Permafrost changes in the northwestern Da Xing'anling Mountains, Northeast China in the past decade

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Abstract. Under a pronounced climate warming, permafrost has been degrading in most areas globally, but it is still unclear in the northwestern part of the Da Xing'anling Mountains, Northeast China. According to a ten-year observation of permafrost and active-layer temperatures, the multi-year average of mean annual ground temperatures at 20 m was −2.83, −0.94, −0.80, −0.70, −0.60 and −0.49 °C, respectively, at Boreholes Gen'he4 (GH4), Mangui3 (MG3), Mangui1 (MG1), Mangui2 (MG2), Gen'he5 (GH5) and Yituli'he2 (YTLH2), with the depths of permafrost table varying from 1.1 to 7.0 m. Ground cooling at shallow depths has been detected, resulting in declining thaw depths in Yituli'he during 2009-2020, possibly due to relatively stable mean positive air temperature and declining snow cover and dwindling local population. In most study areas (e.g., Mangui and Gen'he), permafrost warming is particularly pronounced at larger depths (even at 80 m). These results can provide important information for regional development and engineering design and maintenance, and also provide a long-term ground temperature dataset for the validation of models relevant to the thermal dynamics of permafrost in the Da Xing'anling Mountains. All of the datasets are published through the National Tibetan Plateau Data Center (TPDC), and the link is https://doi.org/10.11888/Geocry.tpdc.271752 (Chang, 2021).

1 Introduction

Permafrost, defined as ground that remains at or below 0 °C consecutively for two or more years, is widespread in high-latitude and high-elevation regions (Zhang et al., 2007). One quarter of the Northern Hemisphere and 17% of the Earth's currently exposed land surface are underlain by permafrost (Gruber, 2012). Due to climate warming (Farquharson et al., 2019; Sim et al., 2021; Zhang et al., 2019; Ran et al., 2018) and surface disturbances (Guo et al., 2018; Li et al., 2019; Li et al., 2021), permafrost has experienced widespread degradation during the last decades (Jin et al., 2000; Jin et al., 2007; Zhang et al., 2019; Jin et al., 2021; Chen et al., 2020), evidenced by deeper seasonal thawing (Luo et al., 2018), thinning and warming permafrost (Gruber, 2012; Jin et al., 2021; Jin et al., 2007; Romanovsky et al., 2010; Wu et al., 2022), and areal reduction (Li et al., 2021; Zhang et al., 2021). Permafrost change has attracted extensive attention worldwide (Biskaborn et al., 2019), because it has significant potential impacts on the terrestrial eco-hydrological processes (Zhang et al., 2017; Schuur and Mack, 2018; Zhang et al., 2018a; Ala-Aho et al., 2021; Ran et al., 2022; Luo et al., 2022) and carbon cycling (Mu et al., 2020; Schuur et al., 2015). In recent decades, huge efforts have been dedicated to developing physically based models aiming to reproduce and predict the thermal dynamic processes of permafrost and their consequences. However, lacking long term and systematic in-situ observation of permafrost temperature becomes an apparent bottleneck for relevant analysis and model calibration or validation. Observations in deep permafrost is especially rare and precious.

The areal extent of permafrost in China is estimated at about 1.59×10^6 km^2 (Ran et al., 2012), mainly in the mountainous areas of northwestern China (Cao et al., 2018), on the Qinghai-Tibet Plateau (about 1.06×10^6-1.17×10^6 km^2) (Zou et al., 2017; Cao et al., 2019), and in northeastern China (about 3.1×10^5 km^2) (Zhang et al., 2021). The northern part of Northeast China, e.g., the Da Xing'anling Mountains, is characterized by thick surficial deposit of organic soil and peat, dense vegetation, and widespread distribution of wetlands in valley bottoms and lowlands, and extensive and stable inversion of air temperature and snow cover in winter, resulting in strong regional differentiations in permafrost features (Jin et al., 2007). Therefore, the permafrost in the Da Xing'anling Mountains is referred to as "Xing'an (Hinggan)-Baikal permafrost (XBP)" (Jin et al., 2007), a distinct type of ecosystem-dominated permafrost (Shur and Jorgenson, 2007). However, the intensity and progress of permafrost observation in this region was falling far behind other permafrost regions in China, e.g., the Qinghai-Tibet Plateau

(Zhao et al., 2021; Wu et al., 2022). Most permafrost investigation and observation in Da Xing'anling Mountains were aimed at serving some specific short-term projects in economic development, engineering design and construction, e.g., road construction and coalmining (Jin et al., 2007), and they were terminated upon the project completion without persistence. In recent years, numerous local studies on permafrost change have been carried out. However, most of them were based on air and/or ground surface temperatures provided by weather stations, reanalysis data (Wei et al., 2011; Zhang et al., 2018b; Zhang et al., 2021), or short-term ground thermal observations (He et al., 2021; Jin et al., 2007). Without direct observation of ground temperature profiles and their temporal changes, it is hard to more accurately feature and evaluate the latest distribution and future changes of permafrost in Northeast China under the combined influences of warming climate and human activities (Serban et al., 2021). Similar to the Circumpolar Active Layer Monitoring (CALM) sites (Brown et al., 2000; Grebenets et al., 2021; Shiklomanov et al., 2012), or CALM-South sites (Guglielmin, 2006; Guglielmin et al., 2012; Hrbáček et al., 2021), a comprehensive and persistent observing system was gradually established since 2009 at Gen'he (GH), Yituli'he (YTLH), and Mangui (MG) in the northwestern part of the Da Xing'anling Mountains, Northeast China. Periodical collection and calibration of data on the thermal regimes of soils in the active layer and permafrost at depths have been carried out in boreholes, generally reaching 20 m in depth and one of them, 80 m. Thus, the observing system presents an opportunity to investigate the thermal characteristics of XBP at depths and to understand and evaluate the temporal changes in permafrost features in different landscapes under a warming climate. It can obtain a long-term ground temperature dataset for calibration and validation of models relevant to the thermal dynamics of permafrost in the Da Xing'anling Mountains, and provide important information for regional planning, development, and engineering design and maintenance in Northeast China.

2 Study area

The Gen'he Station of China Forest Ecological Research Network (CFERN), Yituli'he Permafrost Observatory (YTLH), and Mangui Permafrost Station (MG) are found in the discontinuous permafrost zone of Northeast China (Figure 1), where it is characterized by a cold temperate continental climate under the influences of alternating monsoons. The multi-year average of mean annual air temperature (MAAT) was −4.0 °C at Gen'he (1961–2020), −5.2 °C at Yituli'he (1965–2005), and −5.8 °C at Mangui

(1996–2005). During the same periods, the multi-year average of annual precipitation was 440 mm at Gen'he, 460 mm at Yituli'he, and 480 mm at Gangui (Yang, 2007; Jin et al., 2007). The precipitation falls mainly in the form of summer rain, and snowfall accounts for about 12~20% (in snow water equivalent, or SWE). Stable snow cover on the ground surface usually starts to occur in the late October and generally disappears in the next April.

