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Relationship between thermal anomalies in Tibetan Plateau and summer dust storm frequency over Tarim Basin, China

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Abstract: The dust storm is the most important and frequent meteorological disaster over Tarim Basin, which causes huge damages on local social economics. How to predict the springtime and summertime dust storm occurrence has become a hot issue for meteorologists. This paper employed the data of dust storm frequency and 10-m wind velocity at 35 stations over Tarim Basin and the reanalysis data from the National Center for Environmental Prediction and the National Center for Atmospheric Research (NCEP/NCAR) during 1961–2007 to study the relationship between dust storm frequency (DSF) in summer over Tarim Basin and the thermal anomalies in Tibetan Plateau in May by using the statistical methods, such as Empirical Orthogonal Function (EOF), correlation and binomial moving average. The results show when negative anomalies in Tibetan Plateau and positive anomalies in its southern region are present along 30°N (the second mode of surface temperature anomalies by EOF decomposition) in May, the time coefficient (PC2) plays an important role in summer DSF variation and has a close relation with the summer DSF at both inter-annual and decadal time scales. When negative anomalies in Tibetan Plateau and positive anomalies are present in its southern region (PC2 in positive phase), there is an anomalous anticyclone in North China, which weakens the northwest wind and is not beneficial for cold air moving from high latitude to the Tarim Basin, and the circulation pattern is hard to result in dust storm weather. Furthermore, the sea level pressure (SLP) increased over Tarim Basin and the direction of SLP gradient reversed, which resulted in the 10-m wind velocity slowing down, so the DSF decreased. From above all, it can be conclude that the thermal anomalies in Tibetan Plateau in May has important effects on the summertime dust storm frequency over Tarim Basin and the PC2 can be used as a prediction factor for the summertime dust storm occurrence.

Keywords: dust storm frequency; thermal anomalies; Tarim Basin; Tibetan Plateau

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Dust storm is a common meteorological phenomenon in arid and semi-arid regions. It has been argued that increased dust storms are recently changing both local and global climates, and also impacting local economies (Goudie, 1983). Dust storm and its effects would influence climate change at different scales. 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). The Tarim Basin has the second largest mobile desert in the world, Taklimakan Desert, which is one of the centers with high dust storm frequency (DSF) in China and the farthest and most important source area of dust deposits in northern Pacific (Iwasaka et al., 1988; Wang et al., 2003). Previous studies have indicated that the DSF over Tarim Basin presents a significant descending trend (Ma et al., 2006; Li et al., 2008). Therefore, to understand the forming mechanism of

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the dust storms in Northwest China especially over Tarim Basin and predict them has been one of the hottest issues for global climate and environment studies.

Recently studies have shown that the occurrence of dust storms strongly correlate with anomalous atmospheric circulation patterns, such as Antarctic Oscillation (AAO) (Fan and Wang, 2004), Arctic Oscillation (AO) (Gong et al., 2006), and the Pacific/North American pattern (PNA) (Gong et al., 2007). These anomalous atmospheric circulation patterns can change the climate factors like temperature, precipitation, wind and moisture, etc. These climate factors are significantly associated with DSF (Quan et al., 2001; Liu and Li, 2004). As well known, the thermal effects of Tibetan Plateau has significant influences on weather and climate in the near regions (Gu and Ye, 1955a; Zhao and Chen, 2001; Ning et al., 2012). The dust storm weather over Tarim Basin was associated with large-scale circulation anomalies (Zhang et al., 2002; Ding and Li, 2005), while the heating effects from Tibetan Plateau had important effects on the adjustment of circulation in China (Gu and Ye, 1955b; Liu et al., 2008). Previous studies found that different spatial distribution of thermal anomalies over Tibetan Plateau has different relations with circulation and precipitation in China (Zhao and Chen, 2001; Duan et al., 2003; Duan and Wu, 2003). Is the different spatial distribution of thermal anomalies in Tibetan Plateau related to DSF in summer over Tarim Basin? Little work has been done to reveal the relationship between thermal anomalies in Tibetan Plateau and DSF over Tarim Basin and possible inner physical mechanisms. The aim of this paper is to investigate the relationship between thermal anomalies in Tibetan Plateau and summer DSF over Tarim Basin and further explore the possible relation mechanism.

