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Changing climate and the permafrost environment on the Qinghai–Tibet (Xizang) plateau

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Abstract

Permafrost on the Qinghai–Tibet Plateau (QTP) has undergone degradation as a result of recent climate change. This may alter the thermo-hydrological processes and unlock soil organic carbon, and thereby affect local hydrological, ecological, and climatic systems. The relationships between permafrost and climate change have received extensive attention, and in this paper we review climate change for permafrost regions of the QTP over the past 30 years. We summarize the current state and changes in permafrost distribution and thickness, ground temperature, and ground ice conditions. We focus on changes in permafrost thermal state and in active-layer thickness (ALT). Possible future changes in ground temperature and ALT are also discussed. Finally, we discuss the changes in hydrological processes and to ecosystems caused by permafrost degradation. Air temperature and ground temperature in the permafrost regions of the QTP have increased from 1980 to 2018, and the active layer has been thickening at a rate of 19.5 cm per decade. The response of permafrost to climate change is not as fast as in some reports, and permafrost degradation is slower than projected by models that do not account for conditions deep in permafrost.

KEYWORDS
active layer, air temperature, climate change, ground temperature, permafrost

1 | INTRODUCTION

Tectonic movements over 200 million years have raised the Qinghai–Tibet Plateau (QTP) from below sea level in the Tethys Sea to become the highest plateau of the mid- to low latitudes on Earth. During uplift, the climate of the QTP gradually changed from warm and humid to cold and dry, and permafrost formed as elevation increased. At the Last Glacial Maximum more than 20,000 years ago, at least 2.2 million km^2, or 85% of the plateau, was underlain by permafrost.[1] Since then, the extent of permafrost on the plateau has declined with Holocene climate warming. The climate on most parts of the plateau is now characterized by low humidity, low precipitation and strong solar radiation. It is particularly sensitive to global climate change,[2] due to its high altitude with large dynamic and thermal effects, and is regarded as an indicator region for global climate change.[3–6] As a result of its altitude, the QTP has the lowest mean annual air temperature (MAAT) for its latitude; for instance, average January and July temperatures on the QTP are 15–20°C lower than on the eastern plain of China. However, the daily temperature range is larger than in the eastern plain.[7] The surface energy and water cycles of the QTP influence the East Asian atmospheric circulation and global climate. The QTP has the largest high-altitude permafrost zone of the middle and low latitudes. Since the 1950s, the climate on the QTP has become warmer and wetter,[8] with the warming rate almost twice the global average.

Permafrost currently underlies approximately 1.06×10^6 km^2 or 40% of the total area of the QTP,[9] and permafrost thickness along the Qinghai–Tibet Highway (QTH) varies from 10 to 312 m.[10] As climate warming proceeds, the permafrost area is shrinking, the permafrost temperature is increasing, the active layer is thickening, and permafrost thinning has been widely recorded.[11–13] The lower limit of permafrost on north-facing slopes of the QTP has risen by 25 m in the past 35 years, and the lower elevational limit of permafrost on south-facing slopes has increased by 50–80 m in the past 20 years.[11,14] Meanwhile, ground temperature at a depth of 6.0 m along the QTH has increased by 0.08–0.55°C since 1996.[12,15,16]

Changes in permafrost conditions have affected the surface energy balance and carbon cycles on the plateau.[1,17–19] These changes have increased the decomposition rate of organic matter frozen within the permafrost and the rate of emission of greenhouse gases,[20,21] affecting the local and even the global climate system.[22,23] The changes to permafrost have also affected the stability of engineering structures,[1] and will continue to affect infrastructure design, construction, and maintenance in this region. Permafrost degradation has caused changes in the ecological environment and to hydrological processes, even leading to desertification.[1,11,17]

The Cryosphere Research Station on the Qinghai–Xizang Plateau, Chinese Academy of Sciences, has established a long-term permafrost monitoring network on the QTP. This paper summarizes the changes in climate and active-layer thickness (ALT), ground temperature, and permafrost thickness collected through this network, and also presents predictions of future permafrost changes.

