Impact of South Asian monsoon on summer dust weather occurrence over the Tarim basin in Northwest China

Lixia Meng, Yong Zhao, Anning Huang, Tianzhu Wang and Yang Wu

1 School of Atmospheric Sciences, Chengdu University of Information Technology, Chengdu, 610225, People’s Republic of China
2 State Key Laboratory State of Severe Weather and Joint Center for Atmospheric Radar Research of CMA/NJU, School of Atmospheric Sciences, Nanjing University, No.163 Xianlin Avenue, Nanjing, 210023, Jiangsu, People’s Republic of China

E-mail: anhuang@nju.edu.cn

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Abstract
Based on the observed dust weather occurrence (DWO), precipitation and 10 m wind speed at 23 stations over the Tarim Basin in northwest China and the National Centers for Environment Prediction/National Center for Atmospheric Research reanalysis data during 1961–2015, we have indicated the relationship between the summer DWO over the Tarim basin and South Asian summer monsoon (SASM) and revealed the possible underlying physical mechanisms. Results show that the DWO displays an obvious declining trend during 1961–2015 and has a good relation with precipitation and 10 m wind speed over the Tarim Basin in summer. Meanwhile, the index of SASM well correlates with the summer DWO over the Tarim basin at both interannual and interdecadal time scales. Further analysis of the underlying mechanism related to the impact of the SASM on the DWO over the Tarim Basin in summer indicates that an anomalous cyclone (anti-cyclone) appears in the upper troposphere over Central Asia responding to an anomalous anti-cyclone (cyclone) in the lower troposphere over Indian monsoon region during weak (strong) SASM years, which can cause cooling (warming) at middle and upper troposphere over Central Asia. Based on the relationship of thermal wind, the cooling (warming) results in an anomalous cyclone (anti-cyclone) at middle and upper troposphere over Central Asia and the anomalous south (north) winds prevail over the Tarim Basin. The south (north) winds are favorable for more (less) precipitation formation and inhibit (promote) the cold (warm) air entering into the basin and weaken (strengthen) the 10 m wind speed, further leading to the decreases (increases) of DWO over the Tarim Basin in summer.

1. Introduction
The dust weather is a common meteorological disaster and frequently occurs in arid and semi-arid zone, and about 800 trillion grams of dust are entrained into the atmosphere over Asia every year (Huang et al 2014). The mineral dust aerosol particles cannot only influence the radiative forcing and cloud microphysical processes, but also cause the increases in concentration of PM$_{10}$ and PM$_{2.5}$ (Tegen et al 1996, Chadwick et al 1999, Zhao et al 2008), which results in serious climatic and environmental problems, disruption of social and economic activities and even damage human health. The arid and semi-arid climate dominates the whole North China, especially in Northwest China. In this region, the deserts and Loess Plateau are one of main dust sources in Northern Hemisphere (Prospero et al 2002, Zhao et al 2006). The severe dust weather events occurring in northern China can even influence Korean, Japan, Pacific and western coast of North America (Duce et al 1980, Husar et al 2001, Zhao and Gong 2003) and have attracted more and more attention in the climatic and environmental researches.

Many studies have addressed the distribution, variation and formation mechanism of dust weather (Qian et al 2002, Wang et al 2003a, Fan and Wang 2007, Li et al 2008). The dust events mainly occur in Northwest China, North China, Northwest China and Tibetan Plateau, especially in the Tarim Basin of Xinjiang and Hexi...
corridor of Gansu (Zhou 2001, Wang et al 2003a). The observations indicate the dust weather occurrence (DWO) has shown a strong declining trend over North China in past several decades (Ding et al 2003, Zhang and Ren 2003, Li et al 2008, Zhao et al 2012). Some studies suggest that the decrease of DWO over North China is found to be well related to the westerly jet, polar vortex, and Siberian High though affecting the cold air activity and surface wind speed (Zhao et al 2004, Gong et al 2006, Duan et al 2013). In addition, some studies point out that the large-scale circulation patterns play evident roles in spring dust weather variability over East Asia, such as AO, NAO, AAO and PNA, which can lead to anomalous atmospheric circulation and change regional weather and climate (Fan and Wang 2004, Gong et al 2007, Mao et al 2011, Zhao et al 2013a). Recent studies argue that the variation of underlying surface also is well related to DWO, i.e, the vegetation variations in southeastern Mongolia and central North China have considerable impact on spring dust events over Northeast Asia (Mao et al 2013). The interannual variation of winter sea ice cover in the Barents Sea also plays an important role in dust-related climatic conditions over North China (Fan et al 2017, Ji and Fan 2019).

