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Changes of climate and seasonally frozen ground over the past 30 years in Qinghai–Xizang (Tibetan) Plateau, China

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Abstract

Air temperature, ground surface temperature (GST; 0 cm at depth), precipitation and freezing depth data at 50 meteorological stations in the Qinghai–Tibet Plateau (QTP) were analyzed to examine changes of climate and seasonally frozen ground (SFG) in the past 30 years. The latitude, longitude, elevation, mean annual air temperature (MAAT), annual precipitation (AP) and maximum freezing depth at each station were used as the criterions to group the stations by the Hierarchical Cluster Analysis method. Fifty stations were grouped into four clusters, which are distributed in different regions of QTP. The most significant climate warming occurred in northeastern QTP, and the warming trend was greater in the cold season than in the warm season. Annual precipitation (AP) increased in the northwestern, inland and southeastern regions of QTP, but decreased in the northeastern QTP. The most significant changes of seasonally frozen ground (SFG) occurred in regions with thickest SFG, i.e., inland QTP, then northeastern and northwestern QTP. The duration of SFG shortened differently in different regions. Significant changes also occurred in the inland and northeastern regions of QTP. The cold season air temperature is the main factor controlling SFG change. The warming trends of ground surface temperatures are more significant than air temperature, and the warm season warming is greater than cold season warming. Changes of SFG depth, duration and surface temperature are likely to enhance heat exchanges between ground and atmosphere, in favor of stronger plateau monsoons.

Keywords: Climate changes; Seasonally frozen ground; Qinghai–Tibet Plateau; Hierarchical Cluster Analysis

1. Introduction

The global average surface temperature has increased by 0.6 ± 0.2 °C (Folland et al., 2001), and global land precipitation has increased by about 2% (Jones and Hulme, 1996; Hulme et al., 1998) in the 20th century. The impact of climate change on cold regions is profound (Morison et al., 2000). It is not only on permafrost regions but also on regions with seasonally frozen ground. Seasonally frozen ground (hereafter referred to as SFG), as well as the active layer of permafrost, plays an important role in cold regions because almost all ecological, hydrological, pedological and biological activities take place within

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it (Hinzman et al., 1991; Kane et al., 1991). Soil freezing and thawing processes affect the heat exchange between atmosphere and ground surface (Li et al., 2002).

The changes of SFG would result in changes of ground surface thermal exchange due to the difference in soil thermal conductivity and capacity. Ye and Gao (1979) considered that the land surface of the Tibetan Plateau is a heat source from spring to winter. The changes of heat sources/sink have a significant effect on the South Asian high, subtropics high over West Pacific, the summer precipitation in China and the onset of Asian monsoon (Ye and Zhang, 1974; Zhang and Qian, 2002; Lin and He, 2000; Huang, 1985; Liu et al., 1991). Wang et al.'s (2003) research has shown that when the maximal freezing depth is shallower, the South Asian high in July and the Indian monsoon would be stronger, and the subtropics high over the West Pacific would be weaker. Recent research indicated that when the frozen soil thaws early on the Qinghai–Tibet Plateau (hereafter referred to as QTP), the surface heat source would be weak and the ascending motion would be weak in summer as well; the subtropics high over West Pacific would also be weak. Therefore, the summer precipitation would be more in South China and less in the middle-lower reaches of the Yangzi River and the lower reaches of the Huaihe River (Gao et al., 2004). Plateau monsoons have close relationship with surface temperatures of QTP. It was weaker from 1967 to 1983 and became strong after 1983 (Tang et al., 1998). Increased near-surface temperature over Eurasia in winter and spring is likely to enhance land–ocean thermal gradient conductive to stronger monsoons (Kumar et al., 1999a,b).

From 1955 to 1996, global air temperature increased at a rate of about 0.16 °C per decade, and the climate in regions with higher elevation is more sensitive to global change (Liu and Chen, 2000; Yao et al., 2000; Lin and Zhao, 1996; Zheng and Li, 1999; Liu et al., 1998; Tang et al., 1998). Most of the inland areas on the QTP are underlain with permafrost due to high elevation (more than 4500 m asl in average) and severely cold climate (Zhao et al., 2000; Li et al., 1996). Warming climate and human activities have resulted in permafrost degradation in QTP. The temporal and spatial differences of permafrost degradation observed could be attributed to the combined influences of climate, human activities and geology and other factors (Fan and Yao, 1982; Zhu et al., 1996; Wang et al., 2000; Jin et al., 1997; Zhao et al., 2000). The SFG mainly occurs in the regions with lower elevation around the inland plateau. Its characteristics are influenced by many factors including air temperature, precipitation, surface properties (snow and vegetation cover), soil moisture, ground thermal properties, lithologic compositions and hydrological conditions (Zhou and Guo, 2000; Zhou, 2000). Little was done to study the effect of climate change on the SFG in this high plateau environment.

2. Data sources and methods of analyses

The basic data used in this study include seasonally freezing depth, mean monthly air temperature (MMAT), ground surface temperature (GST) and annual precipitation (AP) recorded with standard equipments at standard meteorological stations on QTP from 1967 to 1997. The freezing depth was measured once every day during the freezing–thawing period every year by reading the upper and lower depths of the distilled water filled in standard frost tubes which were buried in soils. Ground surface temperature is a standardized monitoring parameter at most meteorological stations. It is measured on ground surface with half of the thermometer buried in soils and half was exposed in air. Mean cold season temperatures and mean warm season temperatures are the average value of monthly temperatures from October to March and from April to September, respectively. SFG depth is defined as the maximum frozen depth in each cold season.

There are 119 meteorological stations in the QTP, of which, 7 stations are located within permafrost regions with elevations >4500 m and mean annual air temperature (MAAT) < -2.8 °C. Three of the seven stations are free of permafrost (Maduo, Tuotuohe and Zhongxinzhan) due to the influences of high geothermal flux and/or rivers (Zhou and Guo, 1982; Guo, 2000; Guo et al., 2000). There are no SFG thickness monitoring data at 29 stations, of which, 20 stations are located in the southwest region of the QTP, because of either lack of SFG or freezing temporarily at few winter nights based on the analysis of both mean daily and ground surface temperatures.

Freezing depths have been monitored at 86 stations. These stations are distributed around the fringes of the QTP while most of the inland areas are underlain by permafrost (Li et al., 1996). The data used in this study are available from 1967 to 1997 at 50 stations after some minor adjustments and estimations for missing data.

