Responses to Editor's Comments and Suggestions

(The answers are shown in blue)

Major comment:

The manuscript uses Cheng's (1984) proposed classification system on the grounds that it describes permafrost from an engineering perspective, which many readers would take to mean that there is a relation to load-bearing capacity. Consequently, the thermal stability of permafrost is a function of surficial materials and ground-ice content as much as temperature. Arguably, seasonally frozen ground could be the most stable because there is no ice-rich permafrost to thaw. However, the paper takes a MAAT modelling approach and does not incorporate ground materials. Permafrost borehole data are rare in the study area, and this also impacts appropriateness of the classification system used as it is additionally based on permafrost depths that are also not examined in the paper. From a strictly thermal perspective, the notion that cold permafrost is more "thermally stable" than warm permafrost typically does not hold true. For a given increase in MAAT, MAGT in cold permafrost often responds more quickly than warm permafrost because of relatively low latent heat effects in the former versus the latter. In the extreme case, thawing permafrost appears thermally stable, because heat is used for phase change rather than temperature change and MAGTs appear stable despite being nearly 0 ℃. One wonders how much the statistical relations established by Cheng between MAAT and MAGT have changed since 1984 in this transient environment. Ultimately, the results from the current approach suggest that permafrost everywhere is changing, which implies that all of the permafrost is thermally unstable. Finally, The Cryosphere is an international journal, but those seeking more information on the classification system must be fluent in Chinese (Cheng, 1984), which is somewhat problematic. Given that the modelling approach taken actually focuses on estimating MAAT, and no data on MAGT permafrost depth change, surficial materials, or ground ice are provided, I find it difficult to justify the use of the "permafrost thermal stability" classification scheme. I strongly suggest that the classification system used should be modified to something like "permafrost thermal condition", rather than "permafrost thermal stability". The class types will necessarily change. I suggest something like "Extremely stable" becomes "Very cold", "Stable" becomes "Cold", "Sub-stable" becomes "Cool", "Transitional" becomes "Warm", "Unstable" becomes "Very warm", and "Extremely unstable" becomes "Likely thawing". This change will not affect your results, but will subtly, yet substantially, affect your interpretation and discussion.

Thank you very much. We agree with your comments. Actually, the notion that cold permafrost is more "thermally stable" than warm permafrost typically does not hold true. Field investigation shows that for a given increase in MAAT, MAGT in cold permafrost often responds more quickly than warm permafrost. This process intertwined with the changing geothermal flux makes it is difficult to reflect the thermal stability change using MAAT index. Therefore, we rename the permafrost stability types into thermal condition types include very cold, cold, cool, warm, very warm, and likely thawing types in this paper, according to your very insight and helpful suggestion. Throughout the entire manuscript include figures and tables are revised based on the thermal condition classification system and your specific comments. We have included the revised version of the manuscript and a word track document showing the specific changes made in the manuscript.

Specific comments:

Title: Becomes something like: Climate warming over the past half century has led to thermal degradation of permafrost in the Qinghai-Tibet Plateau"

Thank you. Great! Good title. It is used in the revised manuscript.

P1 L10-13: Becomes "Air temperatures increases thermally degrade permafrost, which is important for engineering design…"

Thank you. This has been modified in the revised manuscript.

P1 L13: "This study evaluates the degradation of permafrost stability over the…" becomes "This study evaluates the potential thermal degradation of permafrost over the…"

Thank you. This has been modified in the revised manuscript.

P1 L15: "MAATs taken at 152 weather stations using geographically" becomes "MAAT date from 152 weather stations with a geographically"
Thank you. This has been modified in the revised manuscript.

P1 L17: The abstract needs a sentence about using a classification matrix to convert modelled MAATs to permafrost thermal conditions.
Thank you. A sentence has been added into abstract.

P1 L18: "The total degraded area of stability" becomes "The total area of thermally degraded permafrost"
Thank you. This has been modified in the revised manuscript.

P1 L18-21: I suggest rounding all reported percentages to 1 decimal place. Also important to note the area of permafrost that likely has not changed.
Thank you. This has been modified.

P1 L24: Oxford comma after "161 m"
Thank you. This has been modified.

P1 L25: "degradation has led" becomes "degradation may lead"
Thank you. This has been modified.

P1 L29: "materials that include ice or organic material and remains at or below" becomes "materials, including ice or organic material, that remain at or below"
Thank you. This has been modified.

P1 L30 to P2 L2: "Temperature rise … often expressed as the degradation of permafrost thermal stability, which" becomes "An increase in air temperatures often thermally degrades permafrost, which"
Thank you. This has been modified.

P2 L13-22: Change to " At Xidatan, near the city of Golmud (Figure 1) at the northern boundary of permafrost adjacent to the Qinghai-Tibet Railway (QTR), the lower elevation limit of permafrost moved upward ~ 25 m from 1975 to 2002 (Nan et al., 2003). On northern and southern slopes of the Bayan Har Mountains (Figure 1), the lower elevation limits of discontinuous permafrost have moved

upward ~ 90 m and ~ 100 m, respectively, from 1991 to 2010 (Lou et al., 2012). On the southern side of the Tanggula Mountains (Figure 1), climate change and infrastructure development have resulted in permafrost degradation; from 2006 to 2012, permafrost temperatures at 10 m depth have increased by 0.03 ℃ in undisturbed areas and 0.06 ℃ beneath an embankment, and respective active layers have deepened by 0.29 m and 0.41 m. (Sun et al., 2014)."
Thank you. This has been modified.

P2 L25 to P3 L27: These paragraphs are difficult to follow, in comparison with much of the text in the rest of the document that reads easily and in a logical order. This section is the cornerstone of your research justification/ gap analysis, needs to be re-written so that it is concise and clear. For example, P3 L19-25 seems out of place and vague, and the line about MAAT as an index should be included somewhere in the text near to where it is first used (P2 L10). Currently, this section (P2 L25 to P3 L27) makes it clear to the reader that the point of the research exercise is to model changes to MAAT over time, but the revised version should emphasize that the objective of the study is to use these estimates to evaluate potential for thermal degradation of permafrost. One piece of the puzzle that also needs to beadded is the relation of LST to MAST to MAAT. The acronym for mean annual land surface temperature (MAST) is defined in the abstract, but must also be defined in the body of the manuscript. MAST pops up on P5 L10, but has not been discussed in the background section. Please carefully revise this section and include phrases that link the ideas together for the reader. E.g., "Naturally, these boundaries are continuous, inexact representations of the permafrost distribution and permafrost degradation (Yang et al., 2010). Ran and Li (2016) assessed the degradation of permafrost stability in China over the past 30 years; however, this study used a near-surface air temperatures reanalysis data set with low resolution and large uncertainties." could be re-written as "However, such boundaries are continuous, inexact representations of the permafrost distribution and permafrost degradation (Yang et al., 2010). As an alternative, Ran and Li (2016) used spatially distributed near-surface air temperature reanalysis data to assess spatial variation in the degradation of permafrost stability in China over a 30-year period, but the data set has a low resolution and large uncertainties."
Thank you very much. We have re-written this section according to your very helpful comment in the revised manuscript.

P3 L11: As defined in the current text, "permafrost stability" types are based on MAGT and permafrost thickness as much as air temperature, but because long-term measurements of MAGT and permafrost thickness are not available to test your predictions on changes over the study period, any discussion of changes to permafrost stability are purely speculative. This highlights why the idea of "permafrost thermal stability" should be modified to something like "permafrost thermal condition".
Thank you very much. We have modified this.

P3 L 29: "the degradation of permafrost stability" becomes " the potential thermal degradation of permafrost"
Thank you. This has been modified.

P4 Section 2.1: This section needs careful revision based upon the major comment. Invoking the term "engineering perspective" is actually not helpful because it is not clear what that perspective is. The way the manuscript reads, permafrost change is described by a spatially distributed perspective, rather than a boundary perspective, evaluating the change in area of the different permafrost classes and the spatial heterogeneity of the changes.

Thank you. We have modified this according to your very helpful comments.

P4-5 Sections 2.2:and 2.3 Everywhere that mathematical notation occurs within the text it is raised. It should be in line. E.g., “yi” should be “yi”. Equation numbers should be in line with the equation. Variables that are in-line with text should also be Italicized. E.g., “yi”. should be “yi”. See other TC articles for presentation examples.
This has been corrected in the revised manuscript.

P5 L10: First use of MAST in text, but variable not defined and acronym not explained
Thank you. This has been modified.

P5 L24-25. This sentence does not make sense, and has phrases that seem repetitive. Please re-write for clarity.
Thank you. This has been modified.

P5 L27: Section title becomes “Evaluation of the rate of permafrost thermal degradation”.
Thank you. This has been modified.

P5 Section 2.3: Please separate the any text regarding “warming rate” and text regarding “degradation rate”. These two calculations are mixed together and should be divided for clarity. I am not sure that you even need to write out the numerical model for a linear regression, but if you do, you need to repeat it for calculations regarding the degradation rate as the model variables are different. Currently the text only defines variables related to calculating warming rates.
Thank you. I think the numerical model for a linear regression is not need to write out. So I removed the equation.

P5 L28:”The following linear regression model…50 years:” becomes “A linear regression model was used to evaluate rates of MAAT change in the QTP over the past 50 years:”
Thank you. This has been modified.

P6 L3: Do not assign the variable Y to two factors. Refer to MAAT here and then edit text near L 11 to indicate linear regression model is used again, but to look at permafrost area changes.
Thank you. This has been modified.

P6 L6-7: insert a space between < or > and the number.
Thank you. This has been modified.

P6 L10: “calculate” becomes “determined” and “decades and the rate of change” becomes “decades and calculated the rate of change”
Thank you. This has been modified.

P7 L10: “Data Center in Lanzhou” becomes “Data Center, Lanzhou”
Thank you. This has been modified.

P8 L13: “Landsat TM/ETM+” becomes “ Landsat Thematic Mapper (TM) or ETM+”\
Thank you. This has been modified.

P9 L3: Change subtitle to something like “Potential thermal degradation”
Thank you. This has been modified.

P9 L4-5: This line clearly states the objective of the analysis, and should be modified and worked into the final statements within the Introduction, somewhere near P1 L26.
Thank you. This has been modified.

