Response to Reviewers' Comments

We would like to thank the reviewers for their comments and suggestions. We have revised the manuscript as possible. Comments from the referees are rearranged and responded one by one as follows, with the responses presented in blue.

Response for comment

General comment

This study investigated the changes in thermal regime of permafrost on the northwestern Da Xing'anling Mountains, Northeast China in the past decade based on a ten-year observation of permafrost and active-layer temperatures. The topic of this study is hot, the results have potential benefit for understanding responses of permafrost to climate change. However, there are some flaws and concerns that should be clarified. I recommend a major revision.

*Response***:** First of all, thank you for your general positive evaluation for our work. We also appreciate your comments and suggestions. We revised the manuscript as possible as we can, and here we give the responses one by one according to your comments.

Specific comment 1

In my opinion, one scientific value of this study is to provide valuable long time series data for other permafrost and related studies, such as, statistic analysis, model evaluation and development, reanalysis dataset validation, etc., however, current version didn't emphasize this point.

*Response***:** Thank you for your suggestion. We have emphasized the potential scientific contribution to the related studies in the introduction section (L54-58, and L78-81), especially for the study of model validation in future.

Specific comment 2

As authors stated, many studies have been analyzed the permafrost changes (e.g., Jin et al., 2000; Jin et al., 2007; Shanshan Chen, 2020; Zhang et al., 2019; Jin et al., 2021), new insights that is expected are few. For example, how the frozen soil has changed in the last decade and how it is different from the past were not clear.

*Response***:** Actually, most of the mentioned literatures are review articles. The permafrost distribution estimation in northeast China by Zhang et al. (2019) was derived from meteorological data without vigorous validation. In the past decades, the studies on permafrost in northeast China is fragmentary and rare, lacking persistent and systematic observation, until Jin et al. established the long-term observing system since 2009. Even up to now, the permafrost in the Qinghai Tibetan plateau is still the main focus, attracting far more attention, although the mechanism for permafrost evolution in northeast China is much complex due to its interactions with snow, forest canopy, and wetland. The immediate consequence is that the in-situ observations on permafrost in this region is rare, let alone long-term observations. To fill this gap, we gradually established the ground temperature observing network for permafrost, including 7 boreholes from Mangui to Gen'he, to monitor the permafrost thermal dynamics under the warming climate expected at the beginning. However, in the progress of study, we found that the thermal state of permafrost in northeast China was regulated by the vegetation, snow, and wetland in a complicated way. In addition, the ground temperature in the shallow soil took an apparent decreasing trend (i.e., referred to as permafrost cooling in the manuscript) in the recent years when there is no decreasing trend in the mean air temperature or even when the mean air temperature is warming, which was completely out of our expectation. This "permafrost cooling" also occurred in some experimental sites nearby, e.g., Nanwen station. This phenomenon has never been reported in the last decades and still

remains incompletely understood. More attention should be paid to its mechanisms. Unfortunately, because this phenomenon was totally out of our expectation and the funding was not sufficient enough at the beginning, systematic observing systems aiming at the influences of vegetation, snow, and moisture condition on the permafrost was not established synergistically. We plan to complement some related observation in future and investigate this "permafrost cooling" comprehensively with the help of some physically based models.

Specific comment 3

The data at Gen'he has large missing values (Figure 5, 6), the linear trend was calculated on base of intermittent series that should be not robust.

Response: Indeed, there exists some long periods with missing data at Gen'he, where the data was collected by a data logger (CR3000). In such a harsh environment, the data collecting system is prone to failure. Without GPRS signal at the observing site, we cannot monitor the system status in time and take a repair. Unfortunately, there is no remedy for these missing data. It is reluctant for us make the trend analysis with these missing data. However, at the surface layers, although the fluctuation of ground temperature is relatively huge, the collected data has generally captured the maximal and minimal ground temperature in years with observing data. Simply by a visual inspection, the minimal or maximal ground temperature has an apparent warming trend from 2012 to 2020, which has a good coincidence with the trend analysis in our manuscript. 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 depths greater than 8 m, the annual fluctuation of ground temperature was much less than the surface layers, as shown in Figure 5 and 6. The missing values will not vary too much from the collected values. Therefore, we speculate the influence of missing values on trending analysis for deep layers will be smaller than that in the surface layers, and it will decrease with depth, which can be inferred from Figure 5 and 6.