The missing data at these 50 stations used in this study, shown in Table 1, were estimated based on the following procedures. The missing MMAT and monthly AP (MAP) data were estimated using linear regression with the best-correlated stations ($R^2 \geq 0.98$, $n \geq 10$ for temperatures and $R^2 \geq 0.7$, $n \geq 10$ for precipitation) nearby. The missing SFG depth data were estimated based on the regressions with frost indices (accumulative negative MDAT in degree days; $R^2 \geq 0.8$, $n \geq 10$) because freezing penetration in the ground is mainly controlled by the negative air temperatures. The missing mean monthly GST data were estimated based on the linear regression with MMAT at the same station ($R^2 \geq 0.95$, $n \geq 10$). It was very difficult to estimate the missing data of the first and last dates of the SFG existences because no significant correlation with other climate factors was found. The mean values from the adjoining 5 years were applied as the substitutes of these missing dates.

The 50 stations are distributed all over the QTP with great variations not only in latitude, longitude and elevation, but also in air temperature and precipitation as well as SFG characteristics. The 31-year mean of SFG depth ranged from 8 to 330 cm at 50 stations. The SFG depth increased at 12 out of 50 stations from 1967 to 1997, while others show decreases at different rates. In order to clarify the differences of SFG changes in different geographic regions, standardized station position (latitude, longitude and elevation), main climate factors (MAAT and MAP) and SFG depth were selected as basic criteria to conduct Hierarchical Cluster Analysis. The median distance method was used during the classification because it classifies clusters based on the median value of the minimum and maximum distances between clusters. This method ensures that each classified cluster of stations have specific, typical and uniform properties.

Table 1
Station numbers with missing data

Items	Number of stations with missing data				
	Missing 1 data	Missing 2 data	Missing 3 data	Missing 5 data	Missing 7 data
Mean monthly air temperature	6	1	2		7
Mean monthly precipitation	4		2		
SFG thickness	7	3	4	1	
Mean monthly ground surface temperature	6	1	2		7

In assumption, group G_r is combined from groups G_p and G_q, the distance D_{ir} between G_r and any other group G_i is:

$$D_{ir} = \sqrt{\frac{1}{2}D_{ip}^2 + \frac{1}{2}D_{iq}^2 - \frac{1}{4}D_{pq}^2} \tag{1}$$

In Eq. (1), D_{ip}, D_{iq} and D_{pq} are Euclidean distances between G_r, G_p and G_q.

For the need of Hierarchical Cluster Analysis, the data with large differences in scaling should be standardized based on the following equation:

$$x_i{'} = \frac{x_i - \bar{x}}{S} \tag{2}$$

where $x_i{'}$ is the standardized value, x_i is the particular data, $\bar{x}$ is the mean value of variables, and S is the standard deviation.

The lower the D_{ir} values, the more clusters could be grouped, the less the stations in each group. As D_{ir} is less than 5.0, 50 stations could be grouped into seven clusters, of which two clusters have one station each and one has two stations. If D_{ir} is less than 7.0–14.0, 50 could be divided into five clusters. Cluster 3, the only station of Tashikurgan located far west of QTP (Table 2 and Fig. 1), cannot represent the characteristics of any region in QTP. If D_{ir} is less than 15.0, all stations located in the northern QTP would be grouped into one, although their climatic and SFG characteristics are greatly different. The distances D_{ir} between the cluster in the northern QTP and each of the other clusters are greater than 20.0. Therefore, clusters with distances D_{ir} between each other of less than 7.0 were grouped into one, and cluster 3 with only one station was neglected in this study. The location and main physical characteristics of these four clusters (regions)

Table 2
Preliminary characteristics of clusters grouped based on location, main climatic factors and SFG depth

No.	Region	Location	Number of stations	Elevation (m asl)	MAAT (°C)	MCSAT (°C)	Precipitation (mm)	SFG depth (cm)
1	NW QTP	Northwest border of QTP, in Kalakunlun Mountains region	8	800–1500	10 to 12; $\bar{x}=11.4$	− 0.2 to 3.0; $\bar{x}=1.5$	27–60; $\bar{x}=38$	40–75; $\bar{x}=55.7$
2	NE QTP	Northeastern of QTP, mainly in Qilian Mountains and Kunlun Mountains	17	1500–3500	0.8 to 8.0; $\bar{x}=4.1$	− 0.5 to − 7.2: $\bar{x}=-4.2$	16–360; $\bar{x}=194$	80–220; $\bar{x}=127.8$
3	Tashikurgan	West Kalakunlun Mountains	1	3090	3.5	− 5.1	67.3	147
4	SE QTP	Southeastern boundary of QTP, mainly in Anymachin and Hengduan Mountains	20	2736–4280	− 0.4 to 8.6; $\bar{x}=3.8$	− 7.2 to 4.0; $\bar{x}=-1.9$	270–900; $\bar{x}=541.7$	8–130; $\bar{x}=64.7$
5	Inland QTP	Inland of QTP, located in the discontinuous permafrost region without permafrost	4	3900–4800	0.3 to − 3.0; $\bar{x}=-1.2$	− 6.2 to − 9.8; $\bar{x}=-8.0$	430–550; $\bar{x}=481$	170–330; $\bar{x}=232.3$

are shown in Fig. 1 and Table 2. NW QTP is located in the northwest margin of the plateau in the south of Tarim Basin with relatively warm air temperature but very dry, i.e., extreme continental climatic condition. NE QTP is located in the northeast of the plateau with dry to semidry climate. The land covers include dry prairie, farmland and desert. SE QTP is located in the southeast of the plateau with humid to semihumid climate. Most of the monitoring sites in this region are distributed within mountainous forest zones. Inland QTP is located in the discontinuous and island permafrost regions of the plateau with cold and semihumid climate.

MAAT, mean cold season air temperature (MCSAT), mean warm season air temperature (MWSAT), mean annual ground surface temperature (MAGST), AP, SFG thickness, the initial freezing and thawing terminal dates of each meteorological station located in each of the four regions were averaged and shown in Figs. 2–9.

