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Article

Global warming weakening the inherent stability of glaciers and permafrost

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ABSTRACT

The Cryosphere has been undergoing a worldwide retreat, as seen in the decrease in the areal extent and volume of glaciers and in the areal extent of permafrost. This paper presents a systematic examination of the inherent stability changes of glaciers and permafrost caused by warming. Various study results suggest that over the past 30 years, the internal temperature of glaciers and permafrost exhibits an overall accelerating warming trend. The warming rate peaked in the mid-2000s and slowed slightly for several years afterward. In recent years, however, the warming rate has seemed to pick up again. The warming of glaciers and permafrost has exerted great impact on their stability, displayed as intensified melting, increased glacier surging, enlargement of supraglacial lakes, and increased permafrost degradation. Even without a future temperature increase, some glaciers will continue to shrink, and the number of surging glaciers will increase. The transition from low-temperature to high-temperature permafrost is a noticeable warning sign of a comprehensive degradation of permafrost. These results indicate that "warming" glaciers and permafrost will exert significant impacts on the hydrology, ecology, and stability of engineering in cold regions.

1. Introduction

The Cryosphere is the collective term for components of the Earth system that contain a substantial fraction of water in the frozen state, comprising snow, river and lake ice, sea ice, ice sheets, ice shelves, glaciers and ice caps, and frozen ground. Ice sheets and glaciers exert a major control on the global sea level; ice loss from these systems, as well as changing seasonal snow cover, may have direct impacts on water resources and tourism [1,2].

With climate warming, the main components of the Cryosphere have undergone significant changes [1]. The systematic evaluation of the changes in global glaciers and permafrost in the fifth assessment report of the Intergovernmental Panel of Climate Change (IPCC) presented these changes over time. From the 1950s and 1960s on, glaciers across the world have been retreating in length, shrinking in area, and decreasing in ice volume, and this retreat has accelerated since the early 1990s. Since the 1980s, the permafrost temperature in most regions has increased, and the depth of seasonally frozen ground has become shallower [1]. The changes in glaciers and permafrost have been displayed mainly in terms of their outer geometrical morphology, such as changes in the length, area, volume, and thickness of glaciers due to mass loss.

For a solid form of water, however, the key factor leading to mass loss of the Cryosphere is the solid-liquid transition: for the snow or ice to melt in the first place, the critical point of 0 °C must be reached. With climate warming, the land-surface air temperature changes in different regions [3], and the threshold-onset time for future 1.5 °C- and 2.0 °C-warming is projected to vary in different regions [4]. Therefore, the rate of mass loss of components of glaciers and permafrost is closely related to their own thermal conditions or their uptake of heat. For instance, there are cold-type glaciers and warm-type glaciers [5], and high-temperature permafrost and low-temperature permafrost [6,7]. Due to the respective temperature states of glaciers and permafrost, the response processes vary greatly under the impact of climate warming, which will further influence the dynamic processes and lead to differences in the changes of glaciers and permafrost.

When the mass balance of a glacier fluctuates around zero or the thickness of the active layer on top of permafrost remains

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stable, glaciers and permafrost will exhibit small changes by fluctuating their extent or volume, which is the so-called inherent stability. When the inherent stability of glaciers and permafrost decreases, abrupt and rapid changes in glaciers and permafrost are displayed. With climate warming, the change in the internal thermal state of glaciers and permafrost is the key factor impacting the rate of change and the trend of their external geometric morphology including length, area, volume, and thickness. What changes have taken place in the thermal state of the interior of glaciers and permafrost, and what impact will they exert on changing glaciers and permafrost in the future, under the influence of climate warming? Currently, observations are available for the temperature of glaciers and of frozen ground. Thus, we try to understand the impact of warming on the Cryosphere by investigating the observed temperatures of glaciers and frozen ground and their impacts on their inherent stability.

Some observations [8,9] suggest that under the impact of continuous climate warming, glaciers and permafrost are warming up. However, there is still a lack of systematic review of the response of the internal stability of the cryosphere to climate warming. This paper systematically examines the available facts on the changes of the internal thermal state of the glacier and permafrost, and analyzes the impact of the inherent stability of glaciers and permafrost on land surfaces and the hydrology in cold regions. The intention is to provide a basic understanding of the changes in the internal thermal state of glaciers and permafrost as well as impacts on their stability.

2. The warming of glaciers and permafrost

2.1. Rising englacial temperatures

As glacier mobility makes englacial boreholes unstable, it is not easy to obtain englacial temperatures at the same altitude over time. The ice temperature at the lower boundary of the active layer of a glacier is usually constant and used to characterize the ice temperature of the glacier, which is not affected by seasonal heat flux. This lower boundary is usually located approximately 10 m below the glacier surface [10]. The ice temperature was generally observed during the melting season from June to August, and the daily fluctuation of the ice temperature at the lower boundary of the active layer of glacier in the melting season was ignored. Thus, although the exact observation date of the englacial temperature of the lower boundary of the active layer of glacier could not be obtained from the literature, the englacial temperatures could still be compared. Limited observations of englacial temperature were mainly available for the Tibetan Plateau (TP), the Alps, and America. The TP includes regions at the hinterland of the Tianshan Mountains on the western side of the TP, the Qilian Mountain region on the north side, and the Himalayas to the south (Table 1).