P9 L6: Change subtitle to something like “Temporal dynamics of thermal degradation”
Thank you. This has been modified.

P9 L7: “The permafrost thermal stability has degraded” becomes Permafrost has thermally degraded”
Thank you. This has been modified.

P9 L20: subtitle becomes something like “Spatial variation of thermal degradation”
Thank you. This has been modified.

P10 L7-9: “The area of permafrost … 12 104 km2 (12.02%).” Becomes “Permafrost stability did not change over a 12 104 km2 (12.02%) located primarily east of Lhasa in the southeastern part of QTP where there are numerous marine glaciers and substantial snow cover (Figure 4j).”
Thank you. This has been modified.

P10 L10 “stability of approximately 1.63 104 km2 of permafrost increased” becomes “stability of a permafrost area of has increased”
Thank you. This has been modified.

P10 L12: “may have large uncertainties; the uncertain MAAT” changes to “may relate to large uncertainties as the MAAT”
Thank you. This has been modified.

P10 L13: “low-elevation areas, due to the lack of” becomes “low-elevation areas. This is because of the lack of”
Thank you. This has been modified.

P10 L15: “than those of the MAAT” becomes “than those of actual MAAT”. You do mean real measurements here, correct?
Thank you. Here, I mean the MAAT itself.

P10 L22: Subtitle becomes something like “Relation of variation of thermal degradation to elevation”
Thank you. This has been modified.

P10 L24: “the elevation” becomes “the mean elevation”
Thank you. This has been modified.

P11 L13: “The permafrost distribution is also very similar to that presented by Zou et al., (2016) … approximately 0.82.” becomes “The permafrost distribution is also very similar (consistency is 92%;

kappa coefficient is 0.82) to Zou et al. (2016) (Figure 5b). Note: There are numerous places in the text that can be shortened in such a manner. Please try to shorten the amount of text in the revised manuscript.
Thank you. This has been modified. We also try to shorten the text manuscript.

P11 L26: "the degradation" becomes "permafrost thermal degradation"
Thank you. This has been modified.

P12 L9: "approximately a hundred metres" becomes "~ 100 m".
Thank you. This has been modified.

P12 L24-26: This sentence hints at the type of class that should be used in the manuscript.
Thank you. All of this description and discussion have been change based on the new type name.

P14 L4: As this … deep layers of soils" becomes "In order to reduce the uncertainties, more field data are required, especially from boreholes."
Thank you. This has been modified.

P14 L 4-5: This doesn't make any sense. How will inexpensive sensor and machine learning methods help obtain data from deep layers of soil? Boreholes are needed.
Thank you. We removed this sentence.

P14 L5-7: Comment: if you want to estimate permafrost stability/sensitivity to thermal disturbance in the future, you will need to think about incorporating data on surficial geology and ground ice.
Thank you. We have rewritten this.

Universal comments:
Change symbology for denominators. E.g., /x becomes x-1, or /a becomes a-1. This affects text in the main body, tables, figures, and captions.
Thank you. This has been modified.

Comments on tables:
From our Manuscript preparation guidelines for authors (https://www.the-cryosphere.net/for_authors/manuscript_preparation.html): Horizontal lines should normally only appear above and below the table, and as a separator between the head and the main body of the table. Vertical lines must be avoided.
Thank you. This has been modified.

Table 1: as the focus of the paper is on MAAT, move the MAAT column in front of the MAGT column. Types should reflect the classes that you actually model.
Thank you. This has been modified.

Table 2: Text in table head does not need to be bolded.
Thank you. This has been modified.

Table 3: The type will likely change, but as it stands, "remely stable" becomes "Extremely stable".

Text in table head does not need to be bolded.
Thank you. This has been modified.

Climate warming over the past half century has led to ~~the~~thermal degradation of permafrost ~~stability~~ in ~~the past half century over~~ the Qinghai-Tibet Plateau

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Abstract. ~~Temperature~~Air temperatures increases ~~cause a unique type of damage to~~thermally degrade permafrost~~. This damage is often expressed as the degradation of permafrost thermal stability~~, which is very important for engineering design, resource development, and environmental protection in cold regions. This study evaluates the potential thermal degradation of permafrost~~ stability~~ over the Qinghai-Tibet Plateau (QTP) from the 1960s to the 2000s using estimated decadal mean annual air temperatures (MAATs) by integrating remote sensing-based estimates of mean annual land surface temperatures (MASTs), leaf area index (LAI) and fractional snow cover values, and decadal mean ~~MAATs taken at~~MAAT date from 152 weather stations ~~using~~with a geographically weighted regression (GWR). The results reflect a continuous rise of approximately 0.04 ~~°C/a~~°Ca^{-1} in the decadal mean MAAT values over the past half century. ~~Climate~~ A thermal condition classification matrix is used to convert modelled MAATs to permafrost thermal type. Result shows that the climate warming has led to a ~~reduction in~~thermal degradation of permafrost ~~stability~~ in the past half century. The total area of thermally degraded ~~area of stability~~permafrost is approximately 153.76×10^4 km^2, which corresponds to ~~87.98~~88% of the permafrost area in the 1960s. The ~~stability~~thermal condition of 75.~~24~~2% of the ~~extremely stable~~very cold permafrost, 89.~~56~~6% of the ~~stable~~cold permafrost, 90.3% of the ~~sub-stable~~cool permafrost, 92.~~31~~3% of the ~~transitional~~warm permafrost, and 32.8% of the ~~unstable~~very warm permafrost has been ~~reduced~~degraded to lower levels of ~~stability.~~thermal condition. Approximately 49.4% of the ~~unstable~~very warm permafrost and ~~95.95~~96% of the ~~extremely unstable~~likely thawing permafrost has degraded to seasonally frozen ground. ~~The sensitivity of the permafrost to climate is dependent on its stability level.~~ The mean elevations of the ~~extremely stable, stable, sub-stable, transitional, unstable~~very cold, cold, cool, warm, very warm, and ~~extremely unstable~~likely thawing permafrost areas increased by 88 m, 97 m, 155 m, 185 m, 161 m, and 250 m, respectively. The degradation mainly occurred from the 1960s to the 1970s and from the 1990s to the 2000s. This degradation ~~has led~~may lead to increases in risks to infrastructure, increased flood risks, reductions in ecosystem resilience, and positive climate feedback effects. It therefore affects the well-being of millions of people and sustainable development at the Third Pole.

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1 Introduction

Permafrost is defined as earth materials~~ that include~~, including ice or organic material~~ and remains~~, that remain at or below 0 ℃ for at least two years (Permafrost Subcommittee, National Research Council of Canada. 1988; Williams et al., 1989). ~~Temperature rise causes a unique type of dynamic damage to permafrost (Zhu et al., 2016). This damage is often expressed as the degradation of permafrost thermal stability~~An increase in air temperatures often thermally degrades permafrost, which is very important for engineering design, construction, resource development, the carbon and water cycles, and ecological protection in cold regions (Collett, 2002; Cheng and Wu, 2007; Tarnocai et al, 2009; Schuur et al, 2009; Schaefer et al, 2011; Hinzman et al., 2013; Mu et al., 2015~~).~~; Zhu et al., 2016). In terms of middle- and high-elevation permafrost regions, the area of permafrost in the Qinghai-Tibet Plateau (QTP) is the largest in the world. The permafrost in the QTP experiences higher temperatures than those observed in Siberia and the Arctic, which are more sensitive to global climate warming and human activity (Wu et al., 2002; Haeberli and Hohmann, 2008; Li et al., 2008; Ran et al., 2012; Ran and Li, 2016).

Monitoring and simulation show that substantial permafrost degradation is occurring on the QTP. For example, the mean annual air temperature (MAAT) increased by approximately 0.2~0.4 ℃ from the 1970s to the late 1990s (Wang et al., 2000). From 1961–2010, the decadal average MAAT rose by 1.3 ℃, with an average rate of increase of 0.03 ~~℃/a~~℃a^{-1} (Jin et al., 2011; Ran and Li, 2016). From 1996 to 2001, the thickness of the active layer increased by 0.15~0.50 metres, and the mean annual ground temperature (MAGT) rose by 0.1–0.5 ℃ in the past 30 years (Yang et al., 2010). At Xidatan, ~~which is ~~near the city of Golmud ~~and~~(Figure 1) at the northern boundary of ~~the ~~permafrost ~~on the QTP along~~adjacent to the Qinghai-Tibet Railway (QTR), the lower elevation limit of permafrost ~~(the lowest elevation of permafrost occurrence) ~~moved upward ~~by approximately~~~ 25 m from 1975 ~~through~~to 2002 (Nan et al., 2003). ~~The lower limit of permafrost on the~~On northern and southern slopes of the Bayan Har Mountains~~, where a region~~ (Figure 1), the lower elevation limits of discontinuous permafrost ~~occurs in the southern part of Qinghai Province,~~have moved upward ~~by approximately~~~ 90 m and ~ 100 ~~metres and 90 metres~~m, respectively, from 1991 to 2010 (Luo et al., 2012). ~~During 2006 to 2012, on~~On the southern side of the Tanggula Mountains ~~permafrost region along the QTR, both the engineered structures and ongoing~~(Figure 1), climate change ~~caused the~~ and infrastructure development have resulted in permafrost degradation~~ to accelerate. For the areas of~~; from 2006 to 2012, permafrost temperatures at 10 m depth have increased by 0.03 ℃ in undisturbed ~~permafrost~~areas and ~~permafrost under~~0.06 ℃ beneath an embankment, ~~the~~and respective active ~~layer~~layers have deepened by 0.29 m and 0.41 m~~, and the ground temperature at a depth of 10 m rose by 0.03 ℃ and 0.06 ℃, respectively~~ (Sun et al., 2014). Cheng et al. (2012) reported on the decadal changes in permafrost distribution on the QTP over the past 50 years (1960–2009) and demonstrated that the rate of permafrost loss had accelerated since the 1980s, and about one-fifth of the total area of permafrost that existed in the 1960s has degraded.