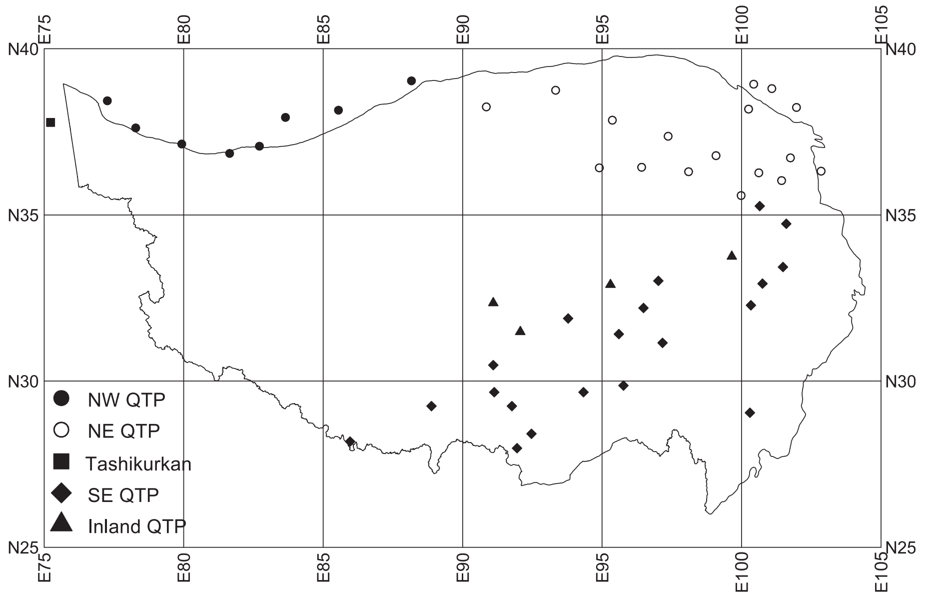


Fig. 1. Study region and distribution of stations grouped by location, main climatic factors and SFG depth.

3. Results and discussion

3.1. Climate changes

The warming trends of climate during 1967 to 1997 are found in all four regions (Fig. 2a,b,c and d). The most significant warming occurred in the northeastern region of QTP. The MAAT increased to about 0.9 °C as the mean cold season air temperature (MCSAT) rose by 1.1 °C and the mean warm season air temperature (MWSAT) increased by 0.6 °C in 30 years. The warming–cooling cycles were about 8 years during the study period, with amplitude of less than 3 °C. The cooler periods occurred around 1967, 1977, 1982 and 1992, and the warmer periods occurred around 1972, 1980, 1989 and 1996.

About 0.55 °C warming amplitudes of MAAT in 30 years were found in the northwestern and inland (Fig. 2a) regions of QTP, where great seasonal variation occurred. The MCSAT in northwestern QTP increased nearly 1 °C while that in inland QTP increased by only 0.5 °C, and there was almost no change for MWSAT in northwestern QTP but an increase of about 0.5 °C occurred in inland QTP

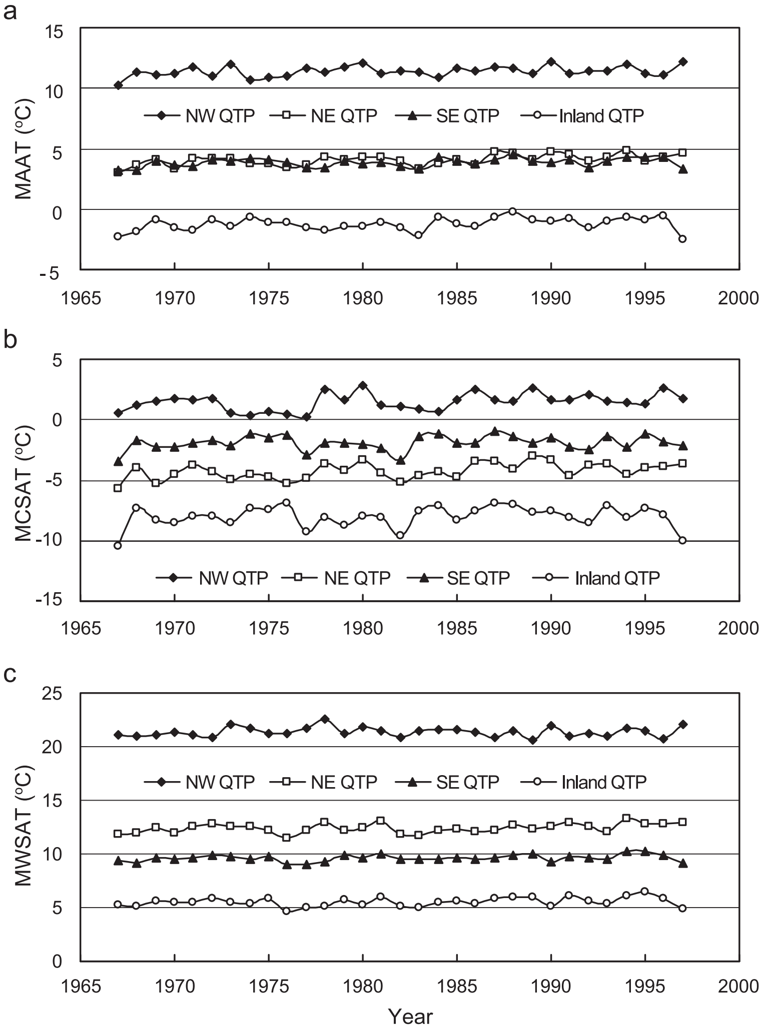


Fig. 2. Changes of mean annual air temperature (a), mean cold season air temperature (b) and mean warm season air temperature (c) in the four regions of QTP.

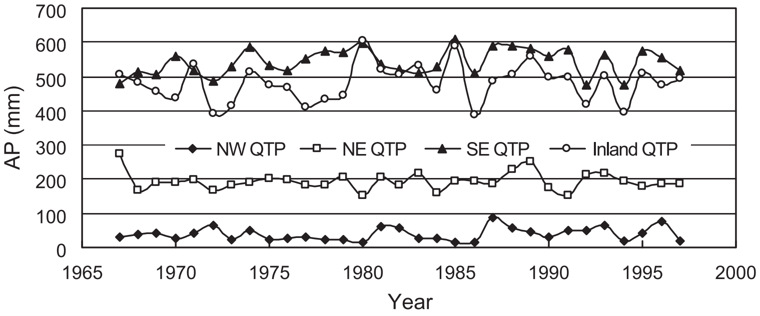


Fig. 3. Changes of annual precipitation in the four regions.

