Two different periods of high dust weather frequency in northern China

FAN Ke, XIE Zhi-Ming and XU Zhi-Qing

Nansen-Zhu International Research Centre, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China; Collaborative Innovation Center on Forecast and Evaluation of Meteorological Disasters, Nanjing University of Information Science & Technology, Nanjing, China; University of the Chinese Academy of Sciences, Beijing, China; Climate Change Research Center, Chinese Academy of Sciences, Beijing, China

ABSTRACT
This study reveals that, during the period 1966–2014, dust weather frequency (DWF) in northern China (north of 30°N) features two high-DWF periods, in 1966–1979 (P1) and 2000–2014 (P2), when the linear trend of DWF is removed during the study period. Here, DWF denotes the number of days of dust weather events in the spring season (March–April–May), including dust haze, blowing dust, and dust storms, which occurred in northern China. The results show that the DWF is much higher in P1 than in P2, with increased DWF distributed over southern Xinjiang, the central part of northern China. The main cause is the SST difference in the Atlantic and Pacific between the two periods. It is also found that a meridional teleconnection over East Asia in P1 and a zonal wave-like pattern over Eurasia in P2 at 200 hPa play a significant role in the interannual variability in the two periods, respectively. SST over the subtropical North Atlantic (extratropical SST between the Norwegian and Barents seas) may partly contribute to the upper-level meridional (zonal) teleconnection in P1 (P2).

1. Introduction

Dust weather in northern China, including dust haze, blowing dust, and dust storms, mainly occurs in spring (March–April–May), affecting human health, the environment, and climate change via its direct and indirect effects on radiation over the Asia–Pacific region. Studies show that the long-term variation in dust weather frequency (DWF) in northern China features a decreasing trend during the past several decades, but increased after 1997, with a remarkable increase in DWF in 2000–2002 (Qian, Quan, and Shi 2002; Zhang et al. 2002; Kurosaki and Mikami 2003; Fan and Wang 2004, 2006a; Zhou and Zhai 2004). The variability of DWF in northern China is influenced by the surface wind and vegetation (Kurosaki and Mikami 2003; Zhou and Zhai 2004; Lee and Sohn 2009), northern cyclone frequency (Sun, Zhang, and Liu 2001; Qian, Quan, and Shi 2002), Eastern Asian winter monsoon (Qian, Quan, and Shi 2002; Kang and Wang 2005; Fan and Wang 2006a, 2006b; Wu et al. 2010), and large-scale atmospheric teleconnection, including the Antarctic Oscillation (AO) (Fan and Wang 2004, 2007), Arctic Oscillation (AO) (Kang and Wang 2005), and the Pacific–North America pattern (Gong et al. 2007). Based on this knowledge, an effective dust climate prediction model containing the AAO, AO, and dust-related climate factors was developed to improve the ability to predict the dust climate in China (Lang 2008).

In this study, considering the long-term decreasing trend of DWF in northern China is partly related to global...
the underlying physical mechanisms involved. The overall purpose of this work is to further our understanding of DWF variability in northern China.

2. Data and method

The monthly data of the number of days of dust weather, including dust haze, blowing dust, and dust storms, at 245 warming (Zhu, Wang, and Qian 2008), we remove the linear trend of DWF during 1966–2014 and discover that the detrended-DWF in northern China exhibits two high-DWF periods, in 1966–1979 (P1) and 2000–2014. These features can be detected using the moving t-test and Lepage test statistical methods, with the statistical significance exceeding the 95% confidence level. We then present the characteristics of the two high-DWF periods and explore the underlying physical mechanisms involved. The overall purpose of this work is to further our understanding of DWF variability in northern China.

Figure 1. (a) The first spatial EOF mode of normalized DWF at 245 stations in northern China during 1966–2014 (dots denote stations). (b) The time series of the first EOF mode of DWF, in which the red lines denote the average value of DWF for 1966–1979, 1980–1999, and 2000–2014. (c) The decadal change points of DWF variation as determined by a moving t-test, where the upper (lower) transverse lines denote significance at the 95% (90%) confidence level. (d) The difference in the spatial pattern of DWF between 1966–1979 and 2000–2014.
These differences of the above atmospheric circulation, particularly for the polar regions, show more active cold air over east Asia in P1, generating favorable dynamical conditions for increased DWF in northern China, which may explain why the intensity of DWF is stronger in P1 than in P2. As shown in Figure 2(b), while a greater portion of the SSTs (excluding those of the subtropical and tropical North Pacific) are cooling in P1 than in P2 (Figure 2(b)), along with decreased surface air temperature over the Eurasian continent (figure not shown), accordingly, the land–ocean thermal contrast over East Asia can increase, resulting in more robust northeasterly flow over East Asia in P1 than in P2 (Figure 2(c)). Therefore, the change in the SST pattern provides favorable dynamical conditions for a stronger intensity of DWF in P1. Additionally, compared with P2, spring precipitation over Mongolia and northern China decreases in P1, resulting in poorer vegetation coverage in these regions (Figure 2(d)) (Zhou and Zhai 2004; Kurosaki, Shinoda, and Mikami 2011).

