The Role of Winter Warming in Permafrost Change Over the Qinghai-Tibet Plateau

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Abstract Winter warming is fast than summer warming on the Qinghai-Tibet Plateau (QTP). However, no assessment of winter warming effects on permafrost has been attempted. Here we conducted hypothetical control experiments and used the Noah land surface model to evaluate the impacts of winter warming on the QTP permafrost. The results show that air temperature in winter (November–April) was increasing at a rate of 0.66 °C/decade during 1980s–2000s, over double that in summer (May–October). The mean annual ground temperature of permafrost increased by 0.13 °C/decade. The summer warming dominated the thermal regime of permafrost before 2000. After that, the influence of winter warming on permafrost has gradually grown and exceeded that of summer warming. Winter warming has amplified the thermal degradation of permafrost. Our findings reveal that alpine continuous permafrost on the northern QTP has experienced a prominent regional warming due to rapid winter warming since 2000.

Plain Language Summary As the highest and largest permafrost region in mid-latitudes, Qinghai-Tibet Plateau (QTP) has experienced prominent winter warming in the past three decades. To date, no study has been made to assess the impacts of winter warming on the QTP permafrost. We used the Noah land surface model to investigate this effect, based on controlled experiments including a baseline representing historical climate conditions and two intentionally constituted hypothetical experiments that remove the winter (November–April) or summer (May–October) warming from the historical records. We analyzed the seasonal changes in air temperature, evaluated the effects of winter and summer warming on the changes of frozen ground in terms of several key indicators (including active layer thickness, permafrost area, mean annual ground temperature of permafrost, and maximum freezing depth of seasonally frozen ground) and investigated the possible underlying mechanism of winter warming on permafrost. The results indicate that winter warming accelerates permafrost thermal degradation. Especially since 2000, alpine continuous permafrost on the Qiangtang High Plain, Northern QTP, has undergone an obvious regional warming induced by rapid winter warming.

1. Introduction

One quarter of the Northern Hemisphere and 17% of the Earth’s exposed land surface are underlain by permafrost (Biskaborn et al., 2019), which is defined as the ground with a temperature remaining at or below 0 °C for at least 2 consecutive years. Permafrost, as one of the cryospheric indicators of global climate change, is sensitive to changing climatic conditions and in particular to rising air temperature (Isaksen et al., 2007; Zhang et al., 2008). The global averaged air temperature showed a warming of 0.85(0.65 to 1.06) °C in the period of 1880–2012. The past three consecutive decades are very likely the warmest 30-year period of the last 800 years in the Northern Hemisphere (Intergovernmental Panel on Climate Change, 2013; Rogelj et al., 2012). The warming rate varied in different regions. The atmosphere in high-latitude and high-altitude regions has warmed faster than elsewhere (Arp et al., 2016; Pepin et al., 2015). With an average elevation of more than 4,000 m above sea level, the Qinghai-Tibet Plateau (QTP) is the highest and most extensive permafrost region in mid-latitudes around the world, and it is considered to be a sensitive region as a test field of global warming (Yao et al., 2000; 2012).

The observations and simulation studies indicate that most regions on the QTP have experienced a prominent warming since the 1980s. The warming trend in the cold season was greater than the warm season,
especially on the northern QTP (Qian & Lin, 2004; Ran et al., 2018; Zhao et al., 2004). Research on temperature extremes shows that the rate of winter warming is generally higher than the annual basis in China (You et al., 2013; Yue et al., 2013). Some direct evidence demonstrates that ground surface warming in winter was especially prominent, at a rate of 0.82 °C/decade, more intense than other seasons in the central QTP (Wu et al., 2013). These findings indicate that winter warming on the QTP is significant, and its warming trend is more noticeable than summer. It raises the question that how winter warming affects permafrost in this region.

