Dynamic Changes in Surface Freeze-Thaw Indices and Their Driving Factors in Inner Mongolia: A Postprint

Authors: Zhang Haochen

Date: 2023-01-17T00:00:00+00:00

Abstract

Based on daily average surface temperature data from 45 meteorological stations in Inner Mongolia from 1980-2019, combined with China's first-generation global land surface reanalysis product (CRA) data and NDVI data, and using trend analysis, correlation analysis, and grey relational analysis, the spatiotemporal variation characteristics and driving factors of surface freeze-thaw indices in Inner Mongolia over the past 40 years were analyzed. The results show that: (1) The spatial distribution characteristics of the annual mean SFI (Surface Freezing Index) exhibit an increasing trend from southwest to northeast, while the STI (Surface Thawing Index) shows the opposite pattern; latitude is the key factor influencing the spatial distribution of surface freeze-thaw indices. During the study period, SFI and STI exhibited significant decreasing and increasing trends, respectively, with multi-year variation ranges of 956.1~1848.3 ℃ · d and 3717.6~4442.3 ℃ · d, and change rates of -156.4 ℃ · d · $(10a)^{-1}$ and 152.4 ℃ · d · $(10a)^{-1}$, respectively; compared with seasonal frozen ground regions, the freeze-thaw indices in permafrost regions were more sensitive to climate warming. (2) Over the past 40 years in the study area, soil surface water content, precipitation, and NDVI showed increasing trends, while snow depth showed a decreasing trend, but interannual variations exhibited different spatial differences; permafrost regions showed a warming-drying development trend, while seasonal frozen ground regions showed a warming-wetting development trend. (3) The relationship between surface freeze-thaw indices and influencing factors was primarily negative; SFI showed positive correlations with influencing factors in most permafrost regions and negative correlations in most seasonal frozen ground regions, while STI showed the opposite pattern. Changes in surface freeze-thaw indices in Inner Mongolia were jointly driven by influencing factors; 0.4 m soil water content was the dominant factor affecting SFI changes, while NDVI was the dominant factor affecting STI changes. The research results can provide scientific references for permafrost degradation, agricultural

and pastoral production, etc. in Inner Mongolia.

Full Text

Dynamic Changes and Driving Factors of the Surface Freeze-Thaw Index in Inner Mongolia

ZHANG Haochen[12], **SA Chula**[12], **MENG Fanhao**[12], **LUO Min**[12], **WANG Mulan**[12], **GAO Hongdou**[12], **ADIYA Saruulzaya**[3]

[1]College of Geographical Sciences, Inner Mongolia Normal University, Hohhot 010022, Inner Mongolia, China
[2]Key Laboratory of Remote Sensing and GIS, Inner Mongolia Autonomous Region, Hohhot 010022, Inner Mongolia, China
[3]Institute of Geography and Earth Ecology, Mongolian Academy of Sciences, Ulaanbaatar 15170, Mongolia

Abstract

Based on daily average surface temperature data from 45 meteorological stations in Inner Mongolia spanning 1980–2019, combined with China' s first-generation global land surface reanalysis product (CRA) data and NDVI data, this study analyzed the spatiotemporal variation characteristics and driving factors of surface freezing and thawing indices in Inner Mongolia using trend analysis, correlation analysis, and gray correlation methods. The results show that: (1) The spatial distribution of the annual mean Surface Freezing Index (SFI) exhibited an increasing trend from southwest to northeast, while the Surface Thawing Index (STI) showed the opposite pattern, with latitude being the key factor controlling the spatial distribution of surface freeze-thaw indices. During the study period, the SFI and STI showed significant decreasing and increasing trends, respectively, with multiyear variation ranges of 956.1–1848.3 °C·d and 3717.6–4442.3 °C·d, and change rates of -156.4 °C·d·$(10a)^{-1}$ and 152.4 °C·d·$(10a)^{-1}$. Compared with the seasonal permafrost zone, the freeze-thaw index in the multiyear permafrost zone was more sensitive to climate warming. (2) Surface soil water content, precipitation, and NDVI showed increasing trends, while snow depth showed a decreasing trend, but interannual variations exhibited different spatial heterogeneity. The multiyear permafrost zone showed a warm-dry development trend, while the seasonal permafrost zone showed a warm-wet trend. (3) The SFI and STI were mainly negatively correlated with influencing factors. The SFI was positively correlated with influencing factors in most of the multiyear permafrost zone and negatively correlated in most of the seasonal permafrost zone, while the STI showed the opposite pattern. Changes in surface freeze-thaw indices in Inner Mongolia were driven by the combined effects of influencing factors, with 0.4 m soil water content being the dominant factor affecting SFI change and NDVI being the dominant factor affecting STI change. The results provide scientific references for permafrost degradation and agricultural and pastoral production in Inner Mongolia.

