

Impacts of climate abnormality on remarkable dust storm increase of the Hunshdak Sandy Lands in northern China during 2001–2008

Tao Gao,^{a*} Jingwei Han,^b Yingshun Wang,^c Hao Pei^d and Shiqing Lu^a

^a Inner Mongolia Meteorological Institute, Hohhot 010051, People's Republic of China

^b Inner Mongolia Observatory, Hohhot 010051, People's Republic of China

^c Xilinhot National Climatological Observatory, Xilinhot 026000, People's Republic of China

^d Inner Mongolia Meteorological Bureau, Hohhot 010051, People's Republic of China

ABSTRACT: From 1961 to 2008, the overall frequency of dust storms in northern China has shown an unquestionable reduction. However, the Hunshdak Sandy Lands of northern China display an increasing frequency in dust storm activities, especially during the period 2001 to 2008. In an attempt to explore the cause of this increase, a comprehensive investigation was conducted by examining the climate variables, the average normalized difference vegetation index (NDVI) and the local inhabitant migrations. The climate variables include local precipitation, temperature, aridity, evaporation, relative humidity, soil moisture and wind speed. Moreover, by analyzing the 2001–2008 average anomaly charts (relative to the 30 year climatology of 1971–2000) of the upper air and surface conditions, an advantageous atmospheric circulation background for drought development over the Hunshdak was confirmed. Meanwhile, a multivariable step-regression model was employed to distinguish the significant variables of the climate elements mentioned before. The model output suggests that aridity is the leading factor impacting the Hunshdak dust storm frequency. During 2001 to 2008, the lack of local precipitation, higher temperature and strong evaporation deteriorated the local surface condition to below that before 2000, which is verified by the reduction of vegetation cover (NDVI), soil moisture and relative humidity. Furthermore, compared to the 30 year climatology of the wind speed observed during dust storm occurrence time, the mean velocity of 2001–2008 was reduced by 3.0 m s^{-1} , indicating that even with relatively weaker winds, dust storms still occurred primarily due to the degeneration of surface conditions around the Hunshdak. Copyright © 2011 Royal Meteorological Society

KEY WORDS Hunshdak sandy lands; climate condition; drought development; dust storm increase; wind velocity

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1. Introduction

A dust storm is an undesirable weather phenomenon which is more likely to occur in arid and semiarid regions in the world. There are two major regions in Northwest China where dust storms frequently occur (Gao and Han, 2010a): the Taklimakan, located in Xinjiang Uigur Autonomous Region, and north central China ($94\text{--}120^\circ\text{E}$; $35\text{--}45^\circ\text{N}$), which is mentioned as northern China in this article. The Hunshdak Sandy Lands is located in the Xilin Gol League, which is in the middle area of Inner Mongolia, a part of China's semiarid area (Figure 1). The ecological environment is extremely vulnerable and sensitive to climate influences (Cheng *et al.*, 2004). The dust storms of the Hunshdak Sandy Lands and the elements influencing them have been discussed in several studies. During the period 3–14 April 2000 it was discovered that about 20.9% of the suspended dust in dust storms throughout all of North China came from

the Hunshdak Sandy Lands (Cheng *et al.*, 2005). A significant negative relationship existing between soil water content and precipitation levels, as well as wind speeds during dust storm occurrence times, was observed in a study focusing on dust storms at the Chinese-Mongolian border town of Erlianhot, which is just outside the northwest edge of the Sandy Lands, from 2002 to 2003 (Li *et al.*, 2006). The dust-emitting wind speed measured at a height of 1 m and the longest distance that the Hunshdak dust aerosol particles travel are estimated at 5.6 m s^{-1} and from 7.6×10^4 to $7.6 \times 10^5 \text{ km}$ respectively (Yue *et al.*, 2008). A study regarding the period 1961–2000 has demonstrated that the region of the Hunshdak has become warmer and a little wetter since 1961, while the dust storm frequency changes are in an uptrend with a fluctuant pattern (Cheng *et al.*, 2004). In addition, there is much literature which focuses on East Asian dust storms. These researches refer to monitoring methods and equipments, characters of temporal-spatial distributions, synoptic situation and atmospheric circulation analyzes for some particular dust storm events, climate controls, moving paths, numerical simulating models, anthropogenic

* Correspondence to: T. Gao, Inner Mongolia Meteorological Institute, Xincheng Hailaer Str. No. 49, Hohhot 010051, Inner Mongolia, People's Republic of China. E-mail: Frautao@yahoo.com

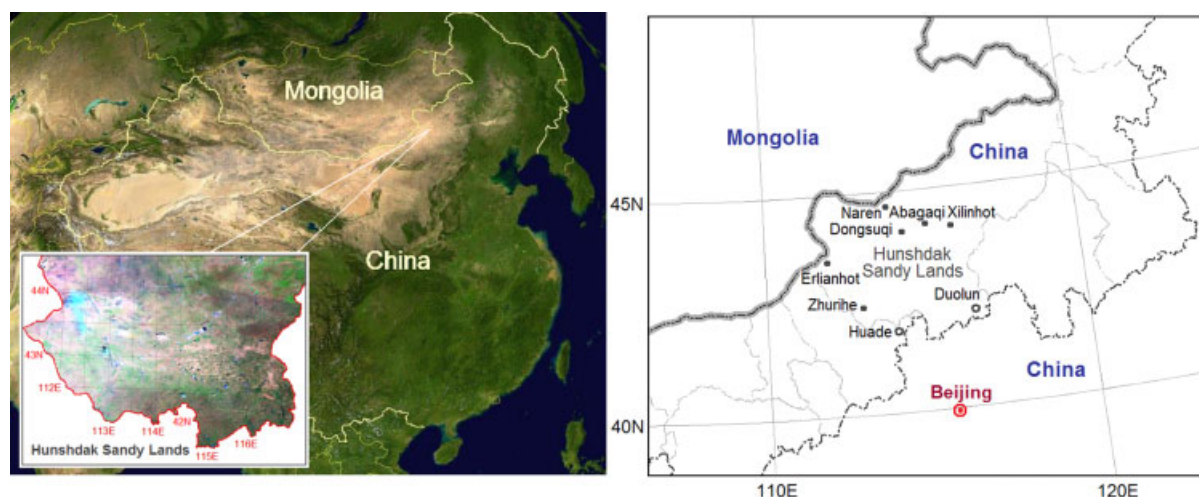


Figure 1. Location of the Hunshdak Sandy Lands in China and the selected stations in the studied domain and the downwind nearby regions. The open circles represent dust storm observation points located around the Hunshdak and the black dots denote the selected stations used in calculations. This figure is available in colour online at wileyonlinelibrary.com/journal/met

influence and air pollution. The chemical, psychical and optical characters of dust aerosols, suspending particles (TSP), particulate matter $10\ \mu\text{m}$ (PM_{10}) or smaller in aerodynamic diameter are analyzed by using monitoring data of satellites, lidar apparatus and sand-dust filter instruments (Augustine *et al.*, 2003; Miller, 2003; Chung *et al.*, 2005; Yasui *et al.*, 2005; Zhang *et al.*, 2005). Studies on dust storms associated with suspended dust weather observations and analyses indicate that Northwest China is the most dust storm frequently hit region and its downwind areas, such as the Korean Peninsula, Japan and Taiwan are influenced by dust storms which occurred in their upwind regions (Zhao *et al.*, 1997; Chung *et al.*, 2003). Outcomes of analyzing dust storm temporal-spatial distributions, moving paths as well as numerical models for simulating sand and dust traces, transportation and depositions show that the dust storm particles are transported *via* the moving path of the currents or jet flows in the upper air and then dropped on to the surface (Huang and Wang, 1998; Qiou and Cao, 2001; Lee *et al.*, 2003; Gong *et al.*, 2006). Some other studies focus on climate controls. The study of Qian *et al.* (2002) displays a significant relationship between precipitation and dust storms in Northwest China. Furthermore, based on detailed analyses of the influence of previous sea surface temperature, atmospheric circulation conditions and indices, some climate controlling elements and potential climate predictors have been examined in the research of Gao and Han (2010a). Despite the achievements mentioned above, some studies also focused on designing dust storm weather or seasonal prediction models and have developed some acceptable forecast results (Sun *et al.*, 2003; Gao *et al.*, 2009, 2010b). In addition, dust storms and associated pollution events in Beijing and Asia are explored by Fang *et al.* (2003) and Seinfeld *et al.* (2004). Others researchers examined anthropogenic influences and the effects on human health related to dust storms (Liu *et al.*, 2006) and the identification of the

correlations between surface conditions and dust storms (Zou and Zhai, 2004).

