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Permafrost Degradation on the Qinghai–Tibet Plateau and its Environmental Impacts

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ABSTRACT

An increase of mean annual air temperature (MAAT) of about 0.2–0.4 °C on the Qinghai–Tibet Plateau as compared with the 1970s, and especially winter warming, has resulted in extensive permafrost degradation. An increase of 0.1–0.5 °C in the mean annual ground temperature (MAGT) has been observed. Discontinuous permafrost bodies and thawed nuclei have been widely detected. The lower altitudinal limit of permafrost has risen 40–80 m on the Qinghai–Tibet Plateau. The total permafrost area on the Plateau has shrunk about 10^5 km^2. Permafrost degradation has caused environmental deterioration, including the destabilization of buildings, impacted upon cold regions hydrology and water resources, and accelerated desertification. Copyright © 2000 John Wiley & Sons, Ltd.

RÉSUMÉ

Une augmentation de la température moyenne annuelle (MAAT) d'environ 0,2 à 0,4 °C sur le plateau Qinghai-Tibet (QTP) et aussi un réchauffement d'hiver particulièrement important pendant les années 1970 ont provoqué une dégradation extensive du pergélisol. Une augmentation de 0,1–0,5 °C de la température moyenne annuelle du sol (MAGT) a été observée. Des parties déconnectées de pergélisol et des noyaux dégelés ont été détectés en de nombreux endroits. La limite inférieure en altitude du pergélisol s'est élevée de 40 à 80 m sur le plateau Qinghai-Tibet. La surface totale couverte par le pergélisol sur le plateau a diminué d'environ 10^5 Km^2. La dégradation du pergélisol a causé des dégradations environnementales dont la déstabilisation de constructions, a eu des impacts sur l'hydrologie et les ressources en eau et a accéléré la désertification. Copyright © 2000 John Wiley & Sons, Ltd.

KEY WORDS: climatic warming; environmental impacts; permafrost degradation

INTRODUCTION

Many extensive, intensive and persisting glacial–interglacial permafrost shifts occurred on the Qinghai–Tibet Plateau during the Quaternary, owing to the rapid uplifting of the Plateau and to changing climates (Wang, 1989). In the early Pleistocene, permafrost developed only in the high mountains, until about 1.1–0.6 Ma BP, when the average elevation of the Plateau rose to 3500 m. The penultimate glaciation occurred during 0.6–0.8 Ma BP, with a MAAT about −4 to −12 °C. Permafrost developed extensively, especially in the western part of the Plateau. The following inter-

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glacial period was very warm, and permafrost almost completely disappeared except in extremely high mountains (Shi, 1998; Shi *et al.* 1995). During the glacial period between 200 and 330 ka BP, permafrost was almost continuous in distribution (Shi *et al.* 1992). Pan and Chen (1997) identified at least four periods of permafrost expansion during the last 150 ka BP. The permafrost area during the last glacial maximum (LGM: 16–32 ka BP) was estimated at 2.2×10^6 km^2 (cf. present 1.5×10^5 km^2), and its lower limit decreased by 1000–1400 m under a cooling of 6–8 °C. During the LGM, permafrost was widespread on the Plateau, including the Quidam Basin, the Qinghai Lake, the Upper Yaluzangpu River and the surrounding mountainous regions (Shi, 1998; Xu *et al.* 1984).

The warm period in the Holocene occurred from 9.0 to 3.5 ka BP, when the MAAT was about 2–5 °C higher, resulting in permafrost degradation. Sand-wedges stopped developing about 9 ka BP, indicating the start of warming. During the period 8–3 ka BP, the climate was warm and comparatively humid; peat and palaeosols rich in humus developed as a result (Liu *et al.* 1997). The warmest period was between 9 and 5 ka BP, when the MAAT was about 3–5 °C higher, and the optimum occurred between 6 and 4.5 ka BP (Zhao *et al.* 1995a). Regional differentiation of climate during this period was also strong; for example, in the Hoh'xil region, maximum warming occurred about 7–5 ka BP, when the upper 20–30 m of permafrost, formed during the Last Glaciation, thawed (Li and Li, 1993). Therefore, permafrost on the Qinghai–Tibet Plateau is largely relict and has been degrading since the Last Glaciation.