2 | WARMING CLIMATE IN THE PERMAFROST REGION

Meteorological stations on the QTP are sparsely and unevenly distributed. Most are located in cities on the eastern plateau, although there are few in the vast western part, especially in the permafrost regions at high altitude. Most previous studies have reported climate change on the entire QTP, indicating warming rates of 0.40–0.52°C per decade since the 1980s.[8,24,25] The warming rate has varied seasonally, especially in the high plain. For 1998–2012, MAAT increased by 0.20°C per decade overall, but in the high plain summer warming has been 0.34°C per decade. The rate has been lower in spring and winter and there has been cooling in autumn.[26] The increase in precipitation has been less apparent than for temperature and has been spatially variable. From 1979 to 2001, precipitation rose by 4 mm per decade in the northwest of the plateau and approximately 17 mm per decade in the southeast.[27,28] The increase in precipitation was not evident in the source region of the Yangtze River, but was significant in the source region of the Yellow River.[29]

The climate changes summarized above are for the entire plateau; however, in the permafrost regions, with limited data acquisition, the characteristics of climate change are less well understood. Data from eight meteorological stations in the permafrost regions reveal the characteristics of climate change over 37 years (1981–2017) (Table 1 and Figure 1).

In permafrost regions of the QTP, MAAT has been below 0°C in all stations except Gaize (0.64°C). The lowest MAAT, −4.82°C, was recorded at Wudaoliang. Annual precipitation was between 300 and 550 mm at all stations except 181.8 mm at Gaize (Table 1). The average rate of increase in MAAT was 0.62°C per decade at the eight stations, indicating warming in the permafrost regions on the QTP. The highest warming rate was 0.71°C per decade at Tuotuohe, while the lowest values were 0.54°C per decade at Wudaoliang and Anduo. The warming trend was greater in the cold season of May–September (0.83°C per decade) than in the warm season of November–March (0.44°C per decade) (Figure 1a). Climate warming has occurred faster in the permafrost regions than in the non-permafrost areas. Annual precipitation also showed a significant trend (16.3 mm per decade) in the permafrost regions during 1981–2017 (Figure 1b). Overall, the climate in most permafrost regions on the QTP is becoming warmer and wetter.[8]

3 | CURRENT STATUS OF PERMAFROST DISTRIBUTION

3.1 | Permafrost distribution and temperature

Almost all permafrost maps at the continental or regional scale are based on statistical relationships between permafrost distribution and air or ground surface temperature. The limit of permafrost coincides with the 0°C isotherm of MAAT in the circum-Arctic, but with the −2 to −3°C isotherms on the QTP.[9,30–32] Reliable data on the spatial distribution of permafrost temperature, thickness, and ground ice were not acquired on the QTP until 2017 because borehole data were available previously at only a few locations.[33,34] Since 2009, we have conducted extensive investigations and monitored the distribution and characteristics of permafrost on the QTP,[7,35,36] and have constructed a model for the temperature at the top of the permafrost (TTOP model) with full consideration of vegetation, geomorphological, and geological factors. The modeled permafrost distribution has been clearly verified.[36,37] The results indicated that the areas of permafrost and seasonally frozen ground on the QTP are 1.06×10^6 and 1.45×10^6 km^2, respectively, accounting for 40% and 56% of the entire QTP (Figure 2).[9]

Using the regression model to infer mean annual ground temperatures (MAGTs), the permafrost on the QTP can be classified into five types: very stable (MAGT < −5°C), stable (−5°C < MAGT <−3°C), substable (−3°C < MAGT < −1.5°C), transitional (−1.5°C < MAGT < −0.5°C) and unstable (−0.5°C < MAGT < 0.5°C), with the areas of 0.059×10^6, 0.195×10^6, 0.308×10^6, 0.224×10^6, and 0.229×10^6 km^2, respectively (Figure 2). Substable (30.4%), transitional (22.1%), and unstable permafrost (22.6%) make up the majority of permafrost regions on QTP.

TABLE 1 Climate change in permafrost regions on the QTP during 1981–2017

Site	Latitude (°N)	Longitude (°E)	Elevation (m)	MAAT (°C)	Trends in MAAT (°C per decade)	Annual precipitation (mm)	Trends in precipitation (mm per decade)
Wudaoliang	35.13	93.05	4,612.2	−4.82	0.54	311.6	29.71
Gaize	32.09	84.25	4,414.9	0.64	0.69	181.8	31.49
Anduo	32.21	91.06	4,800.0	−2.20	0.54	459.1	6.34
Naqu	31.29	92.04	4,507.0	−0.40	0.64	455.2	13.80
Tuotuohe	34.13	92.26	4,533.1	−3.51	0.71	301.6	21.23
Qumalai	34.08	95.47	4,231.2	−1.49	0.66	424.5	6.59
Maduo	34.55	98.13	4,272.3	−3.11	0.58	337.4	12.37
Qingshuihe	33.48	97.08	4,415.4	−4.07	0.63	526.7	−0.81