Recognizing the differences between a dust storm day (DSD) and a dust storm event (DSE) for a particular domain is the fundamental issue in dust storm studies. Currently, a dust storm frequency series is counted using a daily time scale at individual stations and is widely used in most dust storm research. The definitions of a DSD, floating dust weather, a severe dust storm day, or a strong dust storm day, have been identified by meteorological organizations or by scientists for a single station. For example, a DSD is simply defined as a day where horizontal visibility is below 1000 m accompanied by wind speeds over $10.8\ \text{m s}^{-1}$ observed at four regular daily observation times: 0000, 0600, 1200 and 1800 UTC (CCMB, 1979). A DSE may be measured by using horizontal visibility and wind velocity, satellite images or even creating a dust storm index (Qian *et al.*, 2002; Gao *et al.*, 2003; Ding and Li, 2004; Peng *et al.*, 2004; Wang *et al.*, 2006; Zhang *et al.*, 2006; Song *et al.*, 2007). Various statistical definitions can cause dissimilar time series of dust storm frequencies, which will lead to different outcomes in dust storm investigations and analysis, especially in making long term observations of the frequencies for climate influence analysis. This occurs because dust storms happen not only simply at a single station or on a single day. In general, a DSE or a SDSE may include a few, or perhaps many, stations with dust storm records or reports, and based on the power of a cold front, may have durations from several hours to several days. Therefore, the definition of a DSE or SDSE should be considered objectively based on the size of the focus domain as well as the researcher's intention in conducting the research. In the newly published GB/QX 2008 a DSE is identified if there are at least three nearby national reference climatological stations that have recorded a dust storm score at the same time. But in regional dust storm investigating practices it is still somehow too strict. For instance, it has just

13 national reference climatological stations scattered in Inner Mongolia, which is a very large province in China. If this DSE standard is used to identify the dust storm events, there would be less dust storm processes that meet the criteria, especially in the period of infrequent occurrence of dust storms of 1980–1990s. Otherwise, only a small part of long term dust storm observation data can be utilized for dust storm studies because the number of the national reference climatological stations (143 stations) takes only a small part of all available meteorological observatories (752 stations) in China. The definition which is arrived at in this paper is more comprehensive, due to the use of multiple stations, which takes into account a larger temporal and spatial variation, as well as factoring more of the climatic conditions, than previous definitions.

It has been demonstrated that the surface condition is the primary determining element for dust storm outbreaks in grassland regions. This is revealed by clarifying the regional differences of the dust storm occurrence area in East Asia, in which the Hunshdak Sandy Lands is classified as a grassland region (Kurosaki and Mikami, 2005). By investigating dust storms and the land surface characteristics of China, it is proven that dust storm occurrences have a strong correlation with wind speeds during 1980–2000, which in turn is strongly related to land surface features. Therefore, the deterioration of surface vegetation cover may significantly influence the occurrence of dust storms in China (Xu *et al.*, 2006). The correlations are calculated in the analysis from Liu *et al.* (2004) among spring dust storms, wind speed, precipitation, soil moisture and vegetation conditions in northern China during 1982–2001. The analysis suggests that spring dust storms have a strong positive relationship with upwind wind velocity, and strong negative correlations with previous summer precipitation, soil moisture anomalies, as well as vegetation conditions. Furthermore, the relationship between vegetation and dust storms over China from 1982 to 2001 is discussed in the research of Xukai *et al.* (2004). It is revealed that vegetation cover plays an important role in interannual dust storm occurrences. A coefficient of -0.59 at 99% confidence level exists between vegetation coverage and areas affected by dust storms.

Although the temporal-spatial variations of dust storms in the whole area of northern China display a decreasing tendency during 1961–2008, in this study an opposite trend of dust storms in temporal-spatial changes has been found in the Hunshdak and its nearby region in the same period. This increase leads to investigations of the Hunshdak in more detail, mainly considering of the climate conditions in decadal time scale. The article is laid out as follows: data sources, definitions, calculation and analysis methods are presented in Section 2. In Section 3, the observed variations of dust storms and wind velocity changes of the Hunshdak during 1961–2008 are displayed, and the climate influence factors are diagnosed in Section 4. The main cause is explored in Section 5 and summary and conclusions can be viewed in Section 6.

2. Data, definitions and methods

2.1. Data source

The daily dust storm observation data set is obtained from the Data Service Centre of China Meteorological Administration, whose data, including horizontal visibility and wind speed during dust storm occurrence time, is recorded at four regular observation times (0000, 0600, 1200 and 1800 UTC) at 591 stations with available records in China. This set is used for statistical accounting and analyzing dust storm frequencies both in northern China and in the Hunshdak Sandy Lands. Eight meteorological stations in the Hunshdak and the nearby downwind region are selected as representative observatories that are employed to investigate and analyze dust storm and climate situations in the past 48 years (1961–2008). Since there are no weather observation stations set in the innermost part of the Hunshdak, available and high-quality data from six stations around it are selected. Data from two other stations (Huande and Duolun, WMO numbers 53391 and 54208 respectively) are chosen in the nearby downwind region (Figure 1) to report dust storms in the Hunshdak. Detailed information on all eight selected stations is available in Table I.

The monthly data sets of precipitation, temperature and evaporation capacity recorded at those eight selected

Table I. Information of the eight selected stations around the Hunshdak.

Region	Station name	WMO number	Latitude (N)	Longitude (E)
Around the Hunshdak Sandy Lands	Xilinhot	54 102	43°57'	116°04'
	Zhurihe	53 276	42°24'	112°54'
	Erlianhot	53 068	43°39'	111°58'
	Naren	53 083	44°37'	114°09'
	Abagaqi	53 192	44°01'	114°57'
	Dongsuqi	53 195	43°52'	113°38'
In nearby downwind region	Huade	53 391	41°54'	114°00'
	Duolun	54 208	42°11'	116°28'

WMO, World Meteorological Organization.

Table II. Statistical definitions of dust storm and severe dust storm events.

Region	Dust storm	Total number of stations on the worst day	Horizontal visibility (m)	Influence radius of core region (km)
Northern China	DSE	≥ 5	≤ 1000	≥ 79.4
	SDSE	≥ 5	≤ 500	≥ 79.4
Hunshdak Sandy Lands	DSE	≥ 3	≤ 1000	≥ 57.4
	SDSE	≥ 3	≤ 500	≥ 57.4

DSE means dust storm events and SDSE denotes severe dust storm events.

stations are obtained from Inner Mongolia Meteorological Information Centre. The regional mean precipitation, temperature, evaporation and aridity index of the Hunshdak Sandy Lands are calculated by averaging the corresponding records of those six stations around the Sandy Lands. The 30 year climatology (1971–2000) and the anomaly charts of 2001–2008 (compared to the 30 year climatology) including the relative humidity at 850 hPa, surface soil moisture, sea level pressure, geopotential height at 500, 700 and 850 hPa. The wind vectors, air temperature fields at the surface and at 850 hPa are created by employing the monthly reanalysis datasets that were downloaded from the National Centre for Environment Prediction-National Centre for Atmospheric Research, America (NCEP-NCAR).