Global average air temperature has increased about 0.5–1.0 °C since the 1940s. The climatic fluctuations on the Plateau show trends similar to those in the northern hemisphere. Observations on the Plateau indicate the 1950s to have been warmer than the 1960s. The 1960s were cooler than the 1970s, which were still colder than the 1980s. The 1980s was the warmest decade during the past four decades and its MAAT increased about 0.3 to 0.4 °C compared with the 1970s (Kang, 1995). The average winter air temperature was unusually warm in the 1980s (Wang *et al.* 1996). Observations from 39 meteorological stations in Qinghai Province (Ma *et al.* 1992) also indicate a warming during the past 30 years, and this trend continues, although the increase of air temperature signifies that the summers have been cooling (Table 1). As a result, the annual range of air temperature on the Plateau has decreased at an annual rate of 0.06 °C (Table 2). Precipitation does not show a clear trend.

Permafrost degradation on the Plateau has been inferred based on permafrost monitoring. Rising MAGTs, a deepening in thaw depths, the disappearance of island permafrost, and the increase and expansion of taliks have all been observed (Wang, 1993).

PERMAFROST DEGRADATION

Rising Temperatures in the Island Permafrost Zone

Monitoring along the Qinghai–Tibet Highway indicates an increase in the MAGT of about 0.3–0.5 °C in seasonally frozen ground and taliks in the island permafrost zone, and about 0.1–0.3 °C in the continuous permafrost zone (Table 3).

Xidatan (4480 m ASL) is located in the island permafrost zone near the northern lower limit of permafrost. The observation site is on the first terrace of a small river, where the soils consist of fluvial sands and gravels. The surface is dry and barren of vegetation. Seasonal thaw depth varies from 2.0 to 2.6 m. Drilling in 1983 indicated a lower bottom to permafrost at 24–25 m. As shown in Table 4, the lower base of permafrost has risen to 20 m, and the ground temperatures at 12–20 m depth have risen 0.2–0.3 °C, suggesting a trend similar to that observed in a borehole in the Jingxiangu Valley (Wang *et al.* 1996), (i.e. permafrost degrades upward only). However, at a site at 4428 m ASL, approximately 1 km south-east of the Xidatan site, both upward and downward degradation has been detected. Drilling and temperature readings in 1975 suggested a permafrost layer at a depth of 5–15 m (Table 5). Measurement in 1989 proved the existence of permafrost only at depths from 8 to 11 m, indicating degradation of at least 4 m, and a warming of 0.2–0.4 °C.

In marginal permafrost with MAGT of −0.5 to 0 °C, permafrost is also warming and thinning rapidly (Zhao *et al.* 1995b). Permafrost disappearance is striking. For example, buried permafrost was detected at 11.4–16.0 m depth at Xidatan along the Qinghai–Tibet Highway near the northern lower limit of permafrost in 1960. Drilling at the same place in 1975 revealed no permafrost. A second example is at Jingxiangu, located at the northern lower limit along the Highway. The bottom of permafrost here has been rising since 1975 – about 20 metres in the past 20 years. The MAGTs at a depth of 15–20 m have increased

Table 1 Mean deviations of air temperature (°C) at selected stations in Qinghai Province, 1950–90.

Stations	Minhe	Guide	Xining	Qilian	Gangcha	Xinghai	Doulan	Dacaidan	Lenghu	Wudaoliang	Qingshuihe	Angqian	Dari	Average
Jan.	0.04	0.03	0.07	0.03	0.05	0.08	0.06	0.08	0.05	0.03	0.00	0.01	0.03	0.04
Av. min.	0.00	0.00	0.04	0.02	0.04	0.07	0.03	0.0	0.02	0.03	0.01	0.03	0.04	0.03
Jul.	−0.03	−0.04	−0.01	−0.02	−0.02	−0.01	−0.04	−0.00	−0.02	−0.01	−0.02	−0.01	0.00	−0.02
Av. max.	−0.01	0.00	0.00	−0.01	−0.00	−0.00	0.01	0.00	−0.01	0.01	−0.01	0.02	0.01	0.00

Table 2 Decadal mean deviation of air temperature range (°C) at selected stations in Qinghai Province, 1950–90.