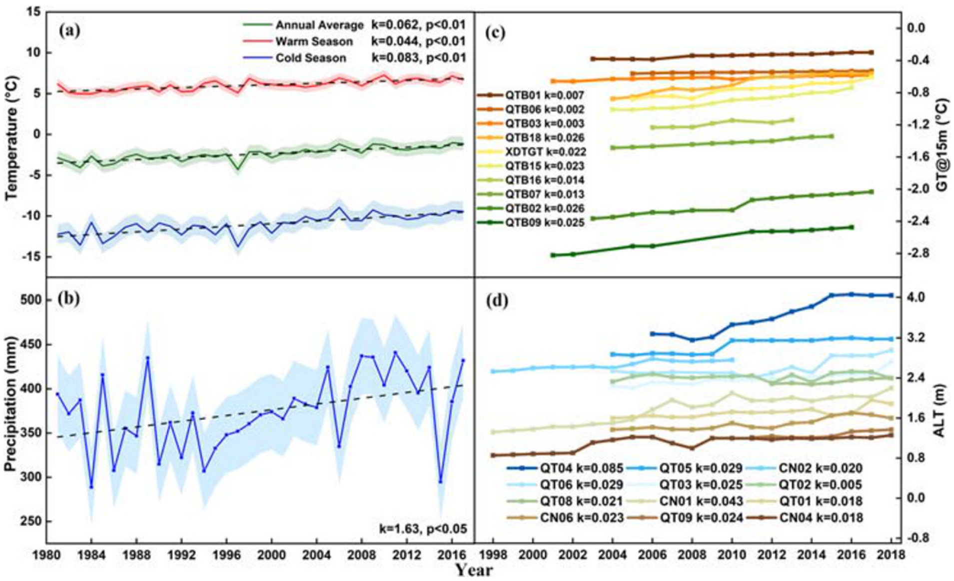

FIGURE 1 (a) Changes in MAAT and (b) annual precipitation in permafrost regions of the QTP during 1981–2017 (the solid lines indicate average values, and the light-colored areas show the mean ± SD), (c) variation of ground temperature at 15 m depth and (d) active-layer thicknesses along the Qinghai–Tibet highway in the last two decades. For all graphs, *k* gives the average annual rate of change

3.2 | Permafrost thickness and ground ice

Permafrost thickness and ground ice content are two key factors affecting engineering construction in cold regions. Permafrost thickness is mainly influenced by MAGT and geothermal gradient.[38] On average, for every 1°C increase in MAGT, permafrost thickness decreases by about 31 m on the QTP. The spatial distribution of permafrost thickness on the QTP has been obtained using MAGT (Figure 2a) and this inverse relationship (Figure 1d). The thickness ranges from several meters to about 350 m. Permafrost is thicker on the Qiangtang Plateau and the Kunlun Mountains which lie in the central QTP. Permafrost thickness is more than 200 m near the mountain ridges at high elevation (generally above 5,500 m a.s.l.), 60–130 m in hilly landscapes, and less than 60 m in valley bottoms on the high plateau.

The formation and variation of ground ice have influenced the regional hydrological cycle,[39] ecological system,[40] climate system,[41] topography and construction stability. Using data for dry density and water content from 164 boreholes, the horizontal and vertical distribution of ice content in different sedimentary types on the QTP has been analyzed.[7] The gravimetric ice content ranges from 12% to 48%, is highest in fluvioglacial sediments, then in lacustrine sediments and in weathered residual slide rock. The ice content is relatively low in alluvial sediments and carbonatite, clastic, pyrogenic, and metamorphic rocks. Ice-rich layers are consistently found near the permafrost table on the plateau, where ALT is generally 2–3 m. The ice content increases with depth from 3 to 10 m and remains relatively stable below 10 m.[7] Total ground ice storage on the QTP of about 12.7×10^3 km^3 water-equivalent has been calculated based on the ice content distribution, permafrost distribution, Quaternary sedimentary type, and permafrost thickness (Figure 2b).[7] Ground ice content increases from south to north and from east to west on the QTP, and is higher in the HohXil area and West Kunlun Mountains than in other regions.[7] The estimate is within the range obtained for ice content along the QTH (10.9–17.4 $\times 10^3$ km^3 water-equivalent) by Nan *et al.*[37] but higher than the estimate based on the ground ice distribution in different topographic units along the highway (9.5 $\times 10^3$ km^3 water-equivalent).[32]