The Tarim Basin is the largest inland basin and covers the largest desert-Taklimakan desert in China which is an important source area for dust weather (Wang et al 2003a, Zhao et al 2006). In this region the dust weather frequently occurs in spring and summer, but the DWO in most North China is concentrated in spring (Zhou 2001, Wang et al 2003a, 2003b, Li et al 2008, Zhao et al 2012). Previous studies mainly focus on the influencing mechanism of the dust weather in spring, and less attention has not paid to the dust weather in summer over the Tarim Basin (Yang et al 2006, Zhao et al 2013a, 2013b). The causes of the declining trend of DWO over the Tarim Basin in summer is still unclear. Wu et al (2010) shows that the East Asian Summer Monsoon (EASM) correlates well with DWO in North China via influencing circulation and precipitation. However, there are no evidences indicate that the EASM can affect the weather and climate over the Tarim Basin. Our previous studies found the South Asian Summer Monsoon (SASM) has important indirect effects in precipitation and surface wind speed over the Tarim Basin which are important meteorological factors related to DWO (Ma et al 2006, Li et al 2008). Current analysis shows that the SASM is well related to the DWO over the Tarim Basin in summer. The aim of this study is to explore how the SASM affects the DWO over the Tarim Basin in summer and further address the possible underlying physical mechanisms.

2. Study data and analytical method

2.1. Study data

The data used in this study are listed as follows: (1) the DWO, 10 m wind speed and precipitation derived from the records at 23 meteorological stations over the Tarim Basin (figure 1) during 1961 to 2015. The DWO denotes the number of days with dust weather events, including dust haze, blowing dust and dust storms defined by Goudie and Middleton (1992). (2) The National Centers for Environment Prediction (NCEP) and National Center for Atmospheric Research (NCAR) reanalysis dataset (Kalnay et al 1996) (https://psl.noaa.gov/data/gridded/data.ncep.reanalysis.html) during 1961 to 2015 is used to analyze the large-scale anomalous circulation. Following Webster and Yang (1992), the South Asian Summer Monsoon index (SASMI) is defined...
by the zonal wind shear between 850 hPa and 200 hPa regionally averaged over South Asia (0–20 °N, 40–110 °E). We concentrate on the analysis of the results during boreal summer months (June–August, JJA).

2.2. Analytical method
The Pearson correlation coefficient and simple linear regression are used in this study. The t-test is both used to test the significance of the correlation coefficient and simple linear regression as follows:

\[ t = \frac{r \sqrt{n - 2}}{\sqrt{1 - r^2}} \]

Where \( r \) is the correlation coefficient between two time series, \( n \) is the sample size for the time series and in this study \( n = 55 \). When \(|t| > t_\alpha\) (critical value, \( \alpha = 0.10, 0.05, 0.01 \)), it indicates the correlation coefficient can pass the significance level (\( \alpha = 0.10, 0.05, 0.01 \)).

3. Results
We firstly show the annual and linear trend variation of summer DWO over Tarim Basin and its related meteorological factors during 1961 to 2015. As shown in figure 2(a), it is clear that the DWO presents an obvious declining trend with the change over \( \alpha = 0.01 \) significant level. More DWO occurs in 1970s and less DWO occurs after 2000. The meteorological factors, such as surface wind speed, air temperature and precipitation contribute to trigger the dust weather over the Tarim Basin (Ma et al 2006, Li et al 2008). The correlation coefficient of DWO with 10 m wind speed (precipitation) is 0.80 (−0.40), which is over \( \alpha = 0.01 \) significance level. It is clear the 10 m wind speed plays an important role in influencing the DWO, but the precipitation is also contributed the occurrence of DWO over the Tarim Basin.