1 Study area

With an area of 5.30×10^6 km^2, Tarim Basin is the largest inland basin in China, surrounded by the Tianshan Mountains, Kunlun Mountains and Altun Mountains. It is about 1.5×10^3 km from east to west and 6.0×10^2 km from north to south. The basin has an extremely arid climate, with an average annual precipitation of less than 50 mm (Zhang and Deng, 1987). Tibetan Plateau has important effects on the climate over the Tarim Basin. Firstly, Tibetan Plateau hinders water vapor transport from the tropical Indian Ocean to the basin; and secondly, the thermal and dynamic effects of Tibetan Plateau are not beneficial for the precipitation in the basin, which resulted in the formation of the Tarim Desert (Zhang and Shi, 2002). Due to the presence of China's largest desert, dust storm is, to some extent, the most frequent meteorological disaster over Tarim Basin.

2 Data and methods

The data from 1961 to 2007 used in this study include: the NCEP/NCAR monthly surface temperature in Tibetan Plateau (75–105°E, 25–40°N), which is Gauss grid and is bi-linearly interpolated into 2.5°×2.5° for our conveniences, NCEP/NCAR monthly mean 500 hPa wind fields and surface level pressure (SLP) (Kalnay et al., 1996), dust storm frequency and monthly mean wind velocity (WV) data at 10-m height at 35 stations over Tarim Basin (Fig. 1). All above mentioned data were averaged for boreal summer months (June, July and August, or JJA). As a composite physical variable to reflect heat flux and surface net radiation, the surface temperature reflects the strength and changes of surface heat sources in Tibetan Plateau to some extent.

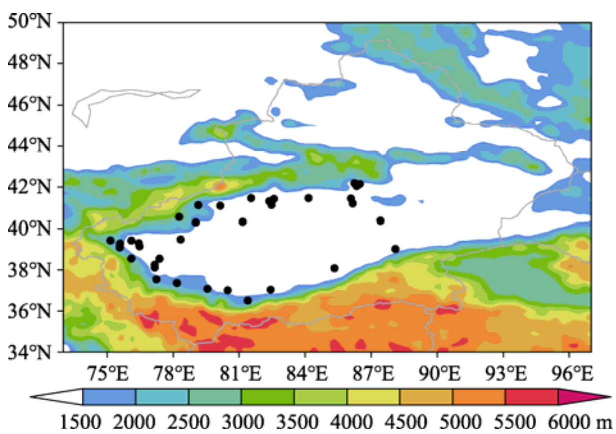

Fig. 1 The distribution of the 35 meteorological stations for observation of dust storm and 10-m wind speed over Tarim Basin during 1961–2007; shaded areas show the terrain height.

3 Results

The 47-a time series of surface temperature anomalies in Tibetan Plateau in May from 1961 to 2007 were revealed by EOF (Fig. 2). The variance contributions of the first four modes are 36%, 18%, 16% and 10%, respectively, while the variance contribution from the fifth mode is under 5%. Therefore, only the first four modes are discussed in this study. The first mode represents an integrated pattern (Fig. 2a), the second mode represents a north-south pattern (Fig. 2b), the third mode represents an east-west pattern (Fig. 2c), and the forth mode represents a southwest-northeast pattern (Fig. 2d). It is clear that the surface thermal anomalies in Tibetan Plateau have regional type changes besides integrated pattern changes.

Which spatial pattern of the surface thermal anomalies in Tibetan Plateau in May has the closest relationship with summer dust storm frequency over Tarim Basin? Figure 3 shows the correlation distributions between time coefficients of four modes and summer dust storm frequency. As shown by Fig. 3a, the correlation between time coefficients of the first mode (PC1) and summer DSF-JJA has basically negative correlation, and the regions with relatively high correlation coefficients failing to pass 95% significant test are located in the southeast of Tarim Basin. The correlation between time coefficients of the second mode (PC2) and DSF-JJA is basically negative, and the regions with high correlation coefficients are mainly located in the southwest parts of Tarim Basin which has relatively greater dust storm frequency (Fig. 3b) (Wang et al., 2003). The third and fourth time coefficients have weak correlations with DSF in summer over Tarim Basin (Figs. 3c and 3d).