In the vicinity of CFERN, five boreholes were installed at Gen'he, and the datasets at GH4 and GH5 (Figure 1) with good quality were presented in this study. Two boreholes (YTLH1 and YTLH2) and three boreholes (MG1, MG2 and MG3) were installed at YTLH and MG, respectively (Figure 1). The vegetation differs slightly from site to site at all mentioned boreholes (Table 1). For example, GH4 is located in a larch (*Larix gmelinii*) forest, whereas GH5, YTLH1, YTLH2 and MG2 are in sedge (*Carex tato*) meadows. MG3 is in an open backyard, and MG1 is located in a birch (*Betula*) shrubland with sedges (*Carex tato*) as an understory. The soil types at all boreholes are the same, i.e., brown coniferous forest soil.

Among the seven boreholes, YTLH1 with a depth of 8.15 m was first installed for monitoring the hydrothermal dynamics of active layer and shallow permafrost at the end of 2008, with weekly manual measurement of soil temperatures since 2009. However, in order to monitor the permafrost temperature at the depth of zero annual amplitude (generally at 10-25 m in Northeast China), YTLH2 was drilled to a depth of 20 m at a nearby site (10 m away from the YTLH1) with almost identical physical and vegetative conditions on the ground surface. Thermistor cables for monitoring the ground temperatures were permanently installed in the boreholes since 2010. GH4, GH5, MG1, MG2 and MG3 have been installed and started working since the beginning of 2012, but with different observational frequencies (Table 1). All the thermistor cables were assembled with same technology standards by the State Key Laboratory of Frozen Soils Engineering (SKLFSE) in Cold and Arid Regions Environmental and Engineering Research Institute (CAREERI; now renamed to the Northwest Institute of Eco-Environment and Resources, or NIEER) of CAS (Chinese Academy of Sciences). The accuracy of ground temperature measurement is ±0.05 °C in the temperature range from −30 to +30 °C, and ±0.1 °C in ranges from −45 to −30 °C and from +30 to +50°C.

For continuous observation, the thermistor cables at GH4 were connected to a Micrologger of CR3000 (USA), and the ground temperatures were automatically collected in an hourly time step, whereas the ground temperatures at other boreholes were manually measured with a multi-meter (Fluke 189®).

Unfortunately, not all records for ground temperatures are complete in time for all boreholes. For example, there were two hiatuses for the records of GH4 (2014-2016 and 2017-2019) due to the logger damage. Manual records from January to June in 2014 for other boreholes were lost in mailing. The measurement at MG3 was halted in 2016 because of borehole damage and that at GH5 and YTLH2, in 2020, due to the outbreak of the COVID-19 virus and the ensued traffic control. The specifics are presented in Table 1.

3 Results

3.1 Ground temperatures in near-surface permafrost and active layer

Ground temperatures of near-surface soil (e.g., at depths of 1 and 2 m) responds quickly to changes in air temperature, but the change patterns of ground temperatures show a reduction of amplitude with increasing depth in all boreholes. In boreholes GH4, MG3, YTLH1 and YTLH2, seasonal variations in ground temperature still could be detected at the depth of 5 m. However, at depths of 3 and 4 m, variations in winter ground temperatures gradually flattens out in boreholes GH5, MG1 and MG2, and only the annual variability in summer ground temperatures can be detected at the depth of 5 m (Figure 2). Therefore, only a small temperature amplitude (0.5~1.0°C) was detected at the depth of 5 m in comparison with that at 3 m (2~3°C).

Based on the thermal observation at MG1, 2.6 m (2017) and 1.9 m (2020) in depth were respectively the maximum and minimum depths of permafrost table (Table 2). Combining the data in Figure 2b and other observational data, the active layer thickness (ALT) at MG2 increased from 4.3 m (2012) to 4.8 m (2016), but thinned to 4.2 m (2019) afterwards. The permafrost table at MG3 was located at 2.8 m (2012 and 2013), 4.0 m (2014) and 3.3 m (2015) in depth during the observation period. Subtle freeze-thaw cycles were observed at 2.0 m in depth in GH4 (Figure 2a_2), and the 0 °C isotherms in Figure 3a indicated a range of ALT from 2.2 m (2016) to 2.0 m (2018). In GH5, there still exist obvious freeze-thaw cycles at the depth of 6.0 m, despite with a small varying range in ground temperature (0.5°C). However, the ground temperature at the depth of 7.0 m stayed constantly below 0 °C all year round during the monitoring period, approximating to 0 °C and with a multi-year average of mean annual ground temperature at –0.08°C. That is, the thawing front reached down to the depth of 7.0 m every year (Figure 3b), which means the permafrost table here has been lowered to 7.0 m in depth. In YTLH1, ground thawing occurred occasionally at 2.0 m, for an example, in October 2016, but the ALT mostly varied from 1.5 m (2011) to 1.0 m (2017) during the observation (Figure 3c). In the same period in 2016, –0.1 °C was registered as the highest temperature at 2.0 m in depth in YTLH2 (Figure $2c_2$), but an above-zero temperature at 1.5 m depth. The depth of permafrost table fluctuated between 1.6 m (2017) and 2.0 m (2011 and 2016) (Figure 3d and Table 2).

3.2 Changes of permafrost temperature at depth

Figure 4 highlights the changes in thermal regimes of permafrost at different depths in boreholes MG1, MG2 and MG3. Ground temperature was on the rise, but its amplitude decreased with depth since the beginning of observation in 2012. The depth of zero annual amplitude (ZAA) was estimated to be the place where ground temperature changes by no more than 0.1°C throughout a year (Everdingen, 1998 (revised 2005)). Although the ground temperature was not measured periodically with a very fine time step and some values were lost, the estimation could still be reasonable, because the temperature fluctuation in deep ground is significantly dampened. According to the monitoring data, the depth of ZAA varies among different boreholes (Table 2) without considering interannual changes. In order to show more accurate thermal statses of permafrost, ground termperatures of 20 m were chosen to compare within different boreholes in this study. In MG1, the varying amplitudes of ground temperatures for depths deeper than 8 m were no more than 0.4 °C, and seasonal variability was hardly detectable at depths of 16 and 20 m. The results of linear fitting (red trend lines) indicate an overall warming trend of permafrost during 2012-2020. A mulit-year average of mean annual ground temperature (MAGT, at 20 m; from 2012 to 2020) of –0.77 °C was obtained in borehole MG1. In MG2, the ground temperature varied slightly (±0.06°C) with the seasons even at the depth of 20 m, where the MAGT was about –0.69 °C. Permafrost here was also warming, with a rising amplitude of 0.1~0.2 °C from 2012 to 2020. The valid monitoring period was less than 5 years in MG3 (1 January 2012 to 29 April 2016), when the largest ground temperature range of 0.2-0.5 °C was detected between the depths from 8 to 20 m. Similar to that in MG2, the pemafrost temperature at the depth of 20 m in borehole MG3 has been experiencing some seasonal variations, with a multi-year average of MAGT at –0.94 °C (Table 2).