(Fig. 2b). The least warming region was the southeastern QTP. All the MAAT, MCSAT and MWSAT raised nearly 0.4 °C from 1967 to 1997 (Fig. 2). Similar 8-year warming–cooling cycles during the study period are also identified in these three regions.

In conclusion, air temperature increase in QTP was more significant in cold season than in warm season, especially in the northern QTP where the MCSAT increased about 1 °C, while it only increased by about 0.4–0.5 °C in inland and southeastern QTP. The warm season temperature increased 0.35–0.65 °C in eastern and inland plateau but increased by less than 0.05 °C in western QTP.

Annual precipitation (AP) decreased in the northeastern QTP, and increased in the northwestern, inland and southeastern regions of QTP (Fig. 3). The most significant increase of AP was about 13 mm, or 35% of its 31-year mean in northwestern QTP. The increase of AP was about 30 mm from 1967 to 1997 in southeastern QTP, about 5.3% of the 31-year mean. In inland QTP, the increase was about 20 mm and 4.1% of its 31-year mean. The AP in northeastern QTP decreased about 4 mm, 2% of the 31-year mean. Geographically speaking, the amount of annual precipitation in most regions of the QTP was increasing under the warming climate except in the northeastern region. Generally, the increasing of precipitation in most parts of QTP in the last century seems to be related to the warming trends of climate (Liu et al., 1998).

3.2. Changes of SFG depth

The most significant decrease of SFG depth occurred in inland QTP (Fig. 4), which was 22 cm, with an average decreasing rate of 0.71 cm/year, accounting for 9% of the 31-year mean. In NE QTP, SFG depth decreased 21 cm, 16% of the mean value, from 138 to 117 cm with an average decreasing rate of 0.67 cm/year. The SFG depth in the northwest of QTP decreased about 6 cm with an average rate of 0.19 cm/year, accounting for 10% of the average value. The least decrease in SFG depth was in cluster 4, the SE QTP, which was about 5 cm with an average rate of

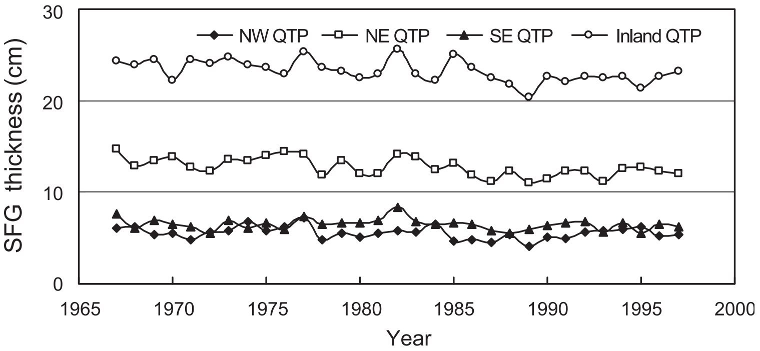


Fig. 4. Changes of SFG thickness in the four regions.

0.17 cm/year, 8% of the average value. These results indicated that the most significant changes of SFG depth occurred in inland and NE QTP with colder climate, higher elevation and thicker SFG.

Good relationships between SFG depths and mean cold season air temperatures were found for three regions, i.e., the NE, NW and SE QTP ($R^2 = 0.59$, 0.76 and 0.65, respectively, as $n = 31$; Fig. 5a,b and d). It indicates that the SFG depth changes could be attributed to rising MCSAT. The SFG depth in NE QTP was more sensitive to MCSAT; it decreased about 13.6 cm with 1 °C rise in MCSAT (Fig. 5a). In SE QTP, the decreasing rate was 8.3 cm/°C (Fig. 5d) as about 7.2 cm/°C for NW QTP (Fig. 5b). For inland QTP, the lower R^2 value and SFG depth–MCSAT gradient (about 6.6 cm/°C; Fig. 5c) indicates that cold season climate warming is not the main controlling factor of the SFG changes. The distribution and changing amplitudes of SFG depths in all four regions show very good relationship with MCSAT (Fig. 6). Nearly linear correlation between MCSAT and SFG depth exists for inland, NE and SE QTP. The SFG depth in NW QTP is greater than the corresponding MCSAT value compared with other regions. It may have been induced by the extreme continental climate conditions, i.e., very low precipitation and great annual differences of air temperatures.

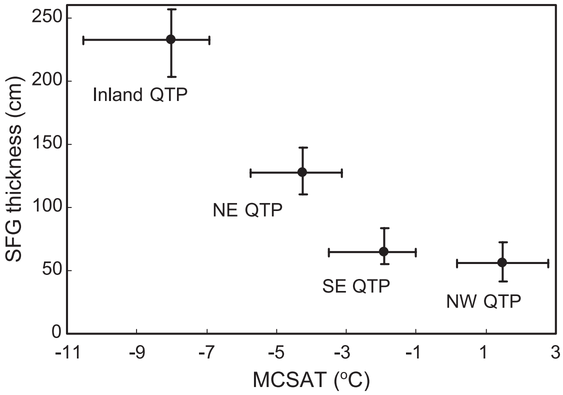
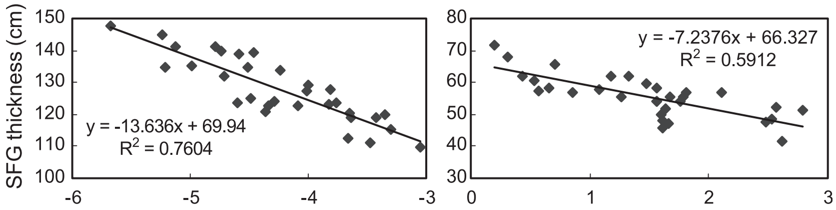
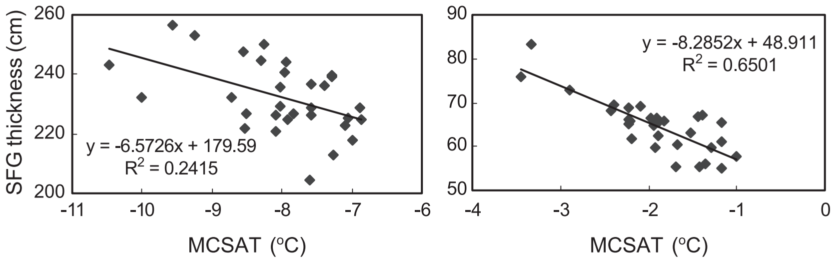


Fig. 6. Distribution and changing amplitudes of mean cold season air temperatures and seasonally frozen ground depths in different regions of QTP.