The dust storm frequency index (DSFI) is firstly defined by averaging the observation data of the total dust storm days in summer at the 35 stations. Figure 4 shows the normalized time series of summer DSFI over Tarim Basin and PC2 in May and their 11-a running mean. Both the PC2 in May and summer DSFI present a distinct decadal change. The summer DSFI is in positive and negative phases during 1961–1986 and 1987–2007, respectively, showing a clear decreasing linear trend for the period 1961–2007. The PC2 in May is in negative and positive phases during

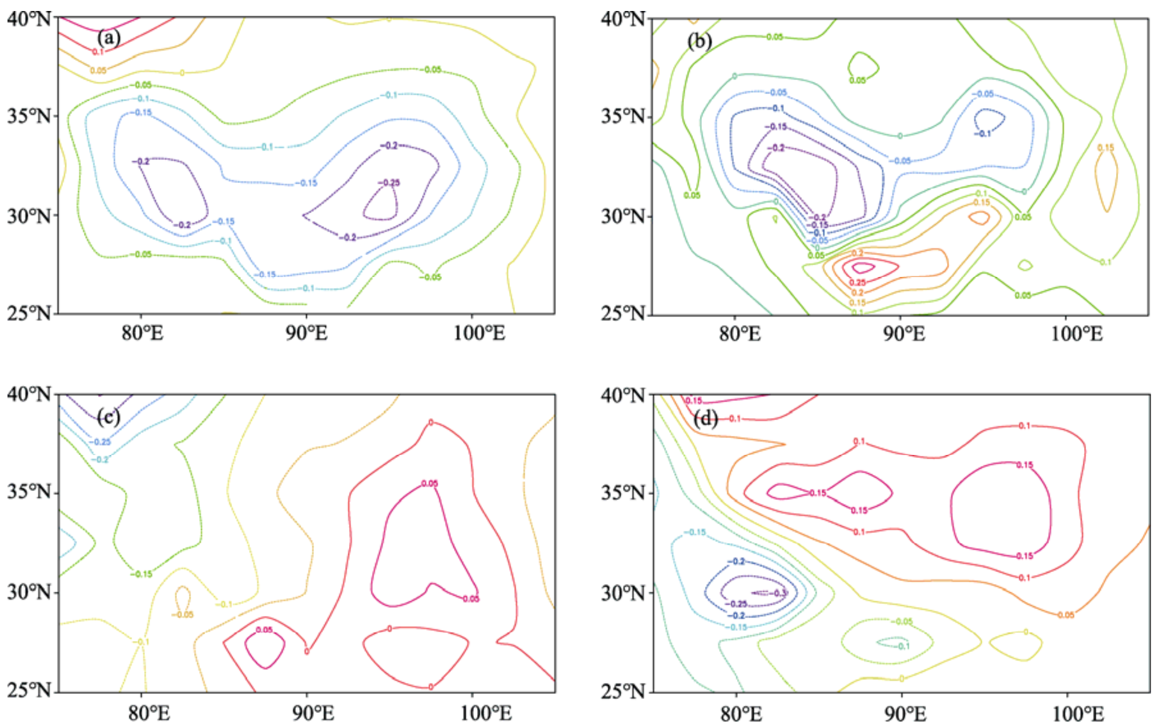

Fig. 2 The EOF eigenvector distribution computed by monthly mean surface temperature anomalies; (a) the first mode, (b) the second mode, (c) the third mode, (d) the fourth mode

