Spatiotemporal Variation Characteristics of Gale Days (≥ Level 6) in Inner Mongolia, 1961–2018 (Postprint)

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Abstract

The study of gale day variations holds great significance for regional climate change, disaster prevention and mitigation, and wind energy development. Based on gale data from 85 meteorological observation stations in Inner Mongolia and its surrounding areas from 1961 to 2018, statistical methods were employed to analyze the spatiotemporal distribution characteristics of gale days in the Inner Mongolia region. The results indicate that: (1) Over the past 58 a, the number of gale days in Inner Mongolia has exhibited a significant decreasing trend overall, with a climatic trend rate of -16.52 d · (10a)-1. Among the seasons, spring has the most gale days, accounting for 44.30% of the annual total, and also shows the most significant decrease [-6.24 d · (10a)-1]; across gale categories, level-6 gale days are the most frequent, accounting for 80.93% of the total gale days, and also exhibit the most pronounced decline [-11.99 d · (10a)-1]. (2) The spatial distribution of gale days in Inner Mongolia exhibits a pattern of more in the central region and fewer in the northeast and southwest. Areas with higher frequencies of gale days are located in Xilingol League, Ulanqab City, and Chifeng City, while areas with lower frequencies are located in Ordos City and Hohhot City. (3) Level-6 and level-7 gale days are mainly concentrated in central cities/leagues, while level-8 and above gale days are distributed in western and eastern cities/leagues; all cities/leagues exhibit a decreasing trend, with Ulanqab City having the largest climatic trend rate of -5.49 d · (10a)-1, and Hohhot City the smallest, only -0.01 d · (10a)-1.

Full Text

Spatiotemporal Variation Characteristics of High Wind Days (Category 6 and Above) in Inner Mongolia from 1961 to 2018

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Abstract

Research on variations in high wind days is crucial for understanding regional climate change, disaster prevention and mitigation, and wind energy development. Based on daily wind speed data from 85 meteorological observation stations in Inner Mongolia and surrounding areas from 1961 to 2018, this study analyzes the spatiotemporal distribution characteristics of high wind days in Inner Mongolia using statistical methods. The results indicate: (1) Over the past 58 years, the number of high wind days in Inner Mongolia has shown a significant decreasing trend overall, with a climate tendency rate of -16.52 $d \cdot (10a)^{-1}$. Among the seasons, spring had the most high wind days, accounting for 44.30% of the annual total, and also experienced the most significant decrease [-16.52 $d \cdot (10a)^{-1}$]. Across all wind categories, Category 6 high wind days were the most frequent, representing 80.93% of total high wind days, with the most pronounced decline [-11.99 $d \cdot (10a)^{-1}$]. (2) Spatially, high wind days exhibited a pattern of "more in the central region, less in the northeast and southwest." Areas with frequent high wind days were concentrated in Xilin Gol League, Ulanqab City, and Chifeng City, while fewer occurrences were observed in Ordos City and Hohhot City. (3) Category 6 high wind days were mainly concentrated in central cities, while Category 8 and above high wind days were distributed in western and eastern cities. All cities showed decreasing trends, with Ulanqab City exhibiting the highest climate tendency rate of -5.49 $d \cdot (10a)^{-1}$ and Hohhot City the lowest at -0.01 $d \cdot (10a)^{-1}$.

Keywords: high wind days; spatiotemporal distribution; climate tendency rate; Inner Mongolia

Introduction

Under the background of global climate change, research on wind speed variations has gradually gained attention. Near-surface wind speed controls the transfer of water, energy, and momentum between the land surface and the lower atmosphere, representing an important meteorological factor influencing environmental and climate change. Studying long-term variations in wind speed, particularly high winds, is significant for understanding surface energy balance, water cycles, and the occurrence of haze and dust storms, as well as for wind energy resource assessment.

Previous studies have demonstrated a widespread declining trend in wind speeds across tropical and mid-latitude regions worldwide over the past 30–50 years, including in the United States, Portugal, Spain, and Germany. Domestic research also indicates that most regions in China have experienced decreasing wind speeds, with more pronounced reductions in areas with higher average wind speeds. Furthermore, studies suggest that the decrease in average wind speed may be attributed to declines in high wind speeds, and that while high wind days in China overall show a decreasing trend, significant regional characteristics exist.

Inner Mongolia Autonomous Region is located in northern China, spanning longitudinally with a total area of 1.183$\times10^{6}$ km^{2} between 37°24 -53°23 N and 97°12 -126°04 E. The climate transitions from semi-humid to semi-arid and arid, with annual mean temperatures of 0–8°C and annual precipitation of 50–450 mm. The terrain extends diagonally from northeast to southwest in a long, narrow shape, characterized by temperate pastures in the east that gradually transition to desert westward, with extensive deserts in the western region. Strong winds in pastoral areas can scatter livestock herds, threatening animal husbandry production. They also cause soil wind erosion and desertification, damage ecological environments, and serve as primary triggers for dust weather events. Additionally, high winds affect agricultural production, transportation, energy generation, and people' s livelihoods.