Stations	Minhe	Guide	Xining	Qilian	Gangcha	Xinghai	Doulan	Dacaidan	Lenghu	Wudaoliang	Qingshuihe	Angqian	Dari	Average
Before 1960	27.5	25.1	26.8	27.0	25.5	25.8	26.9	30.6	31.6	23.1	24.2	19.8	22.0	25.8
1961–70	27.0	25.4	25.8	26.5	24.8	24.8	25.8	29.7	30.4	22.7	23.5	20.0	22.5	25.3
1971–80	25.8	24.5	25.4	25.9	24.3	23.8	24.2	28.6	29.3	21.8	22.9	19.6	21.6	24.4
1981–90	25.7	24.0	24.5	25.6	23.8	23.2	24.1	28.5	29.3	22.2	23.6	19.4	21.8	24.3
Annual range	−0.06	−0.07	−0.06	−0.05	−0.06	−0.08	−0.09	−0.06	−0.06	−0.03	−0.02	−0.03	−0.06	−0.06

about 0.5–0.8 °C (Table 6). This has been caused by the thermal influence of intrapermafrost water made available only after waterways were created by the gradual and downward thawing of the near-surface permafrost layer.

A third example is at Liangdaohe, located at the southern lower limit of permafrost. Permafrost was detected at depths of 3.0–8.5 m in June 1975. However, subsequent temperature readings revealed a significant temperature increase in 15 years, and a gradual disappearance of permafrost (Table 7).

Thawing permafrost bodies have been detected widely at Xidatan and Amdo (Anyemaqen Mountains), Qingshuihe, and Huashixia along National Highway 214 in the eastern Qinghai–Tibet Plateau (Zhu *et al.* 1995). As a result, the spatial distribution of permafrost has changed significantly.

Rising Temperature in the Continuous Permafrost Zone

Ground temperatures at a borehole at the Kunlun Pass have also increased 0.2–0.4 °C at 6–15 m depth in the past 15 years (Table 8). This site, located at 4700 m ASL, is underlain by fluvial gravels above 2.5 m depth with a soil moisture of 12–18%, and by lacustrine sediments below with an ice content of 30–45% by volume. The thaw depth reaches its maximum of 1.3–1.4 m in summer and the MAGT is −2.6 to −2.5 °C. The permafrost is 80–100 in thickness. The ground temperatures at shallow depths in the transitory and quasi-stable permafrost have been increasing noticeably. For example, at Borehole CK2956 on the Cumar High Plateau in the interior of the Plateau, ground temperatures at 5–10 m depth have increased about 0.3–0.4 °C and those at 12–14 m depth have increased about 0.1–0.3 °C. Those below 15 m depth have remained fairly stable because of an underlying thick ground-ice layer.

Elsewhere in the Plateau interior, for example at Fenghuoshan, ground temperatures also have been increasing. There, ground temperatures at 15–20 m and 25–35 m depth have increased 0.2–0.3 °C and 0.1–0.2 °C respectively during the past 35 years (Table 9).

The widespread and rapid permafrost degradation on the Qinghai–Tibet Plateau can be attributed mainly to climatic warming. This can be illustrated by the records at the Wudaoliang and Fenghuoshan meteorological stations in the interior of the Plateau. The rising trend of air temperatures is clear, despite significant

Table 3 Changes of MAGT along the Qinghai–Tibet Highway (°C).

Borehole	JXG	CK114	CK124–4	CK123–4	CK–7	K2956	No.1	CK123–7
Location	Xidatan	Taoerjiu	Valley	Basin	Tongtian	Cumar	FHS	Basin
Permafrost zone	NLM	C/IPB	SLM	SFG	RT	CPZ	CPZ	IPZ
Present MAGT (°C)	0.3	0.8	0.8	0.8	0.8	−0.9	−2.8	−1.0
Rise 1970–1990s (°C)	0.5	0.3	0.3	0.3	0.4	0.1	0.2	0.2

NLM, northern lower limit; SLM, southern lower limit; C/IPB, continuous/island permafrost boundary; SFG; seasonally frozen ground; RT, river talik; CPZ, continuous permafrost zone; IPZ, island permafrost zone; JXG, northern mouth of the Jingxiangu Valley.

fluctuations. Other meteorological stations in Qinghai Province also indicate a warming trend of about 0.45 °C (Ma *et al.* 1992) during the past 30 years.

Relict Permafrost and Thawed Bodies

Climatic warming has caused a decrease of 10–40 cm in the depth of seasonal freezing and an increase of 5–30 cm in the depth of seasonal thawing. As a result, thawing zones have formed towards the edges of the permafrost regions on the Plateau, where the permafrost table is now buried as deep as 4–7 m. In these regions, seasonal freezing only reaches 2–3 m.

Relict permafrost is widespread in the island permafrost zones on the Plateau. Examples can be revealed either by excavation or by drilling. The following examples are typical.