Specific comment 4

The possible reasons for cooling permafrost in the last decade on the northwestern slope of the Da Xing'anling Mountains should be further investigated, its relations to winter precipitation, snow cover and maximal snow depth are just appearances, how snow affect the soil temperature of permafrost through surface energy budget (e.g., albedo effect, insulation effect, etc.) should be clarified.

Response: Actually, the observed permafrost cooling is out of our expectation at the beginning, and the mechanisms still remains incompletely understood. We speculated that it 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) in this region barely changed, 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 will reduce the solar irradiance incident onto the soil surface in summer and cast a cooling effect on the ground temperature. 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 will be weakened when the snow the depth of snow cover decreased, which will lead to a larger heat removal from the permafrost to air in winter and drive the permafrost cooling. The detail 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.

Specific comment 5

Uncertainties of some quantitative results should be discussed, for example, line 183 "warming at an average rate of 0.004-0.020 °C /yr", its magnitude is much small than the observation error.

Response: Yes, the observed ground temperature by the thermistor has an error within ±0.05 °C when the ground temperature ranges from -30 to +30 °C. However, we cannot conclude that the warming rate is meaningless because its magnitude is smaller than the observing error, because the warming rate was a statistic number derived from a large sample of observation. Its uncertainty should be inferred based on the law of large numbers or central limit theorem, instead of based on the observation error. For example, according to the law of large numbers, the variance of the mean of the distribution of a random variable can be calculated as,

$$Var(\bar{X}_n) = \frac{1}{n^2} Var\left(\sum_{i=1}^{n} X_i\right) = \frac{\sigma^2}{n}$$

where σ^2 is the variance of random variable X_i.

That is, although every single observation of ground temperature by using a thermistor may has an error within ±0.05 °C, the uncertainty of the calculated mean ground temperature was much reduced when the observing sample was large enough, although the magnitude of the mean ground temperature could be very small, i.e., smaller than 0.05 °C. Similarly, we cannot judge the significance of the calculated warming rate by comparing its magnitude directly with the observation error.

For the sake of simplicity, we assume that an ordinary least squares (OLS) estimator was used in the trend analysis, and a general linear regression equation for predicting the ground temperature changing with time could be described as follow,

$$\mathbf{y} = \beta_0 + \beta_1 \mathbf{t} + \boldsymbol{\epsilon}$$

where $\mathbf{y}$ is the ground temperature (°C), and $\mathbf{t}$ is time (d) in this case. β_1 is the regression coefficient, which could stand for the warming rate of ground temperature with time. β_0 is the intercept. $\boldsymbol{\epsilon}$ is the error term.

According to DeGroot and Schervish (2011), the regression coefficient β_1, i.e., the warming rate or trend of ground temperature, could be estimated as,

$$\widehat{\beta_1} = \sum_{i=1}^{n}(y_i - \bar{y})(t_i - \bar{t}) / \sum_{i=1}^{n}(t_i - \bar{t})^2$$

and the variance of β_1, which could be used to weight its uncertainty, could be calculated as,

$$var(\widehat{\beta_1}) = \frac{var(y_i)}{\sum_{i=1}^{n}(t_i - \bar{t})^2}$$

Because the random variables $y_1,...,y_n$ at each observing time are independent and each has variance σ^2,

$$var(\widehat{\beta_1}) = \frac{\sigma^2}{\sum_{i=1}^{n}(t_i - \bar{t})^2}$$

where the σ^2 can be estimated as,

$$\widehat{\sigma^2} = \frac{1}{n}\sum_{i=1}^{n}\left(y_i - \widehat{\beta_0} - \widehat{\beta_1}t_i\right)^2$$