However, many of these studies focus on either the local or in situ scales, and few studies have focused on the regional scale. Although the decadal changes in the permafrost distribution over the QTP were simulated by Cheng et al. (2012), this study

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emphasized the migration of permafrost "boundaries" ~~based on the relation between air temperature and the lower limit of the permafrost. Naturally, these~~. However, such boundaries are continuous, inexact representations of the permafrost distribution and permafrost degradation (Yang et al., 2010). As an alternative, Ran and Li (2016) ~~assessed the degradation of permafrost stability in China over the past 30 years; however, this study~~ used ~~a~~spatially distributed near-surface air temperature reanalysis ~~dataset with~~data to assess spatial variation in the thermal degradation of permafrost in China over a 30-year period, but the data set has a low resolution and large uncertainties. These studies are not comprehensive and do not adequately reflect changes in the thermal state of the permafrost, especially in the interior of permafrost zones ~~and at high spatial~~. Therefore, the thermal state of permafrost should be evaluated with a higher resolution~~. Additionally, regional-scale evaluations usually rely on meteorological~~ at a longer period than previous studies. However, the evaluation is general limited by the sparse data. ~~The~~Of the most commonly used ~~variable is air temperature, but~~index, i.e. MAAT and MAGT, the MAGT is the most direct indicators of the thermal state of permafrost (Cheng, 1984); however, long-term measurements of ~~this quantity are sparse on the QTP.~~the MAGT is almost impossible due to the high cost of drilling boreholes. Although the potential problems of the MAAT in predicting permafrost degradation are well known, for example, the performance of the MAAT model is generally affected by the thermal inertia of deep soil layers and geothermal flux (Smith and Riseborough, 2002; Jin et al., 2006; Wu et al., 2010a~~sparse air temperature~~), the MAAT is easy to measure and has high spatial representativeness. Importantly, long-term in situ measurements ~~are~~of MAATs are available. However, the MAAT measurement stations are sparse on the QTP, especially in the western part of QTP. The sparse MAAT measurements was interpolated onto grids based on digital elevation models (DEMs~~),~~) in previous studies, the uncertainty of the gridded ~~air temperatures~~MAAT is significant because of the heterogeneity of the surface characteristics, including snow cover and vegetation, and the locations of weather stations (Vancutsem et al., 2010).

Fortunately, the remote sensing era has led to changes in this situation. Thermal infrared remote sensing provides direct observations of land surface temperatures (LSTs) at high spatial and temporal resolutions. For example, the Moderate Resolution Imaging Spectroradiometer (MODIS) LST product is freely available and has been validated over large areas via a series of field campaigns. Its accuracy is better than 1 ℃ (0.5 ℃ in most cases) (Wan et al, 2002; 2004; 2008). Remote sensing-based estimates of LSTs provide a key high-resolution temperature pattern of the land surface that can potentially be used in monitoring permafrost degradation; however, criteria for using LST estimates to distinguish permafrost types are not traditionally available, and the relatively short time series of LST data does not meet the needs of long-term permafrost monitoring. ~~Of the three commonly used predictors for permafrost, the MAGT and permafrost thickness are the most direct indicators of the thermal stability of permafrost (Cheng, 1984); however, long-term measurements of the MAGT and permafrost thickness are almost impossible due to the high cost of drilling boreholes. The MAAT is frequently used in mapping the distribution of permafrost. It is easy to measure and has high spatial representativeness. Importantly, long-term in situ measurements of MAATs are available, and it is possible to estimate MAATs over the QTP using remote sensing-based methods. Therefore, the remote sensing-based LST values can be converted to MAATs and used to monitor the permafrost thermal state, although the potential problems of the MAAT model in predicting permafrost degradation are~~

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well known. For example, the performance of the MAAT model is generally affected by the thermal inertia of deep soil layers and geothermal flux (Smith and Riseborough, 2002; Jin et al., 2006; Wu et al., 2010a).

Several previous studies have demonstrated the high correlation between satellite-based LST and near surface air temperature and the potential of satellite-based methods in estimating near-surface air temperatures (Hachem et al., 2009; 2012; Vancutsem et al., 2010; Yao and Zhang, 2013).; Ran et al., 2015). The variation in the uncertainty is mainly related to the underlying surface type such as snow cover and vegetation, the amount of solar radiation, and cloud cover (Henderson-Sellers and Hughes, 1982; Zhang, 2005; Vancutsem et al., 2010; Lawrence et al., 2011; Hachem et al., 2012; Ran et al., 2015). Additionally, the highly accurate remote sensing-based snow cover and vegetation products are also available. All of theseOverall, the high resolution remote sensing-based data products are very important for estimating the MAAT, which is an air temperature index used in monitoringLST and the thermal stability oflong-term in situ MAAT measurement can be integrated to monitor the permafrost. thermal state.

Therefore, the objective of this study is to evaluate the thermal degradation of permafrost stabilityincluding temporal changes, spatial changes in the map plane, and spatial changes with elevation over the QTP from 1960 to 2010 by integrating multi-criterion remote sensing observations and an air temperature observation network.

2 Methods and Datasets

In this study, the potential thermal degradation of permafrost stability is evaluated based on the MAAT model and the improved MAAT data over the QTP in the past half century. The MAAT in situ measurement data at 152 sites over the QTP and remote sensing data with six independent variables were combined using a Geographically Weighted Regression (GWR) model to estimate the MAAT with a 1 km resolution over the QTP during the past five decades.

2.1 Permafrost thermal stabilitycondition classification system

We use the thermal stabilityIn this study, a permafrost thermal condition classification system is used. That is defined according to the high altitude permafrost zonation proposed by Cheng (1984). In thisCheng's system, permafrost is classified into extremely stable, stable, sub-stable, transitional, unstable, and extremely unstable types, as shown in Table 1. This system is more useful to describe permafrost degradation from an engineering perspective, rather than changes in the extent of permafrost. The MAAT criterion is available in this system to assess the stability types. On the QTP, a MAAT of −2 °C has typically been used to distinguish permafrost from seasonally frozen ground (Cheng, 1984; Ran and Li, 2016). The permafrost stability. The system was proposed based on the MAGT measurement as an index by analysis of the three-dimensional zonation of the high elevation altitude permafrost (vertical, latitudinal, and aridity). It is a high level summary of high altitude permafrost zonation. The MAAT index was given according to the statistical relation between MAGT, elevation, and the in situ MAAT measurement (Cheng, 1984). However,On the QTP, a MAAT of −2 °C has typically been used to distinguish permafrost from seasonally frozen ground (Cheng, 1984; Ran and Li, 2016). The extremely unstable type in the thermal stability classification system proposed by Cheng (1984) refers to regions that include cave ice and frozen gravel below the lower limit of permafrost, which is a very scattered distribution. In this paper, a MAAT of −1 °C is simply used to distinguish extremely unstable permafrost from seasonally frozen groundHowever, the thermal stability of permafrost is a function of surficial materials and ground-ice content as much as temperature. From a strictly thermal perspective, the notion that cold permafrost is more "thermally stable" than warm permafrost typically does not hold true. From a changing stability perspective, for a given increase in MAAT, MAGT in cold permafrost often responds more quickly than warm permafrost because of relatively low latent heat effects in the former versus the latter. In the extreme case, thawing permafrost appears thermally stable, because heat is used for phase change rather than temperature change and MAGTs appear stable despite being nearly 0 °C. This process intertwined with the changing geothermal flux makes it is difficult to reflect the thermal stability change using MAAT index, as a thermal condition. Therefore, we rename the permafrost stability types into thermal condition types include very cold, cold, cool, warm, very warm, and likely thawing types in this paper, as shown in Table 1. This system is more useful to describe permafrost degradation from a spatially distributed perspective, rather than a boundary perspective. Additional, a MAAT of −1 °C is simply used to distinguish likely thawing permafrost from seasonally frozen ground in this paper.

2.2 Simulation of MAAT using geographically weighted regression

In this study, geographically weighted regression (GWR) is used to simulate MAATs. Local parameters are employed in the GWR model to estimate MAATs while considering the spatial locations of meteorological stations (Brunsdon et al., 1998; Kumar et al., 2012). The weighting is a function of the distance between the location of each regression point and the sites where observations are available. The GWR model used in the present study is shown below in Equation (1):

$$y_i = \beta_0(\mu_i, \upsilon_i) + \sum_{k=1}^{m} \beta_k(\mu_i, \upsilon_i) x_{ik} + \varepsilon_i$$

$$y_i = \beta_0(\mu_i, \upsilon_i) + \sum_{k=1}^{m} \beta_k(\mu_i, \upsilon_i) x_{ik} + \varepsilon_i \quad (1)$$

where y_i y_i is the MAAT at pixel *i*, x_{ik} x_{ik} is the k^{th} explanatory factor at pixel *i*, $\beta_0(\mu_i, \upsilon_i)$ $\beta_0(\mu_i, \upsilon_i)$ and $\beta_k(\mu_i, \upsilon_i)$ $\beta_k(\mu_i, \upsilon_i)$ represent the intercept and slope for the k^{th} explanatory factor, m is the number of explanatory factors, and ε_i ε_i is the residual term.

The quantities $\beta_0(\mu_i, \upsilon_i)$ $\beta_0(\mu_i, \upsilon_i)$ and $\beta_k(\mu_i, \upsilon_i)$ $\beta_k(\mu_i, \upsilon_i)$ are estimated using Equation (2):

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~~$\hat{\beta}(\mu_i, \upsilon_i) = (X^T W(\mu_i, \upsilon_i) X)^{-1} X^T W(\mu_i, \upsilon_i) Y$~~

$$\hat{\beta}(\mu_i, \upsilon_i) = (X^T W(\mu_i, \upsilon_i) X)^{-1} X^T W(\mu_i, \upsilon_i) Y \qquad (2)$$

where ~~$\hat{\beta}(\mu_i, \upsilon_i)$~~ $\hat{\beta}(\mu_i, \upsilon_i)$ is an unbiased estimation of the regression coefficients. It is a vector that includes an intercept and *m* regression coefficients associated with *m* explanatory factors, i.e., the 6 independent variables selected by a stepwise linear regression analysis (see below). ~~X~~ X is a matrix of explanatory factors (~~$n \times m$~~ $n \times m$); ~~$W(\mu_i, \upsilon_i)$~~ $W(\mu_i, \upsilon_i)$ is the spatial weight matrix, which is a diagonal matrix; ~~Y~~ Y is a vector (~~$n \times 1$~~ $n \times 1$) for the dependent variables, i.e., the decadal mean MAAT in the 1960s, 1970s, 1980s, 1990s, and 2000s; and n is the number of MAAT observation stations for each year.

