# Responses of permafrost to climate change and their environmental significance, Qinghai-Tibet Plateau

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Received 8 July 2006; revised 21 March 2007; accepted 24 April 2007; published 8 June 2007.

[1] In this paper we summarize recent research in geocryological studies carried out on the Qinghai-Tibet Plateau that show responses of permafrost to climate change and their environmental implications. Long-term temperature measurements indicate that the lower altitudinal limit of permafrost has moved up by 25 m in the north during the last 30 years and between 50 and 80 m in the south over the last 20 years. Furthermore, the thickness of the active layer has increased by 0.15 to 0.50 m and ground temperature at a depth of 6 m has risen by about 0.1° to 0.3°C between 1996 and 2001. Recent studies show that freeze-thaw cycles in the ground intensify the heat exchange between the atmosphere and the ground surface. The greater the moisture content in the soil, the greater is the influence of freeze-thaw cycling on heat exchange. The water and heat exchange between the atmosphere and the ground surface due to soil freezing and thawing has a significant influence on the climate in eastern Asia. A negative correlation exists between soil moisture and heat balance on the plateau and the amount of summer precipitation in most regions of China. A simple frozen soil parameterization scheme was developed to simulate the interaction between permafrost and climate change. This model, combined with the NCAR Community Climate Model 3.6, is suitable for the simulation of permafrost changes on the plateau. In addition, permafrost degradation is one of the main causes responsible for a dropping groundwater table at the source areas of the Yangtze River and Yellow River, which in turn results in lowering lake water levels, drying swamps and shrinking grasslands.

**Citation:** Cheng, G., and T. Wu (2007), Responses of permafrost to climate change and their environmental significance, Qinghai-Tibet Plateau, *J. Geophys. Res.*, *112*, F02S03, doi:10.1029/2006JF000631.

## 1. Introduction

[2] Climate change has caused public concern over the last several decades and greater attention has been paid to its impact on the cryosphere [*Nelson*, 2003; *Barnett et al.*, 2005]. As a main component of the cryosphere, permafrost is extremely vulnerable to climate change on different spatial and temporal scales. Changes in permafrost thermal regimes are often a reliable indicator of climate change [*Lachenbruch and Marshall*, 1986; *Pavlov*, 1994; *Guglielmin and Dramis*, 1999; *Anisimov and Reneva*, 2006]. Numerous studies have reported permafrost degradation under climate warming in the 20th century in the Northern Hemisphere [*Osterkamp and Romanovsky*, 1999; *Harris et al.*, 2003; *Payette et al.*, 2004; *Camill*, 2005; *Osterkamp*, 2005]. Permafrost degradation may affect local hydrology, ecology, engineering infrastructure, and even the climate [*Cheng and Zhao*, 2000; *Nelson et al.*, 2001; *T. Zhang et al.*, 2005; *Zimov et al.*, 2006]. The highest and most extensive high-altitude permafrost on earth is located on the Qinghai-Tibet Plateau, one of the most sensitive regions to climate change [*Liu and Chen*, 2000]. The objective of this paper is to review recent studies conducted on the plateau with regard to responses of permafrost to climate change and their environmental significance.

## 2. Responses of Permafrost to Climate Change

### 2.1. Permafrost Distribution

[3] Similar to permafrost distribution in other regions of central Asia, the plateau is underlain by extensive high-altitude permafrost. On the basis of the characteristics of permafrost distribution in China, Chinese scientists have classified permafrost into three categories based upon the percentage of area underlain by permafrost. They are predominantly continuous permafrost (with 70% to 90% of area underlain by permafrost), predominantly discontinuous island permafrost (with 30% to 70% of area underlain by permafrost), and sporadic island permafrost (less than 30% of area underlain by permafrost). This classification differs substantially from that adopted by the International Permafrost Association (IPA) (see Table 1) [*Zhou et al.*, 2000; *Heginbottom et al.*, 1993; *Brown et al.*, 1997; *Zhang et al.*, 1999, *Zhang*, 2005]. The key difference in the two classification systems lies in the mapping criterion (i.e., percentage of area underlain by permafrost). No continuous

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0148-0227/07/2006JF000631

**Table 1.** Comparison of Chinese and IPA Permafrost Classification Systems [*Zhang*, 2005]

| Chinese Permafrost Classification | | IPA Permafrost Classification | |
|---|---|---|---|
| Permafrost Zones | Percentage of Area Underlain by Permafrost | Permafrost Zones | Percentage of Area Underlain by Permafrost |
| Predominantly continuous permafrost | 70–90% | continuous permafrost | 90–100% |
| Predominantly continuous and island permafrost | 30–70% | discontinuous permafrost | 50–90% |
| Sparsely island permafrost | 0–30% | sporadic permafrost | 10–50% |
| Alpine permafrost | not defined | isolated patches of permafrost | 0–10% |
| No permafrost | 0% | no permafrost | 0% |

permafrost exists on the plateau according to the IPA classification, because of its unique geological history and the climate conditions of the plateau. If the IPA classification system is applied to the plateau permafrost, approximately 36.6% of the permafrost will be in the discontinuous zone (50% to 90% of area underlain by permafrost), 46.6% in the sporadic zone (10% to 50% of area underlain by permafrost), and 16.8% in the isolated patch zone (<10% of area underlain by permafrost) (see Figure 1).

