) show a strong correlation of −0.58, which is over the 99% significance level on interdecadal time scales. The correlation coefficient is −0.28 (over the 95% significance level at interannual time scales) after removing the interdecadal variation (original data minus smoothed data). The winter NAOI has a quite close relation with the spring DSFI on both interdecadal and interannual time scales.

Previous studies found that the strengthened westerly jet at 200 hPa can result in a greater DSF in spring over northwest China (Chen *et al* 2005, Chen *et al* 2006a). Figure 3 gives the correlation between the winter NAOI and the spring zonal wind at 200 hPa. It is clearly seen that one negative correlation center at over 95% significance level is located over Tarim Basin. During the positive (negative) phase of the winter NAO, the decreased (increased) westerly jet at 200 hPa weakens (strengthens) the ascending motion and suction effect, and further hinders (benefits) the downward momentum transportation from the upper level and the increase of the wind speed below the westerly jet axis over Tarim Basin (Uccellini 1986). Therefore, this situation is not favorable for the large scale dynamic conditions of dust storms

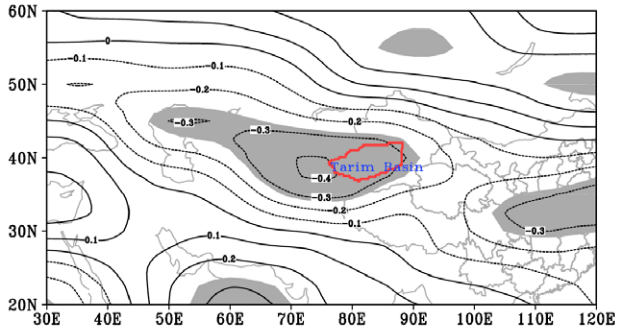

Figure 3. Correlation between the winter NAOI and the spring wind component u at 200 hPa. The values in the shaded areas are significant at the 95% t-test confidence level. The region bounded by the red curve indicates the location of Tarim Basin.

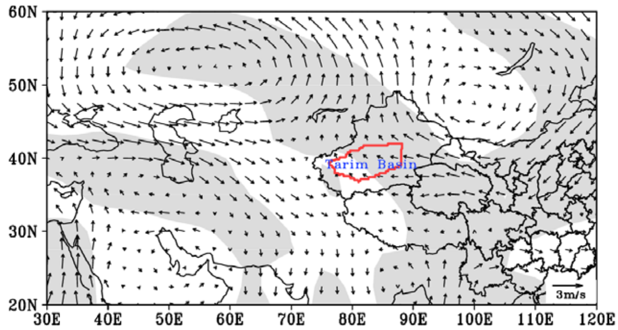

Figure 4. Composite difference in the spring 500 hPa horizontal wind vectors (in m s^{-1}), between positive and negative winter NAOI years. The shaded areas are the same as those shown in figure 3. The region bounded by the red curve indicates the location of Tarim Basin.

occurring during the strong winter NAOI years, and results in a decrease of the DSF.

The DSF is closely associated with large scale anomalous atmospheric circulation patterns (Westphal *et al* 1988, Tang *et al* 2005). Figure 4 shows the composite difference in the spring 500 hPa horizontal wind vectors between the positive and negative winter NAOI years. The composite difference between the positive and negative NAOI displays a clear zonal wave train along 40–50°N from the Atlantic to the Pacific. One significant anomalous cyclone (anticyclone) located over Central Asia (East Asia) can be noted along this zonal wave train. Tarim Basin is on the southwest side of the later anomalous anticyclone. The significant southeast wind anomalies over Tarim Basin indicate that the decrease in the northwest winds, which strongly affect the cold weather over Xinjiang (Hao *et al* 2011), results in weaker cold weather anomalies during the strong winter NAOI years. Therefore the changes in the spring 500 hPa winds provide large scale dynamical conditions favorable to decrease in the spring DSF over Tarim Basin during the strong winter NAO years.

Besides large scale anomalous atmospheric circulations providing dynamical conditions for the spring DSF mentioned above, various local climate factors, such as the 10 m wind speed, precipitation, 2 m air temperature etc, are closely related to the spring DSF and directly affect the DSF (Hao

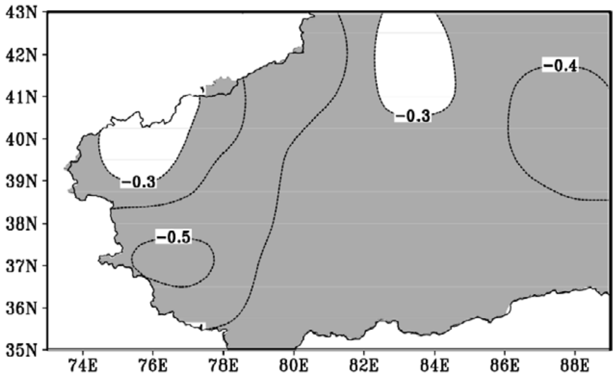

Figure 5. Correlation between the winter NAOI and the spring 10 m wind velocity over Tarim Basin during 1961–2008. The shaded areas are the same as those shown in figure 3.

