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Review of climate and cryospheric change in the Tibetan Plateau

Shichang Kang^{1,2,6}, Yanwei Xu¹, Qinglong You^{1,3,4},
Wolfgang-Albert Flügel³, Nick Pepin⁵ and Tandong Yao^{1,2}

¹ Key Laboratory of Tibetan Environment Changes and Land surface Processes, Institute of Tibetan Plateau Research, Chinese Academy of Sciences (CAS), Beijing 100085, People's Republic of China

² State Key Laboratory of Cryospheric Science, CAS, Lanzhou 730000, People's Republic of China

³ Department of Geoinformatics, Friedrich-Schiller University Jena, Jena 07743, Germany

⁴ Graduate University of Chinese Academy of Sciences, Beijing 100049, People's Republic of China

⁵ Department of Geography, University of Portsmouth, PO1 3HE, UK

E-mail: shichang.kang@itpcas.ac.cn

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Abstract

The Tibetan Plateau (TP), with an average elevation of over 4000 m asl and an area of approximately 2.5×10^6 km², is the highest and most extensive highland in the world and has been called the 'Third Pole'. The TP exerts a huge influence on regional and global climate through thermal and mechanical forcing mechanisms. Because the TP has the largest cryospheric extent outside the polar region and is the source region of all the large rivers in Asia, it is widely recognized to be the driving force for both regional environmental change and amplification of environmental changes on a global scale. Within China it is recognized as the 'Asian water tower'. In this letter, we summarize the recent changes observed in climate elements and cryospheric indicators on the plateau before discussing current unresolved issues concerning climate change in the TP, including the temporal and spatial components of this change, and the consistency of change as represented by different data sources. Based on meteorological station data, reanalyses and remote sensing, the TP has shown significant warming during the last decades and will continue to warm in the future. While the warming is predominantly caused by increased greenhouse gas emissions, changes in cloud amount, snow-albedo feedback, the Asian brown clouds and land use changes also partly contribute. The cryosphere in the TP is undergoing rapid change, including glacier retreat, inconsistent snow cover change, increasing permafrost temperatures and degradation, and thickening of the active layer. Hydrological processes impacted by glacial retreat have received much attention in recent years. Future attention should be paid to additional perspectives on climate change in the TP, such as the variations of climate extremes, the reliability of reanalyses and more detailed comparisons of reanalyses with surface observations. Spatial issues include the identification of whether an elevational dependency and weekend effect exist, and the identification of spatial contrasts in temperature change, along with their causes. These issues are uncertain because of a lack of reliable data above 5000 m asl.

Keywords: Tibetan Plateau, climate change, cryosphere

1. Introduction

The Tibetan Plateau (TP), with an average elevation of over 4000 m asl and an area of approximately 2.5×10^6 km², is the

highest and most extensive highland in the world. Referred to as the 'Third Pole', the TP exerts a huge influence on regional and global climate through thermal forcing mechanisms (Duan and Wu 2005, Yanai *et al* 1992, Yeh and Gao 1979). Therefore it has been called 'the sensitive area' and 'the startup region' in

⁶ Author to whom any correspondence should be addressed.

China (Feng *et al* 1998) and is characterized as ‘the driving force’ and ‘the amplifier’ for global climate change (Pan *et al* 1996). Many studies have analyzed climate change in the TP using observational data from meteorological stations, reanalyses and remote sensing (Frauenfeld *et al* 2005, Liu and Chen 2000, Yao *et al* 2001, Zhang 2007). Some studies attempt to link observed climate variability and changes in atmospheric circulation and examine model simulations of change (Chen *et al* 2003, Liu and Yin 2001, Yin *et al* 2000). Others stress the importance of cryospheric change, examining snow, river and lake ice, glaciers and ice caps, and frozen ground (Lemke *et al* 2007). The cryosphere is considered to be one of the most sensitive indicators of climate change, because the temperature rise in cryospheric regions (where mean annual temperatures are near or below 0 °C) is generally larger than that in other regions on the global scale (Pepin and Lundquist 2008) and the positive feedback mechanisms inherent in the cryospheric system can enhance climate warming (Lemke *et al* 2007, Li *et al* 2008, Xiao *et al* 2008). The cryosphere in China is primarily located in the TP and is experiencing rapid change as summarized in recent reviews (Li *et al* 2008, Xiao *et al* 2008, 2007).