## 2.2. Monitoring of Permafrost and Active Layer

[4] For the last 40 years, Chinese geocryologists and cold regions engineers have established and monitored a permafrost monitoring network along the Qinghai-Tibet Highway (Figure 2). Eighteen boreholes with depths ranging from 20 to 127 m have been drilled along the Qinghai-Tibet Highway to monitor permafrost temperatures and active layer depths. Calibrated thermistor sensors were installed on cables at certain depth intervals and were lowered into these boreholes. Initially, soil temperatures at different levels were measured three times per month by hand and then averaged over a year. The accuracy of the temperature measurement was estimated to be within 0.01°C. In 1998 automated temperature loggers were installed to record temperatures at various depths. Since 1998, temperature readings have been automatically recorded 12 times per day at 2-hour intervals.

[5] Thirteen monitoring sites were set up to measure soil temperature, moisture content, and heat fluxes within the active layer. Some of these sites are located near the boreholes (Figure 2). Four automated weather stations and two eddy covariance systems were installed for measuring a number of parameters including wind velocity and direction, air temperature, soil temperature and moisture content, precipitation, surface evaporation, solar insolation, and $CO_2$ fluxes. As part of the Global Energy and Water Cycle Experiment (GEWEX), the GAME-Tibet Project was initiated in 1997 by the Sino-Japan cooperation group. Eight sets of soil moisture and temperature measurement systems were installed for this joint venture (Figure 2) [*Ding et al.*, 2000].

## 2.3. Permafrost Degradation

### 2.3.1. Permafrost Degradation in Sporadic Permafrost Zone

[6] Permafrost on the plateau has experienced noticeable degradation during the past 40 years. The evidence of this

