Response of Seasonal Frozen Soil to Climate Change in the Typical Steppe of Inner Mongolia, 1981–2018: Postprint

Authors: Su Yue

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Abstract

This study examines the seasonal frozen soil of typical grasslands in Inner Mongolia from 1981 to 2018, analyzing the spatiotemporal distribution characteristics, interannual and interdecadal variations of maximum frozen soil depth, and investigating meteorological factors influencing its changes using methods including climate tendency rate, Mann-Kendall test, and multiple linear regression. The results show that: (1) The initial freezing date of seasonal frozen soil in typical grasslands of Inner Mongolia occurs in September-November, the final thawing date in April-June, with the maximum frozen soil depth within the year appearing in February-March at depths ranging between 100-280 cm. (2) The interannual variation of maximum frozen soil depth can be categorized into downward-opening parabolic, upward-opening parabolic, and sinusoidal patterns; based on the climate tendency rate of maximum frozen soil depth, 68% of stations exhibit a decreasing trend. (3) The interdecadal variation of maximum frozen soil depth can be divided into decreasing-by-decade, decrease-increase, and no obvious pattern types, with 50% of stations experiencing an abrupt change in maximum frozen soil depth after 1989. (4) Multiple linear regression indicates that air temperature freezing index, annual average wind speed, and annual extreme minimum temperature exert significant influences on maximum frozen soil depth. This study reveals the degradation of maximum frozen soil depth, providing guidance for grassland adaptation to climate change and offering insights for research on carbon cycle exchange between terrestrial soil and atmosphere.

Full Text

Response of Seasonal Frozen Soil to Climate Change on a Typical Steppe of Inner Mongolia During 1981–2018

SU Yue[1], ZHANG Cunhou[1,2], Amuersana[3], LI Ke[4] [1]Inner Mongolia Autonomous Region Meteorological Disaster Monitoring and Warning Center, Hohhot 010051, Inner Mongolia, China
[2]Inner Mongolia Autonomous Region Ecological and Agricultural Meteorology Center, Hohhot 010051, Inner Mongolia, China
[3]Hohhot Bureau of Meteorology, Hohhot 010000, Inner Mongolia, China
[4]Xuzhou Bureau of Meteorology, Xuzhou 221000, Jiangsu, China

Abstract: This study investigates the response of seasonal frozen soil to climate change on the typical steppe of Inner Mongolia using data from 1981 to 2018. Through climate tendency rate, cumulative anomaly, Mann-Kendall mutation test, and multiple linear regression methods, we analyzed the spatiotemporal distribution characteristics, interannual variations, and interdecadal changes of maximum frozen soil depth, and identified the meteorological factors influencing these changes. The results show that: (1) The initial freezing date of seasonal frozen soil on the Inner Mongolian typical steppe occurs in September–November, the final thawing date occurs in April–June, and the maximum frozen depth appears in February–March, ranging between 100–280 cm. (2) Interannual variations in maximum frozen depth can be classified into three patterns: lower-opening parabolic, upper-opening parabolic, and sinusoidal curves. Based on climate tendency rates, 68% of stations exhibited a decreasing trend in maximum frozen depth. (3) Interdecadal variations show three types: chronologically decreasing, decreasing then increasing, and no clear pattern. After 1989, the maximum frozen depth underwent a sudden change, indicating degradation. (4) Multiple linear regression reveals that temperature freezing index, annual mean wind speed, and annual extreme minimum temperature significantly influence maximum frozen depth. This study reveals the degradation of maximum frozen depth and provides guidance for grassland adaptation to climate change, offering insights for research on carbon exchange between terrestrial soil and the atmosphere.

Keywords: seasonal frozen soil; climate change; typical steppe; multiple linear regression

1. Introduction

Frozen soil refers to various rocks and soils containing ice at temperatures below zero degrees Celsius, and is classified into short-term frozen soil, seasonal frozen soil, and permafrost. Seasonal frozen soil, defined as soil that freezes in winter and thaws in summer with a freezing duration exceeding one month, serves as an important intermediary of climate change. Previous studies have demonstrated that air temperature and snowfall frequency affect frozen soil depth and freeze-thaw cycles in northern Indiana. As an unstable geological body highly influenced by topography and underlying surfaces, frozen soil provides clear indications of regional climate change. Seasonal frozen soil is particularly sensitive to climate change as it directly participates in Earth' s heat balance and is easily affected by seasonal variations.