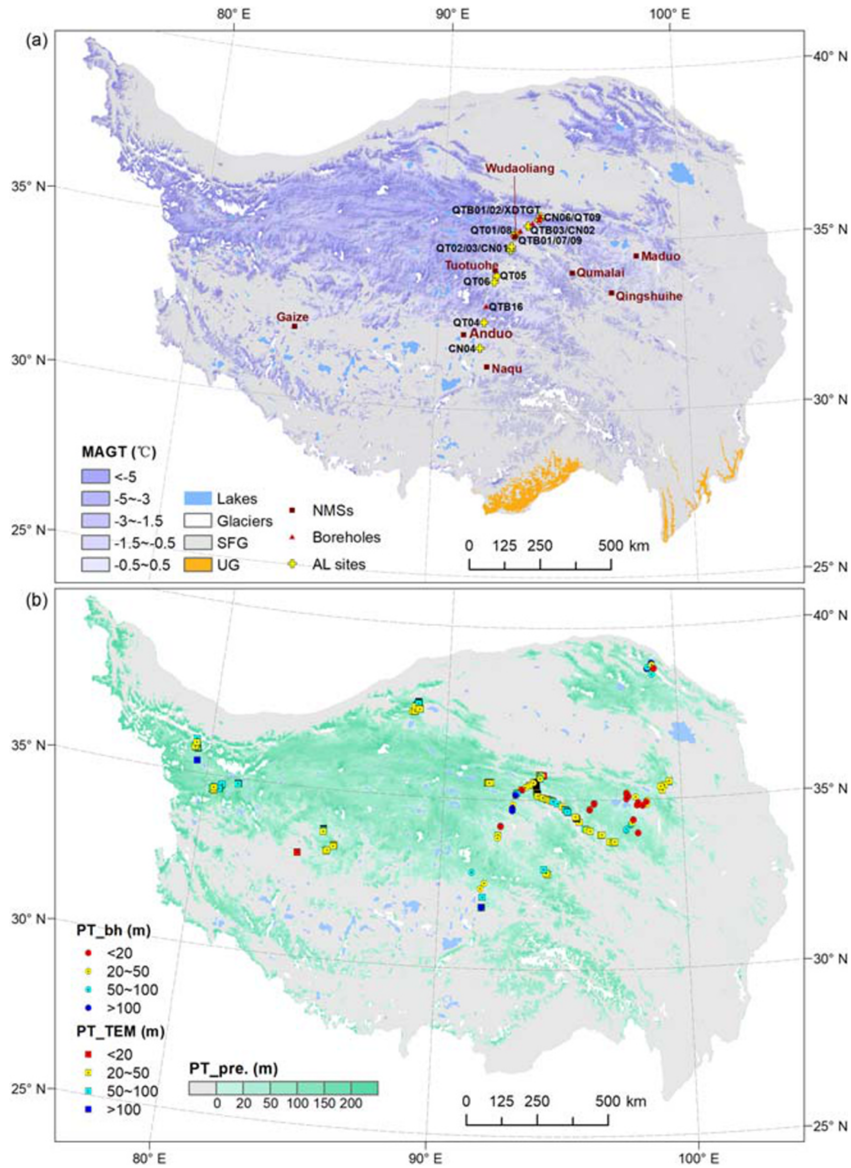

FIGURE 2 (a) Predicted MAGT at a depth of 10–15 m and (b) permafrost thicknesses on the QTP. SFG, seasonally frozen ground; UG, unfrozen ground; NMSs, China meteorological stations; AL, active layer; PT_bh, permafrost thicknesses observed from boreholes; PT_TEM, permafrost thicknesses derived by the time domain electromagnetic method

