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Permafrost degradation and its environmental effects on the Tibetan Plateau: A review of recent research

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ABSTRACT

A significant portion of the Tibetan Plateau is underlain by permafrost, and is highly sensitive to climate change. Observational data from recent Chinese investigations on permafrost degradation and its environmental effects in the Tibetan region indicate that a large portion of the Tibetan Plateau has experienced significant warming since the mid-1950s. The air temperature increase is most significant in the central, eastern, and northwestern parts of the Plateau. The warming trend in the cold season was greater than that in the warm season. The duration of seasonal ground freezing has shortened due to the air temperature increase in winter. Numerical simulations indicate that air temperature on the Plateau will continue to increase in the 21st century. Significant warming has resulted in extensive degradation of permafrost. Over the last 30 years, a 25 m increase in the lower altitudinal occurrences of permafrost has taken place in the north. In the south the increase is 50–80 m over the past 20 years. Active-layer thickness and mean annual ground temperature have increased by 0.15–0.50 m during 1996–2001 and by 0.1–0.5 °C during the last 30 years on the Tibetan Plateau, respectively. Widespread permafrost degradation has already caused environmental deterioration. Extensive desertification processes are apparent in the eastern and western portions of the Tibetan Plateau, with the area occupied by desert increasing annually by about 1.8%. With rapid retreat and thinning of permafrost, large carbon pools sequestered in permafrost could be released to increase net sources of atmospheric carbon, creating a positive feedback and accelerated warming. Damage to human infrastructure is also caused by frost heave, thaw settlement, and thaw slumping in the permafrost-affected region. The impact of permafrost degradation on energy and water exchange processes between the ground and atmosphere require further examination. Large-scale intensive monitoring networks, remote sensing investigations, and models for frozen soil are needed to clarify regional details of climate change, permafrost degradation, and their environmental effects.

Contents

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1. Introduction

The Tibetan Plateau, known by various names (e.g., Qinghai–Xizang (Tibetan) Plateau, Qinghai–Tibetan Plateau), encompasses a singular region in southwestern China distinguished by unique geography, climate, and history. Zhang et al. (2002) used data obtained from extensive field studies to define the aerial extent of the Tibetan Plateau and its physiographic boundaries. Based on homogeneity of major geologic and geomorphic characteristics, they concluded that the Tibetan Plateau extends for a maximum of 2945 km across 31° of longitude from east to west, and for 1532 km across 13° of latitude. The Plateau occupies an area of 2572.4×10^3 km^2, approximately one quarter of China's mainland territory. Administratively, the Plateau incorporates 201 counties (cities) in six provinces: Tibet Autonomous Region, Qinghai Province, northwestern Yunnan Province, western Sichuan Province, southwestern Gansu Province, and southern Xinjiang Uygur Autonomous Region (Fig. 1; Zhang et al., 2002). With an average elevation of more than 4000 m, the Tibetan Plateau is the highest and the most extensive plateau in the world (Liu and Chen, 2000). It has long been known as the "roof of the world." Its high elevations and complex topography create a distinctive atmospheric circulation pattern that affects both regional and global climate profoundly (He et al., 1987; Barnnet et al., 1989; Yasunari et al., 1991; Vernekar et al., 1995; Wu and Zhang, 1998; Yang and Yao, 1998; Chen and Wu, 2000; An et al., 2001; Qian et al., 2003; Wu and Qian, 2003; Zhang, 2007; Zhao and Qian, 2007; Wang et al., 2008).

As in high-latitude regions of the Northern Hemisphere, high-altitude areas are especially susceptible to global climate change. Pan and Li (1996) suggested that, along with the polar regions, the Tibetan Plateau has warmed more, and perhaps sooner, than the rest of the globe. Based on station observation data from 1961 to 2006, Ding and Zhang (2008) demonstrated that the annual and seasonal mean surface air temperature on the Tibetan Plateau have shown increasing trends. Mean annual surface air temperature began to increase from the mid-1980s and a rapid and significant increase in surface air temperature began in the mid-1990s. Based on reconstructed climatic data, Liu and Zhang (1998) demonstrated a significant warming trend over the Tibetan Plateau during the last 90 years. This trend is confirmed by ice core records in Tibet, including those from Dunde, Guliya, Puruogangri, and Dasuopu (Yao et al., 2006). These four ice cores show increasing δ^{18}O trends, indicating warming on the Tibetan Plateau over the past 100 years (Fig. 2; Yao et al., 1995; Yang and Yao, 2004; Yao et al., 2006). The widespread retreat of mountain glaciers (e.g., Yao et al., 2004) is probably the most notable manifestation of climatic change on the Tibetan Plateau.

Permafrost is defined as ground that remains at or below 0 °C continuously for two or more years (Muller, 1947). It is widespread in high latitudes and in high-elevation regions (Zhang et al., 2007). The permafrost regions occupy about a quarter of the terrestrial Northern Hemisphere (Zhang et al., 1999; Wu et al., 2009). About 22.3% of China's land area (2.15×106 km^2) is underlain by permafrost (Zhou and Guo, 1983). Most of China's permafrost (1.73×10^6 km^2) occurs at high altitudes on the Tibetan Plateau. A significant portion of the Tibetan Plateau is underlain by permafrost varying in thickness from 1 to 130 m, depending on such local characteristics as slope and exposure, altitude, geological structure, soils, and soil water content. Permafrost temperature varies between −0.5 and −3.5 °C (Cheng,

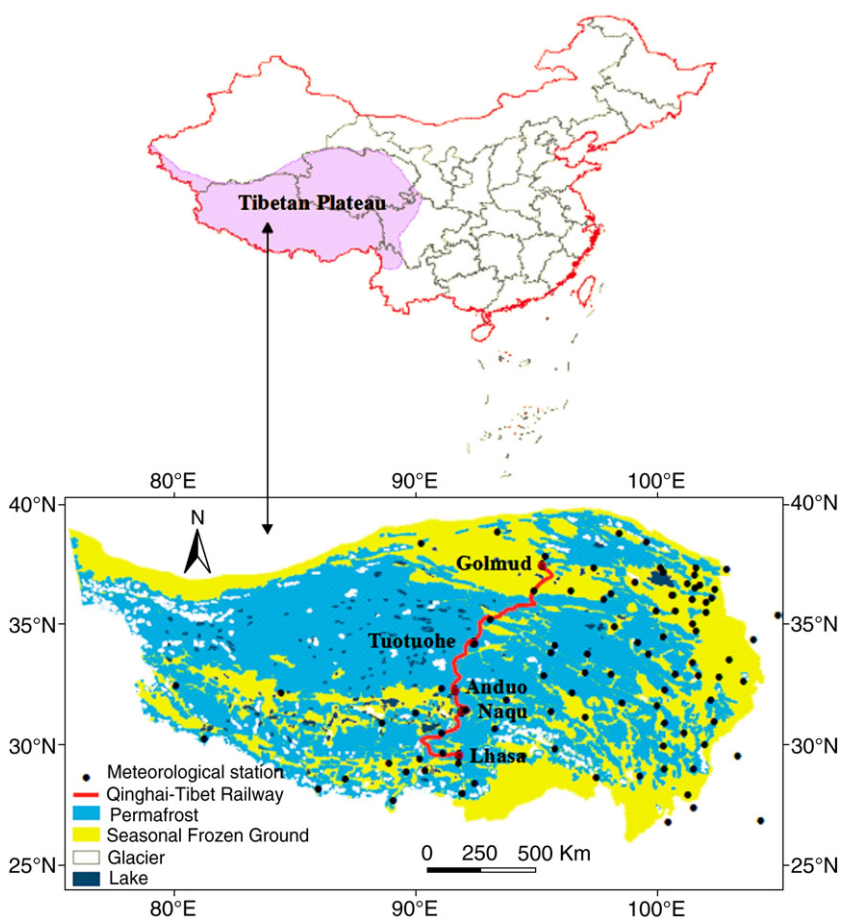

Fig. 1. Distribution of frozen ground (After Li and Cheng, 1996, and digitized by Nan, 2003) and location of meteorological stations above 2000 m a.s.l. on the Qinghai–Xizang (Tibetan) Plateau. Red lines represent highways on the Plateau.

