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The relationship between the Spring Asian Atmospheric circulation and the previous winter Northern Hemisphere annular mode

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With 14 Figures

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Summary

By using the NCEP/NCAR reanalysis data, the Northern Hemisphere annular mode index (NAMI), China dust storm frequency data and China's 160-station monthly precipitation data, the relationship between the previous winter (December–February) Northern Hemisphere annular mode (NAM) and the following spring (March–May) Asian atmospheric circulation is examined statistically in this study. Results demonstrate that the relationship between the spring Asian atmospheric circulation and the previous winter NAM is more significant on decadal time scales than on interannual time scales. There are significant negative correlations between the previous winter NAM and the spring temperature in what is almost a troposphere over Northwest China. There is a significant positive correlation between the winter NAMI and following spring geopotential height field over the Mongolian Plateau and Middle Siberia (MPMS) at the upper level. The positive correlation coefficients center moves to the south with the level from high to low. At lower level the high correlation coefficients center is located over the North China. There is a significant negative correlation between the winter NAMI and the surface horizontal wind intensity in the following spring for Northwest China on decadal timescales. The results suggest that a strong NAM in winter is followed by a negative temperature anomaly and a positive anomaly of the spring 500 hPa geopotential height over the MPMS, while at the same time the spring anomaly of the southeast wind is experienced in the surface layer in Northwest China, implying that the intensity of the northwest wind tends to weaken, and *vice versa*. This circulation pattern can affect the change of the spring dust storm frequency in Northwest China on decadal time scales.

1. Introduction

The Northern Hemisphere annular mode (NAM), also called the Arctic Oscillation (AO), is a zonal see-saw fluctuation in atmospheric mass between middle and high latitudes of the Northern Hemisphere (Thompson and Wallace, 1998, 2000a, b; Li and Wang, 2003; Li, 2005). The NAM is a major mode of climate variability in the Northern Hemisphere. First identified by Lorenz (1951), it was then reinvestigated by Thompson and Wallace (1998) who named it the AO. Much evidence (Lorenz, 1951; Thompson and Wallace, 1998, 2000a, b; Gong et al., 2001; Gong and Ho, 2002, 2003; Li and Wang, 2003; Ding et al., 2005; Li, 2005) demonstrates that the NAM has a broad and important influence on the climate of the Northern Hemisphere. NAM is also closely connected with Asian atmospheric circulation. Gong et al. (2001, 2002, 2003) found a close relationship between the winter NAM, the winter Siberia high and the East Asian summer and winter monsoons. However, although previous studies have dedicated much attention to the relationship between the NAM and Asian atmospheric circulation in summer and winter, few investigations have been carried out concerning the connections between the previous winter NAM and spring Asian atmospheric circulation. Ding et al. (2005) found that the decadal anomaly of the following spring 500 hPa geopotential height field over the Mongolian Plateau and Middle Siberia (MPMS) can affect dust storm frequency (DSF) in Northwest China. However, they didn't indicate which factors can cause the change of the 500 hPa geopotential height field. As a major mode of low-frequency variability in the Northern Hemisphere, the question as to whether the previous NAM is closely related, or if it significantly influences the Asian spring atmospheric circulation anomaly was not addressed. This paper will try to explore these questions and focus on the relationship between spring Asian atmospheric circulation and the previous winter NAM.

The data and the definitions of indices and methodologies used in this paper are described in Sect. 2. Section 3 gives the relationship between the previous winter NAM and the spring Asian circulation, such as temperature field, geopotential height field and wind field. The possible influence of the previous winter NAM on the dust storm frequency in Northwest China is discussed in Sect. 4. A summary and discussion of the results is given in Sect. 5.

2. Data and methodology

The main datasets employed in this study include the NCEP/NCAR reanalysis data (1953–2003, resolution is $2.5^\circ \times 2.5^\circ$), NAM index (NAMI) (1873–2003) (Li and Wang, 2003), China dust storm frequency data (1954–2003) and China's 160-station monthly precipitation data (1951–2004) (Nan and Li, 2003) from the National Meteorological Information Center of China. To reflect the change of atmospheric circulation over the MPMS, as indicated in the studies from Ding et al. (2005), the atmospheric circulation index (ACI) over the MPMS is defined as the 500 hPa geopotential height averaged over the domain (85–110°E, 40–65°N). Positive (negative) ACI denotes the positive (negative) anomaly of the 500 hPa geopotential height field. To show the relationship between the previous winter NAM and the spring surface horizontal wind in Northwest China, the domain-average 700 hPa horizontal wind field over Northwest China (75–110°E, 35–45°N) is defined as a wind index (WI) in this region. The WI is used to represent the intensity of the spring surface wind velocity in Northwest China.

The year in which the NAMI values are greater (smaller) than one standard deviation of the normalized time series of the NAMI is defined as a strong (weak) NAM year. From 1953 to 2002, there are seven strong winter NAM years (1988/1989, 1989/1990, 1991/1992, 1992/1993, 1998/1999, 1999/2000, 2001/2002) and seven weak winter NAM years (1955/1956, 1962/1963, 1964/1965, 1967/1968, 1968/1969, 1969/1970, 1976/1977). The DSF data observed by 48 stations in Northwest China from 338 meteorological observing stations in China (Wang et al., 2003) are used to give the DSF index (DSFI) (Ding et al., 2005), which is defined by averaging the observations from the 48-stations for the total days of dust storm occurrences for the spring (March–May).

