
VOLUME 69, ISSUE 1, OCTOBER 2011
ISSN: 0165-232X
ELSEVIER
cold regions
science and technology

Cold Regions Science and Technology 69 (2011) 105–111

Contents lists available at ScienceDirect

Cold Regions Science and Technology

journal homepage: www.elsevier.com/locate/coldregions

Observed trends in surface freezing/thawing index over the period 1987–2005 in Mongolia

Tonghua Wu [a], Qinxue Wang [b,*], Lin Zhao [a], Ochirbat Batkhishig [c], Masataka Watanabe [d]

[a] Cryosphere Research Station on the Qinghai–Tibet Plateau, State Key Laboratory of Cryospheric Sciences, Chinese Academy of Sciences, Lanzhou 730000, China
[b] Center for Regional Environmental Research, National Institute for Environmental Studies, 16-2 Onogawa, Tsukuba 305-8506, Japan
[c] Institute of Geography, Mongolian Academy of Sciences, Ulaanbaatar 210620, Mongolia
[d] Graduate School of Media and Governance, Keio University, 5522 Endo, Fujisawa, Kanagawa 252-8520, Japan

ARTICLE INFO

Article history:
Received 29 May 2011
Accepted 11 July 2011

Keywords:
Surface freezing/thawing index
Trend
Permafrost
Climatic warming

ABSTRACT

The annual ground surface freezing and thawing indices can be useful to assess the temporal changes of ground thermal regime in permafrost and seasonally frozen ground regions. The previous analyses of in-situ observation results show that the annual freezing/thawing index could be reliably obtained from monthly observation data. We thus employ monthly ground surface temperature to calculate the annual surface freezing/thawing index in Mongolia. In this study we used Mann–Kendal test and Sen-slope estimate to perform the temporal and spatial trend analysis of annual surface freezing/thawing index at a set of 20 meteorological stations in Mongolia. The study indicates that the annual surface freezing index displays a general increasing trend at 70% of stations although the trend is not statistically significant, which corresponds to a slight winter cooling over the period 1987–2005 in Mongolia. However, the annual surface thawing index shows a statistically significant increase in Mongolia during the past 19 years. The surface thawing index has increased by 29 °C-days/yr in Mongolia, which is far greater than that in the high-latitudinal regions of Northern Hemisphere during recent decades. The intensive increase of annual surface thawing index is predicted to be responsible for the increase in active layer thickness, as well as the changes of permafrost distribution in this country.

1. Introduction

Mongolia is located in central Asia at the latitudes between 41°35′ N and 52°09′N and at the longitudes between 87°44′E and 119°56′E, and occupies a territory of about 1.56 million km^2 in area. The Mongolian relief is characterized by relatively high elevation, which is 1580 m above the sea level on average in this landlocked country. Owing to the continental cold and dry climate with severe winters in Mongolia, approximately 67% of the country is underlain by permafrost (Tumurbaatar and Mijiddorj, 2006). During the last 60 years, the mean annual air temperature in Mongolia has significantly increased by 1.66 °C (Nandintsetseg et al., 2007) and the warming trend was predicted to continue in the following 80 years (Sato and Kimura, 2006). In the context of great warming occurring in the last decades, the noticeable increase in permafrost temperatures and active layer thickness has been observed in Mongolia (Sharkhuu et al., 2007, 2008a; Zhao et al., 2010). The prominent permafrost degradation has exerted profound influence on the stream hydrology, taiga forest distribution, ecosystems, and sustainable development in Mongolia (Bohannon, 2008; Dulamsuren et al., 2010).

The annual freezing and thawing indices of the ground surface are one of the most important parameters to assess the permafrost and seasonally frozen ground distribution and to estimate the seasonal freeze and thaw depth in cold regions (Anisimov et al., 2007; Frauenfeld et al., 2004; Nelson and Outcalt, 1987; Shiklomanov and Nelson, 2002; Zhang et al., 2005), applied extensively in engineering designs in cold regions (Lunardini, 1981), and considered as a useful indicator of climate change as well (Frauenfeld et al., 2007). Freezing index reflects combined magnitude and duration of air or surface temperatures below freezing during given cold season and is one of the major parameters used to assess the ground-freezing potential of a given climate. The most important applications of freezing index are to determine the seasonal ground frost depth, to estimate the effect of freezing conditions on the soil foundations of structures, and to provide implications for design of road pavement and maintenance operations of infrastructures in cold regions (Schmidlin and Dethier, 1985; Steurer, 1996). Similarly, a close relationship between thawing index and active layer thickness has been demonstrated in many studies (Brown et al., 2000; Frauenfeld et al., 2004; Hinkel and Nelson, 2003; Nelson et al., 1998; Romanovsky and Osterkamp, 1997). In Geocryology, the square root of surface annual thawing index is used

* Corresponding author at: Center for Regional Environmental Research, National Institute for Environmental Studies, Japan. Tel.: +81 298 502 128.
E-mail address: wangqx@nies.go.jp (Q-X. Wang).

0165-232X/$ – see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.coldregions.2011.07.003

to directly determine active layer thickness in Stefan equation (Nelson and Outcalt, 1983, 1987; Zhang et al., 2005). An important parameter, n-factor, was introduced to reflect the relationship between the air temperature and the ground surface temperature in cold regions (Lunardini, 1978). The surface freezing and thawing indices are essential variables involved in the calculation of the n-factor.