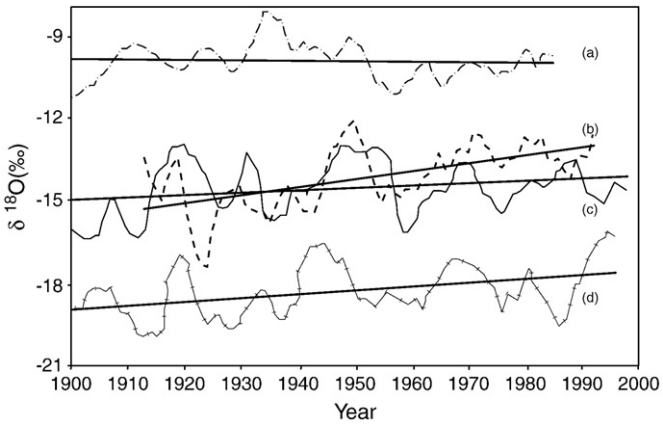

Fig. 2. Comparison of the temperature proxies between the (a) Dunde, (b) Guliya, (c) Puruogangri, and (d) Dasuopu ice cores. Straight line indicates the trend over time (after Yao et al., 2006).

1997). Tibetan permafrost comprises 74.5% of the Northern Hemisphere's mountain permafrost, and is a direct consequence of land uplift on the order of 3000 m over the last 2 million years. Because the Plateau is geologically young and active, the geothermal gradient is steep (0.0514 °C/m), resulting in a thin, relatively warm permafrost layer containing many taliks (Wu, 2005). The region also experiences a high solar radiation load, making permafrost highly sensitive to surface disturbance and climate change. Permafrost temperature varies greatly from place to place and depends to a large extent on altitude and latitude. Permafrost on the Plateau is generally ice-poor as a consequence of the arid climate, high evaporation, and glacial history. Ice segregation, ground heave and subsidence, and related periglacial landforms are rare in comparison with high-latitude permafrost regions. Frost mounds of the open-system type occur in association with structural faults, which are also the most important factors influencing the ground thermal regime (Wang and French, 1994, 1995).

Permafrost in the Tibetan Plateau is highly sensitive to climate change and has experienced significant temperature increases and widespread degradation during the last several decades (Zheng et al., 2002; Qin et al., 2006). Widespread permafrost degradation has already caused environmental deterioration, including changes in surface hydrology, accelerated desertification, and destabilization of human infrastructure.

The population of the Tibetan Plateau is sparse at present. Although historical population data are few and unreliable, beginning in the 1950s the region's population has been increasing continuously at a rate averaging 2.19% per year (Fu and Zheng, 2000). Population has tripled over the last 45 years (Fu and Zheng, 2000). Population growth is likely to continue, and will be accompanied by accelerated industrial and urban development, promoted by the construction of the Qinghai–Tibet Railway. Development will undoubtedly exert additional stresses on the sensitive permafrost environment.

The Qinghai–Tibet railroad traverses the Tibetan Plateau from north to south, stretching over a distance of 1118 km from Golmud to Lhasa, the capital of the Tibetan Autonomous Region. Along its route, more than 965 km of the railway lie above 4000 m a.s.l., and at its highest point the elevation is 5072 m. Approximately 550 km of the railway is underlain by permafrost (Cheng, 2002). As in early 20th-century Russia, when the construction of the Trans-Siberian Railway generated substantial scientific interest in frozen ground phenomena, construction of the Qinghai–Tibet Railway has served to promote detailed permafrost investigations in China. In this paper we provide an overview of recent studies on climate change and permafrost on the Tibetan Plateau.

2. Permafrost observation and monitoring network

Although reports about soil freezing and thawing can be found in Chinese literature extending over thousands of years, systematic study of frozen ground did not start until the 1950s (Zhang, 2005). In that decade, permafrost investigations were limited to isolated projects driven by local economic and industrial needs, such as construction and maintenance of the Qinghai–Tibetan Highway (Zhang, 2005). In 1958, the Chinese Academy of Sciences organized a "Snow-Ice-Research Group," which led to the establishment of the Lanzhou Institute of Glaciology, Geocryology, and Desert Research in 1965. The first permafrost investigations conducted by trained scientists on the Tibetan Plateau were initiated in the 1960s (Shi, 1988). During the 1960s and 1970s, permafrost investigations continued to serve the operational needs of the Qinghai–Tibet Highway and anticipated railway construction (Qiu, 1980), and were primarily restricted to short-term surveying along the 1178 km highway corridor (Wang and French, 1995; Zhang, 2005). Exceptions include the permafrost observation site at Fenghuo Shan, where periodic permafrost temperature monitoring has been conducted in a 35 m borehole since the early 1960s. In 1990, the Qinghai–Xizang (Tibet) Observatory Station of the Chinese Academy of Science in Germud initiated systematic permafrost monitoring along the Qinghai–Tibet Highway, followed by the establishment of a permafrost station at Wudaoliang on the northern Tibetan Plateau in 1991 (Zhang, 2005). The Global Energy and Water Cycle Experiment (GEWEX) Asian Monsoon Experiment on Tibet (GAME-Tibet) was initiated in 1997. Soil moisture and temperature at different depths have been collected in the permafrost and seasonally frozen regions of the Plateau at 11 GAME-Tibet sites (Yang et al., 2003, 2006a, b, 2007a, b, 2008a, b).

Systematic permafrost investigations have been expanded significantly since the beginning of construction on the Qinghai–Tibet Railway in 2001. Eighteen ground temperature monitoring sites and 13 active-layer monitoring sites were established along the 800 km railway, which traverses the Plateau from south to north. Monitoring parameters include permafrost temperature at several depths and the thickness of the active layer, supplemented by meteorological and climatic observations (Fig. 3; Wu, 2005). In 2004, the Institute of Tibetan Plateau Research (ITP) was established in Lhasa, with branch offices in Beijing and Kunming. The ITP specializes in studies of land surface processes, biodiversity, and endangered species. The ITP Field Monitoring and Research Platform (FMRP) consists of three field stations, established at Namcuo Lake, Linzhi, and Dingri near Mount Everest. The Namcuo Lake and Dingri stations are underlain by permafrost, and are home to extensive research projects linked to other long-term permafrost monitoring programs. Permafrost monitoring is a priority of the FMRP expansion.

3. Recent progress

3.1. Permafrost monitoring

During recent decades a series of empirically derived maps of permafrost in China have been published, including the 1:4 000 000 *Map of the Snow, Ice and Frozen Ground in China* (Shi et al., 1988) and the 1:600 000 *Permafrost Map along the Qinghai–Tibet Highway* (Tong and Li, 1983). Contemporary knowledge about permafrost distribution on the Tibetan Plateau is summarized in the 1:3 000 000 *Map of Permafrost Distribution on the Qinghai–Tibet Plateau* by Li and Cheng (1996), reproduced here as Fig. 1.

To assess the geographic distribution of Tibetan permafrost further, Nan (2003) evaluated several spatial permafrost modeling approaches. Four methods were selected for analysis: the Altitude Model (AM) (Cheng, 1984); the Mean Annual Ground Temperature (MAGT) Model (Nan, 2003); the Surface Frost Number (Nelson and Outcalt, 1987); and the Temperature at the Top of Permafrost (TTOP) Model (Smith and