According to the Intergovernmental Panel on Climate Change Fourth Assessment Report (IPCC AR4; IPCC 2007), global mean surface temperatures have risen by $0.74\text{ °C} \pm 0.18\text{ °C}$ when estimated by a linear trend over the last 100 years (1906–2005), and the rate of warming over the last 50 years is almost double that over the last 100 years. Impacts related to climate warming are very evident and the cryosphere is undergoing marked change, including an increasingly negative mass balance of glaciers, thickening of the active layer and increasing permafrost temperature (Zhang 2007).

Although much research has been done to quantify climate change and its effects in the TP, there are still some uncertainties. In this study, we review recent processes in quantification of this change. Changes in climate elements are summarized in section 2, including air temperature, precipitation and sunshine duration. In section 3, changes in the cryosphere are reviewed. The mechanism of warming is represented in section 4. Section 5 summarized some unresolved issues concerning the spatial and temporal dynamics of those changes. Section 6 concisely summarizes the way forward.

2. Observed changes in climate elements in the TP

2.1. Temperature

Most meteorological stations in the TP were established during the 1950s, and these datasets are widely used for climate change, which sometimes leads to inconsistent results, depending on the time period or stations examined (Li *et al* 2004). Nevertheless most studies show that the TP temperature was high in the early 1960s and decreased from the mid-1960s to the 1980s, before entering a sustained increase from the late 1980s onwards. The amplitude of change is generally larger and occurred earlier than that in the east of China (Lin and Zhao 1996). Both the warming beginning

in the 1980s and the decadal temperature fluctuation since 1955 started firstly in the southeast of the TP, and transmitted gradually to the whole of eastern and northern parts of the TP (Feng *et al* 1998). However the most recent research (Ding and Zhang 2008) suggests that the recent acceleration of warming in the TP has occurred later than that to the north of the Yangtze River in East China, especially in winter and spring. Linear rates of temperature increase over the entire TP during 1955–1996 are about 0.16 °C/decade for the annual mean and 0.32 °C/decade for the winter mean, which exceed the averages for the Northern Hemisphere and the same latitudinal zone (Liu and Chen 2000). During 1960–2007, the annual mean surface temperatures averaged over 90 stations in the TP have increased by about 1.8 °C , the rate is 0.36 °C/decade (Wang *et al* 2008), which doubles the previous estimate by Liu and Chen (2000). During 1961–2003 linear trends of mean daily minimum and maximum temperature reached 0.41 °C/decade and 0.18 °C/decade (Liu *et al* 2006), which also confirms the asymmetric pattern of greater warming trends in minimum temperature than in maximum temperature found in many studies elsewhere (Du 2001).

According to the IPCC AR4 under the SRES A1B scenario (a ‘middle of the road’ estimate of future emissions), a 4 °C warming will likely occur over the TP during the next 100 years (Meehl *et al* 2007). This projected warming represents the largest elevated warming in the middle troposphere globally. This is consistent with the previous model simulations (Xu *et al* 2003) which suggest that future warming in the TP in the 21st century will be more obvious than in the rest of China. Models also indicate that the increase of minimum temperatures will be more pronounced than maximum temperatures, and that winter warming will be greater than in summer. This would not only melt glaciers that feed the rivers but also potentially change downstream precipitation. Numerical experiments indicate that atmospheric heating induced by the rising TP temperatures can enhance East Asian subtropical frontal rainfall (Wang *et al* 2008). Some researchers also extend use of ERA-40 reanalysis to analyze the climate change in the TP (Frauenfeld *et al* 2005), indicating that ERA-40 captures the inter-annual variability very well. However, no dramatic warming trends are observed in ERA-40.