There are two kinds of freezing and thawing indices in terminology of climatology; air freezing/thawing index and surface freezing/thawing index. Generally, the air and surface freezing/thawing indices are defined as the cumulative number of degree-days below/above 0 °C for air temperature and ground surface temperature respectively during a given time period. There are a lot of studies to introduce the freezing and thawing indices of air temperature (Frauenfeld et al., 2007; Hanson et al., 2010; Jiang et al., 2008; Schmidlin and Dethier, 1985; Steurer, 1996; Wu et al., 2008). The widely applied air freezing/thawing index during the past decades was described by Frauenfeld et al. (2007), while at present there are relatively few literature demonstrating the surface freezing and thawing indices because of unavailability of consecutive instrumental records of long-term ground surface temperature time series.

In this paper we document the variations of surface freezing/thawing index in Mongolia, on the basis of analysis of continuous instrumental records of monthly ground surface temperature series at 20 meteorological stations relatively evenly distributed in this country from 1987 to 2006. The 3-year observation of ground surface temperature acquired by infrared sensor and thermistor sensor at the depth of 5 cm at a representative automatic weather station is used to assess the validity of using monthly ground surface temperature data in the calculation of the approximate annual surface freezing/thawing index. The estimation of variations in the annual freezing/thawing index would be counted on to enhance our understanding of climate change and variations in thermal regime of ground surface near the southern boundary of Siberian permafrost regions.

2. Data and methodology

We use mean monthly ground surface temperature data to calculate the surface freezing/thawing index at 20 meteorological stations (Fig. 1), whose ground surface temperature series is available and continuously covering the period of 1987–2006. The ground surface temperature was measured at a depth of 0 cm at each standard meteorological station. The monthly ground surface temperature series dataset was provided by the Institute of Meteorology and Hydrology of Mongolia (IMH). Few missing values are interpolated from the monthly air temperature series at the same station over the same period by means of linear regression methods at the 99% confidence level. The distribution of those selected 20 stations is relatively even in the country. The elevation of stations ranges from 747 m to 2417 m.

We define the freezing period to be July–June (next year) in order to sum the freezing index in a continuous cold season and the thawing period of January–December. The surface freezing/thawing index is calculated using the following equations.

$$FI_s = \sum_{i=1}^{M_F} \left|\overline{T}_{si}\right| \cdot D_i, \overline{T}_{si} < 0^{\circ}\mathrm{C}$$

$$TI_s = \sum_{i=1}^{M_T} \overline{T_{si}} \cdot D_i, \overline{T}_{si} > 0^{\circ}\mathrm{C}$$

where FI_s and TI_s are the annual surface freezing and thawing indices respectively; M_F and M_T are those months when the mean monthly temperature is above/below 0 °C during the freezing/thawing periods; $\overline{Tsi}$ is the mean monthly surface temperature; D is the number of days in the month of M_F or M_T. Therefore, time series of annual freezing/thawing index from 1987 to 2005 were obtained.

The estimation of accuracy of using monthly air temperature observations in the calculation of the approximate annual air freezing/thawing index was discussed in previous studies (Frauenfeld et al., 2007; Zhang et al., 1996). Zhang et al. (1996) revealed the magnitude of the error for using monthly air temperature to estimate the air freezing/thawing index was less than 5%. On a regional basis, Frauenfeld et al. (2007) discovered that the relative errors for the freezing/thawing index are generally low across the Northern Hemisphere on the basis of analysis of ERA-40, CRU TS2.1, and CAI 1.02 datasets. In this study, we used the daily ground surface temperature dataset obtained from an automatic weather station in Davaat (Fig. 2), which was deployed in June, 2007 in Khentei mountainous regions. The ground surface temperature was observed

