Analysis of Variation Characteristics of Consecutive Precipitation-Free Days in the Desert Steppe of Inner Mongolia from 1960 to 2020 (Postprint)

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Abstract

Based on daily precipitation data from nine meteorological stations in the desert steppe of Inner Mongolia and reanalysis data from the National Centers for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR), this study employs statistical methods to analyze the characteristics of consecutive precipitation-free events and circulation features in anomalous years in this region from 1960 to 2020. The results indicate: (1) Consecutive precipitation-free events occur most frequently in summer, but the mean duration and maximum duration are shortest in summer. The summer precipitation distribution pattern is characterized by the alternating occurrence of short-term consecutive precipitation-free events and relatively longer-term precipitation events, whereas the opposite pattern is observed in other seasons. (2) The annual average number of precipitation-free days in the study area is 304.1 $d \cdot a^{-1}$, the annual average frequency of consecutive precipitation-free events is 39.6 times $\cdot a^{-1}$, the annual average mean duration of consecutive precipitation-free events is 8.0 $d \cdot a^{-1}$, and the annual average maximum duration is 43.7 $d \cdot a^{-1}$. (3) The three parameters of consecutive precipitation-free events show no significant changes over the past 61 years; however, during 2005–2020, the frequency of consecutive precipitation-free events increased significantly while the mean duration decreased significantly. (4) Both the annual mean duration and maximum duration exhibit significant negative correlations with the frequency of consecutive precipitation-free events, whereas the mean duration and maximum duration show a significant positive correlation. (5) During anomalous consecutive precipitation-free events, significant temperature, humidity, and geopotential height anomalies are observed in the middle and upper troposphere.

Full Text

Variation Characteristics of Dry Spells in the Inner Mongolia Desert Steppe from 1960 to 2020

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Abstract

Based on daily precipitation data from nine meteorological stations and NCEP/NCAR reanalysis data, this study analyzes the long-term variation characteristics of dry spells in the Inner Mongolia desert steppe from 1960 to 2020 using statistical methods. The atmospheric circulation features during extreme events are examined through composite analysis. The results indicate that: (1) Dry spells occur most frequently in summer, yet exhibit the shortest mean and maximum durations during this season. The summer precipitation pattern is characterized by alternating short dry spells and long precipitation events, whereas other seasons show the opposite pattern with long dry spells and short precipitation events. (2) The annual mean number of non-precipitation days is 304.1 $d \cdot a^{-1}$, with an average of 39.6 dry spell events per year, a mean duration of 8.0 $d \cdot a^{-1}$ per event, and a maximum duration of 43.7 $d \cdot a^{-1}$. (3) While no significant trends are detected for these parameters over the entire 61-year period, dry spell frequency increased significantly and mean duration decreased significantly during 2005–2020 (both significant at the 90% confidence level). (4) Mean duration shows a strong negative correlation (r = -0.91) with dry spell frequency and a positive correlation (r = 0.61) with maximum duration, while frequency correlates negatively (r = -0.51) with maximum duration (all significant at the 99% level). (5) During prolonged dry spell events, significant anomalies in temperature, humidity, and geopotential height are observed in the mid-to-upper troposphere.

Keywords: dry spell; average duration; maximum duration; Inner Mongolia desert steppe

Introduction

Grassland represents one of the most important terrestrial ecosystems. Desert steppe, located in the transitional zone between grassland and desert ecosystems, constitutes a xeric grassland ecosystem marking the transition from steppe to desert, and represents a vulnerable ecological zone. In Inner Mongolia, desert steppe is distributed across the arid and semi-arid regions of west-central Inner Mongolia Plateau, primarily on the stratified high plain north of the Yinshan Mountains, extending from Sunite in the east to Urad in the west, connecting with the desert steppe in southern Mongolia to the northwest, and linking with the warm temperate desert steppe in central and western Ordos Plateau via the Yellow River barrier to the southwest. The region receives 150–250 mm of mean annual precipitation, concentrated in summer, with frequent spring droughts and a mean annual temperature of 2–5°C. With accumulated temperature $ $10°C of 2200–2500°C, this region represents a zonal vegetation type transitioning gradually from grassland to desert. Its location along the monsoon margin makes the ecosystem exceptionally sensitive to climate change.