In Urumqi Glacier No. 1 in the Tianshan Mountains, China, the englacial temperature at a depth of 10 m at an altitude of 3,845 m was −6.0 °C in 1964 and remained relatively stable during the 1960s up until 1986 [8]. After 1986, the englacial temperature increased significantly, which was consistent with the process of climate warming. This increase was particularly large and was as much as 0.065 °C a^{-1} between 1986 and 2006 (Fig. 1). Between 1964 and 2012, the average rate of englacial temperature at a depth of 10 m increased by 0.027 °C a^{-1}. The cumulative temperature increase of 1.3 °C at a rate of 0.054 °C a^{-1} between 1986 and 2012 suggests that the warming rate has decreased after 2006.

In the Qilian Mountains, the englacial temperature of Laohugou Glacier No. 12 increased by approximately 1.3 °C at a depth of 7 m at an altitude of 4,550 m, with a rate of increase of 0.038 °C a^{-1} between 1976 and 2010 (Table 1). Because the glacier mass balance in the Qilian Mountains was positive during 1970–1980 [19–21], the increasing rate of increase of englacial temperature in the Qilian Mountains should be the same as that in the Tianshan Mountains from 1970 to 2010.

In contrast, Himalayan glaciers experienced a more significant temperature increase. After correcting for the impact of the differences in observational data taken at different altitudes and depths, we found a significant increase in the rate of increase of the englacial temperature at a depth of 20 m in the Rougbuk Glacier on the northern slope of Mt. Qomolangma, in the Central Himalayas of 0.041 °C a^{-1} from 1968 to 2002 (Table 1). By comparing the ice temperature of ice borehole drilling in 1992 and 2015 at Guliya ice cape in western Kunlun Mountains on northwest of TP, ice temperature at about 5 to 30 m depth was warmer than ice measured in 1992 over the same depth interval, with the greatest differences occurring between 5 and 10 m (4 °C difference at 10 m, about 6–7 °C difference at 5 m) [14], which was notably greater than that observed in the Tianshan and Qilian Mountains during the same period.

In the Mont Blanc region in the European Alps at an altitude of 4,250 m, the englacial temperatures at depths of 40 and 20 m increased by 1 and 1.6 °C, respectively, between 1994 and 2005, with corresponding rates of temperature increase of 0.09 and 0.15 °C a^{-1} [15]. Between 1994 and 2011, the englacial temperature

Table 1
Englacial temperature variations of several glaciers in the world.

Glacier name	Observation date	Altitude (m a.s.l)	Depth (m)	Englacial temperature (°C)	Warming rate (°C a^{-1})	Source
Urumqi Glacier No. 1	1986.7.15	3840	10	−6.1	0.054	[8]
	2012.9.3	3840	10	−4.7		This study
Laohugou Glacier No. 12 in Qilian Mountain	1976	4550	7	−6.3	0.038	[11]
	2010.8.10	4551	7	−5.0		This study
Rongbu glacier in Mt. Qomolangma	1968	6325	25	−12.3	0.041*	[12]
	2002	6518	20	−9.7		[13]
Guliya ice cape, western Kunlun Mountains	1992	6200	5		About 0.3	[14]
	2015		10		0.17	
Col du Dôme, Mont Blanc area, Alps	1994–2005	4250	20		0.15	[15]
			40		0.09	
3 Sites in Mont Blanc area, Alps	1994–2011	4240–4300	40		0.024 (Site2)	[16]
					0.071 (Site3)	
Colle Gnifetti glaciers Monte Rosa area, Alps	1991–2000	4452	20		0.056	[17]
	2000–2008		20		0.163	
Brooks Range McCall Glacier, Alaska	1972–1995	1400–1900	10	>1	>0.04	[18]

* Estimated data at the same altitudes based on given temperature and latitude.

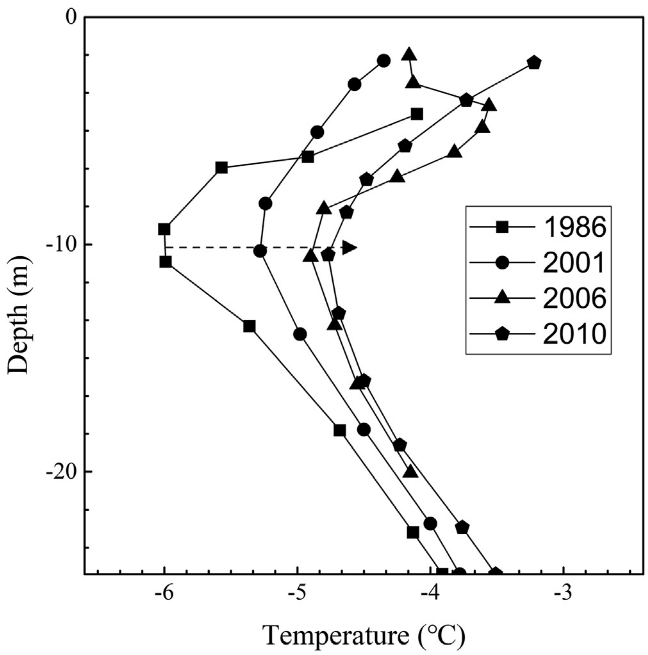

Fig. 1. Comparisons of ice temperature profiles obtained in 1986, 2001, 2006 and 2012 in elevation of 3,840 m on Urumqi Glacier No. 1, Tianshan Mountains, China. The dashed line suggests that the ice temperature at 10 m depth continually increased from 1986 to 2012.

at a depth of 40 m increased at a rate of 0.024 and 0.071 °C a^{-1} at sites 2 and 3, and the rate of increase slowed slightly after the mid-2000s [16]. In the Monte Rosa area on the border between Switzerland and Italy, the englacial temperature at a depth of 20 m in the Colle Gnifetti glacier at an altitude of 4,452 m did not change much from 1982 to 1991 but increased at a rate of 0.05 °C a^{-1} between 1991 and 2000 and further increased at a rate of 0.16 °C a^{-1} between 2000 and 2008. Despite disparities in the extent of englacial temperature increase in different regions, the observational data from different boreholes in the entire Monte Rosa area suggested that glaciers have been warming significantly since 1991 [17]. The englacial temperature at a depth of 10 m in the ablation area of the Brooks Range McCall Glacier, Alaska, increased at a rate of more than 0.04 °C a^{-1} between 1972 and 1995 [18].