To analyze the composite difference of the physical quantity, we used the mean of the spring physical quantity of seven previous winter strong NAM years to subtract the mean of the spring physical quantity of seven previous winter weak NAM years. Stationary waves in this paper for the previous winter low and high NAMI years are defined as the 7-yr mean of the local geopotential height departures from the zonal-mean of the 7-yr mean of the geopotential height.

3. The relationship between the previous winter NAM and the spring Asian circulation

Figure 1 gives the correlations between the previous winter NAMI and the spring 500 hPa temperature field. It shows a negative correlation area with a high correlation center over Northwest China at approximately 85°E, 40°N and a positive correlation area with a high correlation center at approximately 60°E, 70°N (Fig. 1). The correlation coefficients are significant at the 95% confidence level. It implies that the previous winter NAM and the spring temperature have the same variation at approximately 60°E, 70°N and the opposite variation at approximately 85°E, 40°N. To further show the character of this nega-

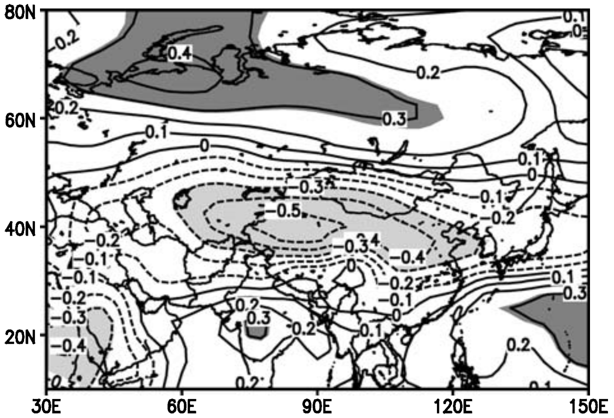

Fig. 1. Correlations between the previous winter NAMI (1953–2002) and the spring 500 hPa temperature field (1954–2003). The interval is in 0.1. The shaded areas are significant at the 95% level according to the Student's *t*-test

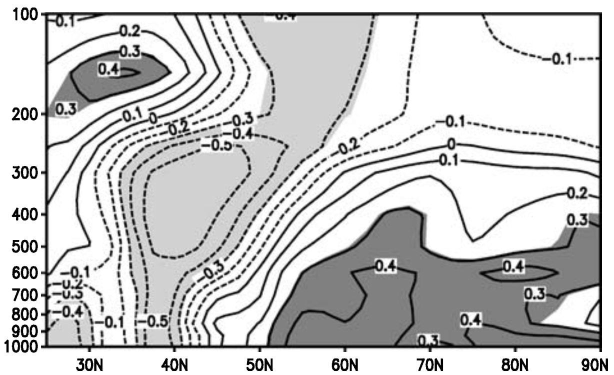

Fig. 2. Pressure-latitude section for the correlations between the previous winter NAMI (1953–2002) and the spring regionally zonal mean (80–100°E) temperature field (1954–2003). The interval is in 0.1. The shaded areas are significant at the 95% level according to the Student's *t*-test

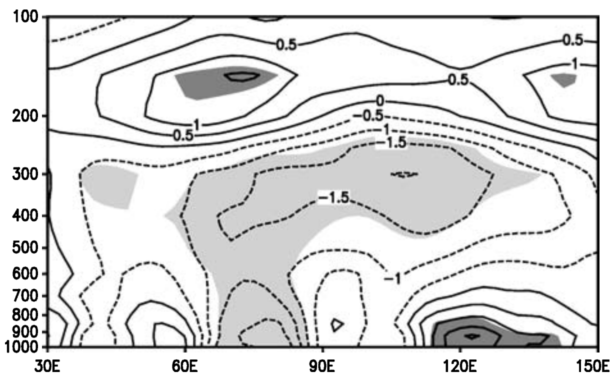

Fig. 3. The composite difference of the spring temperature (°C) between the previous winter high and low NAMI years. The interval is in 0.5 °C

tive correlation at approximately 60°E, 70°N in a vertical direction, Figs. 2 and 3 give the pressure-latitude section for the correlation map and the pressure-longitude section for the correlation map at 40°N. Figure 2 shows that there is a high negative correlation center at approximately 40°N lower than 300 hPa, while the high negative correlation center runs from 40 to 55°N with the level ranging from 300 to 100 hPa. This implies that there is a baroclinic structure over the region from 40 to 55°N. There are significant positive correlation coefficients approximately below 500 hPa and north of 50°N (Fig. 2). Figure 3 shows that there are negative correlation coefficients over the region ranging from approximately 70 to 90°E at 40°N below 300 hPa and negative correlation coefficients over the region ranging from approximately 70 to 120°E between 300 and 400 hPa. The correlation coefficients are significant at the 95% confidence level. This indicates that strong winter NAM years are all followed by negative anomalous spring temperatures over the region which runs approximately from 70 to 90°E at 40°N below 300 hPa, while weak winter NAM years are all followed by positive anomalous spring temperatures over the same region. The scenario described above implies that the temperature is negatively anomalous over the region (80–100°E, 35–45°N) in almost the entire troposphere and positively anomalous below 500 hPa and north of 50°N, corresponding to the previous winter high and low NAMI respectively and *vice versa*.

