SNOW COVER AND DEPTH OF FREEZE-THAW ON THE TIBETAN PLATEAU: A CASE STUDY FROM 1997 TO 1998

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Abstract: An increase in snow cover on the Tibetan Plateau has been observed over the past 50 years. The frequency of snow disasters on the Plateau has also increased. Much of the Qinghai-Xizang (Tibetan) Plateau is underlain by permafrost. Some observation sites of the GEWEX Asian Monsoon Experiment (GAME)–Tibet are located in the Naqu-Anduo

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area, and have been operating since 1997. A data set obtained from the GAME-Tibet measurement network was used to examine variations in the active layer, with emphasis on the heavy snow cover in 1997/1998. Analysis in this study is focused on air and soil temperature, soil moisture, freeze-thaw depths, and snow depth in years of normal (1998/1999) and abnormally heavy (1997/1998) snow cover. Results indicate that anomalously deep snow cover influenced the pattern of soil freeze-thaw depth through its control over ground temperature. Although air temperature was lower than normal during this period, ground temperatures were appreciably warmer under the heavy snow cover, which retarded frost penetration at depth. Snow cover can also contribute to the cooling process through its high albedo. Because the anomalously heavy snow load lasted well beyond the normal date of meltout, soil thaw developed later than usual during the summer of 1998. Interannual variations in snow depth have significant implications for the maintenance of Tibetan permafrost. [Key words: active layer, China, ground temperature, precipitation, snowcover, Qinghai-Xizang (Tibetan) Plateau.]

INTRODUCTION

The Qinghai-Xizang (Tibetan) Plateau occupies about one-quarter of China's mainland territory, and is sometimes referred to as Earth's "third pole" (Zhang et al., 2002; Yi et al., 2006). It is the highest and most extensive plateau in the world, occupying about 150×10^4 km^2, with complex topography and an average elevation of approximately 4000 m. The Tibetan Plateau's aerodynamic and thermodynamic effects play an important role in regional and global climate (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; Qian, Zheng, and Zhang, 2003; Wu and Qian, 2003).

Seasonally and perennially frozen soils occupy two-thirds of the Chinese land area. China's permafrost regions are more extensive than those of any nation except Russia and Canada (Jin et al., 2000). The Tibetan Plateau contains one of the highest and largest permafrost areas in Earth's mid- and lower latitudes. Depending on such factors as aspect, altitude, geological structure, rock characteristics, and underground water content, permafrost thickness generally varies between 1 and 25 m. The observed maximum permafrost thickness on the Plateau is 128 m. Permafrost temperature is also affected by these factors, and varies between -0.5° and -3.5°C (Cheng, 1997). The normally shallow depth of winter snow cover on the Plateau is an important factor encouraging the maintenance of permafrost in the region.

The net insulating effect of snow is attributable primarily to snow depth and density. Temperature variations caused by changes in these parameters are far larger than those attributable to vegetation changes (Brown, 1978). Results from numerical simulations have demonstrated that snow cover significantly influences both ground-surface temperature and the depth of seasonal frost (Goodrich, 1982).

Snow cover has a great influence on the seasonally frozen soils of the Tibetan Plateau. Dai and Li (1981) noted that under a relatively deep snow cover, the amplitude of the ground temperature curve is small in the permafrost region in the northern part of the Great Xinan Mountains. In the Altai Mountains, the presence of snow decreases the depth of seasonal freezing but has little effect on the depth of seasonal thaw (Zhang et al., 1985).