In addition to air temperatures, other factors, such as precipitation, ground surface conditions (snow cover and vegetation), soil properties, etc., may play their roles in SFG development. Decreasing AP in NE QTP is likely to result in less water evaporation and reduces the latent heat loss from soils. Many researches indicated that the grassland degradation and desertification occurred in the past several decades, and it is more significant in the NE QTP (Li, 2000; Dong, 1999; Tu and Shi, 1998). It may have



a) NE QTP b) NW QTP



c) Inland QTP d) SE QTP

Fig. 5. Linear regression between mean annual cold season air temperatures and seasonally frozen ground depths in different regions of QTP.

resulted in the increase of ground temperature due to more exposed mineral soils following the loss of vegetative cover (Li and Bao, 1999). According to Ke and Li (1998), accumulated snow depth increased 1.9% in the alpine regions of QTP in 36 years from 1957 to 1992, accompanied by about 0.51 °C increase of the cold season air temperature. The snowing days further increased in inland regions but less in NW QTP from 1980 to 2000 (Gao et al., 2003). Research also shows that, when the number of snowing days increases, the mean air temperature in winter and spring would increase and the number of days with air temperature below 0 °C would decrease(Gao et al., 2003). Therefore, it could be concluded that the greater increase of snow in inland QTP resulted in greater decrease of SFG thickness.

3.3. Changes of SFG duration

Ground-based observations show about 2 weeks' reduction of annual duration of lake and river ice in the mid- to high latitude of the Northern Hemisphere over the past 100–150 years (Folland et al., 2001). SFG duration in QTP also shows such trends. Fig. 7 shows the changes of average initial freezing dates, SFG disappearing dates and SFG durations. The long-lasting existence of SFG occurs in inland QTP (Fig. 7c) due to its extreme high elevation and cold climate.

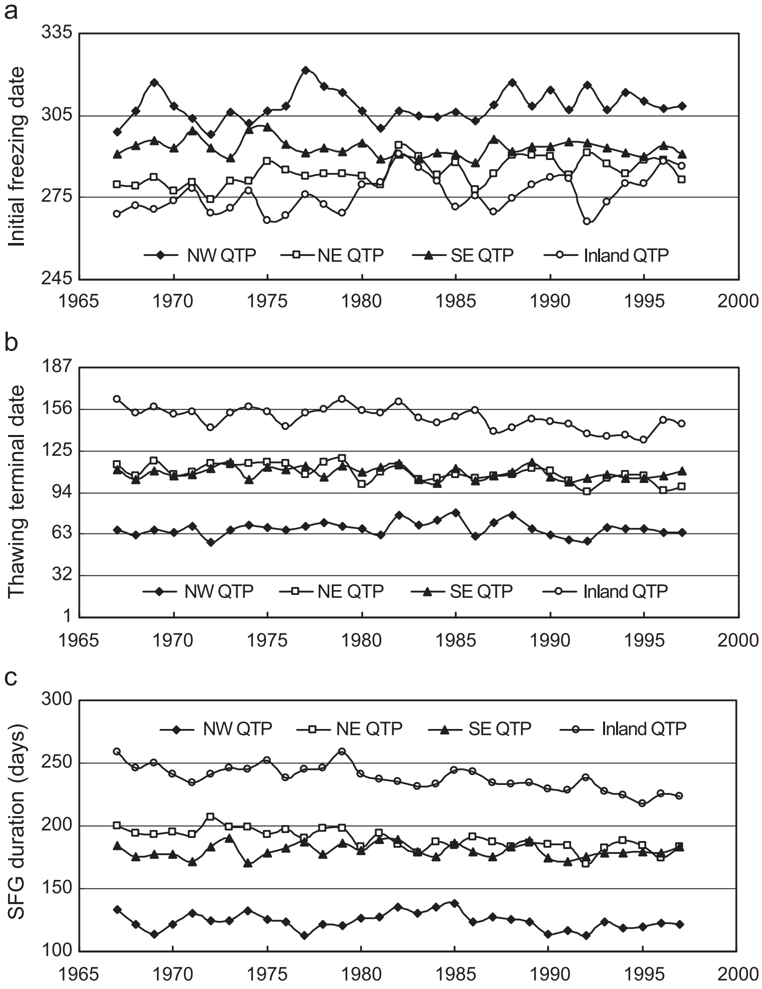
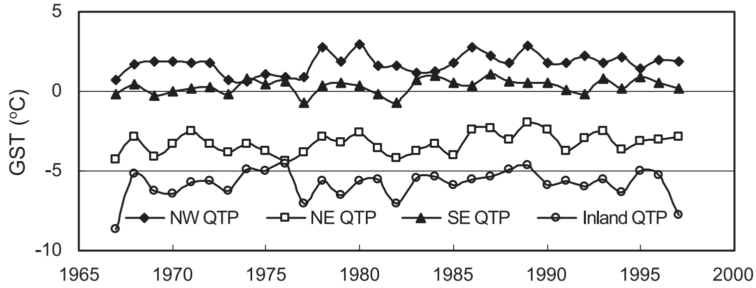


Fig. 7. Changes of the initial freezing (a), thawing terminal date (b) and seasonally frozen ground duration (c).

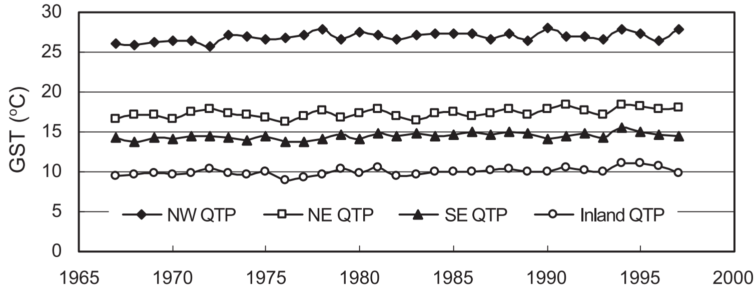
The freezing process begins around October 2 (Fig. 7a), and the thawing process ends around May 28 (Fig. 7c), lasting about 238 days in average. The SFG in NE QTP begins to form around October 10 and thawed completely around April 17, lasting about 189 days. The SFG lasted from October 19 to April 17 in SW QTP and from November 3 to March 7 in NW QTP, with a duration of about 180 and 124 days, respectively. The duration of SFG were well correlated with MAWATs and SFG depths. The lower MCSAT is, the longer the SFG lasts, and the thicker the SFG becomes.