Because the series of the previous winter NAM and the spring temperature include the variation both on an interannual time scale and on a decadal time scale, the significant positive area and the significant negative area are reduced in the correlation map between the previous winter NAMI and the spring 500 hPa temperature field (figure not shown) after the linear trend was removed. The negative correlation area lies over the region ranging approximately from 70 to 100°E and from 35 to 45°N. The positive correlation area lies over the region ranging approximately from 35 to 80°E and north of 60°N. The significant positive area and the significant negative area are also reduced in the pressure-latitude section for the correlations between the previous winter NAMI and the spring regionally zonal-mean (80–100°E) temperature field (figure not shown). There are negative correlation coefficients

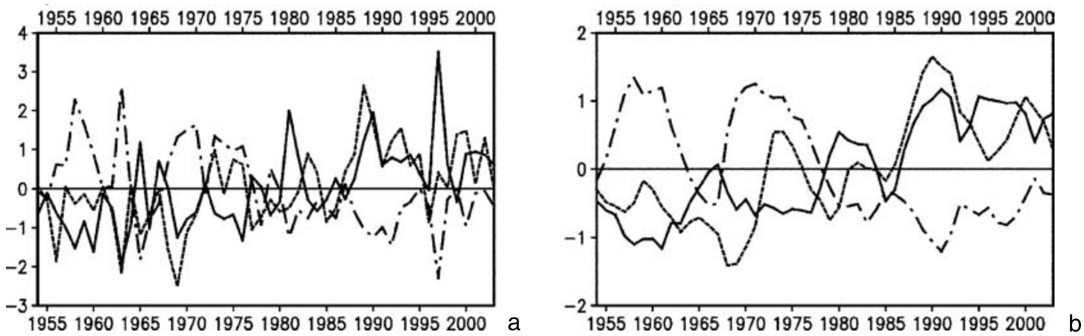

Fig. 4. (**a**) Normalized time series of the winter NAMI (dashed line), spring ACI (solid line) over the MPMS and spring WI (dot-dashed line) in Northwest China. (**b**) 9-yr running mean series of the winter NAMI (dashed line), spring ACI (solid line) over the MPMS and spring WI (dot-dashed line) in Northwest China. Normalized time series of the spring ACI and WI and their 9-yr running mean series correspond to the top x-axis which denotes spring for the period of 1954–2003. Normalized time series of the winter NAMI and its 9-yr running mean series correspond to the bottom x-axis which denotes winter for the period of 1953–2002

lying over the region ranging approximately from 35 to 40°E below 300 hPa. The positive correlation area lies over the region below 550 hPa and north of 75°N. All these data indicate that the relationship between the previous winter NAM and the spring temperature field is more significant on decadal timescales than on interannual timescales.

A normalized time series of the spring ACI in Northwest China and the previous winter NAMI (Fig. 4a) demonstrates the relationship between the previous winter NAM and the spring atmospheric circulation over the MPMS. It is shown that normalized time series of the previous winter NAMI and the spring ACI over the MPMS have the same variation. The correlation coefficient between these two series is 0.42 (Table 1). However, if the linear trend is removed, the correlation coefficient between these two series isn't significant.

Table 1. The correlation coefficients between the previous winter NAMI, the spring DSFI in Northwest China, the spring ACI over the MPMS and the spring WI in Northwest China for the period 1954–2003

	NAMI	DSFI	ACI	WI
NAMI	1	−0.47 (−0.63)	0.42 (0.68)	−0.40 (−0.55)
DSFI		1	−0.63 (−0.83)	0.52 (0.64)
ACI			1	−0.80 (−0.87)
WI				1

The numbers in the table are correlation coefficients of a normalized time series, while those in brackets are correlation coefficients for a 9-yr running mean series

This implies that the relationship between the previous winter NAMI and the spring ACI over the MPMS isn't significant on interannual timescales.

9-yr running mean series of the previous winter NAMI and the spring ACI over the MPMS are shown in Fig. 4b. We can see the previous winter NAMI and the spring ACI over the MPMS have a distinct decadal change during the mid-1980s. The intensity of two indices in the period 1985–2003 is significantly higher than the earlier period (1960–1985). The correlation coefficient between these two series is 0.68, which is significant at the 95% confidence level. The same change trends between the previous winter NAM and the spring ACI over the MPMS imply that the continuously high previous winter NAMI is closely associated with the persistently positive anomaly of the following spring ACI over the MPMS, and *vice versa*. The previous winter NAM has an influence on the spring ACI over the MPMS mainly on a decadal timescale.