Currently, research on Inner Mongolia predominantly focuses on wind speed variations, with fewer studies examining high wind days, particularly across different categories. This study analyzes the spatiotemporal distribution characteristics of high wind days in Inner Mongolia using long-term observational data from 85 meteorological stations, aiming to provide scientific guidance for disaster prevention and mitigation, rational wind energy resource utilization, and ecological environment improvement in the region.

1.1 Data Sources

The high wind data used in this study were obtained from the China Meteorological Data Service Center (http://data.cma.cn/). All data underwent standard quality control and correction procedures, covering the period 1961-2018. To ensure data homogeneity, stations with defects or insufficient temporal coverage were eliminated, resulting in a final dataset of 85 meteorological observation stations in Inner Mongolia and surrounding areas [Figure 1: see original paper].

1.2 Research Methods

High winds are defined according to the National Standard of the People' s Republic of China (GB/T 28591—2012) and meteorological forecasting operational specifications: when the daily maximum 10-minute average wind speed reaches Category 6 or above ($ 10.8$m \cdot s^{-1}$), it is classified as a high wind day. If a high wind occurs one or more times in a day, it is recorded as one high wind day. Seasonal divisions follow Ren et al. [12]: December-February as winter, March-May as spring, June-August as summer, and September-November as autumn. For convenience, the decades 1961-1969, 1970-1979, 1980-1989, 1990-1999, 2000-2009, and 2010-2018 are referred to as the 1960s, 1970s, 1980s, 1990s, 2000s, and 2010s, respectively.

Long-term changes in high wind days were analyzed using a univariate linear regression equation, with the climate tendency rate [24] employed to describe trends and magnitudes of change. Inverse Distance Weighted (IDW) interpolation [25] was used to analyze spatial variation characteristics, and the Mann-Kendall test [26] was applied for significance testing of trends. The standardized statistical test value Z indicates an increasing trend when positive and a decreasing trend when negative. A trend is considered significant when $|Z| > 1.96$ (corresponding to $p < 0.05$).

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2 Results and Analysis

2.1 Temporal Variation Characteristics

2.1.1 Interannual Variations of Annual and Seasonal High Wind Days From 1961 to 2018, annual high wind days in Inner Mongolia initially increased then decreased, showing an overall decreasing trend [Figure 2: see original paper]. The mean annual high wind days were 47.17 d, with a climate tendency rate of -16.52 d $\cdot$ $(10a)^{-1}$ ($P < 0.05$). The variation can be broadly divided into three phases: an increasing trend from 1961 to 1972, with a peak of 127 d in 1972; a significant decreasing trend from 1973 to 1990, with a climate tendency rate of -44.35 d $\cdot$ $(10a)^{-1}$ ($P < 0.05$); and relatively stable, non-significant variation from 1991 to 2018, fluctuating between 10-29 d. Overall, the 1960s and 1970s were high-incidence decades, accounting for 61.47% of total high wind days, while occurrences became less frequent after the 1990s, with 21st-century high wind days representing only 10.86% of the total.

Seasonal high wind days showed similar patterns, initially increasing then decreasing with an overall decreasing trend [Figure 3: see original paper]. Spring had the highest mean seasonal high wind days at 20.90 d, accounting for 44.30% of annual high wind days, with the most significant decrease [-6.24 d$\cdot$(10a)$^{-1}$, P $<$ 0.05]. The most frequent year was 1972, with 73 d. After the 1990s, changes became non-significant. Winter ranked second with mean high wind days of 12.97 d (27.49% of annual total) and a climate tendency rate of -4.59 d$\cdot$(10a)$^{-1}$ (P $<$ 0.05), with the most frequent year in 1972. Autumn had mean high wind days of 8.19 d (17.36% of annual total) and a climate tendency rate of -3.47 d$\cdot$(10a)$^{-1}$ (P $<$ 0.05), peaking in 1974. Summer had the fewest high wind days with the smallest reduction magnitude, averaging 5.12 d (10.86% of annual total) and a climate tendency rate of -0.57 d$\cdot$(10a)$^{-1}$ (P $<$ 0.05), peaking in 1971.