These observed englacial temperature changes in the TP, the Alps, and America indicate that englacial temperatures show an upward trend, the rate of increase globally is most pronounced at the start of the 21st century, and the warming rate seems to have slowed after the middle of the 2010s.

2.2. Warming permafrost

The observed temperature data for permafrost are relatively plentiful and come from the TP, Mongolia, the Alps, Russia, Alaska, and Canada (Fig. 2).

The average warming rate of the Mean Annual Ground Temperature (MAGT) measured at a depth of 6 m in the TP at various monitoring stations was 0.02–0.06 °C a^{-1} from 1996 to 2001 [21]. The average warming rate of the MAGT was 0.03 °C a^{-1} from 1995 to 2010, slowing to 0.02 °C a^{-1} from 2006 to 2010 [7]. The MAGT at a depth of 10–15 m in the northern Tianshan Mountains increased by 0.01 °C a^{-1} between 1974 and 2009 [23]. In Mongolia, the MAGT at depths of 10–15 m increased by 0.02–0.038 °C a^{-1} in the Hovsgol Mountain region and by 0.01–0.028 °C a^{-1} in the Hangai and Hentei Mountain regions from 1998 to 2009.

In Piz Corvatsch (Upper Engadine) in the Swiss Alps, the MAGT at a depth of 25 m increased rapidly by 0.143 °C a^{-1} between 1987 and 1994 [37]. A similar significant temperature increase was