Figure 5a shows the correlation map between the previous winter NAMI and following spring 500 hPa geopotential height. There is an area (significant at the 95% t-test confidence level) over the MPMS with significant positive correlation, implying that the previous winter NAM has the same change trends with the spring 500 hPa geopotential height. Figure 5b shows that there is a positive anomaly over the MPMS and that the anomaly of the geopotential height ranges from 30 to 50 gpm. This then suggests that the previous winter NAM could have an influence on the following spring atmospheric circulation over

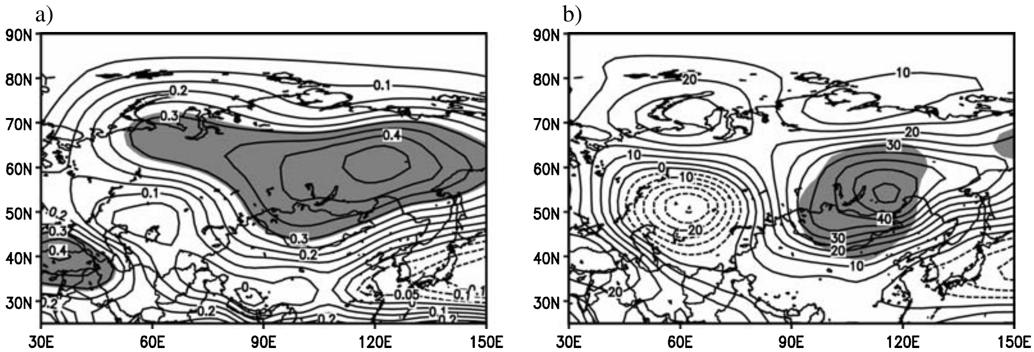

Fig. 5. Same as Figs. 2 and 3, respectively, but for the spring geopotential height (gpm) at 500 hPa

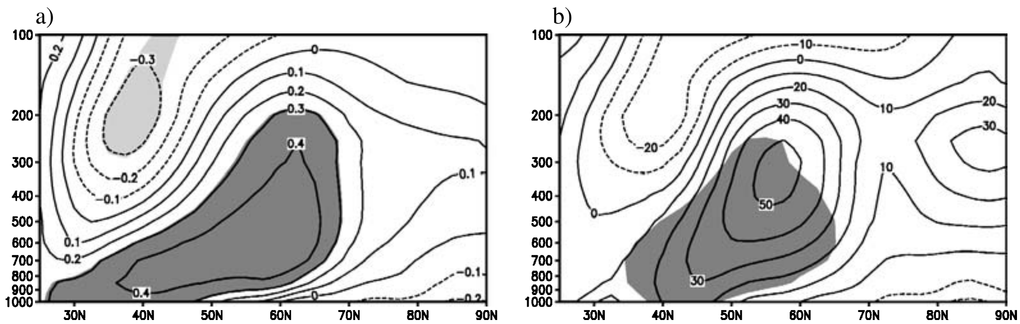

Fig. 6. Same as Fig. 5 but for pressure-latitude sections for the spring regionally zonal mean (100–120°E) geopotential height (gpm)

the MPMS. Strong previous winter NAM years are all followed by positively anomalous spring 500 hPa geopotential heights, while weak previous winter NAM years are all followed by negatively anomalous spring 500 hPa geopotential heights. These results indicate that the following spring 500 hPa geopotential height over the MPMS tends to be above-normal when the previous winter NAM is in its positive phase, and *vice versa*.

After the linear trend was removed, the significant positive correlation area in Fig. 5a is diminished (figure not shown). The positive correlation areas lie over the region 50–70°E, 65–70°N and the region 100–150°E, 55–70°N, respectively. There is a significant negative correlation area lying over the region 75–100°E, 35–40°N. Comparing this with Fig. 5a, we can see that the same variation between the previous winter NAMI and the spring geopotential height is mainly located over the region 100–150°E, 55–70°N on an interannual timescale and over the MPMS on a decadal timescale.

An analysis of the pressure-latitude sections (Fig. 6) for the correlations between the previous winter NAMI and the spring zonal mean geopotential height field as well as the composite difference of the spring zonal-mean geopotential height between the previous winter high and low NAMI years, shows that the high correlation coefficients center at the upper level of the troposphere lies over the MPMS (approximately at approximately 60°N) and moves to the south with the levels ranging from high to low. At the lower level the high correlation coefficients center is located over northern China (approximately 40°N) (Fig. 6a). Baroclinic structure can be seen in Fig. 6. The positive anomaly south of 65°N and below 200 hPa (Fig. 6b) indicates the same variation between the previous winter NAM and the spring geopotential height. The anomalous geopotential height is about 20 gpm at the lower level and about 50 gpm at the upper level respectively. A possible mechanism is that the deep trough of East Asia is shallower than normal with the NAM changing from weak to strong. This pattern would explain the observed positive anomaly in the geopotential height field.