As the primary water source in this arid and semi-arid region, atmospheric precipitation constitutes the key limiting factor for vegetation growth. Under global warming, precipitation patterns have changed significantly worldwide, manifested in annual and seasonal precipitation distribution and extreme precipitation events (single precipitation events, precipitation pulses). Precipitation deficits trigger drought, leading researchers to define numerous drought indices for analyzing drought characteristics and causes, including the Standardized Precipitation Index and Palmer Drought Severity Index, which have been widely applied. Extreme climate events deteriorate ecological environments, with extreme drought significantly impacting plant eco-physiological processes and biodiversity in ecosystems. Researchers have proposed different extreme drought indices, among which consecutive dry days (Dry spell) have been widely applied in drought analysis. Studies based on this index have analyzed non-precipitation days and consecutive dry days in different regions, as well as circulation conditions and the impacts of precipitation pulses on ecosystems and fires in arid and semi-arid regions.

Previous studies on consecutive dry days in different regions of China have focused on spatiotemporal distribution patterns, with some combining analyses of consecutive precipitation days. Research indicates that the Pacific Decadal Oscillation and Southern Oscillation Index are closely related to consecutive dry days in China, with dry days in South China correlating strongly with precipitation and non-precipitation days but weakly with temperature. In Inner Mongolia, consecutive dry days mainly concentrate in 1–10 day periods, with nearly half of non-precipitation days occurring in 1–5 day periods, yet long consecutive dry periods exist, indicating high drought risk due to concentrated non-precipitation days. Located in the arid and semi-arid region of central-western Inner Mongolia with only 250 mm of annual precipitation, the Inner Mongolia desert steppe experiences drought as its main precipitation characteristic. Drought impacts on agriculture and ecology depend not only on precipitation amount but also on its temporal distribution—drought can occur due to uneven precipitation distribution even when total precipitation shows no significant change. The number of dry days between precipitation events is particularly important for precipitation distribution and soil moisture dynamics. Therefore, this study employs consecutive dry days as a drought index to analyze variation characteristics, providing a theoretical basis for understanding climate change impacts on precipitation distribution patterns and water resource management in desert steppe regions.

Data and Methods

1.1 Data Sources

Daily precipitation data from nine meteorological stations (Erenhot, Narenbaolige, Mandula, Sunite Left Banner, Sunite Right Banner, Zhurihe, Urad Middle Banner, Baiyun Obo, and Damao Banner) in the Inner Mongolia desert steppe from 1960 to 2020 were obtained from the National Meteorological Information Center. Trace precipitation, pure fog, dew, and frost were recorded as non-precipitation days. Monthly and multi-year average geopotential height, temperature, relative humidity, and wind data at 850 hPa and 500 hPa levels with 2.5°$×$2.5° resolution were derived from NCEP/NCAR reanalysis data.

1.2 Research Methods

Definition of Events: A precipitation event is defined as a process with continuous precipitation for three or more days. Correspondingly, a dry spell is defined as consecutive days without precipitation. Three dry spell parameters are analyzed: dry spell frequency (number of events), mean length of dry spells (average duration), and maximum length of dry spells (maximum duration). The first day of each dry spell or precipitation event is designated as the event occurrence date.

Analysis Methods: Pearson correlation analysis and regional averaging were used to analyze precipitation dynamics. Correlation coefficients between total precipitation at all stations were positive and significant at the 99% confidence level, indicating strong correlation and small differences among stations. Therefore, arithmetic averaging of all nine stations was used for regional analysis.

Composite Analysis: To analyze circulation characteristics during extreme events, the longest consecutive precipitation event (August 7-14, 1979) and longest dry spell (August 9-31, 2007) were selected for composite analysis. Precipitation formation requires both moisture transport and upward dynamic conditions. Since 850 hPa is the primary moisture transport layer and 500 hPa provides the background for upward motion, these two levels were selected for circulation analysis.