Table 1. Summary of the Locations[a]

	D66	Tuotuohe	D110	WADD	NODA	Anduo-PBL	MS3608	MS3637
Latitude	35°31.39N	34°13N	32°41.49N	32°33.07N	32°27.60N	32°14.47N	31°13.60N	31°01.05N
Longitude	93°47.08E	92°26E	92°51.27E	91°49.47E	91°48.05E	91°37.51E	91°47.01E	91°39.42E
Altitude/m	4,560	4,533	5,000	5,080	4,850	4,710	4,610	4,650
Frozen type	Permafrost	Seasonal frozen	Permafrost	Permafrost	Permafrost	Seasonal frozen	Seasonal frozen	Seasonal frozen
T-probe	263	271	180	160	245	279	242	234
M-probe	225	230	180		180	258	196	188

[a]T-probe denotes the maximum depth (cm) of the ground temperature probes and the M-probe is the maximum depth (cm) of the soil moisture probes.

Unusually heavy snowfall occurred in the Anduo-Naqu region during the winter of 1997/1998 (Miller, 1998). A very severe flood in the drainage area of the Yangtze River in 1998 was associated with the abnormal snow cover on the Tibetan Plateau (Song et al., 2000; Chen, 2001). Eight GEWEX Asian Monsoon Experiment (GAME)–Tibet observation sites are located in this area, and have been operating since 1997 (Table 1). The variation of the ground temperature and its relationship with the heavy snow cover was analyzed by Yang et al. (2006) using the soil moisture and temperature data set, based on the GAME-Tibet measurement network. In this paper, the patterns of freeze/thaw depth induced by the heavy snow cover in 1997/1998 are examined.

OBSERVATION SITES AND DATA COLLECTION

Observation Sites

Observation sites used in this study are located primarily along the Qinghai-Xizang (Tibetan) Highway (Fig. 1). The longitude, latitude, and altitude of these locations are listed in Table 1. Except for the northernmost site (D66), observations were conducted on grazing lands. To prevent damage by animals, the observation sites were enclosed by chain-link fences.

Data Collection

The soil-temperature observing system is composed of 10 Platinum (Pt) ground temperature probes and two data loggers (Datamark-LS3000, 256k). Ground temperature sensors were positioned at 4, 20, 40, 60, 80, 100, 130, 160, and 200 cm below the ground surface (except at sites D110 and WADD, the maximum depths are 180 cm and 160 cm, respectively), and the maximum depth varied with the different observation sites (Table 1). Soil moisture was monitored with six Time-Domain Reflectometers (TDR) and one data logger. TDR probes, measuring volumetric liquid water content in thawed soil and unfrozen water content in frozen soil, were positioned at 4, 20, 60, 100, and 160 cm; the position of the deepest