Existing studies reveal that winter ground surface temperatures were strongly correlated with rapid thawing permafrost dynamics in northeast China, for example, Zhang et al. (2019), implying that winter warming has a great potential to influence the thermal regime of frozen ground. However, this result is limited by sparse observation sites and still inadequate in reflecting the permafrost dynamics on a regional scale. The unique geography and plateau climate make the QTP permafrost more distinct in response to winter warming than the high latitude regions. Hence, the assessment of winter warming effects on the QTP permafrost is motivated both by its global importance and by its unique properties. To date, no study has been conducted to assess the permafrost response to winter warming.

In this paper, we set up hypothetical control experiments to evaluate the impacts of winter warming on permafrost changes on the QTP during the 1980 to 2009 using the Noah land surface model (LSM). First, we examined the air temperature changes in winter (November–April) and summer (May–October). Second, the changes in frozen ground key indicators (including active layer thickness (ALT), permafrost area, mean annual ground temperature (MAGT) of permafrost, and maximum freezing depth (MFD) of seasonally frozen ground) in response to climatic warming were modelled and analyzed. Third, we assessed the effects of winter and summer warming on permafrost by a means of intercomparison between the intentionally constituted hypothetical scenarios and a baseline scenario, and investigated the possible underlying mechanism of the effects of winter warming on permafrost.

2. Model and Experiment

The Noah LSM uses the Penman-Monteith equation for simulating latent heat flux to solve surface energy balance, a four-layer soil model with thermal conduction equations for simulating soil heat transport, and the diffusivity form of Richards's equation for soil water movement. It explicitly considers the coupling interaction between water and heat flows in the frozen soil (Chen et al., 1997; Wang & Yang, 2018; Yang et al., 2018). It has been widely used in studying land surface processes worldwide and has proved to be effective for simulating the freezing-thawing processes of frozen ground on the QTP with proper modifications (Barlage et al., 2010; Chen et al., 2011; Chen et al., 2015). In this study, we used the improved Noah LSM version 3.4.1 (Wu et al., 2018). Wu et al. (2018) improved this version of Noah LSM and simulated permafrost distribution and its hydrological and thermal states in 2010 over the QTP. The results demonstrate that the improvements made to the model are applicable for modeling permafrost over the QTP. There are some differences between the model used in this study and Wu et al. (2018). First, we adjusted the initialization scheme with a longer spin-up period of 30 years to minimize the effects of the initial conditions to the results. Second, the bedrock type in the soil texture dataset used in the modeling was updated by a latest map of the depth to bedrock (Shangguan et al., 2017). To alleviate the possible impacts of parameter migration, we used the default values of soil parameters in the Noah LSM, while the adding gravel parameters were measured from the gravel layer in the soil column at the Tanggula permafrost station.

We designed hypothetical control experiments, including a baseline representing historical climate conditions and two intentionally constituted hypothetical scenarios through removing the winter or summer warming from the historical records. The baseline scenario is based on the China Meteorological Forcing Dataset (Chen et al., 2011), which has proved acceptable accuracy in modeling land surface processes on the QTP (Guo & Wang, 2013; Wu et al., 2018). It contains seven atmospheric variables (air temperature, precipitation, wind speed, atmospheric pressure, specific humidity, downward solar radiation, and downward longwave radiation). We divided each year into winter (November–April) and summer (May–October) in view of the distinctive characteristics of the local climate and freeze-thaw cycle (Duan et al., 2015; Wu & Zhang, 2010). The air temperature data of each year in two hypothetical scenarios were separated into two parts, the summer and winter temperatures. The winter scenario keeps the summer temperature fixed.
throughout the entire modeling period while the other forcing variables are identical to the baseline scenario. In this scenario, the summer temperatures are replaced for all years by the summer temperatures of 1979, while the winter temperature and other six atmospheric variables remain the same as the historical records. The summer scenario fixes the winter temperatures through the modeling period by replacing them with the winter temperatures of 1979. The baseline scenario aims to present the permafrost variations under historical climate conditions. The winter scenario was designed for evaluating the impacts of winter temperature changes on permafrost, whereas the summer scenario for the effects of summer temperature changes. The two hypothetical scenarios represent largely low temperature conditions compared to the baseline, as the substituted air temperatures are positioned at the lower end of the entire time series. However, opposite trends in air temperature changes may also exist in subregions in the two hypothetical scenarios owing to spatial thermal inhomogeneity.