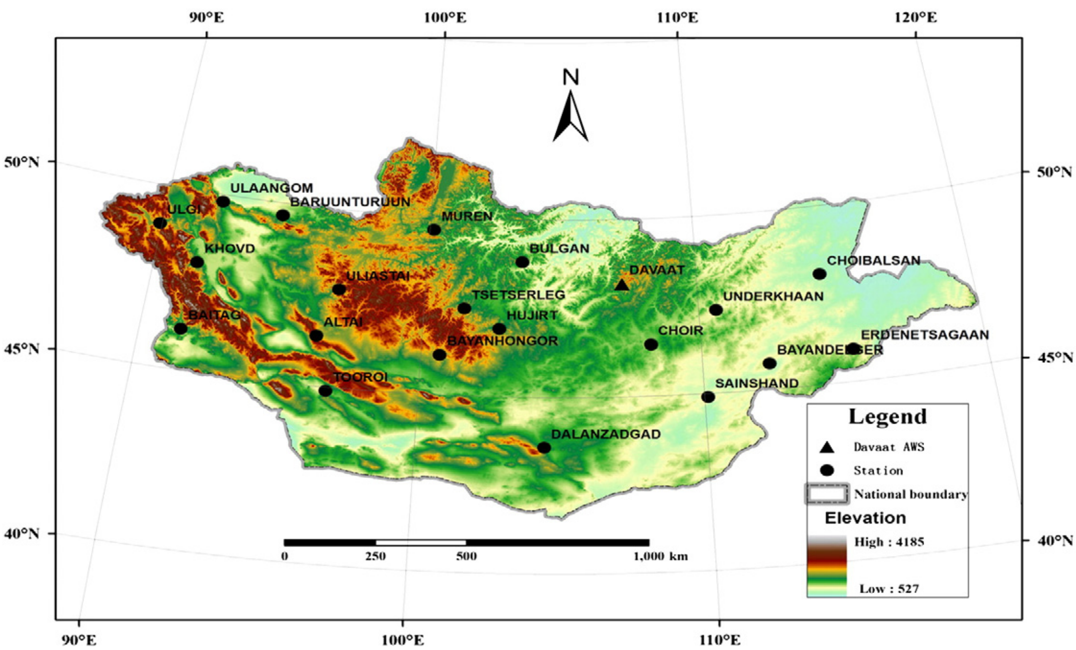

Fig. 1. The relatively even distribution of 20 meteorological stations and an automatic weather station used in this study in Mongolia.

Fig. 2. A full view of an automatic weather station deployed at Davaat, in the continuous permafrost regions of Mongolia. The continuous observation data of ground surface temperature obtained from infrared temperature sensor were used in this study to validate the annual surface freezing/thawing index based on calculating monthly surface temperature data.

at an interval of 30 min by an infrared temperature sensor manufactured by Campbell Scientific, Inc (Fig. 2) and by a thermistor located at the depth of 5 cm from the ground surface (Fig. 3). The infrared temperature sensor provides a non-contact method for measuring the ground surface temperature and its absolute accuracy amounts to ±0.5 °C at the temperature ranging from −40 °C to 70 °C. The infrared temperature sensor is deployed on the weather station tripod (1.5 m above the ground surface) (Fig. 2). The observation data obtained from the infrared temperature sensor corresponds to the surface temperature of vegetation in summer and to the surface temperature of snow cover in winter. In order to well represent the ground surface temperature which integrates the effects of vegetation and snow cover (Romanovsky et al., 2010; Sharkhuu et al., 2008b; Smith et al., 2009), we further utilized the observation data of ground surface temperature at the depth of 5 cm to assess the relative error of calculating surface freezing/thawing index by using monthly observed data. A small pit was excavated in the ground surface till the depth of 65 cm when the automatic weather station was installed. Five calibrated thermistors (PT-100) were installed in the pit at irregular intervals from the surface. The thermistors (PT-100) are located at the depth of 5 cm, 15 cm, 40 cm, 50 cm, and 65 cm respectively, in the light of the different soil structures (Fig. 3). The range of the thermistors was −40 °C to +20 °C and the accuracy was ±0.1 °C. The observation data of ground surface temperature at the depth of 5 cm were used in this study. The observation data from June 14, 2007 to November 5, 2010 is available for covering 3 entire cold and warm seasons to calculate the freezing and thawing indices (Figs. 4 and 5). Both Figs. 4 and 5 illustrate that the transition from above- to below-freezing temperature (and vice versa) occurs rather quickly and only slightly impacts less than one month. The annual freezing/thawing indices from daily and monthly temperature values are calculated respectively to analyze the relative errors defined by Frauenfeld et al. (2007). The results indicated that the relative error for annual freezing index is less than 1.5% and for annual thawing index less than 2.2% for the entire period of observation from infrared sensor measurements (Table 1). Similar to the observation from infrared temperature sensor, the relative error for annual freezing index is less than 1.5% and for annual thawing index less than 1.2% for the entire period of 3-year observation from thermistor sensor measurements (Table 2). Therefore, we assume that less error is involved in the estimation of annual freezing/thawing index using monthly observation data in Mongolia.

The significance of statistical trends in annual surface freezing/thawing index was examined using the non-parametric Mann–Kendall trend test (Kendall, 1975; Mann, 1945). Mann–Kendall test is a rank-based nonparametric test which was widely used for detecting trends in climate research because of its robustness and suitability for analyzing non-Gaussian distribution data (You et al., 2010). The Mann–Kendall test statistic (S) is given by

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sgn\left(x_j - x_i\right) \tag{1}$$

Fig. 3. The thermistors (PT-100) were installed in the excavated soil profile at the depth of 5 cm, 15 cm, 40 cm, 50 cm, and 65 cm respectively from the ground surface. The daily observation data from the depth of 5 cm were used to validate the annual surface freezing/thawing index based on calculating monthly surface temperature data.

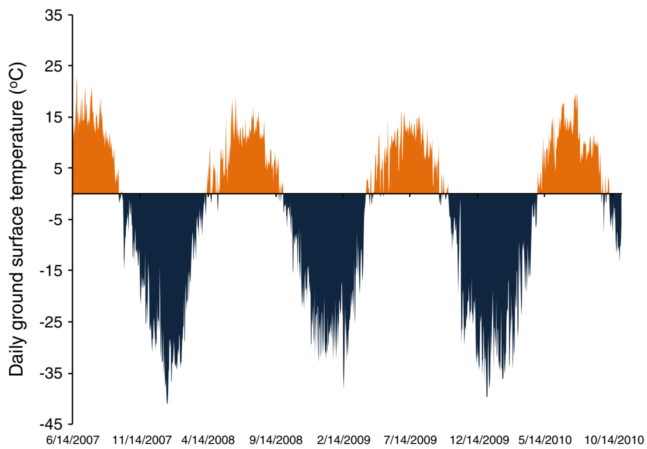

Fig. 4. The schematic of the freezing/thawing index calculation using daily ground surface temperature data measured by infrared temperature sensor at Davaat station acquired from June 14, 2007 to November 5, 2010. The freezing/thawing index corresponds to the time series integrals in blue/orange respectively.

