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

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PAPER

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

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**Keywords:** Tarim basin, South Asian summer monsoon, summer dust weather occurrence

## 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 semiarid 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

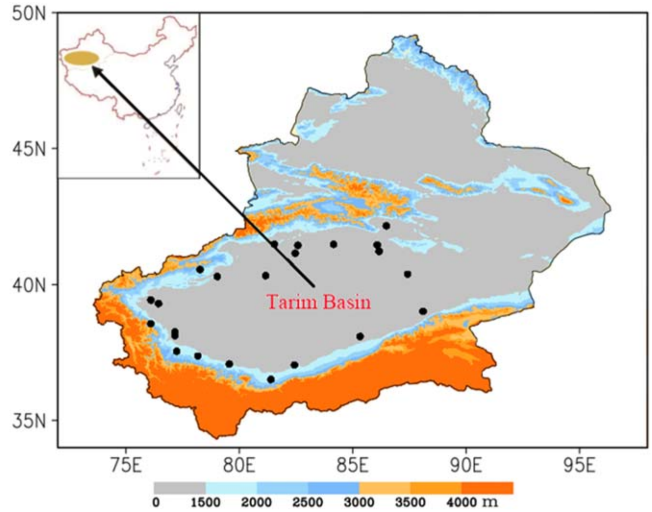


**Figure 1.** The location of Tarim Basin and the distributions of the 23 meteorological stations (black dots). The shaded regions denote the terrain height.

corridor of Gansu (Zhou 2001, Wang *et al* 2003a). The observations indicate the dust weather occurrence (DWO) has shown a strong declining trend overNorth 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

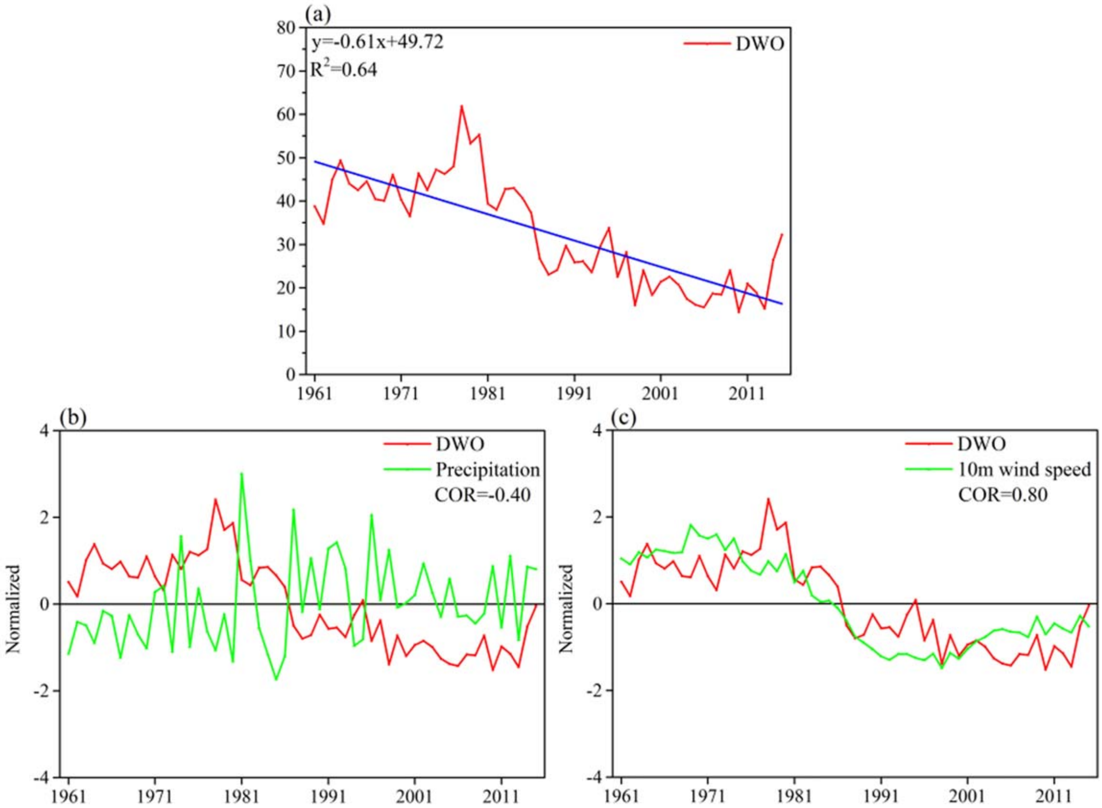


**Figure 2.** (a) Time series of the summer DWO (red line) and the linear trend (blue line) during 1961–2015, (b) Normalized time series of the summer DWO (red line) and precipitation (green line) over the Tarim Basin during 1961–2015, (c) as (b) but for the DWO (red line) and 10 m wind speed (green line).