After the linear trend was removed, the significant positive correlation area in Fig. 6a is diminished (figure not shown) and is identical with that of Fig. 5a. The positive correlation area is located approximately at 65°N. When compar-

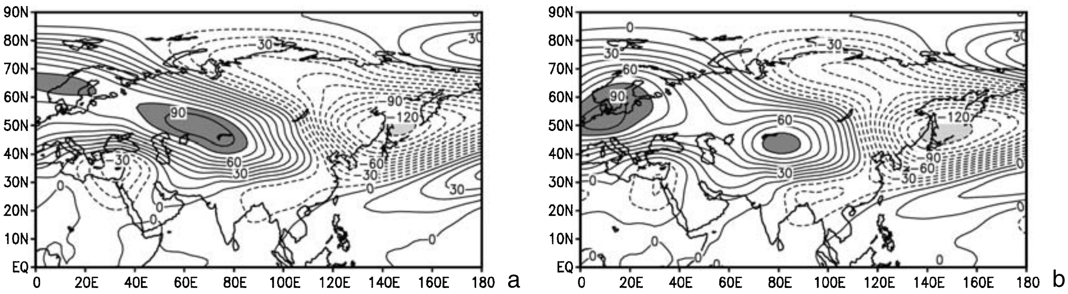

Fig. 7. The spring geopotential-height stationary wave (gpm) at 500 hPa over Eurasia for (**a**) the previous winter low NAMI years and (**b**) the previous winter high NAMI years. In both panels, the positive stationary perturbation with a value greater than +80 gpm is shaded dark. The negative stationary perturbation with a value less than −80 gpm is shaded light

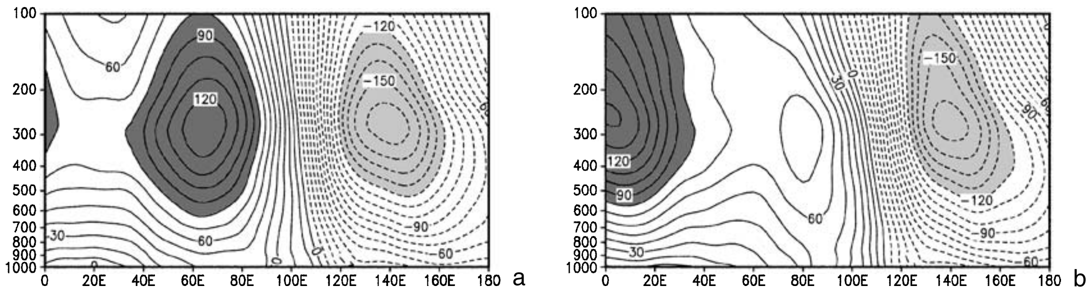

Fig. 8. Same as Fig. 7 but for pressure-longitude sections at 50°N

ing this with Fig. 6a we can see that the same variation between the previous winter NAMI and the spring geopotential height is more significant on a decadal timescale than on an interannual timescale.

Figures 7 and 8 represent the spring geopotential-height stationary wave at 500 hPa over Eurasia for the previous winter low and high NAMI years and its pressure-latitude section at 50°N, respectively. The positive spring stationary perturbation center lies west of Balkhash Lake when the previous winter NAM is weak (Fig. 7a). When the previous winter NAM is strong, the positive spring stationary perturbation center is located east of Balkhash Lake (Fig. 7b). From the pressure-latitude section at 50°N we can see that the positive spring stationary perturbation center moves from approximately 60 to 80°E with the previous winter NAM changing from weak to strong (Fig. 7b). Figures 7 and 8 both display a systematic eastward migration of the positive stationary perturbation center and that the magnitude of the positive stationary perturbation center weakens as it migrates eastward. These changes can have influence on the change of the wind field (this will be discussed later).

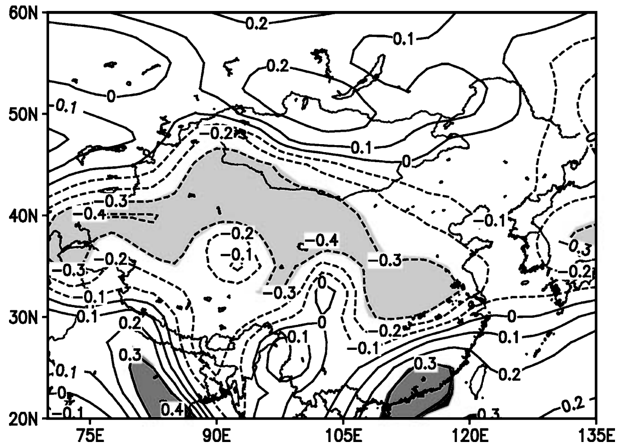

Fig. 9. Same as Fig. 1 but for the spring horizontal wind field at 700 hPa

Figure 9 is a correlation map between the previous winter NAMI and the spring 700 hPa horizontal wind field. Figure 9 shows that there is a significant negative correlation region over Northwest China between the previous winter NAMI and the spring 700 hPa horizontal wind field. The correlation coefficient between the previous winter NAMI and the spring WI is −0.40 (Table 1), which is significant at the 90% confidence level. However, a significant negative correlation over