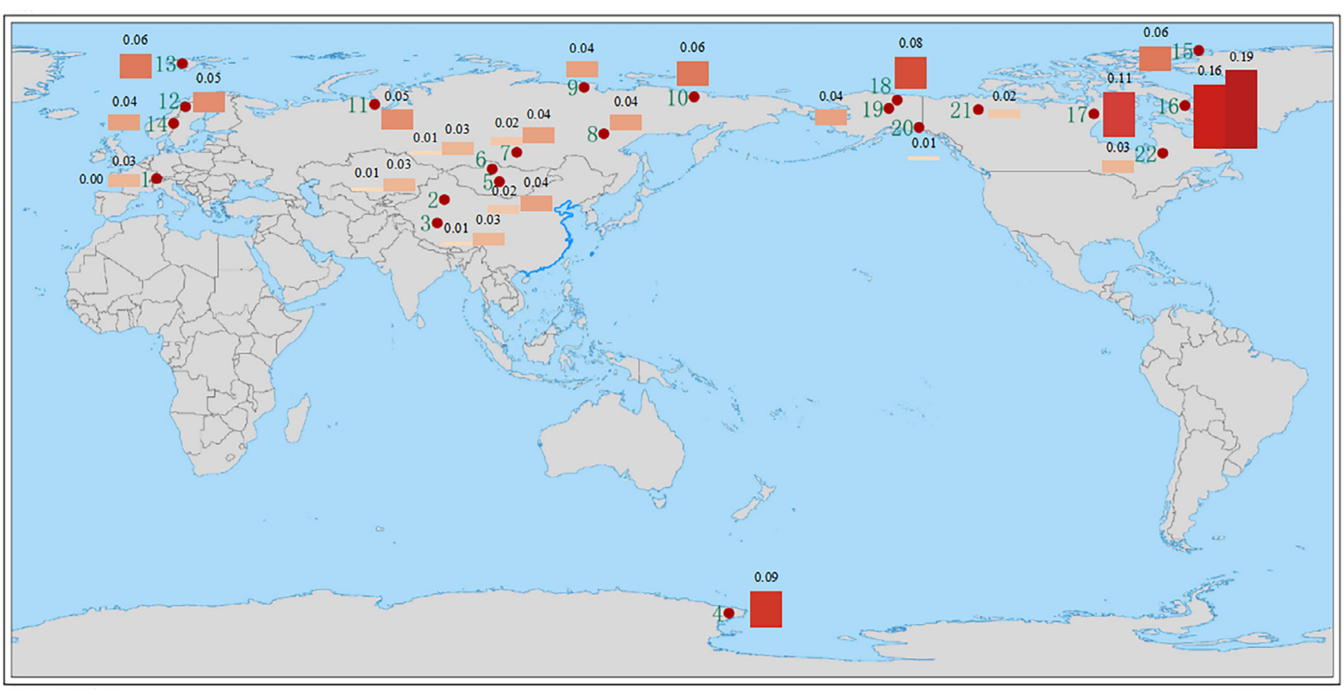

Fig. 2. Rising rate of permafrost temperature in various regions (°C a^{-1}). 1, European Alps at 15–20 m, 1990–2010 [22]; 2, Tien Shan at 10–15 m, 1974–2009 [23]; 3, Tibet Plateau at 6 m, 1996–2010 [7,9,24]; 4, Boulder Clay at 0.3 m, 1997–2009 [25]; 5, Hangai & Hentei Mt at 15 m, 1998–2009 [23]; 6, Hovsgol Mt at 10–15 m, 1998–2009 [23]; 7, Trans-Baykal at 20 m, 1988–2009 [1,26]; 8, Yakutsk at 15 m, 1961–1996 [27]; 9, Duvanny Yar at 15 m, 2007–2012 [28]; 10, Western Siberia at 10 m, 1977–2009 [1,26]; 11, Bykovsky peninsula at 15 m, 2007–2012 [29]; 12, Abisko at 12 m, 1980–2009 [30]; 13, Svalbard at 20 m, 1998–2009 [1,26]; 14, Juv-P31 at 10 m, 2000–2010 [31]; 15, CFS Alert at 15 m, 1978–2010 [6,32]; 16, Iqaluit at 5 m, 1988–2004 [33]; 17, Umiujaq at 20 m, 1998–2006 [34]; 18, Deadhorse at 20 m, 1978–2012 [29,35]; 19, Oldman at 15 m, 1984–2012 [29,35]; 20, Gulkana at 15 m, 1984–2012 [29,35]; 21, Norman Wells at 12 m, 1984–2010 [6,36]; 22, Baker Lake at 3 m, 1975–2006 [33]

found even at a depth of 60 m [38]. In the Abisko region of northern Sweden, the temperature of the top and bottom of the permafrost increased by 0.018–0.045 °C a^{-1} between 1980 and 2002, with the rate of warming at 12 m being 0.05 °C a^{-1} [30]. In the Jotunheimen and Dovrefjell in northern Norway, the warming rate of the MAGT at depths of 6.6–9.0 m was 0.015–0.095 °C a^{-1} at 16 monitoring stations, with temperatures at some stations surpassing at 0 °C [31].

The MAGT in northern Russia has increased by 0.033–0.067 °C a^{-1} over the past 30 years [26,39,40]. In East Siberia, the MAGT continued to increase between 1961 and 1996 [28], and the MAGT at 10 m increased by approximately 0.02 °C a^{-1} based on observed and estimated data [27]. The average rate of warming of the MAGT at a depth of 3 m was 0.03 °C a^{-1} across northern Russia [41]. From Yakutsk city in the east to the Bykovsky Peninsula in the northwest, for most regions across Russia, the warming rate of the MAGT at depths of 10–20 m was 0.04–0.06 °C a^{-1} during the past 20–30 years [1,26–28] (Fig. 2).

Although there are local disparities, the overall temperature at the depth with zero seasonal variance increased by 0.025–0.100 °C a^{-1} from the 1980s to the year 2000 in Alaska [32]. Between 1984 and 2012, the rate of warming of the MAGT at a depth of 15 m in Gulkana in northern Alaska was 0.01 °C a^{-1}, while the rate at the same depth in Oldman in central Alaska was 0.04 °C a^{-1}. The warming rate of the MAGT at a depth of 20 m was 0.08 °C a^{-1} between 1978 and 2012 in northernmost Alaska [26,29].

The warming rate of the MAGT was 0.02 °C a^{-1} in the mid-1980s in the Mackenzie Valley in central and northern Canada. The warming rate of permafrost was 0.08 °C a^{-1} across the entire tundra region in northwestern Canada since the 1970s. In the east arctic region, in northern Quebec, the warming rate reached 0.12 °C a^{-1} [42]. In Umiujaq, the MAGT at a depth of 20 m increased by 0.11 °C a^{-1} between 1998 and 2006 [34]. Permafrost warming in the high arctic region started in the 1970 s, with a warming rate of 0.04 °C a^{-1} [36], and this rate increased to 0.1 °C a^{-1} since the 1990s [42]. The most recent observation data from the Nunavut region in Canada from 2008 to 2014 suggest that the warming rate of the MAGT at 15 m is 0.04–0.25 °C a^{-1}. The average rate of warming for all the monitoring stations across the region reached 0.17 °C a^{-1} [43], suggesting an acceleration of the warming process of the permafrost.

In summary, over the past several decades, the temperature of the permafrost across the world has increased overall, with the rate of warming in cold permafrost (with temperatures $\leq$2.0 °C) notably greater than that in warm permafrost (with temperatures $\geq$−2.0 °C) [1]. The changes in permafrost temperature displayed distinctive regional patterns. For instance, the temperature change of permafrost in western Canada was similar to that in Alaska, while the change in the Canadian east and high arctic region was similar to that in the Nordic regions, particularly the Svalbard area, which has recently experienced a significant temperature increase [27,42]. Permafrost temperature increases in the Alps, Central Asia, and the TP were relatively consistent.

The change in permafrost temperature varied greatly from place to place due to the impact of multiple local factors, such as snow cover, slope aspect, vegetation cover, soil properties, etc., which resulted in disparities in the warming rate or even a decrease in temperature in some places [7,27,41]. In general, the rate of warming of permafrost reached its peak value in the mid-2000s and slowed slightly in the following several years. In recent years, however, there has been another upward trend in the warming of permafrost, and the rate of warming has started to increase again [43,44]. Current data show that the MAGT at a depth of 10–30 m has increased by approximately 1.5 ± 1 °C in the northern hemisphere over the past 30 years.

3. The impact of warming on the stability of glaciers and permafrost

The englacial temperature rise and permafrost warming imply that they are "heating up" on a global scale, which led to a weakening of their internal stability and will lead to more rapid and intense changes in the future.