In summary, previous studies (Chen *et al* 2003, Duan *et al* 2006, Frauenfeld *et al* 2005, Liu and Chen 2000, Liu *et al* 2006, Meehl *et al* 2007, Niu *et al* 2004, Wang *et al* 2008, Xu *et al* 2003, You *et al* 2008a) showed significant warming in the TP during the last half century which is projected to continue in the future at a faster rate than the global mean. Based on the monthly mean temperature during 1950–1990, Lin and Zhao (1996) divided the TP into five sub-regions in terms of temperature consistency and found that southeastern Xizang and western Sichuan was the first area entering the last warm period. Stations in the northwestern, southwestern, and southeastern TP have larger trend magnitudes of temperature (You *et al* 2008a, 2008b). However, the mechanisms driving the future temperature rise have not been completely clarified.

2.2. Precipitation

The TP climate is characterized by wet and humid summers with cool and dry winters. Most of the precipitation, greater than 60–90% of the annual total, falls between June and September and less than 10% between November and February (Xu *et al* 2008). Summer precipitation gradually decreases from the southeast to the northwest, from approximately 700 mm to lower than 50 mm. Such changes are also reflected in vegetation, which varies from forest to grassland and then desert (Liu and Yin 2001). The dominant spatial pattern of inter-annual variability of the summer precipitation is a seesaw structure between the southern and northern parts of the TP, which shows correlation with the North Atlantic oscillation (NAO) (Liu and Yin 2001). Due to inaccessibility and the complex terrain, it is difficult to obtain direct meteorological observations over large portions of the TP. Satellite measurements, including the Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (MI) have therefore been used to retrieve precipitation with reasonable accuracy (Yao *et al* 2001). For example, monthly $1^\circ \times 1^\circ$ rainfall estimates obtained from the Special Sensor Microwave Imager (SSM/I) and TRMM 3B42 version 5 products for summer (April–October) 1998–2002 have been compared with surface precipitation observations at 94 stations. Although the explained variance in observed precipitation was 34% and 38%, respectively for SSM/I and TRMM 3B42 version 5 products using raw data alone, this increased to over 70% when corrections based on location and topographic variables were taken into account (Yin *et al* 2008). Time series analysis of the normalized difference vegetation index (NDVI) through satellite imagery has also been used for studying land use and precipitation interaction in the TP (Immerzeel *et al* 2005).

In contrast to temperature trends, changes in precipitation are less spatially consistent and there is larger inter-annual variability. Based on monthly mean precipitation during 1950–1990, Lin and Zhao (1996) divided the TP into nine sub-regions in terms of precipitation regimes and found that some sub-regions have become drier while others have become wetter. Precipitation in the TP has increased in most regions over the past several decades, especially in the eastern and central TP, while the western TP has dried during the same period (Xu *et al* 2008).

2.3. Changes in other meteorological elements

Changes in other meteorological elements, such as sunshine duration, total cloud cover, and relative humidity, have also been documented in the TP. Annual sunshine duration has decreased significantly by 34.1 h/decade during 1971–2005, which is thought to be a result of increased surface vapor pressure (Du *et al* 2007). Niu *et al* (2004) shows that from 1961 to 1998, sunshine duration has increased in the middle and eastern part of the TP, but decreased in the southern part of the TP. Since the mid-1980s, the TP as a whole experienced a climatic discontinuity with a transition to a markedly moister regime, characterized by increased relative humidity and surface pressure, decreased sunshine duration and decreased total cloud amount (Niu *et al* 2004). Yet another

study, based on the monthly total cloud amounts at 75 stations in the TP during 1971–2004, suggests that annual and seasonal total cloud amounts have declined, possibly due to an increase of atmospheric aerosol content and ozone concentration in the TP, although it has been difficult to quantify the driving forcing mechanism up to now (Zhang *et al* 2007). Studies of cloud are important, because cloud cover exhibits a strong negative correlation with the diurnal temperature range (DTR) and may explain different trends in the daytime and nighttime temperatures observed (Duan and Wu 2006). Total and low-level cloud amounts show contrasting trends during day and night, with decreases during daytime but increases (especially low-level cloud) at night (Duan and Wu 2006). This will exacerbate rates of warming for the plateau, and increased nighttime cloud cover may partially explain the enhanced nocturnal warming observed in the TP.