In this study, the Gaussian function is used as a spatial weighting function, as shown in Equation (3):

~~$W(\mu_i, \upsilon_i) = \exp(-\frac{1}{2}(\frac{d_i}{r})^2)$~~

$$W(\mu_i, \upsilon_i) = \exp(-\frac{1}{2}(\frac{d_i}{r})^2) \qquad (3)$$

where ~~d_i~~ d_i is the distance between the *i*th observation station and the point to be estimated, and *r* is the bandwidth parameter. To accommodate different station densities, the corrected Akaike information criterion (AICc) is used to determine the optimal bandwidth parameters.

A stepwise linear regression analysis is used to select the independent variables for the GWR model (Table 2). The analysis shows that the use of the ~~MAST,~~mean annual land surface temperature (MAST), the leaf area index (LAI), the fractional snow cover (FSC), elevation, latitude, and longitude as independent variables results in the highest degree of explanatory power for the past five decades, and the significance level is less than 0.0001. The variance inflation factor (VIF) is used to assess the multicollinearity of the model. A VIF value <1.5 shows that the degree of tolerance is high, and the multicollinearity of the model is thus acceptable. The performance of the GWR model in the 2010s is shown in Table 2. The five GWR models are then used to estimate the decadal mean MAAT over the QTP for the past five decades. The SAGA (System for Automated Geoscientific Analyses) (Conrad et al., 2015) is used to implement the GWR. Specifically, the GWR for multiple predictor grids geoprocessing tool is used. The Gaussian weighting function and the global search range are used.

Due to the unavailability of the vegetation, snow cover, and LST datasets during the 1960s to 2000s, the effect of the dynamics of vegetation, snow cover, and LST on MAAT during this period is unknown. This will inevitably cause some errors in the estimation of MAAT. Recent studies show that vegetation is increasing overall during the past 30 years, and the

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snow cover is decreasing overall during the past 15 years over the QTP (Wang et al., 2016; Huang et al., 2017). The effect of vegetation and snow cover change on MAAT and its feedback process is highly complex. For example, the vegetation-snow interaction effect on MAAT is related to humidity (Zhong et al., 2010; Wang et al., 2013; Wu et al., 2015; Yuan et al., 2017). However, we believe this error mainly occurs at the local level in the nature vegetation dominated areas ~~where the change has occurred at the local level within the last 50 years~~ (Wang et al., 2016; Huang et al., 2017), and it can be partially compensated by the in situ time series MAAT measurement over the QTP for the past 50 years.

2.3 Evaluation of the ~~degradation~~rate of permafrost thermal ~~stability~~degradation

~~The following~~A linear regression model is used to evaluate the ~~warming rate or degradation rate~~ rates of MAAT change in the QTP over the ~~QTP in the~~ past 50 years~~:~~

~~$Y = a + bx + \varepsilon$ (4)~~

~~where Y denotes the MAAT or permafrost area, x is the time, ε is the error, a is the intercept, and b is the slope (i.e., the warming rate or degradation rate).~~. The statistical significance ~~of the warming rate or degradation rate~~ is evaluated using Student's *t*-test.

Thirteen elevation ranges (< 3600 m, 3600-3800 m, 3800-4000 m, 4000-4200 m, 4200-4400 m, 4400-4600 m, 4600-4800 m, 4800-5000 m, 5000-5200 m, 5200-5400 m, 5400-5600 m, 5600-5800 m, and > 5800 m) are used to evaluate the elevation dependence of the warming rate.

The degradation of permafrost thermal ~~stability~~condition is evaluated from two perspectives, the change in area of the different ~~thermal stability~~ permafrost types and the spatial heterogeneity of the change. For the area change, we ~~calculate~~determined the total area of each ~~thermal stability~~permafrost type during the past five decades and calculated the rate of change (i.e., the degradation rate) using the linear regression model ~~shown in Equation (4)~~.. The spatial pattern of the degradation of permafrost thermal ~~stability~~condition is evaluated at two levels. At the pixel level, the spatial distribution of the degradation is evaluated. At the level of the ~~thermal stability~~permafrost types, a transfer matrix is used to evaluate the conversions among the ~~thermal stability~~ types (Stehman, 1997). We also analyse the changes in the elevation histograms for each ~~thermal stability~~permafrost type in the past 50 years.

2.4 Datasets

2.4.1 Mean annual land surface temperature

MODIS Terra/Aqua daytime and nighttime LST products (MOD11A1 and MYD11A1, version 5) with a spatial resolution of 1 km and covering 2006 to 2010 were acquired from the Distributed Active Archive Center (DAAC) operated by the U.S. National Aeronautics and Space Administration (NASA). These data are used in this study to estimate MASTs. A pragmatic approach proposed by Ran et al. (2015; 2017) is employed to estimate the MASTs using the four daily MODIS LST

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products. This approach assumes that the arithmetic average of the daytime and nighttime LSTs represent the daily mean LST with acceptable accuracy, and the daily amplitude of LST is more homogeneous than the LST itself (Liu et al., 2006; Kogan et al., 2011; Ran et al., 2015). The approach allows the full use of every value at any time in any pixel of the MODIS LST products through the use of the temporally and spatially complete LST daily amplitude, which is interpolated using a gap filling algorithm (Garcia, 2010). This algorithm employs a penalized least squares regression based on discrete cosine transforms that explicitly utilize information from a time series to predict the missing values. The penalized least squares regression is a thin-plate spline smoother for a generally one-dimensional data array, and it can trade off fidelity to the data versus the roughness of the mean function (Garcia, 2010; Wang, et al., 2012). This approach is easy to implement and independent of other observations. Validation shows that the scheme is effective in restoring the missing values in MODIS instantaneous LST observations and produces a spatially and temporally continuous daily average LST dataset that displays good agreement with observations made at the ground surface. The errors in the results originate mainly from the original instantaneous LST MODIS products. A more detailed description of this scheme can be found in Ran et al. (2015; 2017). The temporally and spatially continuous daily mean LSTs from January 1, 2006 to December 31, 2010 and the corresponding MASTs used in this study are produced using the above approach.

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2.4.2 Fractional snow cover

Arithmetic mean values of daily cloud-removed FSC products from 2006 to 2010 are used in this study. This product is derived from the daily MODIS 500-m snow cover product (MOD10A1) using a gap filling process based on a cubic spline interpolation algorithm. A comparison with reference FSC data obtained from Landsat Enhanced Thematic Mapper Plus (ETM+) shows the high accuracy with which this product reflects snow cover information over the QTP (Tang et al., 2013). The cloud-removed FSC products were acquired from the Cold and Arid Regions Science Data Center ~~in~~, Lanzhou, China (http://westdc.westgis.ac.cn).

2.4.3 Leaf area index

Annual mean LAI values obtained from the Global Land Surface Satellite (GLASS), which make up a high-quality LAI product with an eight-day temporal resolution and a 1-km spatial resolution and cover the period from 2006 to 2010, are used in this study. The GLASS LAI product is derived from the fused MODIS and CYCLOPES LAI products, and the remaining effects of cloud contamination have been removed using MODIS time series surface reflectance data and general regression neural networks (Xiao et al., 2014). The results of validation show that the GLASS LAI product has a lower uncertainty than the MODIS and CYCLOPES LAI products (Xiang et al., 2014). The GLASS LAI product was acquired from the GLASS project website (http://glass-product.bnu.edu.cn/en).

2.4.4 In situ MAAT observations

The MAAT measurements, which were collected at 131 stations for the 1960s and 1970s, 133 stations for the 1980s, 144 stations for the 1990s, and 152 stations for the 2000s within the QTP and the surrounding area, were acquired from the data centre of the China Meteorological Administration (http://cdc.nmic.cn). The distribution of the 152 stations for the 2000s is shown in Figure 1. The density of stations in the eastern QTP is higher than other years. The decadal mean MAAT values over the past five decades are used in this study.

2.4.5 Validation data

Validation of the long-term ~~stability of~~ permafrost thermal condition is difficult due to the limited amounts of reference data that are available. In this study, we evaluate the results by comparing the estimated permafrost distribution in the 2000s with previous regional-scale permafrost maps and borehole measurements at individual sites. The permafrost maps that cover the QTP from Li and Cheng, (1996), Nan et al. (2002), and Zou et al., (2016) are used at the regional scale. In particular, the map of Zou et al., (2016) integrates the MODIS eight-day LST product within the framework of the temperature at the top of the permafrost (TTOP) model (Smith and Riseborough, 1996), and careful validation of this map has been performed using MAGT data. At the site scale, the MAGT values used in this study were collected from 142 boreholes presented in the existing literature (Yu et al., 2008; Wang et al., 2013; Luo et al., 2013) and the International Permafrost Association (IPA)-International Polar Year (IPY) Thermal State of Permafrost (TSP) Snapshot Borehole Inventory downloaded from the National Snow and Ice Data Center (NSIDC) (http://nsidc.org) (International Permafrost Association, 2010). The distribution of these boreholes is shown in Figure 1.

2.4.6 Ancillary data

The distribution of water bodies in the MODIS land cover product (MOD12Q1) and the map showing the distribution of glacier ice from the second Chinese glacier inventory are used to support the permafrost area statistics. The MOD12Q1 product is used for consistency with the other remote sensing products employed in this study. On the other hand, the glacier extents from the second Chinese glacier inventory are compiled based on Landsat Thematic Mapper (TM~~/~~) or ETM+ images acquired from 2004 to 2011, as well as other ancillary data, such as digital elevation models (DEMs). The robust band ratio segmentation method is first used to delineate the glacier outlines, and intensive manual improvements are then performed to improve its accuracy. An error assessment shows that the area error for all of the glaciers in China is approximately 3.2% (Guo et al., 2015).

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3 Results

Decadal mean MAAT estimates with a 1 km resolution ~~of 1 km~~ over the QTP in the past 50 years are produced using the GWR model. The mean determination coefficient of ~~determination of this~~the model is approximately 0.95. The permafrost stability map in the past five decades is then produced based on the simulated MAAT and the permafrost ~~stability~~ types defined in Table 1.