Research indicates that global warming has led to phenomena such as thinning frozen soil layers, delayed freezing dates, and advanced thawing dates across many regions. Studies show that temperature rise and increased precipitation are unfavorable for frozen soil thickening. On the Tibetan Plateau, seasonal frozen soil has experienced a reduction in freezing days. In the Taxkorgan River Valley of Xinjiang, seasonal frozen soil changes are strongly influenced by regional climate warming, with the initial freezing date delayed, final freezing date advanced, annual freezing days reduced, and maximum frozen depth decreased. Similarly, in Liaoning Province, although soil remains frozen for a certain period each year, maximum frozen depth is decreasing annually. In the eastern Hexi Corridor, the initial freezing period has been delayed while the thawing period has advanced, showing quasi-periodic variations in time series.

The Fourth Assessment Report of the IPCC indicates that global average surface temperature has risen by 0.74°C over the past century. As a "sensor" of climate change, frozen soil degradation and ablation not only affect ecological environment construction and water conservancy planning but also release carbon stored in frozen soil, exacerbating global warming. In Inner Mongolia, near-surface negative accumulated temperature changes are commonly used to reflect frozen soil depth variations, with freezing index serving as a climatic parameter to quantify seasonal frozen soil depth changes. The freezing index, defined as the cumulative value of all temperatures below 0°C during a freezing period, is frequently applied in assessing frozen soil distribution patterns and climate change.

The typical steppe of Inner Mongolia, located in the hinterland of the Eurasian continent, features abundant sunlight, scarce precipitation, and a sensitive ecological environment. Most of this region belongs to the seasonal frozen soil zone. However, analyses based on long-term frozen soil data examining the response of Inner Mongolian grassland seasonal frozen soil to climate change remain relatively scarce. Therefore, this study utilizes 38 years (1981–2018) of frozen soil and meteorological factor data from 15 stations, applying climate diagnostic analysis methods to examine intra-annual, interdecadal, and climate mutation characteristics of seasonal frozen soil on the Inner Mongolian typical steppe. This research aims to reveal the facts of seasonal frozen soil reduction and provide theoretical support for grassland adaptation to climate change.

1.1 Study Area Overview

The typical steppe of Inner Mongolia, formed under semi-arid climatic conditions, constitutes the main body of Inner Mongolia' s natural grassland and represents an important component of the Eurasian steppe region. It is primarily located in central and eastern Inner Mongolia. While the typical steppe in the northeastern Hohhot region experiences colder climates and mainly belongs to the permafrost zone, the central and southeastern regions have relatively warmer climates and exhibit seasonal frozen soil phenomena. This study focuses on seasonal frozen soil changes in the central and southeastern typical steppe of Inner Mongolia (111°07 ~123°04 E, 40°12 ~46°42 N). The region features a mid-temperate semi-arid continental monsoon climate with distinct seasonal changes, an average elevation of 1024 m, mean annual temperature of 4.9°C, annual precipitation of 223.6 mm (concentrated in June–August, accounting for 50%–60% of annual precipitation), annual evaporation of 1852.4 mm, maximum snow depth of 8.5 mm, and mean annual wind speed of 3.0 $m \cdot s^{-1}$. Dominant plant species include *Leymus chinensis*, *Stipa grandis*, *Agropyron cristatum*, *Carex duriuscula*, *Cleistogenes squarrosa*, *Potentilla bifurca*, *Artemisia frigida*, and *Caragana microphylla*.