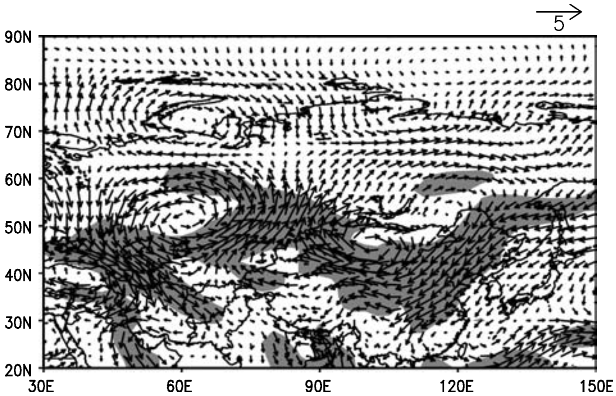

Fig. 10. Same as Fig. 3 but for the spring horizontal wind field (m s^{-1}) at 700 hPa

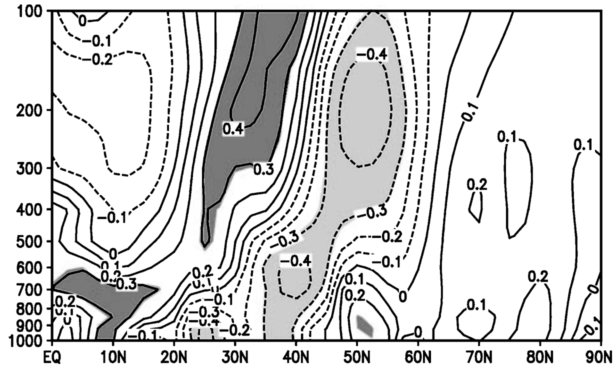

Fig. 11. Same as Fig. 2 but for the pressure-latitude section for the spring regionally zonal mean (80–100°E) zonal-wind field

Northwest China is neither observed between the previous winter NAMI and spring 700 hPa horizontal wind field, nor between the previous winter NAMI and the spring WI after the linear trend was removed. This implies that the previous winter NAM has an influence on the spring intensity of surface wind velocity in Northwest China on a decadal timescale. The spring intensity of surface wind velocity in Northwest China becomes continuously weaker (stronger) than normal due to the persistently positive (negative) anomaly of the previous winter NAMI. Composite differences of the spring 700 hPa horizontal wind field between the previous winter high and low NAMI years are shown in Fig. 10. It shows that there is a strong anomalous anticyclone in MPMS and a strong anomalous cyclone in the region west of MPMS (located mainly in Kazakstan) in the following spring with NAM changing from weak to strong in the previous winter. The strong anomalous anticyclone in MPMS can induce an anomalous southwest wind, subsequently weakening wind velocity which flows from high latitude to Northwest China, and *vice versa*. This further illustrates the negative relationship between the spring surface wind velocity and the previous winter NAM on a decadal timescale.

Figure 11 is a correlation map between the previous winter NAMI and the spring regionally zonal-mean (80–100°E) zonal-wind field. It shows that a significant positive correlation coefficient exists over the region from 20 to 30°N, with negative correlation coefficients over the region from 35 to 45°N below 400 hPa and negative correlation coefficients over the region from 45 to 55°N above 400 hPa. The correlation coefficients are significant at the 95% confidence level. Figure 11 also shows baroclinic structure. This indicates that the subtropical jet is intensified (weakened) over the region 20–30°N while the westerly wind is negatively (positively) anomalous over the region from 35 to 55°N with a positive (negative) anomaly for the previous winter NAM. To distinguish between the variation on an interannual timescale and that on a decadal timescale, the linear trend in Fig. 11 has been removed, resulting in a reduction in the negative correlation area spanning from 35 to 55°N. The negative correlation coefficients are located above 300 hPa. This would imply that the previous winter NAM has an influence on the spring zonal-wind both on interannual and decadal timescales above 300 hPa, while the previous winter NAM has an influence on the spring zonal-wind mainly on an interannual timescale below 300 hPa.

Figure 12a shows that there is a southerly anomaly approximately at approximately 45°N corresponding to the previous winter NAM positive anomaly. The same southerly anomaly also can be seen from Fig. 12b. It is mainly located approximately from 80 to 100°E and has magnitude of 1.5 m s^{-1}. The results can be explained by the change of the positive stationary perturbation center. The eastward migration and the decrease in amplitude of the positive stationary perturbation center cause conditions over Northwest China to shift from the ahead-of-ridge and back-of-trough region in the weak NAMI years to the ridge region of the stationary wave in the strong NAMI years. This then results in a weak-

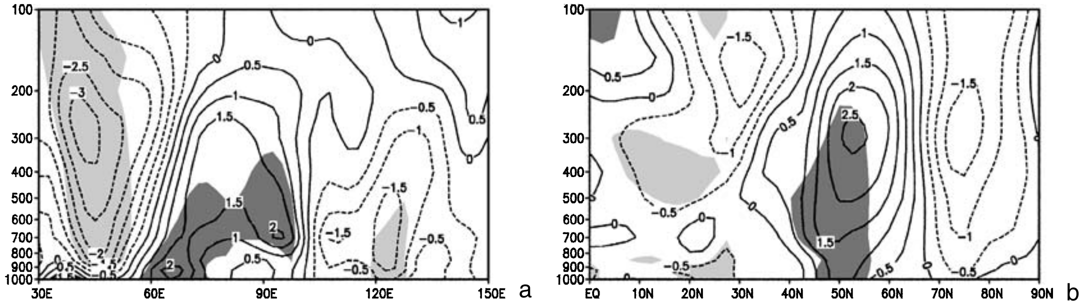

Fig. 12. (**a**) Same as Fig. 3 but for pressure-longitude section at 45°N for the spring meridional wind. (**b**) Same as (**a**) but for pressure-latitude section of the spring regionally zonal mean (100–120°E) meridional wind. Units in $m\,s^{-1}$

ening of the northwest air flow over Northwest China.