3.1 Change of MAAT over the QTP in the past 50 years

The MAATs over the QTP have risen continuously in the past 50 years. The mean MAAT values for the 1960s, 1970s, 1980s, 1990s, and 2000s are -2.38 ℃, -1.85 ℃, -1.78 ℃, -1.32 ℃, and -0.58 ℃, respectively. These values reflect a continuous rise with a rate of approximately 0.04 ~~℃/a~~℃ a^{-1}. This value is higher than the global average warming rate, as well as the estimated warming rates for the QTP reported by Cheng et al. (2012) and Ran et al. (2016) that are based on interpolated elevation-based air temperature data or surface air temperature reanalysis data. The warming rate in the western part of the QTP is higher than that in the eastern part and depends on elevation, as shown in Figures 2 and 3. The warming rate increases with increasing elevation from approximately 0.33 ℃ per decade at 3600 m to 0.49 ℃ per decade at 5200 m. This finding is similar to that of previous studies (Liu and Chen, 2000; Qin et al., 2009). The physical mechanisms of this phenomenon may be related to the combined effects of the cloud-radiation and snow-albedo feedbacks (Giorgi et al., 1997; Liu et al., 2009; Pepin et al., 2015). These elevated warming rates may have a substantial impact on the thermal ~~stability~~condition of the permafrost.

3.2 ~~Thermal stability~~Potential thermal degradation

Based on the map of permafrost ~~stability~~ types covering the past five decades (Figure 4a-e), we analyse the degradation from three perspectives, including temporal changes, spatial changes in the map plane, and spatial changes with elevation.

3.2.1 Temporal dynamics of thermal ~~stability~~degradation

~~The permafrost thermal stability~~Permafrost has thermally degraded continuously over the past 50 years. The area occupied by the ~~stable~~cold types has decreased continuously, and the area occupied by the ~~unstable~~very warm types has increased continuously (Table 3). The areas occupied by the ~~extremely stable, stable, sub-stable~~very cold, cold, cool, and ~~transitional~~warm types display net decreases of approximately 8.99×10^4 km^2 (72.79%), 27.06×10^4 km^2 (70.12%), 9.30×10^4 km^2 (27.24%), and 1.18×10^4 km^2 (4.77%) from the 1960s to the 2000s, respectively. In particular, the ~~stable~~cold type displays the most serious degradation, and its rate of loss is approximately 6.15×10^4 km^2 (15.94%) per decade. Moreover, the area occupied by the ~~unstable~~very warm type has increased by approximately 3.99×10^4 km^2 (9.02%) at a rate of 1.06×10^4 km^2 (2.4%) per decade. Specifically, this degradation mainly occurred during the 1960s to 1970s and the 1980s to 1990s for the ~~extremely stable~~very cold type, the 1960s to the 1970s and the 1990s to the 2000s for the ~~stable~~cold type, and the 1980s to the 2000s for the ~~sub-stable~~cool type. The area occupied by the ~~extremely unstable~~likely thawing type has not changed substantially. Overall, the warming climate has caused a degradation of permafrost ~~stability.~~thermal condition. If glaciers and the ~~extremely unstable~~likely thawing type are included, the total permafrost area has decreased significantly from 174.76×10^4

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km^2 in the 1960s to 133.1×10^4 km^2 in the 2000s at a rate of approximately 9.52×10^4 km^2 (5.45%) per decade, and this loss of area occurred mainly during the 1960s to the 1970s and the 1990s to the 2000s (Table 3).

3.2.2 Spatial ~~changes in~~variation of thermal ~~stability~~degradation

The degradation of thermal ~~stability~~condition has occurred over a broad region of permafrost on the QTP within the past 50 years, especially during the 1960s to the 1970s and the 1990s to the 2000s. The degradation of permafrost ~~stability~~ condition in the western QTP was serious during the 1960s to the 1970s. In the subsequent 40 years, the degradation of permafrost ~~stability~~ condition in the QTP was relatively homogeneous (Figure 4f-i). Specifically, the extents of the ~~extremely stable, stable~~very cold, cold, and ~~sub-stable~~cool types retreated from the south to the north (Figure 4a-e). The extents of the ~~transitional, unstable~~warm, very warm, and ~~extremely unstable~~likely thawing types extended northward correspondingly. Approximately 42.30% of the ~~area occupied by the extremely stable~~very cold type, 42.09% of the ~~area occupied by the stable~~cold type, and 39.83% of the ~~area occupied by the sub-stable~~cool type have degraded to the ~~stable, sub-stable~~cold, cool, and ~~transitional~~warm types from the 1960s to the 1970s, respectively. At the same time, approximately 57.26% of the ~~area occupied by the transitional~~warm type, 29.34% of the ~~area occupied by the unstable~~very warm type, and 59.47% of the ~~area occupied by the extremely unstable~~likely thawing type, have degraded to the ~~unstable~~very warm type, ~~the extremely unstable~~likely thawing type, and seasonally frozen ground, respectively. Overall, approximately 75.24% of the ~~area occupied by the extremely stable~~very cold type, 89.56% of the ~~area occupied by the stable~~cold type, 90.3% of the ~~area occupied by the sub-stable~~cool type, 92.31% of the ~~area occupied by the transitional~~warm type, and 32.8% of the ~~area occupied by the unstable~~very warm type have degraded to lower levels of ~~stability~~thermal condition in the past 50 years (Table 4). The reduction in the area ~~occupied by the~~of permafrost is mainly due to the degradation of the ~~area occupied by the unstable~~very warm and ~~extremely unstable~~likely thawing types. Approximately 49.4% of the ~~area occupied by the unstable~~very warm type and 95.95% of the ~~area occupied by the extremely unstable~~likely thawing type has degraded to seasonally frozen ground (Table 4). The total degraded area is approximately 153.76×10^4 km^2, which accounts for 87.98% of the area occupied by the permafrost region in the 1960s (Figure 4j). ~~The area of permafrost for which the stability has~~Permafrost thermal condition did not ~~changed is approximately~~change over a 21×10^4 km^2 (12.02~~%). This area is mainly distributed~~%) located primarily in the central part of the plateau, which contains extremely high mountains, and it is dominated by the ~~extremely stable~~very cold type.

Notably, the ~~stability~~thermal condition of a permafrost area of approximately 1.63×10^4 km^2 has ~~increased~~improved. This area is ~~found~~located primarily east of Lhasa in the southeastern part of ~~the QTP, which is a major centre of~~QTP where there are numerous marine glaciers and substantial snow cover ~~in China~~ (Figure 4j). The ~~increased~~improved permafrost ~~stability~~thermal condition in this area may ~~have~~relate to large uncertainties~~;~~ as the ~~uncertain~~ MAAT trend is estimated using regression parameters that are appropriate for low-elevation areas~~, due to~~. This is because of the lack of long-term MAAT measurements in the high mountain regions where glaciers and snow are prevalent. The effects of snow or glacier cover may

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be more important than those of ~~the~~ MAAT. Although records of long-term snow cover and glacier changes in the past 50 years are not available in this study, the sensitivity of glacier and snow cover in a warming climate is dependent on the climate zone. Low snow–climate sensitivities have been found in continental interior climates with relatively cold and dry winters (Brown and Mote, 2009). Larger glaciers have lower climate sensitivities (Ding and Haeberli, 1996; Ye et al., 2001). Additionally, the complex process and limited knowledge for permafrost-glacier interactions may enhance the uncertainty (Haeberli, 2005; Otto and Keuschnig, 2014). Therefore, we believe the permafrost ~~stability~~thermal condition in this area has not changed substantially in the past 50 years, based on this low climate sensitivity. Of course, these need further investigation in the future.

~~**3.2.3 Elevation changes in permafrost stability type distributions**~~

3.2.3 Relation of variation of thermal degradation to elevation

The elevation statistics of the permafrost type distribution ~~of the permafrost stability types~~ over the QTP in the past five decades indicate that the mean elevation occupied by each permafrost ~~stability~~ type in the QTP has increased continuously (Table 5). For the ~~extremely stable~~very cold type, the mean elevation of the distribution decreased from 5240 m to 5161 m from the 1960s to the 1970s and then rose continuously at a rate of approximately 56.4 m per decade. The reduction in elevation is mainly due to the degradation of the ~~extremely stable~~very cold permafrost type in the Kailas Mountains. This caused the fluctuation of the mean elevation for ~~extremely stable~~very cold permafrost during the 1970s to 1980s and reduced its statistical significance (low R in Table 5) for the increasing rate of mean elevation over the past 50 years. Overall, in the past 50 years, the mean rate of increase of the ~~extremely stable~~very cold type has been approximately 24.7 m per decade. Moreover, the mean elevation of the ~~stable, sub-stable, transitional, unstable~~cold, cool, warm, very warm, and ~~extremely unstable~~likely thawing types have risen at a rate of 23.6 m, 36.3 m, 43 m, 36.5 m, and 56.2 m, respectively. Overall, the mean elevation of the ~~extremely stable, stable, sub-stable, transitional, unstable~~very cold, cold, cool, warm, very warm, and ~~extremely unstable~~likely thawing types increased by 88 m, 97 m, 155 m, 185 m, 161 m, and 250 m, respectively, over the past 50 years. ~~This result indicates that the climate sensitivity of permafrost is dependent on the stability level. The extremely unstable permafrost type is the most sensitive of the permafrost types to climate warming.~~ As in the last section, the degradation mainly occurred from the 1960s to the 1970s and from the 1990s to the 2000s.

4 Discussion

4.1 Cross validation and uncertainty analysis

We validate the permafrost extent only in the 2000s because long-term records of permafrost ~~stability~~thermal condition and extent are not available in earlier periods, as mentioned in section 2.4.5. Comparison of the estimated permafrost extent in the 2000s with the permafrost map provided by Zou et al., (2016) ~~shows~~show that the difference is small. Within permafrost

~~areas~~area, the ~~extremely unstable type of~~likely thawing permafrost type mainly refers to cave ice and frozen gravel, which are distributed below the lower limit of permafrost (Cheng, 1984). This kind of permafrost is usually not counted in the total area of permafrost. Therefore, the permafrost area in the 2000s is approximately 107.19 $\times 10^4$ km^2 if glaciers and lakes are neglected. This result is similar to that of Zou et al., (2016), who showed that the permafrost area in the 2000s was approximately 106.47$\times 10^4$ km^2. The permafrost distribution is also very similar ~~to that presented by Zou et al., (~~(~~2016) (Figure 5b). The~~ consistency ~~between the two distributions~~ is 92~~%, and the~~%; kappa coefficient is ~~approximately~~ 0.82) to Zou et al. (2016) (Figure 5b).~~.~~ At the site scale, 89% of the 142 locations are consistent with the borehole survey, whereas this proportion is only 74%, 28%, and 86% for the maps of Li and Cheng, (1996), Nan et al. (2002), and Zou et al. (2016), respectively. These proportions indicate that the accuracy of the permafrost extent identified in this study is at least comparable with that of Zou et al. (2016).