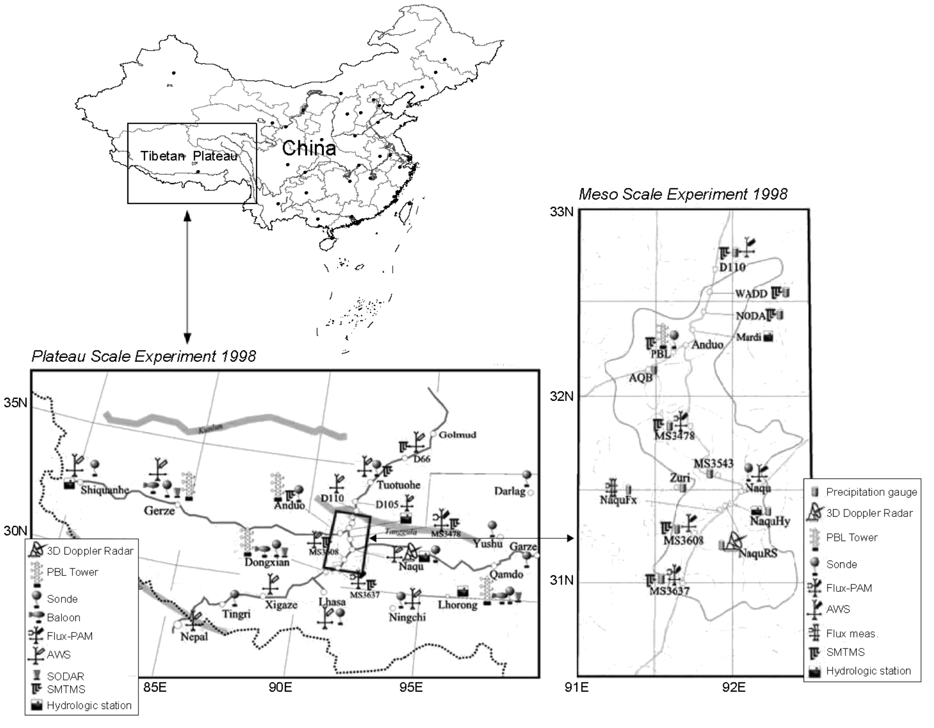

Fig. 1. Locations of the observation sites.

sensor depends on soil characteristics at the different observation sites (Table 1; also see Yang et al., 2003). An observation interval of one hour was employed at all sites.

The daily temperature at different depths was calculated using hourly observations. Linear interpolation was then used to create comparable vertical soil temperature profiles. Following geocryological convention (e.g., van Everdingen, 1998), we refer here to the depth at which soil temperature reaches 0ºC as the depth of freezing (or thawing). The monthly snow depths at three meteorological stations (Anduo, Naqu, and Tuotuohe) during 1966–1999 and the daily snow depths derived from SSM/I (Special Sensor Microware/Imager) in 1998 at GAME-Tibet observation sites (D66, Tuotuohe, D110, and Anduo-PBL) were also used in our analysis. The Anduo-PBL site is 7 km west of the Anduo meteorological station.

RESULTS AND ANALYSIS

Heavy Snow in Winter of 1997/1998

The monthly (August–July) snow depths during 1997/1998, 1998/1999, and the 34-year average (mean) from 1966 to 1999 at three meteorological stations (Naqu, Anduo, and Tuotuohe [TTH]) are shown in Figure 2. From September to March, snow-cover depth in 1998/1999 was slightly less than the monthly mean of the

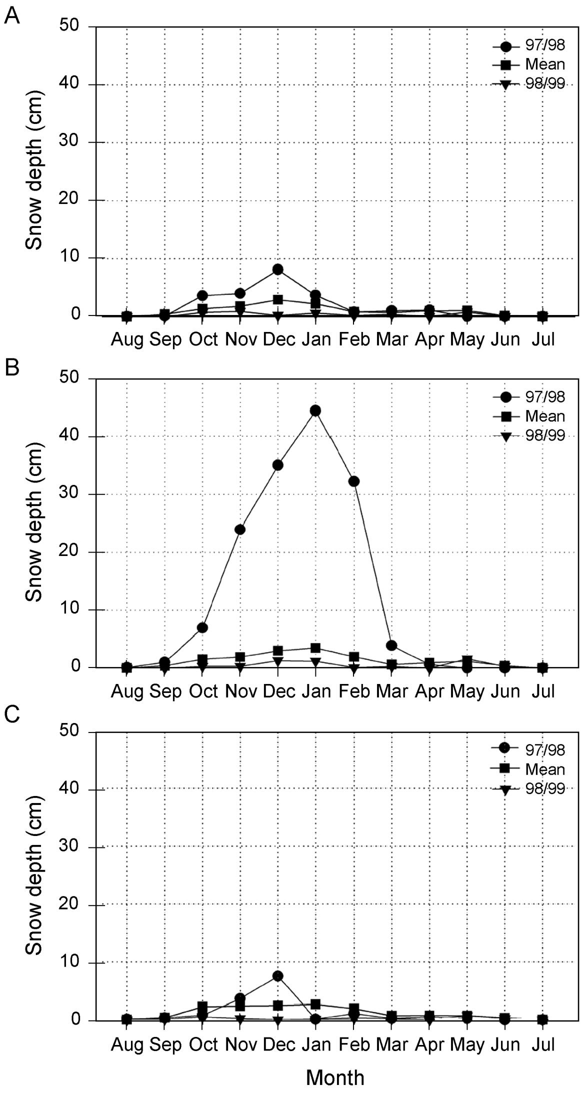

Fig. 2. Monthly (August–July) snow depths during 1997/1998, 1998/1999, and the 34-year average from 1966 to 1999 at the (A) Naqu, (B) Anduo, and (C) Tuotuohe (TTH) meteorological stations.