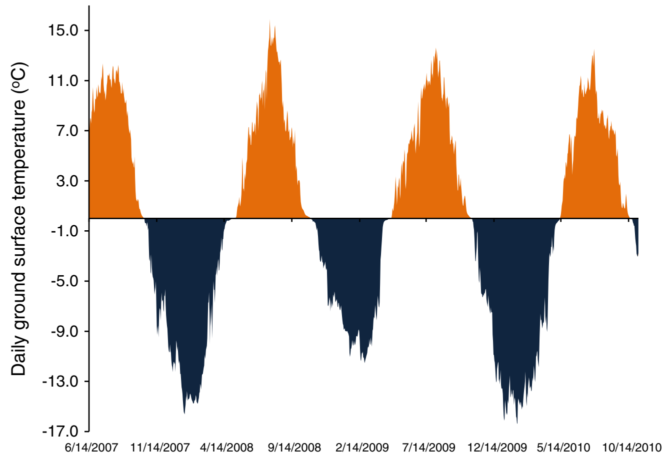

Fig. 5. The schematic of the freezing/thawing index calculation using daily ground surface temperature data measured by thermistor (PT-100) at the depth of 5 cm at Davaat station acquired from June 14, 2007 to November 5, 2010. The freezing/thawing index corresponds to the time series integrals in blue/orange respectively.

$$sgn(\theta) = \begin{cases} 1 & \text{if } \theta > 0 \\ 0 & \text{if } \theta = 0 \\ -1 & \text{if } \theta < 0 \end{cases} \quad (2)$$

where, n is the data set record length; x_j and x_i are the sequential data values.

The mean E[S] and variance Var[S] of the statistic S may be given as

$$E(S) = 0 \quad (3)$$

$$Var(S) = \frac{n(n-1)(2n+5) - \sum_{p=1}^{q} t_p\left(t_p-1\right)\left(2t_p+5\right)}{18} \quad (4)$$

where t_p is the number of ties for the pth value and q is the number of tied values. The second term represents an adjustment for tied or censored data. The normal Z-test statistic is calculated by

$$Z = \begin{cases} \frac{S-1}{\sqrt{Var(S)}} & \text{if } S > 0 \\ 0 & \text{if } S = 0 \\ \frac{S+1}{\sqrt{Var(S)}} & \text{if } S < 0 \end{cases} \quad (5)$$

A positive or negative value of Z indicates an upward or downward trend, respectively. To test for either an increasing or decreasing trend at the p significance level, the null hypothesis H_0 of data being independent random variables is accepted if $|Z| \le Z_{p/2}$, where $F_N(Z_{p/2}) = p/2$, F_N being

Table 1
Relative error in the freezing/thawing index from infrared temperature sensor observations at Davaat for three entire cold and warm seasons. FI_{sd} and TI_{sd} denote the freezing and thawing index calculated by daily ground surface temperature data respectively; FI_{sm} and TI_{sm} denote the freezing and thawing indices calculated by monthly ground surface temperature data.

	FI_{sd}	FI_{sm}	TI_{sd}	TI_{sm}	RE of FI_s	RE of TI_s
2007	3637	3584			1.46%	
2008	3605	3582	1400	1369	0.62%	2.20%
2009	4306	4295	1366	1337	0.26%	2.13%
2010			1480	1466		0.93%

Table 2
Relative error in the freezing/thawing index for the ground surface temperature at the depth of 5 cm observations at Davaat for three entire cold and warm seasons. FI_{sd} and TI_{sd} denote the freezing and thawing index calculated by daily ground surface temperature data respectively; FI_{sm} and TI_{sm} denote the freezing and thawing index calculated by monthly ground surface temperature data.

	FI_{sd}	FI_{sm}	TI_{sd}	TI_{sm}	RE of FI_s	RE of TI_s
2007	1617	1592			1.50%	
2008	1129	1126	1160	1159	0.22%	0.05%
2009	1857	1850	1153	1147	0.40%	0.50%
2010			1040	1027		1.22%

the standard normal cumulative distribution function. In this study, the significance level of p = 0.01 and p = 0.05 are adopted.

Linear trends for annual surface freezing/thawing index are obtained using Kendall's τ-based Sen's robust slope estimator (Sen, 1968). The slope estimates are determined by

$$\beta = \text{Median}\left[\frac{Xj-Xk}{j-k}\right] \text{for all } k < j \quad (6)$$

where $1 < k < j < n$. β is the median over all possible combinations of pairs for the whole data set. A positive value of β indicates an upward trend, while a negative value of β indicates a downward trend.

3. Results and discussion

Table 3 summarizes the annual trends of surface freezing and thawing indices at the selected 20 stations in Mongolia during the period 1987–2005. As for the reminiscent reflector of cold-season temperature climatology, the surface freezing index at Baruunturuu and Uliastai station shows a significant increase at a rate of 18 °C-day/yr and 39 °C-day/yr at the 95% level of confidence. However, no significant change in surface freezing index for the time period 1987–2005 is observed at the other 18 stations. The annual surface freezing indices at only 30% of stations in Mongolia display decreasing trend but statistically insignificantly. In general, the annual surface freezing

Table 3
List of the selected 20 stations in Mongolia, including the Country code, Station name, Latitude (Lat.), Longitude (Lon.), Elevation (Ele.), and annual rate of surface freezing index (R_{FI}) and thawing index (R_{TI}) obtained from non-parametric Mann–Kendall trend test and Sen's slope estimates, P value denotes the significance level during the period 1987–2005.