During 2012-2020, permafrost at depths of 8 and 20 m in GH4 and GH5 (Figure 5) warmed by 1.5-0.2 and 0.2-0.1°C, respectively. The warming of permafrost at GH5 was insignificant in comparison with that at other sites. Mean annual ground temperature at 8 m in depth have slightly warmed from –0.17 °C in 2012 to −0.16 °C in 2019, and; the MAGT at 20 m in depth, from −0.60 to −0.57 °C over the same period. MAGT at 20 m in depth was averaged at −0.59 °C during 2012-2019. However, permafrost at GH4 was obviously colder, with a multi-year average of MAGT at −2.84 °C at 20 m in depth. According to Figure 5, ground temperatures at depths of 8-20 m fluctuated seasonally. However, seasonal variations in ground temperature dwindled gradually at depths deeper than 30 m (Figure 6), leaving only inter-annual variations. Ground temperatures in GH4 increased with increasing depth (−2.51, −1.76 and −0.41 °C at 30, 50 and 80 m, respectively), whereas the thermal fluctuations declined downwards (0.2 °C at 20 and 30 m in depth, but 0.03 °C at 80 m). During 2012-2020, the permafrost at depths of 30-80 m at GH4 was warming at an average rate of 0.04-0.20 °C /dec.

In Borehole YTLH2, remarkable seasonal variations were noted at each measured depth. The seasonal amplitude of ground temperature gradually dampened with increasing depth, varying from approximately 0.5 °C at 8 m in depth to less than 0.1 °C at 20 m. Unlike permafrost in Mangui town and Gen'he city, a significant cooling of permafrost was detected at all depths except 20 m at YTLH2 during the 10-year observation (Figure 7). The average rate of temperature change at 20 m depth is close to 0 °C /dec and the MAGT here has been roughly maintained at −0.49 °C in the past decade (Table 2).

4 Discussion

4.1 Changes of near-surface permafrost temperatures

Based on the analysis in Section 3.1, it can be inferred that changes in ground thermal regimes (especially in ALT) of the ecosystem-dominated permafrost on the northwestern slope of Da Xing'anling Mountains are mainly controlled by the changes in local factors, such as vegetation and snow covers and human activities. For example, ALT ranges from 2.5 m in 2016 and 2017 to 1.9 m in 2020 for the borehole in shrubs (MG1), 4.8 m in 2017 to 4.2 m in 2020 for the borehole in sedge meadow (MG2), and 2.9 m in 2012 to 4.0 m in 2014 for the borehole in a farmer's backyard (MG3) during the observation period. Apparently, the borehole MG1, far away from downtown Mangui, had the least ALT because of more shading effect of shrubs than that of meadow (MG2) and less anthropogenic impact than that of backyard (MG3). A declining trend of ALT was also observed in the Nanwenghe Wetlands Reserve on the southern slope of the Da Xing'aning-Yile'huli Mountain Knots, Northeast China, probably driven by a rising surface and thermal offsets of vegetation cover and organic soils (He et al., 2021). Additionally, at MG3, the smaller ALT could be attributed to the shading effect of the farmer's house and more heat loss to the atmosphere caused by snow removal in the yard in winter as well. In Gen'he, at the site of GH4 in a primeval forest, ALT remained unchanged at 2.2 m from 2012 to 2016 and, without human disturbance, permafrost was well-preserved. On the contrary, at the GH5 site in the suburb meadow frequently disturbed by the nearby livestock, a complex thermal regime was observed in the active layer. Ground temperatures at the depths of 3.5-6.0 m were below 0^{o} C from March to September and above 0^{o} C in other time every year, and; not until 7.0 m in depth, where it became below 0^{o} C all the year round. By definition, the active layer is the layer above permafrost that freezes in winter and thaws in summer. Therefore, 7 m is supposed to be the reasonable ALT or the depth of permafrost table, and there might be no supra-permafrost subaerial talik (Jin et al., 2021) between the active layer and the permafrost table at this site, i.e., attached permafrost. However, the supra-permafrost subaerial talik, which has appeared in the Nanwenghe Wetlands Reserve about 300 km to the east of the study site (He et al., 2021), may develop at this site in future. In Yituli'he, the two boreholes (YTLH1 and YTLH2) are, about 20 m apart, both in the meadowy swamp to the east of the railway and to the west of highway. Permafrost here is well developed, partially attributed to the sufficient moisture provided by lowland swamp, which also possibly facilitates the formation of ice wedges (Yang and Jin, 2011).

Notably, there was a decreasing trend in ground temperatures at shallow depths no matter in summer or winter during 2010-2020 (Figure 2), suggesting a cooling permafrost at shallow depths in the last decade on the northwestern slope of the Da Xing'anling Mountains. The maximum thaw depth (MTD) in Yituli'he rose gradually with fluctuations during 1980-2005, and it showed a downward trend during 2010-2019 (Figure 8). This could be related to the thriving vegetation, and declining winter precipitation or snow cover in this area during the observational period. In the last decade, although the mean positive air temperature (MPAT) barely changed in Gen'he (Fig 9b), precipitation in warm seasons increased slightly, leading to a wetter condition in favor of vegetation thriving. For example, the maximum vegetation height of *Carex tato* at YTLH1 and YTLH2 grew significantly from 2009 to 2014. Bushes have also emerged recently near the borehole. Thriving vegetation reduces the solar irradiance incident onto the soil surface in summer, cooling the ground. On the contrary, the winter precipitation (Figure 9a) and snow cover, including the maximal snow depth (Figure 9c) and snow duration (Figure 9d), declined slightly. The thermal insulation effect of snow cover weakens when the depth of snow cover declines, which will lead to a larger heat removal from the permafrost to air in winter and drive the permafrost cooling. Detailed mechanisms for the cooling permafrost will be further investigated with the help of some physically based models after complementing observations on the interactions of energy balance between the permafrost, vegetation, and snow cover.

4.2 Changes of permafrost temperatures at depth

Permafrost in Mangui

During the observation period, the averages of MAGTs at the depth of 20 m were –0.79, –0.70 and –0.93 ^{o}C, respectively, in shrubs (MG1), meadow (MG2) and the farmer's backyard (MG3), indicating a poor correlation between the thermal state of deep permafrost and vegetation cover or anthropic disturbances. However, there was a close relationship between the permafrost change at depth and land surface conditions. The permafrost deeper than 8 m was significantly warming in the last decade under a warming climate (Figure 4). In MG1 and MG2 in particular, the rates of ground warming increased slightly with depth (<0.3 ℃/dec for MG1 and <0.2 ℃/dec for MG2). Within the zone of discontinuous permafrost, the negative relationship between effective leaf area index (LAI_e) and soil moisture content may contribute to differential rates of permafrost thaw (Baltzer et al., 2014). Therefore, more effective water uptake by shrubs than meadow results in lower soil moisture, leading to a more rapid thaw of permafrost at MG1 than that at MG2. The warming rate of permafrost in MG3, with a large warming range, decreased with depth (0.5 ℃/dec at depths of 10 and 12 m, but approximately 0.2 ℃/dec at depths of 16 and 20 m), probably due to short monitoring period and less data. However, it does verify that, in Mangui, permafrost at depth is warming or degrading in the last decade.

Permafrost in Gen'he

Indeed, there exists some long periods with missing data at GH4. However, although the fluctuation of ground temperatures is relatively large at surface layers, the collected data have generally captured the maximal and minimal ground temperature for some important years. Simply by a visual inspection, the minimal or maximal ground temperatures in the observed years has an apparent warming trend from 2012 to 2020, which has a good coincidence with the trend analysis in this study. That is, although the missing values could make some loss for the accuracy of trending analysis, or make it less robust, they will not change the trend in an antipodal way. In addition, in the ground deeper than 8 m, the annual fluctuation of ground temperature was much less than that in the surface layers, as shown in Figures 5 and 6. The missing values will not vary too much from the closest collected values in time. Therefore, we assume that the influence of missing values on the trending analysis of ground temperature at depth will be smaller than that in the surface layers, and it will decrease with depth, which can be inferred from Figures 5 and 6.