The Noah LSM was employed to simulate permafrost dynamics for all experiments from 1980 to 2009 after a 30-year spin-up by duplicating forcing data of 1979. The temporal and spatial resolution is 3 hr and 0.1° × 0.1° (latitude × longitude), respectively, and the total modeling depth is 15.2 m with 18 soil layers. A pixel is identified as permafrost where the maximum monthly mean temperature remains below 0 °C for 24 months in at least one soil layer. The ALT is determined through linear interpolation between two neighboring depths above and below the 0 °C isotherm. The MAGT is defined as the ground temperature at the depth of zero annual amplitude, located by linearly interpolating ground temperatures in neighboring layers as a depth where seasonal oscillation is less than or equal to 0.1 °C. We computed four key thermal-related indicators of frozen ground (including ALT, MAGT, permafrost area, and MFD) through the three experiments and evaluated the effects of winter and summer warming on them. The baseline results were validated using available historical records of ALT and MAGT of various lengths at a total of 27 sites (Wu et al., 2012), mainly along the Qinghai-Tibet Highway. The preliminary validation showed generally acceptable accuracy of the simulated baseline results considering existent spatial scale effects. Then the winter/summer scenario results were compared against the baseline results in terms of the consistency and proximity. If the permafrost changes under the winter scenario are simulated closer to the changes under the baseline, it indicates that winter warming has a greater impact to permafrost. Spatially, we drew difference maps of those indicators by subtracting the baseline results from the winter/summer scenario results. If smaller differences are detected on the difference maps for the winter scenario, winter warming has a larger impact on permafrost. By intercomparison between the hypothetical scenarios and the baseline, the effects of other climate variables on permafrost are excluded and only the effects of seasonal warming are identified.

3. Results and Discussion

3.1. Seasonal Changes in Air Temperature

The summer (Figure 1a) and winter (Figure 1b) air temperatures averaged across the entire QTP present increasing trends throughout the study period but with notable differences in both trend and magnitude. The mean air temperature was increasing at a rate of 0.66 °C/decade in winter, more than double that in summer, which was 0.27 °C/decade. The magnitude of change in winter was over 3 °C, ranging from −10.91 °C to −7.54 °C, much larger than a range of 4.22 °C to 5.90 °C in summer. In the beginning, the summer temperature (Figure 1a) was maintained at a stable low level until 1987. Since then, it increased gradually but fluctuated, reaching a peak of 5.90 °C in 1998, which is the warmest year on record. After that, the temperature fell sharply till 2005, followed by another moderate warming. It is important to stress that although summer temperature presented a steep decline after 1998, the mean level was still above the average of the entire period. In other words, the summer temperatures after 1998 remained warming but at a slower rate. The increasing trend of winter temperature was more remarkable (Figure 1b) than summer temperature. Prior to 1999, it presented a slight increasing trend. After 2000, it rose sharply and maintained a high level afterward. It is obvious that the QTP has experienced considerable climate warming in the past three decades, and the trend of winter warming was greater than that of summer in the entire period. More specifically, before 1998, both seasons had rising air temperatures, at a higher rate in summer than in winter. A critical seasonal shift has occurred on the QTP around 1998, after which winter temperature rapidly warmed up but summer temperature steadily declined for several years, that is to say, the summer warming has slowed and winter warming began to accelerate. The turn point in 1998 was also identified
by the annual mean air temperature, identical with the turn point identified in the time series of observed annual surface air temperature in this region (Gao et al., 2014).