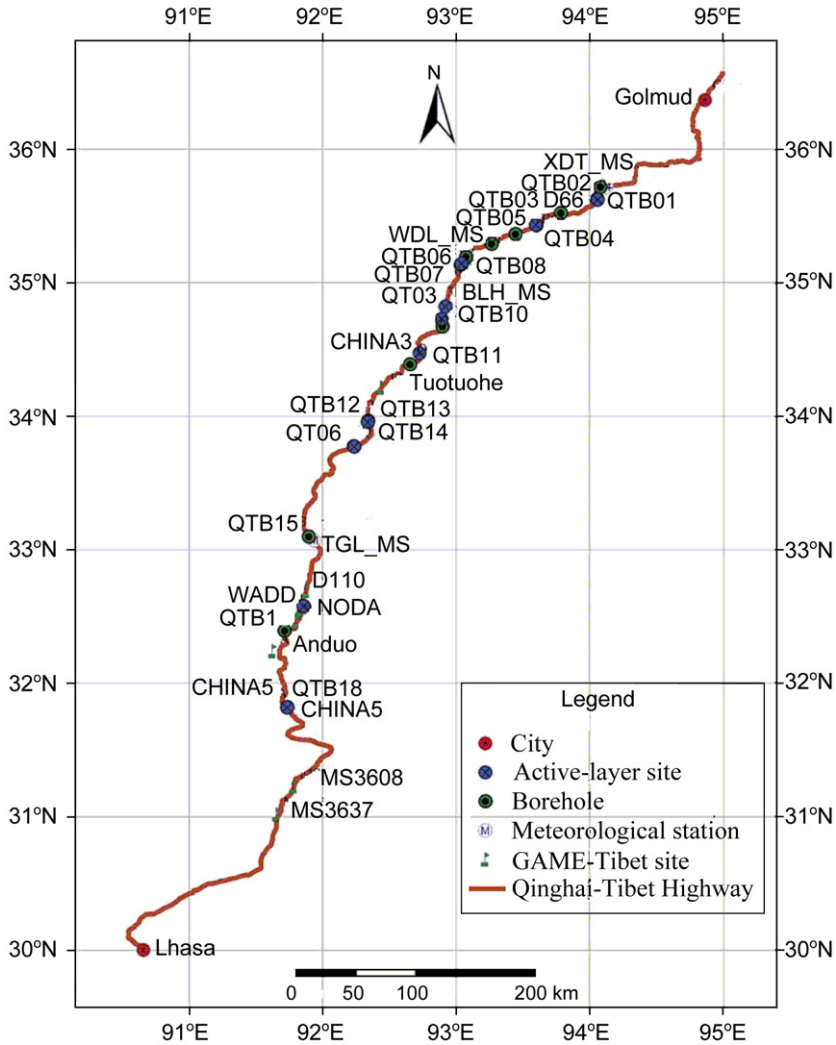

Fig. 3. Permafrost monitoring network along the Qinghai–Tibet Highway (after Wu, 2005).

Riseborough, 1996). The output parameter of AM is the lower "boundary" of permafrost as a function of latitudinal position. The MAGT model estimates mean annual ground temperature at the depth of zero annual amplitude, as a linear function of latitude and altitude. The Surface Frost Number is an index calculated using the air freezing and thawing degree–day ratios to determine the zonal arrangement and extent of seasonally frozen ground, discontinuous permafrost, and continuous permafrost. The TTOP model is based on a simplification of Kudryavtsev et al. (1974) methods. The model links permafrost temperature with surface climatology through seasonal surface transfer functions and subsurface thermal properties, providing a rational method for small-scale estimation of permafrost temperatures.

Results from these methods were compared with the *Map of Permafrost Distribution on the Qinghai–Tibetan Plateau* (Li and Cheng, 1996). All four approaches are capable of providing reasonable assessments of permafrost distribution on the Qinghai–Tibetan Plateau (Fig. 4). However, the AM, MAGT, and TTOP models tend to overestimate the extent of permafrost. The closest agreement with the empirical map was achieved by the Surface Frost Number approach. The total area of the Tibetan Plateau underlain by permafrost, as estimated by the different methods, is shown in Table 1 (Wu, 2005).

3.2. Air temperature and precipitation

The network of meteorological stations on the Tibetan Plateau is sparse and unevenly distributed (Fig. 1). Most of the stations are located in the eastern portion and along the plateau's margins. Only four stations (Shiquanhe, Gaize, Pishan and Pulan) exist west of 85°E longitude and there are no stations in the northwestern part of the Plateau. Meteorological stations are located primarily in river valleys, at relatively low elevations. The average altitude of the Tibetan meteorological network is 3368 m, which is significantly lower than the average elevation (4320 m) of the plateau (Li et al., 2003). Moreover, the station data are largely insufficient for establishing long-term climatic trends because most stations were established after 1950, with few observational records extending back to the 1930s.

Despite these shortcomings, station records have been used extensively to analyze spatial and temporal characteristics of the Tibetan climate. A comprehensive analysis of station records was conducted by Liu and Chen (2000), who used data from 197 stations, 97 of which are located above 2000 m, including the highest mountain station (Anduo) at 4801 m (Fig. 1). Their results indicate that a large portion of the Tibetan Plateau has experienced significant warming since the mid-1950s. The most significant increase in mean annual temperature was observed at locations above 2000 m a.s.l., with disproportionate warming during the cold season. The rate of temperature increase over the entire Plateau during the 1955–1996 period, obtained by arithmetic averaging of records from 97 stations located at least 2000 m a.s.l., was approximately 0.16 °C/decade for the annual mean and 0.32 °C/decade for the winter mean temperature. These rates exceed those for the Northern Hemisphere and the

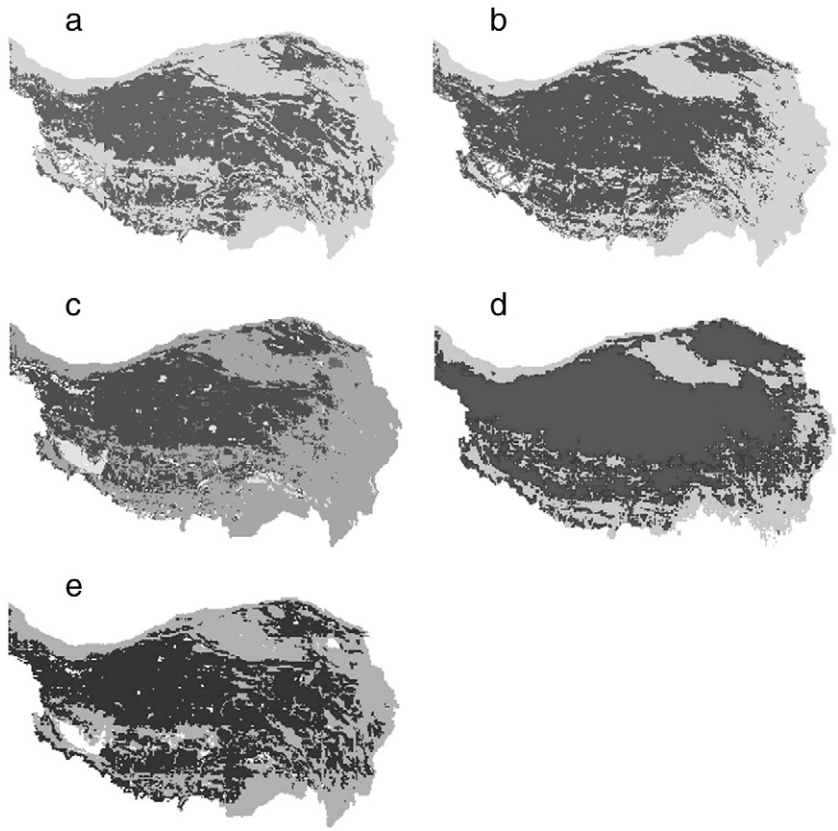

Fig. 4. Map of frozen ground on the Qinghai–Xizang (Tibetan) Plateau from different models. (a) digitized map; (b) altitude model; (c) mean annual ground temperature model (d) surface frost number (e) TTOP. Black color indicates permafrost, gray indicates seasonally frozen soil, and white represents snow cover (After Nan, 2003).

corresponding latitudinal zone (Jones et al., 1986; Jones and Briffa, 1992). The statistically significant warming in the Tibetan Plateau began in the mid-1950s to early 1960s, while corresponding temperature increases in the Northern Hemisphere and global average air temperature did not occur until the mid-1970s (Jones et al., 1986; Vinikov et al., 1990; Houghton et al., 1996). According to Liu and Chen (2000), the air temperature increase is most significant in the central, eastern, and northwestern parts of the Plateau, with warming tending to increase with elevation. Despite this pronounced warming trend, mean annual air temperature did not reach the level of the 1940s warm period until the late 1990s in the central and eastern portions of the Plateau (Fig. 5). However, the cause of 1940s warm period is not explained in the paper. This issue should be made a high priority in future investigations.