Keywords: Inner Mongolia; surface freeze-thaw index; climate change; spatiotemporal characteristics; driving factors

1 Data and Methods

1.1 Study Area Overview

Inner Mongolia is located between 97°12 -126°04 E and 37°24 -53°23 N, covering a total area of 118.3$\times10^{4}$ km^2, which accounts for 12.3% of China' s total land area. The terrain is dominated by plateaus, with plains, sandy lands, hills, and mountains, and most areas have elevations above 1000 m. The climate belongs to the temperate continental monsoon climate zone, located in the arid and semi-arid climate belt, with annual average temperatures ranging from 0–8 °C and increasing from northeast to southwest. The region receives low and unevenly distributed precipitation, with annual totals of 50–450 mm decreasing from northeast to southwest. The vegetation transitions from cold temperate coniferous forests, deciduous broad-leaved forests, meadow steppes, typical steppes, to desert steppes from northeast to southwest. The study area is located at the southern boundary of the Eurasian permafrost region in the circum-Arctic area. Winters are severely cold, summers are hot, and local diurnal temperature differences are large. Soil freezing and thawing phenomena are prominent in spring and winter, while soil moisture alternates between dry and wet in summer and autumn. Multiyear permafrost is mainly distributed in the Hulunbuir region, while seasonal permafrost is widely distributed in other areas, with shallow surface soils freezing in winter and completely thawing in summer.

1.2 Data Sources and Processing

Surface temperature observation data from 45 meteorological stations were obtained from the China Meteorological Administration' s Daily Climate Dataset (http://data.cma.cn). To better reflect the freeze-thaw characteristics of the study area, common time periods from different observation stations were used to calculate surface freeze-thaw indices. Missing data were interpolated using the following methods: for single-day missing data, the average of the data from the previous and following days was used; for consecutive missing days, the average of the data from the days before and after the missing period was taken; for continuous missing periods longer than five days, linear correlation checks were performed using temperature averages from adjacent stations in the same month, and the station with the best temperature correlation was selected for linear regression temperature estimation interpolation. The inverse distance weighted method was used for spatial interpolation of surface freeze-thaw indices with a resolution of 34 km.

Permafrost type zoning was based on the 1:10,000,000 map from the Qinghai-Tibet Plateau Scientific Data Center (http://data.tpdc.ac.cn). Through integration of permafrost types, the region was divided into multiyear permafrost zones and seasonal permafrost zones for zonal discussion of surface freeze-thaw indices and influencing factors.

Surface soil water content at 0.1 m and 0.4 m depths, precipitation, and snow depth data were all derived from China' s first-generation global atmospheric and land surface reanalysis product CRA/Land monthly land products (http://data.cma.cn/cra) with a spatial resolution of 34 km, used to analyze the spatiotemporal changes of influencing factors for surface freeze-thaw indices in Inner Mongolia.

NDVI data included the MODIS composite product from the University of Maryland (https://modis.umd.edu) and GIMMS NDVI3g product from NASA' s Global Land Cover Facility (https://ecocast.arc.nasa.gov/data/pub/gimms/). Based on GIMMS NDVI data, linear regression analysis was used to reconstruct the time series, resampling the data to the same spatiotemporal scale. Using overlapping MODIS and GIMMS NDVI data for modeling, the modeling results were used to extend GIMMS NDVI data to obtain longer time series. Preprocessing of NDVI data mainly included coordinate transformation, numerical clipping, data conversion, outlier removal, and monthly maximum value acquisition to ensure consistency in spatial resolution. The data were resampled to 34 km resolution.