1.2 Data Sources

This study selected 15 meteorological observation stations with relatively long time series and seasonal frozen soil observations on the Inner Mongolian typical steppe. Frozen soil depth was measured using frozen soil apparatus. Daily data on frozen soil depth, average temperature, average relative humidity, average wind speed, precipitation, sunshine duration, snow depth, and ground temperatures at 40 cm and 80 cm depths from 1981–2018 were obtained from the Inner Mongolia Meteorological Bureau. The maximum value of frozen soil depth is defined as maximum frozen depth, the first soil freezing date in the second half of the year is the initial freezing date, and the last frozen soil occurrence in the first half of the following year is the final freezing date. The freezing index refers to the cumulative value of all temperatures below 0°C during a freezing period. To maintain continuity in frozen soil freezing time, this study calculated the freezing index from July 1 of the current year to June 30 of the following year. Maps were sourced from the Standard Map Service website of the National Administration of Surveying, Mapping and Geoinformation.

1.3 Methods

1.3.1 Climate Tendency Rate of Maximum Frozen Depth A univariate linear regression equation was established between maximum frozen depth and its corresponding time, calculated as:

$$x_i = a + bt_i, \quad i = 1, 2, \dots, n$$

where x_i represents the annual maximum frozen depth value (cm), t_i represents the corresponding time (year), a is the regression constant, b is the linear trend term estimated by least squares method, and n is the sample size.

1.3.2 Cumulative Anomaly of Maximum Frozen Depth Cumulative anomaly analysis was used to determine interannual variation trends of maximum frozen depth, calculated as:

$$x_t = \sum_{i=1}^{t} (x_i - \bar{x}), \quad t = 1, 2, \ldots, 38$$

where x_t is the cumulative anomaly value, x_i is the annual maximum frozen depth value (cm), $\bar{x}$ is the multi-year average of maximum frozen depth (cm), and n is the sample size ($n = 38$).

1.3.3 Mann-Kendall Mutation Test The Mann-Kendall method is a nonparametric statistical test that does not require samples to follow a specific distribution and is not affected by outliers. It can identify mutation start times and regions, making it suitable for ordinal variables. For a maximum frozen depth time series x with n samples, an order series is constructed:

$$S_k = \sum_{i=1}^{k} r_i, \quad k = 1, 2, \ldots, n$$

where r_i is the count of $x_i > x_j$ ($j = 1, 2, \ldots, i$), and S_k is the cumulative count of values greater than previous values. When $x_1, x_2, \ldots, x_n$ are independent with identical continuous distributions, the mean $E(S_k) = k(k-1)/4$ and variance $\sigma^2(S_k) = k(k-1)(2k+5)/72$. The statistic is defined as:

$$UF_k = \frac{S_k - E(S_k)}{\sigma(S_k)}, \quad k = 1, 2, \ldots, n$$

where UF_k follows a standard normal distribution. The sequence is then arranged in reverse chronological order to calculate variable UB_k. The intersection point where UF_k and UB_k curves cross within the confidence interval indicates a mutation point.

1.3.4 Freezing Index Calculation The freezing index formula calculates the cumulative negative daily mean temperatures during a freezing period:

$$FI = \sum_{i=1}^{n} |T_i|, \quad T_i < 0$$

where FI is the freezing index (°C • d), T_i is the negative daily temperature (°C), and n is the number of days with negative temperatures in the year.

1.3.5 Pearson Correlation Analysis Pearson correlation coefficient (r) measures linear correlation between variables Y and X, ranging from $[-1, +1]$. Values of $|r| < 0.3$ indicate weak correlation, $0.3 \leq |r| < 0.5$ low correlation, $0.5 \leq |r| < 0.8$ moderate correlation, and $|r| \geq 0.8$ high correlation:

$$r = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2 \sum_{i=1}^{n}(y_i - \bar{y})^2}}$$

where r is the correlation coefficient, x_i is the annual maximum frozen depth value (cm), $\bar{x}$ is the multi-year average of maximum frozen depth (cm), y_i is the meteorological factor value, $\bar{y}$ is the meteorological factor mean, and n is the sample size ($n = 38$).