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:

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

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

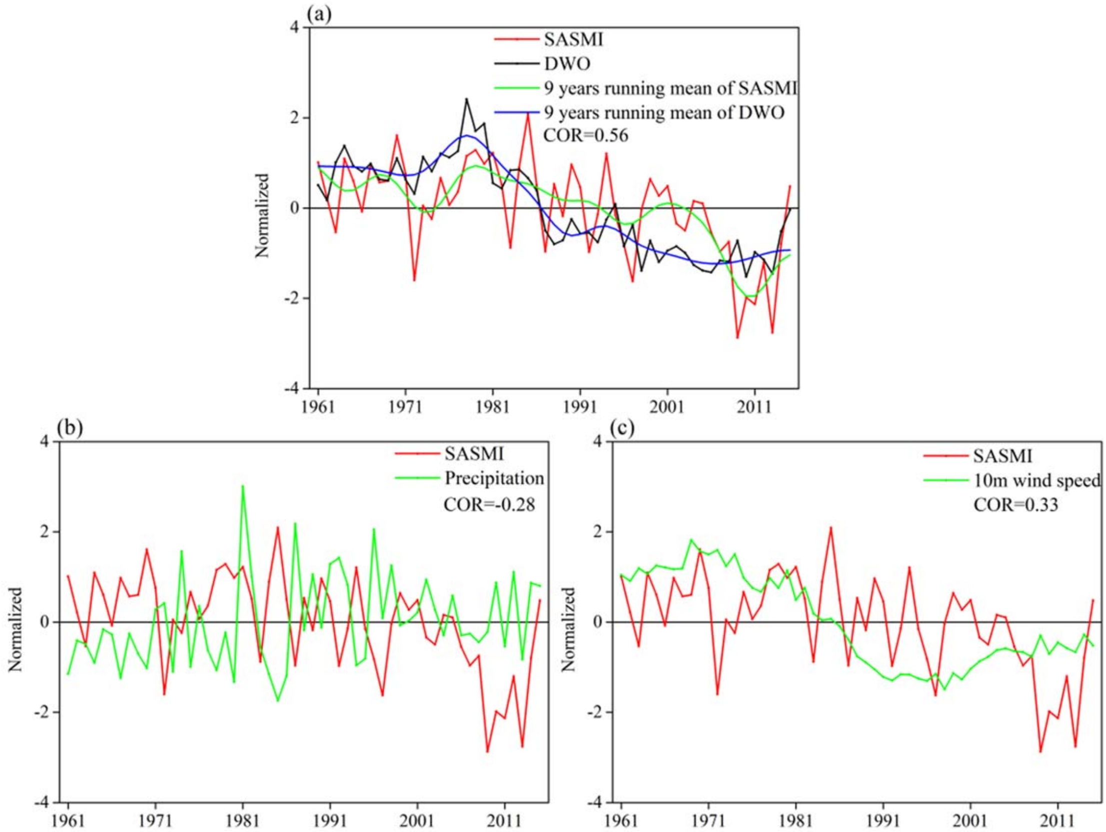


**Figure 3.** (a) Normalized time series of the summer DWO (black line) and SASMI (red line) and their 9-years running means (SASMI, green line; DWO, blue line) during 1961–2015, (b) Normalized time series of the SASMI (red line) and precipitation (green line) regionally averaged over the Tarim Basin in summer during 1961–2015, (c) as (b) but for the SASMI (red line) and 10 m wind speed (green line).