The uncertainty of the results may result primarily from the MAAT model, insufficient resolution, inaccuracies in the surface station data, or the sparseness of these stations, which are especially sparse in high mountain areas. First, the response time and the depth to which permafrost is affected by climate warming depend on the extents, durations, amplitudes, and rates of climate warming and are closely related to soil types, surface coverage, ice content, groundwater occurrence, geothermal anomalies, and human activities (Stieglitz et al., 2003; Zhang, 2005; Lawrence et al., 2008; Cheng and Jin, 2013; Westermann et al., 2016). For example, the low heat conductivity of soil leads to lags between increases in surface temperatures and the subsequent increases in permafrost temperature or reductions in permafrost thickness (Li et al., 1996). The delay time is longer for permafrost thickness than temperature and varies with the thermal ~~stability type~~condition (Li et al., 1996; Wu et al., 2010a). For the ~~stable type~~cold permafrost, the thermal degradation ~~of permafrost~~ may be delayed by “thermal offset” and “seasonal offset” effects in the permafrost table due to the negative heat budget; i.e., the amount of heat released from the active layer during the winter is greater than the amount of heat absorbed in summer (Smith and Riseborough, 2002; Wu et al., 2010a). For the ~~unstable type~~warm permafrost, a positive heat budget appears in the upper soil layer that leads to a greater degradation rate than that seen in ~~stable~~cold permafrost, since the thickness of the ~~unstable~~warm type is smaller than that of the ~~stable~~cold type (Li et al., 1996; Wu et al., 2010a). However, the complex physical mechanisms of the interactions between climate change and permafrost are currently poorly understood (Jin et al., 2011), and a large degree of uncertainty may exist in previous evaluations as well as the permafrost area change over the past 50 years in this study. Despite current warming, large permafrost areas may persist due to the thermal inertia of permafrost (Cheng et al., 2012). Second, the thawing of the base of the permafrost induced by the geothermal heat flux leads to the permafrost degrading from bottom to top (Jin et al., 2006; Wu et al., 2010a). The MAAT model cannot reflect the change of geothermal flux from the crustal interior. Additionally, the geothermal flux data are generally limited or unavailable. The missing geothermal heat flux may lead to a delay in permafrost degradation, especially for the ~~stable~~cold permafrost, because the geothermal flux is independent of air temperature. Third, although the resolution of the simulation has been significantly improved to 1 km, it is still coarse relative to the degradation rate of mountain permafrost. The degradation of mountain permafrost is presented in terms of the increase in the elevation of the lower limit of the permafrost, which is generally ~~approximately a hundred metres.~~ ~ 100 m. A 1 km

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change in the horizontal extent change may correspond to a change in elevation of hundreds of metres. Last, the lack of long-term MAAT measurements in the glacier- and snow-dominated high mountain regions may lead to errors in the estimated MAATs.

Overall, the "accelerated degradation" effect of the MAAT model may be partly counteracted by the "delayed degradation" effect of the missed geothermal heat flux. Long-term observation shows that the mean increasing rate of ground temperature at 10-20 m depth in the QTP is approximately 0.024 ℃ (Zhao et al., 2010; Wu et al., 2010b; Jin et al., 2011), which is comparable with the warming rate of air temperature. This shows that the evaluation results of permafrost ~~stability~~thermal degradation using the MAAT model is generally accepted at the overall QTP scale.

4.2 The implications of the degradation of thermal ~~stability~~condition

The degradation of permafrost ~~stability~~thermal condition in the QTP has important impacts on the safety of infrastructure in permafrost regions, water quality, ecosystem health, and the feedbacks on regional and global climates. First, as the permafrost ~~stability~~thermal degrades, the risk of deterioration and damage to engineered structures in permafrost zones will increase. This indicates that the measures used to prevent permafrost degradation may need to be enhanced for new structures. For example, permafrost accounted for 90.1% of a 10-km-long segment of the QTR from Golmud to Lhasa in the 1960s, and these permafrost areas were dominated by the ~~sub-stable~~cool type; however, after 50 years (i.e., in the 2000s), these permafrost areas accounted for only 67.77% and were dominated by the ~~unstable~~very warm type. For ~~"warm" permafrost areas that are dominated by unstable~~the very warm permafrost, an enhanced measure to prevent permafrost degradation, i.e., the proactive roadbed cooling approach, has been successfully applied in constructing the QTR (Cheng, 2004; 2005; Cheng et al., 2008). Second, the degradation of permafrost in the QTP may affect the hydrologic cycle in the Third Pole region, which includes the QTP and the surrounding arid regions. Permafrost controls the distribution, recharge, flow paths, discharge, dynamics, and hydrochemistry of groundwater (Cheng and Jin, 2013). The degradation of permafrost affects the interactions among the surface water, subsoil water, and groundwater by changing the hydraulic conductivity and hydraulic connectivity of the soil. The degradation of the ice-rich permafrost itself makes important contributions to surface runoff and the development of thermokarst lakes in the inner Tibetan Plateau (Zhang et al., 2013). The enhanced drainage may lead to increases in flood risk (Larsen et al., 2008) and reductions in ecosystem resilience via seasonal shifts in stream flow and groundwater abundance, because the decrease in permafrost water storage capacity in the QTP will lead to a reduction in dry-season water availability. All of these changes will affect the well-being of millions of people and sustainable development at the Third Pole, which contains the headwater areas of several of the major rivers in Southeast Asia, such as the Yellow, Yangtze, Mekong, Yarlung Zangbo and Shiquan Rivers. The Third Pole also includes many inland rivers, such as the Shiyang, Heihe, Shule, and Tarim Rivers, in northwestern China. Last, the permafrost region in the QTP contains approximately 160 Pg of organic carbon (Mu et al., 2015~~) and~~), many thermokarst lakes, and wetlands (Niu et al., 2011; Luo et al., 2015). Thawing of the permafrost may lead to the disappearance or growth of thermokarst lakes (Smith et al., 2005), which may further affect greenhouse gas emissions and produce a feedback effect on climate change (Tarnocai et al., 2009;

Schuur et al. 2009; Schaefer et al., 2011; McCalley et al., 2014). Additionally, changes in thermokarst lakes may both accelerate and delay permafrost thawing (Westermann et al., 2016; You et al., 2017).

5 Conclusions

This study evaluates the ~~stability~~permafrost thermal degradation ~~of permafrost~~ over the QTP from the 1960s to the 2000s based on the ~~estimated~~improved, decadal means of the mean annual air temperatures (MAATs) data over the Qinghai-Tibet Plateau (QTP) in the past 50 years obtained by integrating remote sensing-based mean annual land surface temperatures (MASTs), leaf area index (LAI~~)~~), and fractional snow cover values, ~~and~~as well as decadal mean MAATs measured at 152 weather stations using a geographically weighted regression (GWR) model. Cross validation shows that the accuracy of the estimated permafrost extent is greater than that of previous maps.

The decadal mean MAATs reflect a continuous rise at a rate of approximately 0.04 ℃~~/a~~ a^{-1} during the past half century. The warming rate increases with increasing elevation from approximately 0.33 ℃ per decade at 3600 m to 0.49 ℃ per decade at 5200 m and then decreases as elevation increases further. Climate warming has led to the thermal degradation of permafrost ~~stability~~ in the past half century. The area occupied by the ~~stable~~cold permafrost types has continuously decreased, and the area occupied by the ~~unstable permafrost~~very warm types has continuously increased. The total degraded area is approximately 153.76×10^4 km^2, which accounts for 87.98% of the permafrost area in the 1960s. The ~~stability~~thermal condition for all permafrost types have degraded to lower levels. The extent of the ~~extremely stable, stable~~very cold, cold, and ~~sub-stable~~cool types retreated from the south to the north, whereas the extent of the ~~transitional, unstable~~warm, very warm, and ~~extremely unstable~~likely thawing types extended northward. The mean elevations of the ~~extremely stable, stable, sub-stable, transitional, unstable~~very cold, cold, cool, warm, very warm, and ~~extremely unstable~~likely thawing types increased by 88 m, 97 m, 155 m, 185 m, 161 m and 250 m, respectively. ~~This result indicates that the climate sensitivity of permafrost is dependent on the stability level.~~ The degradation mainly occurred during ~~two periods that include~~ the 1960s to the 1970s and the 1990s to the 2000s. The thermal degradation of permafrost ~~stability~~ in the QTP has important impacts on the safety of infrastructure, flood risks, ecosystem resilience, and climate feedbacks, as well as the well-being of millions of people and sustainable development at the Third Pole.

The uncertainties inherent in this analysis cannot be discounted. These uncertainties are due to asynchronous changes in near-surface air temperatures and deep soil layer temperatures, the missing geothermal flux, insufficient resolution, or the inaccuracies and sparseness of the surface station data employed. ~~As this evaluation is empirically based, obtaining more convincing results requires additional data, especially from the deep layers of soils. The development of new, fast, and inexpensive sensors and robust machine learning methods will assist in this effort. A physically based definition of permafrost stability and an improved physically based model will contribute to the prediction of permafrost stability degradation and its interactions with the engineering stability of infrastructure, the water cycle, and climate change~~In order

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to reduce the uncertainties, a deep layers soil map, surficial geology, and ground ice map are required. All of this will benefit from the accumulation of field data in the future, especially from boreholes.