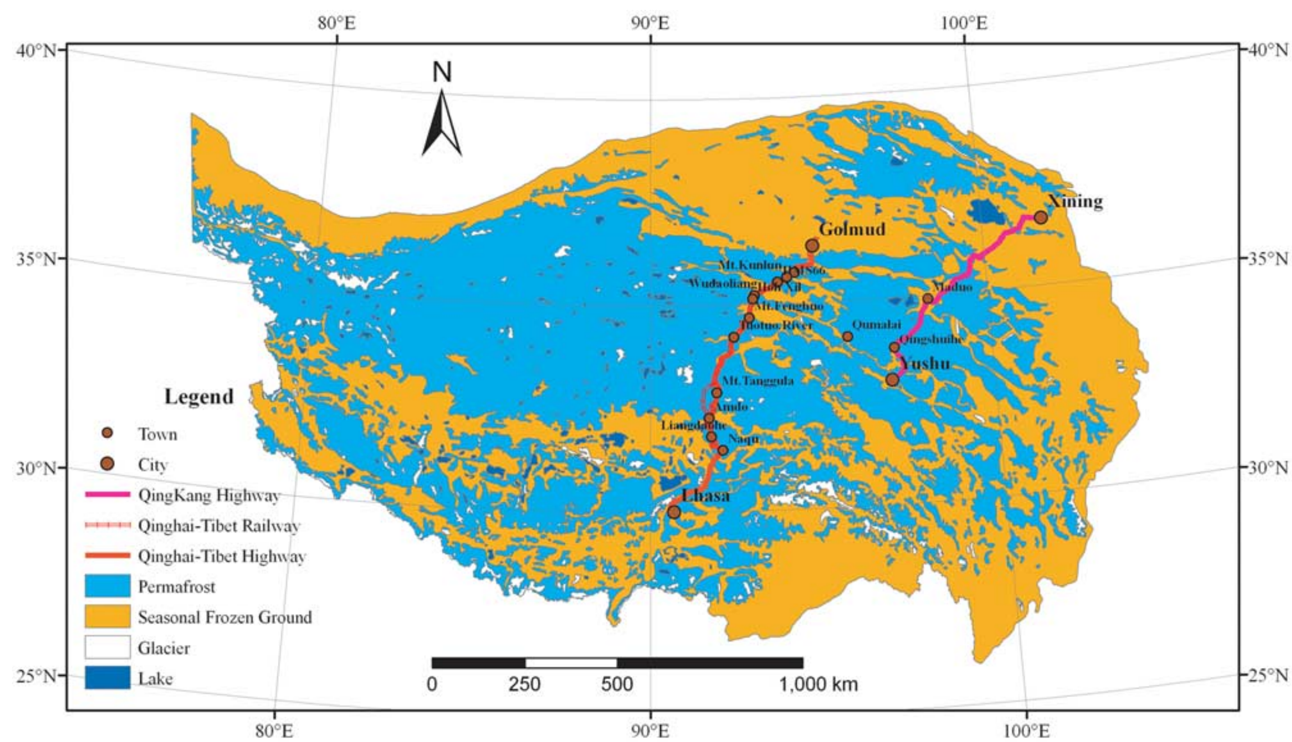


**Figure 1.** Map of permafrost distribution on the Qinghai-Tibet Plateau.

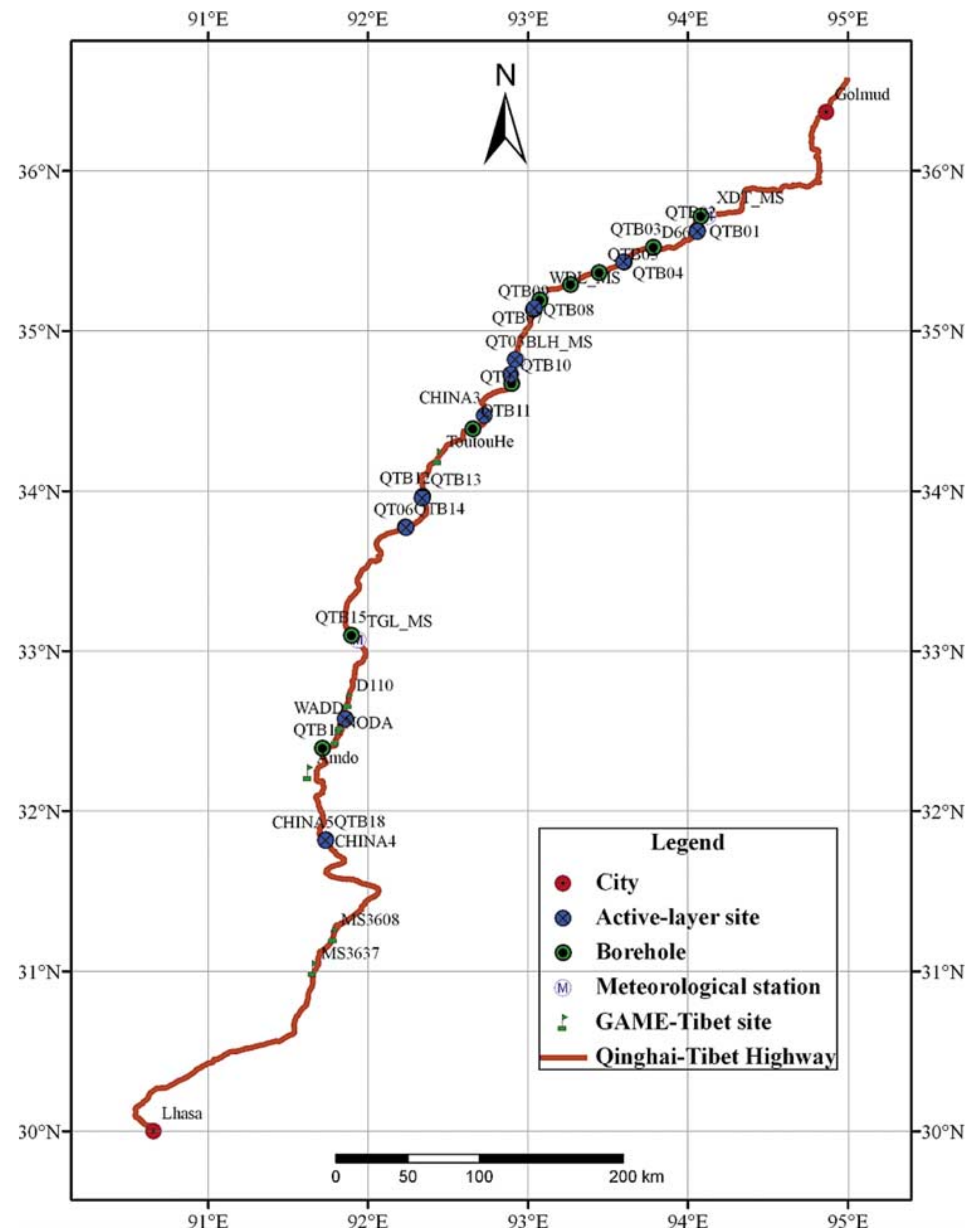


**Figure 2.** Permafrost monitoring network along the Qinghai-Tibet Highway.

degradation includes increased mean annual ground temperature (MAGT), increased active layer thickness, talik and thermokast development, and disappearance of permafrost islands [*Wang*, 1993; *Ding*, 1998; *Ding et al.*, 2000; *Jin et al.*, 2006]. Ground temperature measurements at Xidatan, located in the vicinity of the northern altitudinal lower limit of permafrost (i.e., the zone above which permafrost occurs), indicate that the mean annual ground temperature is warmer than −0.5°C. The observation site is located on the first terrace of a stream, where the soil consists of fluvial sand and gravel. The surface is dry and devoid of vegetation except for some localized depressions near a hill [*Jin et al.*, 2000b]. Ground temperature data taken between 1975 and 1989 indicate that permafrost has disappeared at some locations near the northern altitudinal lower limit of permafrost. The MAGT at 20 m depth increased by 0.2°–0.3°C in the same period [*Cheng et al.*, 1993; *Jin et al.*, 2000a]. The base of permafrost rose by about 4 m from 1983 to the end of the 1990s.

[7] A borehole was drilled in 1983 to a depth of 30 m at the Cryosphere Research Station on the Qinghai-Tibet Plateau (CRSQTP) site (35°43′N, 94°05′E) to monitor changes in permafrost temperature. The drilling results indicated that the depth of active layer at this site ranges from 2.0 to 2.6 m and the depth of permafrost base ranging from 24 to 25 m. As shown in Table 2 and Figure 3, the location of permafrost base have risen to a depth of 20 m in 1993. Thawing proceeds from the permafrost base upward. The ground temperatures at depths of 12–20 m have risen by 0.15°–0.36°C. A new thermistor cable was installed in 2000 in the borehole. New data show that soil temperatures at depths from 5 to 10 m increased by about 0.2°C between 2001 and 2003. Temperature readings have also been taken from a borehole on the first terrace of a stream at a nearby