3.1. The impact of warming glaciers

A "warming" glacier accelerates its dynamic response processes. Monitoring ice temperatures in the European Alps has shown that the temperature distribution has been far from a steady state, and all glaciers have been warming since the 1980s [15,17,45]. In fact, the actual rate of glacier warming is far greater than the simulated temperature increase in the early 2000s [46,47]. The overall rise in the englacial temperature is a response to warming of the atmosphere, which is reflected in glacier mass loss mainly through internal thermal and dynamic processes. Warming englacial temperatures indicate that there will be more significant changes in glaciers in the future.

The significant glacier mass loss since 1985 and the accelerated mass loss in the 1990s of Urumqi Glacier No. 1, Tianshan, was primarily due to the increasing englacial temperature, the prolonging ablation season, and the expanding ablation area under climate warming [48]. The impact of the current climate warming on englacial thermodynamics and kinetics has far exceeded expectations. Numerous studies [1,49–51] suggested that the relationship between the state of glaciers and the current climate has been out of balance on a global scale, and glaciers will continue to retreat even if they do not warm up any more.

On a global scale, although the rate at which temperatures are rising has increased in the 20th century, the mass loss has not been significantly greater in the second half than it was in the first half of the century [52,53]. That is, the global glacier mass balance tends to be less negative than the global rate of air temperature rise, or the ice mass loss rate was not as significant as expected. The simulated global glacier mass balance [51,54] indicated that the mass loss of glaciers in the 21st century was largely controlled by the response of glaciers to the climate in the 20th century, and further, only approximately one quarter of climate warming was caused by human emissions. However, since the late 20th century, the human contribution to global warming has increased significantly, and from 1991 to 2010, nearly 70% of glacier mass loss resulted from the accumulation of greenhouse gases in the atmosphere. These results indicate that glaciers exhibit a delayed response to climate change, which is not only due to the strength and speed of global atmospheric warming but is also closely linked with a glacier's internal heat and its dynamics.

The global temperature rise weakened the inherent stability of glaciers, and the activities of glaciers were significantly enhanced. Recently, glacier surging began to emerge in regions where such activities have been rarely observed for a long time, even in the past 100 years. For example, the Karayaylak Glacier on the north side of Kongur Tagh in the eastern Pamirs suddenly advanced a few kilometers in late April 2015 [55]. The Karayaylak glacier is the largest, with an area of 115.2 km^2 and a length of 20 km in this region. The terminus of the glacier is in an area of summer pastures, and its sudden movement buried 300 acres of pasture. Fortunately, no herders were present, and there were no casualties. Meanwhile, new type of diasters, such as the twin avalanches in Ali in 2016 appeared in TP [56]. This phenomenon indicates that the glacier's internal thermal and dynamic conditions have been greatly affected, and energy accumulated in the past will continue to be released under the ongoing effects of 20th-century climate warming. Due to the significant change in glacier stability, warming glaciers will probably continue to produce more unexpected results.

As glaciers warm and glacier lakes increase in area, the number of englacial hydrology channels also increases, which further promotes the increase in englacial temperature. More supraglacial lakes are discovered at high altitudes. At the Ngozumpa Glacier in Khumbu Himalaya, Nepal, the supraglacial lakes have expanded rapidly by 22,000 m^2 a^{-1} and can disappear when they connect with the englacial drainage system [57]. Our recent survey found that in the past 40 years, the area of the supraglacial lake at the Rougbuk Glacier on the northern slope of Mt. Qomolangma, Central Himalayas, increased by approximately 10 times. Observation results suggested that since 2000, the seeping and permeation of melting water and its refreezing increased dramatically at Alps Colle Gnifetti in Switzerland, which led to an increase in englacial temperature of 6.8 °C between 1982 and 2008 by the latent heat released during the process of seeping and permeation of melting water [17].

Englacial temperature change can also exert a significant impact on glacier mass balance [58]. Cold glaciers can reach a new balance within decades, and they are more sensitive to englacial temperature change under climate warming [59]. The Storglaciären glacier, a polythermal glacier in Sweden's subarctic region, experienced a reduction of 1/3 of its glacier surface between 1980 and 2009, with an average thinning rate of 0.80 ± 0.24 m a^{-1}. The rapid thinning of the ice surface was closely related to the englacial temperature increase caused by climate warming since the 1980s [60].

The thinning rate of the glacier surface of Hei Valley Glacier No. 8 in the Tianshan Mountains, China, was 0.42 ± 0.56, 1.47 ± 0.79, and 1.92 ± 0.98 m a^{-1} for the periods 1969–2000, 2000–2008, and 2008–2009, respectively. The increase of englacial melting water and the prolongation of time of glacier surface melting were considered to be the main driving forces for these changes [61]. Studies on the changes of the Svalbard glacier found that the thinning of the glacier surface began in approximately 1990, and the thinning rate had increased by 4 times at the beginning of the 2000s. The loss of ice volume increased as the altitude increased, with the most significant loss at the upper reaches of these Arctic glaciers [62,63]. When drilling ice cores at Mount Yuzhu of Kunlun Mountains in the TP in 2007, a water-rich ice layer was found in the glacier at a depth of 34.3–34.6 m. The liquid water was under pressure, with the water head reaching as high as 8.5 m [64].

A similar situation was found in Urumqi Glacier No. 1, Tianshan Mountains, China. In 2004, an ice surface melting pool covering an area of 30 m^2 was found in the firn area at an altitude of 4,225 m in the east branch of Urumqi Glacier No. 1. The depth of the average annual runoff of Urumqi Glacier No. 1 has doubled since 1986. This might be attributed to the reduction in glacial heat uptake due to the effects of glacier melting and continuous temperature increase [8].

