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# Stronger winds increase the sand-dust storm risk in northern China†

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The biggest sand-dust storm from Mongolia in the past decade swept across northern China on March 15, 2021. Before this sudden outbreak, the number of sand-dust storms in northern China had been decreasing for 50 years. Wind and sand resources are the two key elements for sand-dust storms to occur. With an abrupt shift to a drier and hotter climate in the past 20 years over inner East Asia providing more sand resources and an increasing wind speed trend, the sand-dust storm in 2021 may herald the beginning of an era with more sand-dust storms. To answer whether increasing wind speed will significantly influence the sand-dust storm frequency, this study analyzed the relationship between the annual average wind speed and sand-dust storm days in northern China and Mongolia, finding that they have a high correlation ($R = 0.94$) in northern China and a moderate correlation ($R = 0.41$) in Mongolia. We further found that the wind speed during sand-dust storms also decreased, which further supports that the decrease of sand-dust storm frequency is mainly reasoned from the decrease of wind speed. Therefore, as the wind speed increases, the sandstorm frequency can increase as well, which has been seen clearly in Mongolia but may be just beginning in China.

**Environmental significance**

The outbreak of sand-dust storms in 2021 influenced a wide area of Asia and caused serious economic loss and health consequences including nine deaths. Our findings demonstrate that since 2012, both the wind speed and sand-dust storm frequency have increased slightly after decades of decreasing, leading to the large sand-dust storm event in the spring of 2021. A reversal in wind speed portends that sand-dust storms may become more frequent and severe in the future. Complicating this process is the hotter and warmer climate in the inner East Asia providing more sand resources. While rehabilitation will help mitigate sand-dust storm generation by increasing vegetation cover in part of the source area, it may require fine tuning to be most effective in the new situation.

## Introduction

The worst sand-dust storm in a decade was triggered in the Gobi Desert Plateau of East Asia in March of 2021, smothering local communities, degrading ecosystems, disrupting travel, and producing severe health consequences, including nine deaths, in downwind locations of Mongolia, China, and Korea.[1–5] While sand-dust storms are a natural wind related hazard of the world's second largest rain shadow desert,[6] concerns in recent decades have grown regarding how their frequency and severity would be affected by anthropogenic activities (*e.g.*, vegetation loss, overgrazing, water resource mismanagement)[7–9] and variability associated with large-scale climate systems including the East Asian winter monsoon, the Arctic Oscillation, ENSO, Pacific Decadal Oscillation, and climate change in general.[8,9] Collectively, the interaction between these phenomena influences several variables that control wind erosion, namely wind speed distribution, surface moisture (related to precipitation and evapotranspiration), and protective vegetative cover. The genesis of the 2021 sand-dust storm was triggered by strong winds, exceptionally dry soil surface conditions, and an unstable vegetation cover in the semi-arid and arid areas of the Gobi. In particular, strong cyclonic activity associated with synoptic disturbances produced exceptionally strong spring winds reaching peaks of 30–40 m s$^{-1}$ in various provinces.[3,10]

In agreement with others, our new analysis shows that the sand-dust storm frequency in China had been decreasing for decades,[11–13] from about 20 sand-dust storm days per year in 1970 to fewer than 10 in 2010 (Fig. 1b). In Mongolia, sand-dust storm days have fluctuated over the past five decades, ranging from 35 to 70 sand-dust storm days per year, but with a slight increase since 1970 (Fig. 1a). The increasing trend in Mongolia is consistent with reports of co-occurring regional desertification proliferation and regional drying related to both precipitation decreases and temperature increases.[14] Complicating the

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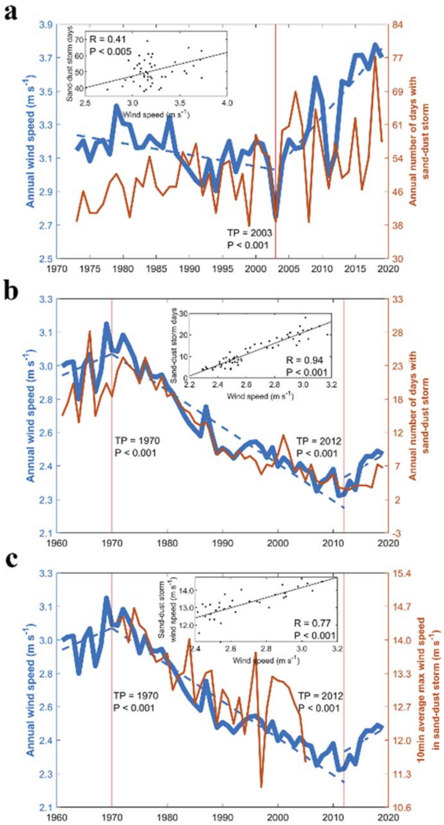