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Table 1. Classification system used to assess permafrost stability (thermal degradation (Modified according to Cheng, 1984)

Type			Mean annual groundair temperature (°C)	Thickness of permafrost (m)	Mean annual airground temperature (°C)
Extremely stable Very cold	<-5.0	170	<-8.5		<-5.0
Stable Cold	-3.0~-5.0	110~170	-6.5~-8.5		-3.0~-5.0
Sub-stable Cool	-1.5~-3.0	60~110	-5.0~-6.5		-1.5~-3.0
Transitional Warm	-0.5~-1.5	30~60	-4.0~-5.0		-0.5~-1.5
Unstable Very warm			-2.0~-4.0		+0.5~-0.5 0~30 -2.0~-4.0
Extremely unstable Likely thawing	>+0.5		-1.0~-2.0		>+0.5

Table 2. The statistics of the stepwise linear regression analysis

Model	Independent variables	Adjusted R^2
1	MAST	0.83
2	MAST, LAI	0.87
3	MAST, LAI, FSC	0.88
4	MAST, LAI, FSC, Elevation	0.90
5	MAST, LAI, FSC, Elevation, Longitude	0.91
6	MAST, LAI, FSC, Elevation, Longitude, Latitude	0.93

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Table 3. The area statistics of the permafrost thermal stability types over the QTP in the past 50 years (×10^4 km^2)

Permafrost stabilitytype	1960s	1970s	1980s	1990s	2000s	Net change (1960s to 2000s)		2000s excluding glaciers	Change rate (×10^4 km^2/decadekm^{2}decade^{-1})
						Area	Percent (%)		
remely stableVery cold	12.35	8.56	8.74	5.66	3.36	-8.99	-72.79	1.86	-2.09
StableCold	38.59	28.30	27.64	20.91	11.53	-27.06	-70.12	10.39	-6.15
Sub-stableCool	34.14	34.75	34.09	31.94	24.84	-9.30	-27.24	24.03	-2.14
TransitionalWarm	24.73	23.95	23.59	23.39	23.55	-1.18	-4.77	23.12	-0.29
UnstableVery warm	44.22	43.89	43.70	46.51	48.21	3.99	9.02	47.80	1.06
Extremely unstableLikely thawing	20.73	21.05	20.54	20.16	21.63	0.90	4.34	21.56	0.09
Total area	174.76	160.50	158.32	148.57	133.10	-41.66	-23.84	128.76	-9.52

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Table 4. Transfer matrix of permafrost ~~stability~~ types from the 1960s to the 2000s in the QTP (%)

1960s / *2000s*	~~Extremely stable~~Very cold	~~Stable~~Cold	~~Sub-stable~~Cool	~~Transitional~~Warm	~~Unstable~~Very warm	~~Extremely unstable~~Likely thawing	*Seasonally frozen ground*
~~Extremely stable~~Very cold	24.75	0.78	0.00	0.00	0.00	0.00	0.00
~~Stable~~Cold	59.42	9.67	1.33	0.02	0.00	0.00	0.00
~~Sub-stable~~Cool	15.82	50.93	8.37	1.45	0.03	0.00	0.00
~~Transitional~~Warm	0.00	35.91	23.18	6.16	0.57	0.00	0.00
~~Unstable~~Very warm	0.00	2.72	67.07	66.82	17.19	0.66	0.00
~~Extremely unstable~~Likely thawing	0.00	0.00	0.05	25.49	32.80	3.39	0.12
Seasonally frozen ground	0.00	0.00	0.00	0.06	49.40	95.95	99.88
Class changes	75.25	90.34	91.63	93.84	82.81	96.61	0.13

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Table 5. The mean ~~change in~~ elevation change of the permafrost ~~thermal stability~~ types over the QTP in the past 50 years (unit: metre)

Permafrost ~~stability~~type	1960s	1970s	1980s	1990s	2000s	Rate (m~~/~~ decade^{-1})	R^2
~~Extremely stable~~Very cold	5240	5161	5169	5232	5328	24.7	0.34
~~Stable~~Cold	5050	5052	5055	5094	5147	23.6	0.80
~~Sub-stable~~Cool	4881	4932	4937	4985	5036	36.3	0.96
~~Transitional~~Warm	4756	4799	4804	4859	4941	43.0	0.91
~~Unstable~~Very warm	4614	4670	4675	4713	4775	36.5	0.94
~~Extremely unstable~~Likely thawing	4392	4503	4513	4565	4642	56.2	0.94

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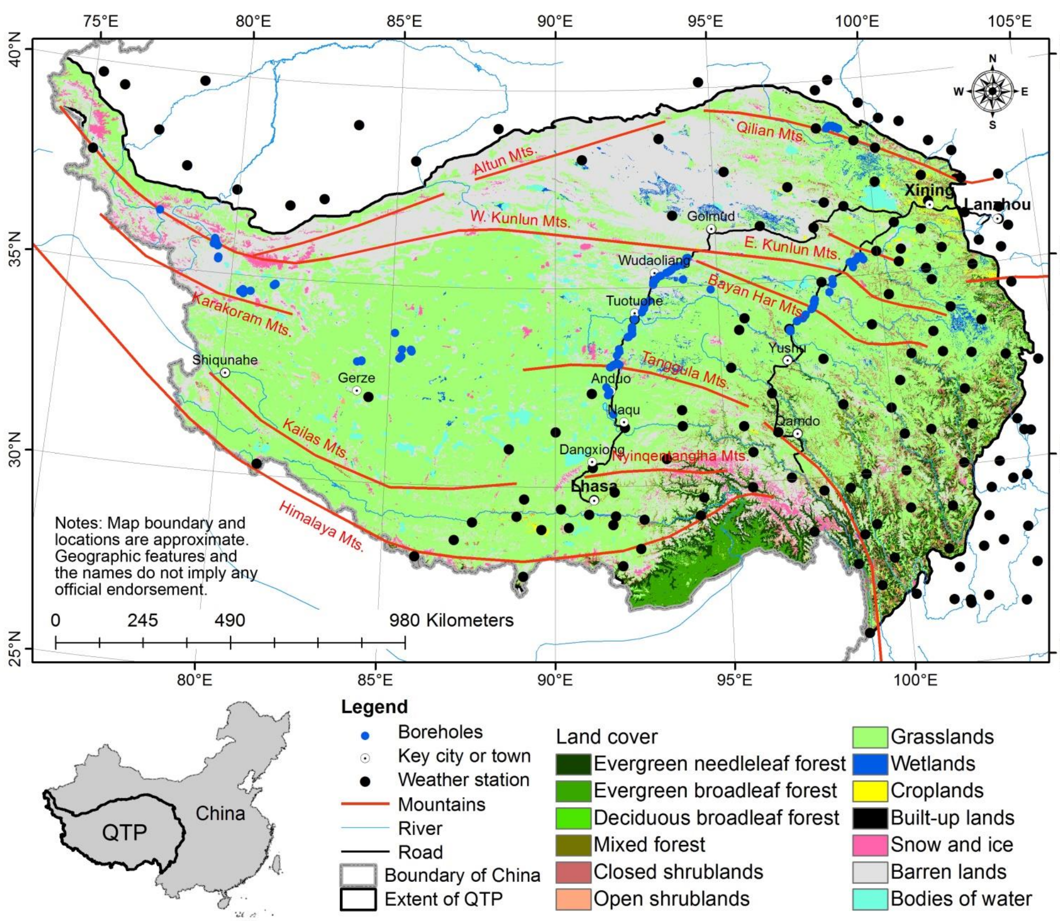


Figure 1. The distribution of in situ MAAT observation stations and MAGT boreholes over the QTP.

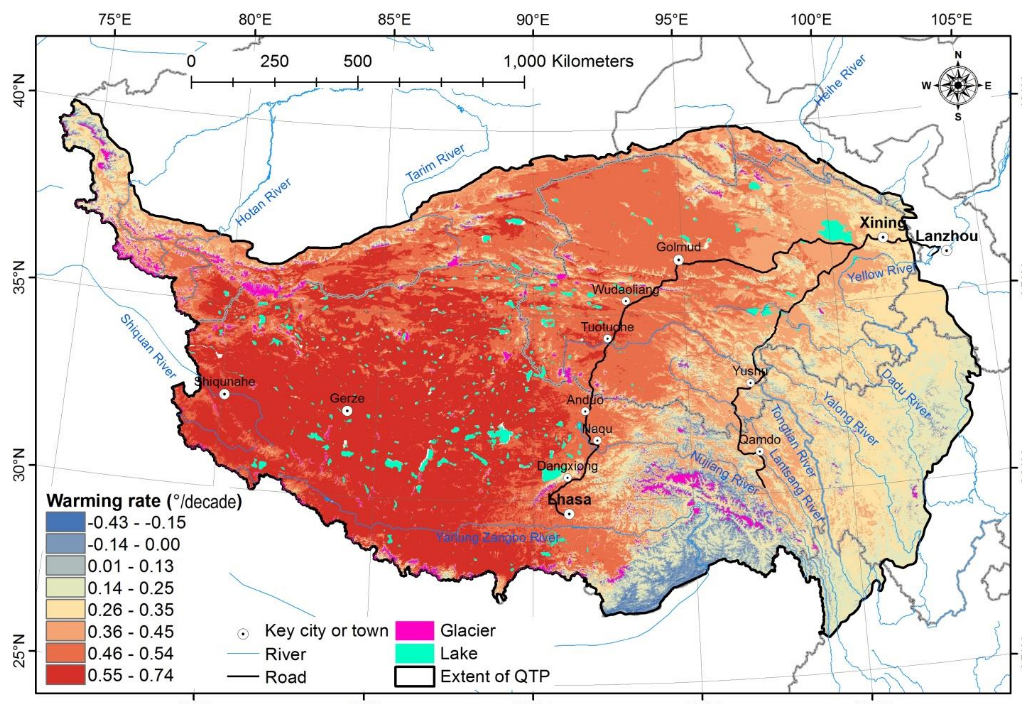


Figure 2. Spatial variability of MAAT warming rates over the QTP in the past 50 years.

