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Spatiotemporal variations of climate warming in northern Northeast China as indicated by freezing and thawing indices

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A B S T R A C T

As the thermal state of the upper boundary conditions of the soil layer, ground surface and air temperatures sensitively indicate the heat transferring process between atmosphere and land surface. Due to the combined effects of high latitude and elevation, northern northeast (NNE) China is the second largest permafrost region in China. Based on the daily ground surface and air temperatures at 21 selected stations in NNE China, the Mann–Kendall test and Sen's slope estimate were used to detect changes in the mean annual ground surface temperature (MAGST), mean annual air temperature (MAAT), annual ground surface freezing index (GFI), annual air freezing index (AFI), annual ground surface thawing index (GTI), annual air thawing index (ATI), and surface offset of MAGST–MAAT for the period between 1972 and 2005. The results show a significant warming in NNE China during the past three decades. The MAGST and MAAT averaged 0.72 and −0.50 °C, with mean increasing rates of 0.61 and 0.72 °C/10y, respectively. The lowest MAGST and MAAT were observed in the northernmost and middle parts of the Da Xing'anling Mountains. The multiyear average GFI is 2822.1 C°/y with a range between 1827.6 and 3919.6 C°·d. The multiyear average AFI is 2688.8 C°/y with a range between 1729.5 and 3606.1 C°·d. Over the same period, the multiyear average GTI ranged between 2451.8 and 3705.5 C°·d, with an average of 2514.0 C°/y, and the multiyear average of ATI ranged from 1902.7 to 2990.1 C°·d, with an average of 2508.3 C°. Trend analyses show a significant decline in annual GFI (−13.5 C°·d/y) and annual AFI (−13.4 C°·d/y), and a significant increase in annual GTI (9.96 C°·d/y) and annual ATI (8.71 C°·d/y). The most pronounced warming has occurred in sporadic permafrost regions of NNE China. However, in continuous permafrost, and discontinuous permafrost regions with extensive presence of taliks, such as at Ta'he and Xinlin stations, no significant trend is detected. Study of the variations of freezing and thawing indices may provide some implications of spatiotemporal changes in the thermal regimes of active layer and permafrost soils, and facilitate better understanding of cold environment changes in permafrost regions of Northeast China.

1. Introduction

Northeast China is the second largest expanse of permafrost and the primary region of latitudinal permafrost in China, and the southernmost part of the Eurasian cryosphere (Wei et al., 2011). Latest statistics indicates that the areal extent of permafrost in Northeast China has shrunk to 0.24×10^6 km^2, most of which is in northern northeast (NNE) China, the Da and Xiao Xing'anling Mountains (Ran et al., 2012). Driven by many programs and projects on engineering explorations, design, and construction, and ecological rehabilitation, research on permafrost in NNE China has received increasing attention from scientists, engineerers, and governmental administrators since the late 1950s (Jin et al., 2010; Wei et al., 2011). Among them, delineating the southern limit of permafrost with isotherms of mean annual air temperatures (MAAT) and zoning of permafrost regions (e.g., Guo and Li, 1981; Lu et al., 1993), is one of the most important. Due to its thin and warm nature of the permafrost, and its sensitivity to climate change and anthropogenic activities, permafrost degradation in the Xing'anling Mountains has been clearly observed during the past several decades (Jin et al., 2007; He et al., 2009; Chang et al., 2013). For example, the northward shifting of the southern limit of permafrost from the 1970s to the 2000s has been confirmed by on-site data

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along highways in the Da and Xiao Xing'anling Mountains and the China–Russia Crude Oil Pipeline (CRCOP) route from Mo'he to Daqing (Jin et al., 2007). However, the lack of long-term observation data has made it difficult to quantitatively analyze the spatial and temporal variations of permafrost changes in NNE China. Moreover, these studies on the northward shifting of the southern limit of permafrost in NNE China were based on the analysis of isotherms of MAAT, but without support from adequate data on ground surface temperatures.

The ground surface is the direct interface where energy and mass exchanges between earth and atmosphere take place. It is therefore of great importance for predicting thermal regime of permafrost soils and mapping permafrost distribution (Frauenfeld et al., 2007; Wu et al., 2013). Myriad local variations in vegetation, topography, and snow cover can produce differences with a range of several degrees between the MAGST and MAAT over a small region (Smith and Riseborough, 2002). Therefore, the ground surface temperature and related parameters, such as annual GFI and GTI, play important roles in dynamics of active layers and permafrost soils.