1966–1999 period. Snow-cover depth in 1997/1998, however, was much higher compared to the average for 1966–1999. This is especially true at Anduo meteorological station, which is the closest meteorological station to D110. From October to March, the snow depth in 1997/1998 was much higher than the long-term average.

Figure 3 shows snow depth derived from SSM/I at different sites (D66, Tuotuohe, D110, and Anduo-PBL) in 1998. Snow-cover depth in the spring (January–March)

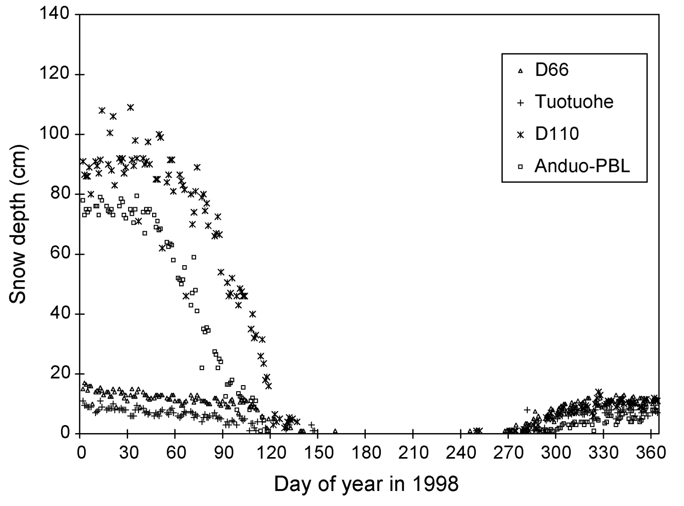

Fig. 3. Snow depth on the SMTMS observation point, derived from SSM/I in 1998.

of 1998 was much higher than that of the following winter (October–December). From October to December 1998, snow depth was around 10 cm at most sites. However, from January to March 1998, it was nearly 90 cm at some sites. The reason for differences in snow depth between Figures 2 and 3 is unclear, but is probably attributable to noncoincidence between the observational sites or to use of different observational methods. It is important to note that snow depth derived from the SSM/I was not validated. Both figures demonstrate clearly, however, that snow conditions on the Tibetan Plateau in winter 1997/1998 were anomalous.

The heavy snow cover resulted in many difficulties for local residents. Grasslands were covered by thick snow over long periods. Numerous yaks and sheep died from starvation and cold. Consistently low temperatures, as low as -40°C, and the abnormally large amounts of snow affected over a million herdsmen in the Naqu regions of Tibet and Yushu regions of Qinghai, who were moving between pastures when the freeze hit. An estimated three million head of livestock were lost in the Tibetan Autonomous Region, amounting to some US$125 million in economic losses. In some local administrative units, as much as 70% of all livestock were killed (Miller, 1998).

Soil Temperature Variations and Freeze-Thaw Depths in 1997/1998

Monthly mean ground temperatures at the D66, D110, and Anduo-PBL sites are shown in Figure 4. During the winter of 1997/1998, ground temperature was lower than that in 1998/1999 at the D66 and Anduo-PBL sites. The difference at Anduo-PBL was larger compared to D66. At site D110, ground temperature at 4 cm in September and October in 1997 was colder than in 1998. However, from November 1997 to March 1998, ground temperature at 4 cm depth was higher than that from November 1998 to March 1999. The ground temperature in January was