**Table 2.** Average July Ground Temperature at the Xidatan Observation Site From 1991 to 1997[a]

| | Depth, m | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Year | 0.4 | 1.6 | 4 | 6 | 8 | 10 | 14 | 18 | 20 | 23 | 26 | 29 |
| 1991 | 1.20 | −0.08 | −0.89 | −0.87 | −0.38 | −0.34 | −0.48 | −0.43 | −0.17 | −0.18 | 0.23 | 0.27 |
| 1992 | 4.03 | −0.18 | −0.74 | −0.74 | −0.27 | −0.24 | −0.42 | −0.09 | −0.02 | 0.18 | 0.49 | 0.53 |
| 1993 | 3.56 | −0.36 | −0.86 | −0.84 | −0.29 | −0.22 | −0.40 | −0.08 | 0.06 | 0.21 | 0.54 | 0.56 |
| 1994 | 4.20 | * | −0.85 | −0.85 | −0.45 | * | −0.35 | −0.07 | 0.00 | 0.25 | 0.40 | 0.55 |
| 1996 | 6.81 | −0.21 | −0.96 | −0.72 | −0.46 | −0.50 | −0.26 | −0.12 | 0.03 | 0.24 | 0.48 | 0.71 |
| 1997 | 5.57 | −0.30 | −1.28 | −0.85 | −0.55 | −0.48 | −0.24 | −0.07 | 0.17 | 0.28 | 0.55 | 0.75 |

[a]Temperatures are in °C. Asterisk indicates that the data at this depth are missing because of the malfunction of the sensor.

location, which is 1 km southeast of the CRSQTP site and at an elevation of 4428 m a.s.l. The data indicate that permafrost table lowered by 3 m and MAGT rose by 0.2°–0.4°C from 1975 to 1989 [*Jin et al.*, 2000a]. Permafrost base in the Jingxiangu Valley (10 km south of the CRSQTP site) has risen by 10–15 m and the MAGT has increased by 0.5°–0.8°C over the last 20 years. The rate of thaw on the plateau is much greater than that reported for Alaska [*Osterkamp*, 2005]. Climate change will have a profound influence on permafrost dynamics, but groundwater flow may have played a more important role in permafrost degradation in this area.

[8] Early temperature data taken from a borehole drilled in the 1960s suggested the existence of permafrost at depths between 11.4 m and 16.0 m, but no frozen layer was found at the same site in 1975 [*Wang et al.*, 1996]. A comparison was made between the 1975 drilling records and the 2002 ground-penetrating radar survey results. The data indicate that the lower altitudinal limit of permafrost at Xidatan rose by 25 m and permafrost shrank in area considerably [*Wang et al.*, 1999; *T. Wu et al.*, 2005]. A comparison of ground temperatures taken in the 1970s and 1990s indicates widespread degradation of permafrost along the Qinghai-Tibet Highway [*Wang*, 1993].

[9] The Amdo-Liangdaohe section of the Qinghai-Tibet Highway is located in the vicinity of the southern lower altitudinal limit of permafrost and is underlain by sporadic permafrost. Permafrost has decreased in area by 35.6% and the lower altitudinal limit of permafrost has risen by 50–80 m [*Wang*, 1997]. The southern boundary of permafrost has displaced northward by 1.0–2.0 km over the past 30 years [*Wang and Zhao*, 1997]. A 19.53 m borehole was drilled near Amdo in July 1975 to monitor permafrost change. Drilling records indicate that the permafrost table was at a depth of 3.5 m and that the thickness of permafrost was 6.5 m. However, temperature measurements made in July 1989 demonstrate that the MAGT had increased by 0.1°–0.2°C and no frozen layer was detected. Another borehole was drilled in June of 1975 to the south of the Highway Maintenance Squad (HMS) 124. Records show that the permafrost table was at a depth of 3 m and permafrost was 5.5 m in thickness. However, ground temperature records taken in 1989 indicate that the MAGT had increased by 0.2°–0.3°C and permafrost had completely disappeared [*Pan et al.*, 2002; *Zhao et al.*, 2004].

[10] The Qinghai-Kang (West Sichuan) Highway travels through the hilly terrain of eastern Qinghai-Tibet Plateau, which is underlain by sporadic and discontinuous perma-