Next, we investigate the differences in the interannual variability of DWF-related atmospheric circulation in the two periods. Figure 3 shows a regression of the spring wind field at 200 and 850 hPa on the DWF index in northern China in P1 and P2, separately. Associated with the high DWF index in P1, a remarkable meridional atmospheric pattern at 200 hPa is apparent, consisting of an anomalous cyclone and an anomalous anticyclone over the north and south of 40°N over the area (15–60°N, 90–135°E), respectively. Accordingly, the upper westerly East Asian jet at 40°N can be strengthened, which facilitates not only low-level cyclogenesis but also the upper westerly momentum downward. Correspondingly, there is an anomalous cyclone centered over Northeast Asia (45°N, 135°E), causing strong northwesterly flow from its rear (Figures 3(a) and (b)). As a result, greater quantities of dust can be transported from Mongolia to the central part of northern China by the northwesterly, and that is why the increased DWFs are distributed over the central part of northern China (see Figures 3(a) and 1(c)). Note that cold air activity from the polar region can easily invade southward via a weakened polar jet over Eurasia. Therefore, the DWFs in P1 are stronger than in P2, with most dust transported via Mongolia (Figure 1(d)). Moreover, spring soil moisture decreases more over Mongolia and northern China in P1 than in P2, which is favorable for increased DWFs in the central part of northern China in P1 (figure not shown).

In contrast, a zonal wave-like atmospheric pattern at 200 hPa is prominent in P2, which is characterized by a different anomalous cyclone over the extratropical North Atlantic centered at 60°N, an anomalous anticyclone over the Caspian Sea at 40°N, and an anomalous cyclone spanning from Mongolia to northern China at 35°N where the Mongolian cyclogenesis occurs (Figures 3(c) and (d)). Consequently, greater quantities of dust from the deserts weather stations in China during 1966–2014 are from the National Climate Information Center, China. The DWF at a station in China denotes the number of days of dust haze, blowing dust, and dust storms in the spring (March–April–May) at that station. The monthly reanalysis data used, with a horizontal resolution of 2.5° × 2.5°, are from the NCPEP–NCAR data-set (Kalnay et al. 1996). The monthly SST data used, with a horizontal resolution of 1.0° × 1.0°, are from the Characteristics of the Global Sea Surface Temperature data-set of the Japan Meteorological Agency, covering 1891–2015. EOF analysis is used to present the spatiotemporal structure of DWF in northern China. As the first spatial EOF mode (EOF1) of DWF in northern China at 245 weather stations shows basically coherent change, accounting for 28.4% of the total variance of DWF, DWF PC1 is defined as the index of DWF in northern China (Figure 1(a)). All calculations are based on the detrended data.

3. Results

There are three decadal change points, 1970/1971, the mid-1980s, and 2000/2001, in the variation of PC1 DWF in northern China, all statistically significant at the 0.05 level (Figure 1(c)). This indicates that DWF in northern China increased both in 1966–1979 (P1) and in 2000–2014 (P2), and decreased in 1980–1999. Moreover, the intensity of DWF in 1966–1979 (P1) is much larger than that in 2000–2014 (P2), accompanied by increased DWFs over the central part of northern China, including Inner Mongolia, the Hetao region, North China, and the southern part of Xinjiang (Figure 1(d)). But which climate factors likely influenced the two high-DWF periods? To address this question, we investigate the decadal differences in mean SLP and SST between them, as well as the dust-related interannual variation in these two periods.

We begin by plotting the decadal differences of mean SLP and SST between P1 and P2 (P1–P2). As shown in Figure 2(a), relative to P2 in March–April–May, negative phases of the North Atlantic Oscillation (NAO) and AAO are evident in P1, with increased SLP over the high latitudes of the North Atlantic and Antarctic and decreased SLP over the midlatitudes of the Eurasian continent and the SH. Previous research shows that the winter and spring NAO and AAO may impact upon the Siberian high and Aleutian low, upper-level polar jet, and subtropical east Asian jet via atmospheric teleconnection, further influencing DWF variation in northern China (Wu and Wang 2002; Fan and Wang 2004, 2006a, 2006b, 2007; Kang and Wang 2005; Gong et al. 2007). Meanwhile, the Siberian high and Aleutian low are more robust in P1 compared with P2 and stronger northeasterly flow prevails along the eastern flank of the Siberian high and East Asian coast. These differences of the above atmospheric circulation,
of Northwest China can be transported to northern China via the strong westerly flow of the southern part of the Mongolian cyclone. Therefore, a dust-related atmospheric pattern plays a key role in the northwesterly (westerly) dust pathways of P1 (P2).