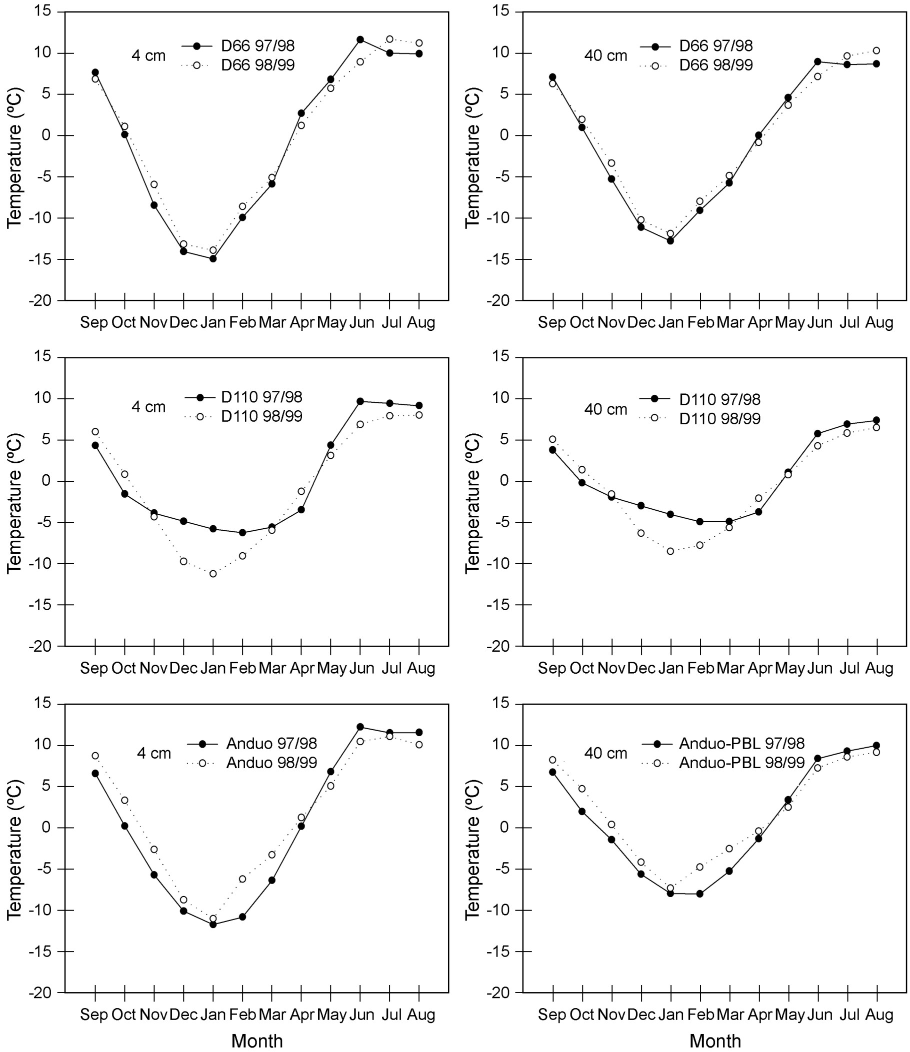

Fig. 4. Monthly mean ground temperature at the 4 and 40 cm depths at the D66, D110, and Anduo-PBL observation sites during 1997/1998 and 1998/1999 (September–August).

5.5ºC higher in 1998 than in 1999. The snowfall events at site D110 in late 1997 have a significant contribution to this unusual pattern of ground temperature progression.