Zhao et al. (2004) examined changes in climate and seasonally frozen ground over the last 30 years using data from 50 meteorological stations in the Qinghai–Tibet Plateau describing air temperature, ground-surface temperature, precipitation, and frost-penetration depth. The latitude, longitude, elevation, mean annual air temperature, annual precipitation, and maximum freezing depth at each station were used as station grouping criteria for hierarchical cluster analysis. This procedure grouped stations into four clusters representing distinctive

Table 1
Total area of the Tibetan Plateau underlain by permafrost, calculated using different methods. Reference data are in the form of a digitized map (126.7×10^4 km^2). "+" refers to increase, "−" refers to decrease (after Wu, 2005).

Methods	Permafrost area (10^4 km^2)	Deviation from reference data (%)	Data sources
Regional statistical survey	150.0	+18.4	Zhou and Guo (1983)
Historical data analysis	140.1	+10.6	Li and Cheng (1996)
Digitized map	126.7	0	Nan (2003)
Altitude model	136.0	+7.3	Nan (2003)
Mean annual ground temperature model	111.8	−11.8	Nan (2003)
Surface frost number	127.8	+0.9	Nan (2003)
TTOP model	138.7	+9.5	Nan (2003)

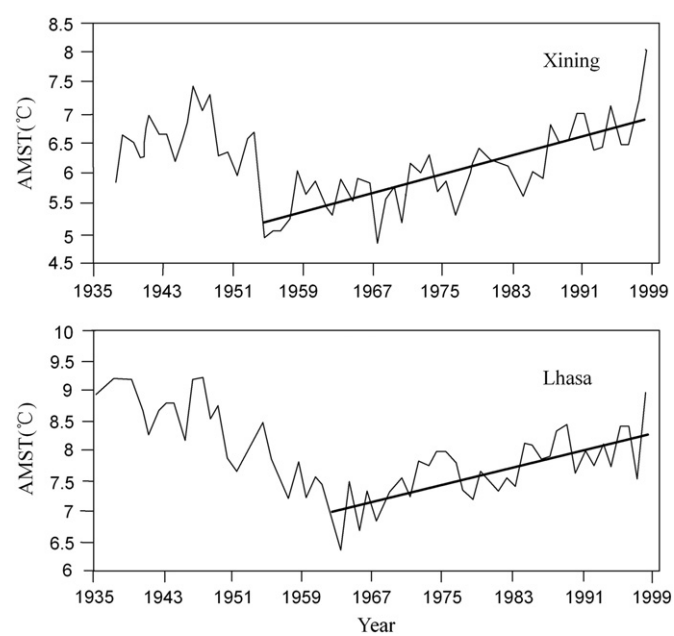

Fig. 5. Mean annual surface temperature (MAST) for 1935–1998 in Xining (36.6°N, 101.8°E, 2262 m a.s.l.) and Lhasa (29.7°N, 101.1°E, 3650 m a.s.l.). The heavy solid lines indicate the trends of annual mean surface temperature for recent warming periods (After Liu and Chen, 2000).

regions (northwestern, northeastern, southeastern and interior Qinghai–Tibetan Plateau, and Tashikurgan in the West Karakunlun Mountains). The analysis showed that the most significant climate warming occurred in the northeastern part of the Tibetan Plateau, and that the warming trend was greater in the cold season than in the warm season. Annual precipitation increased in the northwestern, central, and southeastern regions, but decreased in the northeastern part. Changes in ground-surface temperature showed a more pronounced warming trend as compared to air temperature, with a greater increase of ground-surface temperature in summer. The most significant decrease in the depth of seasonal ground freezing occurred in regions with the deepest propagation of seasonal frost: the central, northeastern, and northwestern portions of the Plateau. The duration of seasonal ground freezing has shortened over the 30-year period in response to the increase in winter air temperature. The most significant changes in the duration of freezing occurred in the central and northeastern regions of the Plateau. It was concluded that changes in seasonal freezing depth and duration and an increase in ground-surface temperature are likely to enhance heat exchange between the ground and the atmosphere, and can potentially result in amplification of plateau monsoons.

Li et al. (2005b) used principal-component analysis to evaluate air temperature trends from 86 stations in the Tibetan Plateau as a function of elevation and latitude. The first principal-component represented an obvious warming trend during the last 30 years, over the entire Plateau. Monthly mean, maximum, and minimum temperatures and monthly precipitation from 84 stations were also analyzed by Ma and Li (2003) and Ma and Hu (2005), by dividing the Plateau into eight subregions. Results indicated that standardized mean annual temperature has been increasing at a rate of 0.21–0.42 °C/decade over the period of observation. The rate of minimum temperature increase was 1–3 times higher than the rate of maximum temperature increase. It was also demonstrated that the daily temperature range was decreasing significantly, at the rate of −0.08 to −0.51 °C/decade. The most abrupt temperature changes were found during the 1980s. The data also showed a gradual increase of precipitation throughout the Tibetan Plateau. The largest precipitation increase (10.3%) was observed in the southern portion of the Plateau. Based on temperature and precipitation data at 101 meteorological stations on the Plateau and its surroundings, Wu (2005) developed a multivariable linear regression model that demonstrated a close relation between climatic characteristics (temperature and precipitation) and geographical factors, including longitude, latitude, and elevation. He found that the annual mean air temperature is higher in the east and south than in the west and north (Fig. 6). Altitude is the most dominant factor determining annual mean air temperature. Precipitation decreases significantly from southeast to northwest (Fig. 7).

Although caution should be taken in the interpretation of regional details provided in these analyses due to the inadequate distribution of stations and significant gaps in the data record, the general trend indicates a significant increase in air temperature over the last few decades. The trend in precipitation is more complex, with some stations showing increases while a decrease is apparent in others. In general, northern stations located at higher elevation demonstrate a consistent increase in summer precipitation Lin and Zhao (1996). Based on meteorological data from the last 35 years, Liu et al. (2008) demonstrated that changes of both air temperature and rainfall in Tibet exhibited evident zonal patterns. In general, air temperature increases become larger from east to west, whereas rainfall decreases in the south but increases in the north. Yang et al. (2006a,b) hypothesized that the increase may be related to an enhancement of water recycling between land and atmosphere associated with the increase of air temperature, because the proportion of local convective precipitation is quite high in the northern Plateau. Wu et al. (2005a) evaluated potential evapotranspiration for 77 meteorological stations on the Tibetan Plateau for the 1971–2000 period by applying the Penman–Monteith method (Walter et al., 2000) and an index of aridity. It was shown that the rise of temperature and precipitation increase resulted in a decrease of potential evapotranspiration, which caused the Plateau to become more humid.

As noted earlier, the small number of stations on the Tibetan Plateau and their uneven distribution may affect the overall accuracy of regional assessments of climatic conditions. To address this problem, several interpolation routines were applied to station records over the Plateau. Li et al. (2003) evaluated several interpolation schemes, including inverse distance weighting, trend surface analysis, kriging, and co-kriging, for their ability to reproduce the observed spatial pattern of the 30-year mean January atmosphere temperature from 1961 to 1990 over the Plateau. It was found that, given the geographic distribution of available stations, the four methods produced very similar fields but none adequately reproduces the low temperature characteristic of northwestern Tibet (Fig. 8). To correct for this deficiency, they applied an interpolation method based on a combination of statistical and physical principles of air temperature field formation (i.e., a combination method similar to the "smart interpolation" procedures described by Willmott and Matsuura (1995)). Station air temperature was first "brought down" to sea level using latitude and altitude-specific lapse rates. Kriging was then performed on the adjusted-to-sea-level station air temperatures. Finally, the gridded sea-level air temperatures were brought up to the DEM-grid height, again using lapse rates. The resulting air temperature fields provided estimates far superior to those derived from those that fail to consider elevation effects explicitly, and were able to

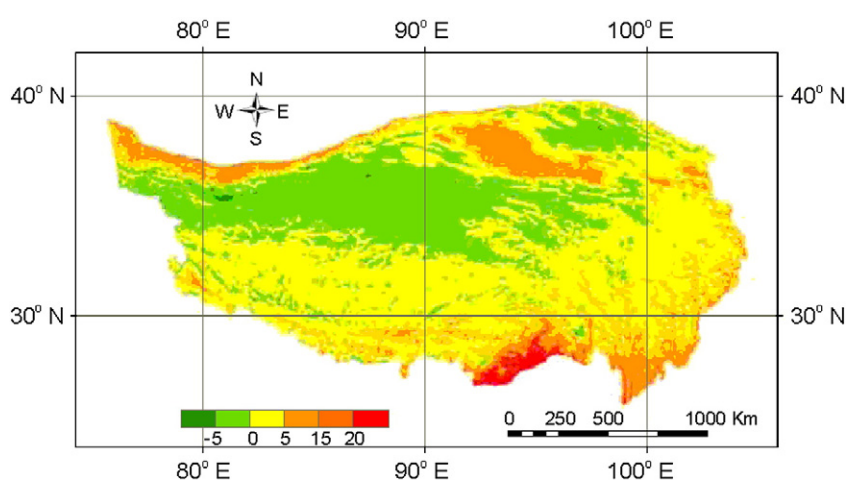

Fig. 6. Distribution of annual mean surface temperature for 1961–2000 on the Qinghai–Xizang (Tibetan) Plateau (after Wu, 2005).