Land cover classification was based on MODIS data (Figure 1). Within the study area, regions with NDVI < 0.15 were considered to have no vegetation cover based on actual conditions.

1.3 Research Methods

Surface Freeze-Thaw Index Calculation. Based on Klene et al.' s definitions of freezing and thawing periods, the freezing period was defined as between September 1 and June 30 of the following year, and the thawing period was defined as between July 1 and August 31. The annual freezing index was calculated as the sum of negative temperatures throughout the cold period, and the thawing index as the sum of positive temperatures throughout the warm period. The formulas are:

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

$$TI = \sum_{j=1}^{N_T} T_j, \quad T_j > 0$$

where T_i and T_j are daily negative and positive surface temperatures (°C), respectively; FI and TI are the freezing and thawing indices (°C·d); and N_f and

N_T are the number of days with surface temperatures below and above 0°C, respectively.

Trend Analysis. A linear regression method was used to calculate interannual variation trends of freeze-thaw indices and influencing factors, with slopes fitted by least squares reflecting the trend magnitude. A slope greater than 0 indicated an increasing trend, while a slope less than 0 indicated a decreasing trend. The trend calculation formula is:

$$\text{Slope} = \frac{n\sum_{i=1}^{n} iX_i - \sum_{i=1}^{n} i\sum_{i=1}^{n} X_i}{n\sum_{i=1}^{n} i^2 - (\sum_{i=1}^{n} i)^2}$$

where Slope represents the trend of surface freeze-thaw indices or influencing factors; n is the time series length; and X_i is the average value of research object X in year i.

Correlation Analysis. The correlation coefficient between surface freeze-thaw indices and corresponding influencing factors was calculated to represent their relationship. The formula is:

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

where n is the total number of years in the study period; r_{xy} is the correlation coefficient between x and y; x_i and y_i are the values of x and y in year i; and $\bar{x}$ and $\bar{y}$ are the average values of the two factor samples. The correlation coefficient ranges from -1 to 1, with larger absolute values indicating stronger relationships between surface freeze-thaw indices and influencing factors. A positive correlation is indicated when $r_{xy} > 0$, and a negative correlation when $r_{xy} < 0$. Significance testing was performed using the T-test method, with correlation degrees classified as significant ($P < 0.05$) and not significant ($P \geq 0.05$).

Gray Correlation Analysis. Gray correlation analysis was used to study the main factors influencing surface freeze-thaw indices and their importance. Gray correlation degree can measure relationships between systems and identify dominant controlling factors among related factors. The time series of surface freeze-thaw indices was used as the target variable, while influencing factors including 0.1 m soil water content, 0.4 m soil water content, precipitation, snow depth, and NDVI were used as impact variables. The gray correlation coefficient is expressed as:

$$\xi_i(k) = \frac{\min_i \min_k |x_0(k) - x_i(k)| + \rho \max_i \max_k |x_0(k) - x_i(k)|}{|x_0(k) - x_i(k)| + \rho \max_i \max_k |x_0(k) - x_i(k)|}$$

$$G_i = \frac{1}{n}\sum_{k=1}^{n}\xi_i(k)$$

where $\xi_i(k)$ is the gray correlation coefficient between impact variables and target variables; ρ is the resolution coefficient, which was set to 0.5 based on previous studies; $\min_i \min_k$ and $\max_i \max_k$ are the secondary minimum and maximum differences; $|x_0(k) - x_i(k)|$ is the absolute difference between each point on comparison sequence x_i curves and each point on reference sequence x_0; and G_i is the gray correlation degree of comparison sequence x_i to reference sequence x_0, expressing the closeness of their relationship. Values closer to 1 indicate better correlation.