In GH4, lower ground temperatures and greater warming rates were observed in comparison with those in GH5 in the last decade (Figure 5). Even at the depths of 70 and 80 m, the ground temperatures were still rising with time at appreciable warming rates (Figure 6). A subtle warming trend of permafrost at depths of 8-20 m in GH5 was also detected with a rate of 0.04 °C/dec during the observation period (Figure 5). This warming rate of ground temperature is similar to that of the Borehole 85-8A in the southern zone of discontinuous permafrost in North America, where the permafrost is often vertically in isothermal condition and close to 0 °C in ground temperature (Smith et al., 2010). In this situation, latent heat effects are considered as the key factor for leading to isothermal conditions in the ground and allowing permafrost to persist under a warming climate (Smith et al., 2010). If the effect of large thermal inertia lasts long enough, the supra-permafrost subaerial talik will be highly likely to form and permafrost will be gradually buried. Overall, the permafrost at depth in forested landscape in Gen'he is in an evident warming trend at present.

Permafrost in Yituli'he

According to a previous study (Jin et al., 2007), MAGT at 13 m in Yituli'he rose by 0.2 °C during 1984-1997, continuously rising from −1.00 °C in 1997 to −0.55 °C in 2010, except during the short suspension of monitoring (2005-2008), and peaking at −0.53 °C in 2013. After that, it kept lowering consecutively and by 2018 it was lower than −0.70 °C, showing an evident cooling trend of permafrost in a sharp contrast to the ground warming trends in Gen'he, Mangui, and other permafrost regions in the world (Douglas et al., 2021; Farquharson et al., 2019). Based on an investigation, there was once a Railway Branch Administration in Yituli'he town since 1964s to 1970s, with a population of over 30,000, but the branch was terminated in 1998. After that, more and more people emigrated and less than 10,000 residents have remained at present, thus leaving a chance for recovery of the local eco-environment and permafrost temperature.

So far, the mitigation of permafrost degradation becomes considerably difficult in the context of a persistent climate warming (Brown et al., 2015; Luo et al., 2018). However, within the dried margin of the Twelvemile Lake (66°27′N, 145°34′W), permafrost aggradation has taken place due to willow shrub uptake of summer recharge and summer shading recharge reduction (Briggs et al., 2014). Beer et al. (Beer et al., 2020) also found that most permafrost-affected soil could be preserved by increasing the population density of big herbivores in northern high-latitude ecosystems as a result of reducing insulation of winter snow cover. The fact that permafrost is cooling in Yituli'he demonstrates that the ecosystem-protected permafrost in discontinuous permafrost zone may recover if the disturbances, such as human activities, dwindle. Thus, our research results would provide key evidence for the preservation of permafrost in areas with intense past anthropic disturbances (Serban et al., 2021).

5 Conclusions

Long-term records of permafrost monitoring presented here from the northwestern flank of the Da Xing'anling Mountains in Northeast China show some important characteristics of ground thermal regimes in the past eight years (2012-2020). The lowest MAGT at 20 m in depth was −2.83 °C in GH4 in a primeval larch forest, and −0.94, −0.80, −0.70, −0.60 and −0.49 °C, respectively, at MG3, MG1, MG2, GH5 and YTLH2. The maximum of burial depth of permafrost table at about 7.0 m was discovered in GH5, and the minimum, 1.1 ~ 1.5 m at YTLH1. The permafrost table was at depths of about 2.0 m at GH4 and YTLH2, and 2.5, 5.0 and 4.0 m at MG1, MG2 and MG3, respectively. Local factors, such as vegetation and snow cover and human activities, are supposed to be mainly responsible for the changes in ALT and thermal state of shallow permafrost in the study area. The most important fact is that ground cooling at shallow depths, as well as the declining ALT in Yituli'he after 2009, has been detected during the observation period, which is probably caused by fairly constant MPAT (mean positive air temperature) and weakened insulation of winter snow cover.

Apart from Yituli'he, permafrost warming at depth was particularly pronounced during the observation period, even at depths of 70 and 80 m, with different ground warming rates. It is noteworthy that the geothermal gradient at depth in GH5 is almost zero (vertically no change) and with MAGT at about 0 °C due to huge thermal inertia of the ice-rich permafrost. This may most likely lead to the formation of supra-permafrost subaerial talik soon. At the Yituli'he Permafrost Observatory, permafrost has been cooling since the re-establishment of monitoring program in 2010; the rapidly declining local population might have relieved its stress on the eco-environment and resulted in permafrost recovery. This fact makes it possible to mitigate the permafrost degradation in zones of ecosystem-dominated permafrost, offering a new thought for permafrost protection.

Author Contributions

XC, HJ, and RH designed the study. XC wrote the manuscript and performed the analysis. YZ plotted the figures. XL, XJ and GL contributed parts of the field data. HJ improved the writing and structure of the paper.

Competing interests

The contact author has declared that neither they nor their co-authors have any competing interests.

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Data availability

The dataset is available from the National Tibetan Plateau/Third Pole Environment Data Center (https://doi.org/10.11888/Geocry.tpdc.271752, Chang X, 2021).

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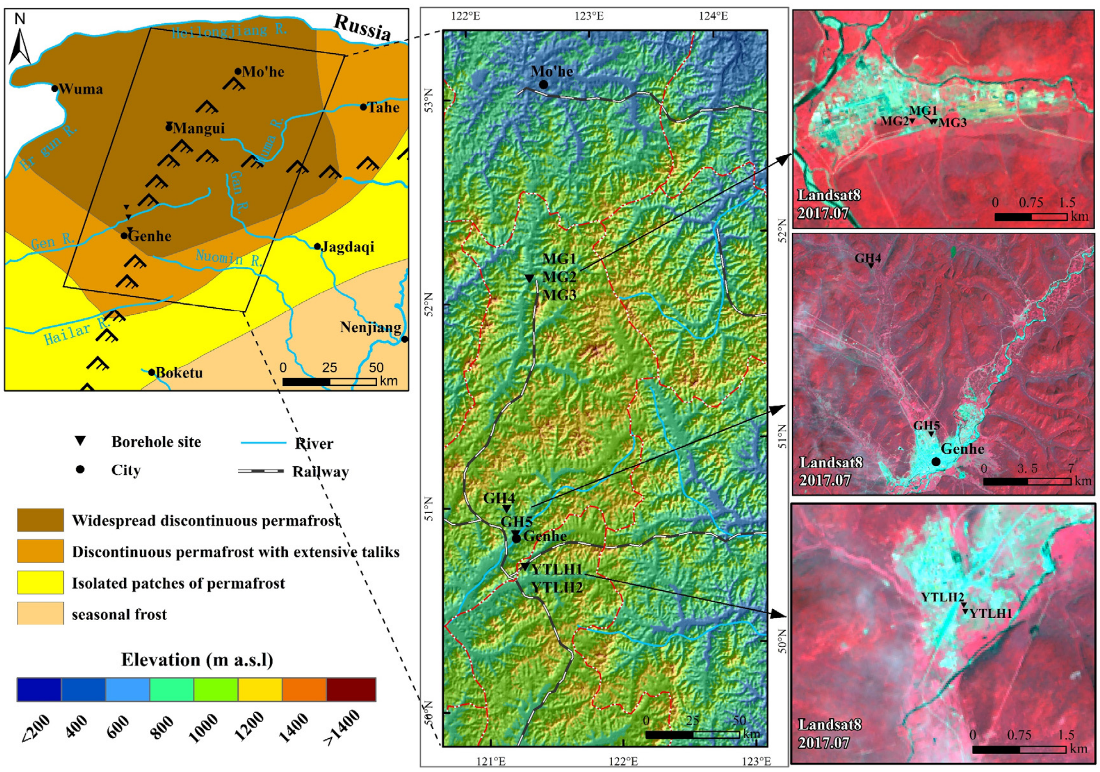