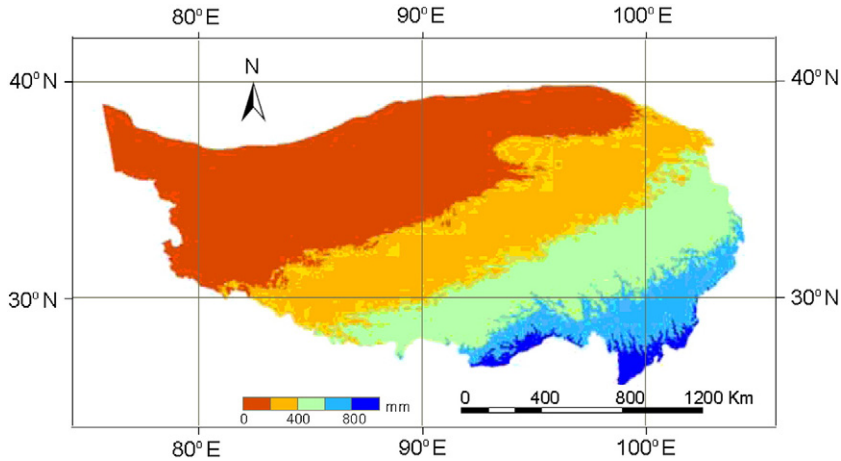

Fig. 7. Distribution of annual mean precipitation for 1961–2000 on the Qinghai–Xizang (Tibetan) Plateau (after Wu, 2005).

correctly reproduce latitudinal and altitudinal patterns (Fig. 8). This method of analyzing air temperature fields allowed more realistic January temperature regionalization over the Tibetan Plateau. The eastern and southern portions of the Plateau generally had higher mean January temperatures (−3 to 6 °C) than did the western and northern parts, where mean January temperature can reach −25 °C.

Wu (2005) used data from 101 meteorological stations on the Tibetan Plateau and its surroundings to examine statistical relations between air temperature, precipitation, longitude, latitude, and elevation. The strong correlation between climate parameters and geographic position (longitude, latitude, and elevation) allowed the use of a multiple linear regression model to develop regional gridded fields of air temperature and precipitation.

Because some of the meteorological stations on the Tibetan Plateau were established since the 1960s, Zhou et al. (2005) developed a continuous series of monthly mean air temperature at 50 meteorological stations located above 3000 m a.s.l. for 1950–2000, based on the statistical relationship between the surface temperature and 500 hPa NCEP/NCAR re-analysis monthly mean air temperature. They demonstrated that surface air temperature over the Tibetan Plateau has risen over that period. Regional and seasonal differences in air temperature change over the 50 year period were apparent, however. The temperature warming in spring and winter is more obvious than in summer and autumn. Changes in mean annual air temperature are almost uniform over the Tibetan Plateau.

Future potential climate changes in the Tibetan Plateau were examined by Xu et al. (2003, 2005) using results from coupled General Circulation Models (GCMs), including the NCAR (Meehl et al., 2000), HADL (Mitchell et al., 1995), GFDL (Haywood et al., 1997), DKRZ (Tett et al., 1999), CSIRO (Roeckner et al., 1999), CCSR (Emori et al., 1999), and CCC (Boer et al., 2000) models. Results from these simulations indicate that the air temperature increase will be more pronounced in the Tibetan Plateau than in the rest of the China, regardless of emission scenario. By the middle of the 21st century the air temperature will increase by 2.8–3.0 °C, depending on the scenario, for areas adjacent to the Qinghai–Xizang Railway, and could potentially warm by 3.8–4.8 °C by the end of the 21st century. The temperature increase will be more pronounced in winter and will be accompanied by an increase in precipitation. This progressive climate warming would have a significant impact on permafrost conditions in the Tibetan Plateau.

Observational data indicate that significant warming has occurred over most of the Tibetan Plateau since the mid-1950s. The most significant increase in air temperature occurred in the central, eastern, and northwestern parts of the Plateau. The magnitude of the warming tends to increase with elevation (Liu and Chen, 2000). Over the last 30 years the warming trend in the cold season was greater than that in the warm season (Zhao et al., 2004). The period during which seasonal freezing affects the ground has shortened due to the air temperature increase in winter. Numerical simulations indicate that air temperature will continue to increase on the Tibetan Plateau during the 21st century (Xu et al., 2003, 2005). However, studies of regional details are still restricted due to the uneven distribution of sparse stations and significant gaps in the data record. Precipitation distribution is quite complex and spatially heterogeneous on the Plateau (Yang et al., 2007a,b, 2008a,b) and large-scale intensive meteorological station observations, especially in the northwestern part of the Plateau, are needed to clarify regional details of air temperature and precipitation. Meanwhile, interpolation methods better suited to the Tibetan Plateau's unusual geographical characteristics should be developed to reproduce temperature and precipitation fields.

3.3. Ground temperature and permafrost distribution

Over the past two decades ground temperature and auxiliary observations have been used to estimate the rate and extent of permafrost degradation on the Tibetan Plateau. Many of these studies emphasized migration of permafrost "boundaries," which are by nature fuzzy, inexact representations of permafrost distribution.

Cheng et al. (1993) analyzed permafrost temperature at several stations on the Tibetan Plateau between 1974 and 1989. During this 15-year period the ground temperature at 20 m depth increased by 0.2–0.3 °C, resulting in degradation and disappearance of permafrost near its lower margins. Drilling along the Qinghai–Xizang (Tibetan) highway indicates that the southern "boundary" of permafrost has moved northward by 16 km while in the north it moved southward by 2 km over the same period (Wang and Mi, 1993). An increase of 0.1–0.5 °C in the mean annual ground temperature (MAGT) on the Tibetan Plateau was reported by Wang et al. (2000). The elevation of the lowermost occurrences of permafrost has increased by 40–80 m and the total permafrost area on the Plateau was reduced by about 10^5 km^2, causing environmental deterioration, including changes in surface hydrology, accelerated desertification, and destabilization of infrastructure built on permafrost. Permafrost with mean annual ground temperature of 0.0 to −0.5 °C is most vulnerable to environmental change. For instance, at Jingxiangu in the northern part of the Plateau, the lowermost elevation at which permafrost is found has risen since 1975 by about 20 m. Mean annual ground temperatures at depths of 15–20 m have increased by 0.5–0.8 °C (Table 2; Wang et al., 2000; Jin et al., 2000). Overall, the temperature of seasonally frozen ground and sporadic permafrost rose 0.3–0.5 °C during the past 15–20 years, while the mean annual ground temperature in areas underlain by permafrost more continuously has increased by 0.1–0.3 °C (Wang et al., 1996). Long-term temperature