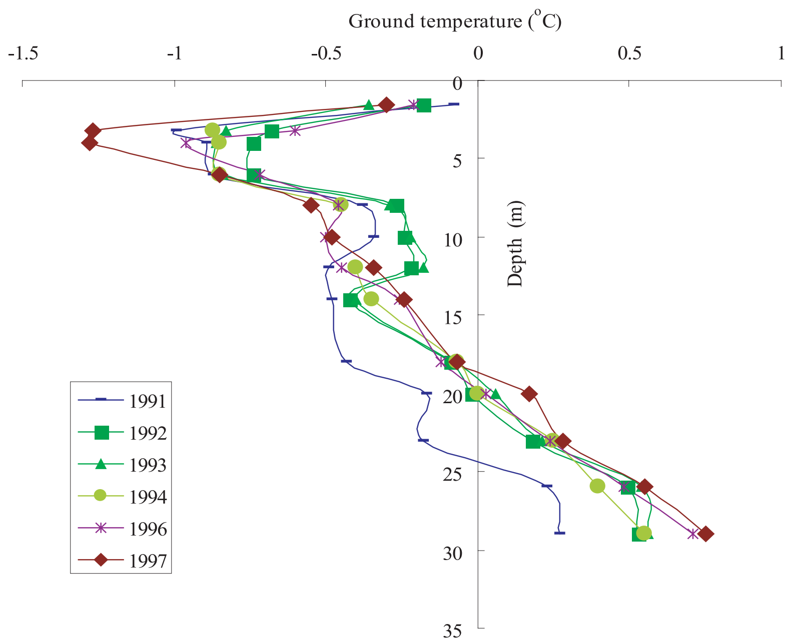


**Figure 3.** Average July ground temperature (°C) profiles at the Xidatan observation site from 1991 to 1997.

**Table 3.** Changes in Lower Altitudinal Limit of Permafrost Along the Qinghai-Kang Highway [*Zhu et al.*, 1996]

| Site | Latitude | Lower Altitudinal Limit, m | | Vertical Rise, m |
|---|---|---|---|---|
| | | 1960s | 1990s | |
| North slope of southern Mt. Qinghai | 36°25′N | 3650–3700 | 3700–3800 | 50–100 |
| North slope of Mt. Heka'nanshan | 35°49′N | 3800–3840 | 3860–3900 | 60 |
| North slope of Mt. Ngola | 35°25′N | 3850 | 3900 | 50 |
| Southwest slope of Mt. Animaqing | 34°35′N | 4180 | 4250 | 70 |

frost (Figure 1). Approximately 300 km of the Qinghai-Kang Highway is over permafrost. Recent studies reveal that permafrost along the highway in the eastern part of the plateau is undergoing degradation [*Zhu et al.*, 1995a, 1995b; *Pan et al.*, 2003]. Taliks have developed at Madoi, Qingshuihe, and the Huashixia Permafrost Station. To the east of Huashixia, a 2.2 m test pit was dug in a marsh at an elevation of 4230 m in June 1992. At that time, soil was thawed to a depth of 0.60 m; ice was found from 0.60 to 1.20 m. A thawed layer was located between 1.20 and 1.60 m; soil was frozen below. A 7 m borehole was drilled near Qingshuihe in May 1995. The borehole records indicate that the ground was frozen to a depth of 1.5 m and a talik was located between 1.5 and 3.0 m. The layer below was frozen from 3 to 7 m. Another borehole, 154.88 m deep, was drilled in 1990 at Qingshuihe. The drilling records indicate that a talik was located between 1.50 and 15.34 m and the layer below was frozen from 15.34 to 37.32 m [*Zeng et al.*, 1996]. A number of boreholes and test pits were drilled or dug to map the distribution of permafrost along the Qinghai-Kang Highway in the 1960s and 1990s. It appears that the lower altitudinal limit of permafrost along the highway rose by approximately 50–100 m over a 30-year period (Table 3).

### 2.3.2. Permafrost Degradation in Discontinuous Permafrost Zone

[11] From 1980s to 1990s in the discontinuous permafrost zone, active layer thickness increased by several centimeters to 1 m, even 2 m at some sites [*Wang and Zhao*, 1997]. Two boreholes were drilled in 1995 to monitor ground temperatures at the Kunlun Pass and Mt. Fenghuo. Measurements at both sites show a warming trend in permafrost from 1996 to 2002 (Figure 4). Ground temperatures taken from seven monitoring sites in undisturbed permafrost terrain along the Qinghai-Tibet Highway indicate that the active layer thickness increased and ground temperature at the top of permafrost and at a depth of 6 m rose at different rates between 1996 and 2001 (Table 4).

[12] Field data obtained from the discontinuous permafrost zone on the plateau show a general tendency for rising ground temperatures in recent decades. Although significant changes in the thickness and extent of permafrost have not been observed in the past 40 years, ground temperature has increased considerably. On the basis of field observations of permafrost temperatures, *Wu* [2005] reports that the annual rate of increase in MAGT is 0.042 to 0.065°C/yr for stable permafrost (MAGT $< -3$°C), 0.016 to 0.098°C/yr for quasi-stable permafrost (MAGT between $-0.5$ and $-3$°C), and 0.011 to 0.041°C/yr for unstable permafrost (MAGT $>$ $-0.5$°C), respectively. It is estimated that the base of permafrost rose at a rate of 0.1 to 0.2 m per decade on average during the last four decades throughout the plateau [*Zhao et al.*, 2003]. This trend is expected to continue under the current climate conditions.

[13] At the source areas of the Yangtze and Yellow rivers, permafrost temperature rose by 0.11°–0.14°C between 1980 and 1998 and the active layer thickness increased at rates ranging from 2 to 10 cm/yr. In addition, the lower altitudinal limit of permafrost rose by 50–70 m during the same period [*Yang et al.*, 2004]. These changes in permafrost conditions have affected surface energy and moisture balance, hydrology, hydrogeology, carbon exchange between the atmosphere and the ground, and biodiversity and productivity. Thus permafrost degradation is of great importance for engineering structures, ecosystems and the