The duration of SFG shortened by about 28, 23 and 4 days in inland, NE and NW QTP, respectively, and remained stable in SE QTP. The initial freezing date moved afterwards for about 10 days for inland QTP, 9 days for NE QTP and 4 days for NW QTP but slightly ahead for about 3 days for SE QTP. The thawing terminal dates of SFG moved ahead for about 18, 14, 4 days for inland, NE and SE, respectively, but remained stable for NW QTP.

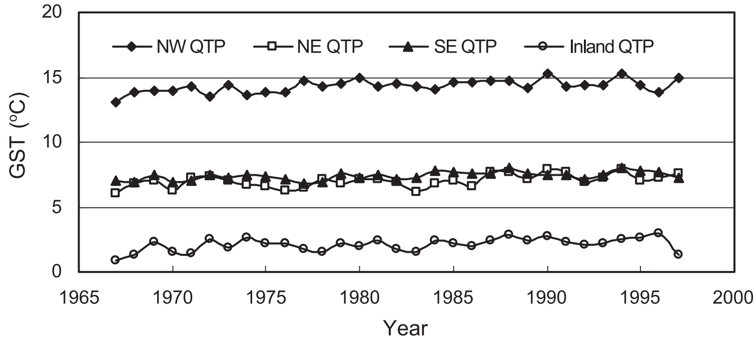
Changes of SFG depth, the initial and terminal dates of SFG development and its durations in different regions did not correlate well with the climate



a) Cold season mean



b) Warm season mean



c) Annual mean

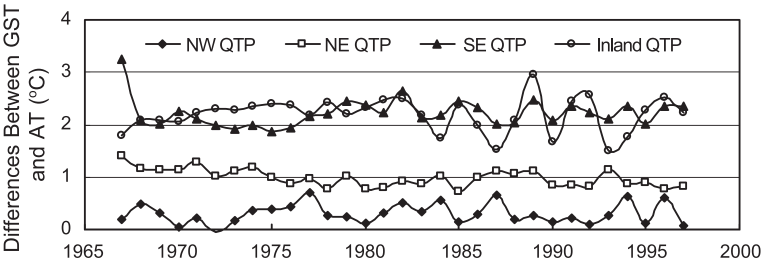
Fig. 8. Changes of ground surface temperatures: (a) cold season mean; (b) warm season mean; (c) annual mean.

warming trends. It implies that SFG changes are more complicated than climate changes. As SFG is the product of interaction between earth and air, other factors, such as precipitation, surface conditions (snow cover and vegetation), soil properties, and geo–hydro conditions, may contribute their effects to SFG changes.

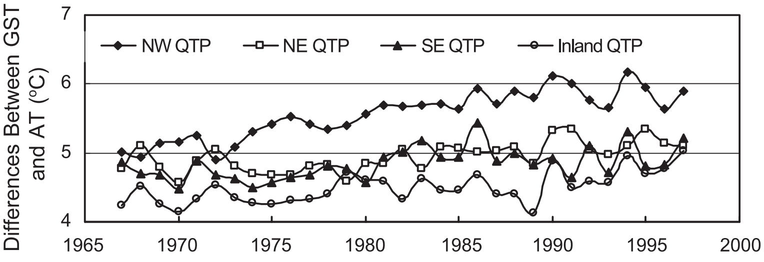
3.4. Changes of ground surface temperature (GST)

The warmest region in GST is NW QTP. The mean values of GST are about 14.3, 1.7 and 26.9 °C annually, in cold and warm seasons, respectively (Fig. 8a,b and c). It is about 7.4, 0.3, 14.5 °C in SE QTP, and 7.0, − 3.3 and 17.3 °C in NE QTP. The mean annual GST in these two regions is very close, but the mean warm season GST is higher, and the mean cold season GST is lower in NE QTP due to the more continental climate conditions. The lowest mean GST is in inland QTP. It is 2.1, − 5.8 and 10 °C annually, in cold and warm seasons, respectively.

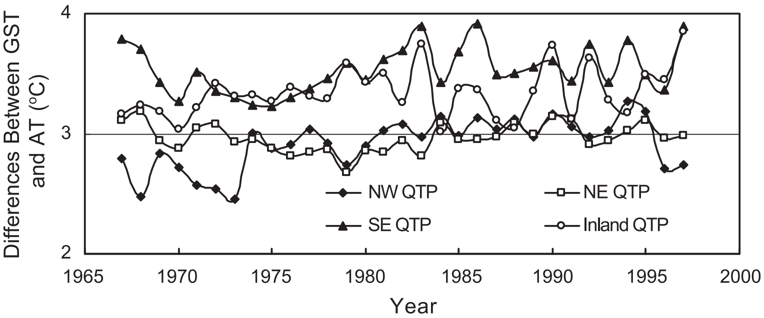
Warming trends of mean annual ground surface temperature (MAGST) in QTP are more significant than MAAT (Figs. 2a and 8). MAGST increased about 1.0, 0.9, 0.6 and 0.8 °C over 30 years for NW, NE, SE and inland QTP, respectively. In comparison with the more cold season warming in air temperature, greater increases in warm season GST (MSGST) were observed in all regions with an amplitude of about 1.1, 1.1, 0.8 and 1.0 °C for the NW, NE, SE and inland



a) Cold season mean



b) Warm season mean



c) Annual mean

Fig. 9. Changes of the differences between ground surface temperature and air temperature in different regions of the QTP.

QTP, respectively, whereas the mean cold season GST (MWGST) rose by about 0.8, 0.8, 0.4 and 0.5 °C in these four respective regions. MAGST, MSGST and MWGST rose higher in the northern QTP, i.e., high-latitude regions. Inland QTP was the most stable region in terms of GST.

3.5. Possible feedback of SFG changes to climate warming

The modulation effects of soil freezing–thawing processes to ground temperature was well known (Allison et al., 2001; Li et al., 2002) but not well understood. The freezing of soils would release latent heat by water–ice phase changes, thus lessening the cooling trend of soils, and the thawing of soils would absorb heat to lessen the warming trend of ground. When soil is frozen, its thermal conduction would be higher and thermal capacity would be lower than in its thawed state. This would evidently affect the surface heat exchanges. Decreases in SFG depth and shortening of SFG duration are likely to lessen such modulation effects.