But what about the linkage between the interannual variation of SSTs and dust-related atmospheric circulation in the two periods? As shown in Figure 4, associated with the increased DWF in P1, a negative SST anomaly (SSTA) occurs in the subtropics of the North Atlantic, persisting from winter to spring, which is related to the negative phase of the NAO (e.g. Rodwell and Rowell 1999). A so-called 'North Atlantic horseshoe pattern,' with warm SST southeast of Newfoundland and cold SST to the northeast.
and southeast, precedes a positive phase of the NAO. The predictability of the winter NAO partly derives from the SSTA over the subtropical North Atlantic (Fan, Tian, and Wang 2015; Tian and Fan 2015). Meanwhile, the SSTA pattern over the North Pacific is characterized by a positive SSTA extending from the subtropical North Pacific to the South China Sea and a negative SSTA surrounding the other regions, which favors a strengthened east Asian jet. However, the North Pacific SSTA may mainly reflect the results of atmospheric forcing (Yang, Lau, and Kim 2001). On the other hand, corresponding to increased DWF in P2, a positive SSTA over the Barents Sea and a negative SSTA over the Norwegian Sea are apparent. Thus, we next focus on how the SSTA over the North Atlantic and Barents–Norwegian Sea may influence the DWF-related atmosphere in the two periods.

We define the NA1 index as the averaged SST in the subtropical North Atlantic (40–50°N, 25–45°W) in P1. NA2, meanwhile, is defined as the averaged SST over the Barents Sea (70–75°N, 30–40°E) minus the averaged SST over the Norwegian Sea (60–65°N, 0°–5°E) in P2, because an opposite change in SSTA between the two regions is prominent.

**Figure 3.** Regression of spring wind on the DWF index in (a, c) 1966–1979, and (b, d) 2000–2014 at (a, b) 200 hPa and (c, d) 850 hPa. Notes: Shading indicates statistical significance at the 95% level (Student’s t-test; units: m s⁻¹).

**Figure 4.** Regression of SST in (a) 1966–1979, and (b) 2000–2014. Notes: Dotted regions are statistically significant at the 95% confidence level (Student’s t-test; units: °C).
4. Summary

This study reveals two high-DWF periods in northern China during the overall study period of 1966–2014, when the decreasing trend of DWF is removed; namely, 1966–1979 (P1) and 2000–2014 (P2). Compared with P2, the intensity of DWF is much stronger in P1, together with the increased DWFs being mainly distributed in the central part of northern China and the south of Xinjiang. The results show a remarkable difference in mean atmospheric circulation and the global SST pattern between the two periods, including prominent changes in the polar regions. The magnitude of land–sea thermal contrast over East Asia can provide different dynamical conditions for the two high-DWF periods. Moreover, decreased spring precipitation over Mongolia and northern China in P1 may result in poor vegetation coverage over these regions. Actually, it was found that the sharp decrease of spring vegetation coverage over northern China in recent years was one of the major contributors to frequent spring dust storms over northern China during 2000 and 2001 (Zhou and Zhai 2004; Kurosaki, Shinoda, and Mikami 2011). In terms of the interannual variation of the two high-DWF periods, it is found that an upper-level meridional teleconnection in P1 is favorable for a strengthening of the East Asian westerly jet around 40–45°N, which can facilitate not only low-level cyclogenesis but also westerly momentum downward from the upper level (Uccellini 1986; Fan and Wang 2004). Thus, greater quantities of dust can be transported from Mongolia into northern China by the northwesterly flow. In P2, a zonal wave-like pattern at 200 hPa results in westerly flow from the southern part of the Mongolian cyclone, with most of the dust transported from the deserts of Xinjiang. The SSTA over the subtropical North Atlantic and extratropical ocean may induce, via sea–atmosphere interaction, the meridional and zonal wave-like patterns of P1 and P2, respectively, which is partly illustrated by the result of the regression of the wave activity flux in the troposphere on NA1 and NA2. However, the extratropical SST change in P2 might be the response of the rapidly declining Arctic Sea ice, and the atmospheric circulation related to the high-DWF in P2 might be related to change in the Pacific Decadal Oscillation (Zhu et al. 2011). These questions will be explored in future work.

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Notes on contributors

**FAN Ke** is a professor at IAP, NZC. Her main research interests are climate dynamics, climate prediction. She has published over 70 scientific papers, over 40 of which are SCI-indexed.

**XIE Zhi-Ming** is a masters student at IAP, NZC. His main research interests are climate change and climate variability.

**XU Zhi-Qing** is a PH at IAP, NZC. His main research interests are climate variability.

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