Figure 3(a) displays the normalized time series of the DWO over the Tarim Basin and the SASMI and their 9-year running means. Both the DWO and the SASMI present a clear interdecadal change. The DWO is in positive (negative) phase during 1961–1985 (1986–2015) and shows a clear declining trend during 1961–2015. Similarly, the SASMI is in positive (negative) phase during 1961–1992 (1993–2015) and presents an obvious weakening trend during 1961–2015. The DWO and SASMI show a strong correlation of 0.56, which is over...
\[ a = 0.01 \text{ significant level.} \] After removing the long-term trends in these time series, the correlation coefficient between the DWO and SASMI is 0.27 \((a = 0.05 \text{ significant level})\). This suggests the linkage between them is strong at both interannual and interdecadal time scales. In addition, the SASMI is well related to the 10 m wind speed (precipitation) over the Tarim Basin in summer with the correlation coefficient of 0.33 \((-0.28)\), which is over \( a = 0.05 \) significant level.

According to figures 2 and 3, the relationship between the SASM and summer DWO is mainly through the effects of the SASM on the surface wind speed and precipitation over the Tarim Basin. The interannual and interdecadal variations of SASM can affect regional and global climate (Lawrence and Webster 2001), but it can’t directly influence the weather and climate over the Tarim Basin because of the terrain block of the Tibetan Plateau. Our previous study shows that the SASM can influence the temperatures variations at middle and upper troposphere, furthermore, the anomalous temperature can cause the adjustment of large-scale circulation over Central Asia (Zhao et al. 2014). Figure 4(a) displays the regressions of the temperature vertically averaged from 500 to 200 hPa and wind at 200 hPa against the SASMI. According to the well-known Matsuno–Gill-type response to tropical forcing (Matsuno 1966, Gill 1980), a low-level cyclonic pattern is corresponded to an upper level anti-cyclonic pattern in the northwest side of the heating source (the Indian monsoon region). The regressions of 200 hPa wind against the SASMI show such feature. It is clear that there is an anomalous anti-cyclonic pattern Plateau in the upper troposphere over west Tibetan corresponding to the strengthened SASM. During the weak SASMI years, an anomalous cyclone over the west Tibetan Plateau responds to the cold air advection and hence a cooling located at the middle and upper troposphere over Central Asia. Meanwhile, the SASMI is well related to the index of middle and upper tropospheric temperature (MUTTI), which is defined by the normalized air temperature at the middle to upper troposphere \(500–200 \text{ hPa}\) regionally averaged over Central Asia \((35–45^\circ \text{N}, 55–75^\circ \text{E})\) during 1961–2015, and the correlation coefficient is 0.34 which is over \( a = 0.05 \) significant level.

Weak correlations between the SASMI and winds at 500 hPa over the Tarim Basin confirm the SASM can’t directly affect the climate over the Tarim Basin, but it can influence the temperature variations at the middle and upper troposphere. According to the relationship of thermal wind, the warming (cooling) would be
corresponded to an anomalous anti-cyclone (cyclone). Figure 5(a) displays the regressions of the 500 hPa wind against the MUTTI. It is clear that the warming corresponds to an anomalous anti-cyclone over Central Asia. When the SASM weakens, an anomalous cyclone over Central Asia corresponded to the cooling is a key circulation system influencing the climate over the Tarim Basin in summer (Yang and Zhang 2007, Zhao et al 2014). The anomalous cyclone can cause the south wind prevailing over the Tarim Basin. Figure 5(b) shows the regressions of the water vapor flux vertically integrated from surface to 300 hPa against the MUTTI. The negative
MUTTI is well associated with an anomalous anticyclone over the Indian Peninsula and cyclone over central Asia. At the first step, the anomalous anticyclone over the Indian Peninsula strengthens the transport of the water vapor from the tropical Indian Ocean into the middle latitude regions. Then the anomalous cyclone over central Asia continues to intensify the transport of the water vapor from the middle latitude regions to Tarim Basin (Zhao et al 2014). So the Tarim Basin receives more precipitation in summer. Above indicate that the anomalous south wind in east side of the anomalous cyclone over central Asia is the key circulation system in influencing the weather and climate over the Tarim Basin. Figure 5(c) displays the annual variation of the MUTTI and the middle tropospheric meridional wind index (MTVI), which is defined by the normalized summer 500 hPa meridional wind speed regionally averaged over Central Asia (35–45 °N, 75–90 °E) during 1961–2015. MUTTI and MTVI correlate well with a correlation coefficient of −0.68 which is over α = 0.01 significant level, indicating that the cooling at the middle and upper troposphere can cause anomalous cyclone over Central Asia and south wind prevailing over the Tarim Basin. On one hand, the south winds of the anomalous cyclone can transport warm and wet air into the Tarim Basin and lead to more precipitation in summer. The correlation between the MTVI and the regionally averaged rainfall over the basin also confirms above results (figure 5(c)). On the other hand, the magnitude of the summer horizontal sea level pressure (SLP) gradients over the Tarim Basin is weakened (strengthened) due to the prevailing anomalous south (north) winds at 500 hPa (figure 6(a)), further leading to weakening (strengthening) surface wind speed and influencing the DWO (Kuroasaki and Mikami 2003, Zhai and Li 2003). Meanwhile, the MTVI and the regionally averaged 10 m wind speed over the basin shows a correlation coefficient of −0.33 (figure 6(b)) over α = 0.05 significant level, which further confirms the explanation of figure 6(a).