3. Cryospheric changes in the TP

3.1. Shrinking of glaciers

The TP contains 36 800 glaciers, amounting to a total glacial area of 49 873 km², and a total glacial volume of 4561 km³ (Yao *et al* 2004a). Since the 1990s the majority of glaciers have retreated rapidly, although there is still a minority of glaciers advancing. Many studies have reported accelerations in glacial retreat and increasingly negative mass balances in the TP in recent years (Kang *et al* 2007, Yao *et al* 2004a, 2004b). Recent research showed that more than 80% of glaciers in western China have retreated, losing 4.5% of their combined areal coverage (Ding *et al* 2006). Hydrological changes resulting from glacial retreat, such as increased discharge, rises in lake level, more frequent glacial lake outbursts leading to flooding, enhanced glacial debris flows, and changes in water resources have been the focus of many studies (Li *et al* 2008, Xiao *et al* 2008, Yao *et al* 2004a, 2004b). Glacial retreat in the 1990s has caused an increase of 5.5% in river runoff in Northwest China (Yao *et al* 2004b). The quantitative contribution of glacial melt water to rising lake level has been investigated using remote sensing (RS) and geographical information system (GIS) for many lakes, including Nam Co, Selin Co, Yamzhog Yumco and Mapam Yumco (Yao *et al* 2004a, Ye *et al* 2008, 2007). Nevertheless, changes in glacier volume and the concurrent environmental implications of glacial retreat require much more study.

3.2. Increases in snow cover

The most persistent snow cover in the TP is located on the southern and western edges where precipitation from the Indian monsoon spills over onto the high plateau (Pu *et al* 2007). Based on the daily snow depth data at 60 stations in the TP, snow covers appears to have increased during 1957–1992. This is inconsistent with the reduced extent of snow cover in other extra-tropical areas in the late 1980s but coincides with the recent increases in Antarctic and Greenland snow accumulation (Li 1996). The increased snow depth in the TP after the mid-1970s is concurrent with a deeper India–Burma trough, an intensified subtropical westerly jet and

enhanced ascending motion over the TP during most of the year (Zhang *et al* 2004). This could lead to a weaker or later Asian summer monsoon through the well-documented snow–monsoon interaction (Zhu and Ding 2007). Similar to other climatic factors, there are limited surface snow cover/depth data at the high elevations. Pu *et al* (2007) therefore evaluated the accuracy of Moderate Resolution Imaging Spectroradiometer (MODIS) high resolution snow cover data by comparing it with *in situ* Chinese snow observations. There is limited published literature on seasonal changes in the beginning and ending dates of recorded snow fall and in the duration of snow cover (Li *et al* 2008).

3.3. Changes in frozen ground

Frozen ground, in a broad sense, includes the near surface soil affected by short-term freeze–thaw cycles, seasonally frozen ground and permafrost. The presence of frozen ground depends on the ground temperature, which is controlled by the surface energy balance (Lemke *et al* 2007). Most of the permafrost in China is distributed on the TP, thus it is another important indicator of change in the TP environment.

3.3.1. Increasing permafrost temperature and permafrost degradation. Increasing permafrost temperature and permafrost degradation have been reported in the TP and are expected to continue in the further. Permafrost temperature increased by between 0.2 and 0.5 °C from the 1970s to the 1990s over most of the TP, and by up to 0.5 °C along the Qinghai–Tibetan Highway from 1995 to 2002 (Lemke *et al* 2007, Zhao *et al* 2004). Permafrost temperature monitoring through 10 boreholes down to 10.7 m depth from 1996 to 2006 along the Highway shows that long-term mean annual permafrost temperatures at 6.0 m depth have increased by 0.12–0.67 °C with an average increase of about 0.43 °C during the past decade (Wu and Zhang 2008).