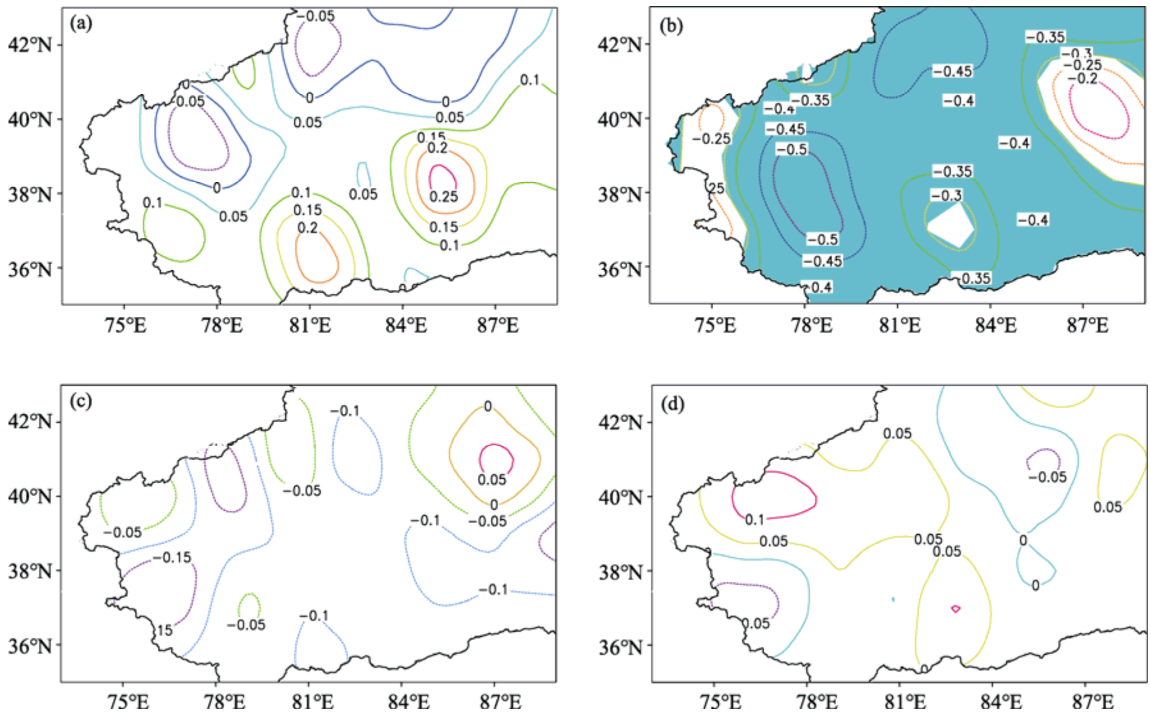

Fig. 3 The correlation distributions between the time coefficients of the first four modes of EOF decomposing by surface temperature anomalies in Tibetan Plateau and summer DSF over Tarim Basin; (a) the first mode, (b) the second mode, (c) the third mode, (d) the fourth mode; shaded areas represent 95% significant test level.

1961–1984 and 1985–2007, respectively, presenting a significant increasing linear trend during 1961–2007. DSFI and PC2 therefore show a strong correlation of –0.69 which is over 99% significant level. The correlation coefficient is –0.22 (over 90% significant level) after removing the linear trend. So the PC2 in May has a close relation with the summer DSF at both inter-annual and decadal time scales.

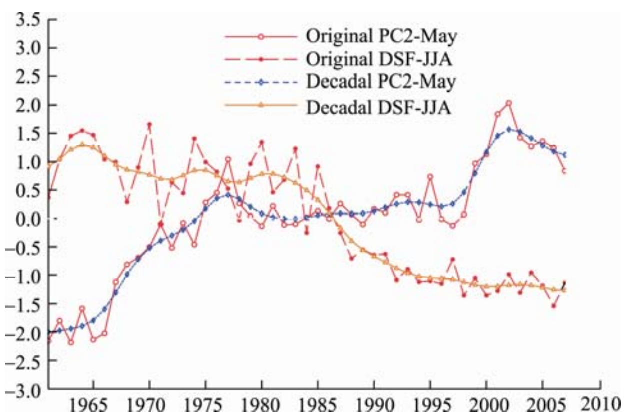

Fig. 4 Normalized time series of DSFI-JJA and PC2 in May and their 11-a moving mean series