4. Conclusion and discussion

In North China the DWO mainly occur in spring, but over the Tarim Basin the DWO is also concentrated in summer different from other region of North China (Ma et al 2006, Li et al 2008). Many previous studies have revealed the possible mechanism of the DWO in spring over the Tarim Basin (Yang et al 2006, Li et al 2008, Zhao et al 2013a), but what cause the DWO in summer over the Tarim Basin is still unclear. In this study, we identify a possible physical mechanism of the SASM on the DWO in summer. As well known, because of the Tibetan Plateau, the SASM cannot directly influence the climate over the Tarim Basin, but it plays an important indirect role in influence the precipitation and surface speed over the Tarim Basin through affecting middle and upper temperature over central Asia. According to the Matsuno–Gill-type atmospheric response (Matsuno 1966, Gill 1980), a possible mechanism indicates that an anomalous anti-cyclone at the lower troposphere over Indian monsoon region and an anomalous cyclone over Central Asia at the middle and upper troposphere corresponding to the weakened SASM lead to the cooling at the middle and upper troposphere over central Asia, which show low vortex or trough in synoptic circulation (Zhang et al 2012). On the one hand, the south wind at the east side of the anomalous cyclone (trough) can transport more warm and wet air into the Tarim Basin favoring to form more rainfall, on the other hand it can inhibit the cold air from the high latitudes entering into the basin and weaken the surface wind speed. Above all are contributed to decrease the DWO over the Tarim Basin in summer.

Figure 6. (a) Regressions of the magnitude of the summer SLP gradients against the MTVI. Shaded regions in (a) and (b) show over \( \alpha = 0.05 \) significant level. (b) Normalized time series of the summer MTVI (green line) and 10 m wind speed (red line) regionally averaged over Tarim Basin in summer during 1961–2015.
In current study, we emphasize that the impact of the SASM on summer DWO over the Tarim Basin, but weaknesses still exist in our analysis. For example, the reasons for changes in the SASM are not discussed. Previous studies suggest that the current and future changes in the SASM are related to the sea surface temperatures (SSTs) warming in the Indian Ocean (Li et al. 2015). As well known, the El Niño Southern Oscillation (ENSO) plays an important role in the SSTs warming in the Indian Ocean (Watanabe and Jin 2002, Yu and Lau 2005, Abish et al. 2018). Then whether the ENSO can impact the summer DWO over the Tarim Basin? Partial correlation shows the ENSO cannot well correlate with the summer DWO over the Tarim Basin. So the effect of ENSO on DWO maybe is indirect and unclear at present. In the future studies, based on the model and comprehensive analysis, we will report the effects of SASM on the DWO with and without ENSO influence and reveal the possible mechanism.

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ORCID iDs

Anning Huang @ https://orcid.org/0000-0001-9872-440X

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