A preliminary estimate for the reduction of the permafrost area in the TP is 100 000 km² from 1970s to mid-1990s (Li *et al* 2008). Based on data from ground penetration radar combined with *in situ* measurements, the mean lower elevation limit of permafrost has moved upward by about 25 m from 1975 through 2002 on the north-facing slopes of the Kunlun Mountains. From Amdo to Liangdehe along the Qinghai–Tibetan Highway, the areal extent of permafrost islands has decreased by approximately 36% over the past three decades (Lemke *et al* 2007). Other long-term temperature measurements indicate that the lower altitudinal limit of permafrost has moved up by 25 m in the north of the TP during the last 30 years and between 50 and 80 m in the south of the TP over the last 20 years (Cheng and Wu 2007). The areal extent of taliks (i.e., patches of unfrozen ground in an area of permafrost) expanded about 1.2 km along the Highway (Lemke *et al* 2007). A numerical permafrost model developed to predict changes of permafrost distribution in the TP over the next 50–100 years shows that even more rapid shrinkage will likely occur (Nan *et al* 2005).

3.3.2. Changes in seasonally frozen ground. Seasonally frozen ground, as opposed to permafrost, refers to a soil layer that freezes and thaws annually regardless of whether there is underlying permafrost. It includes both seasonal soil-freeze–thaw in non-permafrost regions and the development of active layers above the permafrost (Lemke *et al* 2007). Significant changes in seasonally frozen ground have been observed, including in the thickness of the active layer.

The mean active layer thickness has increased by up to 1.0 m along the Qinghai–Tibetan Highway in the TP since the early 1980s (Zhao *et al* 2004), which is of similar magnitude to the increase of 0.15–0.50 m (between 1996 and 2001) reported by Cheng and Wu (2007) elsewhere in the TP. Models indicate that in most places the active layer thickness has increased by more than 0.3 m in the northern plateau from 1980 to 2001, and in selected local areas the increase has reached 0.9 m (Oelke and Zhang 2007). In contrast, the thickness of seasonally frozen ground in the TP has decreased by 0.05–0.22 m from 1967 to 1997, and the duration of seasonally frozen ground decreased by more than 20 days during the same period, mainly due to the earlier onset of the spring thaw (Zhao *et al* 2004). As well as being an indicator of climate change, recent studies show that freeze–thaw cycles in the ground intensify the heat-exchange between the atmosphere and the ground surface, which is likely to enhance the plateau monsoons (Cheng and Wu 2007) and also release carbon dioxide trapped in earlier times into the atmosphere during thaw (Zhang 2007). Consequently, understanding possible climatic feedbacks as a result of thawing of seasonally frozen ground should be a priority.

4. Understanding the mechanisms of warming in the TP

In order to explain the environmental changes occurring in the TP, it is crucial to try to understand the relationship among all the above elements because the climate system acts as a complex and interdependent entity. The emerging consensus on the causes of climate change in the TP includes:

- (1) Anthropogenic greenhouse gas emissions are generally considered as the main cause of climate warming in the TP (Duan *et al* 2006, Zhou *et al* 2008, IPCC 2007), as elsewhere on the planet, but impacts of the increased greenhouse gas emissions upon the climate change in the TP are probably more serious than the rest of the world (Duan *et al* 2006), although exact reasons are still unclear. Most model studies show enhanced climate warming in the TP due to doubling of carbon dioxide (Chen *et al* 2003).
- (2) Changes in cloud amount likely contribute to the recent climate warming in the TP (Duan and Wu 2006). An increasingly low-level cloud amount exhibits a significant increasing trend during the night leading to strong nocturnal surface warming, while both total and low-level cloud amounts during daytime display decreasing trends, resulting in more absorption of direct solar radiation at the surface and an associated surface warming (Duan and Wu 2006).