Country code	Sta. name	Lat. (N)	Lon. (E)	Ele. (m)	R_{FI}	P value	R_{TI}	P value
442770	Altai	46°24′	96°15′	2181	4	0.3121	31	0.0059
442650	Baitag	46°07′	91°28′	1186	12	0.1315	17	0.0072
442130	Baruunturuu	49°39′	94°24′	1232	18	0.0126	16	0.0709
443520	Bayandelger	45°44′	112°22′	1101	−5	0.6368	29	0.0002
442870	Bayankhongor	46°08′	100°41′	1859	4	0.3632	16	0.0344
442640	Bulgan	46°05′	91°32′	1190	20	0.0619	37	0.0000
442590	Choibalsan	48°05′	114°33′	747	15	0.1039	35	0.0001
442980	Choir	46°27′	108°13′	1286	−4	0.6102	33	0.0010
443730	Dalanzadgad	43°35′	104°25′	1465	1	0.5000	26	0.0005
443170	Erdenetsagaan	45°54′	115°22′	1076	8	0.1815	32	0.0021
442850	Hujirt	46°54′	102°46′	1662	5	0.2878	32	0.0039
442180	Khovd	48°01′	91°34′	1405	−3	0.5831	24	0.0250
442310	Muren	49°38′	100°10′	1283	−12	0.9082	28	0.0039
443540	Sainshand	44°54′	110°07′	938	−4	0.6102	27	0.0001
443250	Tooroi	45°09′	97°46′	2417	14	0.1815	23	0.0026
442820	Tsetserleg	47°27′	101°28′	1691	3	0.4169	32	0.0002
442120	Ulaangom	49°48′	92°05′	939	−2	0.6102	26	0.0021
442140	Ulgii	48°56′	89°56′	1715	8	0.2006	27	0.0032
442720	Uliastai	47°45′	96°51′	1759	39	0.0006	29	0.0105
443040	Undurkhaan	47°19′	110°38′	1033	22	0.2207	24	0.0002

Notes: Units of R_{FI} and R_{TI} are °C-day per year.

indices show an increasing trend in Mongolia during the last 19 years although no significant trend is detected, implying an insignificant winter cooling.

The annual surface thawing index at all stations shows a statistically significant increase at a significance level of 0.10 and the annual surface thawing index at most of stations has noticeably increased at a significance level of 0.05 over the time period 1987–2005 (Table 3). Mann–Kendall trend tests show a significant increase of annual surface thawing indices at 80% of stations at the 99% level of confidence. The Sen's slope analysis shows that the annual surface thawing indices are increasing at a rate ranging from 16 °C-day/yr to 37 °C-day/yr in Mongolia. The great increase in annual surface thawing index corresponds to an intensive summer warming on the Mongolian Plateau.

The spatial pattern of annual surface thawing index trends is shown in Fig. 6. The most significant trends are observed in the central (5 stations) and eastern regions (2 stations). A large magnitude of increasing surface thawing index was discovered in the eastern slope of the Hangai Mts. in continuous permafrost regions of the central of Mongolia (Tsetserleg and Hujirt Station in Fig. 6), which amounts to a rate of more than 30 °C-day/yr. In permafrost regions, active layer thickness was dependent on surface thawing index to a great extent. The intensive increase of annual thawing index in Hangai Mts. is predominantly responsible for an increasing rate of 0.5–2.0 cm/yr in active layer thickness in this region (Zhao et al., 2010).

The annual surface freezing/thawing index data of 20 stations are averaged into a time series representing Mongolia for the period 1987–2005, which is shown in Figs. 7 and 8. Fig. 7 show that the annual surface freezing index displays an apparent increase from the middle of 1990s. The trend analysis of annual surface freezing index time series by Mann–Kendall test indicates the presence of a positive trend at the 90% level of confidence. The analysis of annual surface freezing index by Sen's slope method reveals that the annual surface freezing index is increasing at a rate of 7 °C-days/yr in Mongolia. The significant increase of annual surface freezing index corresponds to a slight decrease of winter air temperature (−0.119 °C/yr) for the period of 1990–2006 reported by Dagvadorj et al. (2009). Frauenfeld et al. (2007) observed a statistically significant decrease of 8.7 °C-day/yr from the 1966/1967 to 2001 in the high latitudes north of 50°N in Northern Hemisphere. In addition, Wu et al. (2008) found that the surface freezing index on Qinghai–Tibet Plateau had also decreased by about 2 °C-day/yr on a decadal scale over the period 1961–2000. The nearly opposite trends of annual surface freezing index between Mongolia and high-latitudinal regions of Northern Hemisphere; Qinghai–Tibet Plateau are possibly due to the use of time series of temperature data over different period. However, it can be inferred that different modes of winter climatic changes exist between Mongolia and the other regions of Northern Hemisphere.