This would suggest that the previous winter NAM and the spring intensity of wind in Northwest China have opposite change trends. The relationship is more significant on decadal time scales than on interannual time scales. In detail, with the positive (negative) anomaly of the previous winter NAM, the positive stationary perturbation center turns weak (strong) and moves eastward (westward), this is then followed by an anomalous anticyclone (cyclone) on 700 hPa wind field over North China and MPMS, followed by an decrease (increase) in the intensity of surface wind in Northwest China. Another conclusion that can be drawn is that the subtropical jet in spring turns strong (weak) when the previous winter NAM is positively (negatively) anomalous. The results illustrate that the spring Asian atmospheric circulation has a close connection with the previous winter NAM. The relationship is more significant on decadal timescales than on interannual timescales.

4. Possible impacts of the previous winter NAM on the decadal variation of spring dust storm frequency in Northwest China

Dust storms frequently occur over Northwest China in the spring (Chen and Chen, 1987). Large amounts of soil dust can be transported eastward as far as the tropical North Pacific (Duce et al., 1980; Shaw, 1980). Heavy dust and sand transport cause severe damage to agriculture and desertification of the surrounding areas. Many studies indicate that some climatic factors such as ENSO, local precipitation, surface temperature etc., can influence the occurrence and change of DSF (Qian et al., 2002; Zhang et al., 2002). Ding et al. (2005) found that there is significant negative correlation between the spring ACI over the MPMS and the spring DSFI in Northwest China. At the same time there is positive correlation between the previous winter NAMI and the spring ACI over the MPMS on a decadal time scale with a correlation coefficient of 0.68 (Table 1), which is significant at the 95% confidence level. The same change trends between these two series also can be seen from Fig. 4b. Therefore, there exists a negative correlation between the previous winter NAMI and the spring DSFI in Northwest China. A significant negative correlation can be drawn from Table 1. The correlation coefficient between these two 9-yr running mean series is -0.63, which is significant at the 95% confidence level. This means that the continuously strong previous winter NAM corresponds to the decrease of the spring DSF in Northwest China in the period from 1985 to 2003, while the persistently weak previous winter NAM is associated with the increase of the spring DSF in Northwest China in the period from 1954 to 1985 (Fig. 4b). Consequently, the previous winter NAM is likely to be an important climatic factor that influences the occurrence and change of the spring dust storm in Northwest China on a decadal time scale.

Generally, Asian DSF has positive correlations to the wind intensity (Littmann, 1991; Liu et al., 2004). Therefore, we also calculate the correlation coefficient between the 9-yr running mean series of the spring WI and that of the spring DSFI in Northwest China, with a value of 0.64 (Table 1), significant at the 95% confidence level. This result further illustrates the positive correlation. These results, however, raise additional questions: Does the spring WI in Northwest China result in a corresponding change when the previous winter NAM and the spring atmosphere circulation over the MPMS have changed? Further, can the change of the spring WI in Northwest China result in the variation of the DSF in Northwest China?

The Fig. 4b shows that the spring WI in Northwest China has a distinct decadal change during the mid-1980s. The intensity of the spring WI in the period 1985–2003 is significantly lower than earlier period (1954–1985). The spring WI has opposite change trends with the spring ACI over the MPMS and there is a significant negative correlation between the spring WI in Northwest China and the ACI over the MPMS on a decadal time scale. The correlation coefficient between 9-yr running mean series of these two series is −0.87 (Table 1), which is significant at the 99% confidence level. This implies that the spring WI in Northwest China is persistently negatively anomalous when the spring 500 hPa geopotential height over the MPMS is continuously positively anomalous in the period from 1985 to 2003. Considering the positive correlation between the spring WI and DSFI in Northwest China, we can then understand the continuous decrease of the spring DSF in recent decades.

The variability of dust storm occurrence in China is also associated with other climatic factors such as precipitation, soil moisture conditions and snow cover etc. (Zhang et al., 2003; Gong et al., 2004; Kurosaki and Mikami, 2004; Liu et al., 2004; Zhao et al., 2004). The correlation between the previous winter NAMI and the spring precipitation in Northwest China isn't significant on an interannual time scale (figure not shown), whereas there is a positive correlation area in Northwest China between the previous winter NAMI and the spring precipitation on a decadal time scale with correlation coefficients significant at the 95% confidence level (Fig. 13). This implies that the previous winter NAM has an impact on the spring precipitation in Northwest China to a certain degree.