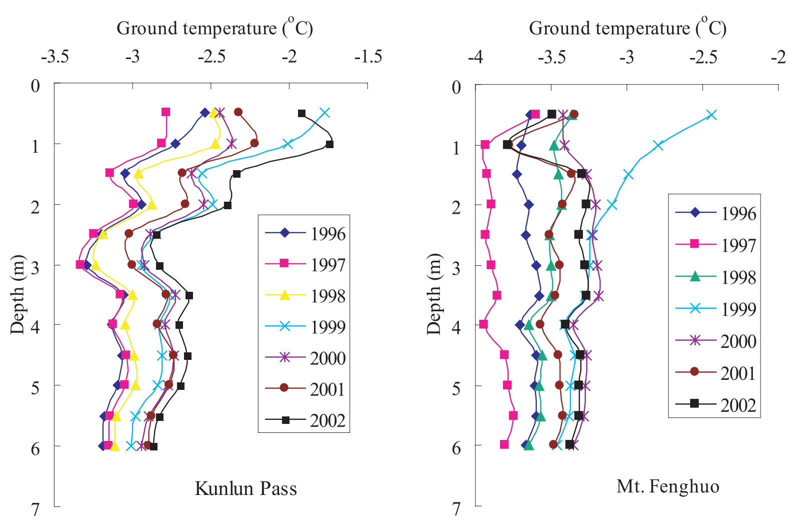


**Figure 4.** Evolution of permafrost temperatures at Kunlun Pass and Mt. Fenghuo from 1996 to 2002.

**Table 4.** Temperature Data Taken From Seven Natural Sites on the Plateau [*Q. Wu et al.*, 2005]

| Site | Permafrost Table, m | | TTOP, °C | | $TP6_6^*$,[a] °C | |
|---|---|---|---|---|---|---|
| | 1996 | 2001 | 1996 | 2001 | 1996 | 2001 |
| Number 1 site at Kunlun Pass | 1.09 | 1.50 | −3.05 | −2.68 | −3.19 | −2.90 |
| Number 2 site at Kunlun Pass | 1.22 | 1.40 | −3.08 | −2.78 | −3.06 | −2.77 |
| Mt. Fenghuo | 1.26 | 1.60 | −3.73 | −3.36 | −3.67 | −3.48 |
| Wudaoliang | 2.53 | 2.75 | −1.82 | −1.75 | −1.63 | −1.50 |
| HohXil | 1.64 | 2.00 | −2.14 | −1.63 | −2.01 | −1.69 |
| HMS 66 | 1.94 | 2.40 | −0.82 | −0.63 | −0.91 | −0.83 |
| Cumar Riverside | 3.24 | 3.50 | −0.43 | −0.30 | −0.56 | −0.40 |

[a]$TP_6^*$ denotes permafrost temperature taken at 6 m depth.

environment on the plateau [*Jin et al.*, 2000a; *Cheng and Zhao*, 2000; *Cheng and He*, 2001; *Q. Wu et al.*, 2005].

### 2.4. Numerical Simulation of Permafrost Thermal Regimes

[14] On the basis of heat transfer theory, energy balance models with phase change at the boundary between frozen and unfrozen layers were developed to simulate the thermal regime of permafrost [*Li and Cheng*, 1996; *Li et al.*, 2002a; *Li and Wu*, 2004]. The model takes into consideration a number of parameters in order to realistically predict changes in permafrost. These parameters include thermal conductivity, volumetric heat capacity of frozen and unfrozen soils, dry density, ice/water content, and unfrozen water content in frozen soils. The values of these thermal and physical properties were empirically determined from average values of permafrost and soil samples taken from 202 boreholes across the plateau. Initial values of MAGTs and mean annual ground surface temperature ($T_s$) were used as upper boundary conditions for calculating the mean annual soil temperature at different depths with successive time steps. Table 5 shows the simulated changes in permafrost temperature, with different initial values of mean annual ground surface temperature (i.e., 0, −0.5, −1.5, −2.5, −3.5, and −4.5°C), and with different rates of increase in ground surface temperature. These simulated variations in ground temperature for the next 50 years can be used to predict changes in a permafrost thermal regime under similar climate change scenarios. A numerical model was also used by *Li et al.* [1996] to simulate the permafrost thermal regime by assuming an increase in air temperature at a rate of 0.04°C/yr. Results suggest a decrease in both the area and thickness of permafrost and an increase in ground temperature. *Tong and Wu* [1996] estimated possible changes of stable (MAGT < −3.0°C), quasi-stable (−3.0°C < MAGT < −0.5°C) and unstable permafrost (MAGT > −0.5°C) under a scenario that air temperature will increase by 1°C in the next 30 years. *Li and Cheng* [1999] incorporated the altitude factor into the GCM model HADCM2 to predict permafrost responses to future climate change. The simulation shows that the plateau permafrost may not undergo significant changes within the next 20 to 50 years and the decrease in the area of permafrost may be less than 19%. However, the area decrease by 2099 may amount to 58%; permafrost in the southern and eastern parts of the plateau may undergo extensive degradation and may even disappear or become relict.

[15] *Nan et al.* [2005] developed a numerical model to predict changes in permafrost occurrences on the plateau for the next 50 and 100 years under different global warming scenarios. The result indicates that the area of permafrost on the plateau may decrease by 8.8% in 50 years and by 13.4% in 100 years if the air temperature rises at a rate of 0.02°C/yr. If the rate is increased to 0.052°C/yr, the area of permafrost may decrease by 13.5% in 50 years and by 46% in 100 years.

[16] *Jian* [2000] used an improved terrestrial biosphere model (BIOME3China) in combination with a coupled ocean-atmosphere GCM to investigate the response of the plateau terrestrial ecosystem to climate change. The model indicates that the boundary between discontinuous and sporadic permafrost on the plateau may shift northward by 1−2°N in latitude during the 21st century.