---

2 Results and Analysis

2.1.1 Temporal Variation Characteristics of Surface Freeze-Thaw Indices

Analysis of SFI and STI in Inner Mongolia revealed temporal variation characteristics for the entire study area and different permafrost zones. Overall, SFI showed a significant decreasing trend, with the decline rate in the multiyear permafrost zone higher than in the seasonal permafrost zone. The multiyear variation range in Inner Mongolia was 956.1–1848.3 °C · d, with minimum and maximum values occurring in 2019 and 1984, respectively, an annual average of 1457.0 °C · d, and a change rate of -156.4 °C · d · (10a)$^{-1}$, indicating a continuous decreasing trend in seasonal freezing potential. Further analysis of individual stations showed that SFI at all stations decreased during 1980–2019, though variation characteristics differed among stations. The minimum and maximum changes occurred at the Alxa Right Banner station in Alxa League [-20.7 °C · d · (10a)$^{-1}$] and the Arshan station in Xing' an League [-711.1 °C · d · (10a)$^{-1}$], respectively.

Overall, STI showed a significant increasing trend, with the increase rate in the multiyear permafrost zone higher than in the seasonal permafrost zone. The multiyear variation range in Inner Mongolia was 3717.6–4442.3 °C · d, with minimum and maximum values occurring in 1984 and 2019, respectively, an annual average of 4040.9 °C · d, and an increase rate of 152.4 °C · d · (10a)$^{-1}$, indicating increased maximum thawing depth during the soil melting period. Areas with higher STI increase rates (Slope $>$ 150 °C · d · (10a)$^{-1}$) were mainly distributed in the central, east-central, and northeastern parts of the study area, possibly due to human activities. All stations showed increasing STI trends during 1980–2019, with the minimum and maximum changes occurring at the Chifeng station [43.1 °C · d · (10a)$^{-1}$] and the Balinzuo Banner station [221.1 °C · d · (10a)$^{-1}$], respectively.

2.1.2 Spatial Distribution and Variation of Surface Freeze-Thaw Indices

The spatial distribution of multiyear average SFI in Inner Mongolia (Figure 3) was influenced by longitude, latitude, and elevation, showing an overall pattern of low values in the west and high values in the east, gradually increasing from southwest to northeast. Latitude had the greatest influence (Table 1), with a correlation coefficient of 0.82. The distribution pattern was consistent with freeze-thaw index changes in the circum-Arctic region, confirming that the original island permafrost area is currently in a seasonal frozen state. The spatial distribution of STI showed the opposite pattern, decreasing from southwest to northeast. The multiyear average STI showed high values in the west and low values in the east, gradually decreasing from southwest to northeast. STI values in the multiyear permafrost zone were generally smaller than in the seasonal permafrost zone, with point-shaped high-value areas appearing in Hohhot and Chifeng, closely related to recent agricultural development, urban expansion, and industrial development.

2.2.1 Temporal Variation of Influencing Factors for Surface Freeze-Thaw Indices

During 1980–2019, the annual average 0.1 m soil water content ranged from 0.1388–0.1779 $m^3 \cdot m^{-3}$, while the 0.4 m soil water content ranged from 0.1401–0.1673 $m^3 \cdot m^{-3}$. The 0.1 m soil water content was slightly greater than the 0.4 m soil water content. Both depths showed upward trends, with average interannual change rates of 0.001 $m^3 \cdot m^{-3} \cdot (10a)^{-1}$. However, the 0.4 m soil water content did not show a consistent upward trend but rather experienced a "rise-fall-rise" fluctuation stage with climate variations: a fluctuating rise stage during 1980–1998, a fluctuating decline stage during 1999–2010, and another fluctuating rise stage after 2010. The 0.1 m soil water content showed similar fluctuations.

Precipitation showed a non-significant increasing trend at a rate of 10.0 mm $\cdot$ $(10a)^{-1}$, with annual averages ranging from 240.1–415.9 mm. The 1980s and 1990s were relatively wet periods, while 2000–2010 was a relatively dry period. Snow depth showed a weak decreasing trend at a rate of -0.82 mm $\cdot$ $(10a)^{-1}$, with annual averages ranging from 11.4–32.8 mm and a mean of 22.1 mm. NDVI showed a significant increasing trend at a rate of $0.005 \cdot (10a)^{-1}$.