The vegetation activities were observed through monitoring indicators equipped on the satellite. The satellite-based normalized difference vegetation index (NDVI) set used in this study is derived from two periods of satellite monitoring data sets. For the period 1981–2001, the NDVI data (1.1×1.1 km) measured by Advanced Very High Resolution Radiometer (AVHRR) were downloaded from the website of the National Oceanic and Atmospheric Administration (NOAA/AVHRR). For the period 2002–2007, the Moderate-Resolution Image Spectroradiometer (MODIS) was sourced from the satellite data (250×250 m) of the National Aeronautics and Space Administration (NASA/MODIS), which were unified into spatial resolution 1.1×1.1 km after a spatial sampling process.

The population data referred to seven counties of the Xilin Gol League that cover the Hunshdak region, and the total investment of financial support for ecological migration project was obtained from the local Statistical Office of Xilin Gol League, Inner Mongolia, China.

2.2. Definition of dust storm event

According to current investigations, in northern China, spring (March to May) has been identified as the most frequent dust storm occurrence season in a year. However, severe dust storms can also occur in February or June in some years. An example of this occurred on 4 June 1990, one of the most severe dust storms recorded, where two of the six stations reported a horizontal visibility below 1000 m and three others observed a visibility below 500 m (the sixth station recorded no dust storm

due to an observed visibility over 1000 m). Since then, a longer term is concerned in this research which starts on the first day of February and ends on the last day of June. Hereafter, all calculations and estimations referring to dust storm and strong wind frequency will be under the consideration of this time scale, which will be referred to as a dust storm frequent season (DSFS).

A dust storm or severe dust storm score will be given to a individual station if one of the four measured horizontal visibilities is below 1000 or 500 m (CCMB, 1979) among the daily surface observation records at four regular measurement times (0000, 0600, 1200 and 1800 UTC). The total number of the scored stations among the six observatories in the Hunshdak on the worst day is used to distinguish dust storm event (DSE) and severe dust storm event (SDSE) for this specific domain. Furthermore, by employing a Geographic Information System, the estimated radius of the core influence area of the SDE and SDSE is calculated within the circle which is drawn from the five or three nearest stations in northern China or in the Hunshdak. Statistical definitions of DSE and SDSE in the DSFS for northern China and the Hunshdak Sandy Lands are presented in Table II.

2.3. Calculating and analyzing method

By consulting the available data sets, the monthly precipitation and potential evaporation capacity data are firstly standardized and then, following the calculation method introduced in the book of Zhang (2008), a simple aridity index is computed by using monthly precipitation to divide monthly mean potential evaporation at the six selected stations for the period from 1961 to 2008. This kind of aridity index has a value range varying from 0 to 1. A bigger index indicates a severer drought, and *vice versa*. The Hunshdak regional precipitation, temperature, evaporation and the aridity index are obtained from calculating the mean of the values at the six stations and the regional soil moisture is evaluated by averaging the values of all grids in the rectangle (112.25° – 116.25° E; 42.25° – 44.75° N) which covers the Hunshdak.

All unified NDVI data mentioned above were normalized into values ranging from 0 to 255. A pixel of the satellite NDVI monitoring image represents the vegetation situation in a square of 1.1×1.1 km². The square value (the pixel value) will be recorded as '0' if there is no surface vegetation cover in the area and the value of

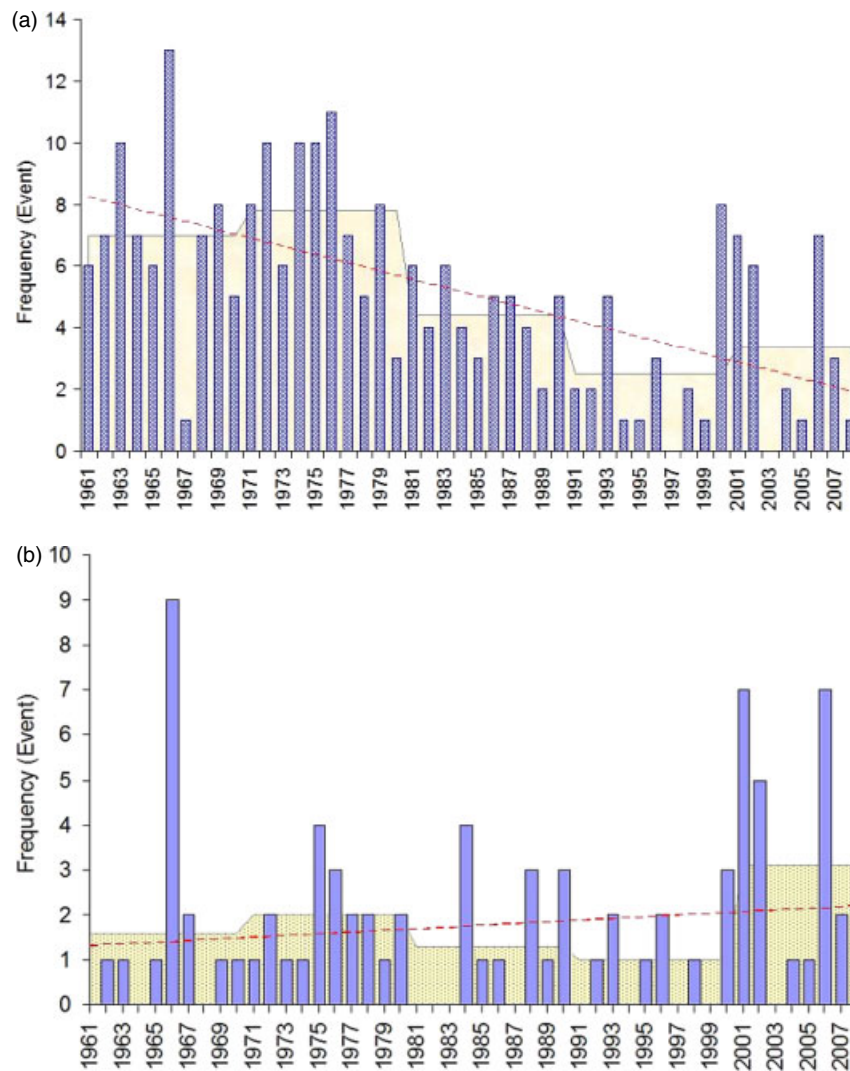


Figure 2. Yearly variations of dust storm events observed from 1961 to 2008 (The trend indicated by dashed line is a linear fitting line), (a) for northern China, (b) for Hunshdak. Decadal mean , Dust storm events , Trend . This figure is available in colour online at wileyonlinelibrary.com/journal/met

‘255’ indicates full vegetation cover in the square. Here, August NDVI data were employed to represent annual surface vegetation features. The regional mean NDVI of the Hunshdak and its vicinity for each year within the period from 1981 to 2007 were estimated by averaging the NDVI values at all grids in the region which covers the Hunshdak (see the inset small map in Figure 1).

The classical multivariable step-regression model was employed for analyzing and finding the major impacting elements from all investigated climate variables that affect dust storms in the Hunshdak Sandy Lands. The model was then set with backward step, which means that during initialization, all candidate independent variables are input into the model simultaneously, not sequentially.

3. Observed variations of dust storms and wind speeds

The results of the investigation of yearly dust storm variations indicate that the dust storm frequency of

northern China exhibits a declining trend (indicated by a fitting line) in the past 48 years (1961–2008). The 1970s was the decade that had the highest frequency of dust storms while the 1990s showed the lowest frequency, with a mean DSE of 7.8 and 2.5 respectively. The mean DSE of 2001–2008 is 3.4, which is larger than that of the 1990s with a value of 2.5, but smaller than the decadal frequencies of 1960s, 1970s and 1980s, which was 7.0, 7.8 and 4.4 (Figure 2(a)). The increasing trend of DSE yearly variations of the Hunshdak Sandy Lands during 1961–2008 (Figure 2(b)) is contrary to the dust storm trend of the whole region, northern China. A notable find in this research is the significant increase of DSE frequency of the Hunshdak in the period of 2001–2008, with a mean value of 3.1 for DSE and 1.9 for SDSE separately. Both of the frequencies of 2001–2008 are higher than that of all the last four decadal means of the 20th Century (Table III). In addition, a noticeably extended and more frequent dust storm area can be seen over the Hunshdak Sandy Lands by a comparison of

Table III. Decadal mean of dust storm events, aridity index, precipitation anomaly and NDVI of the Hunshdak.