4 | CHANGES AND PROJECTIONS OF PERMAFROST CONDITIONS

4.1 | Changes of permafrost temperature

At present, permafrost is warming or degrading globally due to climate change. There are substantial regional differences in the rate of permafrost warming due to differences in ground ice content, ground temperature, and regional climate patterns. In the high Arctic continuous permafrost zone, permafrost temperatures increased by 0.39 ± 0.15°C over the decade 2007–2016.[42] Over the same period, discontinuous permafrost in the Arctic regions warmed by 0.20 ± 0.10°C and mountain permafrost in the European Alps, the Nordic countries, and central Asia (including the QTP) increased by 0.19 ± 0.05°C.[42] The most substantial increase has been observed where permafrost temperatures are lowest. At ice-rich locations with permafrost temperatures close to 0°C, the increase has been relatively low due to the influence of phase change in soil pore water. At Alert on northern Ellesmere Island, Canada, where MAGT was −14°C, a warming rate of 0.6°C per decade at 15 m depth has been recorded since 1978.[43] In the central and southern Mackenzie Valley, the warming rates of permafrost (> −2°C) monitored at Norman Wells and Wrigley were 0.14 and 0.09°C per decade respectively over a similar period.[43]

Previous studies have indicated that the depth of zero annual amplitude in ground temperature is generally between 3.5 and 17 m in the permafrost regions along the QTH.[44] Ground temperature at a depth of 15 m was taken as the reference depth for MAGT to analyze changes in 10 boreholes from 2001 to 2017 (Table 2). The MAGT of these boreholes ranged from −2.61 to −0.34°C. Ground temperatures increased from 2001 to 2017, indicating noticeable permafrost warming. Higher warming rates (0.25–0.26°C per decade) were observed at boreholes QTB02, QTB09, and QTB18, with average MAGT of −2.19, −2.61, and −0.68°C respectively, while slower warming occurred at QTB01, QTB03, and QTB06 (0.02–0.07°C per decade), with average MAGT of between −0.34 and −0.61°C

TABLE 2 Information from boreholes along the QTH for long-term ground temperature observations

SN	Longitude (°E)	Latitude (°N)	Elevation (m)	Warming rate (°C per decade)	Position	Permafrost distribution type
QTB01	35.72	94.08	4,516	0.07	Xidatan	Northern limit, island permafrost
QTB02	35.63	94.06	4,747	0.26	Kunlun Mountain	Continuous permafrost
QTB03	35.52	93.78	4,580	0.03	66 Daoban	Continuous permafrost
QTB06	35.49	93.68	4,526	0.02	Hoh Xil grand bridge	Continuous permafrost
QTB07	35.19	93.07	4,642	0.13	Wudaoliang	Continuous permafrost
QTB09	35.14	93.04	4,717	0.25	Wudaoliang	Continuous permafrost
QTB15	33.10	91.90	4,936	0.23	Tanggula Mountains	Continuous permafrost
QTB16	33.07	91.94	5,045	0.14	Tanggula Mountains	Continuous permafrost
QTB18	31.82	91.74	4,802	0.26	Liang Daohe	Southern limit, island permafrost
XDTGT	35.72	94.13	4,450	0.22	Xidatan	Northern limit, island permafrost

(Table 2). Warming rates in boreholes with MAGT lower than −0.6°C were between 0.1 and 0.3°C per decade, and were low or even negligible in boreholes with MAGT above −0.6°C (Figure 1c). The lowest temperature change was recorded in "warm" permafrost close to 0°C caused by the steep slope of the unfrozen water content characteristic curve in this temperature range.[45–47] Laboratory tests on the soil freezing–thawing process showed that for silt, the temperature of spontaneous nucleation for ice is at −0.55°C.[48]

4.2 | Changes in active-layer thickness

Due to rising air temperatures, ALT has increased in the circum-Arctic permafrost region since the 1990s, but, as on the QTP, there is regional variation in the rate of active-layer deepening (Figure 1d). For example, since 2013, ALT has increased in eastern Siberia and the far east of Russia at a rate of about 1 cm/year, with up to 4 cm/year measured at several locations such as at Isit, Sanaga, Norils'k and Suntar.[49] In 2016, measurements of the Circumpolar Active Layer Monitoring network indicated ALT at all Arctic sites to be at or near the maximum for the past 18–21 years.

Monitoring of 10 boreholes on the QTP show that from 1981 to 2018, the active layer has thickened at an average rate of 19.5 cm per decade and that the thickening has been accelerating recently (Figure 1d). In the past 21 years (1998–2018), ALT increased by 28 cm per decade on average[50] and MAGT at the bottom of the active layer increased at a rate of 0.49°C per decade. Even in 2017/18, MAGT increased by nearly 0.1°C at the bottom of the active layer.[50]