$\alpha = 0.01$ significant level. After removing the long-term trends in these time series, the correlation coefficient between the DWO and SASMI is 0.27 ($\alpha = 0.05$ 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 $\alpha = 0.05$ 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 hPa) regionally averaged over Central Asia(35–45 °N, 55–75 °E) during1961–2015, and the correlation coefficient is 0.34 which is over $\alpha = 0.05$ 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

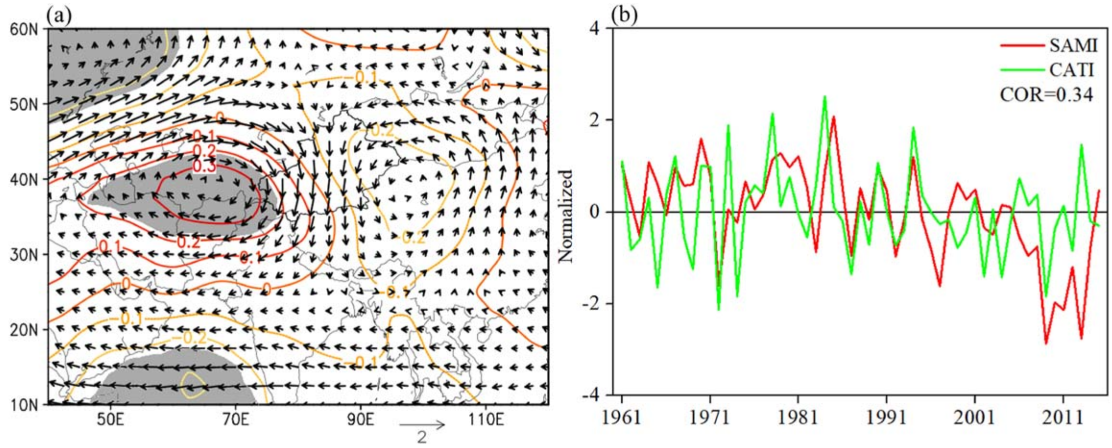


**Figure 4.** (a) Regressions of the air temperature (contour, °C) vertically averaged from 500 to 200 hPa and wind vector (vector, $ms^{-1}$) at 200 hPa against the SASMI. Shaded regions show over $\alpha = 0.05$ significant level. (b) Normalized time series of the summer SASMI (red line) and MUTTI (green line) in summer during 1961–2015.