1.3.6 Multiple Linear Regression The multiple linear regression model includes k variables: one dependent variable (maximum frozen depth) and k independent variables (meteorological factors). The model is summarized by n equations:

$$Y_t = \beta_0 + \beta_{1X_{1t}} + \beta_{2X_{2t}} + \cdots + \beta_{kX_{kt}} + \varepsilon_t, \quad t = 1, 2, \ldots, n$$

where Y_t is the maximum frozen depth (cm), $X_{1t}, \ldots, X_{kt}$ are meteorological factors, β_k are fixed unknown parameter vectors, ε_t is the random error term, and n is the sample size ($n = 38$). The matrix equation is:

$$Y = X\beta + \varepsilon$$

where Y is an n-column vector of dependent variable observations, X is an $n \times (k+1)$ matrix of independent variable observations, β is a $(k+1)$-column vector of unknown parameters, and ε is an n-column vector of error observations. In matrix X, each element X_{ij} has row index i (observation) and column index j (variable). All observations related to the intercept equal 1.

This study used OriginPro 8.5 and Microsoft Office 2019 for mapping and calculating climate tendency rates and cumulative anomalies, and SPSS 25.0 for Mann-Kendall mutation tests, Pearson correlation analysis, and multiple linear regression analysis.

2. Results

2.1 Spatiotemporal Distribution of Maximum Frozen Depth

Seasonal frozen soil on the Inner Mongolian typical steppe exhibits significant intra-annual variation with distinct seasonal patterns. The initial freezing date occurs in September–November with probabilities of 33.3%, 46.7%, and 20.0% respectively, while the final thawing date appears in April–June with probabilities of 13.3%, 60.0%, and 26.7%. The maximum frozen depth occurs in February–March. Analysis of maximum frozen depth timing at 15 stations over the past 38 years shows that the annual maximum depth primarily appears between 100–280 cm. The maximum frozen depth value occurred at Chaha' er Right Rear Banner (416 cm), while the minimum appeared at Zhalute Banner (172 cm). Spatially, frozen soil in the north freezes earlier and thaws later than in the south, with longer freezing duration in the north; similarly, the east freezes earlier and thaws later than the west, with longer duration in the east.

[Figure 1: see original paper] Spatial distribution of meteorological stations in typical steppe of Inner Mongolia
[Figure 2: see original paper] Occurrence time distribution of maximum frozen soil depth in typical steppe of Inner Mongolia

2.2 Interannual Variation of Maximum Frozen Depth

To better determine long-term evolution trends and persistent changes, cumulative anomaly analysis was applied to the maximum frozen depth series. The results indicate that the late 1980s represent a critical period of significant decline in maximum frozen depth. Interannual variation trends can be divided into three categories: (1) Lower-opening parabolic type (increasing then decreasing), showing an increasing trend before the mid-1980s and decreasing thereafter. This type includes the most stations (53.3% of total): Jalainur Banner, East Ujimqin Banner, Abag Banner, Chaha' er Right Rear Banner, Zhuozi County, Liangcheng County, Jining District, Gaoliban Town, and Hexigten Banner. (2) Upper-opening parabolic type (decreasing then increasing), showing a decreasing trend before the 1990s and increasing after 2000. This type accounts for 26.7% of stations: Huade County, West Ujimqin Banner, Zhalute Banner, Horqin Left Middle Banner, and Xilinhot City. (3) Sinusoidal type, showing an increasing trend in the 1980s, decreasing in the 1990s, then increasing again. This type represents 20.0% of stations: Chaha' er Right Middle Banner, Shangdu County, Chaha' er Right Front Banner, Bairin Right Banner, Alukeerqin Banner, Zhenglan Banner, and Taibus Banner.

[Figure 3: see original paper] Cumulative anomaly curves of maximum frozen soil depths in typical steppe of Inner Mongolia from 1981 to 2018

2.3 Interdecadal Variation of Maximum Frozen Depth

From 1981–2018, 13 of 15 stations showed decreasing trends in annual maximum frozen depth, with climate tendency rates of -0.70 to -3.05 cm·$(10a)^{-1}$. Ten stations passed significance tests, with rates of -0.70 to -3.05 cm·$(10a)^{-1}$. The largest shallowing occurred at Hexigten Banner (-3.05 cm·$(10a)^{-1}$, passing the 0.01 significance test), while the smallest occurred at Liangcheng County (-0.70 cm·$(10a)^{-1}$, passing the 0.05 test). Two stations showed increasing trends with rates of 0.28–1.31 cm·$(10a)^{-1}$; one station (West Ujimqin Banner, 1.31 cm·$(10a)^{-1}$) passed the 0.05 significance test.