## 3. Environmental Significance of Permafrost Degradation

### 3.1. Effect of Permafrost Degradation on Climate Change

[17] Approximately 57% of land surface in the Northern Hemisphere undergoes seasonal freezing and thawing [*Zhang et al.*, 2003]. Climate change will affect the intensity and duration of this seasonal process. Ground freezing and thawing may also have an impact on climate. Changes in thermal and physical properties of the ground due to freezing and thawing will likely cause variations in energy

**Table 5.** Simulated MAGT Changes of Permafrost With Different Initial Values of $T_s$ and at Different Rates of Increase in Ground Surface Temperature$_s$ for the Next 50 Years

| Initial $T_s$, °C | Initial MAGT, °C | Increase rate of $T_s$ = 0.02°C/yr: Simulated MAGT | Increase rate of $T_s$ = 0.02°C/yr: Increase Velocity, °C/10yr | Increase rate of $T_s$ = 0.04°C/yr: Simulated MAGT | Increase rate of $T_s$ = 0.04°C/yr: Increase Velocity, °C/10yr | Increase rate of $T_s$ = 0.052°C/yr: Simulated MAGT | Increase rate of $T_s$ = 0.052°C/yr: Increase Velocity, °C/10yr |
|---|---|---|---|---|---|---|---|
| −0.5 | −0.42 | −0.11 | 0.062 | 0.00 | 0.084 | 0.00 | 0.220 |
| −1.5 | −1.11 | −0.68 | 0.086 | −0.25 | 0.170 | 0.00 | 0.250 |
| −2.5 | −1.82 | −1.35 | 0.090 | −0.88 | 0.180 | −0.58 | 0.250 |
| −3.5 | −2.49 | −2.02 | 0.094 | −1.57 | 0.186 | −1.31 | 0.250 |
| −4.5 | −3.2 | −2.73 | 0.094 | −2.26 | 0.190 | −1.98 | 0.260 |

exchanges between the atmosphere and the ground surface [*Zhou et al.*, 2005]. Changes in permafrost dynamics may also affect surface and subsurface hydrological processes. Permafrost degradation may result in land desertification and probably a deteriorated ecosystem in cold regions [*Cheng et al.*, 1998]. Changes in the active layer and permafrost conditions may affect carbon pools and fluxes as well [*Lin et al.*, 1996; *Jin and Cheng*, 1997a].

#### 3.1.1. Response of Climate to Permafrost Degradation

[18] Studies have mostly focused on the response of permafrost to climate change on the plateau. In recent years, more attention has been given to the response of climate to changes in ground freezing and thawing conditions. For example, many studies take into account the effect of ground freezing and thawing in climate models [*Stendel and Christensen*, 2002; *Y. Zhang et al.*, 2005; *C. Wang et al.*, 2002]. On the basis of a solution to the Neumann Problem, *Li et al.* [2002a, 2002b] analyzed the effect of ground freezing and thawing on energy exchanges between the atmosphere and the ground surface. The process of soil freezing and thawing greatly increases the heat exchange between the atmosphere and the ground surface. An approximation system method was employed to calculate the thermal regime of silty clay with and without the involvement of freezing and thawing. The calculation illustrates that heat exchange between the atmosphere and the ground surface during freezing and thawing can be two times greater than that without phase change. The influence of freezing and thawing on the level of heat exchange increases with rising soil moisture content. These conclusions have been validated in both permafrost and nonpermafrost areas of the plateau.

[19] Some progress has been made in modeling ground freezing and thawing using GCMs. *Zhang and Lu* [2002b] developed a simplified numerical model for frozen soils based upon the National Center for Atmosphere Research (NCAR) Land Surface Model (LSM). Soil properties, ice content and energy exchange during phase change are all considered in the model. *Y. Zhang et al.* [2004] incorporated this model into the NCAR Community Climate Model (CCM3). The result is consistent with previous studies in terms of permafrost distribution on the plateau and in midlatitudes and high latitudes of the Northern Hemisphere. This model provides a reliable method for simulating the interaction between permafrost and climate change. *Zhang and Lu* [2002a] completed a numerical simulation using the NCAR LSM with the GAME-Tibet IOP (GEWEX Asian Monsoon Experiment-Tibet Intensive Observation Period) data of 1998 for the plateau. They discovered that initial values of ground surface temperature and ground temperature at depth have a great effect on the accuracy of the LSM model. *Wang et al.* [2003] studied the process of seasonal freezing and thawing on the plateau, on the basis of the maximum depth of freezing recorded at 46 meteorological stations, precipitation data at 160 stations, and reinterpreted NCAR/NCEP data. They concluded that ground freezing and thawing on the plateau have a significant influence on the atmospheric circulation of the plateau. Heat and moisture variations caused by the freezing and thawing process may play an important role in the climate of east Asia. An inverse correlation exists between the depth of seasonal freezing and thawing on the plateau and the amount of summer precipitation in most regions of China. Consequently, the maximum depth of freezing on the plateau may serve as an indicator of the amount of summer precipitation in China. *Gao et al.* [2005] analyzed data from 50 meteorological stations and the NCEP/NCAP monthly data on the plateau. They concluded that summer precipitation in southern China increases when spring thaw starts earlier than usual. Meanwhile, summer precipitation in the middle and lower reaches of the Yangtze River and in the lower reaches of the Huai River decreases when spring thaw starts late.