These phenomena suggest that the impact of climate warming has spread to glaciers across the world. The previous thermal and dynamic balances have been disturbed, leading to a sensitive and rapid response of such ice to external disturbances.

3.2. Influence of the warming permafrost

The degradation varies greatly for different types of permafrost under the influence of climate warming. For cold permafrost (in the continuous zone), the main features include a decrease in thermal stability and little change in the active layer thickness. For relatively warm permafrost (discontinuous and sporadic zones), the main features include a gradual and slow overall temperature increase and deepening of the depth of the active layer [65]. This coincides with changes in permafrost extent and active layer thickness monitored by microwave remote sensing, land surface temperatures by Moderate Resolution Imaging Spectroradiometer (MODIS), ERA-Interim reanalysis data, and process model simulations [66].

In mountainous areas in the mid- and low latitudes, since the temperature of the permafrost is close to 0 °C, the degradation of the permafrost, featuring the deepening of the depth of the active layer and the intensification of dynamic processes, is quite remarkable. For instance, the accelerated creep of rock glaciers in the Alps was an important signal of intensive degradation of the permafrost [67]. For the discontinuous permafrost in northern Sweden, the thickness of the permafrost was reduced by 6 m between 1980 and 2009, with degradation accelerating in the past 10 years [30].

4. Discussion

4.1. Mechanism of warming weakening the stability of glaciers

In alpine regions, glaciers mainly experienced the loss of ice mass, whereas at low latitudes, there was shrinkage in area as well as loss of ice mass. This might be because glaciers in mid- to low latitudes had higher englacial temperatures, less heat uptake, and lower thermal stability, leading to a shorter response time to climate change and more significant shrinkage in glacier areas. For east branch of Urumqi Glacier No. 1, a simulation using a deterministic dynamic model, coupled with a vertically integrated finite difference Shallow Ice Approximation Model and a degree-day model, suggested that it would take approximately 180 years for the glacier to reach a steady state in the absence of changes in climatic conditions (Fig. 3) [8], indicating that the warming of glaciers has a long-term impact on glacier change. The discrepancies in the englacial thermal state resulted in a lag in the response of glaciers to climate warming [51–54], which indicated that the wide change in glacier areas in high latitudes might be a signal for a forthcoming drastic change in global glaciers in the future, for which the englacial thermal state is an important indicator.

4.2. Mechanism of warming weakening the stability of permafrost

Under climate warming, the permafrost has undergone several changes, such as overall temperature increase, reduction in vertical temperature gradient, and melting. When the ground temperature of the permafrost is low, there is a large difference between the internal and external temperature of the permafrost in summer,

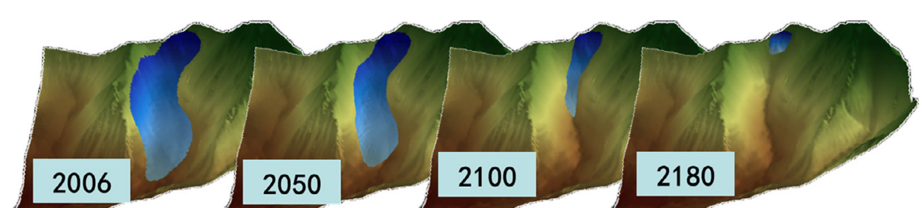

Fig. 3. Potential changes of east branch of Urumqi Glacier No. 1 simulated by dynamic model under stable climate change, which will reach a steady state in 2180 when its area and volume will account for only 4% and 1% of its current size, respectively. The glaciers are depicted in blue.

leading to a strong vertical temperature gradient and strong capacity for downward heat transmission. Thus, the external energy mainly penetrates and transfers into the inside of the permafrost, deepening the Depth of Zero Annual Amplitude (DZAA) of the permafrost. An increase in ground temperature leads to the weakening of the ground temperature gradient, a weaker capacity of heat transmission downward and a reduction in the DZAA, and a portion of the energy is used to increase permafrost temperature (Fig. 4a). When the ground temperature is near the melting point of water, 0 °C, the DZAA will be lifted up to a depth close to the surface. Then, the permafrost will be mainly influenced by latent heat, and a large portion of the energy will be consumed by melting and the blocking of the downward transmission of heat [68]. The observed temperature variation (Fig. 4a) and the one simulated by a numerical model based on the heat conduction equation with a sinusoidal surface [69] (Fig. 4b) indicate that most of the permafrost on the TP is undergoing internal thawing and experiencing latent heat effects. This seems to be a "self-protection" mechanism of the permafrost to withstand external warming [63]. In areas rich in organic matter, permafrost with a ground temperature approaching 0 °C can remain stable for a long period and this is called "ecosystem protected permafrost" [30]. This explains why the temperature of warm permafrost increased at a slower speed in many observations.