Interdecadal variations can be divided into three types: (1) Chronologically decreasing type (33.3% of stations: Gaoliban Town, Hexigten Banner, East

Ujimqin Banner, Abag Banner, Shangdu County, Bairin Right Banner, Zhengbai Banner, Liangcheng County, Jining District), showing decreases of 37.0–87.2 cm per decade, with Hexigten Banner decreasing most rapidly. (2) Decreasing then increasing type (46.7% of stations: Jalainur Banner, West Ujimqin Banner, Zhalute Banner, Horqin Left Middle Banner, Xilinhot City, Taibus Banner, Chaha' er Right Front Banner, Chaha' er Right Middle Banner, Chaha' er Right Rear Banner, Jining District), shallowing by 1.9–45.3 cm before the 21st century then thickening by 7.9–35.6 cm, with East Ujimqin Banner showing the largest decrease and Shangdu County the largest increase. (3) No clear pattern (20.0% of stations: Huade County, Alukeerqin Banner, Zhenglan Banner).

Climate mutation detection using the Mann-Kendall method revealed that maximum frozen depth at 13 stations underwent abrupt changes in 1989, shifting from a relatively deep period to a shallow period, indicating degradation trends across most of the study area.

Linear trend analysis of maximum frozen soil depth changing rates in typical steppe of Inner Mongolia from 1981 to 2018
[Figure 4: see original paper] Linear trend distribution of maximum frozen soil depth changing rates in typical steppe of Inner Mongolia

2.4 Correlation Analysis Between Maximum Frozen Depth and Meteorological Factors

The causes of frozen depth variation are complex, with climate, topography, and human activities all exerting influence, though climate factors have the greatest impact. To understand the response process of seasonal frozen depth to climate change, Pearson correlation analysis was conducted between maximum frozen depth and 12 potential meteorological factors: annual mean temperature, annual temperature range, annual extreme maximum temperature, annual extreme minimum temperature, mean relative humidity, annual precipitation, maximum snow depth, mean ground temperature at 40 cm and 80 cm, sunshine duration, annual mean wind speed, temperature freezing index, and ground freezing index.

Results show significant correlations (passing the 0.01 significance level) between maximum frozen depth and annual mean temperature, temperature freezing index, ground freezing index, annual extreme minimum temperature, mean ground temperature at 40 cm, and mean ground temperature at 80 cm. The strongest correlation was with annual mean temperature, followed by ground temperature at 40 cm. Weak correlations were found with annual extreme maximum temperature, annual precipitation, maximum snow depth, and sunshine duration; low correlations with annual temperature range, mean relative humidity, and annual mean wind speed; and moderate correlations with temperature freezing index, ground freezing index, annual extreme minimum temperature, and mean ground temperatures.

After excluding weakly correlated variables, multiple linear regression analysis was performed using low and moderately correlated variables. The initial model showed multicollinearity among annual mean temperature, temperature freezing index, and ground temperatures (variance inflation factor > 10). Considering that frozen depth variation is affected by both negative accumulated temperature and human factors, temperature freezing index, annual temperature range, mean relative humidity, annual mean wind speed, and annual extreme minimum temperature were selected for regression analysis. The adjusted R^2 of 0.517 indicates these five variables explain 51.7% of maximum frozen depth variation. The Durbin-Watson statistic of 1.831 suggests no autocorrelation. ANOVA shows an F-statistic of 8.445 ($P < 0.001$), confirming significant linear relationships. The final regression equation is:

$$y = -32.340 - 0.056x_1 + 8.445x_2 + 0.313x_3 + 5.963x_4 - 1.096x_5$$

where y is maximum frozen depth (cm), x_1 is temperature freezing index (°C · d), x_2 is annual temperature range (°C), x_3 is mean relative humidity (%), x_4 is annual mean wind speed ($m \cdot s^{-1}$), and x_5 is annual extreme minimum temperature (°C). Model residuals follow a normal distribution. Temperature freezing index, annual mean wind speed, and annual extreme minimum temperature significantly affect maximum frozen depth variation.