Figure 5 shows the freeze/thaw depth during 1997/1998 and 1998/1999 at Sites D66, Anduo-PBL, and D110. The freezing process began earlier in the winter of 1997/1998 compared to winter 1998/1999, at all three sites. This is especially pronounced at site D110. During early winter, the freezing depth was much greater in 1997/1998 at the Anduo-PBL site. Similarly, before December 9, 1997, at site D110, the depth of freezing was greater than on that date in 1998. However, after

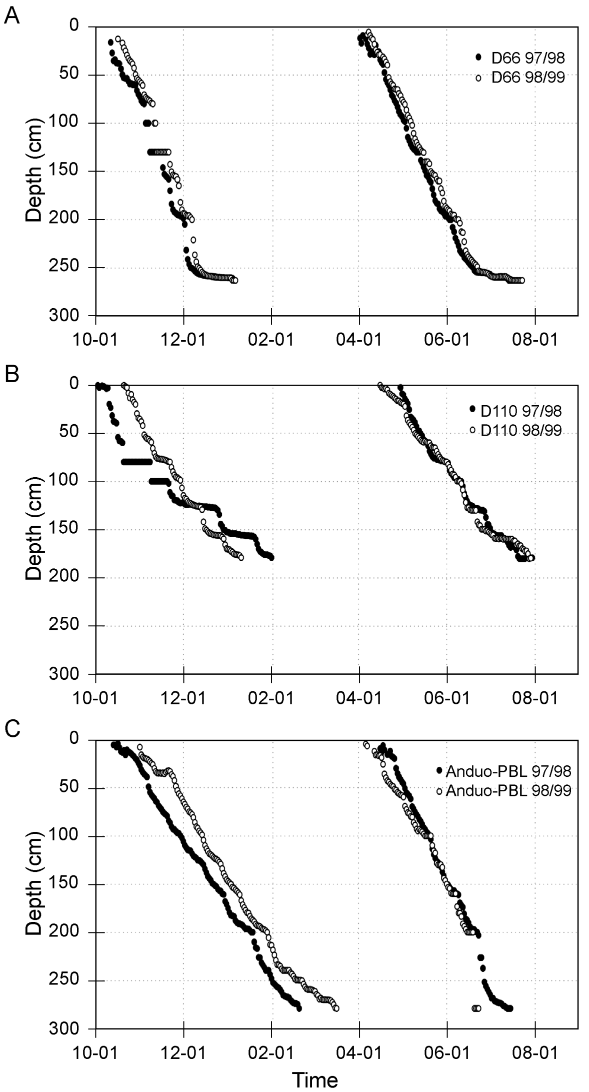

Fig. 5. Freezing and thawing depths at the (A) D66, (B) D110, and (C) Anduo-PBL sites.

December 9, 1997, the depth of freezing on any given date was lower than on corresponding dates in 1998. This "reverse" phenomenon is similar to that of soil temperature. The snowfall events at site D110 in late 1997 retarded frost penetration at depth. The several standstills in November, December, and January were related to the higher soil moisture. Thaw also occurred later at this site. Compared to the D110 and Anduo-PBL sites, differences in the pattern of freezing and thawing depths at site D66 were not significant.

At a site experiencing a thick snow cover, the normal expectation is for the frozen layer to be relatively shallow compared to one with only a thin layer of snow.