In the cold permafrost, as the climate warms, the DZAA does not change quickly, and the change in permafrost is mainly an increase

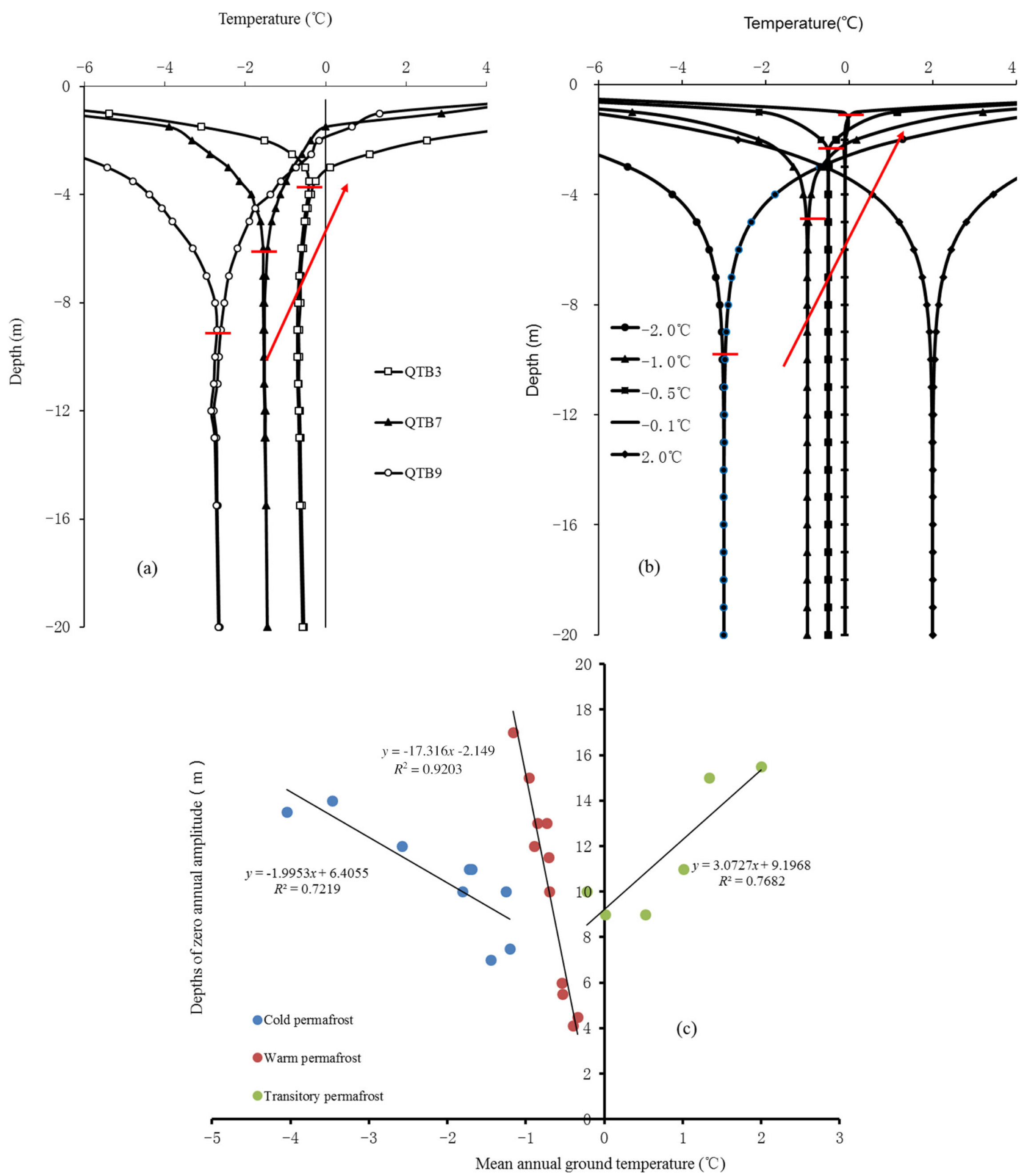

Fig. 4. The depths of zero annual amplitude (DZAA) under different ground temperatures along the Qinghai-Tibet Highway. (a) The thermal trumpet curves of ground temperature and observed DZAA (QTB3 in Qingshui river, QTB7 and QTB9 in Hol Xil). (b) The thermal trumpet curves of ground temperature and simulated DZAA based on the heat conduction equation with a sinusoidal surface temperature variation [63], in which the red bar represent the DZAA, the red arrow suggest that DZAA decrease with the increase of both observed and simulated permafrost temperature. (c) The relationships between DZAA and MAGT.

in temperature. As the permafrost continues to warm up, particularly when its temperature approaches 0 °C, the DZAA will begin to change rapidly (Fig. 4c). In other words, when the temperature of the permafrost approaches the critical point for degradation, the permafrost will consume a large amount of the thermal energy near the surface through the uplifting of the DZAA, which interrupts the transmission of the thermal energy downward. Thus, the melting of the upper limit of the permafrost will be strengthened, the depth of the active layer will be significantly increased, and the permafrost enters the substantive degradation stage [33,36,41].

Despite the close relationship between the degradation of the permafrost and its thermal dynamics, the change in permafrost is complicated by the impacts of multiple local factors, such as soil texture, terrain, vegetation, snow cover, and so on. By analyzing the relationships between the Rate of Active Layer Change (RALC, cm a^{-1}) and the MAGT at a depth of 10–20 m (Table S1 online, Fig. 5), we found that there was no obvious difference between the cold permafrost, warm permafrost and active layer change. Although the periods of observation might contribute to errors in the results, we found that the RALC at 91% of the observation stations was no larger than 10 cm a^{-1} and smaller than 2 cm a^{-1} at 56% of the stations. When the MAGT was less than or equal to −3.0 °C, the RALC was smaller than 5 cm a^{-1}. The RALC is greater than 15 cm a^{-1} only when the MAGT is larger than or equal to 2.0 °C. In other words, large RALCs were observed only in warm permafrost.