(a) Pit 1 is located 10 km north-west of Duocai, Zhiduo, in the source area of the Yangtze River in the eastern Qinghai-Tibet Plateau, at an elevation of 4470 m ASL. There, a thawed layer was at 1.1–1.4 m in depth between two frozen layers in June 1990.
(b) Pit 2 is located on the south slope of Anyemaqen Mountain with an elevation of 4180 m ASL. A thawed layer from 1.1 to 2.9 m in depth was discovered between frozen layers in June 1990
(c) Borehole X, 6.85 m in depth, is located 100 m west of Pump station 6 at Xidatan along the Qinghai–Tibet Highway. Seasonal freezing was to 2.7 m depth in 1991 and permafrost was located at 5.8–6.8 m depth. A thawed layer at 2.7–5.8 was inferred.
(d) Several boreholes at Highway Maintenance Station 61 indicate thawed layers at 3.1–8.0 m between frozen layers during the early summer.
(e) Pit 120–2 at Highway Maintenance Station 120 revealed a thawed layer at 1.3–2.5 m depth between frozen layers on 26 May 1975.

Elevation of the Lower Limits of Permafrost Distribution

The northern lower limit of permafrost has moved 3.0 km southward near West Xidatan and the southern lower limit has retreated 16.0 km near Amdo since 1978 (Cheng *et al.* 1993).

Permafrost lower limits (i.e. the boundary of sporadic permafrost) have been rising in elevation based on comparison of measurements in the 1970s and 1990s (Table 10). Although the amplitude of the changes differs because of the influence of local lithology, slope orientation and moisture conditions, the general increase ranges from 40 to 80 m in elevation.

Shrinkage of Permafrost Area

Increasing ground temperatures have either thinned permafrost by about 5–7 m, or thawed thin permafrost completely, resulting in an altitudinal increase in the island permafrost boundary. For example, the lower limit of permafrost along the Qinghai–Tibet Highway has moved 12 km northward at the southern lower limit, whereas it has moved 3 km southward at the northern lower limit. In the vicinity of Mado in north-eastern Qinghai–Tibet Plateau, the horizontal change of permafrost zones is 15 km. As a result, the areal extent of plateau permafrost has been reduced significantly during the past few decades. The total permafrost area on the Plateau has changed significantly (Table 11). This is attributed to permafrost retreat since the 1970s. The preliminary

Table 4 Average July ground temperatures (°C) at different depths (m) at Xidatan observation site.

Depth	0.4	0.8	1.6	3.2	4.0	6.0	8.0	10	12	14	16	18	20	23	26	29
Date																
1991	1.20	0.42	−0.08	−0.99	−0.89	−0.87	−0.38	−0.34	−0.49	−0.48	−0.43	−0.43	−0.17	−0.18	0.23	0.27
1992	4.03	2.21	−0.18	−0.68	−0.74	−0.74	−0.27	−0.24	−0.22	−0.42	−0.20	−0.09	−0.02	0.18	0.49	0.53
1993	3.56	1.46	−0.36	−0.83	−0.86	−0.84	−0.29	−0.22	−0.18	−0.40	−0.14	−0.08	0.06	0.21	0.54	0.56
1994	4.20	1.55		−0.87	−0.85	−0.85	−0.45		−0.40	−0.35		−0.07	0.00	0.25	0.40	0.55
1996	6.81	4.01	−0.21	−0.60	−0.96	−0.72	−0.46	0.50	−0.45	−0.26	−0.12	−0.12	0.03	0.24	0.48	0.71
1997	5.57	2.17	−0.30	−1.27	−1.28	−0.85	−0.55	−0.48	−0.34	−0.24	−0.11	−0.07	0.07	0.28	0.55	0.75

Table 5 Ground temperatures (°C) at different depths (m) in Borehole CKIII-4, Xidatan.

Depth	1	2	3	4	5	7	9	11	13	15	2	25	30
Date													
8 Nov. 1975	−3.8	−0.1	0.2	0.0	−0.1	−0.2	−0.2	−0.2	−0.2	−0.1	0.0	0.1	0.3
5 Aug. 1979	6.8	1.2	0.2	0.1	0.2	−0.2	−0.1	−0.2	0.1	0.2	0.2	0.3	0.4
25 May 1989	−0.6	−1.3	0.0	0.0	0.1	0.0	−0.1	−0.1	0.1	0.3	0.4	0.5	0.8

estimate for the permafrost reduction is 10^5, excluding statistical errors (Wang, 1997).