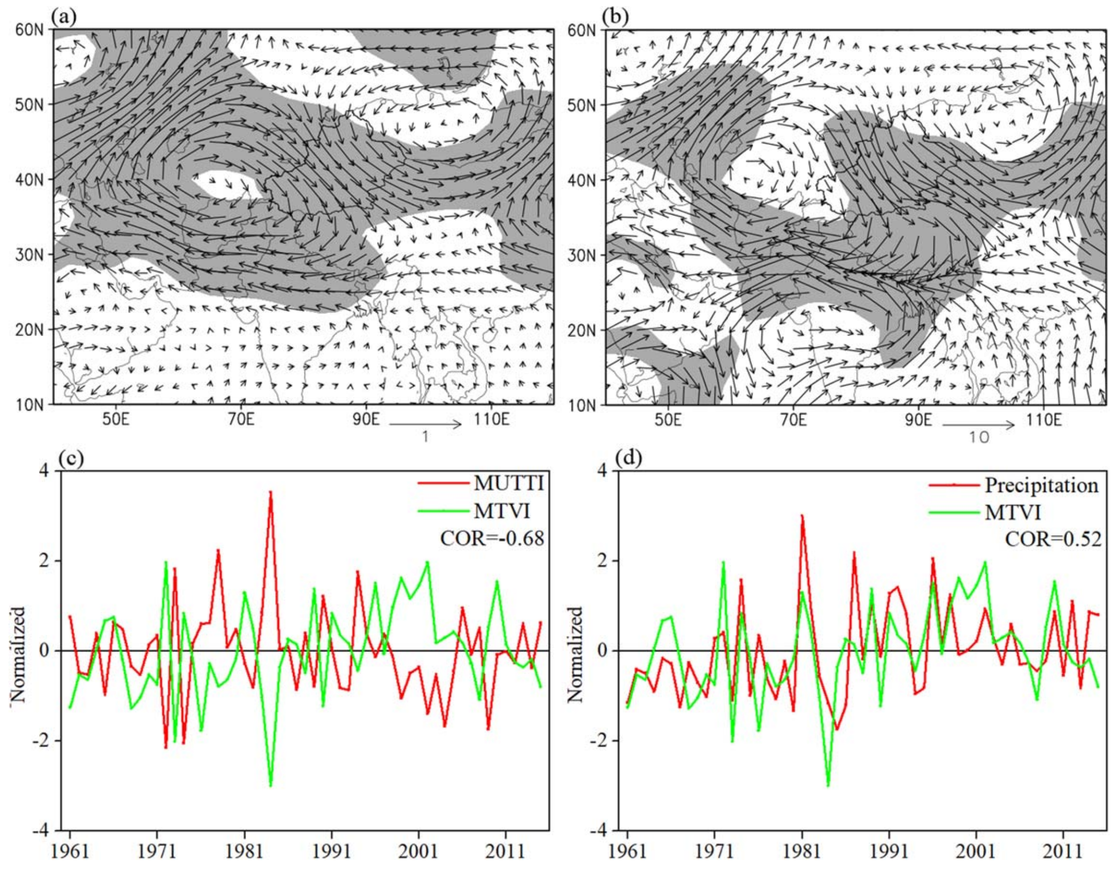


**Figure 5.** (a) Regressions of the wind vector (vector $ms^{-1}$) at 500 hPa against the MUTTI. (b) Regressions of the water vapor flux vertically integrated from surface to 300 hPa against the MUTTI. Shaded regions in (a) and (b) show over $\alpha = 0.05$ significant level. (c) Normalized time series of the MUTTI (red line) and MTVI (green line) in summer during 1961–2015. (d) Normalized time series of the precipitation (red line) regionally averaged over Tarim Basin and MTVI (green line) in summer during 1961–2015.

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

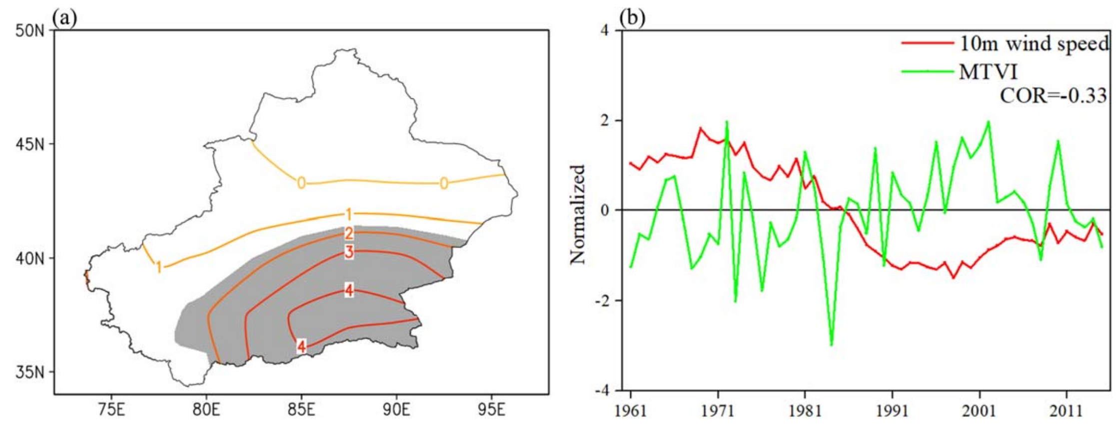


**Figure 6.** (a) Regressions of the magnitude of the summer SLP gradients against the MTVI. Shaded regions in (a) and (b) show over $\alpha = 0.05$ significant level. (b) Normalized time series of the summer MTVI (green line) and 10 m wind speed (red line) regionally averaged over Tarim Basin in summer during 1961–2015.

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 $\alpha = 0.01$ 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 (Kurosaki and Mikami 2003, Zhai and Li 2003). Meanwhile, the MVTI and the regionally averaged 10 m wind speed over the basin shows a correlation coefficient of $-0.33$ (figure 6(b)) over $\alpha = 0.05$ 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.