We classified the data (Table S1 online) according to an interval of the averaged RALC and MAGT. We found that with increasing permafrost temperature, the RALC displayed an obvious upward trend (Fig. 5b). When the MAGT was approximately −2 °C, the RALC changed slowly as the MAGT increased within the low temperature ranges. The RALC rose rapidly with an increase in the MAGT within the high temperature ranges, such as above −2 °C. Such results reflect a correlation between the permafrost temperature and active layer change across the world. In other words, whether the warming of permafrost will lead to significant degradation of the permafrost mainly depends on the extent of temperature increase and the thermal state of the permafrost. The transition from cold permafrost to warm permafrost is a warning sign for the comprehensive degradation of the permafrost.

The changes in permafrost displayed a similar trend. There were differences between the responses of warm permafrost and cold permafrost to climate warming, which led to significant differences in the degradation processes of the permafrost.

4.3. Prospects

The current results have clearly illustrated that the englacial temperature and warming of the permafrost had weaken the inherent stability of the glacier and permafrost. However, there are still many limitations on the understanding of the mechanism and the spatial pattern of the different response of the stability of glaciers and permafrost on warming, and the impact of weakening instability on the hydrology, hazards, and engineering, which need to multi-disciplinary approach with observation, modeling and analysis. The observation sites on englacial temperature are still limited, which lead to difficult to simulate the different response of englacial temperature to glacier mass balance under different climate zones. The permafrost effected by many local factors such as topography, soil texture, shadow, which is very complicated to simulate the spatial pattern of permafrost change. The insufficient studies on how glacial and permafrost disaster chains form and evolve, which frustrates the efforts to understand, predict, and assess the impact of the hazards [56]. These issues are need to further study in the future.

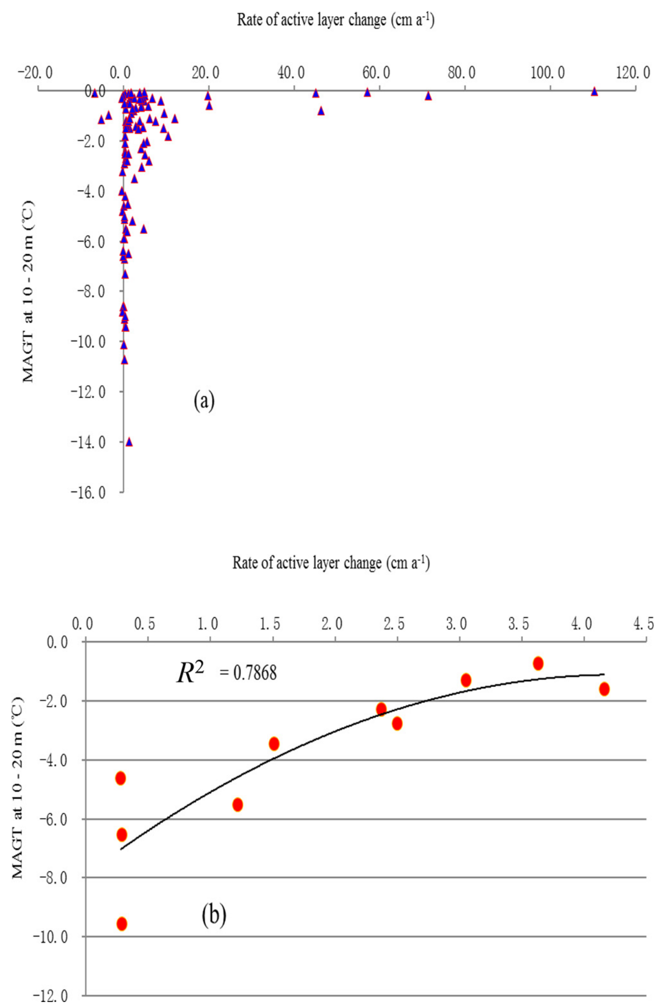

Fig. 5. (Color online) The relationships between MAGT and RALC. (a) RALC and MAGT data at 103 observational stations across the world (Table S1 online); (b) classification of the data of MAGT (Table S1 online) according to the levels of −0.5 ~ −1.0, −1.0 ~ −1.5, −1.5 ~ −2.0, −2.0 ~ −2.5, −2.5 ~ −3.0, −3.0 ~ −4.0, −4.0 ~ −5.0, −5.0 ~ −6.0, −6.0 ~ −7.0, <−7.0 °C, and averaging the MAGT and RALC. The fluctuation range of RALC at the MAGT 0 ~ −0.5 °C was the largest, with the mean value of 12.98 cm a^{-1}.

5. Conclusions

Based on the analysis presented here, we can conclude that the following:

(1) Englacial temperature increase and warming of the permafrost have occurred extensively across the world. The internal temperature of glaciers and permafrost showed an increasing trend in the past 30 years. In the mid-2000s, the rate of warming reached its peak value, slightly declining in the following several years but showed an obvious warming trend again in recent years. The englacial temperature of mountain glaciers displayed a rate of warming of 0.04–0.10 °C a^{-1}. The rate of warming for permafrost differed between warm and cold permafrost. The internal temperature of permafrost at a depth of 10–30 m in the northern hemisphere increased by 1.5 ± 1 °C in the past 30 years.

(2) The warming of glaciers and permafrost has exerted a significant impact on their inherent stability, which is exhibited as intensified melting, increased glacier surging, enlargement of supraglacial lakes, and increased permafrost degradation.

(3) Even if the englacial temperature will no longer increase in the future, glaciers will continue to retreat. Whether the warming of permafrost will lead to significant degradation of permafrost mainly depends on the extent of the temperature increase and the thermal state of permafrost. The transition from low-temperature permafrost to high-temperature permafrost is a warning sign for the comprehensive degradation of permafrost.

Conflict of interest

The authors declare that they have no conflict of interest.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.scib.2018.12.028.

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