Results

2.1 Seasonal Distribution Characteristics of Dry Spells

The month of the first day of each dry spell or precipitation event is recorded as the event occurrence month. Dry spell frequency shows a unimodal annual distribution, peaking in July (approximately 6 events) and decreasing toward both sides. Dry spells concentrate in May-September, the plant growing season, with more events in summer and fewer in spring, autumn, and winter. The mean duration of dry spells shows an opposite pattern, peaking in October-November (maximum 18.2 days) and decreasing toward both ends, with minimum values in June–July (3.6 days). Thus, although summer has the most frequent dry spells, they are predominantly short-term events.

The seasonal distribution of maximum dry spell duration is consistent with mean duration, being shortest in summer (approximately 25 days). The annual peak also occurs in October–November (about 25 days). This pattern indicates that in summer, when precipitation is concentrated, precipitation intervals are short and short-term dry spells occur frequently. In seasons with less precipitation, precipitation events are more widely spaced, resulting in fewer but longer dry spells.

In contrast, precipitation events show a unimodal distribution for frequency, mean duration, and maximum duration, all peaking in summer. Precipitation event frequency peaks in July (6 events), with minimum in winter (1.8 events). Mean precipitation event duration also peaks in July (3.3 days), with maximum duration showing similar patterns. The difference between maximum and mean duration is largest in summer (approximately 3.3 days) and less than 1.0 day in other seasons.

The precipitation pattern in Inner Mongolia desert steppe is characterized by: (1) the most frequent dry spells and precipitation events in summer; (2) alternating short dry spells and long precipitation events as the main summer pattern; and (3) long dry spells and short precipitation events as the main pattern in other seasons.

2.2 Interannual Variation Characteristics of Dry Spells

Time series analysis of dry spell parameters from 1960–2020 reveals:

Non-precipitation Days: Annual total non-precipitation days averaged 304.1 $d \cdot a^{-1}$ (maximum 342.2 days in 1982, minimum 270.6 days in 2003) with no significant trend.

Dry Spell Frequency: Annual mean frequency was 39.6 events (maximum 67 events in 2007, minimum 26.4 events in 1990), showing no significant trend overall but a significant increase during 2005–2020 (significant at 90% level). Short-term dry spells, particularly single-day events, increased significantly.

Mean Duration: Annual mean duration was 8.0 $d \cdot a^{-1}$ (maximum 11.1 days in 1990, minimum 6.0 days in 2007), showing a significant decreasing trend during 2005–2020 (significant at 90% level).

Maximum Duration: Annual maximum duration averaged 43.7 $d \cdot a^{-1}$ (maximum 70 days in 1965, minimum 30 days in 2003) with no significant trend.

Scatter density analysis shows the most common annual dry spell frequency is approximately 40 events, with mean duration concentrated around 6–8 days and maximum duration most frequently observed between 30–50 days.

Correlations: Mean duration shows a strong negative correlation (r = -0.91) with dry spell frequency and a positive correlation (r = 0.61) with maximum duration, while frequency correlates negatively (r = -0.51) with maximum duration. All correlations are significant at the 99% confidence level.

2.3 Comparative Circulation Analysis of Dry Spells and Precipitation Events

Composite analysis of the longest precipitation event (August 7–14, 1979) and longest dry spell (August 9–31, 2007) reveals distinct circulation patterns:

500 hPa Level: During the dry spell, anticyclonic curvature increased over upstream mid-high latitudes, with winds shifting from westerly to northwesterly over the study area. The Western Pacific Subtropical High strengthened but showed little position change. A large-scale warm anomaly dominated mid-high latitudes, with the study area located south of the anticyclonic anomaly center, creating unfavorable conditions for precipitation. During the precipitation event, temperature anomalies showed a north-south symmetric pattern with warm anomalies at 30°–40°N and strong cold anomalies north of the study area, enhancing circulation variability and creating favorable upward motion for precipitation.

850 hPa Level: Similar to 500 hPa, the dry spell period featured warm anomalies over the study area and north-south symmetric temperature anomalies at mid-high latitudes. The Western Pacific Subtropical High extended westward and northward, with relative humidity showing negative anomalies, creating unfavorable moisture conditions. During the precipitation event, strong cyclonic circulation appeared over East Siberia with enhanced anticyclonic circulation over offshore China, positioning the study area in southerly flow favorable for moisture transport and precipitation formation.