3.2. Changes in Active Layer Thickness

The annual changes in ALT under the baseline (black line in Figure 1c) correspond well to the summer temperature changes (Figure 1a). While the ALT remained relatively stable before 1989, it started to increase and reached a maximum thickness of 3.01 m in 2000. Then it declined dramatically in next 5 years. For the entire study period, the baseline ALT presented a slight decrease at a rate of 0.07 m/decade. The ALTs under two seasonal scenarios were modelled to be consistently thinner than the baseline ALT, with the winter scenario being the lowest, because of generally lower seasonal air temperatures in place in the two scenarios than the baseline. Although ALT is measured in summer, the winter temperature changes will also impact ALT through the annual freeze-thaw cycle. Rapid winter warming shortens the duration of freeze-thaw cycles (Yang & Wang, 2019) and is likely to cause the frozen ground more vulnerable to thaw in summer. The ALT changes in the summer scenario (red line in Figure 1c) are in much better agreement with the baseline than the winter scenario in terms of both trend and magnitude especially in the period before 2000. It implies the summer temperature changes have more influences on the ALT variations than the winter temperature changes. Despite of constant air temperature warming in 2000–2005, although in a lowering rate, the ALTs were reduced dramatically in thickness in all three scenarios. It suggests that higher air temperature does not always thicken the ALT of permafrost, other climatic factors may play an important role as well. By examining the forcing variables, we found that the increase in precipitation over this period is closely associated to the thinning of ALT.

The spatial difference maps of the ALT are presented in Figures 2a and 2b, where the thinning in ALT dominated the entire plateau in 2009 in both scenarios, same as indicated by the temporal analysis. In the summer
scenario map (Figure 2b), the ALTs in most permafrost regions were slightly thinner than those in the baseline. The largest differences were found in the continuous permafrost regions on the north, high-temperature island permafrost regions on the southwest and the mountainous permafrost regions on the east. The summer scenario map has less extreme differences (marked by dark blue or high red) than the winter scenario map (Figure 2a), indicating the summer scenario results being much closer to the baseline. As the two seasonal scenarios generally represent lower temperature conditions in one season, the fabricated summer temperature in the winter scenario exert more influences on the changes of ALT. On the northwest QTP, there is a region in the winter scenario map with a contradicting pattern (rectangle in Figure 2a) standing out with thicker ALTs compared to the baseline. By examining the local climate, summer temperatures in this region presented a long-term cooling trend in the study period, such that in the winter scenario the fabricated summer temperatures, which come from the summer of 1979, were higher than those in the baseline, leading to thicker ALT than the baseline in opposition to most regions. The presented spatial variations indicate that the ALT may considerably related to local factors, such as microclimate, soil properties, vegetation, and snow cover.

In seasonally frozen ground areas, instead of ALT, the MFD was examined. The MFDs under three scenarios generally declined over time in a way opposite to that of the winter temperature (Figure 1b). The baseline MFD (black line in Figure 1d) declined at an average rate of 0.17 m/decade throughout the study period. The MFD changes under the winter scenario (blue line in Figure 1d) matched the baseline MFD quite well with only small deviations especially before 1999. In the summer scenario (red line in Figure 1d), the MFD was deeper than the other two scenarios in most years, because the winter temperature remained fixed and no winter warming took effect in this scenario.

In terms of spatial variations of MFD, the winter scenario map (Figure 2c) had smaller differences from the baseline than the summer scenario map (Figure 2d). The smaller differences from the baseline in the winter scenario suggest that the MFD changes are mainly induced by winter temperature changes, consistent with
that revealed in the temporal analysis. There were much more areas in Figure 2d in deep red representing the occurrence of the largest difference between the summer scenario and the baseline. As no winter temperature increment occurred in comparison to the baseline, the summer scenario was simulated to have much deeper MFDs as expected.

3.3. Areal Changes of Permafrost

The changes of permafrost area (Figure 1e) in the study area generally follow the trend of the air temperature changes. Under the baseline (black line in Figure 1e), it grew considerably to a maximal of $1.341 \times 10^6 \text{ km}^2$ (excluding lakes and glaciers) in 1985 from $1.300 \times 10^6 \text{ km}^2$ in 1980. The expansion was followed by a long-term steady shrinkage until 2001, reaching a minimum of $1.248 \times 10^6 \text{ km}^2$. At around 2001, it turned to expand until 2005 and lessen again to $1.258 \times 10^6 \text{ km}^2$ in 2009. The most decreases in permafrost area have occurred in the 1990s. The growth from 2001 to 2005 is likely to due to the combined effects of precipitation increment and dramatic summer temperature drop in this period.