Recent studies (Westphal et al., 1988; Kang and Wang, 2005; Tang et al., 2005) have found that the DSF is closely associated with an anomalous atmospheric circulation. So we firstly consider the relationship between DSFI and summer wind field at 500 hPa. Figure 5a gives the correlation distribution between DSFI and wind field at 500 hPa. We can found that when DSFI is in high value period, North China is dominated by anomalous cyclone circulation, which causes anomalous northwest cold air moving from high latitude to Tarim Basin, and is related to be responsible for more dust storm occurrence (Aoki et al., 2004). How do the thermal anomalies in May in Tibetan Plateau influence the summertime dust storm frequency over Tarim Basin? Previous studies found that because of the good persistence between the thermal anomalies in May and that in summer, the pattern of the thermal anomalies in May in Tibetan Plateau have significant effects on the summer circulation and climate (Duan et al., 2003). The correlation analysis shows that PC2 has a significant relation with summertime surface temperature in Tibetan Plateau, and the correlation distribution pattern is similar to

Fig. 2b (data not shown). According to the above, when the thermal anomalous pattern occurs (Fig. 2b) in May, it very likely presents the same anomalous distribution pattern again in summer in Tibetan Plateau. Furthermore, the thermal anomalies in May in Tibetan Plateau can influence the summer circulation and climate. As shown by Fig. 5b, when PC2 is in positive phase, there is an anomalous anticyclone circulation over North China, which weakens northwest wind over Tarim Basin, so it is not beneficial for cold air moving from high latitude to Tarim Basin.

How does the summer SLP change after the adjustment of large scale circulation? When PC2 is in positive phase, the anomalous southeast wind prevails over Tarim Basin, which results in weaker cold weather anomalies (Hao et al., 2011), so this leads to positive anomalies of the surface air temperature (data not shown). How does the summer SLP change after the adjustment of large scale circulation? Figure 6 displays the correlation between PC2 and summer SLP. As shown by Fig. 6, the summer SLP is positively correlated with the PC2 in May at mid-low latitudes over Asia with the correlation over 95% significant level, indicating that the summer SLP increases at

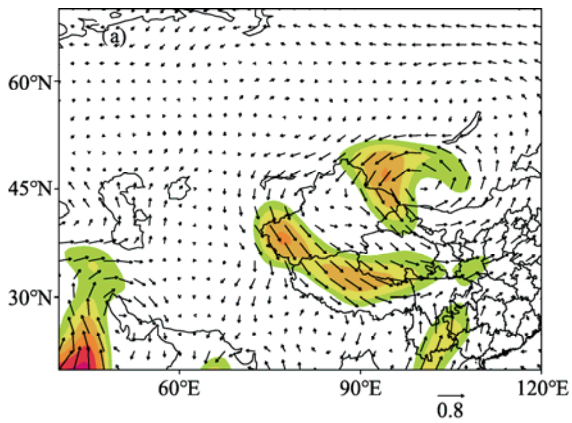

Fig. 5 The correlation distribution between the DSFI and horizontal wind (a) and between PC2 and horizontal wind (b) at 500 hPa in summer; shaded areas represent 95% significant test level.

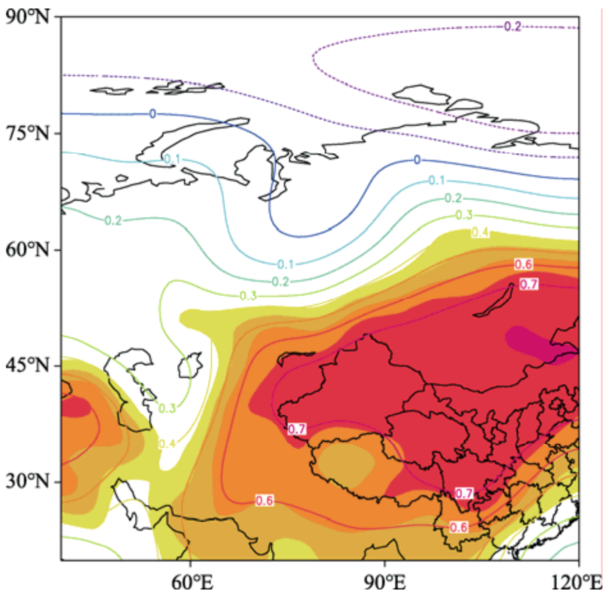

Fig. 6 Correlation between PC2 in May and SLP-JJA; shaded areas represent 95% significant test level.

mid-low latitudes over Asia during the positive phase of PC2 in May. According to the pressure equation P=ρRT, where ρ and R can be seen as constants, when the surface temperature increases, the SLP also increases. Therefore, the high and low pressure centers change, which is closely related with surface wind velocity (Wang and Zhai, 2004; Kang and Wang, 2005).