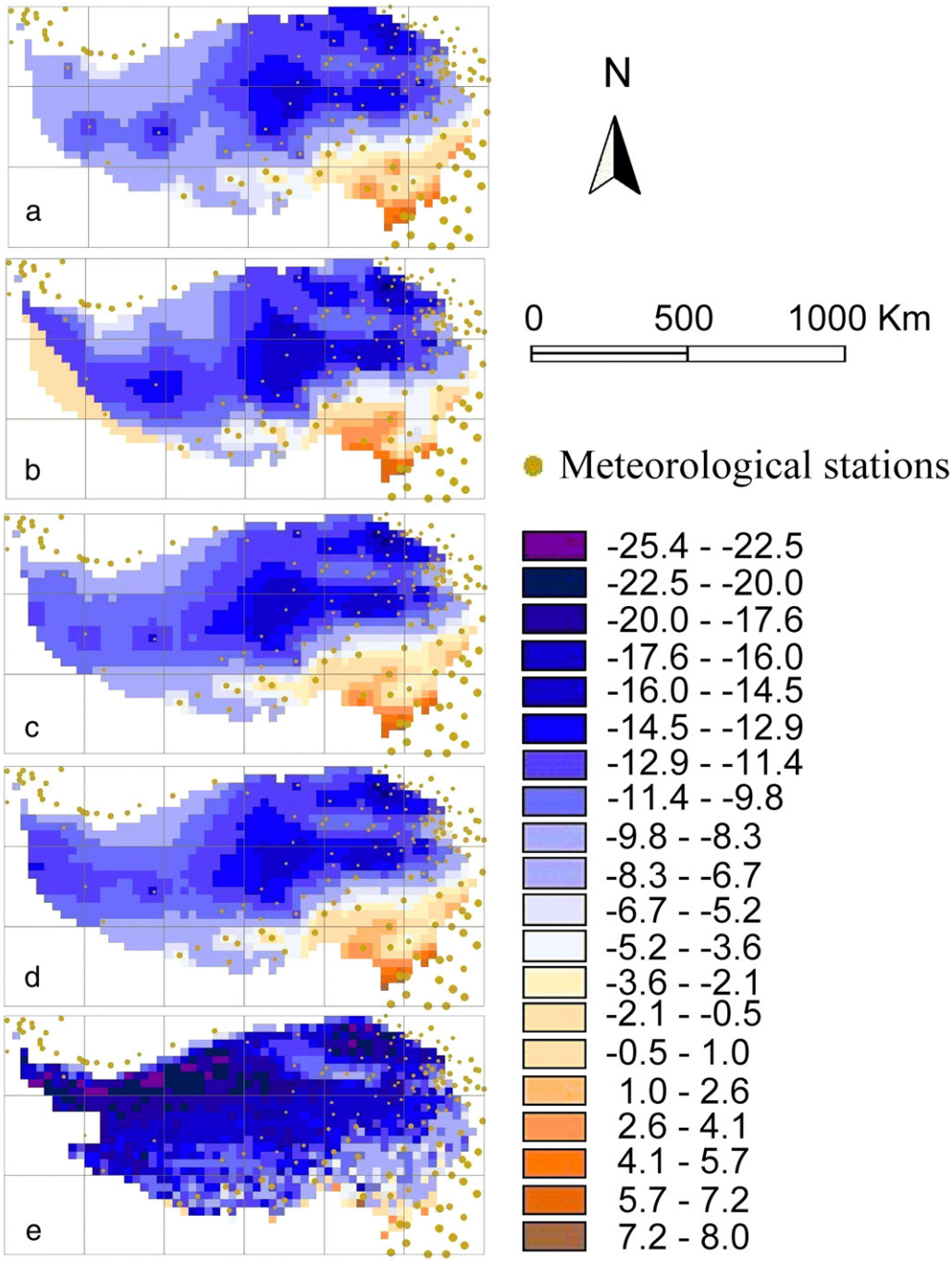

Fig. 8. Mean January air temperature over Qinghai–Xizang Plateau in 1961–1990 from (a) inverse distance weighting, (b) trend surface analysis, (c) kriging, (d) co-kriging, and (e), the "combination method" (after Li et al., 2003).

measurements indicate that the lowermost occurrences of permafrost on the Tibetan Plateau have 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 °C to 0.3 °C between 1996 and 2001 (Cheng and Wu, 2007). Permafrost temperature monitoring in 10 boreholes up to 10.7 m depth was conducted every 2 weeks during the 1996–2006 period along the Qinghai–Tibetan Highway. The primary results show that the long-term mean annual permafrost temperatures at 6.0 m depth vary from −0.19 °C at the Touerjiu Mountains site to −3.43 °C at Fenghuo Mountain, with an average of about −1.55 °C from all 10 sites over the period of their records, confirming that permafrost is relatively warm on the Plateau (Wu and Zhang, 2008).

Ground-penetrating radar (GPR) technology has been used recently on the Tibetan Plateau to detect permafrost degradation. Wu et al. (2005b) used 50-MHz GPR to delimit the extent of permafrost in the Xidatan region (35.7 N, 94.2 E), at the northern margin of sporadic permafrost on the Plateau. The lower altitudinal extent of permafrost was interpreted from nine radar profiles. The locations of the permafrost table along the nine profiles facilitated determination of a characteristic altitudinal permafrost "limit," and assessment of permafrost distribution in the study area. Comparison of these results with those from permafrost surveys conducted in

Table 2
Ground temperature (°C) at different depths (m) at Jingxiangu, Qinghai–Tibet Highway (after Wang et al., 2000).

Depth (m)	6	10	12	14	16	18	20	22	24
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		

1975 indicated that the area underlain by permafrost in the Xidatan region was reduced by 12%, and that the elevation of the lowermost occurrences of permafrost has increased by 25 m. The timing and magnitude of permafrost degradation in the Xidatan region correlate well with the warming trend observed at two meteorological stations (Golmud (36.2°N, 94.6°E) and Wudaoliang (35.3°N, 93.6°E)) in the area. During the last 45 years the mean annual air temperatures at these two stations have experienced warming trends of about 0.06 and 0.02 °C/year, respectively (Fig. 9). The ground temperature monitoring records from these observation sites also indicate a rise of 0.2–0.3 °C at 12–20 m depth from 1983 to 1999.

The rapid warming and degradation of permafrost detected on the Tibetan Plateau have motivated research focused on the prediction of future changes in permafrost conditions. The BIOME3 model (Haxeltine and Prentice 1996), an equilibrium terrestrial biosphere model, used in conjunction with GCM output, predicted almost complete disappearance of continuous permafrost in Tibet by 2100, while the belt of discontinuous permafrost will be displaced northward by 1–2° of latitude (Ni, 2002). Similar results were obtained from numerical simulation of the ground thermal regime (Li et al., 1996a,b) and GIS-based regional modeling (Li et al., 1998; Li and Cheng, 1999; Wu et al., 2000). Li et al. (1998) applied an altitude model using climatic forcing from the HADCM2 general circulation model scenario of climate change (Viner, 1996) to simulate future permafrost distribution on the Tibetan Plateau. Results indicate that the areal extent of permafrost on the Plateau will be reduced by as much as 19% during 2020–2050, and by around 58% by the year 2099, resulting in complete permafrost degradation in the southern and eastern parts of the Plateau (Li and Cheng, 1999). Wu et al. (2000) used a GIS-based permafrost response model in conjunction with GCM output to evaluate changes in permafrost distribution along the Qinghai–Tibet Highway. They concluded that by 2009 degradation would occur in the lower altitudinal occurrences of marginal, sporadic permafrost. However, by 2049 the lower permafrost limit will have retreated approximately 5–10 km from both north and south along the highway.

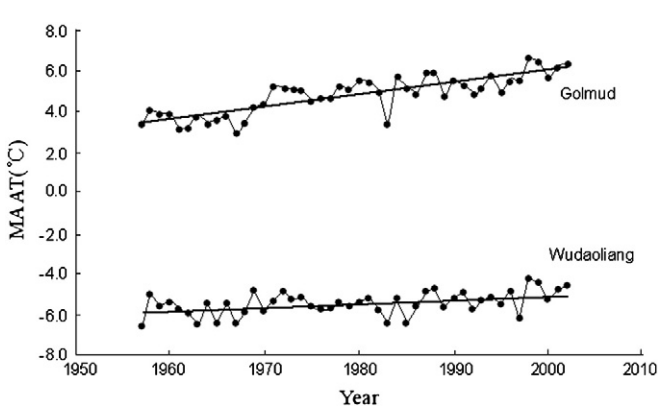

Fig. 9. Mean annual air temperature (MAAT) change at two standard meteorological stations near Xidatan (35.7°N, 94.2°E) from 1957 to 2002 (Wu et al., 2005b).