- (3) The snow/ice-albedo feedback is also regarded as one of the factors contributing to the recent warming in the TP because it is one of the most sensitive areas of snow feedback on Earth (Liu and Chen 2000). However increases in snow cover do not fit well with rapidly decreasing glaciers, which might be dominated by temperature increasing.
- (4) Asian brown clouds, which are mostly results of biomass burning and fossil fuel consumption, could enhance lower atmospheric solar heating by about 50% (Ramanathan *et al* 2007). It is unclear how this enhancement may influence warming in the TP, but how brown clouds affect atmospheric circulation is an important aspect of their climatic consequences in the region.
- (5) Land use changes may also account for spatial differences in the observed warming over the TP (Frauenfeld *et al* 2005, Zhang 2007). Significant land use changes in the TP include permafrost and grassland degradation, urbanization, deforestation and desertification. These changes not only have impacts on local climate and environment, but also have important hydrological implications in the TP (Cui and Graf 2009). Most general atmospheric circulation models testify that human-induced land use changes in the TP would have a significant impact on local to regional scale climate. Some research related to degradation of grassland by livestock grazing (Du *et al* 2004) and urbanization (You *et al* 2008b), also confirm that land use change may be one of the reasons why climate warming in the TP is spatially complex.

5. New perspectives on climate change in the TP

5.1. How have climate extremes changed?

Variations and trends in extreme climate events have recently received much attention on the global scale because extremes are statistically sensitive to even a small change in mean values (Easterling *et al* 2000). Changes in indices of climate extremes were analyzed for 71 meteorological stations above 2000 m asl in the eastern and central TP during 1961–2005 (You *et al* 2008a). In general, changes in extreme indices associated with minimum temperatures occur more rapidly than changes in maximum temperatures. This asymmetry is likely due to a decreasing diurnal temperature range, consistent with an asymmetric pattern of greater warming at night (Liu *et al* 2006). Extreme precipitation indices largely exhibit increasing trends in the southern and northern TP but decreasing trends in the central TP that are associated with increasing meridional wind and water vapor fluxes (You *et al* 2009a). More attention should be paid to the relationship between extreme temperature and precipitation, and the future extreme climate.

5.2. Can reanalyses capture the past and current temperature variability?

The scarcity of surface temperature observations in the TP limits understanding of climate change in the region. Frauenfeld *et al* (2005) has compared ERA-40 with stations,

and finds that reanalysis data are less influenced by local effects. We extend the data periods and compare temperatures and their trends from 71 homogenized surface stations (Li *et al* 2004) with NCEP (Kalnay *et al* 1996) and ERA-40 (Uppala *et al* 2005) reanalyses in the eastern and central TP for 1961–2004 (not shown). ERA reanalysis has lower temperature trend magnitudes than reported at the surface stations. NCEP fails to capture any warming. The ‘observation minus reanalysis’ (OMR) method can therefore be used to estimate the impact of changes in land use (including urbanization and agricultural practices) by computing the trend in the difference between surface observations (which reflect all the sources of climate forcing, including surface effects) and NCEP (which only contains the forcings influencing the assimilated free atmospheric trends) (Kalnay and Cai 2003, Lim *et al* 2008, 2005, Pepin and Seidel 2005). As in other global studies (Pepin and Seidel 2005), the OMR trend averaged over the TP is significantly increasing with a rate of 0.63 °C/decade, which could be partly the result of extensive local and regional land use changes (Kalnay and Cai 2003, Lim *et al* 2008, 2005).