Decadal mean	Dust storm frequencies		Aridity index		Precipitation anomaly (mm)			NDVI
	DSE	SDSE	Prior year	Prior winter	Prior year	Prior summer	Prior winter	Prior August
1960s	1.6	1.3	0.45	0.14	−9.9	−9.0	−0.9	–
1970s	2.0	1.8	0.40	0.13	2.3	1.4	−0.3	–
1980s	1.3	0.2	0.41	0.08	−8.3	−3.2	0.3	164.0
1990s	1.0	0.1	0.42	0.09	6.0	1.8	0.0	168.2
2001–2008	3.1	1.9	0.57	0.22	−34.9	−32.2	−0.2	156.2
Climatological normality (1971–2000)	1.4	0.7	0.41	0.10	–	–	–	–

DSE means dust storm events and SDSE denotes severe dust storm events.

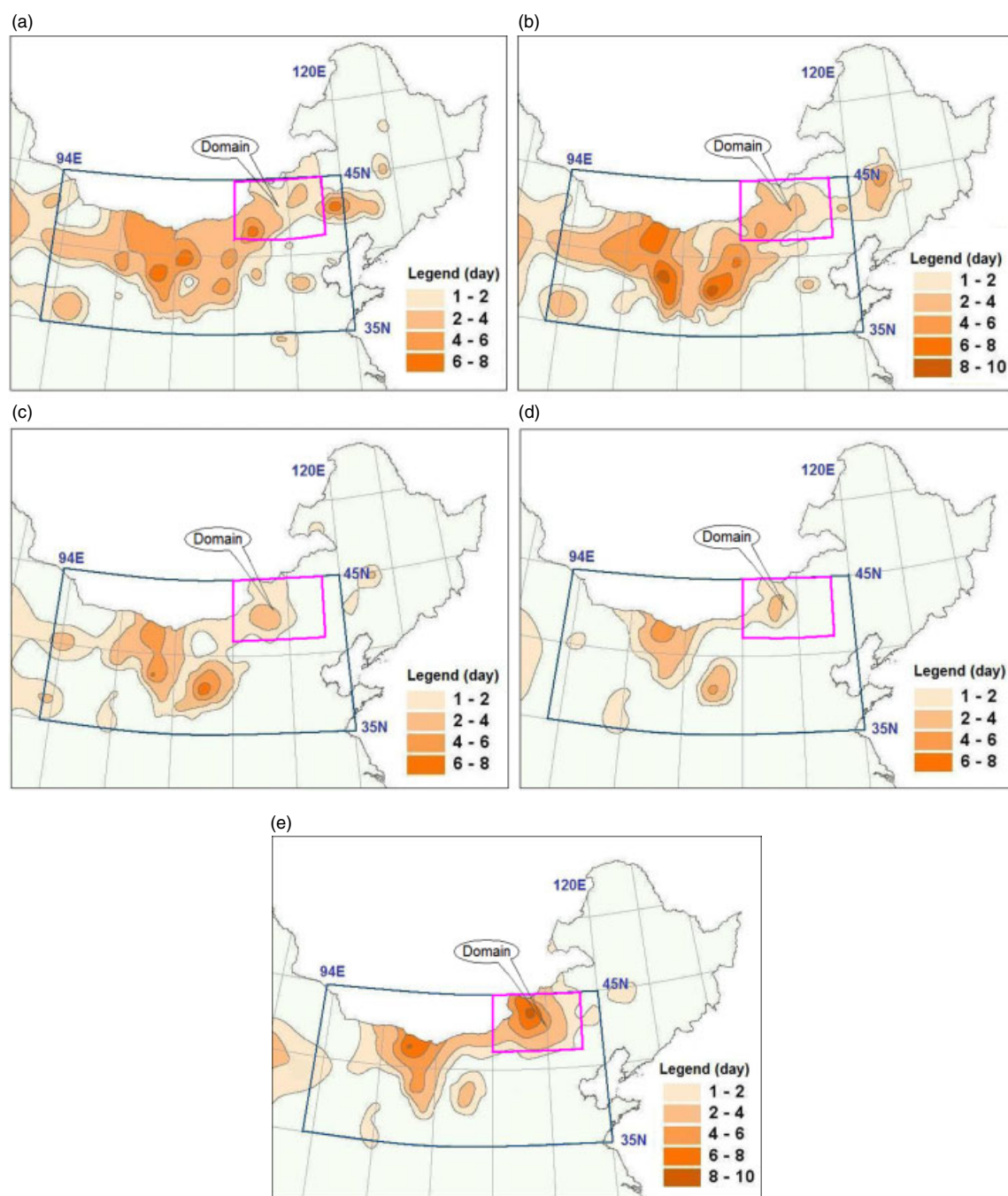


Figure 3. Mean dust storm distribution in northern China and in studied domain, (a) for 1960s, (b) for 1970s, (c) for 1980s, (d) for 1990s, (e) for 2001–2008. This figure is available in colour online at wileyonlinelibrary.com/journal/met

Table IV. Decadal mean of the highest wind speeds (m s^{-1}) during dust storm occurrence time at six selected stations in the Hunshdak.

Decades	Xilinhot	Zhurihe	Erlianhot	Naren	Abagaqi	Dongsuqi	Six station mean
1970s	17.2 (18)	22.1 (28)	21.5 (28)	20.4 (8)	20.2 (17)	18.5 (13)	20.0
1980s	19.5 (4)	19.3 (28)	20.1 (19)	18.0 (15)	18.6 (15)	16.9 (17)	18.7
1990s	17.9 (2)	16.7 (22)	19.7 (14)	20.4 (6)	15.8 (8)	20.1 (19)	18.4
2001–2008 mean	15.0 (24)	15.6 (45)	15.8 (30)	16.7 (15)	15.6 (27)	17.5 (56)	16.0
Climatological normal (1971–2000)	17.6 (23)	19.6 (78)	20.3 (62)	19.2 (29)	18.7 (40)	18.6 (49)	19.0

Numbers in parentheses denote the total dust storm days with available wind speed records during the period in the same row.

the spatial distribution of 2001–2008 to the four decadal spreads from 1960s to 1990s (Figure 3(a)–(e)).

According to our investigations, the strong weather processes display a highly significant correlation with dust storm events in the whole region of northern China during springtime. The coefficient of the two elements is 0.84, at the 0.01 significance level. A station in northern China will be given a strong wind score if the maximum daily wind velocity equals to or over 17 m s^{-1} . The severe wind event is identified if there are more than five stations in the region with the scores on the worst windy day (Gao *et al.*, 2010b). However, the detailed investigated result does not exhibit any significant connection between severe winds and dust storm events in the Hunshdak Sandy Lands. This is an exceptional phenomenon of major concern for northern China in this study. The changes of local vegetation conditions and aridity situations are supposed to be the major disturbing elements. The confirmed surface degeneration of the Sandy Lands should be a critical influence that may yield a possible situation: less strong winds might cause dust storms in Hunshdak in the period 2001–2008. Aimed at verifying this hypothesis, 10 min means of the highest wind speeds during dust storm occurrence periods in dust storm days at the six selected stations have been investigated in detail. A remarkable find in wind speed variations is that the wind speed recorded during dust storm occurrence time decreased noticeably in the period of 2001–2008 in comparison with the 30 year climatology at all six stations. The most notable changes happened at Erlianhot (53068). Comparing the wind speed of 2001–2008 to the station's 30 year climatological mean, it is found that the velocity has decreased by 4.6 m s^{-1} at this station. Meanwhile, the smallest decrease in the wind speed occurred at Dongsuqi (53195) with a value of 1.0 m s^{-1} . The mean of regional changes of the velocity has reduced by 3.0 m s^{-1} (Table IV).