Nan et al. (2005) employed a numerical simulator of the ground thermal regime to provide insight into future permafrost dynamics on the Tibetan Plateau. The vertical extent over which calculations extend is divided into three layers: an unfrozen layer, a frozen layer, and a thawed layer. A phase-transition interface exists between the layers. The numerical simulator calculates soil temperature based on energy balance equations and temperature continuity at both phase-transition interfaces. Simulation results indicate that after 50 years of a continuous 0.02 °C/yr air temperature increase, the total area of Tibet underlain by permafrost will be reduced by 8.8%, primarily due to disappearance of permafrost in areas currently experiencing mean annual ground temperatures (MAGT) above −0.11 °C. In 100 years, permafrost with MAGT > −0.5 °C will degrade, contributing to a 13.4% reduction in the areal extent of Tibetan permafrost. By considering an air temperature increase of 0.052 °C/year, 46% of existing Tibetan permafrost would disappear over the next century, due to degradation of even relatively cold (MAGT > −2 °C) permafrost. Under this scenario, only patches of permafrost at extremely high elevations in northern Tibet would remain in 2100 (Table 3).

Data obtained from the Tibetan permafrost observation network have also been used to improve freeze/thaw parameterizations currently employed in global and regional climate models. Li and Koike (2003) presented a new frozen soil parameterization in the land surface scheme (LSS), calibrated and validated using the GEWEX Asian Monsoon Experiment (GAME)-Tibet observations on the Tibetan Plateau. The new model provides reasonable estimates of the depth of freezing, soil temperature, and time of phase transition. It also significantly improves estimates of soil moisture in the surface layer and the root zone. Zhang et al. (2003) used empirical data from the Tibetan Plateau to adjust parameterization of soil freeze/thaw processes in the NCAR Land Surface Model, providing significant improvements in the simulation of soil temperature and surface fluxes. The Simultaneous Heat and Water Model (Flerchinger and Saxton, 1989) provides a detailed parameterization of soil freezing and thawing. It can closely capture the pattern of the surface energy fluxes and soil temperature with the help of the forcing observations from the Coordinated Enhanced Observing Period/Asia–Australia Monsoon Project (CAMP)-Tibet on the Tibetan Plateau (Guo et al., 2009).

Degradation of permafrost on the Plateau has been confirmed by observational data during the last 30 years. Based on results from numerical simulations, permafrost degradation on the Plateau will continue in the 21st century, depending on the scenario of air temperature increase (Li and Cheng, 1999). Permafrost degradation is likely to affect land-atmosphere exchanges, and may result in further climate change. Present permafrost investigations on the Plateau are based primarily on field observation sites. The sites are sparsely distributed, primarily along the Qinghai–Xizang highway. More and better monitoring networks are needed. Remote sensing and further modeling efforts are also needed to investigate and predict the

Table 3
Predictions of permafrost area on the Qinghai−Tibet Plateau (2001, 2050, and 2100). "−" refers to decrease (after Nan et al., 2005).

	Climatic warming rate/°C a^{-1}	Permafrost coverage/km^2	Deviation from 2001 coverage (%)
2001		1 202 140	
2050	0.02	1 094 010	−8.8
	0.052	1 039 990	−13.5
2100	0.02	1 040 970	−13.4
	0.052	65 3447	−46

regional details of permafrost. Degradation of permafrost will make it necessary for the government to confront some problems in engineering construction and environmental protection, such as maintenance of the Qinghai–Tibetan Railway, water resource change, and soil conservation.

4. Environmental effects of permafrost degradation

4.1. Desertification

Permafrost plays a fundamental role in the existing Tibetan Plateau ecosystem, in part by providing moisture for plant growth. With the increase in the thickness of active layer, the vegetation cover and biomass of the alpine cold meadow could exhibit a significant reduction, the soil organic matter content of the alpine cold meadow ecosystem shows an exponential decrease, and the surface soil materials become coarse and gravelly (Wang et al., 2006). The relationship between permafrost, moisture supply, and vegetation growth was investigated by Wu et al. (2003). Frozen ground and associated heat and water budget-related processes control vegetation growth and extent. Degradation of permafrost will be accompanied by progressive drying of the surface and by a decrease in vegetation cover. These factors will increase the effects of aeolian action and elevate the potential risk of desertification (Wang and French, 1994, 1995).

Dust storms occur frequently in northwest China (Yang et al., 2006a,b). Forty-year observational records from hundreds of meteorological stations in China indicate that sandstorms occur frequently in the Tibetan Plateau and in the arid and semi-arid areas of northern China (Fig. 10; Song et al., 2004). One of the prominent sandstorm centers is located in the Tibetan Plateau and gradually shifts northward as far as Korea and Japan during the December–March period. Dust is transported by a vortex system at lower atmosphere levels, and by the global westerlies at upper levels, causing a multi-layer structure of “kosa” (a yellow sand) in Japan and Korea.

The northern Tibet Plateau is considered to be one of the three sandy desertification zones in China, and has been the subject of extensive research on desertification processes and mechanisms. Dong (2001) conducted a comprehensive analysis of data collected during a survey of sandy desertification in the northern Tibetan Plateau. He concluded that the intense desertification characteristic of this region results from complex interactions between natural and anthropogenic factors. The prime driving mechanism, however, is associated with the increase in air temperature and decrease in precipitation that occurred during the last several decades. These climatic changes resulted in glacial retreat, elevated snow lines, permafrost degradation, lake shrinkage, and drying of wetlands. These factors have also contributed to increased surface salinity and wind erosion, while overgrazing and poor environmental management have resulted in degradation of natural vegetation cover and soils. The shift from grassland to desert ecosystems is widespread and increasing (Yang et al., 2004).

According to Shi (1992), the area occupied by desert has increased annually by 1.8% on the Tibetan Plateau from 1957 to 1977. As reported by Lanzhou Institute of Desert Research, Chinese Academy of Sciences, in 1993, the desert area was 1860.9 km^2 in the middle basin area of the Yaluzangbu River, Lahsa River and Nyingchi River in Tibet, which is equivalent to 97.5% of the total cultivated area in the region. The annual loss of grasslands has had a devastating effect on the rural economies of the region. Extensive desertification processes are also evident in the eastern and western portions of the Tibetan Plateau (Jin et al., 2003; Li et al., 2005a).

Desertification causes further degradation of permafrost because vegetation changes alter surface energy fluxes, leading in many cases to soil warming. This provides an effective feedback mechanism that causes further degradation of grassland and moves remaining Tibetan ecosystems toward desertification (Yang et al., 2004).

4.2. Biochemical processes

Large carbon pools have accumulated in the wetlands of the world's cold regions, primarily in peatlands. Much of this carbon is sequestered in permafrost (Jin et al., 1999; Schuur et al., 2008). Extensive and rapid retreat and thinning of permafrost could accelerate biogeochemical processes, turning these cold wetlands into net sources of atmospheric carbon, creating a positive feedback and accelerated warming. Although primary emphasis has been given to the North polar region, these effects may also occur in mountains of the mid-latitude regions, including the Tibetan Plateau.

Lin and Zhao (1996) analyzed greenhouse gas emissions from the active layer in the Wudaoliang region of the Tibetan Plateau. It was found that, for dry and relatively cold permafrost, carbon emissions occur primarily in the form of CO_2. However, the release of methane is characteristic of cold freshwater wetlands (Jin et al., 1999). The area occupied by wetlands on the Tibetan Plateau is approximately 0.133×10^6 km^2, indicating significant potential for methane emission.

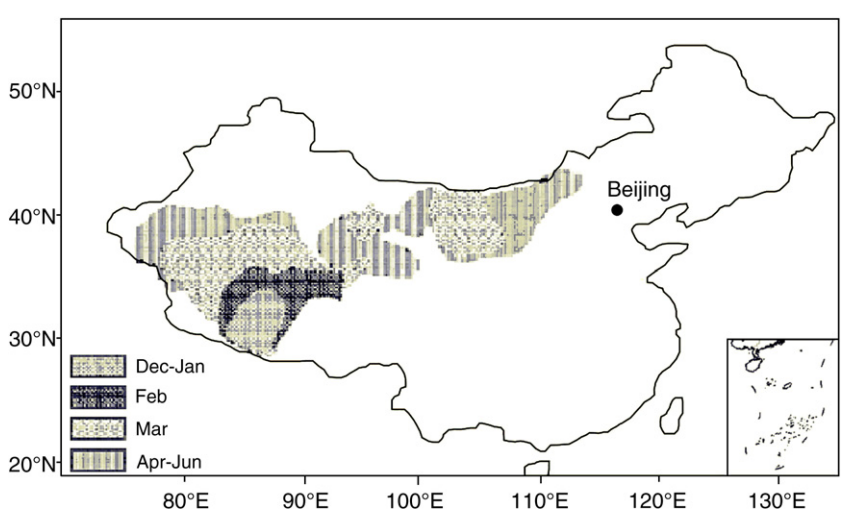

Fig. 10. Space–time distribution of sandstorms in China (Song et al., 2004).