In 1975, according to the 1:100,000 island permafrost map for the southern section of the Qinghai–Tibet Highway (with a width of 2 km on each side of the Highway), the permafrost area was 64.8 km^2, accounting for 20% of the map area. Permafrost was divided into four groups according to its geomorphic location (Table 12). Investigations in 1996 indicated that the permafrost area has decreased to 41.72 km^2, suggesting an areal reduction of 35.6% in island permafrost area.

However, the degradation rate differs geomorphologically. The most rapid shrinking has occurred in mountains and uplands, whereas the island permafrost in valleys and basins has degraded more slowly thanks to fine-grained soils, dense vegetation and high soil moisture content. Wang (1997) concluded that there was a reduction of 6% in permafrost extent in the area where the prospective Trans-Water Project from the Yangtze River to the Yellow River will be built.

IMPACT OF WARMING PERMAFROST

Cold Regions Engineering

Permafrost degradation directly affects the stability of engineering construction and facilities on the Plateau. Some human activities have accelerated permafrost degradation. While roads and other facilities were constructed using principles of permafrost protection due to the warm ground temperatures, these structures are undergoing dramatic changes under the warming climate. Various countermeasures have been proposed and are being continuously adapted to the changing environments. However, the socio-economic damage is substantial (Jin *et al*. 1997).

The most remarkable indication for a warming climate on the Plateau is the thickening of the active layer, in both its natural and artificial states (Table 13). The permafrost table has been increasing in depth since the 1980s and, in the vicinities of the northern and southern lower limits of permafrost, the amplitudes of the increases are greater than those in the interior, such as in the Fenghuoshan and Tanggula Mountains. The thickness of the active layer under the asphalt road surface is 1.5–2.0 m greater than that in the natural state, owing to the alteration of the surface albedo and evaporation. In most cases, the heat accumulation in the road base has resulted in the increased thaw

Table 6 Ground temperatures (°C) at different depths (m) at Jingxiangu, Qinghai–Tibet Highway.

Depth	6	10	12	14	16	18	20	22	24
Date									
8 Nov. 1975	−0.2	−0.2	−0.1	−0.2	0.0	0.0			0.1
26 Apr. 1976	−0.3	−0.2	−0.2	−0.2	0.0	0.0	0.0		0.2
3 Aug. 1979	−0.4	−0.2	−0.2	0.0	0.2	0.3	0.4	0.7	0.8
5 Aug. 1985	−0.4	−0.2	0.0	0.1	0.3	0.6		0.9	1.0
25 May 1989	−0.4	0.0	0.1	0.2	0.5	0.6	0.8	0.9	1.0
24 June 1994		0.2	0.2	0.3	0.6	0.6		1.2	
7 July 1995	−0.3	0.1	0.2	0.2	0.5	0.6	0.8		
14 May 1996	−0.4	0.2	0.2	0.3	0.5	0.6	0.8		
8 July 1997	−0.2	0.1	0.2	0.3	0.4	0.6	0.8		

Table 7 Ground temperatures (°C) at different depths (m) in borehole Ck124-4 near Liangdaohe, Qinghai–Tibet Highway.

Depth	1	2	3	4	5	6	7	8	9	11	13	15	17	19
Date														
5 Aug. 1979	0.6	−0.1	−0.3	−0.1	−0.2	−0.2	0.0	0.2	0.3	0.5	0.5	0.5	0.7	0.8
7 Aug. 1984	−0.2	−0.3	−0.3	−0.1	0.1	0.1	0.0	0.2	0.2	0.7	0.6	0.8	0.7	0.9
26 July 1989	0.7	0.1	0.1	0.0	0.1	0.1	0.2	0.2	0.3	0.6	0.7	0.8	0.9	0.8
5 July 1994	0.0	0.1	0.1	0.7	0.5		0.5	0.6	0.8	0.8	0.7	0.8	1.0	0.9
1 July 1995	−0.1	0.0	0.2	0.4	0.6	0.8	0.9	1.0	1.2	Below 9 m damaged				
27 June 1996	0.4	−0.1	0.2	0.5	0.6	0.8	0.8	1.1	1.2					
6 July 1997	0.4	−0.1	0.3	0.4	0.6	0.8	0.9	1.1	1.2					

Table 8 Annual ground temperatures (°C) at different depths (m) in the borehole of the Kunlun Pass Observation Site.