Because air temperature data are more readily available, most previous studies in Northeast China focused on the spatiotemporal variations of annual, summer and winter air temperatures (e.g., Wei et al., 2008; He et al., 2013). Wei et al. (2008) reported an increase of approximately 1.0 C° in MAAT during 1976–2000 compared with that of 1950–1975. He et al. (2013) reported that during 1961–2005, the increasing rate of MAAT is 0.38 C°/10y, and the warming trend in winter is 0.53 C°/10y, much higher than that in summer (0.24 C°/10y). There is little work detailing changes in GST in permafrost regions in NNE China. The intense increase in ground surface and air temperatures result in major variations of annual freezing and thawing indices, and the active layer thickness (ALT), and eventually extensive permafrost degradation (Wu et al., 2012, 2013). In this study, the spatiotemporal variations of MAAT and MAGST, surface offset between MAAT and MAGST, annual GFI, annual GTI, annual AFI, and annual ATI are analyzed on the basis of daily ground surface and air temperatures from 21 selected meterological stations. The freezing and thawing indices are important for assessing seasonal freeze and thaw depth, as well as the distribution of permafrost and seasonally frozen ground (Klene et al., 2001; Anisimov et al., 2007; Wu et al., 2013). This study will help better understanding changes in the thermal regimes of ground surface, active layer and permafrost soils, and further facilitates the understanding of the stability of cold region environments in Northeast China.

2. Data and methodologies

Daily temperature datasets were obtained from the National Climate Center of China Meteorological Administration (http://cdc.cma.gov.cn/home.do). GST is measured on a standard yard of 2×4 m with sensors on the surface of snow cover in wintertime, and bare ground in summertime, while air temperatures are measured at 2 m height. The earliest systematic observations of GST in NNE China started in 1951 at Nenjiang and Keshan stations, and generally around or after the 1960s–1970s at most other stations. Although the daily GST at Xiao'ergou, Xin'youqi and Arxaan stations have missing values for several years before the year of 1972, the time series of all the stations are complete after 1972 (Table 1). However, for some unknown reasons, the daily GST at most stations in NNE China suffered a serious absence of measurements during the winters (from November to the next February) after 2005. Therefore, considering continuity, uniformity, and long time series of datasets, 21 meteorological stations in or around permafrost regions with complete and continuous data series from 1972 to 2005 were selected to analyze the spatial and temporal changes in the MAGST, MAAT, and freezing and thawing indices. In addition, data quality control and homogeneity assessment of the ground surface and air temperatures were checked using the RClimDex software (http://etccdi.pacificclimate.org/software.shtml).

There are a number of freezing and thawing indices in the literature. Frauenfeld et al. (2007) reviewed the definitions, principles and methods for calculating the freezing and thawing indices. Among the different methods of computing freezing and thawing indices, the criteria of summing all temperatures below or above 0 °C during the freezing (thawing) periods are suitable and plausible (Wu et al., 2011, 2013). The annual freezing (thawing) indices in continuous cold (warm) seasons, the annual freezing index is calculated from July to next June, and the annual thawing index from January to December. The annual freezing and thawing

Table 1
List of metadata for the 21 selected meteorological stations in NNE China.

WMO identification number	Station name	Latitude (N)	Longitude (E)	Elevation (m a.s.l.)	Land use (landscape)	Time series of available measurements
50136	Mo'he	52°58′	122°31′	433.0	forest	1958–2006
50246	Ta'he	52°21′	124°43′	361.9	forest	1972–2005
50439	Xinlin	51°42′	124°20′	494.6	high coverage grassland	1972–2005
50353	Huma	51°43′	126°39′	177.4	open forest	1956–2005
50425	Erguna	50°15′	120°11′	581.4	dry land	1958–2005
50434	Tuli'he	50°29′	121°41′	732.6	open forest	1957–2005
50442	Jagdaqi	50°24′	124°07′	371.7	forest	1966–2005
50468	Hei'he	50°15′	127°27′	166.4	forest	1959–2005
50514	Machuria	49°34′	117°26′	661.7	open forest	1958–2005
50527	Hailar	49°13′	119°45′	610.2	open forest	1956–2005
50548	Xiaoergou	49°12′	123°43′	286.1	forest	1960–2005
50557	Nenjiang	49°10′	125°14′	242.2	dry land	1951–2005
50564	Sunwu	49°26′	127°21′	234.5	forest	1957–2005
50603	Xinyouqi	48°40′	116°49′	554.2	open forest	1961–2005
50618	Xinzuoqi	48°13′	118°16′	642.0	open forest	1960–2005
50632	Bûgt	48°46′	121°55′	739.7	forest	1957–2005
50639	Zalantun	48°00′	122°44′	306.5	forest	1952–2005
50656	Beian	48°17′	126°31′	269.7	open forest	1958–2005
50658	Keshan	48°03′	125°53′	234.6	dry land	1951–2005
50727	Arxaan	47°10′	119°56′	1027.4	forest	1952–2005
50774	Yichun	47°44′	126°55′	240.9	high coverage grassland	1958–2005