As for the time series of annual surface thawing index, the trend analysis by Mann–Kendall test and Sen's slope estimation shows that the annual surface thawing index has increased at a rate of 29 °C-days/yr at a significance level of 0.001 in Mongolia in the last 19 years. The time series of annual surface thawing index is given in Fig. 8. This figure shows the significant increase in annual surface thawing index

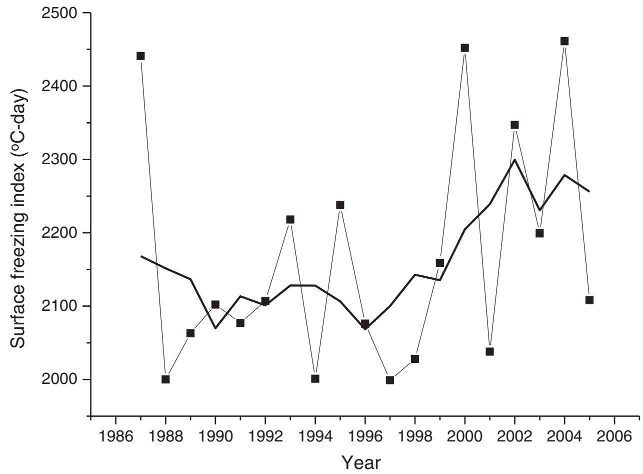

Fig. 7. The time series of annual surface freezing index in Mongolia for the period of 1987–2005. The bold line is the 5-year smoothing average.

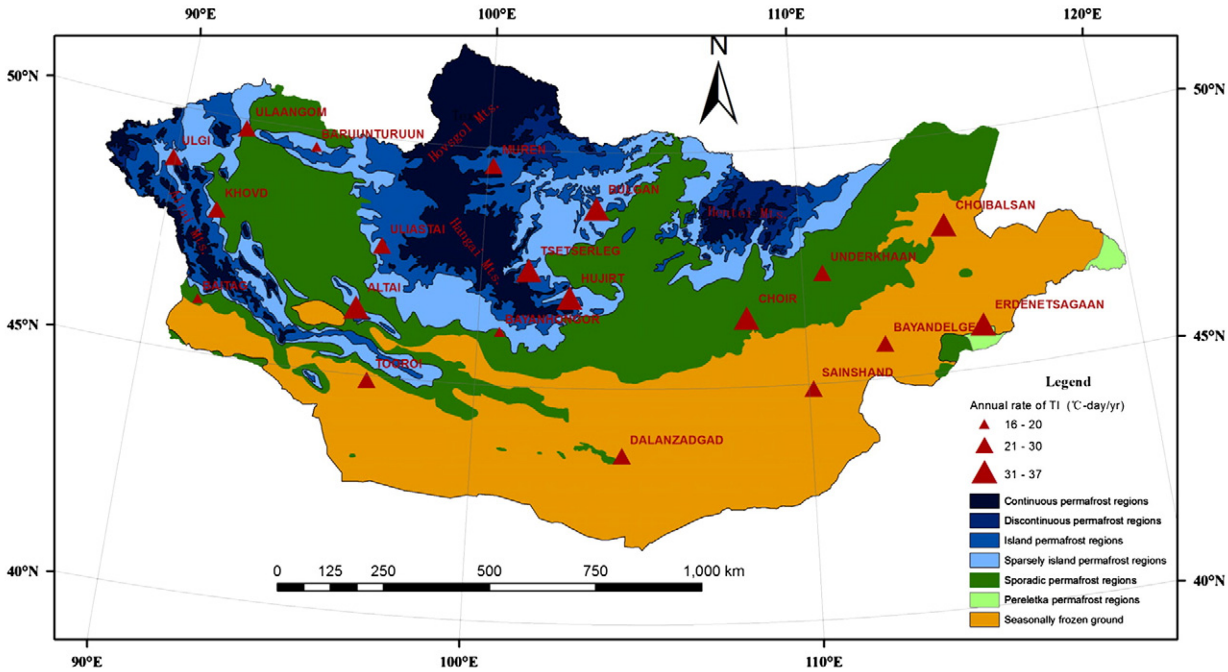

Fig. 6. Spatial distribution pattern of annual trend slopes for surface thawing index at the selected 20 weather stations for 1987–2005 periods. The map of permafrost distribution is drawn after Tumurbaatar and Mijiddorj (2006). The size of triangles is proportional to the magnitude of increasing trend of annual surface thawing index.

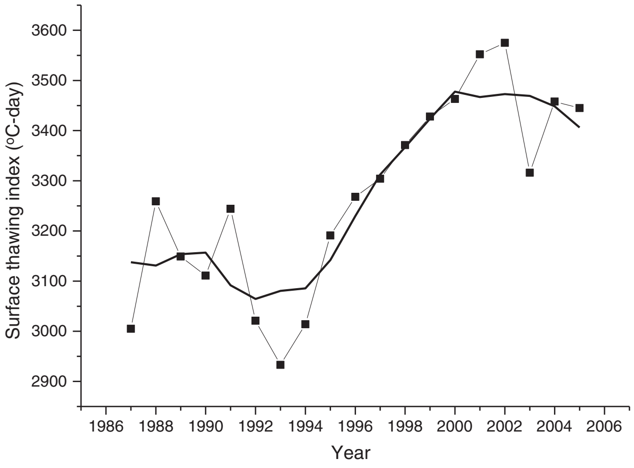

Fig. 8. The time series of annual surface thawing index in Mongolia for the period of 1987–2005. The bold line is the 5-year smoothing average.