4.2.1 | Simulations of permafrost changes on the QTP

Simulations of permafrost changes under different RCP scenarios[51–53] indicate that the permafrost area on the QTP may decrease. The projected decline is by 8.8–20.8% in the next 50 years and 13.4–27.7% by 2100 under the RCP 2.6 scenario. Under the RCP 8.5 scenario, the decline is simulated as 13.5–39.6% in the next 50 years and 60–90% by 2100. These predictions were made using projections of effects on the surface energy balance and heat conduction theory. However, permafrost conditions are a product of particular climatic conditions operating over time.[54] Permafrost in the QTP formed over a long period of cold paleoclimate, during which a large amount of energy was released to the atmosphere, and a so-called "cool-energy-pool" (CEP) developed gradually within the permafrost. Such a CEP is an energy state characterized by low ground temperature and ground ice in permafrost. These properties of permafrost have not been considered in the applied models.[55]

A numerical heat conduction model, in which ground ice distribution, ground temperature, and geothermal heat flow were considered, was used to simulate the impact of future climate change on permafrost temperature in three boreholes on the QTP (XDTGT, QTB09, QTB16; see Figure 2) under the RCP 2.6, 6.0 and 8.5 scenarios (Table 3). The model was validated over the period 1966–2012 with replication of ground warming and ALT at each site.[56] The simulation results indicate that ground temperature at a depth of 15 m increased from −1.2 to −0.6°C at XDTGT, from −1.9 to −1.3°C at QTP09, and from −1.5 to −1.0°C at QTB16 in 1966–2012. ALT increased from 1.2 to 1.5 m at XDTGT, from 2.0 to 2.2 m at QTB09, and from 2.7 to 3.2 m at QTB16. Table 3 presents the state of permafrost projected for the three sites by 2100 under the RCP emissions scenarios. RCP 2.6 gives the smallest change from present conditions, with permafrost still expected at all sites. Under RCP 8.5, the change is the greatest and substantial permafrost degradation is projected. With RCP 6.0, the ground temperature at 15 m depth indicates the continuing presence of permafrost, but at all sites thaw depth is projected to be greater than at present. The specific temperature of the permafrost close to 0°C demonstrates the importance of soil latent heat in the determination of the projected presence or absence of permafrost.

The modeled results indicate that permafrost degradation does not follow a linear trend and the response of permafrost temperature

TABLE 3 Permafrost state by 2100 under different RCP scenarios

Site	Ground temperature at 15 m (°C)			Depth of permafrost table (m)		
	RCP 2.6	RCP 6.0	RCP 8.5	RCP 2.6	RCP 6.0	RCP 8.5
XDTGT	−0.2	−0.2	0	1.8	6.5	15
QTB09	−0.4	−0.3	0	2.95	7.5	15
QTB16	−0.3	−0.3	0.52	3.6	10	18

to climate warming is not as rapid as forecast in many published reports.[34,53,57,58] Under the RCP 8.5 scenario, the permafrost table would deepen slowly, and permafrost would still remain at 40 m at Wudaoliang and Tanggula by 2050, while the permafrost base would move upwards significantly at Xidatan. The former two boreholes are in the continuous permafrost zone with lower ground temperature and thicker permafrost. The Xidatan site is located just at the lower boundary of the permafrost zone on the QTP, where the ground is warmer and permafrost is just 32 m thick. Even so, permafrost would still exist there in 2100.

4.3 | Effects of permafrost changes on the environment

4.3.1 | Hydrology and water resources

The permafrost regions of the QTP contain the source areas of many major rivers. Thickening of the active layer and melting of ground ice may affect the hydrological cycle, runoff generation, and confluence processes in the source basins of these rivers.[59] Changes in base flow may be expected due to alterations in storage capacity and water supply in the thawed active layer.[60]

Permafrost does not significantly affect streamflow regimes where the spatial extent of permafrost is less than 40%, but it strongly affects the discharge regime in regions with higher permafrost coverage.[61] Estimates of permafrost area and ground ice storage in the major river basins on the QTP are presented in Table 4.[7] The area underlain by permafrost in the major river basins ranges from less than 10% to more than 60%. There is relatively little permafrost coverage in the eastern part of the QTP, and, as a result, rivers whose headwaters rise there may be less sensitive to permafrost change than those in the northern and western regions of the QTP. The extent of permafrost coverage in most watersheds is less than 60%, but it is higher than 60% in the watersheds of the Qilian Mountains and between Kunlun and Tangula mountains (Table 4). The extent of permafrost increases with elevation, so the effect of permafrost on river runoff will be more prominent at higher elevations.