The two seasonal scenarios had similar change characteristics with the baseline in the first two decades, with most similarity from the summer scenario (red line in Figure 1e). As the effects of other climate variables have been excluded through intercomparison, it can be reasonably inferred that the permafrost area shrinkage occurred before 1998 was primarily affected by the ascending summer temperature. In the period after 1998, both scenario results heavily deviated the baseline results. In the winter scenario (blue line in Figure 1e), the increasing rate of area was slower than the summer scenario in 2001–2005, and it ended up with a smaller final area than the summer scenario. Considering the occurrence of seasonal air temperature shift as well as the precipitation changes in this period, the dominant role of summer warming on reducing permafrost area has gradually weakened. After 2005, the winter warming seems to take a controlling role over the summer warming. However, for the entire period, there has been only a slight reduction in the permafrost area over the QTP.

The difference maps of frozen ground types, including permafrost, seasonally frozen ground, and unfrozen ground, show that most permafrost kept stable throughout the period in terms of type transition between the seasonal scenarios and the baseline (Figures 3a and 3b). The conversions mostly occurred around the rims of the transitional areas between permafrost and seasonally frozen ground regions on the south and the mountainous permafrost areas on the east QTP. The main conversions were the conversions into permafrost from the seasonally frozen ground, in particular on the southwest QTP in both scenarios. It can be well explained that both the winter and summer scenarios represent lower temperature climatic conditions compared to the baseline, which are in favor of permafrost development. The island permafrost on the southwest QTP are thermally unstable and highly vulnerable to degrade into seasonally frozen ground in the case that air temperature warming has occurred in any season. The inverse conversion of permafrost in the seasonal scenario results into seasonally frozen ground in the baseline, occurred mostly in a small region on the southeast QTP, are related to local climate characteristics that the historical air temperatures in this region present a cooling trend in both seasons in contrast to most regions. In view of the fact that for a complete melting of permafrost in stable permafrost areas, the process may take up to several years (Biskaborn et al., 2019), the changes in frozen ground distribution are likely unable to fully characterize the effects of seasonal warming on permafrost.

3.4. Changes in Permafrost Thermal Regime

The annual changes of the MAGT of permafrost under the baseline (black line in Figure 1f) had a generally similar rising trend as the warming of winter temperature (Figure 1b). The influences of air temperature on permafrost temperature weaken with depth and may need up to several years before reaching a deep soil layer. The MAGT rose and dropped to a new low in 1985 in response to the low air temperatures in 1982 and 1983. Then the MAGT warmed up steadily, attaining a peak in 2004, along with continuous warming in annual air temperature in this period. In 1980s–2000s, the baseline MAGT was increasing at a rate of 0.13 °C/decade.

Similar change trends were observed in three scenarios, with highest MAGTs in the baseline and lowest in the winter scenario (blue line in Figure 1f), until 2004, after which the MAGTs in all scenarios begun to drop and the summer scenario (red line in Figure 1f) severely deviated from the baseline, even lower than the winter scenario. It can be inferred through intercomparison that in 1980s and 1990s the summer temperature changes strongly affected the MAGT. The pattern altered beginning from 1999. Along with continued
rapid winter warming and weakened summer warming in 2000s, the rising rate of MAGT in the winter scenario became faster than the summer scenario. The winter scenario MAGT eventually exceeded that of the summer scenario in 2004. This transition is tightly connected to the seasonal shift occurred on the QTP after 1998 with slowing summer warming and strengthening winter warming. After the seasonal shift, the influence of winter warming on permafrost gradually increases and becomes dominant since 2004.