through the 1987–2005 period. The increasing trend is particularly noticeable since the beginning of 1990s. The increasing magnitude of annual surface thawing index at all stations is far greater than that in the high-latitudinal regions of Northern Hemisphere (4.4 °C-day/yr) from 1971 to 2002 reported by Frauenfeld et al. (2007). The great increase of annual surface thawing index indicates that summer warming plays a predominant role in the climatic warming in Mongolia. The noticeable increase of annual surface thawing index is in coincidence with a drastic increase in summer air temperature (0.106 °C/yr for the period 1981–2006 and 0.147 °C/yr for the period 1990–2006 at a significance level of 0.01) in Mongolia, which is reported by Dagvadorj et al. (2009). Corresponding to the remarkable summer warming, Sharkhuu and Anarmaa (2006) reported that the active layer thickness had increased by 3–30 cm and extensive permafrost degradation has been occurring since the beginning of permafrost monitoring in Mongolia.

4. Conclusions

A set of 3-year continuous daily observation data of ground surface temperature at an automatic weather station in the central Mongolian Plateau is used to assess the accuracy of using monthly observation data to calculate surface freezing/thawing index. The result has shown that the relative errors of surface freezing/thawing index between using daily and monthly measured data are less than 2% for calculation of surface freezing index and less than 3% for calculation of surface thawing index. Consequently we assumed that it is reliable to use monthly ground surface temperature data to obtain annual surface freezing/thawing index in Mongolia.

The application of trend detection techniques to 20 meteorological stations has resulted in the identification of annual freezing/thawing index trends in Mongolia. The annual surface freezing index generally shows an increasing trend although no significant trends were detected over the period 1987–2005. However, the annual surface thawing index has significantly increased at a rate of 29 °C-days/yr during the past 19 years. Spatial trends indicate that the most significant increase in annual surface thawing index occurred in the central and eastern Mongolia, which could be primarily responsible for the increase of active layer thickness and changes of permafrost distribution in this regions during recent decades. This result could provide important implication for mapping permafrost distribution and estimating active layer dynamics responding to a warming climate in recent decades.

Acknowledgment

The study conducted in this paper is funded by the Project "Establishment of Early Observation Network for the Impacts of Global Warming", sponsored by the Ministry of Environment, Japan. The work is also partly supported by the Global Change Research Program of China (2010CB951402). The authors thank the Institute of Meteorology and Hydrology, Mongolian Academy of Sciences, for providing the meteorological data for this study. The constructive comments from two anonymous reviewers are specially appreciated. We would like to express especial gratitude to Dr. Zhang Yizhang from Chiba University for providing bibliography.

References

Anisimov, O.A., Lobanov, V.A., Reneva, S.A., Shiklomanov, N.I., Zhang, T., Nelson, F.E., 2007. Uncertainties in gridded air temperature fields and effects on predictive active layer modeling. Journal of Geophysical Research 112, F02S14. doi:10.1029/2006JF000593.

Bohannon, J., 2008. The big thaw reaches Mongolia's pristine north. Science 319, 567–568.

Brown, J., Hinkel, K.M., Nelson, F.E., 2000. The Circumpolar Active Layer Monitoring (CALM) Program: research designs and initial results. Polar Geography 24, 165–258.

Dagvadorj, D., Natsagdorj, L., Dorjpurev, J., Namkhainyam, B., 2009. Mongolia assessment report on climate change. Published by Ministry of Environment, Nature and Tourism, Mongolia, Ulaanbaatar, Mongolia. .

Dulamsuren, C., Hauck, M., Leuschner, C., 2010. Recent drought stress leads to growth reductions in *Larix sibirica* in the western Khentey, Mongolia. Global Change Biology 16, 3024–3035.

Frauenfeld, O.W., Zhang, T., Barry, R.G., 2004. Interdecadal changes in seasonal freeze and thaw depths in Russia. Journal of Geophysical Research 109, D05101. doi:10.1029/2003JD004245.

Frauenfeld, O.W., Zhang, T., McCreight, J.L., 2007. Northern hemisphere freezing/thawing index variations over the twentieth century. International Journal of Climatology 27, 47–63.

Hanson, J.L., Yesiller, N., Swarbrick, G.E., Liu, W., 2010. New approach for surface n factors. Journal of Cold Regions Engineering 24, 19–34.

Hinkel, K.M., Nelson, F.E., 2003. Spatial and temporal patterns of active layer thickness at Circumpolar Active Layer Monitoring (CALM) sites in northern Alaska, 1995–2000. Journal of Geophysical Research 108 (D2), 8168.

Jiang, F., Hu, R., Li, Z., 2008. Variations and trends of the freezing and thawing index along the Qinghai–Xizang Railway for 1966–2004. Journal of Geographical Sciences 18, 3–16.

Kendall, M.G., 1975. Rank Correlation Methods, 4th edn. Griffin, London.

Lunardini, V.J., 1978. Theory of n-factors and correlations of data. Proceedings of Third International Conference on Permafrost. National Research Council of Canada 1, 40–46.

Lunardini, V.J., 1981. Heat Transfer in Cold Climates. CRREL: Van Nostrand Reinhold Company, New York, pp. 1–671.

Mann, H.B., 1945. Nonparametric tests against trend. Econometrics 13, 245–259.

Nandintsetseg, B., Greene, J.S., Goulden, C.E., 2007. Trends in extreme daily precipitation and temperature near Lake Hovsgol, Mongolia. International Journal of Climatology 27, 341–347.