Figure 1. Location of the study area and the distribution of Mangui1 (MG1), Mangui2 (MG2), Mangui3 (MG3), Gen'he4 (GH4), Gen'he5 (GH5), Yituli'he1 (YTLH1) and Yituli'he2 (YTLH2) in the zones of frozen ground in the northern Da Xing'anling Mountains, Northeast China (The permafrost distribution is from Jin et al. (2007).)

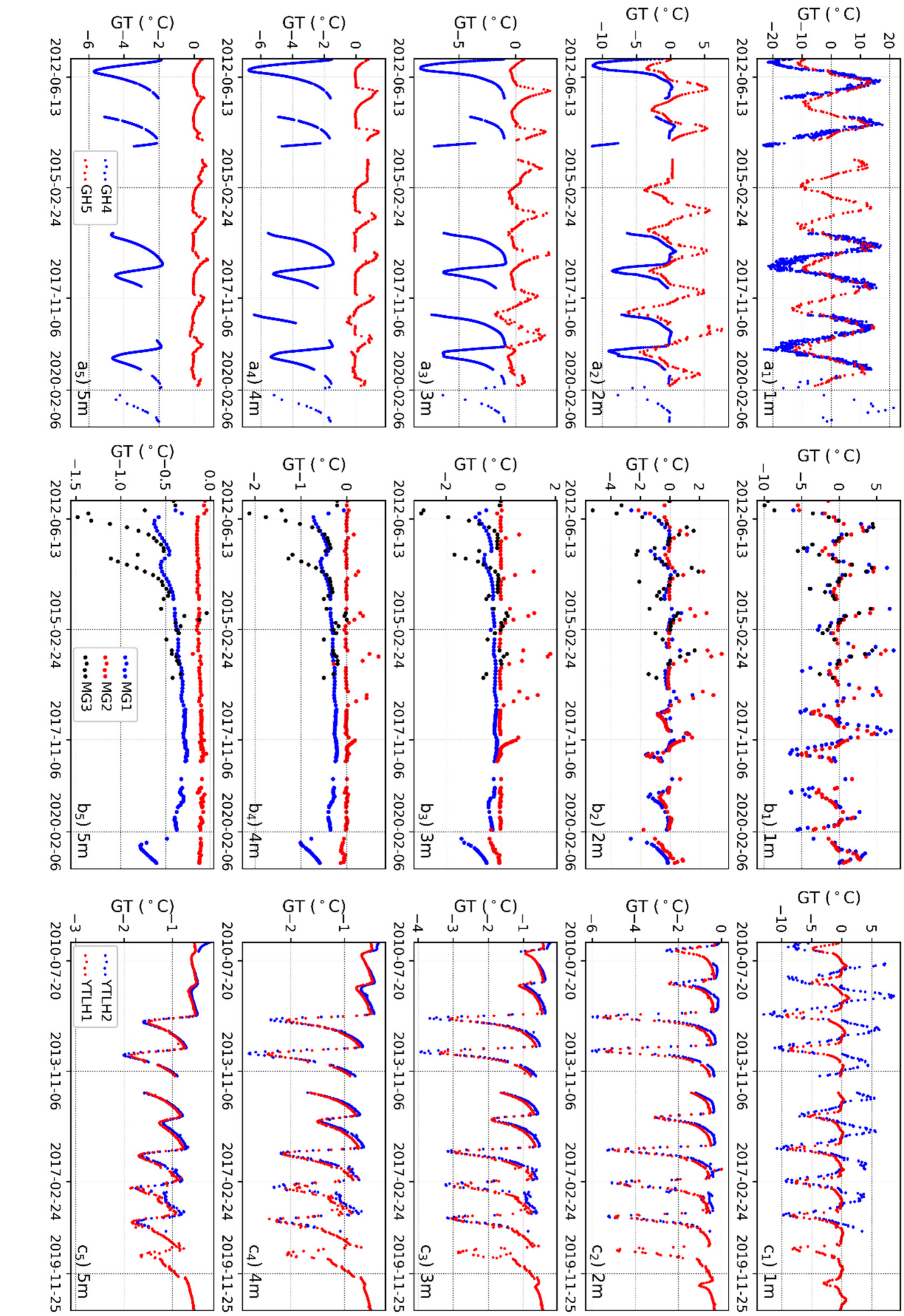

Figure 2. Variability of measured ground temperatures at depths of 1-5 m for Boreholes GH4 and GH5 (a)), MG1, MG2 and MG3 (b)), and YTLH1 and YTLH2 (c)).