Discussion

This study focuses on the desert steppe region of Inner Mongolia, a typical ecologically vulnerable area, analyzing dry spell frequency, mean duration, and maximum duration. Previous research on consecutive dry days in different regions has emphasized maximum duration as a drought index, while paying less attention to frequency and mean duration. Using long-term precipitation data, this study provides statistical analysis of all three parameters.

The seasonal distribution shows that summer precipitation in the Inner Mongolia desert steppe is characterized by alternating short dry spells and long precipitation events, while other seasons show the opposite pattern. This distribution pattern is crucial for water resource utilization in this water-limited ecosystem. The three dry spell parameters show significant interannual variability, with notable changes during 2005–2020: frequency increased significantly while mean duration decreased significantly, driven primarily by increases in short-term (especially single-day) dry spells.

The mechanism behind these changes warrants further investigation. During prolonged dry spells, significant anomalies in temperature, humidity, and geopotential height occur in the mid-to-upper troposphere. At 500 hPa, warm anomalies and anticyclonic circulation dominate, while at 850 hPa, the Western Pacific Subtropical High extends abnormally westward and northward with negative relative humidity anomalies, all inhibiting precipitation formation.

For arid and semi-arid regions where water is the primary limiting factor for vegetation growth, the temporal distribution pattern of precipitation is critical for utilizing limited water resources. The significant changes in precipitation patterns identified in this study will impact soil moisture, agriculture, and ecosystems—effects that require further investigation.

Conclusions

Based on daily precipitation observations from nine meteorological stations in the Inner Mongolia desert steppe from 1960–2020, this study analyzes the climatic characteristics and variation of dry spells, reaching the following conclusions:

1. **Seasonal Pattern:** Summer has the most frequent dry spells and precipitation events. The summer precipitation pattern is characterized by alternating short dry spells and long precipitation events, while other seasons are dominated by long dry spells and short precipitation events.

2. **Climatological Means:** The region averages 304.1 non-precipitation days annually, with 39.6 dry spell events per year, mean duration of 8.0 days per event, and maximum duration of 43.7 days per event. No significant long-term trends are detected for these parameters over the 61-year period.

3. **Recent Changes:** During 2005–2020, dry spell frequency increased significantly while mean duration decreased significantly (both significant at 90% level), driven by increases in short-term, particularly single-day, dry spells.

4. **Correlations:** Mean duration correlates strongly and negatively with dry spell frequency (r = -0.91) and positively with maximum duration (r = 0.61), while frequency correlates negatively with maximum duration (r = -0.51). All correlations are significant at the 99% confidence level.

5. **Circulation Anomalies:** During prolonged dry spells, significant anomalies occur in temperature, humidity, and geopotential height in the mid-to-upper troposphere, with warm anomalies and anticyclonic circulation at 500 hPa, westward-northward extension of the Western Pacific Subtropical High at 850 hPa, and negative relative humidity anomalies, creating unfavorable conditions for precipitation.

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Figures

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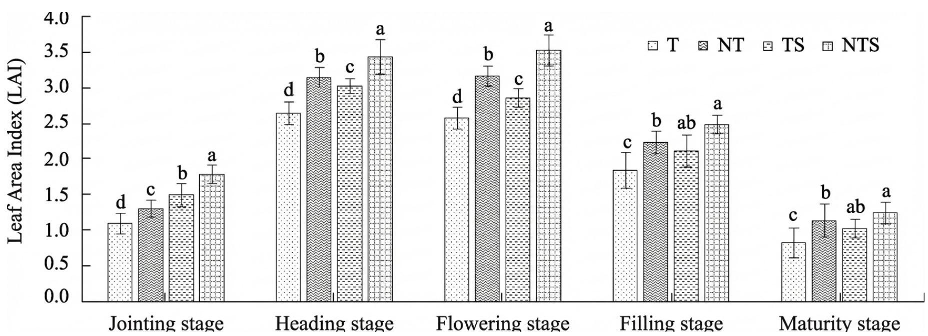

Figure 1: Figure 3