Depth	4	5	6	8	9	10	12	13	14	15	16	18	20
Date													
1982	−2.9	−2.8	−2.8	−2.8	−2.8	−2.7	−2.9	−2.8	−2.6	−2.6		−2.6	
1994	−3.1	−3.0	−2.9	−2.8	−2.7	−2.7	−2.9	−2.7	−2.8	−2.5	−2.9	−2.6	−2.6
1997	−2.02		−2.38	−2.3		−2.34	−2.32		−2.41		−2.55	−2.54	−2.57

Table 9 Ground temperatures (°C) at different depths (m) in a borehole at Fenghuoshan, Qinghai–Tibet Highway.

Depth	8	9	10	15	20	25	30	35
Date								
31 Aug 1962	−4.4	−4.1	−3.7	−3.5	−3.5	−3.3	−3.2	−3.0
3 June 1967	−4.3	−3.9	−3.8	−3.5	−3.4	−3.3	−3.2	−3.0
30 Aug 1980	−3.9	−3.6	−3.6	−3.5	−3.3	−3.2	−3.1	−3.0
30 June 1984	−4.1	−4.0	−3.9	−3.5	−3.3	−3.2	−3.1	−2.8
30 June 1989	−3.8	−3.6	−3.6	−3.3	−3.2	−3.1	−3.0	−2.8
30 June 1994	−3.8	−3.6	−3.6	−3.3	−3.2	−3.1	−3.0	−2.9
30 June 1995	−3.9	−3.8	−3.6	−3.4	−3.2	−3.0	−2.8	−2.8
30 June 1996	−3.6	−3.5	−3.3	−3.2	−3.2	−3.0	−2.7	−2.8
30 June 1997	−3.8	−3.6	−3.4	−3.2	−3.2	−3.0	−2.8	−2.8
30 June 1998	−3.8	−3.6	−3.6	−3.3	−3.2	−3.1	−2.9	−2.8

Table 10 Alteration of the lower limits (m a.s.l.) of permafrost on the Qinghai–Tibet Plateau.

Mountains	Kunlun	S. Amdo	Rubber	Laji	S. Heka	Buqing	Naboeze	Qilian
Location	Xidatan	HMS124, QTH	W. Qihai Lake	N. Tawan	NH 214	Mado	N. Ximencuo	Jingyangling
Present	4350	4680	3780	3760	3900	4270	4140	3500
1970s	4300	4640	3700	3700	3840	4220	4070	3420
Increase	50	40	80	60	60	50	70	80

Table 11 Changes of permafrost area ($\times 10^6$ km^2) on the Qinghai–Tibet Plateau and in Quilian Mountains.

Reference	QTP	Qilian Mts.	Notes
Zhou Youwu and Guo (1982)	1.50	0.134	*Permafrost Map of China*, compiled in 1975
Xu Xiaozu and Wong (1983)	1.493	0.095	1:4M *Permafrost Map of China*, 1982
Shi Yafeng (1988)	1.50	0.095	1:4M *Snow, Ice and Permafrost Map of China*, 1988
Wang Shaoling (1996)	1.23	0.076	1:3M *Permafrost Map on the QTP*, 1996

Table 12 Areal change of island permafrost (km^2) in the southern section of the Qinghai–Tibet Highway.

Geomorphology	Basin	Valley	Fluvial plain	Mountains	Island permafrost	% total mapped area
1975	16.76	34.08	1.74	12.23	64.81	20.2
1996	10.20	25.60	0.82	5.10	41.72	13.1
Reduction (%)	39.1	24.9	52.9	58.9	35.6	7.1

Table 13 Changes in thickness of the seasonally thawing depth along the Qinghai–Tibet Highway.

Location	Asphalt road surface		Natural state surface		Permafrost type
	1980s	1990s	1980s	1990s	
Kunlunshan	3.0	4.2	1.0–2.8	1.8–2.8	Soil with segregated ice layers
Cumar River	3.6	4.0	1.0–3.5	2.0–3.5	Icy and ice-rich permafrost
Wudaoliang	3.8	4.8	1.2–3.0	2.0–3.5	Soil with segregated ice layers
Hoh'xil	2.9	3.6	1.1–2.5	1.8–8.5	Soil with segregated ice layers
Fenghuoshan	2.8	3.4	1.1–2.2	1.3–2.5	Soil with segregated ice layers
Tanggula	2.2	3.0	1.1–3.2	1.5–2.5	Ice-containing and -rich permafrost
Taoerjiu	2.7	3.8	1.0–2.0	1.3–2.5	Ice-rich permafrost
Amdo	2.5	5.5	2.0–3.0	2.2–4.0	Ice-containing permafrost

depth being greater than the refreeze depth. Consequently, there has been a transformation from a vertically-connected permafrost body into disconnected permafrost. Correspondingly, the southern boundary of the continuous permafrost has moved 10 km northward under natural conditions, while that under the asphalt road surface has retreated 15 km.