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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## References

Abish B, Annalisa C and Satyaban B 2018 ENSO and the recent warming of the Indian Ocean *Int. J. Climatol.* **38** 203–14
Chadwick O A, Derry L A, Vitousek P M, Huebert B J and Hedin L O 1999 Changing sources of nutrients during four million years of ecosystem development *Nature* **397** 491–7
Ding R Q, Wang S G, Shang K Z, Yang B D and Li J H 2003 Analysis of sandstorm and sand blowing weather trend and jump in China in recent 45 years *J. Des. Res.* **23** 306–10 (in Chinese)
Duan H X, Li Y H, Pu Z X, Zhao J H and Zhang L 2013 The influence of high level jet on dust transportation in a sandstorm process *J. Des. Res.* **33** 1461–72 (in Chinese)
Duce R A, Unni C K, Ray B J, Prospero J M and Merrill J T 1980 Long-range atmospheric transport of soil dust from Asia to the tropical North Pacific: temporal variability *Science* **209** 1522–4
Fan K and Wang H 2004 Antarctic oscillation and the dust weather frequency in North China *Geophys. Res. Lett.* **31** L10201
Fan K and Wang H J 2004 Antarctic oscillation and the dust weather frequency in North China *Geophys. Res. Lett.* **31** L10201
Fan K and Wang H J 2007 Dust storms in North China in 2002: a case study of the low frequency oscillation *Adv. Atmos. Sci.* **24** 15–23
Fan K, Xie Z M, Wang H J, Xu Z Q and Liu J P 2017 Frequency of spring dust weather in North China linked to sea ice variability in the Barents Sea *Clim. Dyn.* **51** 4439–50
Gill A E 1980 Some simple solutions for heat-induced tropical circulation *Quart. J. Roy. Meteor. Soc.* **106** 447–62
Gong D, Mao R, Shi P and Fan Y 2007 Correlation between East Asian dust storm frequency and PNA *Geophys. Res. Lett.* **34** L14710
Gong D Y, Mao R and Fan Y D 2006 East Asian dust storm and weather disturbance: possible links to Arctic oscillation *Int. J. Climatol.* **26** 1379–96
Goudie A S and Middleton N J 1992 The changing occurrence of dust storms through time *Clim. Change* **20** 197–225
Huang J, Wang T, Wang W, Li Z and Yan H 2014 Climate effects of dust aerosols over East Asian arid and semiarid regions *J. Geophys. Res. Atmos.* **119** 11398–416
Husar R B *et al* 2001 Asian dust events of April 1998 *J. Geophys. Res.* **106** 18317–30
Ji L and Fan K 2019 Climate prediction of dust weather frequency over northern China based on sea-ice cover and vegetation variability *Clim. Dyn.* **53** 687–705
Kalnay E *et al* 1996 The NCEP/NCAR 40-year reanalysis project *Bull. Am. Meteorol. Soc.* **77** 437–71
Kurosaki Y and Mikami M 2003 Recent frequent dust events and their relation to surface wind in East Asia *Geophys. Res. Let.* **30** 1736
Lawrence D M and Webster P J 2001 Interannual variations of the intraseasonal oscillation in the South Asian summermonsoon region *J. Climate* **14** 2910–22
Li H J, Li J and He Q 2008 Study on sandstorm trend and abrupt change in Xinjiang *J. Desert Res.* **28** 915–9 (in Chinese)
Li R, Lü S, Han B and Cao Y 2015 Connections between the South Asian summer monsoon and the tropical sea surface temperature in CMIP5 *J. Meteor. Res.* **29** 106–18
Ma Y, Xiao K and Wang X 2006 Climatological characteristics of dust weather in the Tarim Basin *Acta Sci. Natur. Univ. Pekinensis* **42** 784–90 (in Chinese)
Mao R, Ho C H, Feng S, Gong D Y and Shao Y P 2013 The influence of vegetation variation on northeast Asian dust activity *Asia-Pacific J. Atmos. Sci.* **49** 87–94
Mao R, Ho C H, Shao Y P, Gong D Y and Kim J 2011 Influence of Arctic oscillation on dust activity over northeast Asia *Atmos. Environ.* **45** 326–37
Matsuno T 1966 Quasi-geostrophic motions in the equatorial area *J. Meteor. Soc. Japan* **44** 25–43
Prospero J M, Ginoux P, Torres O, Nicholson S E and Gill T E 2002 Environmental characterization of global sources of atmospheric soil dust identified with the NIMBUS 7 total ozone mapping spectrometer (TOMS) absorbing aerosol product *Rev. Geophys.* **40** 1002
Qian W H, Quan L S and Shao S Y 2002 Variations of the dust storm in China and its climatic control *J. Clim.* **15** 1216–29
Tegen I, Lacis A A and Fung I 1996 The influence on climate forcing of mineral aerosols from disturbed soils *Nature* **380** 419–22