2.2.2 Spatial Distribution and Variation of Influencing Factors

The spatial distribution of influencing factors showed obvious latitudinal zonality and regional patterns (Figure 5). Soil water content increased from southwest to northeast, with regional characteristics and spatial heterogeneity possibly related to irrigation and farmland reclamation. The 0.1 m soil water content showed a spatial pattern of relatively high moisture in the northeast and central-west and relatively low moisture in the west, consistent with permafrost zone distribution. Multiyear permafrost zone values were generally greater than seasonal permafrost zone values. Areas where 0.1 m soil water content showed decreasing trends accounted for only 19.9% of the study area, mainly concentrated in the northwestern and northeastern multiyear permafrost zones.

Precipitation showed a decreasing trend from southwest to northeast, opposite to the SFI distribution pattern. High-value areas appeared in Hohhot, Chifeng, and other locations, likely related to human activities. Central and western Inner Mongolia showed increased precipitation, particularly in the central-southern region, while eastern areas showed decreased precipitation, especially in northwestern Hulunbuir, central Chifeng, and central Tongliao. Snow depth distribution was basically consistent with precipitation but opposite to temperature. The northeastern part of the study area had more precipitation, lower annual surface temperatures, and higher forest coverage, conducive to snow formation and accumulation. In contrast, central and western areas had less precipitation, higher average surface temperatures, and lower vegetation coverage, resulting in shallower and more uniform snow depth. During the study period, 38.5% of the region showed decreasing snow depth, mainly in the northeastern multiyear permafrost zone, while 61.5% showed increasing snow depth, mainly in deserts in the southwest and some grasslands in the central and eastern seasonal permafrost zones.

NDVI showed a decreasing trend in 24.8% of the area, mainly in most of Xilingol League, northern Chifeng, northern Tongliao, southern Xing'an League, and forest areas of Hulunbuir, possibly related to temperature increases, precipitation decreases, and human activities in these regions.

2.3 Correlation Analysis Between Surface Freeze-Thaw Indices and Influencing Factors

Surface freeze-thaw index changes are influenced by multiple factors with strong randomness, making them suitable for gray correlation analysis. As shown in Table 2, the annual average values of surface freeze-thaw indices in Inner Mongolia had gray correlation coefficients greater than 0.6 with 0.1 m soil water content, 0.4 m soil water content, precipitation, snow depth, and NDVI. The gray correlation order for SFI was: 0.4 m soil water content > 0.1 m soil water content > NDVI > precipitation > snow depth, indicating that soil water content had the greatest influence on SFI change, followed by NDVI, precipitation, and snow depth. The gray correlation order for STI was: NDVI > 0.4 m soil water content > 0.1 m soil water content > precipitation > snow depth, indicating that NDVI had the greatest influence on STI change.

To explore the dynamic response of surface freeze-thaw indices to influencing factor changes, pixel-by-pixel correlation coefficients were calculated across Inner Mongolia. The SFI was mainly negatively correlated with influencing factors (Table 3). In the multiyear permafrost zone, most areas showed positive correlations, while in the seasonal permafrost zone, most areas showed negative correlations. The 0.1 m soil water content was significantly negatively correlated with SFI in 47.9% of the region, mainly in the central and southeastern seasonal permafrost zone. Significant positive correlations were concentrated in parts of the multiyear permafrost zone. The 0.4 m soil water content showed similar patterns. Precipitation was significantly negatively correlated with SFI in 46.3% of the region, mainly east of Ordos, Hohhot, and south of Xilingol League. NDVI was significantly negatively correlated with SFI in 48.3% of the region, mainly in forest and wetland areas of the multiyear permafrost zone. Snow depth was significantly negatively correlated with SFI in 32.7% of the region, scattered in southwestern Alxa and central seasonal permafrost areas.