Fig. 1 Sand-dust storm frequency is affected by the annual average wind speed in both Mongolia and Northern China. (a) In Mongolia, the sand-dust storm frequency (thin orange line) is relatively stable yet variable when the annual average wind speed (blue lines; dashed lines are the fitted lines) is decreasing (1973 to 2003). Frequency then increases and becomes even more variable over time as the wind speed increases from 2003 to 2019. The vertical line indicates the turning point (TP; red vertical lines) at which the wind reversal occurred (significant with $P < 0.001$). The weak relationship between the wind speed and sand-dust storm days in Mongolia is shown in the inset (Pearson correlation coefficient $R = 0.41$, $P < 0.005$). (b) Annual wind speed in China increased before 1970, and then decreased from 1971 to 2012, before reversing to increase over the last decade. The trend reversals are significant (TP $p$-values are listed in the graph). The inset shows the strong and significant relationship between the annual wind speed and the number of sand-dust storm days ($R = 0.94$, $P < 0.001$). (c) The sand-dust storm with 10 min average maximum wind speed in China follows the trend of annual average wind speed.

complex environmental situation in the Gobi region are the recent findings that wind speeds have been increasing globally for at least a decade, although with a local-to-regional variation.[15] The increase follows decades of wind-speed decline, known as "stilling".[15] The influence of related wind speed changes on the sand-dust storm frequency in the Gobi Desert region has not received substantial attention to date, particularly during the last decade, which is the period that is most informative for projecting potential trends that will aid future restoration, air pollution management, and renewable energy development.[4,7]

We also find that the sand-dust storm frequency (sand-dust storm days per year) and annual average wind speed are strongly correlated in northern China ($R = 0.94$), but have a weaker association in Mongolia ($R = 0.41$) (Fig. 1a and b). During the 25 year period when the annual average wind speed decreased in Mongolia (1973–2003), the number of sand-dust storm days per year was relatively stable, ranging from 40 to 56 sand-dust storm days per year (Fig. 1a). After 1997, the annual average wind speed increased at a rate of ∼0.05 m per s per year. During this time, sand-dust storm days increased significantly from about 45 to 65 days per year. In China, the annual average wind speed increased between 1961 and 1970. Then, following the turning point in 1970, a steady decline in both the average wind speed and sand-dust storm frequency occurred until the reversal in the trajectory in 2012 (Fig. 1b). After 2008, both the wind speed and sand-dust storm frequency increased slightly (Fig. 1b), leading to the large sand-dust storm event in the spring of 2021. Throughout the entire 60 year period (1961–2019), the association between the annual average wind speed and sand-dust storm days in northern China was both strong and significant ($R = 0.94$; $P < 0.001$; inset Fig. 1b).

Furthermore, the 10 min average maximum wind speed for observed sand-dust storm events (representing the wind speed situation when a sand-dust storm happens) from 1971–2005 is highly correlated with the annual average wind speed in northern China (inset Fig. 1c, $R = 0.77$; $P < 0.001$). The data further reveal the inherent linkage between the wind speed and sand-dust storm occurrence. If not considering changes in other factors, the decline in wind speed is likely to decrease both the sand-dust storm wind speed and the frequency of sand-dust storms (when the wind speed is decreased to less than the initiation wind speed, the sand-dust storm will not happen anymore, see ESI Fig. S1†). Ecology restoration is also likely to decrease the sand-dust storm frequency, however, as the straw checkerboard barrier will protect the dust from being blown up, thus needing stronger wind to generate sand-dust storms (higher sand-dust storm initiation wind speed),[16–18] ecology restoration would make the average sand-dust storm wind speed look higher because the minimum wind speed of the sand-dust storm is raised (ESI Fig. S2†). In conclusion, both the overall wind speed decrease and ecology restoration will reduce the sand-dust storm frequency but they have opposite impacts on the average sand-dust storm wind speeds. Therefore, the observed decreases in both the sand-dust storm frequency (Fig. 1b) and wind speed (Fig. 1c) demonstrate that sand-dust storms during the period 1970–2010 were largely impacted by the decline in wind speed.

Besides, even with ecological restoration efforts to slow down the desertification trend, the overall desertification area still kept increasing from 2100 km$^2$ during 1976–1988 to 3600 km$^2$ during 1988–2000.[19] That means during 1976–2000 when the sand-dust storm frequency was decreasing, the sand resources were still increasing, but with a slower speed year by year. Therefore, the sand resources change can only explain a smaller increasing trend of sand-dust storm frequency instead of a decreasing trend. However, this decreasing trend can be well explained by the reduced cyclone frequency (less wind) in northern China due to warming in Mongolia and cooling in northern China, resulting in the decrease of the meridional temperature gradient.[11] Dust records in Lake Karakul[20] and Lake Daihai[21] also provide evidence from a longer time scale for the idea that a lower wind speed in a warmer climate will cause fewer sand-dust storms.