Decadal variation of the maximum frozen soil depths in typical steppe of Inner Mongolia
Pearson correlation coefficient between maximum frozen soil depths and meteorological factors in typical steppe of Inner Mongolia
Linear regression model between maximum frozen soil depths and meteorological factors in typical steppe of Inner Mongolia

3. Discussion

This study measured soil freezing depth using frozen soil apparatus to investigate spatiotemporal distribution, interannual variation, and interdecadal changes of seasonal frozen soil on the Inner Mongolian typical steppe from 1981–2018. Mann-Kendall mutation tests revealed significant shallowing trends and abrupt changes around 1989. Maximum frozen depth is typically influenced by interactions among multiple meteorological factors. This study found that temperature freezing index and annual extreme minimum temperature affect frozen depth variation. Notably, annual mean wind speed showed a positive correlation with maximum frozen depth, possibly because increased wind speed enhances soil surface water evaporation, which consumes soil heat and leads to deeper freezing—though this mechanism requires further investigation.

Factors influencing maximum frozen depth are extremely complex, extending beyond meteorological factors. Research indicates that altitude increase amplifies frozen depth reduction, different vegetation types affect thawing rates, and water distribution, soil properties, and human activities all constrain frozen depth. In recent decades, socioeconomic development has intensified human impacts. Studies show that human activities such as road construction in cold regions affect frozen soil stability. In vulnerable frozen soil areas, infrastructure development accelerates degradation and impacts road construction. Therefore, research on seasonal frozen depth changes in Inner Mongolian typical steppe provides reference for understanding ecological environmental effects and offers insights for soil-atmosphere carbon cycle research.

The broad regional distribution of Inner Mongolian typical steppe leads to spatial differences in temperature and precipitation. This study used data from 15 automatic meteorological stations to analyze spatiotemporal characteristics and relationships with meteorological factors. However, station data limitations mean the study does not comprehensively represent the entire typical steppe region. Additionally, increasing human activity affects observations—for instance, the appearance of irrigated farmland near study sites influences frozen soil data accuracy. Given the complex, dynamic interactions among factors affecting frozen depth, continuous monitoring, modeling, and validation are needed.

4. Conclusions

Based on 38 years of data from 15 meteorological stations on the Inner Mongolian typical steppe, this study analyzed spatiotemporal distribution, interannual and interdecadal variations, and relationships with meteorological factors, yielding the following conclusions:

1) Seasonal frozen soil on the Inner Mongolian typical steppe shows clear patterns: initial freezing in September-November, final thawing in April-June, and maximum depth of 100-280 cm occurring in February-March. Freezing occurs earlier and lasts longer in the north than south, and earlier with longer duration in the east than west.

2) Interannual variations in maximum frozen depth follow three patterns: lower-opening parabolic, upper-opening parabolic, and sinusoidal. Analysis of climate tendency rates over the past 38 years shows that 68% of stations exhibited decreasing trends, with the largest decrease at Hexigten Banner; the remaining stations showed slight increases, with the largest increase at West Ujimqin Banner. The decreasing trend region is mainly distributed in the central typical steppe area.

3) Interdecadal variations show three types: chronologically decreasing (50% of stations), decreasing then increasing (30% of stations), and no clear pattern (20% of stations). Abrupt changes occurred around 1989, indicating significant degradation trends across most of the typical steppe.

4) Pearson correlation analysis shows that maximum frozen depth has low correlation with annual temperature range, mean relative humidity, and annual mean wind speed; moderate correlation with annual mean temperature, temperature freezing index, ground freezing index, annual extreme minimum temperature, and mean ground temperatures at 40 cm and 80 cm. Multiple linear regression indicates that temperature freezing index,

annual mean wind speed, and annual extreme minimum temperature significantly affect maximum frozen depth, reflecting winter warming in the typical steppe and demonstrating the sensitivity of frozen depth to climate change.

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