4. Influence elements

4.1. Precipitation and temperature

The amount of precipitation in the Hunshdak Sandy Lands in the growing season (from April to September) is very important to the surface vegetation. Commonly, the amount of annual rainfall is insufficient to support vegetation in Hunshdak: the 48 year mean annual precipitation

is only around 261.6 mm (mean of 1961–2008). Spring is the driest season with only 26.8 mm rainfall which accounts for 13.0% of the yearly precipitation. The amount of precipitation averages 166.2 mm in summer (July to September), which is 78.9% of the annual total amount. Therefore, the yearly precipitation of the Sandy Lands is mainly controlled by the amount of summer rainfall.

Around the Hunshdak, the previous year's rainfall will exert a notable influence on dust storm frequencies in the following DSFS over the region. The correlation coefficient between regional prior year precipitation and DSE is -0.45 , and -0.39 for SDSE, both of which are at the 0.01 significance level (Table V). Nevertheless, no significant correlation exists between concurrent precipitations and dust storms in DSFS over the Hunshdak. An alternate pattern of the positive and negative phases of regional precipitation anomalies can be viewed in Figure 4(a). The mean decadal rainfall does not vary to a large extent in the Hunshdak within the period of 1961–2000, ranging from -9.9 to 6.0 mm . Seven out of 8 years (2001–2008) show a negative precipitation anomaly. A significant negative phase with -34.9 mm precipitation anomaly appears during 2001–2008, which takes up a 15.5% deficit of the annual precipitation. This negative value clearly indicates that the average amount of rainfall is much less than the 30 year climatological value of the Sandy Lands, which is revealed by the mean annual precipitation of 1971–2000 (Table III).

Table V. Correlation coefficients between aridity index, precipitation, NDVI and dust storms of the Hunshdak and nearby downwind stations.

Dust storms	Aridity index (48a)		Precipitation (48a)		NDVI (27a)
	Prior year	Prior winter	Prior year	Prior summer	Prior August
DSE	0.52	0.38	-0.45	-0.43	-0.48
SDSE	0.48	0.40	-0.39	$-0.34!$	-0.57
Huad (day)	0.55	0.40	-0.47	-0.41	-0.55
Duolun (day)	0.45	0.46	-0.39	-0.39	-0.47

DSE, dust storm events; SDSE, severe dust storm events. Coefficients are at the 0.01 significance levels. '!', indicates the significance level is at 0.05.

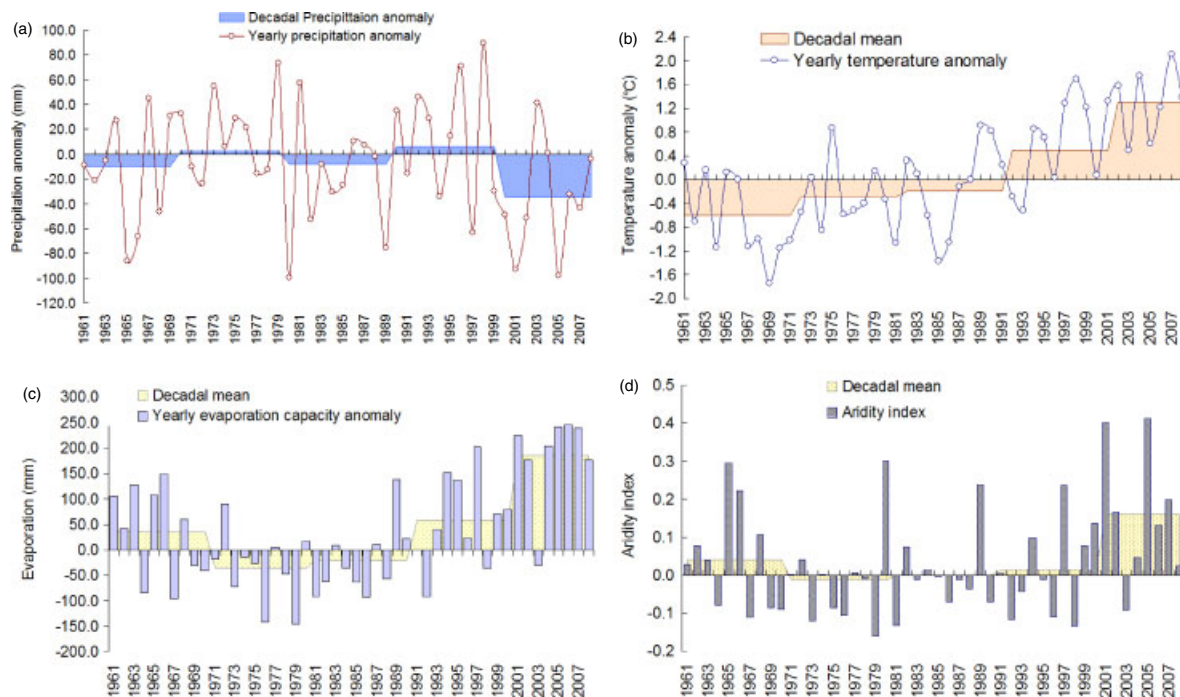


Figure 4. Yearly variations and decadal mean of precipitation, temperature, evaporation and aridity index anomaly of the Hunshdak from 1961 to 2008, (a) for precipitation, (b) for temperature, (c) for evaporation capacity, (d) for aridity index. This figure is available in colour online at wileyonlinelibrary.com/journal/met

The temperature of the Hunshdak Sandy Lands increased constantly during 1961–2008, especially in the last 8 years (Figure 4(b)). Calculated results point out that the local temperature both in previous and concurrent terms does not display a significant statistical correlation with dust storms in the Hunshdak. The correlation coefficient between the previous annual mean temperature and dust storm frequency is 0.16 and 0.19 for the contemporaneous spring time of the two elements. Those coefficients are far below the acceptable statistical significant levels. However, the annual mean potential evaporation capacity of the region has increased since 1980, especially during 2001–2008 (Figure 4(c)), which exhibits a close relationship with the increase of local temperature during 1961–2008, the correlation coefficient separately reaching 0.66 and 0.54 before and after the climatic trend, a linear trend, was removed (at the 0.01 significance level). Compared to the regional climatological normal of annual temperature (the mean of 1971–2000), mean temperature has increased by 1.3 °C during those 8 years, which drives the annual evaporation that has increased by 184.2 mm compared to its 30 year climatology. The significant increase in temperature should be one of the major causes that influence the capacity of potential evaporation over the period of 2001–2008. Therefore, the continuous drought over the Hunshdak in those 8 years is induced by the effects of less than normal precipitation with higher evaporation.

4.2. Aridity and surface conditions

Viewing the Hunshdak region in more detail, the decadal mean aridity index anomaly does not shift much over

1961–2000, but it performs a relatively more valuable role in the period 2001–2008 (Figure 4(d)). Furthermore, it is also suggested from the value of the annual aridity index that the atmosphere over the Hunshdak Sandy Lands has become drier in the period 2001–2008 than that of 1961–2000, and an identical case also appears in the previous winter (from the prior December to February) as well.

As in other arid and semiarid places in the world, precipitation always plays an important role in control of the surface soil moisture of the Hunshdak. The coefficient value between them is 0.55, at the 0.01 significance level. Moreover, a large negative anomaly area, with the value from -20 to -40 mm, can be seen in the anomaly chart of the surface soil moisture of 2001–2008 (Figure 5). This indicates that the soil of this area has become drier in those 8 years. The soil moisture affects the surface vegetation in certain degrees, as is revealed by the relationship between this and the NDVI with the coefficient 0.44, at 0.05 statistical significant levels.