The calculated variances of β_1 at GH4 were listed in Figure 6 as follow, which tells that the uncertainties of warming rate were not great. In addition, significance test has been done for all the trending analysis by using the Man-Kendall method in the revised manuscript, such as Figure r3. Most pvalues are smaller than 0.001.
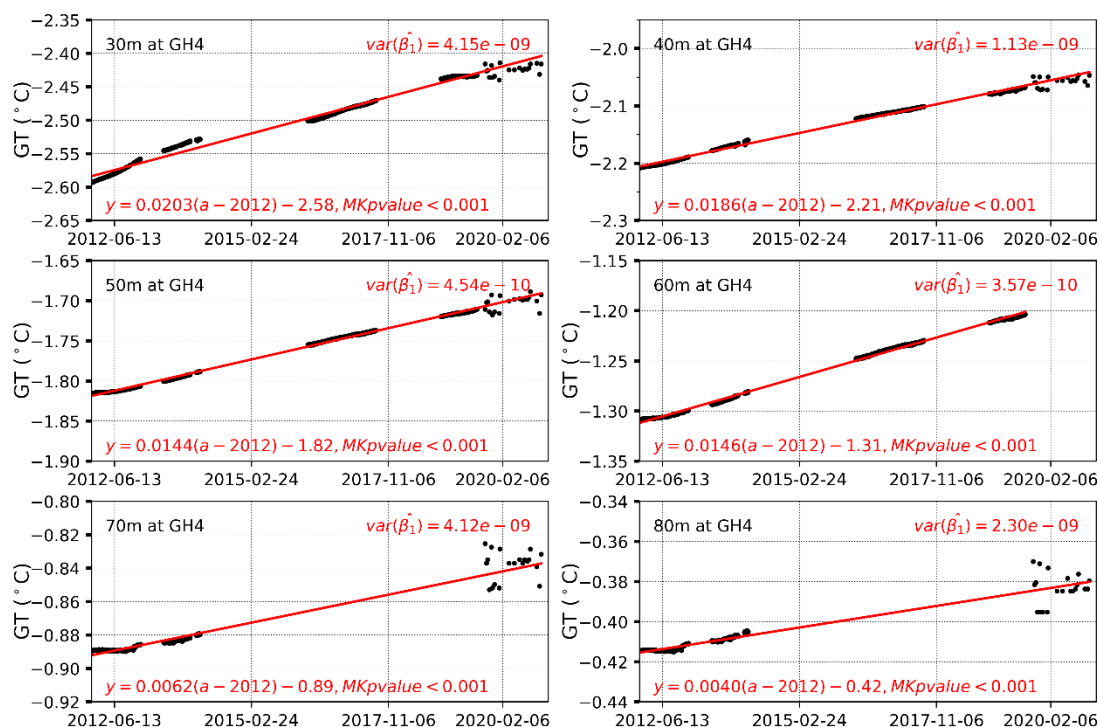

Figure r3 Variability of deep permafrost temperatures at depths of 30 – 80 m for Borehole GH4

References:

DeGroot MH and Schervish MJ. Probability and statistics (4th edition), 2011, publisher: Addison-Wesley, Boston.

Specific comment 6

Linear trend should be made significant test.

Response: Thank you very much. According to your suggestion, we have made the trending analysis by using the Man-Kendall method with significant test done, and p-values are shown in figures in the revised manuscript. Results show that most of the MK p-values for the warming trend of ground temperature are less than 0.001 except for the d) panel in Figure 7, which means that the warming trend of ground temperature are significant although some of the warming rates are a little small in magnitude.

Comment 8 The number of hiatuses in dataset far exceeds the described in the manuscript. Please add the interruption causes, including the sensor changes before and after the interruption (if any).

Response: We are sorry for this mistake. Yes, there are there long hiatuses in the datasets and some short. Actually, there are no sensors change in the entire observation period until CR3000 data logger is totally damaged and the data are collected manually. Except the hiatus between 2014 and 2016, other data interruptions are mainly caused by the problems of power-supply system and expansion board that connects the sensors and data logger. Because there is no GPRS signal at most sites, wireless transmission module was not used in the observing system, and we cannot monitor the system status in time and take a repair. The hiatus between 2014 and 2016 was also caused by the power-supply system, but the system

Comment 9 GH5 and YTLH2 data have repeated the column of date. Does it make a special meaning? Please unify the format of observation data.

Response: Sorry for another mistake. They repeated columns are just a duplicate. We will contact the data center and update the datasets as soon as possible.