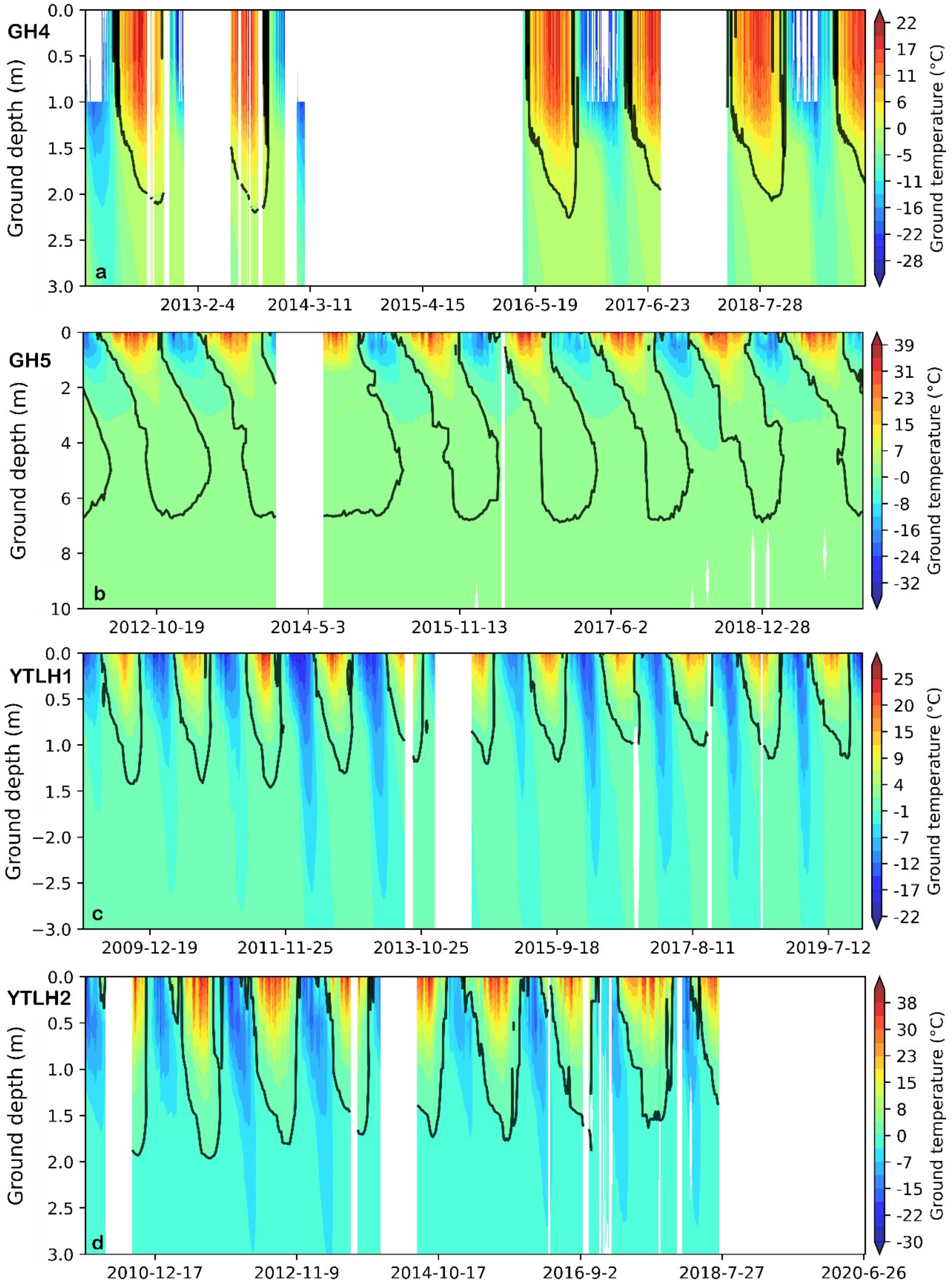

Figure 3 Variability of 0 °C isotherms (black curves) of ground temperature for Boreholes GH4 (a), GH5 (b), YTLH1 (c), and YTLH2 (d). The empty space indicates the period of missing data.

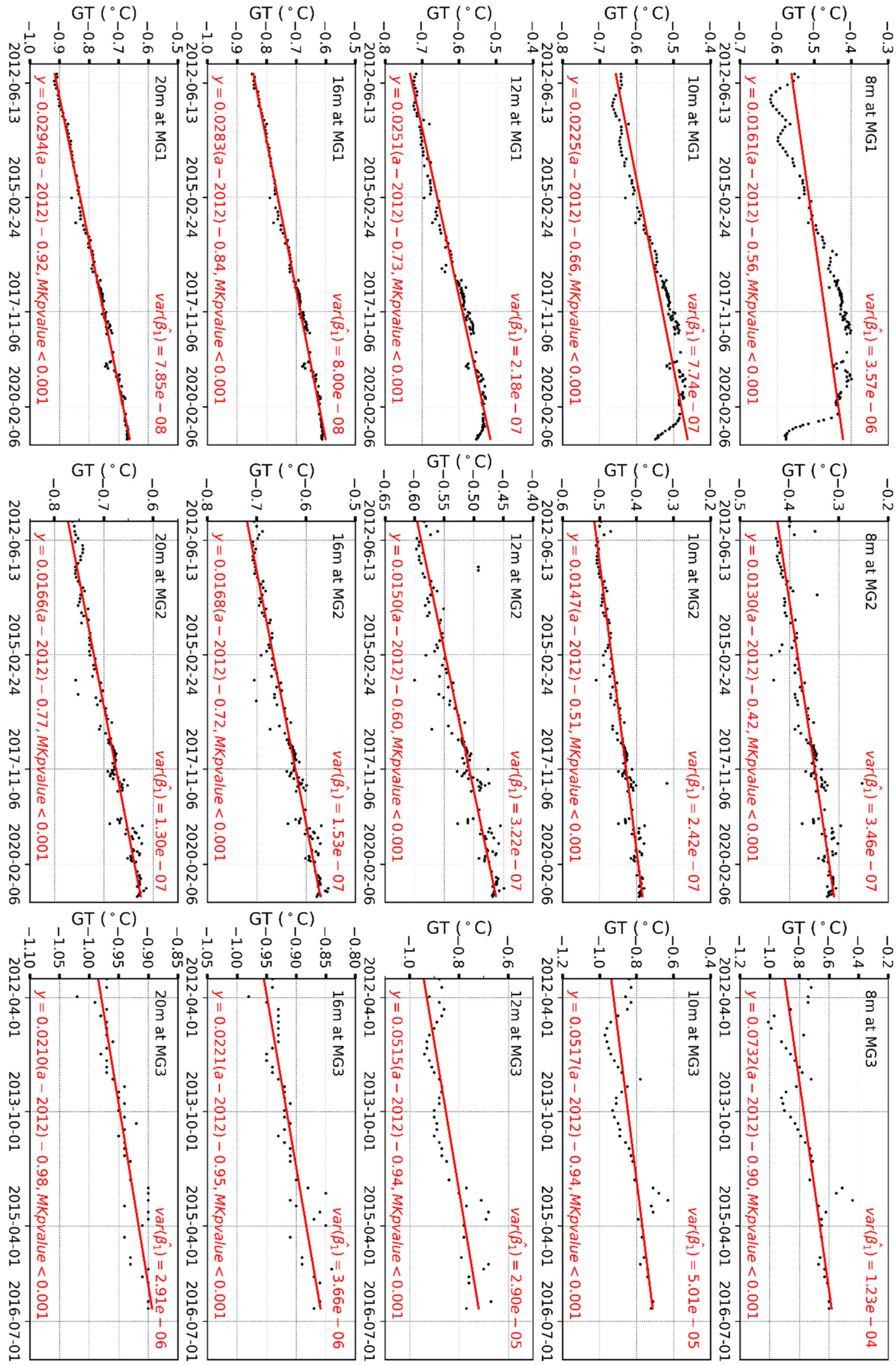

Figure 4. Variability of permafrost temperatures at depths of 8, 10, 12, 16 and 20 m in Boreholes MG1, MG2 and MG3 in Mangui, northern Da Xing'anling Mountains, Northeast China during 2012-2020. GT stands for ground temperature.