TABLE 4 Permafrost area and ground ice storage in the major river basins on the QTP and surrounding areas

River basin	Basin area (km^2)	Permafrost area (km^2)	Ground ice (km^3)	Permafrost coverage (%)	Ice storage per permafrost area (kg/m^2)
Qiantang plateau inflow basin	662,953	415,193	5,594	63	13,474
Qaidam inflow basin	271,017	83,570	1,067	31	12,767
Yangtze River	214,048	115,791	1,014	54	8,757
Cheerchen River	70,472	39,151	689	56	17,590
Yellow River	194,412	62,424	578	32	9,263
Hetian River	38,221	25,410	482	66	18,979
Yarlung Zangbo River	186,290	53,751	433	29	8,050
Nujiang River	108,802	42,145	375	39	8,903
Kyria River	25,595	17,515	318	68	18,184
Qinghai lake inflow basin	40,262	17,954	241	45	13,400
Shule River	31,726	20,066	233	63	11,628
Yarkant River	24,262	13,228	205	55	15,471
Indus River	57,687	21,756	199	38	9,149
Lancang River	80,452	21,945	188	27	8,582
Yalong River	102,554	17,855	149	17	8,352
Tibetan rivers in southern Tibet	98,071	22,545	143	23	6,357
Heihe River	24,305	13,776	127	57	9,226
Dadu River	61,809	4,430	39	7	8,791
Shiyang River	4,466	2,355	25	53	10,540

In addition, using stable isotopes and a multi-source hydrological model, soil moisture in the active layer has been determined to be the main source for replenishing the ice layer in the upper permafrost.[50] Analysis of hydrogen and oxygen isotopes from river water in the Fenghuoshan region of the QTP has shown that the change of soil freeze–thaw depth has an important effect on runoff in the permafrost region.[62] Based on the distribution of ground ice and the current thickening rate of the active layer, on average about 80 km^3 of underground ice in the permafrost region of the QTP is expected to melt each decade in the near future and be introduced to the regional water balance. Deepening of the active layer will intensify the infiltration of soil moisture and reduce the surface soil moisture, leading to vegetation degradation and changes in the interception and distribution of rainfall.[63] In addition, a reduction of root systems and fine soil particles from vegetation decomposition will reduce soil water retention. In general, degradation of permafrost will reduce the ability of grassland ecosystems on the QTP to regulate runoff. Under climate warming, melting of ground ice may release a certain amount of water that then participates in the regional water cycle. Some studies show that melting of ground ice together with runoff yield and concentration may be one of the causes of the increase in lake water levels in most basins in the hinterland of the QTP, accounting for 12% of the lake volume increase.[64]

Observations at the Hoh Xil site (QT01) from 2004 to 2017 show that ALT increased from 160 to 176 cm. As permafrost thawed, melting of ground ice released a large amount of liquid water, resulting in an increase in water content at the bottom of the active layer. Degradation of permafrost has led to more surface water infiltration into groundwater in the basin, resulting in an increase in groundwater storage in the basin[65] and an increase in winter runoff.[66,67] Studies in high latitudes show that the melting of ground ice, deepening of the active layer, and the extension of the melting period may lead to a significant increase in winter base flow and warm season runoff.[68,69] In discontinuous frozen soil regions, the melting of ground ice significantly increases the river base flow in winter, and the increase in area of unfrozen soil reduces the seasonal hydrograph peak.[70,71]

4.3.2 | Impact of permafrost changes on ecosystems

Permafrost degradation may also alter soil nutrient status. Statistical associations between nutrient availability and permafrost dynamics have been investigated in the Tibetan grassland,[72] where topsoil available N increased from the 1980s to the 2010s by 45 and 12% for regions with permafrost and seasonally frozen ground, respectively. Available P in topsoil increased by 25% for permafrost regions, but decreased by 19% in seasonally frozen ground. In contrast, available K in topsoil decreased by 16 and 27% at permafrost and seasonally frozen sites, respectively.[72] These results suggest that if climate warming continues on the QTP, permafrost degradation may increase soil N availability, leading to shifts in nutrient limitation for Tibetan ecosystems.