Wang S G, Wang J Y, Zhou Z J, Shang K Z, Yang B D and Zhao Z S 2003a *Regional characteristics of dust events in China Acta Geographica Sinica* **58** 193–200 (in Chinese)
Wang X, Ma Y, Chen H W and Tao Z Y 2003b Analysis on the climatic characteristics of sandstorms in south Xinjiang *J. Desert Res.* **23** 147–51 (in Chinese)
Watanabe M and Jin F 2002 Role of Indian Ocean warming in the development of Philippine Sea anticyclone during ENSO *Geophys. Res. Lett.* **29** 1478
Webster P J and Yang S 1992 Monsoon and ENSO: selectively interactive systems *Quart. J. Roy. Meteor. Soc.* **118** 877–926
Wu Y, Zhang R, Han Z and Zeng Z 2010 Relationship between East Asian monsoon and dust weather frequency over Beijing *Adv. Atmos. Sci.* **27** 1389–98
Yang L, Zhang G and Yang Q 2006 Circulation dynamical structure of sand dust storm caused by cold air crossing mountains in southern Xinjiang *J. Des. Res.* **26** 71–6
Yang L and Zhang Q 2007 Circulation characteristics of interannual and interdecandal anomalies of summer rainfall in north Xinjiang Chin *J. Geophys.* **50** 412–9 (in Chinese)
Yu J and Lau K 2005 Contrasting Indian Ocean SST variability with and without ENSO influence: a coupled atmosphere-ocean GCM study *Meteor. Atmos. Physics* **90** 179–91
Zhai P and Li X 2003 On climate background of dust storms over Northern China *Acta Geographica Sin.* **58** 125–31 (in Chinese)
Zhang L and Ren G Y 2003 Change in dust storm frequency and the climatic controls in Northern China Acta *Meteor. Sinica* **61** 744–50 (in Chinese)
Zhang Y H, Yang L M and Xiao K T 2012 The central Asian vortexes activity during 1971–2010 (in Chinese) *Plateau Meteor.* **23** 312–21
Zhao C S, Dabu X and Li Y 2004 Relationship between Climatic factors and dust storm frequency in inner Mongolia of China *Geophys. Res. Lett.* **31** L01103
Zhao T L and Gong S L 2003 Modeled size-segregated wet and dry deposition budgets of soil dust aerosol during ACE-Asia 2001: implications for trans-Pacific transport 2003 *J. Geophys. Res.* **108** 8665
Zhao T L, Gong S L, Zhang X Y and Jaffe D A 2008 Asian dust storm influence on North American ambient PM levels: observational evidence and controlling factors *Atmos. Chem. Phys.* **8** 2717–28
Zhao T L, Gong S L, Zhang X Y, Abdel-Mawgoud A and Shao Y P 2006 An assessment of dust emission schemes in modeling east Asian dust storms *J. Geophys. Res.* **111** D05S90
Zhao Y, Huang A, Zhou Y, Huang D, Yang Q, Ma Y, Li M and Wei G 2014 Impact of the middle and upper tropospheric cooling over central Asia on the summer rainfall in the Tarim Basin *J. Climate* **27** 4721–32
Zhao Y, Huang A, Zhu X, Zhou Y and Huang Y 2013a 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 *Environ. Res. Lett.* **8** 024026
Zhao Y, Li H, Huang A, He Q, Huo W and Wang M 2013b Relationship between thermal anomalies in Tibetan Plateau and summer dust storm frequency over Tarim Basin *J Arid Land* **5** 25–31
Zhao Y, Li H J and He Q 2012 Variation of dust storm days in Tarim Basin and its relation with North Atlantic Oscillation *J. Des. Res.* **32** 1082–8 (in Chinese)
Zhou Z J 2001 Blowing sand and sandstorm in China in recent 45 years *Quaternary Sci.* **21** 9–17 (in Chinese)