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Climate change and the distribution of frozen soil in 1980–2010 in northern northeast China

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ABSTRACT

Frozen soil is an important environmental factor in cold regions. Permafrost change, driven by a warming climate, will increase the risk of permafrost thawing, *i.e.*, carbon release accelerating, suprapermafrost water lowering, desertification strengthening, and infrastructure destructing. Based on the energy balance between the atmosphere and the soil, mean annual air temperature (MAAT), annual precipitation (AP), and mean annual wind speed (Vs) were selected for the analysis of the patterns of permafrost environment and its dynamics from 1980 to 2010 in northern northeast China. According to data from meteorological stations, MAAT and Vs increased with the decrease of latitude in the study area, whereas AP increased with the increase of longitude. During 1980 to 2010, the average of MAAT, Vs, AP, freezing index (DDF), and thawing index (DDT) in the study area was −0.73 °C, 473.5 mm, 2.44 m s^{-1}, −2696.7 °C·d^{-1}, and 2458.0 °C·d^{-1}, respectively. Compared with the condition in 1980, the area with MAAT less than 0 °C decreased by 15.8%, 500 mm isotherms of AP moved to the east, the area with Vs of less than 2.2 m/s was expanding, and the area with DDF larger than DDT decreased by 16.9%. The 0 °C isotherm moved to the north and high-altitude direction. The area of permafrost was decreased by 13.67% from 1980 to 2010. However, the area with sparcely island permafrost expanded because of the increase in precipitation, especially in the southeast area. MAAT, Vs, and AP influenced the change and distribution of permafrost, among which MAAT was the dominant factor. The influence of Vs and AP gradually decreased from south to north. Changes in the permafrost environment and distribution would directly affect the vegetation succession and ecological environment. This work will provide basic data for regional research on frozen soil and environment in northern Northeast China.

1. Introduction

Permafrost is a geological phenomenon that results from the exchange of material and energy between the earth and atmosphere under the multiple impacts of regional geographic conditions, such as topographical features, meteorological conditions, geological structure, lithological characteristics, and hydrological features; this phenomenon is sensitive to environmental changes (Cheng and Zhao, 2000). It is an important component of the Quaternary cryosphere. Permafrost in Northern northeast (NNE) China is located in the southern border of Eurasia permafrost (Wei et al., 2011), specifically in the Da and Xiao Xing'anling Mountains (Ran et al., 2012). It has an area of 2.4 × 10^5 km^2. This area is unique and different from other high-altitude and high-latitude permafrost regions (Zhou et al., 2000). Research on permafrost in NNE China has received increasing attention from scientists, engineers, and governmental administrators since the late 1950s (Jin et al., 2006; He et al., 2009).

The natural environment in the permafrost region is called permafrost environment, which mainly refers to the air temperature, wind speed, precipitation, vegetation, terrain, and permafrost distribution. The mean annual air temperature (MAAT) in the NNE China region is rising at a rate of 0.6 °C/10 years in the past 30 years. Permafrost in the Xing'anling area shows significant degradation (Jin et al., 2006; He et al., 2015). This process induces many

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environmental problems, such as hydrologic cycle, vegetation succession, ecosystem degradation, desertification in cold regions (Wang et al., 1996; He et al., 2009; Yang et al., 2010), which leads to engineering damages (Jin et al., 2010; Wang et al., 2016). At the present stage, our research focuses on in situ observations and engineering lines. Further work is needed to study the spatial patterns of permafrost distribution. Meteorological conditions affect the survival and development of permafrost. The spatial extent of permafrost is highly correlated with MAAT (Halsey et al., 1995). At the same time, air temperature (Ta) and radiation parameters can be used directly for quantitative analysis of freezing and thawing (Luo et al., 2014) and play important roles in the dynamics of active layers and permafrost. To some extent, MAAT reflects the energy budget between the ground and atmosphere, as an indicator of permafrost classification (Zhou et al., 1996). The NNE area has stable snow covers. When the average snow depth increases from 5 cm to 15 cm, the mean annual ground temperature will rise to 1 °C (Yershov, 1998). Field surveys in the Amur region revealed that seasonal snow thickness ranges from 21 cm in forests to 36 cm in barren land. Considering the impact of vegetation on soil temperature, snow warming effect in forests is 5 °C, whereas the effect is 2.8 °C in barren land (Liang and Zhou, 1993). Rainfall is closely related with latent heat, and wind speed (Vs) is related to the size of sensible heat flux, which directly influences ground surface temperature (Zhang, 2012). The change of Vs in space and the impact on permafrost distribution have not been extensively studied. At the same time, Ta, precipitation, and Vs are common parameters for several permafrost models (Cheng and Wang, 1982; Chang et al., 2010; Riseborough et al., 2008; Rudy et al., 2016). Therefore, changes in meteorological factors must be analyzed to understand permafrost change.