From a broad view in the distribution of the yearly relative humidity anomaly of East Asia at the 850 hPa geopotential height during 2001–2008, quite a large area with negative values can be found between the boundary of the Mongolia Republic and Inner Mongolia, China (Figure 6). The Hunshdak is included in the area with the relative humidity anomaly value from -4 to -6% compared to the 30 year climatology (1971–2000). This reveals that the region maintains a drier condition in those 8 years. Despite that, the aridity index of DSFS during 2001–2008, in any case, does not present a higher value compared to the indices of the other four decades

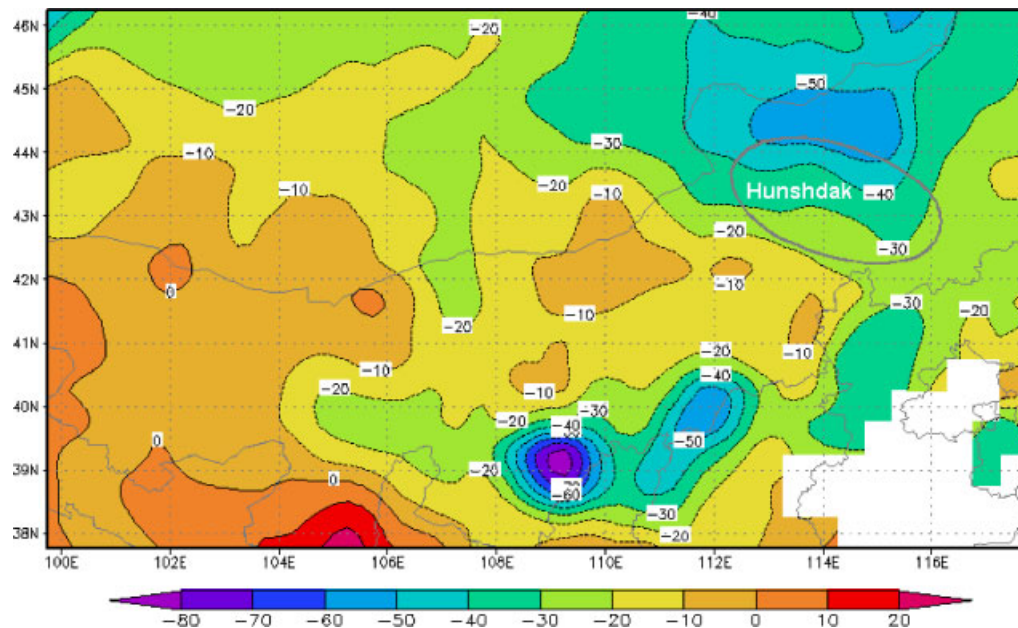


Figure 5. Soil water content anomaly (%) of 2001–2008 in northern China (the time range of climatological mean is from 1971 to 2000). This figure is available in colour online at wileyonlinelibrary.com/journal/met

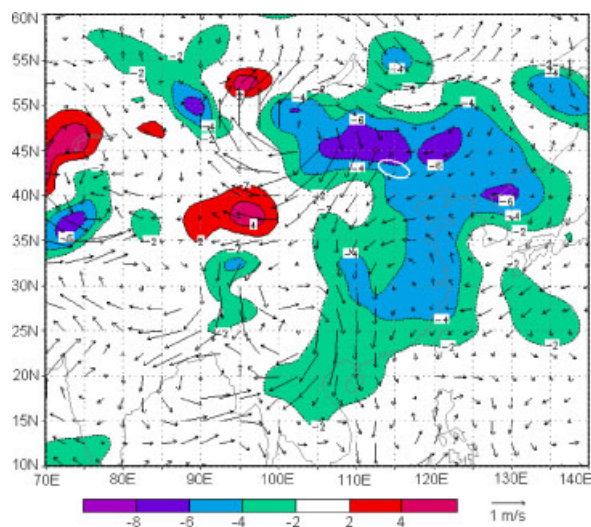


Figure 6. Anomaly distribution of relative humidity (%) and wind vectors (m s^{-1}) at 850 hPa of 2001–2008 (relative to the 30 year climatology of 1971–2000). This figure is available in colour online at wileyonlinelibrary.com/journal/met

starting from 1960s to 1990s (Table III). Additionally, the previous annual and winter aridity indices (1960–2007) exhibit a close relationship with dust storms in DSFS (1961–2008) and the coefficient between the previous annual aridity indices and the DSE is 0.52 and 0.48 for SDSE, both of which are at the 0.01 significance level. Comparatively, the annual indices and winter aridity indices show that the drought situation in the previous year is more important than that of the prior winter only. On the contrary, no favourable relationship is revealed by examining the connection of aridity index in contemporary DSFS with dust storms (Table V). That indicates the concurrent drought situation in DSFS doesn't have a

stronger effect on dust storms than that of the previous year or winter. Therefore, it can be inferred that the local aridity condition of the previous years and winters should be important influential factors of dust storms in DSFS over the Hunshdak.

Based on the available data sets at hand to date, the NDVI is the only index to describe the surface vegetation conditions of the Hunshdak and its nearby regions. Variations of the NDVI after 1981 are examined by using the data. The significant correlation coefficients of the NDVI with dust storms are listed in Table V, which indicates that the surface vegetation conditions clearly contribute to year-by-year influences on dust storm frequencies in the Hunshdak. Dust storms will be infrequent while the vegetation is vigorous in the previous year, and *vice versa*.

Concerning the impacts of the upwind Hunshdak Sandy Lands on its nearby downwind region, two dust storm observatories, Duolun and Huade were selected to report the dust storm cases influenced by climate and surface conditions of the Sandy Lands. The correlation coefficients listed in Table V indicate that those conditions can exert a notable influence on dust storms of the downwind region. The previous year's precipitation (1960–2007) and annual aridity indices (1960–2007) of the upwind region relate strongly with the dust storms (1961–2008), not only of the Hunshdak but also of these two observatories. In these instances, all of the coefficients are at the 0.01 significance levels. Furthermore, the relationship between the prior NDVI (1981–2007) of the upwind region and dust storms of the two stations (1982–2008) is significant, too. Since it cannot find significant coefficients between prior winter or contemporary precipitations and dust storms, this precipitation of the DSFS does not appear to have an obvious influence on dust storms in the Hunshdak.