2.1.2 Interannual Variations by Wind Category Analysis of interannual variations by wind category shows that Category 6 high wind days exhibited a clear decreasing trend over time [Figure 3: see original paper], with the highest frequency—2,216 total days and an annual mean of 38.21 d, accounting for 80.91% of total high wind days. The most frequent year was 1972 with 70.7 d, and the climate tendency rate was -11.99 d$\cdot$(10a)$^{-1}$ (P $<$ 0.05), representing the most significant reduction. Category 7 high wind days totaled 465 d with an annual mean of 8.02 d (17.00% of total), peaking in 1972 with 18.9 d, and a climate tendency rate of -2.17 d$\cdot$(10a)$^{-1}$ (P $<$ 0.05). Category 8 high wind days totaled 70 d with an annual mean of 1.21 d (1.94% of total), occurring only in specific years with no significant change pattern. Category 9 high wind days were extremely rare, with only 8 occurrences (0.15% of total) in 1965, 1966, and 1972. Overall, the 1960s and 1970s were high-incidence decades, while the 21st century has seen significantly fewer high wind days and less extreme high wind events.

2.1.3 Monthly Variations by Wind Category Monthly variations in high wind days across categories show that total high wind days peaked in April (481 d) and reached a minimum in September (8.29 d) [Figure 4: see original paper]. Category 6 high wind days followed the same pattern, decreasing initially, then increasing, decreasing again, and finally increasing, with a minimum in September (173 d) and a maximum in April (369 d). Category 7 high wind days showed a pattern of initial increase, decrease, another increase, and final decrease, peaking in May (228 d) and reaching a trough in September (1.03 d). Category 8 high wind days were relatively rare, with a peak in April (5 d) and no clear variation pattern in other months.

2.2 Spatial Distribution Characteristics

2.2.1 Spatial Distribution of Annual and Seasonal High Wind Days The spatial distribution of high wind days in Inner Mongolia from 1961 to 2018 shows a pattern of "more in the central region, less in the northeast and southwest" [Figure 5: see original paper]. Areas with frequent high wind days were concentrated in Xilin Gol League, Ulanqab City, and Chifeng City, while fewer occurrences were found in Ordos City and Hohhot City. The central region of Inner Mongolia, particularly the junction of Xilin Gol League and Ulanqab City, northern Baotou City, and northern Chifeng City, were high-incidence areas. The highest occurrence was in northern Chifeng City with 555 total high wind days. Northeastern and western Inner Mongolia experienced very few high wind days, with no occurrences in Genhe (Hulunbuir City) and Dengkou (Bayannur City). Northern Hulunbuir City, southern Bayannur City, and southern Ordos City all had fewer than 10 high wind days. Overall, more than half of Inner Mongolia experienced 0–120 high wind days, accounting for 80.93% of all stations.

The reduction rate in the central high-incidence region was significantly greater than in the low-incidence northeastern and southwestern regions. The vast majority of stations (81) showed decreasing trends in high wind days, with 58 passing significance tests. The fastest reduction occurred at Fuhe Station in northern Chifeng City, with a climate tendency rate of -3.38 $d \cdot (10a)^{-1}$ ($P < 0.05$). Only a few stations (4) showed increasing trends, with Hohhot Station increasing fastest at 0.02 $d \cdot (10a)^{-1}$.

Seasonal spatial distributions [Figure 6: see original paper] reveal that spring high wind day anomalies were positive in central Ulanqab City, Xilin Gol League, and northeastern Hulunbuir City, exceeding 100 d, particularly in Xilin Gol League where anomalies reached 166 d. Western Alxa League, central Baotou City, and eastern Tongliao City were moderate-incidence areas with anomalies of 0–100 d. Bayannur City, Ordos City, Hohhot City, and Hinggan League were low-incidence areas with negative anomalies, especially Hohhot City with -195 d.

Summer high wind day anomalies were highest in western Alxa League (229 d), followed by central Baotou City, Ulanqab City, Xilin Gol League, and northeastern Hulunbuir City as moderate-incidence areas. Bayannur City, Ordos City, Hohhot City, Chifeng City, and Hinggan League showed negative anomalies, with Hohhot City being the least prone to summer high winds (-34 d).

Autumn anomalies identified central Baotou City, Ulanqab City, Xilin Gol League, Chifeng City, and northeastern Hulunbuir City as moderate-incidence areas. Bayannur City, Ordos City, Hohhot City, and Hinggan League were low-incidence areas with negative anomalies, particularly Hohhot City (-60 d).

Winter anomalies were concentrated entirely in central Inner Mongolia, with Chifeng City showing anomalies of 241 d, Ulanqab City 119 d, and Xilin Gol League and Baotou City 0–100 d. Western Bayannur City, Ordos City, central Hohhot City, and eastern Hinggan League showed negative anomalies, with Hohhot City again being the least prone (-340 d).