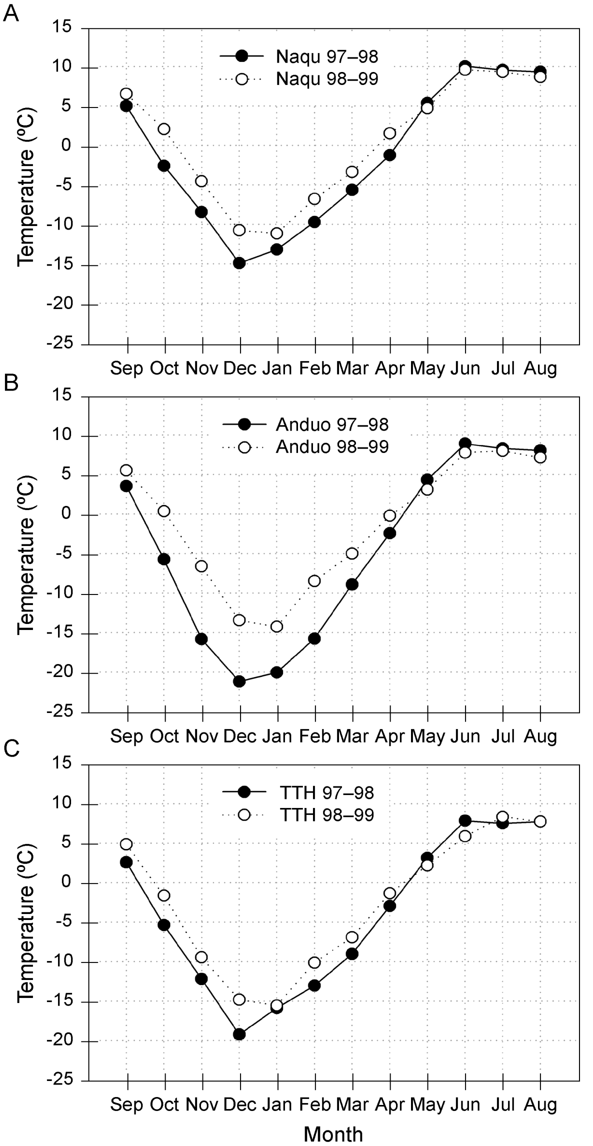

Fig. 6. Monthly mean air temperature at meteorological stations Naqu, Anduo, and Tuotuohe (TTH).

Although there was very heavy snow cover in 1997/1998, and it persisted well past the normal snowmelt period, the depth of freezing was greater than occurred in the winter of 1998/1999 (Fig. 5). Comparison of air temperature records from three meteorological stations (Anduo, Naqu, and Tuotuohe; Fig. 1) demonstrates that monthly mean air temperature at these three stations in 1997/1998 was lower than that in 1998/1999, especially in the winter half of the year (Fig. 6). This is especially true at Anduo, which is the closest meteorological station to site D110. The temperature in November (-6.6ºC) and December (-13.5ºC) in 1998 was higher than the temperature in November (-15.8ºC) and December (-21.2ºC) in 1997. This explains why frost depth was greater in winter 1997/1998, as compared to winter 1998/1999, despite the development of an unusually deep snowpack.

A relatively severe snow cover significantly affects the daily range of the near-surface ground temperature (DRGT). Consequently, the variation of the DRGT, to some extent, would reflect the effects of snow cover at the surface (Yang et al., 2006). At site D110, the DRGT at 4 cm decreased significantly to 0.4ºC on September 19, 1997. However, it decreased significantly to 0.3ºC and 0.4ºC on October 4, 1998 and 1999, respectively. This indicates that the snowfall occurred earlier than normal in September 1997, as reported by local residents. Snow cover has a high albedo, resulting in net cooling. Even though the thermo-insulation effect of snow cover is normally expected to increase with snow depth, the high-albedo cooling effect was quite significant. However, after December, the thermal insulation effect was more significant in 1997 and the frost depth was shallower than in 1998/1999. These results demonstrate that interannual variations in snow depth have significant implications for the maintenance of Tibetan permafrost.

DISCUSSION

Using GAME-Tibet soil temperature and soil moisture observation data, soil temperature and moisture distributions were analyzed by Yang et al. (2003). Temperatures were lowest between January and February, with large variations between sites. The coldest and warmest sites (D66 and D110, respectively) showed a temperature difference of about 8ºC near the surface layer (4 cm depth). Ground temperature in the shallowest soil layers was highest between July and September, although some differences existed among the sites. The average air temperature in July 1998 was 4.8ºC and 6.6ºC at D66 and D110. The average air temperature during January and February 1998 was -17.7ºC and -22.6ºC at D66 and D110, respectively. Site D110 is located south of site D66 (within 3° of latitude), at an altitude 500 m higher than Site D66. The expected latitudinal and altitudinal effects at these two sites cancel one another out. However, in the coldest month, the temperature difference at the two sites was about 8ºC, which cannot be explained by either latitudinal or altitudinal effects. Yang et al. (2006) examined variations of ground temperature on the northern Qinghai-Xizang Plateau and found that the distribution of daily ground temperature from 1997 to 1998 was abnormal. They demonstrated that these departures were associated with the occurrence of extremely heavy snow cover on the northern part of the Plateau during the winter of 1997/1998 (Fig. 3).