Methane fluxes from wet alpine meadows, peat, *Hippuris vulgaris* mires, and secondary marshes were estimated by Jin and Cheng (1998; Jin et al.,1999). It was found that CH_4 emissions began as a "burst" early in the thaw season, and increased afterward in concert with rising soil temperatures. The alpine grassland may be a small source for atmospheric CH_4 during early winter. The rate of methane emission was correlated with ground temperature at the sampling depths, and with air temperature. It should be noted, however, that observed emission rates of methane from the relatively dry grasslands of the Tibetan Plateau are much lower than those of high-latitude permafrost regions.

A potentially larger source of methane is represented by natural gas hydrates in the Tibetan Plateau's permafrost regions. The thermodynamic phase equilibrium relations of thermogenic and biogenic gas hydrates imply that the resource potential of natural gas sequestered in hydrates is about 1.2×10^{11} to 2.4×10^{14} m^3 in Tibetan permafrost (Chen et al., 2005). Gas hydrates may occur at depths of 27–2070 m, in perennially frozen areas with low thermal gradients. Appreciable seasonal thermal fluctuations usually penetrate only the uppermost 10 m of sediments in the Qinghai–Tibet Plateau, however, and do not affect gas hydrates, although a study by Pan et al. (2002) conducted in permafrost-affected areas along the Qinghai–Tibetan Railway indicates that the air temperature increase observed over the past 30 years is beginning to influence permafrost temperatures at 40 m depth. If air temperatures continue to rise and eventually trigger degradation of relatively deep permafrost, gas hydrates could be destabilized, with significant release of greenhouse gas to the atmosphere.

4.3. Human infrastructure

Many engineering problems on the Tibetan Plateau are associated with climate-induced changes in the temperature of the upper permafrost, increased depth of seasonal thaw penetration, and progressive thawing and disappearance of permafrost. These changes can lead to loss of substrate bearing strength, increased soil permeability, and increased potential for development of such cryogenic processes as differential thaw settlement and heave, destructive mass movements, and development of thermokarst terrain. Each of these phenomena has the capacity for severe negative consequences on human infrastructure. The warming trend observed on the Tibetan Plateau over the last several decades is already taking a toll through deformation of engineered structures (Cheng and Zhao, 2000). The primary types of damage to the highway in the permafrost-affected region are caused by frost heave and thaw settlement. For example, 83.5% of damage to the Qinghai–Tibet Highway is related to thaw settlement associated with progressive permafrost degradation; the other 16.5% results from frost heave (Tong and Wu, 1996). Heat absorption and reduced evaporation caused by the asphalt pavement promote large increases in active-layer thickness and permafrost temperature under the road, compared to adjacent undisturbed areas (Wu et al., 2003).

Analysis of the effects of engineering activities on vegetation and soil disturbances, and ultimately on permafrost along the Qinghai–Tibet Highway, has demonstrated that disturbances at the ground surface have led to significant lowering of the permafrost table. The influence of engineering activities on vegetation affects depth to permafrost, ground water level, soils, and other factors in the affected areas (Wang et al., 2004). Since the introduction of asphalt on the Qinghai–Tibet Highway in the 1970s, taliks have formed below 60% of the road previously underlain by permafrost, and most of the remaining permafrost is near the thawing point. Data collected at monitoring stations indicate that countermeasures, such as increasing the thickness of the roadbed and installation of insulation, are relatively effective in areas where permafrost is well below the freezing point, but less so where permafrost is warm (Cheng, 2003).

Wu and Shi (2002) investigated ecological and geocryological changes associated with the construction of the Qinghai–Tibet Highway. Their investigations showed that construction activities caused the permafrost table to descend, creating conditions disruptive to the engineered structures. These effects include frost heaving, thaw settlement, thaw slumping, and changes to the ecological environment, including degradation of vegetation and desertification. Such problems have heightened awareness about the need for careful engineering practice and environmental protection in China's cold regions.

The Qinghai–Tibetan Railway extends for 1118 km, from Golmud to Lahsa (Fig. 4). Construction began in 2001 and was completed in 2006. More than half (632 km) of the railway is in permafrost terrain, including 275 km of warm permafrost (mean annual ground temperature between 0 and −1 °C) and 221 km of ice-rich permafrost (ice content>20% by volume). The section underlain by permafrost that is both warm and ice-rich is 134 km in distance (Cheng et al., 2008). About 550 km of the Railway's roadbed is in terrain underlain continuously by permafrost, with about 82 km in island (discontinuous) permafrost. Permafrost was one of the biggest problems in railway construction. The roadbed of the railway above 4000 m a.s.l. runs for 965 km; the highest elevation traversed by the line is 5072 m a.s.l (Cheng, 2002). Niu et al. (2004) pointed out that engineering measures should be based on the principles of permafrost protection, and that close attention should be paid to drainage of ground water from the subgrade. Special attention has been given to ground temperature and ice content because they are two of the most important and unique parameters for permafrost (Evgeniy et al., 2004; Jin et al., 2006). Based on data collected from recent studies, recommendations have been made to enhance the stability of roadbeds. Under climate warming, a "roadbed cooling" approach was suggested for road constructions in "warm" permafrost (Cheng, 2005).

The impact of permafrost degradation on energy and water exchange processes between the ground and atmosphere is an issue worthy of further examination. A comprehensive long-term monitoring program should be implemented in the near future to obtain further insight into the mechanisms by which degradation of permafrost impacts the Tibetan environment. In addition, appropriate laws and regulations should be enacted or enhanced to protect permafrost from degradation, such as prohibiting overgrazing and improving environmental management. The Qinghai–Tibet Railroad's impact on the environment and sustainable development can be substantial in the long term at the regional, plateau-wide scale. However, awareness of careful engineering practice and environmental protection should be heightened to reduce the impact of engineering activities on the environment.

5. Conclusions

Investigations about permafrost and climatic change on the Tibetan Plateau have intensified recently, as part of an ongoing expansion of research programs by the Institute of Tibetan Plateau Research and Cold and Arid Regions Environmental and Engineering Research Institute of the Chinese Academy of Science. Priorities in these programs include establishing new monitoring sites and deploying advanced instrumentation. Much of the permafrost-related work, however, continues a well-established focus on the Qinghai–Tibetan Highway and Railway. Knowledge about permafrost distribution and dynamics is still limited over large areas of the Plateau. Many aspects related to the effects of climate change on permafrost in Tibet are still unclear. This is especially true in the central and northwestern parts of the Plateau, where no systematic climate and permafrost observation programs have been implemented. Increases in the density and representativeness of the observational network should be made one of the highest priorities in the Tibetan region.

Other research topics in urgent need of attention include the study of interactions between atmospheric and land surface processes, detailed analysis of regional patterns of climate change, collection of field-based data concerning the geographic distribution and dynamics of permafrost, desertification and other ecosystem changes, and the effects of increasing human impacts, especially urbanization, on climate, permafrost, and Plateau ecosystems. The study and protection of the highly sensitive Tibetan environment will also require broader involvement by Chinese scientists in international observation and research programs.

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Appendix A

Acronyms

Acronym	Full name
NCEP	National Center for Environmental Prediction
NCAR	National Center for Atmospheric Research
HADL	Hadley Center, United Kingdom Meteorological Office
GFDL	Geophysical Fluid Dynamics Laboratory, Princeton University
DKRZ	Deutsches KlimaRechenZentrum, German Climate Computer Center
CSIRO	Commonwealth Scientific and Industrial Research Organization, Australia
CCSR	Center for Climate System Research, University of Tokyo
CCC	Canadian Climate Center
BIOME3	The Third Generation Biogenic Model for Emissions
HADCM2	The 2nd Hadley Center Coupled Model

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