With the increasing thickness of the summer thaw depth, thaw settlement and frost heaving problems have increased. Based on field survey in 1990, road damage caused by thaw settlement accounted for 83% of the damage along the Highway. Thaw settlement increased with the increasing seasonal thaw depth during the period, 1985–1990. The settlement at sections with thawed bodies reached 60–70 cm, much greater than those without thawed bodies. About US$13 million were spent on rehabilitation of road damage during 1985–1990, and US$65 million on rebuilding the severely damaged sections, 346 km in total length.

Most of the oil pipelines on the Plateau were buried at depths of about 1.0–1.5 m. Although no thaw settlement has been caused by the warm oil flow at present, the warming permafrost is expected to threaten the stability of the pipelines in the near future. For example, excavations in the Kunlun Pass in September 1997 indicated that the oil pipeline along the Highway, with a diameter of 168 mm and built in 1973, has induced a summer thaw depth of 140–150 cm around the pipe. By contrast, in adjacent terrain the summer thaw reached only 90 cm.

Bridges and water conduits have also been damaged by the thaw settlement on the Plateau. The prospective Trans-Water Project from the Yangtze River to the Yellow River will build a 10^{10} m^3 reservoir, a high dam, a water conduit 50–100 km long, and major auxiliary facilities in a region underlain by warm permafrost, 10–60 m in thickness. Thus, permafrost degradation needs to be considered in advance. The Muli coalmines and Tumen coalmines have suffered great losses since 1965 owing to warming permafrost, with consequent instability and landslides.

The principles for construction on the Qinghai–Tibet Plateau also need to be changed from only permafrost protection, which was widely applied owing to the lack of understanding of permafrost conditions and degradation in the 1960–80s, to diversified principles, which permit permafrost warming and degradation under different conditions.

Cold Regions Hydrology

Climatic warming can affect permafrost hydrology through a warming of ground temperatures and changes in precipitation, evaporation and runoff. Permafrost hydrology is largely determined by the heat–moisture conditions in the active layer. In the Qilian Mountains at the northern edge of the Qinghai–Tibet Plateau, the increasing thaw depth has cast doubts on the stability of water resources in the Hexi Corridor during the next 50 years. It could result in gradual soil moisture depletion, increased evaporation and consequent reduced runoff. In 1991, the precipitation was 6% less than normal, and the mean summer air temperature was 1 °C higher than normal. This resulted in a 35% reduction in runoff in the alpine grasslands and indicated that evaporation increases in a warm and dry period. In many permafrost areas, the most striking effect of permafrost degradation on the water budget is the shrinkage of taliks, the lowering of lake levels, and the shrinkage and disappearance of cold wetlands. These shifts can directly and rapidly decrease the water resources of the major rivers in eastern and southern Asia. However, the impacts on the permafrost hydrology, especially on the river hydrology in the cold regions, are complicated and require intensive research. This is vital for arid western China.

Cold Regions Environments

On the Qinghai–Tibet Plateau, the permafrost serves as an impermeable layer for water infiltration, providing for the high soil moisture in the active layer vital for the development of alpine meadows. As a result, pasturelands dominated by *Cyperus* are well developed in the permafrost zone and very important for the local economy. However, owing to the combined influences of permafrost degradation and ill-planned over-exploitation, extensive deterioration and desertification have occurred since the 1960s. Permafrost warming can be accompanied by either increasing or decreasing precipitation. In the former case, the increased precipitation can offset the loss of soil moisture due to a thickening of thaw depths or the disappearance of permafrost. This occurred on the Plateau during the warm period in the Holocene, when the precipitation increased at least 50–100 mm, and permafrost degradation did not result in widespread grassland deterioration. Many mobile sand dunes were stabilized during the warm–moist period. However, the current expectations are that precipitation will not noticeably increase, or might even decrease (Ma *et al.* 1992). Permafrost degradation has also induced changes in hazardous periglacial phenomena, such as the widespread instability of slopes, enhanced solifluction and thermokarst, resulting in damaged vegetation, followed by accelerated soil and water erosion, and even desertification. On the other hand, warmer soil temperatures can expand the growing season, increase the space for plant roots, enrich nutrients and activate nutrient cycling. The distribution and types of vegetation will also experience a significant shift in the long run.