The differences between air temperature and ground surface temperature are smaller in cold season and greater in warm season on the whole QTP, and vary spatially and temporarily (Fig. 9). The differences between mean annual ground surface and air temperatures (MAGST – MAAT) in all regions increased by about 2.9 to 3.5 °C from 1967 to 1997, and the increases mainly occurred in warmer seasons (Fig. 9) with an amplitude of about 1 °C in NW QTP, and 0.4–0.5 °C in other regions. The differences between GST and air temperatures in colder seasons decreased for about 0.2–0.3 °C in the northern QTP and remained stable in SE and inland QTP over 30 years. This implies that the heat released from Earth to atmosphere in warmer seasons was increasing from 1967 to 1997 due to the increasing ground surface–atmosphere temperature gradients, but remained stable or decreased during the colder seasons.

4. Conclusion

Warming in climate and degradation of SFG in the Qinghai–Tibet Plateau have been significant over the past 30 years. The warming trend of climate was different in different regions. The increase in MAAT in the northeastern QTP was higher than in other regions. The climate in the southeastern region was relatively stable. Although there are geographical differences, increase in air temperature was more significant in cold season than in warm season. A greater level of cold-season air temperature increase occurred in the northern than the southern QTP. Warm-season warming amplitudes were greater in the eastern and inland regions than in the western region of the QTP. Annual precipitation (AP) was on the rise in the northwestern, inland and southeastern regions of QTP, but showed a downward trend in the northeastern QTP.

Changes in SFG depth are somewhat different and complicated compared with climate warming trends. The most significant changes occurred in regions with the thickest SFG, i.e., inland QTP, then northeastern and northwestern QTP. The least change was in the southeastern regions of the QTP. Very good correlations between SFG depth and MCSAT were observed in most regions of the QTP. It can be concluded that the MCSAT is the main factor controlling the SFG changes. However, other factors, such as precipitation, snow covers, etc., also play important roles.

The duration of SFG shortened by more than 20 days over 30 years in inland and NE QTP, but are relatively stable in NW and SE QTP. It was more attributed to advances of thawing terminal date than the postponement of initial freezing date.

Significant warming in GST occurred over the past 30 years in QTP, and the warming trend is greater than upsurges in air temperature. Compared with the significant cold-season warming in air temperature, more upsurges of warmer-season GST were observed in all regions. MAGST, MSGST and MWGST rose higher in the northern part of QTP, i.e., high latitude regions, than in the southern portion. Inland QTP was the most stable region in terms of GST. The warming trends of air temperatures, ground surface temperatures and shortening of SFG duration are likely to contribute their thermal effects to enhance the plateau monsoons.

Although there is almost no stable snow covers in most of the QTP due to much smaller winter precipitation and very strong winds in cold season, especially in the northern and inland regions, temporary snow cover may also contribute its effect to SFG changes.

More detailed studies are needed to improve our understanding about its effects. The complicated landforms and geomorphologic features made the SFG characteristics more complex and variable even within very short distances. The sparsely distributed meteorological stations, especially over the wide range areas with elevation exceeding 4500 m asl and in the southwestern QTP, enhance the difficulties of understanding such variability. Regional climate models as well as expanding observational foundation could improve our ability to understand such uncertainties.

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References

Allison, I., Barry, R.G., Goodison, B.E., 2001. Climate and Cryosphere (CLIC) Project Science and Coordination Plan (Version 1). WCRP-114, WMO/TD No. 1053, Switzerland, p. 76.

Dong, Y., 1999. Progresses and problems in research on sandy desertification in Qinghai–Xizang Plateau. J. Desert Res. 19 (3), 251–255 (in Chinese).

Fan, R., Yao, S., 1982. Discussion on the formation and the trend of development of the perennial frost on southern Qinghai–northern Xizang (Tibet) Plateau. J. Glaciol. Geocryol. 4 (1), 45–54 (in Chinese).

Folland, C.K., Karl, T.R., Christy, J.R, Clarke, R.A., Gruza, G.V., Jouzel, J., Mann, M.E., Oerlemans, J., Sainger, M.J., Wang, S.W., 2001. Observed climate variability and change. In: Houghton, J.T., Ding, Y., Griggs, D.J., Nguer, M., van der Linden, P.J., Dai, X., Maskell, K., Johnson, C.A. (Eds.), Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge Univ. Press, Cambridge, United Kingdom, 881 pp.

Gao, R., Wei, Z., Dong, W., Wang, C., Zhong, H., 2003. Variation of snow and frozen soil over Qinghai-Xizang Plateau in the twentieth century and their relations to climate change. Plateau Meteorology 22 (2), 191–196 (in Chinese).

Gao, R., Wei, Z., Dong, W., 2004. Impacts of the anomalous thawing of the frozen soil in Tibetan Plateau on the summer precipitation in China and its mechanism. Adv. Atmos. Sci. (accepted for publication).

Gou, D., 2000. Chapter 7: talik. In: Zhou, Y., Guo, D., Qiu, G., Cheng, G., Li, S. (Eds.), Geocryology in China. Science Press of China, Beijing, pp. 145–156 (in Chinese).

Guo, D., Zhou, Y., Qiu, G., Li, S., 2000. Chapter 11: southwestern China geocryological area (Qinghai–Xizang Plateau). In: Zhou, Y., Guo, D., Qiu, G., Cheng, G., Li, S. (Eds.), Geocryology in China. Science Press of China, Beijing, pp. 299–365 (in Chinese).

Hinzman, L.D., Kane, D.L., Gieck, R.E., Everett, K.R., 1991. Hydrologic and thermal properties of the active layer in the Alaskan Arctic. Cold Reg. Sci. Technol. 19 (2), 95–110.

Huang, R., 1985. The thermal effect of the Qinghai–Xizang Plateau on formation and maintenance of the mean monsoon circulation over South Asia in summer. J. Trop. Meteorol, 1 (1–8).

Hulme, M., Osborn, T.J., Johns, T.C., 1998. Precipitation sensitivity to global warming: comparison of observations with HadCM2 simulations. Geophys. Res. Lett. 25, 3379–3382.