Spatially, in both scenarios, negative MAGT differences were prevalent on the QTP, reflecting the impacts of general lower temperature conditions in the scenarios. The difference map of the MAGTs in 2009 in permafrost regions from the winter scenario (Figure 3c) shows that the MAGT in most regions was close to that in the baseline. Similar to the ALT maps, positive MAGT differences appeared on the northwest portion (rectangle in Figure 3c). The fabricated summer temperatures there were higher under the winter scenario than the baseline, resulting in higher MAGT than those in the baseline. Meanwhile, the MAGTs in this atypical region under the summer scenario (Figure 3d) were still slightly higher than the baseline, even though the fabricated winter temperatures were lower in this scenario than the real winter temperatures in the baseline. It implies that winter warming had only marginal effects on thermal regime changes in this region. The summer scenario map had larger MAGT differences than the winter scenario map. The largest differences (colored with dark blue) under the summer scenario has been found in the continuous permafrost region on the Qiangtang High Plain on the north QTP (circle in Figure 3d), as well as in the mountainous permafrost regions on the southwest and east QTP. The largest differences in the southwest and eastern regions occurred the same in the winter scenario, suggesting that the thermal regime of permafrost in these regions are susceptible to any seasonal warming. However, the largest MAGT differences in Qiangtang High Plain did not appear in the

Figure 3. Difference maps of the distribution of frozen ground types in 2009 produced by converting the baseline results into the (a) winter and (b) summer scenario results. Difference maps of MAGT of 2009 in permafrost regions from the (c) winter and (d) summer scenarios against the baseline. The rectangle marks an atypical region inconsistent with most regions affected by regional climate. The circle denotes a region with high potential to be affected by winter warming. MAGT = mean annual ground temperature.
winter scenario map. Considering the fixed low winter temperatures in the summer scenario and fixed low summer temperatures in the winter scenario, it can be reasonably concluded that the changes of permafrost thermal regime in this region are induced by winter warming. It was also found that there was no regional warming in MAGT in this region before 2000, because a rapid increase in winter temperature did not occur until after 1999. Therefore, we confirmed that the thermal regimes of permafrost in the alpine continuous permafrost zone on the Qiangtang High Plain has experienced an obvious regional warming due to rapid winter warming since 2000, which is a new finding and not reported by previous studies. Possible mechanism of the effects of winter warming on permafrost is that winter warming reduces the storage of “cold energy” in soils and shortens the duration of the freeze-thaw process. Through energy exchange between land and atmosphere, winter warming warms the ground surface and delays the onset of soil freezing process. The depth of seasonal freezing becomes shallower. As a result of coupled thermal and hydrological processes occurred in the soils, the storage of cold energy in a form of ground ice is reduced. Such effects extend into the thawing period, in which less heat is required to offset the diminished cold energy in soil, affecting the energy budget on an annual basis, the freezing soil can be melt to a deeper depth, and consequently, the cycle of thawing process is advanced. The results from our experiments well demonstrate the underlying mechanism. Currently, the experiments were performed upon only one driving force dataset. However, using multiple driving forces data sets will be beneficial to fully quantify the uncertainty associated with the data. Moreover, fixing air temperature alone in the hypothetical experiments may more or less cause physical mismatch between atmospheric variables, leading to possible uncertainties.

4. Conclusions

This study provides a new perspective for understanding permafrost responses to seasonal warming over the QTP through hypothetical numerical experiments. The following conclusions have been drawn: (a) The winter temperatures were increasing at a rate of 0.66 °C/decade over the QTP in 1980–2009, more than double the rate of summer temperatures of 0.27 °C/decade. In 2000s, the summer warming has slowed and winter warming has accelerated. (b) The ALT of permafrost was primarily affected by the summer warming while the MFD of seasonally frozen ground was mainly induced by the winter warming. The ALT had a slight decreasing trend of 0.07 m/decade over the QTP, even if the climate has continuously warmed. The MAGT of permafrost was warming up at 0.13 °C/decade in the past three decades, although that the total area of permafrost remained relatively stable. (c) The summer warming dominated the variations in thermal regime of permafrost before 2000, then the influence of winter warming on permafrost gradually increased and exceeded that of the summer warming in 2004. Permafrost in the alpine continuous permafrost zone on the Qiangtang High Plain has experienced an obvious regional warming due to rapid winter warming since 2000.

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