The increasing soil moisture in the arid and semiarid regions of northern China and Mongolia in the past decades also explained some of the decreasing sand-dust storm frequency.[14,22–24] Increasing soil moisture can both aid vegetation regeneration[25] and enhance the cohesive forces between soil particles,[26] thus limiting dust emission. However, this wetting trend has been considered to end and shift abruptly to a hotter and drier trend beyond the tipping point in the past 20 years,[14] bringing a more serious situation accompanied by the increasing wind speed. It is also needed to explore the relative influence of wind velocity on drying the landscape in association with other relevant climatic forcing variables (temperature increases, rainfall decreases) that are commonly reported to "prime" the landscape prior to the initiation of a sand-dust storm.[27]

## Methods

We base our analysis on a variety of climate and hazard data products for Mongolia and China. First, we collect Mongolia sand-dust storm days data from two different resources and assimilate them to form a longer time series. First, we used the annual number of days with sand-dust storms reported by the United Nations Framework Convention on Climate Change which contains data during 1960–2005 (data1). Second, we collect data from the Information and Research Institute of Meteorology, Hydrology and Environment (**http://irimhe.namem.gov.mn/**), which includes sand-dust days from 41 stations in Mongolia in 2000–2019 (data2). This dataset contains a spurious "jump" from 2011 to 2012, which is also present in the extreme precipitation field (ESI Fig. S3†). This inconsistency may reason from instrument or criteria adjustment. To address this unexplained issue, we first use a z-score normalization to unify the data before and after 2012:

$$z = \frac{x_1 - \mu_1}{\sigma_1} = \frac{x_2 - \mu_2}{\sigma_2} \quad (1)$$

where $x_1$ and $x_2$ represent Mongolia sand-dust days during 2004–2011 and 2012–2019 accordingly. The terms $\mu_1$ and $\mu_2$ are the average of $x_1$ and $x_2$. $\sigma_1$ and $\sigma_2$ are the standard deviation of $x_1$ and $x_2$. Then, we compared the annual average value of the overlap period from 2000 to 2007 in the two datasets and found that they were highly correlated ($R = 0.98$). We used the linear model from the overlap period ($\text{data1} = 1.360 \times \text{data2} + 5.3557$) to complete the repaired record from 1974 to 2019.

We downloaded the wind speed data of Mongolia from the Hadley Integrated Surface Database (HadISD) from the U.K. Met Office Hadley Centre (achieved from **https://www.metoffice.gov.uk/hadobs/hadisd/** in August, 2021). We only used 9 stations with complete monthly records from 1973 to 2019. A month is considered qualified when it has at least 15 days records and the monthly average wind speed is the mean value of all the records in that month.[16] The annual average wind speed is the average of the monthly wind in that year. To determine the turning points and trends in wind data, we used piecewise regression as done in prior research.[15] We used a *t*-test with the null hypothesis to examine trend differences before and after the tested point.[15]

In China, information on sand-dust days (with a horizontal visibility of less than 1 km caused by strong wind) was collected from the Blue Book on Climate Change in China 2020.[12] Wind speed data were obtained from the China Surface Climatic Data Daily Data Set (CSD) (Version 3.0), which is available at the China Meteorological Data Service Center (CMDC; **http://data.cma.cn/en/?r=data/**; last accessed March 2020). We used the same preprocessing method mentioned before on 258 qualifying stations with latitudes more than 35°N.

The wind speeds during sand-dust storms are from the Strong Sand-dust storm sequences and their supporting datasets in China (Version 1.0) from the China Meteorological Data Service Center (**http://data.cma.cn/en/?r=data/**; last accessed July 2021). The datasets contain the position, initiation and end time, wind speed and wind direction of sand-dust storms during 1954–2007 from 610 stations of China. Included are 51 460 sand-dust storm records in total and 23 453 have 10 min average max wind speed.

## Conclusions

Our findings suggest that the 2021 sand-dust storm in the Gobi Desert may be a harbinger of a period of increasing sand-dust storm activity in the future. A reversal in stilling portends that sand-dust storms may be more frequent and severe in the unforeseen future. Complicating this process is the role of drier and hotter climates that prime the landscape for wind erosion to occur. The reason for recently observed changes in wind velocities in the last decade is still unknown, but they are potentially linked with large-scale synoptic climate forcing (*e.g.*, ENSO, Arctic Oscillation, Pacific Decadal Oscillation, mid-latitude westerlies) that may change on decadal time scales.[28,29] While rehabilitation will play a positive role in mitigating sand-dust storm generation by increasing vegetation ground cover in part of the source area,[14,17,18] rehabilitation efforts may require fine tuning to be most effective. Further investigation is needed regarding the co-location of areas experiencing wind speed changes and exceptionally dry conditions.

## Author contributions

Zhenzhong Zeng: writing – review & editing Yi Liu: conceptualization, methodology, software, data curation, writing – original draft Rongrong Xu: writing – review & editing Alan D. Ziegler: writing – review & editing.

## Conflicts of interest

There are no conflicts of interest to declare.

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