The STI was also mainly negatively correlated with influencing factors (Table 4). However, in the multiyear permafrost zone, STI was mostly positively correlated with influencing factors, while in the seasonal permafrost zone, it was mostly negatively correlated. The 0.1 m soil water content was significantly negatively correlated with STI in 36.9% of the region, concentrated in the eastern multiyear permafrost zone and surrounding leagues. The 0.4 m soil water content showed similar patterns. Precipitation was significantly negatively correlated with STI in 53.8% of the region, mainly in eastern Xilingol League, eastern Xing' an League, and northeastern multiyear permafrost zone. NDVI was significantly negatively correlated with STI in 54.5% of the region, mainly in northern Chifeng, Xing' an League, forest areas of the multiyear permafrost zone, and desert grassland of Xilingol League. Snow depth was significantly negatively correlated with STI in 32.2% of the region, mainly in northwestern Xilingol League, northern Chifeng, and northeastern multiyear permafrost zone.

---

3 Discussion

Under the background of climate warming, the results of this study are basically consistent with conclusions from the Northern Hemisphere, Qinghai-Tibet Plateau, and Northeast China, indicating obvious permafrost environment degradation in Inner Mongolia. The multiyear permafrost zone shows more significant winter warming trends and more severe permafrost degradation. Significant changes in surface freeze-thaw indices may lead to permafrost area reduction, decreased freezing depth, and increased active layer thickness. Changes in the seasonal permafrost zone cannot be ignored, as this zone is the main area for agricultural and pastoral production in Inner Mongolia, and changes in freeze-thaw indices are closely related to crop planting and livestock development.

Although climate warming is the fundamental cause of significant permafrost degradation in the multiyear permafrost zone, various human economic activities have accelerated this degradation. The increasing trends of surface soil water content and precipitation indicate that the permafrost environment in Inner Mongolia is developing toward warm-wet conditions, consistent with conclusions from Ma et al. However, this study found significant differences between permafrost zones: the multiyear permafrost zone is developing toward warm-dry conditions, opposite to the overall trend and most of the seasonal permafrost zone. Increased ground temperature, decreased precipitation, and increased potential evapotranspiration are the main factors causing soil water content decline.

Surface freeze-thaw indices are calculated from surface temperature and are closely related to air temperature and surface temperature, but surface soil water content, precipitation, snow depth, and NDVI also play crucial roles in their changes. Overall, surface soil water content and NDVI are the dominant factors affecting surface freeze-thaw index changes. Permafrost environment degradation negatively impacts biodiversity. Increased temperature and decreased rainfall are detrimental to grassland plant growth but promote forest and wetland plants. In the seasonal permafrost zone, obvious winter warming reduces crop freezing damage, promotes grain yield increases and quality improvement, and helps livestock survive winter and spring. However, it also allows pests and diseases and their eggs to overwinter more easily, potentially causing difficulties in pest control.

Before the 1980s, meteorological data in the study area had many missing measurements. This study only used data from 1980–2019. Future research should be conducted based on longer time series and more station data. After processing surface freeze-thaw indices, it is necessary to further determine the spatial distribution range of multiyear permafrost, active layer thickness, and spatiotemporal variation characteristics of seasonal frozen soil freezing depth to make comprehensive and accurate predictions of permafrost response to climate change in Inner Mongolia. Currently, the CRA/Land data still have relatively low spatial resolution for permafrost research. In future permafrost change studies, it is planned to combine higher spatial resolution reanalysis data with actual observation data to reduce uncertainty in research conclusions.

---

4 Conclusions

Based on daily surface temperature data from 45 meteorological stations in Inner Mongolia from 1980 to 2019, combined with China' s first-generation global land surface reanalysis product (CRA) data and NDVI data, this study analyzed the spatiotemporal variation patterns and key influencing factors of freeze-thaw indices in Inner Mongolia using spatial analysis functions and RStudio programming. The main conclusions are:

1) During 1980–2019, the SFI and STI in Inner Mongolia showed significant decreasing and increasing trends, respectively. Latitude was an important factor controlling the spatial distribution of surface freeze-thaw indices, showing a very significant positive correlation with SFI and a very significant negative correlation with STI. The change rate of surface freeze-thaw

indices in the multiyear permafrost zone was more intense than in the seasonal permafrost zone, with more sensitive response to climate warming.