2.2.2 Spatial Distribution by Wind Category Spatial distribution by wind category shows that Category 6 high wind days were concentrated in central and east-central regions, with the highest anomalies in Chifeng City (250 d), followed by Ulanqab City and Xilin Gol League (200 d) [Figure 7: see original paper]. Category 7 high wind days were concentrated in central and eastern regions, with Tongliao City having the highest anomalies (48 d), followed by Baotou City, Alxa League, and Hulunbuir City (0–5 d). Category 8 high wind days were rare, with only Alxa League and Hulunbuir City showing positive anomalies, indicating that while these regions experience fewer high wind events, they are more prone to extreme high winds requiring special attention. Category 9 high wind days were even rarer, with only Tongliao City showing positive anomalies.

2.2.3 Trends by City/League Climate tendency rates and decadal changes from the 1960s to 2010s for each city/league are shown in . Cities/leagues with tendency rates below -1.00 d $\cdot$ (10a)$^{-1}$ include Ulanqab City (-5.49 d $\cdot$ (10a)$^{-1}$), Xilin Gol League (-3.38 d $\cdot$ (10a)$^{-1}$), and Baotou City (-3.00 d $\cdot$ (10a)$^{-1}$), all located in central Inner Mongolia. Hohhot City had the smallest decrease at -0.01 d $\cdot$ (10a)$^{-1}$, located in southwestern Inner Mongolia. All cities/leagues showed decreasing trends in high wind days, with the largest reduction in Ulanqab City and the smallest in Hohhot City.

From the 1960s to 1980s, all cities/leagues except Alxa League showed significant reductions in high wind days, particularly during the 1980s. From the 1980s to 2010s, all cities/leagues continued to show decreasing trends, especially during the 2000s. Alxa League showed no clear change from the 1960s to 1980s but experienced a slight increase in Category 8 high wind days in the 2010s.

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3 Conclusions and Discussion

Based on meteorological observation data from 85 stations in Inner Mongolia and surrounding areas from 1961 to 2018, this study analyzed the spatiotemporal distribution characteristics of high wind days in Inner Mongolia, yielding the following conclusions:

(1) The annual mean number of Category 6 and above high wind days in Inner Mongolia was 47.17 d, showing an overall decreasing trend with a climate tendency rate of -16.52 d $\cdot$ (10a)$^{-1}$. The reduction was most significant in the 1970s–1980s. Seasonal high wind days also decreased, with spring having the most (44.30% of annual total) and summer the fewest (10.86%). Across wind categories, Category 6 high wind days showed a clear decreasing trend, accounting for 80.93% of total high wind days, while Category 8 high wind days occurred only in specific years and Category 9 days were extremely rare with no significant change. Monthly variations peaked in April and reached a minimum in September.

(2) Spatially, high wind days exhibited a "central high, northeast-southwest low" pattern, with central Inner Mongolia being a high-incidence region, particularly at the junction of Xilin Gol League and Ulanqab City, northern Baotou City, and northern Chifeng City. Northeastern and southwestern regions were low-incidence areas, such as Hulunbuir City and the border region of Alxa League, Bayannur City, and Ordos City. Most stations showed significant decreasing trends, with reduction rates in central regions significantly greater than in northeastern and southwestern regions. Only a few stations showed increasing trends.

Among cities/leagues, Xilin Gol League had the most spring high wind days (166 d anomaly), Alxa League had the most summer days (229 d), and Chifeng City had the most autumn and winter days (244 d and 241 d, respectively). Chifeng City had the most Category 6 high wind days, Tongliao City had the most Category 7 days, and Alxa League and Tongliao City had the most Category 8 days. All cities/leagues showed decreasing trends, with the largest reduction in Ulanqab City [-5.49 d $\cdot$ $(10a)^{-1}$] and the smallest in Hohhot City [-0.01 d $\cdot$ $(10a)^{-1}$].

This study enriches current research through comprehensive analysis of spatiotemporal evolution across wind categories, contributing to understanding of extreme phenomena such as dust storms and haze, as well as wind energy resource development. However, inconsistencies in high wind day definitions across studies—for instance, some using instantaneous wind speeds \$ 17.0$m \cdot s$^{-1}\$—affect comparative results. Therefore, systematic research on spatiotemporal variations in high wind days using unified standards is essential for advancing scientific understanding in this field.

The finding of decreasing high wind days in Inner Mongolia aligns with research in other regions [7,8,9,10,12], though the magnitude varies. The climate tendency rate in Inner Mongolia [-16.52 d $\cdot$ $(10a)^{-1}$] is greater than that in the Chaidamu Basin [-5.80 d $\cdot$ $(10a)^{-1}$] but less than that in the Qaidam Basin [-42.40 d $\cdot$ $(10a)^{-1}$], demonstrating regional differences. The most significant reduction occurred during the 1970s–1980s, likely influenced by ecological restoration projects implemented in Inner Mongolia since the 1980s, which have reduced high wind occurrences to some extent.

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Note: Figure translations are in progress. See original paper for figures.