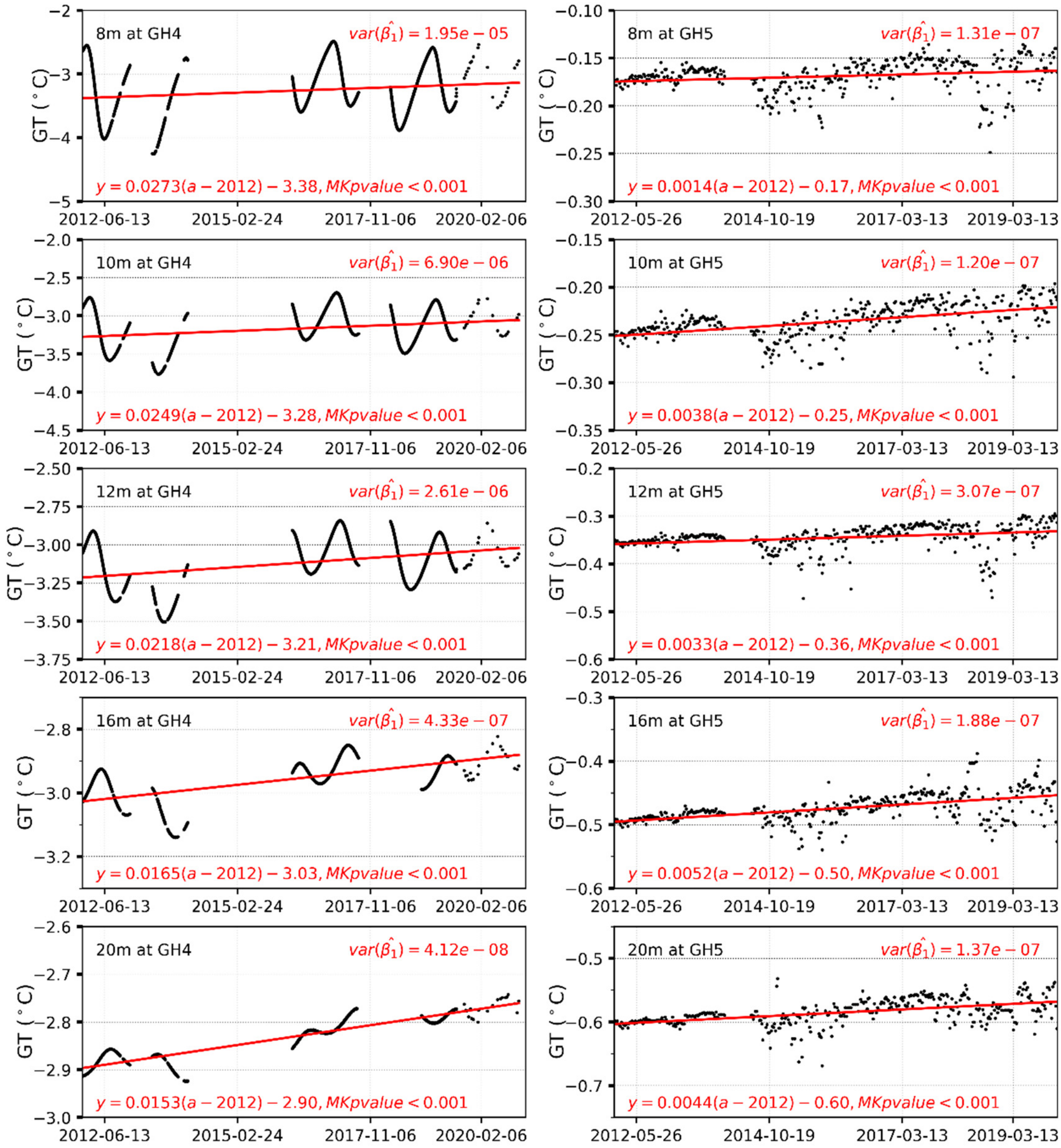

Figure 5. Variations in permafrost temperatures at depths of 8, 10, 12, 16 and 20 m in Boreholes GH4 and GH5 in Gen'he, northern Da Xing'anling Mountains, Northeast China during 2012-2020. GT stands for ground temperature.

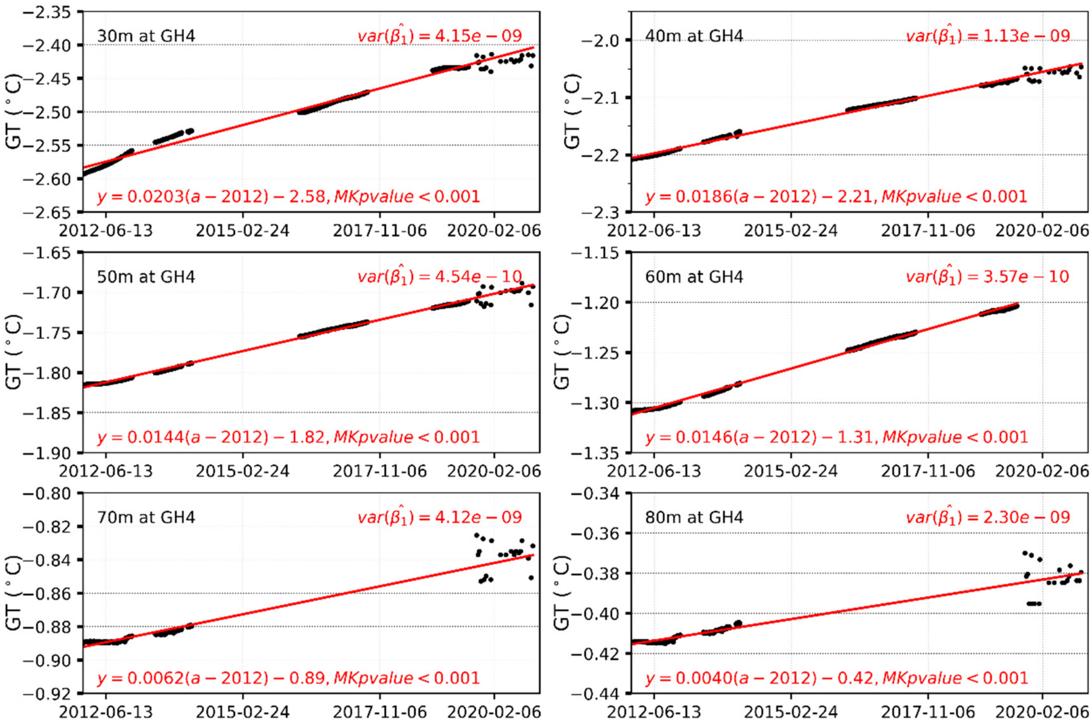

Figure 6. Variability of deep permafrost temperatures at depths of 30 – 80 m for Borehole GH4 in Gen'he, northern Da Xing'anling Mountains, Northeast China during 2012-2020. GT stands for ground temperature.

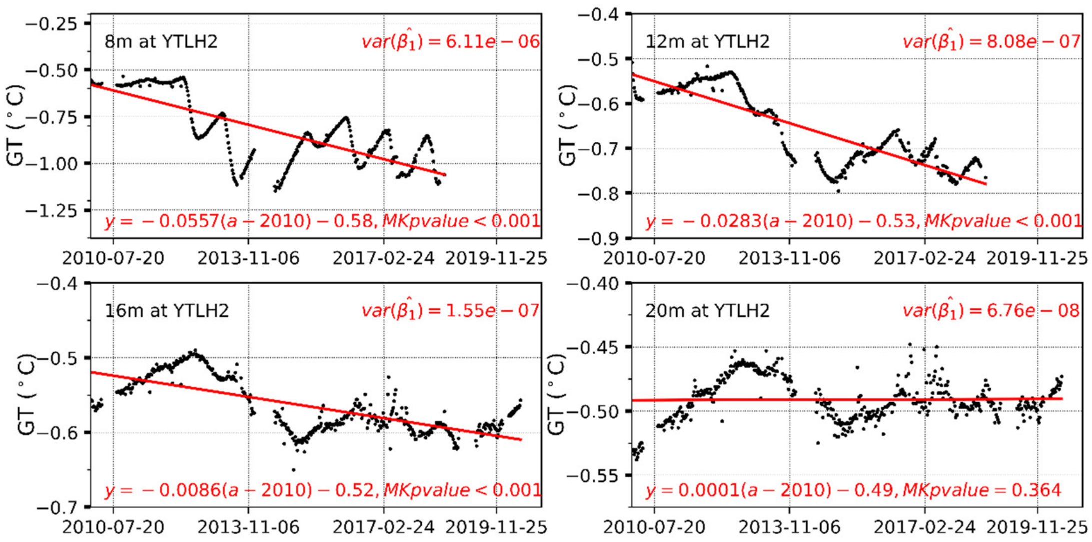

Figure 7. Variability of permafrost temperatures at depths of 8, 12, 16 and 20 m at Borehole YTLH2 in Yituli'he in northern Da Xing'anling Mountains, Northeast China during 2012-2020. GT stands for ground temperature.