Table 14 Ground temperatures (°C) at different depths (m) observed at boreholes with (CK_6) and without permafrost (CK_1) in Tuotuohe River region.

Depth	3	4	5	6	8	10	12	14	16	18	20	23	26	29	32	35	40	45	48
CK_1	1.3	0.6	0.7	1.2	1.3	1.4	1.4	1.5	1.6	1.8	1.8	1.9	2.0	2.0	2.2	2.3			
CK_6	−0.4	−0.5	−0.5	−0.4	−0.4	−0.3	−0.2	−0.1	0.0	0.1	0.2	0.3	0.6	0.7	0.8	0.8	1.2	1.4	1.5

The desertification in permafrost regions has been of recent concern on the Qinghai–Tibet Plateau. The sandy lands occur mainly in river valleys, lake depressions and flat plateau surfaces. They are covered by sand dunes and extensive sand layers. The sand dunes are mainly semi-fixed, flowing sand dunes that parallel aeolian depressions and move fast. As a result, fine sand layers cover the ground surface extensively with a depth from several centimetres to 1 metre. The areas with sand cover are expanding steadily according to observations along the Highway during the past few decades. They indicate an accelerating desertification under a warming and drying climate.

Previous studies indicate that in areas with aeolian deposits, seasonal thawing is greater, ground temperatures are higher and permafrost is thinner than in those without sands (Wang, 1993). Some areas with sand cover, especially at the margins of the permafrost zone, have evolved into taliks. For example, drilling on the northern bank of the Tuotuohe River indicates that permafrost is absent under the sand dunes whereas permafrost is present in adjacent depressions, forming a striped talik and island permafrost region as wide as 10 km. In the Tuotuohe basin, taliks are largely located under the larger sand dunes 3–5 m in diametre and 5–7 m in height, where drainage is good, and the MAGTs range from 1.2 to 2.1 °C under the dry surface. By contrast, permafrost develops beneath the barren areas and in most depressions with an MAGT of −0.2 to −0.4 °C (Table 14).

The ground temperatures under sand dunes are generally higher than beneath flat surfaces. For example, the MAGT at 18 m under a 1.6 m tall sand dune with a diameter of 20 m at Highway Maintenance Station 66 was 0.2 °C higher than the adjacent sand-free surface. The permafrost table under the sand dune was 3.3 m, 0.6 m deeper than the adjacent area.

The thick dry sand layer favours the downward propagating of solar radiation absorbed from the ground surface and the rapid infiltration of warm rain. Both result in significant warming. However, when the ground surface is covered by a thin sand layer, the subsurface temperature is cooler than the adjacent area. Therefore, the thickness of the sand layer overlying the active layer is critical for sand to influence permafrost preservation on the Plateau. As a result, when desertification is fledgling, the thin sand cover can stabilize permafrost; with an increase of sand layer thickness, desertification will induce extensive permafrost degradation, and further deterioration of grasslands, and feed back positively to desertification.

CONCLUSIONS

The climate on the Qinghai–Tibet Plateau has been warming up since the Last Glaciation, and significant warming has been observed since the 1970s. Further warming is expected in the future. This can be inferred from extensive and rapid permafrost degradation over the past few decades. However, strong temporal and spatial differentiation in permafrost degradation has been observed which can be attributed to the combined influence of the fluctuations and regional variations of climatic changes and the non-linear responses of permafrost temperatures to climatic change, as well as to significant environmental variables influencing the permafrost heat–moisture regime.

It is unlikely that permafrost can be reduced to half its present areal extent in one century (Li Xin *et al.* 1998), despite permafrost degrading comparatively rapidly on geological timescales. Permafrost retreat and degradation make it necessary to reconsider the permafrost protection principles for engineering constructions and operations, as well as environmental protection. One of the most important aspects of the possible impacts of permafrost degradation is on water resources. These are poorly understood owing to lack of observation but are very important for the regional economy and environment in Asia. Since the relationships between climatic change, permafrost and environment are complicated, more and better monitoring networks need to be established. In environmental protection, appropriate laws and regulations should be enacted or enhanced which will ensure that construction on the Plateau is compatible with the natural environment, and its environmental impacts should be evaluated in advance and minimized. Major projects should be avoided as much as possible in this last wilderness in China. Water and soil conservation will be an important and strenuous job for a long time under a degrading permafrost environment.

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