Figure 14 gives the pressure-latitude section at 35°N for the correlations between the 9-yr running mean series of the previous winter NAMI and that of the spring vertical velocity field. An area (90–100°E) with significant negative correlation is seen in Fig. 14. An analysis of the relationship between the previous winter NAM and

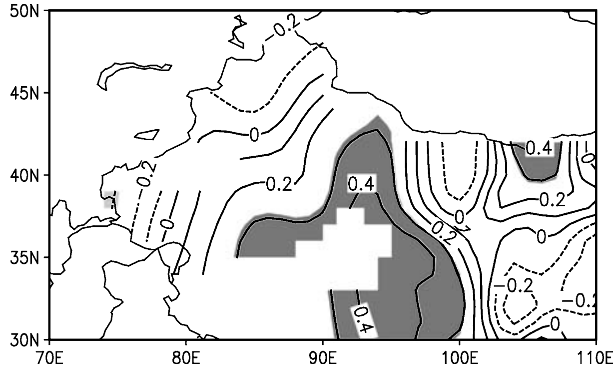

Fig. 13. Correlations between 9-yr running mean series of the winter NAMI (1953–2002) and that of the spring precipitation (1954–2003) in Northwest China. The interval is in 0.1. The correlation coefficients that are significant at the 95% confidence level are shaded

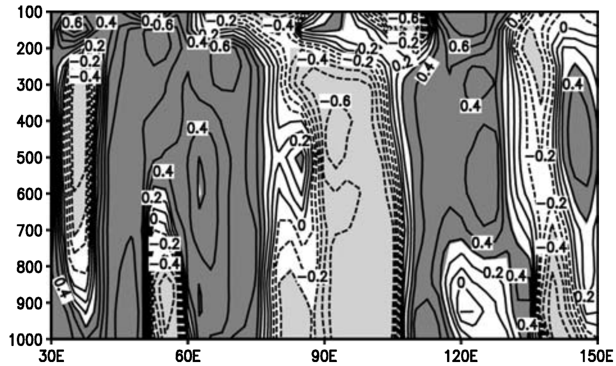

Fig. 14. Same as Fig. 13 but for pressure-longitude section at 35°N for the spring vertical velocity field

the spring Asian vertical velocity at 500 hPa also shows that there are significant negative correlation coefficients over Northwest China (figure not shown). All these results imply that vertical velocity continuously turns weak (strong), and subsequently, that the spring Asian precipitation decreases (increases) persistently corresponding to the previous winter NAM negative (positive) anomaly in the period from 1953 to 1985 (1985 to 2003).

Generally, there is a negative correlation between precipitation and DSF (Littmann, 1991; Liu et al., 2004). Therefore, except for the previously mentioned approach that displays a positive correlation between the previous winter NAM and the spring precipitation in Northwest China, the indication is that the previous winter NAM can effect the change of the spring DSF in Northwest China by directly impacting the spring precipitation in Northwest China.

These conclusions indicate that there is significant negative correlation between the previous winter NAM and the spring DSF in Northwest China on decadal time scales. There are positive correlations between the previous winter NAMI and the spring ACI over the MPMS and negative correlations between the spring ACI over the MPMS and the WI in Northwest China. Therefore, a decadal change of the spring 500 hPa geopotential height field over the MPMS is related to the decadal anomaly of the previous winter NAM, whereas the decadal change of the spring 500 hPa geopotential height field over the MPMS can affect the decadal variability of the spring 700 hPa horizontal wind field as well as that of the spring precipitation in Northwest China. The spring ACI over the MPMS is positively anomalous when the previous winter NAM is in its positive phase in the period from 1985 to 2003, and then the northwest wind continuously becomes weaker than normal at the same time the spring precipitation in Northwest China continuously increases. Finally, the spring ACI resulted in the decrease of spring dust storms for the period from 1985 to 2003. The entire situation is reversed in the period from 1953 to 1985, indicating that the previous winter NAM is likely to be a factor that wields a substantial influence on the spring DSF in Northwest China.

5. Conclusions and discussion

The relationship between the previous winter NAM and the spring Asian atmospheric circulation is investigated in this study. The results show that there are significant negative correlations between the previous winter NAM and the spring temperature over Northwest China as well as significant positive correlations between the previous winter NAM and the spring 500 hPa geopotential height over the MPMS. The relationship is significant both on interannual timescales and on decadal timescales and is more significant on decadal timescales than on interannual timescales. The high positive correlation coefficients center between the previous winter NAM and the spring geopotential height field lies over the MPMS at upper level and moves to the south, and is then located over Northwest China at a lower level. Furthermore, the previous winter NAM has a significantly negative correlation to the spring intensity of surface wind velocity in Northwest China. This relationship is only significant on a decadal timescale, however, the spring 500 hPa geopotential height over the MPMS is usually positively anomalous when the previous winter NAM is stronger than normal. Following this, the spring 700 hPa southeast wind is significantly anomalous and the northwest wind turns weak, while the spring precipitation in Northwest China displays an increasing trend. All these factors provide favorable conditions for a decrease of the spring DSF in Northwest China in recent decades. The conclusions in this paper provide a new clue for us to understand the rules governing the spring Asian atmospheric circulation variation and the change of the spring DSF in Northwest China. However, there are many questions that still need to be answered, such as how to use GCM to simulate and reveal physical processes and mechanisms of the spring Asian atmospheric circulation variation influenced by the previous winter NAM. This as well as other questions require further future investigation.

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