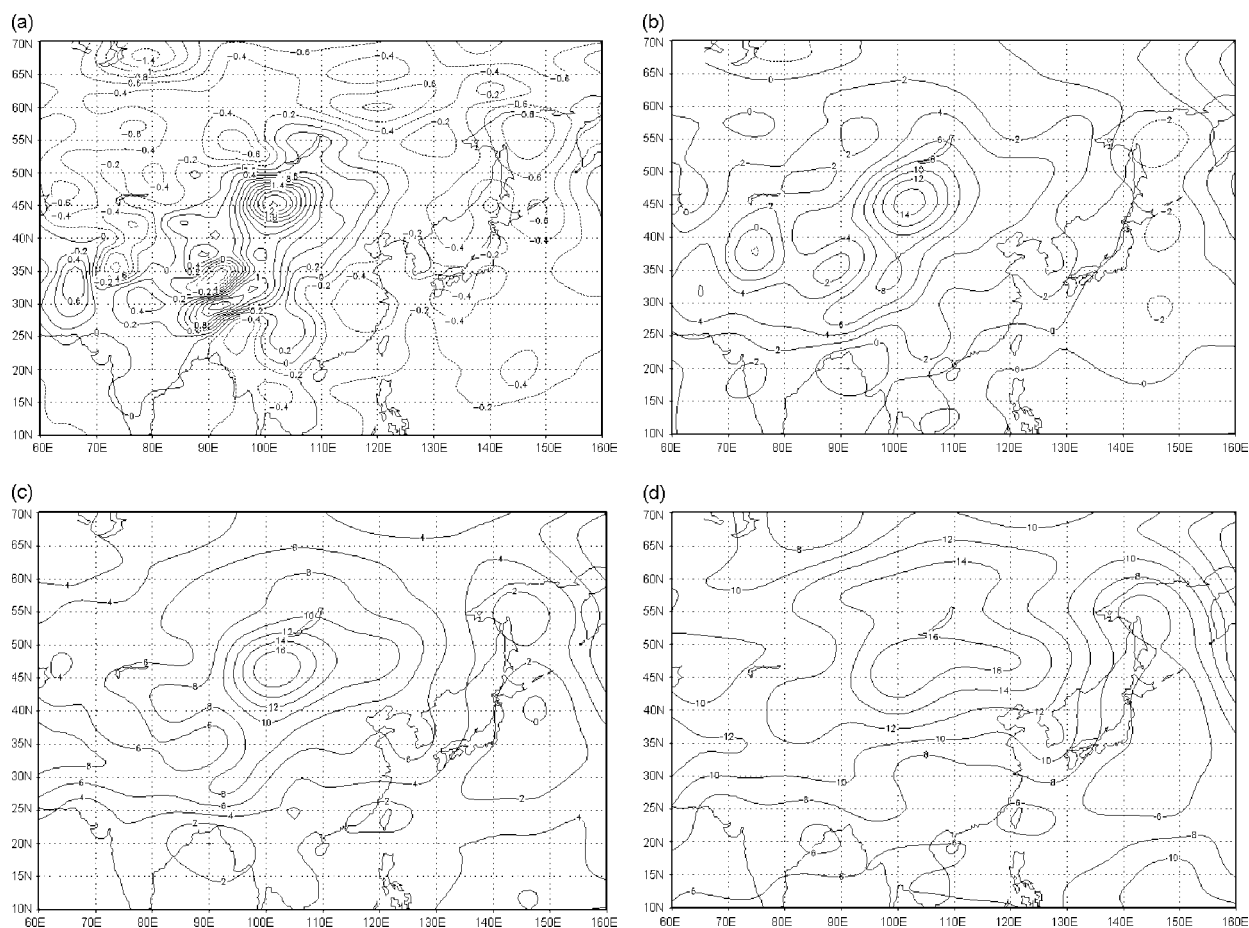


Figure 7. 2001–2008 mean anomaly charts of sea level pressure (contour interval 0.2×10 hPa) and geopotential height (contour interval 2 gpm) compared to climatological mean of 1971–2000, (a) for surface, (b) for 850 hPa, (c) for 700 hPa, (d) for 500 hPa.

4.3. Atmospheric circulation background

2001–2008 average anomaly charts over East Asia, including the sea level pressure, geopotential height, air temperature and the wind vectors of the surface and upper air, were used to diagnose the climatic atmospheric circulation background of the apparent increase of dust storms in Hunshdak. As is commonly recognized by local meteorologists, most of the oceanic water vapour for precipitation of the focused domain, in general, originates from the Bay of Bengal. It is then transferred to the region by air currents *via* a water vapour transportation channel along the eastern side of the Qinghai-Xizang Plateau. Normally, a favourable condition would be required for the water vapour to reach the Hunshdak region efficiently while the transfer channel is under the control of a lower air pressure but, unfortunately, this low pressure did not appear over the water vapour transfer channel on the 2001–2008 mean anomaly chart of sea level pressure (Figure 7(a)). Conversely, the Mongolia Plateau and the water vapour transportation channel were covered by a huge positive anomaly in the chart. Meanwhile, analogous situations can also be seen in the charts of 500, 700 and 850 hPa geopotential heights (Figure 7(b)–(d)). Furthermore, a large anticyclone dominated the Mongolian Plateau and its nearby

areas, which was found in 2001–2008 averaged wind vector anomaly charts of the surface and upper air levels. The charts of surface, 500 and 700 hPa geopotential heights are omitted because they present similar situations as the 850 hPa chart (Figure 6). Under this wind condition, the water vapour transportation channel is firmly controlled by the northeast wind along the southeast edge of the anticyclone. In this case, the water vapour movement is obviously blocked by the northeast current. Therefore, under this disadvantageous condition of atmospheric circulation background, it is difficult to establish and maintain the water vapour transportation. Consequently, the annual precipitation of the Hunshdak during 2001–2008 was reduced by 34.6 mm (relative to the 30 year climatology).

Besides the presence of wind and pressure, the area between 40°N and 60°N of East Asia is predominantly covered by a large positive temperature anomaly (Figure 8(a) and (b)), which indicates that the cold air was inactive over this region during 2001–2008. This can be indirectly verified by the decrease of wind velocity of the Hunshdak. Meanwhile, the warmer condition also means that the evaporation increased by 183.2 mm in the Hunshdak during 2001–2008 compared to the climatological mean (1971–2000). With all the analyses mentioned above, it can be deduced that

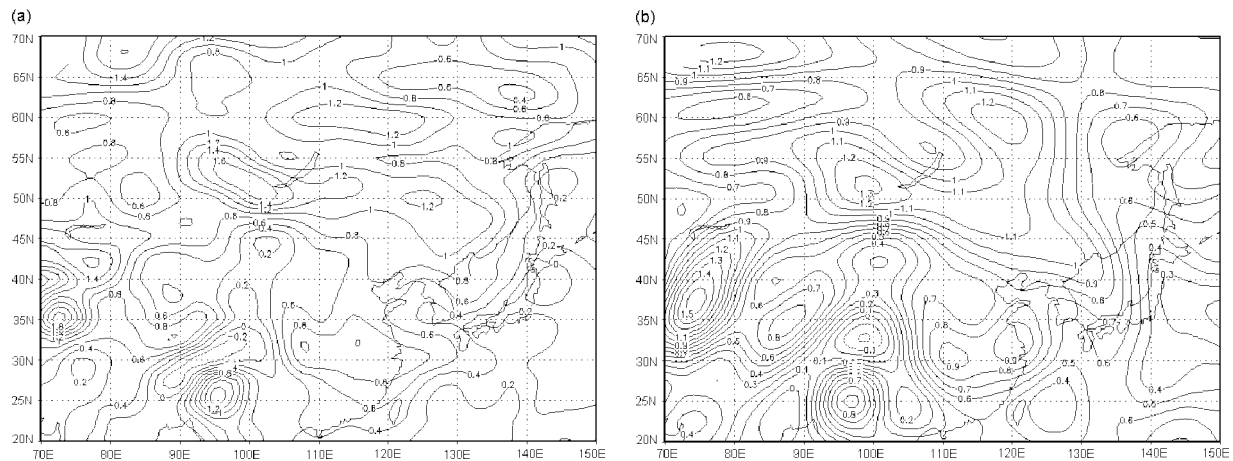


Figure 8. 2001–2008 mean anomaly chart (relative to the 30-year climatology of 1971–2000) of air temperature, (a) for surface (contour interval 0.2 °C), (b) for 850 hPa (contour interval 0.1 °C).

the unfavourable atmospheric circulation background of 2001–2008 induces a drought stage with less than normal rainfall and higher evaporation over the Hunshdak region. The aridity situation is exhibited in both the surface soil moisture and 850 hPa relative humidity anomaly charts (Figures 5 and 6).

4.4. Movement of the local inhabitants

When a long-term wind erosion and grassland degradation observed data set is not available over the whole region of the Hunshdak, then the migration of local inhabitants might reflect the effects of human activities on the surface environment. Unfortunately, there are no wind erosion observation records available before 2004, due to wind erosion measurement being a newly-observed item which is just beginning to be implemented at the selected stations around the Sandy Lands since 2004. Therefore, it is impossible to use data obtained only during these years to conduct an analysis referring to surface wind erosion process in a decadal time scale, especially when comparing the wind erosion of 2001–2008 to that of the climatological mean (1971–2000). Also, it is worth noting that all of the wind erosion measurement points were rightly set inside the selected stations or monitoring sites in grasslands near the stations. These records, in general, cannot address the actual nature of the wind erosion in the Hunshdak, because all of the station locations are in the margin areas.