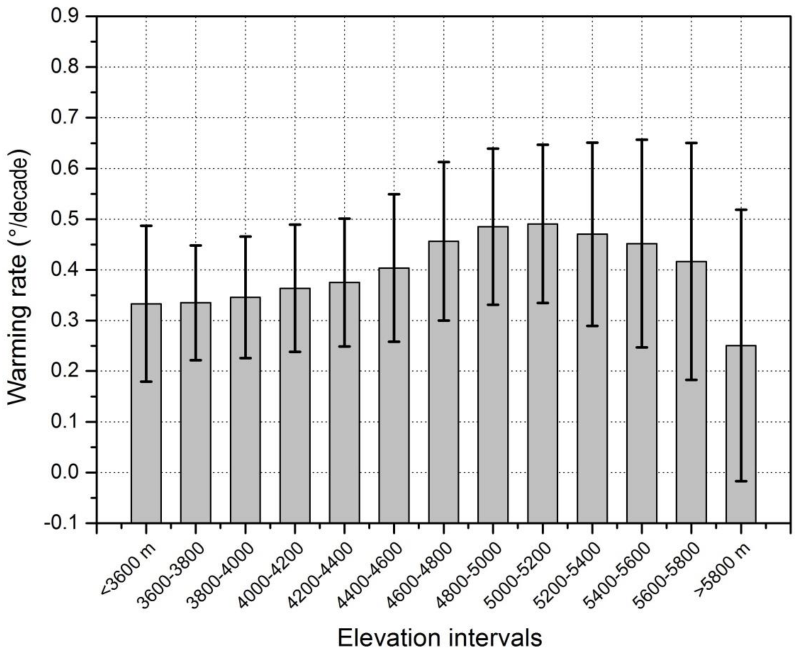
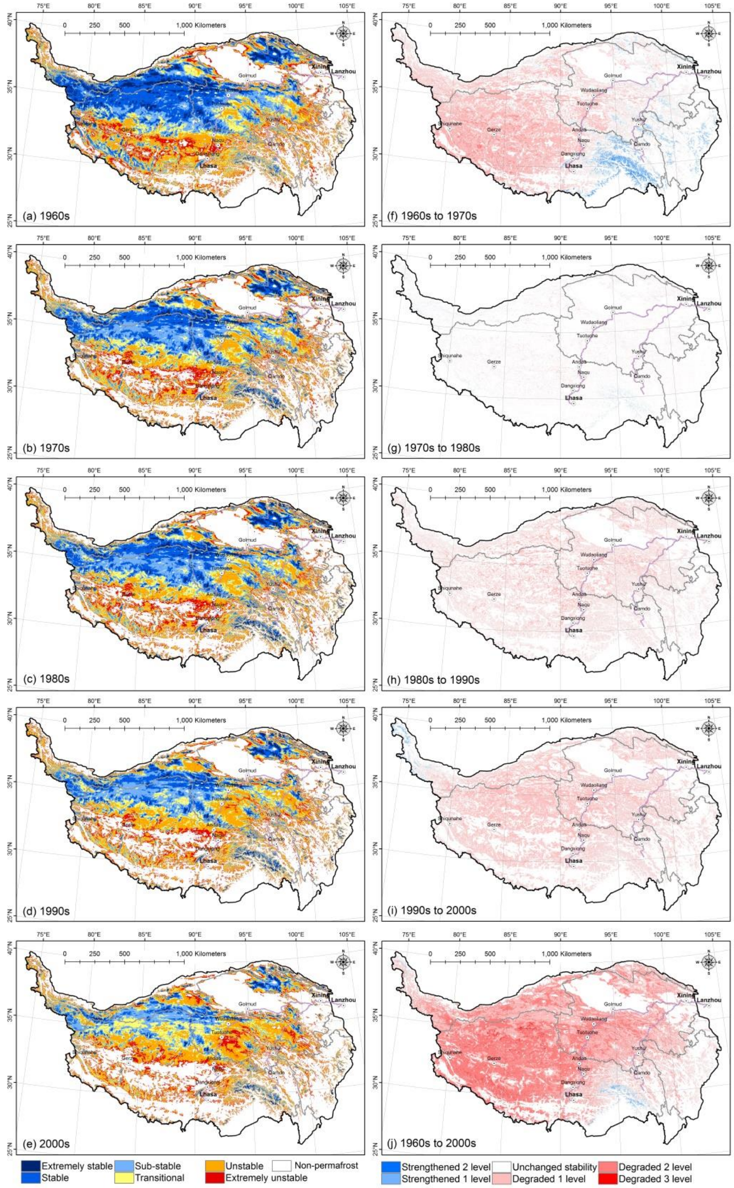


Figure 3. Warming rates with increasing elevation. These rates are derived from MAATs estimated ~~using MODIS LSTs~~by integrating remote sensing-based mean annual land surface temperatures (MASTs), leaf area index (LAI) and fractional snow cover values, and decadal mean MAAT date from 152 weather stations with a geographically weighted regression. Error bars display the standard deviations.


(a) 1960s
(b) 1970s
(c) 1980s
(d) 1990s
(e) 2000s
(f) 1960s to 1970s
(g) 1970s to 1980s
(h) 1980s to 1990s
(i) 1990s to 2000s
(j) 1960s to 2000s
Extremely stable
Stable
Sub-stable
Transitional
Unstable
Extremely unstable
Non-permafrost
Strengthened 2 level
Strengthened 1 level
Unchanged stability
Degraded 1 level
Degraded 2 level
Degraded 3 level

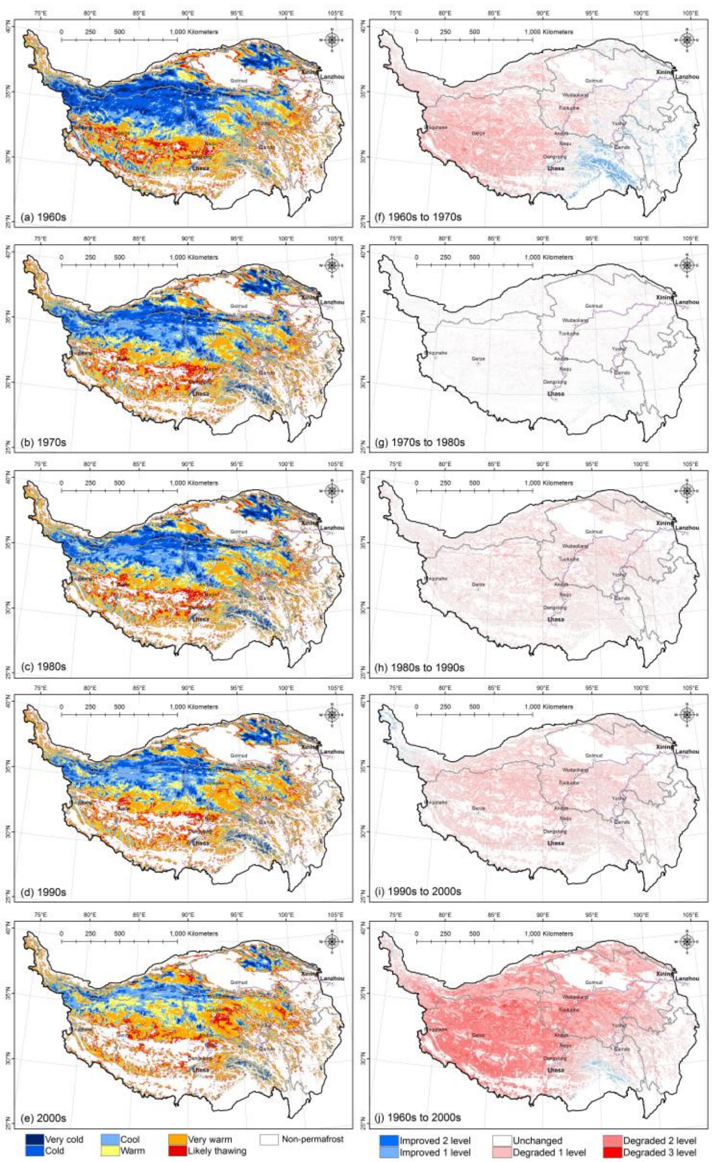


Figure 4. The permafrost ~~stability~~ map in each decade (a-e) and its spatial changes from the 1960s to the 2000s (f-j) over the QTP during the past 50 years.

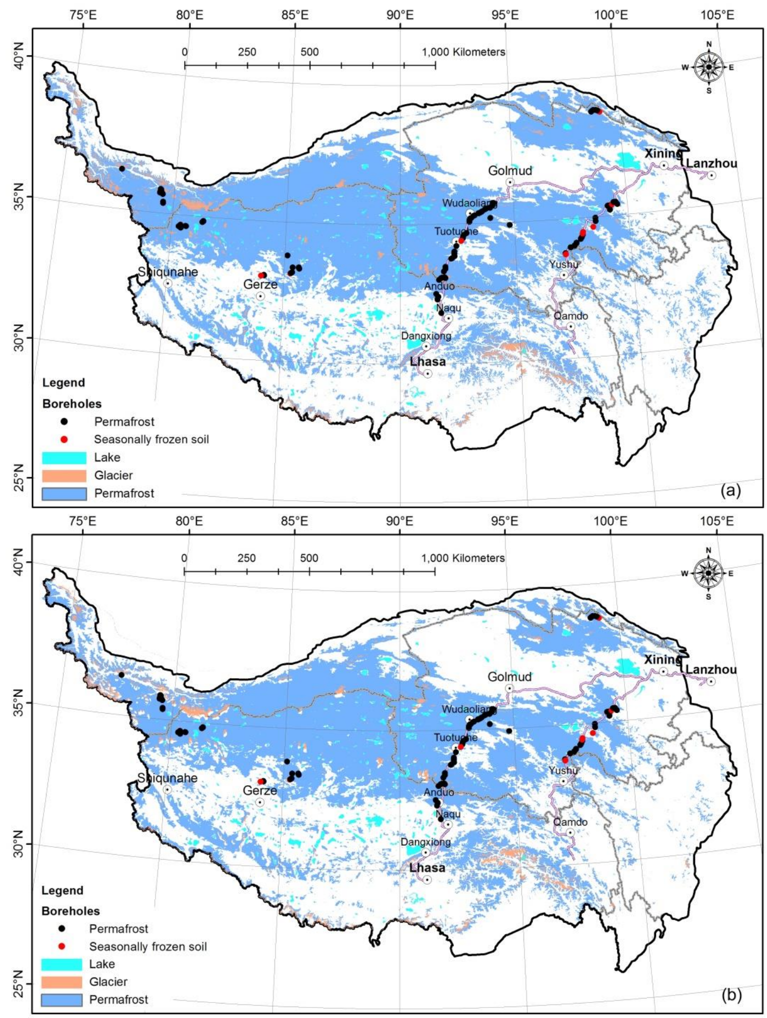


Figure 5. Comparison of the permafrost extent between the results of this study (a) and the permafrost map presented by Zou et al., (2016) (b).