When SLP changes, it can influence meteorological factors of surface land (Liu, 1993; Liu and Guo, 2005; Wang et al., 2008). The various factors are closely related to summer DSF, such as 10-m wind velocity, precipitation and 2-m air temperature. Some studies found that the 10-m wind velocity is the most important climate factor for summer dust storm occurrence over Tarim Basin (Ma et al., 2006; Li et al., 2008). The 10-m wind velocity Index (WVI) over Tarim Basin in summer was defined by averaging the 35-station wind velocity at 10 m height. Figure 7 shows the normalized time series of summer 10-m WVI and PC2 in May and their 11-a running mean. The 10-m WVI-JJA presents an opposite decadal change with PC2 in May and shows a strong correlation of –0.58 which is over 99% significant level. When the linear trend was removed, the correlation coefficient is –0.42 (significance level is 99%). The relation between 10-m wind velocity and DSF is therefore quite significant on both inter-annual and decadal time scales. Because the SLP over Tarim Basin increases, it generates the anomalous high pressure center and weakens the pressure gradients, which results in weak 10-m wind velocity over Tarim Basin.

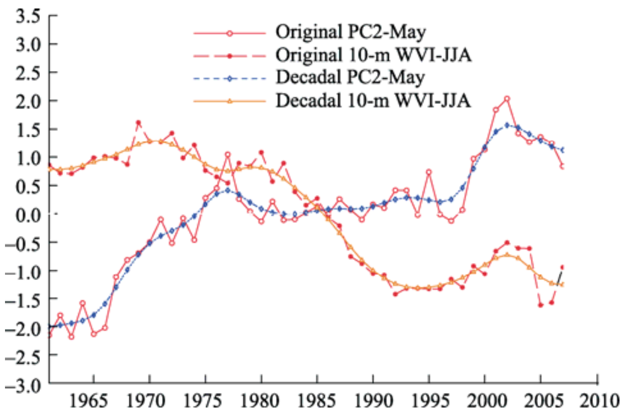

Fig. 7 Normalized time series of 10-m WVI-JJA and PC2 in May and their 11-a moving mean series

4 Discussion and conclusions

As a frequent natural disaster over Tarim Basin in summer, the dust storm can cause huge damages on local economic activities. If the dust storm occurrence can be predicted, it would reduce the economic losses to a great extent. Based on the observed and reanalysis data, this paper analyzed the effects of thermal anomalies in Tibetan Plateau in May on summertime dust storm frequency over Tarim Basin. The main conclusions are as follows:

When negative anomalies in Tibetan Plateau and positive anomalies in its southern region along 30°N (the second mode of surface temperature anomalies by EOF decomposition) are present in May, the time coefficient (PC2) plays an important role in the dust storm related circulation during boreal summer. There is a significant correlation between PC2 and dust storm frequency during boreal summer in Tarim Basin (correlation= –0.69). When PC2 is in positive phase, there is an anticyclone anomalous circulation at 500 hPa in North China in summer, which weakens northwest wind and is not beneficial for cold air moving from high latitude to Tarim Basin. Because the cold air activity frequency was decreased, the surface air temperature increased, which resulted in the strengthening of surface level pressure and the reversing of pressure gradient direction. Furthermore, the anomalous high pressure center generates over Tarim Basin and weakens the pressure gradients, which weakens the surface wind velocity. Above the all are contributed to reduced summertime dust storm frequency over Tarim Basin.

The induced reasons of dust storm are complex, making prediction hard. This paper, based on the view of the thermal anomalies in Tibetan Plateau in May, analyzed the effects on summertime dust storm frequency over Tarim Basin. The results show the thermal anomalies in May have close relations with summertime dust storm frequency, and the former can be used as a prediction factor for the latter. The paper gives a preliminary analysis on the possible relation mechanism between the thermal anomalies in Tibetan Plateau in May and summertime dust storm frequency over Tarim Basin. Further study in future work is needed.

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