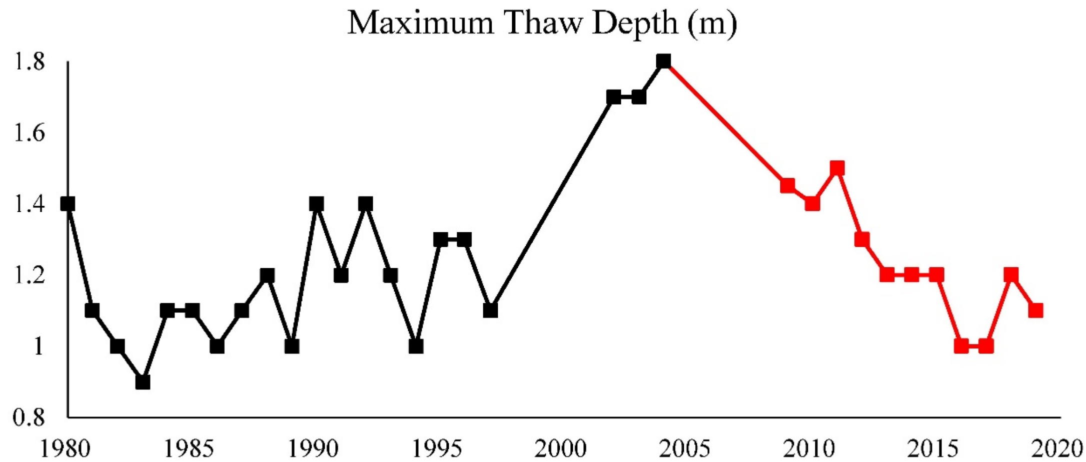

Figure 8. The maximum thaw depth (1980-2019) in Yituli'he on the northwestern flank of the northern Da Xing'anling Mountains in Northeast China (Black squares appeared in the paper from Jin et al. (2007), red ones are obtained in this observation. The two boreholes are 10 m from each other, with similar surface, hydrology and soil conditions.)

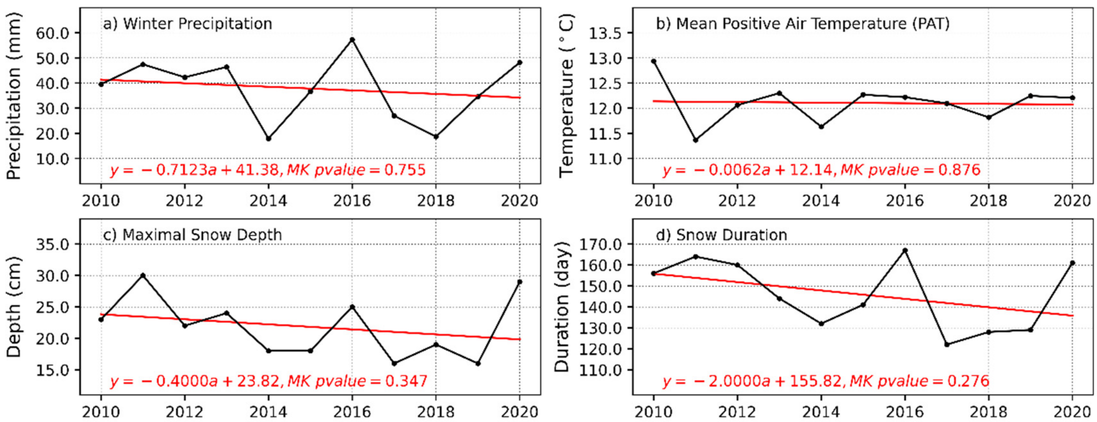

Figure 9. Climatic characteristics of Gen'he on the northwestern flank of the northern Da Xing'anling Mountains in Northeast China in the past ten years

Table 1. Characteristics and monitoring information of ground temperature boreholes in the northwestern part of Da Xing'anling Mountains, Northeastern China

Borehole No.	Lat. (°N)	Long. (°E)	Elev. (m a. s. l.)	Vegetation	Monitoring depths (m)	Time period	Monitoring frequency
MG1	52.037	122.069	633	*Betula fruticosa* shrubs		2012-2020	
MG2	52.036	122.075	642	*Carex tato* meadow	0.0, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5, 5.0, 6.0, 7.0, 8.0, 9.0, 10.0, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20	2012-2020	Monthly
MG3	52.036	122.076	639	Open courtyard		2012-2015	
GH4	50.932	121.502	811	*Betula fruticosa* *Larix gmelini* forest	0.0, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5, 5.0, 6.0, 7.0, 8.0, 9.0, 10.0, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 25, 30, 35, 40, 45, 50, 60, 70, 80	2012-2014, 2016-2017, 2019-2020	Hourly
GH5	50.799	121.530	728	*Carex tato* meadow	0.0, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5, 5.0, 6.0, 7.0, 8.0, 9.0, 10.0, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20	2012-2019	
YTLH1	50.629	121.549	721	*Carex tato* swamp	0.0, 0.1, 0.2, 0.5, 0.8, 1.0, 1.6, 2.0, 3.0, 4.0, 5.0, 6.0, 7.0, 8.15	2009-2019	Weekly
YTLH2	50.630	121.549	725	*Carex tato* swamp	0.0, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5, 5.0, 6.0, 7.0, 8.0, 9.0, 10.0, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20	2010-2017	

Table 2 ALT and average MAGTs of boreholes at larger depths in the northwestern Da Xing'anling Mountains, Northeast China

Borehole	ALT (m)	Average MAGT (°C)				
		8m	10m	13m	16m	20m
MG1	1.9-2.6	-0.48(ZAA)	-0.55	-0.63	-0.71	-0.77
MG2	4.3-4.8	-0.34(ZAA)	-0.44	-0.55	-0.63	-0.69
MG3	2.8-4.0	-0.75	-0.83	-0.87(ZAA)	-0.91	-0.94
GH4	2.0-2.2	-3.26	-3.17	-3.06	-2.96(ZAA)	-2.84
GH5	7.0	-0.17(ZAA)	-0.24	-0.39	-0.47	-0.59
YTLH2	1.5-2.0	-0.82	-0.74	-0.61(ZAA)	-0.56	-0.49