Nelson, F., Outcalt, S.I., 1983. A frost index number for spatial prediction of ground-frost zones. Proceedings of the Fourth International Permafrost Conference 1, 907–911.

Nelson, F.E., Outcalt, S.I., 1987. A computational method for prediction and regionalization of permafrost. Arctic and Alpine Research 19, 279–288.

Nelson, F.E., Hinkel, K.M., Shiklomanov, N.I., Mueller, G.R., Miller, L.L., Walker, D.A., 1998. Active-layer thickness in north-central Alaska: systematic sampling, scale, and spatial autocorrelation. Journal of Geophysical Research — Atmospheres 103, 28963–28973.

Romanovsky, V.E., Osterkamp, T.E., 1997. Thawing of the active layer on the coastal plain of the Alaskan Arctic. Permafrost and Periglacial Processes 8, 1–22.

Romanovsky, V.E., Smith, S.L., Christiansen, H.H., 2010. Permafrost thermal state in the polar Northern Hemisphere during the International Polar Year 2007–2009: a synthesis. Permafrost and Periglacial Processes 21, 106–116.

Sato, T., Kimura, F., 2006. Regional climate simulations to diagnose environmental changes in Mongolia. Bulletin of the Terrestrial Environment Research Center, University of Tsukuba 7, 59–69.

Schmidlin, T.W., Dethier, B.E., 1985. Freezing degree-days in New York State. Cold Regions Science and Technology 11, 37–43.

Sen, P., 1968. Estimates of the regression coefficient based on Kendall's tau. Journal of the American Statistical Association 63, 1379–1389.

Sharkhuu, N., Anarmaa, S., 2006. Monitoring of permafrost in Mongolia. Proceedings of the Asian Conference on Permafrost, Lanzhou, China, August, pp. 184–186.

Sharkhuu, A., Sharkhuu, N., Etzelmuller, B., Heggem, E.S.F., Nelson, F.E., Shiklomanov, N.I., Goulden, C.E., Brown, J., 2007. Permafrost monitoring in the Hovsgol mountain region, Mongolia. Journal of Geophysical Research 112, F02S06. doi:10.1029/2006JF000543.

Sharkhuu, N., Sharkhuu, A., Romanovsky, V.E., Yoshikawa, K., Nelson, F.E., Shiklomanov, N.I., 2008a. Thermal state of permafrost in Mongolia. In: Kane, D.L., Hinkel, K.M. (Eds.), Proceedings of the 9th International Conference on Permafrost. Institute of Northern Engineering, University of Alaska, Fairbanks, Fairbanks, pp. 1633–1638.

Sharkhuu, A., Sharkhuu, N., Etzelmuller, B., Heggem, E.S.F., Goulden, C.E., 2008b. Effects of vegetation and grazing on soil temperatures, soil moisture, and the active layer in the Hovsgol Mountain forest steppe zone, Mongolia. In: Kane, D.L., Hinkel, K.M. (Eds.), Proceedings Ninth International Conference on Permafrost, 2. Institute of Northern Engineering, University of Alaska Fairbanks, Fairbanks, pp. 1627–1632.

Shiklomanov, N.I., Nelson, F.E., 2002. Active-layer mapping at regional scales: a 13-year spatial time series for the Kuparuk Region, North-Central Alaska. Permafrost and Periglacial Processes 13, 219–230.

Smith, S.L., Wolfe, S.A., Riseborough, D.W., Nixon, F.M., 2009. Active-layer characteristics and summer climatic indices, Mackenzie Valley, Northwest Territories, Canada. Permafrost and Periglacial Processes 20 (2), 201–220.

Steurer, P.M., 1996. Comparison of probability distributions used in estimating the 100-year return period of the air-freezing index. Journal of Cold Regions Engineering 10, 23–35.

Tumurbaatar, B., Mijiddorj, B., 2006. Permafrost and permafrost thaw in Mongolia. In: Goulden, C.E., et al. (Ed.), The Geology, Biodiversity and Ecology of Lake Hovsgol (Mongolia). Backhuys Publishers, Leiden, The Netherlands, pp. 41–48.

Wu, T., Zhao, L., Xie, C., Li, S., Pang, Q., Zhang, W., 2008. Freezing/thawing index variations during the last 40 years over the Tibet Plateau. Proceedings: the Ninth International Conference of Permafrost, Fairbanks, University of Alaska, pp. 1969–1973.

You, Q., Kang, S., Pepin, N., et al., 2010. Climate warming and associated changes in atmospheric circulation in the eastern and central Tibetan Plateau from a homogenized dataset. Global and Planetary Change 72, 11–24.

Zhang, T., Osterkamp, T.E., Stamnes, K., 1996. Some characteristics of the climate in northern Alaska, U.S.A. Arctic and Alpine Research 28, 509–518.

Zhang, T., Frauenfeld, O.W., Serreze, M.C., et al., 2005. Spatial and temporal variability in active layer thickness over the Russian Arctic drainage basin. Journal of Geophysical Research 110, D16101. doi:10.1029/2004JD005642.

Zhao, L., Wu, Q., Marchenko, S.S., Sharkhuu, N., 2010. Thermal state of permafrost and active layer in Central Asia during the International Polar Year. Permafrost and Periglacial Processes 21, 198–207.