This study primarily aims to investigate the change in permafrost environment and distribution in NNE China by using data and information obtained from meteorological stations and the China Meteorological Forcing Dataset (CMFD). From the perspective of energy balance, MAAT, annual precipitation (AP), and Vs as basic elements, we first focus on studies on the average and change rate of the meteorological elements in different permafrost regions. We then investigate the changing trends of elements in space and their influence on permafrost distribution. Finally, we assess the change of spatial distribution in NNE China. This work can provide basic data for other studies related to the Quaternary cryosphere.

2. Data and method

2.1. Study area description

The terrain is high in the eastern and western parts of the NNE region and lower in the middle part. It is distributed with herringbone in the plane. From the southern limit of the permafrost to the northern part and from the southeastern to the northwestern part, MAAT decreased from 0 °C to 1.0 °C to −5 °C to −6 °C; AP ranged from 500 mm–600 mm to 200 mm–300 m; the annual range of Ta increased from 35 °C to 50 °C. Most of the area is covered by forests, bushes, moss grass, and moss layer. The predominantly continuous permafrost (PCP), predominantly continuous and island permafrost (PCIP), sparcely island permafrost (SIP), and middle-thick seasonally frozen ground (MSF) were distributed from north to south in the study area (Zhou et al., 2000).

2.2. Data description

The distribution and evolution of permafrost are complex processes and influenced by various climate factors (Gao et al., 2015). MAAT, AP, and Vs are used to analyze the environmental changes in cold regions. From the perspective of energy balance, these three parameters indirectly reflect the changes in radiation as well as sensible and latent heat.

Data types include the data obtained from meteorological stations and the CMFD. Data obtained from 29 meteorological stations from 1980 to 2012 were used in the current study (Fig. 1). The data from meteorological stations are the point data in space. The distribution of them is uneven in the permafrost region, mainly in the MSF and SIP regions. Only five meteorological stations are in the PCP and PCIP regions. Changes in the regional permafrost environment are difficult to detect through direct meteorological station survey. Moreover, the meteorological station data cannot reflect the spatial variation, especially in the permafrost regions. Combination of point and spatial data, would analyze the spatial variation of meteorological elements better.

Meteorological station data were obtained from the National Climate Center of China Meteorological Administration (http://cdc.cma.gov.cn/home.do). The CMFD was developed by the Data Assimilation and Modeling Center for Tibetan Multi-spheres, Institute of Tibetan Plateau Research, Chinese Academy of Sciences (Chen et al., 2011; He and Yang, 2011). The temporal and spatial resolution of this data set is every 3 h and 0.1° × 0.1° in longitude and latitude from 1980 to 2010, covering the entire NNE area. The data is extensively used in permafrost research and has a grid size 1000 m (Guo and Wang, 2013; Gao et al., 2015).

3. Method

Based on the sequence of data obtained from meteorological stations and CMFD, we analyzed the changes in Ta, precipitation, and Vs, such as the annual average value, annual change rate, and spatial contours. The calculation parameter included DDT, DDF, and A/Ta. DDT and DDF can reflect the turnover of heat, which can be calculated using Formulas (1) and (2) (Frauenfeld et al., 2007).

$$\mathrm{DDT} = \sum_{1}^{n} |T_a| \quad \mathrm{Ta} > 0\,^{\circ}\mathrm{C} \tag{1}$$

$$\mathrm{DDF} = \sum_{1}^{n} |T_a| \quad \mathrm{Ta} < 0\,^{\circ}\mathrm{C} \tag{2}$$

A/Ta is used for permafrost classification (Zhou et al., 2000). This classification and zoning indicators are widely accepted due to their rationality and applicability (Sun et al., 2007; Wei et al., 2011), which can be calculated using Formula (3).

$$A/\mathrm{Ta} = \frac{\mathrm{T_{a\,max}} - \mathrm{T_{a\,min}}}{\mathrm{MAAT}} \tag{3}$$

where $T_{a\,max}$ is the annual maximum air temperature and $T_{a\,min}$ is the annual minimum air temperature.

4. Results

4.1. Parameter changes in the weather station

The meteorological parameters of all weather stations in the area were averaged, and the time sequence of the parameters is shown in Fig. 2. From 1980 to 2012, MAAT and DDT increased, whereas AP, Vs, and DDF decreased continuously. The parameters significantly changed from 1980 to 1990. The MAAT changed between −2.2 °C and 0.62 °C, with an average of −0.73 °C; the increase rate was 0.032 °C/year. AP ranged from 335.7 mm to 602.2 mm, with an average of 473.5 mm; the decrease rate was