Snow cover can result in higher than normal soil temperatures because of its insulating effects. To investigate how observed changes in permafrost temperature in northern Alaska resulted from changes in near-surface air temperature and snow depth, Stieglitz et al. (2003) used a one-dimensional thermodynamic snow and ground-thermal model with observed air temperature and snow depth data from Barrow, Alaska. Results indicated that variations in snow cover can influence below-ground temperature as much as near-surface air temperature does (Stieglitz et al., 2003). The excellent insulating qualities of snow effectively restrict heat exchange between the atmosphere and substrate. When snow is present, the mean annual temperature at the ground surface is usually warmer than the mean annual air temperature (Stieglitz et al., 2003). The amount of snow cover and its duration, timing, and accumulation rate play an important role in determining propagation of the air temperature signal into the ground (Goodrich, 1982; Zhang et al., 1996b; Osterkamp and Romanovsky, 1999).

When the effective conductivity of the snow cover was incorporated in a soil freezing model through the depth fractions of snow layer with different structure, the results showed that a change of the depth hoar layer fraction (part of a total snow depth) in the snow cover from 0 to 0.6 could reduce the seasonal freezing depth by up to 80% (Zhang et al., 1996a). Observations in Japan by Yamazaki et al. (1998) indicated that the depth of frost penetration depends more on the temperature profile within a snowpack than on the degree of soil moisture or vegetation cover.

CONCLUSION

Snow cover, an important component of the cryosphere, is considered to be particularly sensitive to regional and global climate changes (Arnell, 1999; Ye and Ellison, 2003). In the context of global warming, changes in snow mass, snow-cover extent, and duration assume great significance (Li, 1999). Global warming induced by emission of greenhouse gases could result in major changes of snow mass, the extent of the area affected by snow cover, and snow residence time, affecting water resources and runoff volume and timing in areas experiencing significant snow cover. Such effects are particularly important in arid and semiarid regions (Watson et al., 1996).

Seasonal snow cover is the most important water resource in China's arid western region. Average snow cover during winter snow maxima is 361.0×10^8 m^3 in water equivalent, accounting for 38.2% of the total surface runoff in this region (Li, 1999). The snow cover in this large area increases the surface albedo, reducing the surface absorption of solar radiation by more than 60%. Snowmelt also absorbs latent heat, causing the soil to become wet and soil temperature to decrease. These factors result in changes in land surface-atmosphere interactions in snow-covered areas and those in which snow cover has recently ablated, affecting regional and possibly global climate.

Except on the Pamir Plateau, the Himalaya region and the eastern part of the Nianqing Tanggula Mountains are snow covered the whole year; other places on the Tibetan Plateau are subject to seasonal snow cover. Generally, snow cover begins to accumulate in mid-September and reaches its maximum between December and February. The maximum snow-covered area is about 79% of the Tibetan Plateau. Snowmelt generally occurs during the period between late February to early June (Li, 1996a, 1996b). Snow-cover variations affect the strength of the Asian monsoon, its onset, and the speed of its advance (Yang and Yao, 1998; Wu and Qian, 2003). They are also related to precipitation elsewhere in China (Chen and Wu, 2000; Wu and Qian, 2000; Qian, Zhang, and Zheng, 2003; Qian, Zheng, et al., 2003).

Under climate-change scenarios based on different estimates of greenhouse-gas emissions and aerosols, warming trends in China will continue. Mean annual precipitation in China will also increase (Qin et al. 2006). If these changes involve snowpack depth on the Tibetan Plateau, snow cover will play a prominent role in the evolution of Tibetan permafrost, which can in turn exert significant controls over local and regional hydrological regimes.

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