#### 3.1.2. Permafrost Degradation and Carbon Cycles

[20] Permafrost degradation under climate warming scenarios will likely increase the emission of major greenhouse gases in frozen layers. More greenhouse gases in the atmosphere may cause further changes in the climate. *Lin et al.* [1996] used a static chamber method to measure the emission of $CH_4$ and $CO_2$ from the plateau permafrost. Results indicate that the $CO_2$ exchange between the ground and atmosphere in an alpine grassland ecosystem is characterized by emission while the $CH_4$ exchange is characterized by absorption. *Jin et al.* [1999] estimate that the methane emission from the wetland on the plateau amounts to 0.7–1.0 $T_g$ per year. According to the observed densities of $CH_4$ and $CO_2$, they report that dry meadows in permafrost regions serve as a carbon source emitting $CH_4$ but as a carbon sink absorbing $CO_2$. *G. Wang et al.* [2002] report that the annual soil respiration in the grasslands of the plateau may account for 26.5% of that in all of China. Carbon cycles of plateau grasslands are of great significance to the variations of $CO_2$ content in the atmosphere. *X. Zhang et al.* [2005] conducted a 2-year experiment in Pangkog County on the plateau at an elevation of 4800 m a.s.l. to measure $CO_2$ emissions in an alpine grassland ecosystem using a static closed chamber technique. The emission values, combined with measured net productivity data, indicate that the alpine grassland ecosystem on the plateau is a carbon sink. *Pei et al.* [2003] measured carbon emissions from an alpine grassland at the Wudaoliang site at an elevation of 4764 m a.s.l. Their measurements are consistent with earlier conclusions that describe the plateau as simultaneously a carbon source and sink [*Lin et al.*, 1996].

### 3.2. Permafrost Degradation and Ecosystem and Hydrology

#### 3.2.1. Source Areas of the Yangtze and Yellow Rivers

[21] On the basis of the analysis of the active layer process operating on the plateau, *Wu et al.* [2003] report that the depth of thaw is a major factor controlling the amount of moisture content in the active layer. The dynamics of permafrost is closely associated with hydrological and thermal processes near the ground surface, as well as other components of the ecosystem. *Yang et al.* [2004, 2005] carried out a study on spatial distribution and dynamic changes of the vegetation cover at the source areas of the Yangtze and Yellow rivers over the last 20 years, using the 8-km-resolution multitemporal NOAA AVHRR-NDVI data taken between 1982 and 2001. Combining their observations with subsurface temperature data from local meteorological stations, they concluded that the Normalized Difference Vegetation Index (NDVI) is very sensitive to

changes in soil temperature at a depth of 40 cm, and that the freezing and thawing process plays an important role in plant growth, soil temperature, and moisture content. Ecosystem deterioration and decreased runoffs on the plateau have caused great concern among local communities and numerous levels of government. Permafrost degradation as a result of climate warming leads directly to the lowering of local water tables and lake water levels, and shrinking of wetlands and grazing grasslands [*Cheng and Zhao*, 2000]. A mathematical model was built by *Cao et al.* [2003a] to simulate environmental changes in cold regions. *Cao et al.* [2003b, 2006] attribute the deterioration of marshy meadows at the source area of the Yellow River to the lowering suprapermafrost water table. The diminishing marshy meadows allow for a greater depth of thaw and thus further lowering of the water table. This conclusion is consistent with observations made by other researchers [e.g., *S. Zhang et al.*, 2004; *Peng et al.*, 2003].

### 3.2.2. Permafrost Degradation and Desertification

[22] Some recent studies have focused on the relationship between permafrost degradation and desertification on the plateau. *Zhao et al.* [2005] have summarized the spatial and temporal characteristics of the depth of seasonal freezing and sandstorms over the past 50 years by analyzing data from 685 sandstorm monitoring stations in inland China, 112 seasonal freezing depth monitoring stations, and 706 air temperature monitoring stations. The statistical results indicate that a close relationship exists between the occurrence of sandstorms and the minimum depth of freezing. *S. Wang et al.* [2002] studied the relationship between permafrost degradation and desertification on the plateau by analyzing surface energy balance and ground temperature data. The result shows that ground temperature under sand dunes and thick sand layers (10–20 cm) is higher than that without the sand layer and that ground temperature under a thin sand layer (<10 cm) is lower than that without the sand. *Han et al.* [2004] believe that the plateau is an important source region providing much of the sand grains for sandstorms. When compared with other source regions of sandstorms, sandstorm occurrences on the plateau are more frequent. The plateau sand can be transported by westerlies to places as far away as the northern Pacific.

## 4. Conclusions

[23] 1. Long-term monitoring of permafrost on the plateau indicates that the area of permafrost has been undergoing extensive shrinkage. The lower altitudinal limit of permafrost has risen by 50–100 m over the past 20 years along the Qinghai-Kang Highway located on the eastern edge of the plateau and 25 m over the last 30 years at Xidatan in the interior of the plateau.

[24] 2. According to the results from numerical simulations and predication models using GCMs, no significant change will take place in permafrost conditions on the plateau over the next 50 years, but more than half of the permafrost may become relict and/or even disappear by 2100.

[25] 3. The results of GCM prediction models can only be improved when soil freeze-thaw processes are adequately considered. A simple permafrost parameterization can significantly improve simulation results of the CCM3.6, commonly used by the NCAR.

[26] 4. Although permafrost on the plateau has been experiencing a warming trend, the alpine grassland ecosystem of the plateau is still considered a carbon sink environment.

[27] 5. Regional lowering of groundwater tables triggered by degrading permafrost has become one of the major factors responsible for the deteriorating environment, as evidenced by dropping lake water levels, shrinking wetlands, and degenerating grasslands. Permafrost degradation will likely cause a drier ground surface and as such, land desertification may become an important environmental issue for the plateau.

[28] **Acknowledgments.** The authors are grateful to three journal reviewers, the associate editor, and the editor Robert Anderson's valuable suggestions for improving this paper. We also thank the financial support from KZCX1-SW-04 of Chinese Academy of Sciences. The logistical support from the Cryosphere Research Station on the Qinghai-Tibet Plateau, Chinese Academy of Sciences, is appreciated for our field surveys.

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