Jin, H., Wang, G., Cheng, G., et al., 1997. Deterioration of the cold regions environments on the Qinghai–Tibet Plateau. Proceedings of 5th International Symposium on Cold Regions Development, Anchorage, Alaska, USA, May 4–10, US CRREL, pp. 309–312.

Jones, P.D., Hulme, M., 1996. Calculating regional climatic time series for temperature and precipitation: methods and illustrations. Int. J. Climatol. 16, 361–377.

Kane, D.L., Hinzman, L.D., Zarling, J.P., 1991. Thermal response of the active layer to climate warming in a permafrost environment. Cold Reg. Sci. Technol. 19 (2), 111–122.

Ke, C., Li, P., 1998. Spatial and temporal characteristics of snow cover over the Qinghai–Xizang Plateau. Acta Geogr. Sin. 53 (3), 209–215 (in Chinese).

Kumar, K.K., Kleeman, R., Crane, M.A., Rajaopalan, B., 1999a. Epochal changes in Indian monsoon–ENSO precursors. Geophys. Res. Lett. 26, 75–78.

Kumar, K.K., Rajaopalan, B., Crane, M.A., 1999b. On the weakening relationship between the Indian monsoon and ENSO. Science 284, 2156–2159.

Li, M., 2000. Countermeasures for environmental protections in the Qinghai–Tibet Plateau. Resour. Sci. 22 (4), 78–82 (in Chinese).

Li, Y., Bao, X., 1999. Characteristics of ground temperatures of gelic chuxintu in Qinghai–Tibet Plateau. Soil 4, 169–174.

Li, S., Cheng, G., Zhou, Y., et al., 1996. Map of Permafrost on Tibetan Plateau, Lanzhou. Gansu Culture Press, Lanzhou (in Chinese).

Li, S., Nan, Z., Zhao, L., 2002. Impact of soil freezing and thawing process on thermal exchange between atmosphere and ground surface. J. Glaciol. Geocryol. 24 (5), 511–515 (in Chinese).

Lin, J., He, J., 2000. The anomalous convection over the Tibetan Plateau in spring and summer and its effect on the Western Pacific subtropical high. J. Nanjing Inst. Meteorol. 23, 346–355 (in Chinese).

Lin, Z., Zhao, X., 1996. Spatial properties of air temperature and precipitation changes in Qinghai–Tibet Plateau. Sci. China (D) 26 (4), 254–258 (in Chinese).

Liu, X., Chen, B., 2000. Climate warming in the Tibetan Plateau during recent decades. Int. J. Climatol. 20 (1), 1729–1742.

Liu, X., Hui, X., Chen, B., 1991. Influence of heat source abnormal of underlying surface over Tibetan Plateau and western tropical Pacific on short-term climate in China. Plateau Meteorol. 10, 305–316 (in Chinese).

Liu, X., Zhang, M., Hui, X., 1998. Contemporary climate change of the Qinghai–Xizang Plateau and its response to greenhouse effect. Sci. Geogr. Sin. 18 (2), 113–121 (in Chinese).

Morison, J., Agaard, K., Steele, M., 2000. Recent environmental changes in the arctic: a review. Arctic 53 (4), 359–371.

Tang, M., Bai, C., Feng, S., Cai, Y., 1998. Climate abrupt change in the Qinghai–Xizang Plateau in recent century and its relation to astronomical factors. Plateau Meteorol. 17 (3), 250–257 (in Chinese).

Tu, J., Shi, C., 1998. Study on degeneration of alpine meadow grassland in Qingzang Plateau with remote sensing techniques. Acta Agrestia Sin. 6 (3), 226–233 (in Chinese).

Wang, S., Jin, H., Li, S., Zhao, L., 2000. Permafrost degradation on the Qinghai–Tibet Plateau and its environmental impacts. Permafr. Periglac. Process. 11, 43–53.

Wang, C., Dong, W., Wei, Z., 2003. Studies on relationship between freezing–thawing processes of the Qinghai–Tibet Plateau and the atmospheric circulation over East Asia. Chin. J. Geophys. 46, 309–316 (in Chinese).

Yao, T., Liu, X., Wang, N., 2000. Study on the amplitude of climate change in Qinghai–Tibet Plateau. Chin. Sci. Bull. 45 (1), 98–108 (in Chinese).

Ye, D., Gao, Y., 1979. The Qinghai–Tibet Plateau Meteorology. Science Press, Beijing (in Chinese).

Ye, D., Zhang, Q., 1974. Simulation test for influence of heating effect of Qinghai–Xizang Plateau to circulation over East-Asia in summer. Sci. China 8 (1), 301–320 (in Chinese).

Zhang, Y., Qian, Y., 2002. Thermal effect of surface heat source over the Tibetan Plateau on the onset of Asian summer monsoon. J. Nanjing Inst. Meteorol. 25, 298–306 (in Chinese).

Zhao, L., Chen, G., Cheng, G., Li, S.X., 2000. Chapter 6: permafrost: status, variation and impacts. In: Zheng, D., Zhang, Q., Wu, S. (Eds.), Mountain Geoecology and Sustainable Development of the Tibetan Plateau. Kluwer Academic Publishers, The Netherlands, pp. 113–137.

Zheng, D., Li, B., 1999. Progress in studies geographical environments on the Qinghai–Tibetan Plateau. Sci. Geogr. Sin. 19 (4), 296–302 (in Chinese).

Zhou, Y., 2000. Chapter 3: the seasonal freeze and seasonal thaw of ground. In: Zhou, Y., Guo, D., Qiu, G., Cheng, G., Li, S. (Eds.), Geocryology in China. Science Press of China, Beijing, pp. 63–91 (in Chinese).

Zhou, Y., Guo, D., 1982. Principle characteristics of permafrost in China. J. Glaciol. Geocryol. 4 (1), 1–19 (in Chinese).

Zhou, Y., Guo, D., 2000. Chapter 1: the zonal and regional conditions for development of frozen ground in China. In: Zhou, Y., Guo, D., Qiu, G., Cheng, G., Li, S. (Eds.), Geocryology in China. Science Press of China, Beijing, pp. 9–36 (in Chinese).

Zhu, L., Wu, Z., Zang, E., Pan, B., Liu, Y., Tao, G., 1996. Difference of permafrost degeneration in the east of the Tibetan Plateau. J. Glaciol. Geocryol. 18 (2), 104–110 (in Chinese).