Changes to thermal and hydrologic processes in the active layer may affect alpine ecosystems. Plant above-ground biomass has been negatively associated with ALT on the QTP, suggesting that the active layer can directly affect plant growth through water supply, as permafrost degradation may lead to a decrease in plant biomass when precipitation does not change significantly.[63]

Laboratory experiments indicate that climate warming not only promotes plant growth during growing seasons, but also increases ecosystem carbon flux during the rest of the year on the QTP. Research suggests that enhanced plant biomass in summer may not lead to an increased ecosystem carbon sink.[73] Ecosystem carbon flux on the QTP is higher in non-permafrost regions than in areas with permafrost,[74] but accumulation of soil active carbon fractions shows the opposite.[75] These results reveal that permafrost degradation could accelerate the decomposition of soil carbon, so that, potentially, the soil organic carbon pool in the Tibetan permafrost regions may decrease by approximately 3% by 2050.[36] However, the effect of permafrost degradation on soil carbon remains uncertain (Figure 3).

5 | CONCLUSION

The QTP has the largest high-altitude permafrost zone in the middle and low latitudes on Earth. Permafrost underlies approximately 1.06×10^6 km^2 or 40% of the total area of the QTP. The majority of the permafrost on the QTP is of the substable (30.4%), transitional (22%), and unstable (23%) types. Since the 1950s, climate on the QTP has become warmer and wetter, with the warming rate in the permafrost regions being higher than in the non-permafrost regions. For every 1°C increase in MAGT, the permafrost thickness is estimated to decrease by 31 m. Ground ice storage in the permafrost region on the QTP is 12.7×10^3 km^3 water-equivalent and is higher in the northern and western QTP than in the eastern and southern part. The temperature of permafrost has risen at a rate of 0.02–0.26°C per decade. The warming rate is relatively low in "warm" permafrost regions because melting of ground ice absorbs large quantities of heat and the permafrost temperatures have only increased slightly or have remained constant. The response of permafrost to climate warming is a slow and lagged process. Current models of future permafrost degradation do not consider the historical energy accumulation in permafrost and the impact of ground ice buried 1 m or further below the ground surface. As a result of permafrost degradation, permafrost plays a key role in the changing water cycle and river runoff on the QTP, but the amount and process by which melting of ground ice stored in permafrost contributes to surface runoff remains unclear.

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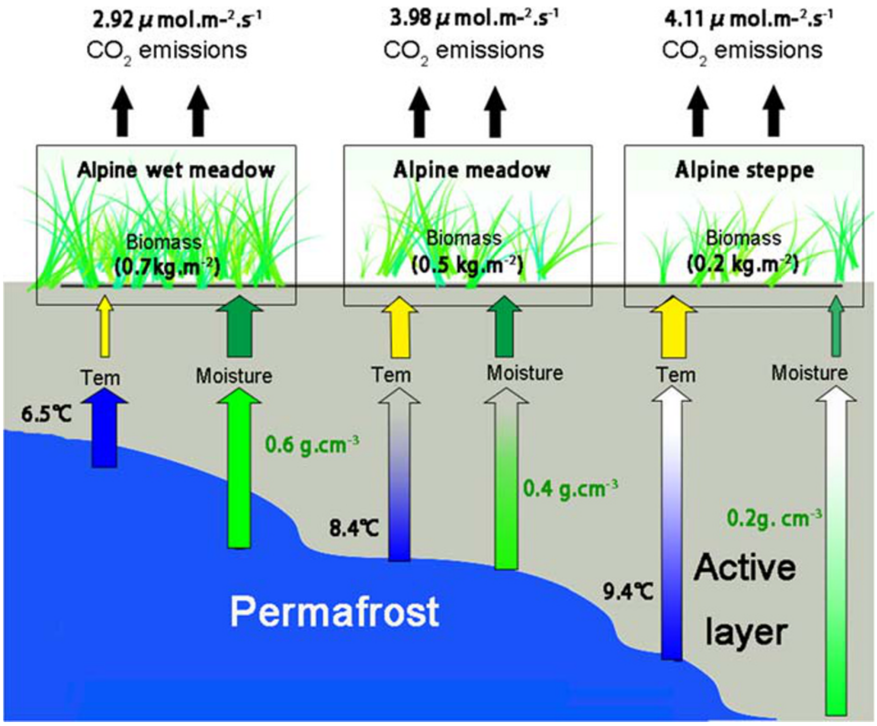

FIGURE 3 Schematic diagram of the effects of permafrost on ecosystem respiration. The blue and green arrows show the effects of permafrost on soil temperature (Tem) and moisture, and the faded arrows show the effects of permafrost decrease as the active layer deepens. The yellow and dark green arrows show the positive effects of soil temperature and negative effects of moisture on ecosystem respiration. The larger arrows indicate stronger effects[73]

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