2) The 0.1 m and 0.4 m soil water content, precipitation, and NDVI showed increasing trends, while only snow depth showed a decreasing trend. The average interannual change rates of soil water content at different depths were 0.001 $m^3 \cdot m^{-3} \cdot (10a)^{-1}$. Precipitation showed a non-significant increasing trend at 10.0 $mm \cdot (10a)^{-1}$, NDVI showed a significant increasing trend at $0.005 \cdot (10a)^{-1}$, and annual average snow depth showed a weak decreasing trend at -0.82 $mm \cdot (10a)^{-1}$. The multiyear mean values of 0.4 m soil water content and snow depth in the multiyear permafrost zone were generally greater than in the seasonal permafrost zone. Influencing factors also showed different spatial heterogeneity in interannual variation, with the multiyear permafrost zone showing a warm-dry development trend and the seasonal permafrost zone showing a warm-wet trend.

3) Surface freeze-thaw indices were mainly negatively correlated with influencing factors. The SFI was positively correlated with influencing factors in most of the multiyear permafrost zone and negatively correlated in most of the seasonal permafrost zone, while the STI showed the opposite pattern. Changes in surface freeze-thaw indices in Inner Mongolia were driven by the combined effects of influencing factors, with 0.4 m soil water content being the dominant factor affecting SFI change and NDVI being the dominant factor affecting STI change.

References

[1] Zhou Youwu. Permafrost in China[M]. Beijing: Science Press, 2000.

[2] Shen Yongping, Wang Guoya. Key findings and assessment results of IPCC WGI fifth assessment report[J]. Journal of Glaciology and Geocryology, 2013, 35(5): 1068-1076.

[3] Qin Dahe. Climate and environmental evolution in China[J]. Resources Environment and Development, 2007(3): 1-4.

[4] Qin Dahe, Zhou Botao, Xiao Cunde. Progress in studies of cryospheric changes and their impacts on climate of China[J]. Acta Meteorological Sinica, 2014, 72(5): 869-879.

[5] Shi Peijun, Sun Shao, Wang Ming, et al. Climate change regionalization in China (1961-2010)[J]. Science China: Earth Sciences, 2014, 44(10): 2294-2306.

[6] Li Qian. A review of research on permafrost change under the background of global warming[J]. Jilin Meteorology, 2013, 80(1): 25-28, 44.

[7] Liu Xiu, Li Jia. Research on temporal and spatial variation of freeze thaw index in Northeast China during the past 1960-2012[J]. Heilongjiang Science,

2018, 9(20): 162-164.

[8] Su Yue, Zhang Cunhou, Amursana, et al. Response of seasonal frozen soil to climate change on a typical steppe of Inner Mongolia during 1981-2018[J]. Arid Land Geography, 2022, 45(3): 684-694.

[9] Chen Bo, Li Jianping. Characteristics of spatial and temporal variation of seasonal and short term frozen soil in China in recent 50 years[J]. Chinese Journal of Atmospheric Sciences, 2008, 32(3): 432-443.

[10] Riseborough D W. Thawing and freezing indices in the active-layer[C]//Proceedings of the 8th International Conference on Permafrost. Rotterdam: A. Balkema. 2003: 953-958.

[11] Peng X Q, Zhang T J, Frauenfeld O W, et al. Past and projected freezing/thawing indices in the Northern Hemisphere[J]. Journal of Applied Meteorology and Climatology, 2019, 58(3): 495-510.

[12] Sturm M, Holmgren J, Liston G E. A seasonal snow cover classification system for local to global applications[J]. Journal of Climate, 1995, 8(5): 1261-1283.

[13] Nelson F E, Outcalt S I. A computational method for prediction and regionalization of permafrost[J]. Arctic and Alpine Research, 1987, 19(3): 279-288.

[14] Frauenfeld O W, Zhang T, Mccreight J L. Northern hemisphere freezing/thawing index variations over the twentieth century[J]. International Journal of Climatology, 2010, 27(1): 47-63.

[15] Shi Y, Niu F, Lin Z, et al. Freezing/thawing index variations over the circum arctic from 1901 to 2015 and the permafrost extent[J]. Science of the Total Environment, 2019, 660(APR.10): 1294-1305.

[16] Liu L, Luo D L, Wang L, et al. Dynamics of freezing/thawing indices and frozen ground from 1900 to 2017 in the upper brahmaputra river basin, Tibetan Plateau[J]. Advances in Climate Change Research, 2021, (1): 6-17.