The administrative area of the Hunshdak is covered by seven counties (Xilinhot, Abagaqi, Dongsuqi, Xisuqi, Lanqi, Baiqi and Xianghuangqi) in the Xilin Gol League which is located in the middle part of Inner Mongolia, China (Figure 9). Depending on local climate conditions, there are no farmed fields, but pastures surrounding it instead. As with other deserts in the world, the central area of the Sandy Lands is uninhabitable for human beings, since most parts of it are covered by moving dunes. Since it is very difficult for people to find potable water there the central area is a sparse wasteland with unfriendly living conditions. Therefore, the population in

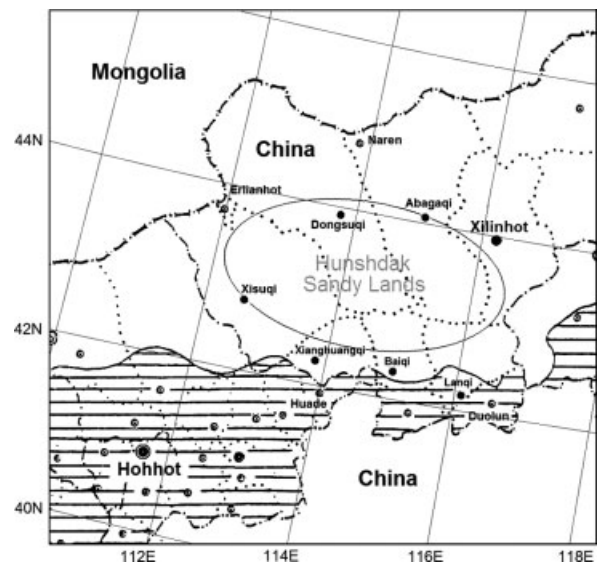


Figure 9. The seven counties covered the Hunshdak in Xilin Gol League, Inner Mongolia, China (the straight line shaded areas are farming places and the unshaded region inside the boundary are pasturing regions or sandy lands; The solid circles are capital towns or cities of the seven counties in Xilin Gol League).

the seven counties is distributed mostly outside or in the margin places of the Hunshdak, leaving the central areas largely unpopulated.

Of particular concern is the Beijing-Tianjin Region, frequently attacked by dust storms during 2000–2002, and the crucial upwind location of the Sandy Lands had drawn much attention from both the public and the local authority. A large-scale ecological migration project was conducted by authority of the Xilin Gol League during 2000–2006. All of the herdsman living in ecologically vulnerable places around the Hunshdak were moved to the herdsman's settlements established by the local authority, which after lengthy investigation were estimated to be favourable for future sustainable development. The sufficient effects of the migration project can be seen through the population figure change of 2001–2008. This project has reduced the herdsman

population by 45 983 compared to the average of that in 1990s (Table VI). As a result of the ecological migration, the human influence on local surface environment is considered to be smaller during those 8 years. Besides the migration measurement, there are 165 333 ha of grain plots in the south boundary of the Hunshdak being managed to return them to forestry, grass and husbandry, which is possible due to the decrease of the farmer populations during 2001–2008. The urban residents of the seven counties are not listed in this table, as they inhabit densely in relatively small city areas and, as such, they will not exert great influence on the surface environment of the Hunshdak.

5. Exploring the main causes

The multivariable step-regression model is employed in an attempt to distinguish if the main impact factors of the dust storm increases are the analyzed climatic elements or stem from another source. Since the aridity index is calculated from the observed precipitation and evaporation, it must be correlated with those two elements. Therefore, the precipitation and evaporation elements will not be inputted to the model while the aridity index is regarded as one of independent variables for the regression model. In addition, other regarded independent variables for the model include the previous annual mean temperature, surface soil moisture, local herdsmen population and the NDVI. The frequencies of the DSE are assigned to the dependent variable set. The amount of samples can be as high as 27, the number of which depends on the limited available NDVI data. It is indicated in the output of the regression model that all independent variables are removed from the model on the variable selecting steps except the aridity index, which was kept in the model on the final step. It reveals a fact that among all of the concerned influence factors, aridity is the most significant impact element on DSE frequencies of the Hunshdak. Therefore, it can be inferred that the abnormal drought condition in 2001–2008 should be the main influencing factor leading to the significant DSE increase of the Hunshdak during this term. In other words, the influence of human activities around the region, as mentioned above, would not be the crucial influence on the increase of dust storms in the Hunshdak during 2001–2008. On one hand, most of the herdsmen live in the outlying regions of the Hunshdak and its vicinities. People rarely inhabit in the interior area because of the moving dunes. On the other hand, the herdsmen population of 2001–2008 has decreased which is the result of the actions of the ecological migration project, causing the year-by-year

influence of human activities to decrease. In spite of this, the possible delayed effects of the previous long-term human activities are not to be neglected, i.e. the influence of unreasonable human activities during the previous decades. To analyze and examine the actual influence of local human activities, an in-depth exploration is needed and more relevant observation data must be available. These observations would account for the amount of local livestock, the detailed migration patterns of the local herdsmen, changes in the living style of the local inhabitants, the efficient wind erosion, and the grassland degradation and the grazing area variations in the past several decades. Unfortunately, some of the necessary monitoring was not implemented over the Sandy Lands in the past decades. Since the required data are not currently available, the chance of undertaking more in-depth research upon the long-term human influence of the surface environment in the Hunshdak is remote.

6. Summary and conclusions

Two notably related factors of dust storms in the Hunshdak Sandy Lands in northern China are studied. One is the obviously increasing trend of the dust storm frequency during the period 1961–2008, especially in 2001–2008, whose mean frequency is significantly higher than that of all the last four decades, collectively, of the 20th Century. As an expectation in northern China, this trend disagrees with the dust storm variation tendency of northern China, which decreases continuously during 1961–2000 and increases slightly in 2001–2008 comparing with the frequency of the 1990s. The other is that the mean velocity of 2001–2008 observed rightly during dust storm occurrence times was down by some 3.0 m s^{-1} (compared to the 30 year climatology of 10 min mean wind speed measured in dust storm occurrence time). This indicates that in the Hunshdak, dust storms are still possible even with weaker wind speeds, when deteriorated surface conditions of less vegetation and more dust exposure lower the thresholds for dust storm initiation.

From analysis of the variations of local precipitation, temperature, aridity, potential evaporation, relative humidity, surface soil moisture, the NDVI, wind speed and inhabitant migration of the Hunshdak during the past 48 years (1961–2008), it can be concluded that the leading cause of the significant increase of dust storms in the Hunshdak is the abnormal climate condition which led to the drought of 2001–2008. During those 8 years, huge areas in East Asia were controlled by a higher pressure,

Table VI. Decadal mean farming and pasturing populations of the seven counties the covered the Hunshdak (unit: person).

Type	1966–1970	1970s	1980s	1990s	2001–2008
Farmer	36 933	66 493	64 564	65 263	58 059
Herdsmen	106 333	160 781	184 590	185 541	139 558

which was coupled with the water vapour transportation channel for the Hunshdak region and was interdicted by the northeast current of the big anticyclone which mainly covers the Mongolia Plateau. With the increase in temperature and evaporation during this period and the unfavourable atmospheric circulation background, the Hunshdak Sandy Lands became drier compared to the mean case of 1971–2000. Thus, it can be inferred that the abnormal drought condition mainly results in the local surface degradation, less vegetation coverage and the exposed surface soil with excessive sand and dust particles during 2001–2008, and consequently, leads to the significant increase of dust storms in Hunshdak. Moreover, the long-term and lagged influence of human activities should not be neglected. This topic still needs more available observation records and deeper investigations in this region. However, in the present investigation, the influence of local human activities has been proven to have a smaller impact than that of the aridity on the surface environment of the Hunshdak Sandy Lands during those 8 years.

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