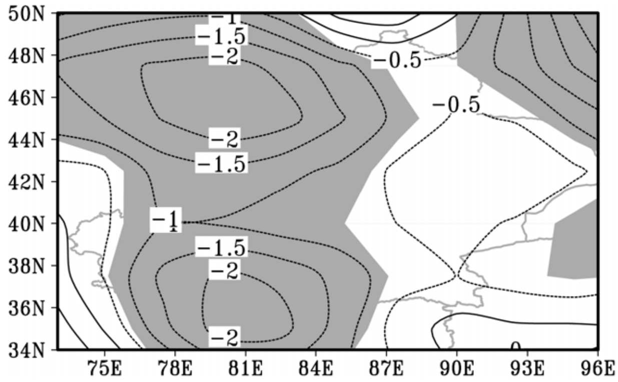

Figure 6. Composite difference in magnitude of the spring horizontal sea level pressure (SLP) gradients (in 10^{-4} Pa m^{-1}), between the positive and negative winter NAOI years. The shaded areas are the same as those shown in figure 3.

et al 2011). Earlier studies revealed that significant (slight) increases in the spring 2 m air temperature (precipitation) resulted in increases in the soil moisture and vegetation cover in Tarim Basin during the past half-century (Liu and Wei 2005). However, a large part of Tarim Basin is dominated by deserts with little vegetation cover and an extremely arid inland climate with rare precipitation; the main factors which cause the DSF interdecadal changes over Tarim Basin may relate not to the desertification condition but to the interdecadal changes of atmospheric circulation at lower levels (Qian *et al* 2006). Recent studies indicated that compared to other local climate factors, the 10 m wind speed is the most important climate factor for spring dust storm occurrence over Tarim Basin (Kurosaki and Mikami 2003, Li *et al* 2008b).

To show how the winter NAO affect the spring 10 m wind speed over Tarim Basin through anomalous atmospheric circulations, in figure 5 we display the correlation between the winter NAOI and the spring 10 m wind speed over Tarim Basin during 1961–2007. It shows a significant negative correlation with a maximal center located in the southwest part of Tarim Basin where the spring dust storms occur most frequently (Wang *et al* 2003b). How does the change in the large scale circulations affect the lower level local winds over Tarim Basin? As shown in figures 3 and 4, the anomalies in large scale circulation prevent the cold air from the polar region entering Tarim Basin during the strong winter NAOI years; this leads to positive anomalies of the surface air temperature (not shown) and negative anomalies in magnitude of the spring horizontal sea level pressure (SLP) gradients (figure 6). And then the 10 m wind speed over Tarim Basin decreases, corresponding to decreased magnitude of the horizontal SLP gradients. This is consistent with the previous studies (Wang and Zhai 2004). The decreased local 10 m wind speed over Tarim Basin contributes to the declining DSF over this region.

How does the winter NAO affect the spring DSF over Tarim Basin in northwest China? The physical mechanism is complex and unclear. We can conclude at least two plausible physical mechanisms from the analysis shown above. One is that the decreased westerly winds at 200 hPa in middle latitudes over the Northern Hemisphere hindering the downward momentum transportation from the upper level to the lower level and an anomalous anticyclone with significant southeast wind anomalies at 500 hPa prevent cold air from the polar region entering Tarim Basin during the strong winter NAO years—these large scale atmospheric dynamical conditions possibly contribute to the weaker cold air activities over Tarim Basin in boreal spring. The other is that the negative anomalies in magnitude of the spring horizontal SLP gradients result in a decrease of the local 10 m wind speed over Tarim Basin, corresponding to the anomalies of the large scale atmospheric circulations during the strong winter NAO years, and thereupon a decline of the spring DSF over Tarim Basin.

4. Conclusion

In summary, the winter NAO has a statistically significant relation with the spring DSF over Tarim Basin on both interannual and interdecadal time scales. The change of the winter NAO plays an important role in the occurrence of spring dust storms over Tarim Basin, related to large scale circulations. One possible mechanism for the relation between the winter NAO and the spring DSF over Tarim Basin is the zonal wave train from the Atlantic to the Pacific at mid-latitude in the Northern Hemisphere. The winter NAO provides anomalies in the large scale atmospheric circulations related to the spring DSF over Tarim Basin in northwest China. The anomalous circulations in spring over the middle to high troposphere prevent the cold air from moving from high latitudes into Tarim Basin during the strong winter NAO years. The large scale anomalous circulations related to the winter NAO supply the background of dynamical conditions for the DSF. Another possible mechanism is the anomalous patterns of the local horizontal SLP gradient and 10 m wind speed in spring, corresponding to changes in the large scale circulations. The decreased local 10 m wind speed due to the reduced horizontal SLP gradients over Tarim Basin contributes to the declining spring DSF during the strong winter NAO years.

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