[17] Wu T, Qin Y, Wu X, et al. Spatiotemporal changes of freezing/thawing indices and their response to recent climate change on the Qinghai Tibet Plateau from 1980 to 2013[J]. Theoretical & Applied Climatology, 2018, 132(3): 1187-1199.

[18] Wang Rui, Zhu Qingke, Ma Hao. Changes in freezing and thawing indices over the source region of the Yellow River from 1980 to 2014[J]. Journal of Forestry Research, 2019, 30(1): 257-268.

[19] Cao Bin, Zhang Tingjun, Peng Xiaoqing, et al. Spatial variability of freezing/thawing index over the Heihe River Basin[J]. Advances in Earth Science, 2015, 30(3): 357-366.

[20] Uri Khan. Dynamic Characteristics of Vegetation in Inner Mongolia from 2001 to 2016, and Its Response to Climate Change[D]. Hohhot: Inner Mongolia

Normal University, 2020.

[21] Guo Yang, Zhang Tingjun, Cao Lin, et al. Relationship between surface freezing/thawing index and runoff in upper reaches of Heihe River[J]. Bulletin of Soil and Water Conservation, 2018, 38(3): 222-227.

[22] Wang Ziyu, Xu Duanyang, Yang Hua, et al. Impacts of climate change and human activities on vegetation dynamics in Inner Mongolia, 1981-2010[J]. Progress in Geography, 2017, 36(8): 1025-1032.

[23] Zhao Yaru. Soil Freezing and Thawing Variation Characteristics under Different Land Use Types in Mudan Ridge[D]. Jilin: Northeast Normal University, 2014.

[24] Li Yunyun, Liu Hongyan. Responses of vegetation growth to climate change in permafrost distribution region in Northeast China[J]. Acta Scientiarum Naturalium Universitatis Pekinensis, 2021, 57(4): 783-789.

[25] Liu Zhenhai, Wang Shaoqiang, Chen Bin. Spatial and temporal variations of frozen ground and its vegetation response in the eastern segment of China Mongolia Russia economic corridor from 2000 to 2015[J]. Acta Geographical Sinica, 2021, 76(5): 1231-1244.

[26] Klene A E, Nelson F E, Hinkel SKM. The N-factor in natural landscapes: Variability of air and soil surface temperatures, Kuparuk River Basin, Alaska, U.S.A[J]. Arctic Antarctic & Alpine Research, 2001, 33(2): 140-148.

[27] Jin L Q, Zhang J Q, Wang R Y, et al. Analysis for spatio temporal variation characteristics of droughts in different climatic regions of the Mongolian Plateau based on SPEI[J]. Sustainability, 2019, 11(20): 5767.

[28] Ye Jiaqi, Li Zhenghai, Wuyun Qiqige, et al. The response of steppe, wetland and forest vegetation to climate change in Hulun Buir[J]. Chinese Journal of Grassland, 2018, 40(6): 26-32.

[29] Suo Yuxia, Wang Zhengxing, Liu Chuang, et al. Relationship between NDVI and precipitation and temperature in Middle Asia during 1982-2002[J]. Resources Science, 2009, 31(8): 1422-1429.

[30] Deng J L. Control problems of grey systems[J]. Systems & Control Letters, 1982, 1(5): 288-294.

[31] Wang Zhichun, Yang Jun, Chen Suhua, et al. Impact of warmer climate on agricultural and animal husbandry climatic resources in eastern Inner Mongolia[J]. Journal of Arid Land Resources and Environment, 2016, 30(4): 132-137.

[32] Wang Q, Lv W, Li B, et al. Annual ecosystem respiration is resistant to changes in freeze thaw periods in semi arid permafrost[J]. Global Change Biology, 2020, 26(4): 2630-2641.

[33] Ma Zice, Yu Hongbo, Zhang Qiaofeng, et al. Characteristics and abrupt change of temperature and precipitation in Inner Mongolia area over the period

1960-2016[J]. Research of Soil and Water Conservation, 2019, 26(3): 114-121.

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