5.3. Do the warming trends have an elevation effect?

Many studies have investigated the evidence for systematic change in warming rates with elevation in surface observations, both on a global scale (Diaz and Bradley 1997, Diaz *et al* 2003, Pepin and Lundquist 2008, Pepin and Seidel 2005) and over the TP (Liu and Chen 2000, Liu *et al* 2009, You *et al* 2008b). These do not all come to the same conclusions, probably because of differing datasets, periods of analysis, and lowland stations used for comparison. Liu and Chen (2000) revealed a more pronounced warming at high elevations when compared with surrounding regions in the TP, which has since been confirmed by numerical experiments (Chen *et al* 2003), and such a tendency may continue in future climate change scenarios (Liu *et al* 2009). Analysis of remote sensing data from MODIS during 2000–2006 fails to identify this (Qin *et al* 2009). Using temperature trend magnitudes at 71 surface stations with elevations above 2000 m asl in the eastern and central TP (You *et al* 2008b) fails to find an elevation dependency in the trends of temperature extremes in the eastern and central TP. Temperature trend magnitudes at the same stations compared with 56 grid points from ‘surface’ NCEP and ERA-40 reanalyses in the TP also show no relationships with elevation (not shown). It is clear that the exact driving mechanisms which may be responsible for elevational dependency need further investigation.

5.4. Does there exist a ‘weekend effect’ on TP climate?

The ‘weekend effect’ method (defined as the average for Saturday through Monday minus the average for Wednesday through Friday) has been used to identify fingerprints of anthropogenic emissions (Forster and Solomon 2003, Gong *et al* 2006). Diurnal temperature range is an important indicator (Forster and Solomon 2003). Based on daily maximum and minimum temperatures from the China Meteorological Administration homogenized datasets (Li *et al* 2004), the weekend effect in diurnal temperature range (DTR)

at 71 stations with elevations above 2000 m asl in the eastern and central Tibetan Plateau (TP) during 1961–2004 has been examined (You *et al* 2009b). The DTR in autumn and winter demonstrates a much stronger weekend effect and provides strong evidence of anthropogenic activity in this region, especially in the central TP. An interaction between anthropogenic aerosols and atmospheric dynamics on local and/or larger scales has been invoked to explain the horizontal and vertical extent of the detected cycles (Baumer and Vogel 2007, Forster and Solomon 2003, Gong *et al* 2006, Laux and Kunstmann 2008).

6. Summary

The TP is the highest and most extensive highland in the world and has therefore been called the ‘Third Pole’. It exerts a huge influence on the regional and global climate through thermal forcing. Here, recent progress in understanding climate change and cryospheric change in the TP has been reviewed.

Recent changes in climate elements are summarized as follows.

- (1) Many studies using observational data from meteorological stations, reanalyses and remote sensing show a significant warming in the TP during the last half century. Models suggest this warming will continue in phase with global trends, but at a higher magnitude. Anthropogenic greenhouse gas emissions are generally considered as the main cause of the climate warming in the TP, and impacts there are probably more serious than the rest of the world. However, other confounding factors, such as changes in cloud cover, snow/ice-albedo feedback, the Asian brown clouds and land use changes, also contribute to recent climate dynamics in the TP, although it is currently difficult to determine the relative contribution of each of these factors.
 - (2) Compared with temperature trends, changes in precipitation are less consistent and the climatology has larger inter-annual variability. The dominant spatial pattern of inter-annual variability of the summer precipitation is a seesaw structure between the southern and northern parts of the TP, which is closely associated with the North Atlantic oscillation (NAO). Satellite remote sensing, such as TRMM, can be used to fill in the gaps where station data are not available.
 - (3) In the mid-1980s, the TP experienced a climatic jump characterized by increased relative humidity, surface pressure, and by decreased sunshine duration and total cloud amount.
- Most of the cryosphere in China is located in the TP and is also experiencing rapid changes which are shown as follows.
- (1) Since the 1990s, glaciers have retreated rapidly, although a few are still advancing. Recent studies report an accelerating retreat and increasingly negative mass balances. More attention should be paid to the resulting hydrological processes, including increased discharge, rising lake levels, more frequent glacial lake outburst floods, glacial debris flows, and the impact upon water resources in the TP.
 - (2) The most persistent snow cover in the TP is located on the southern and western edges, on large mountain ridges and in the western part of Yarlung Zangbo valley. Although data are scarce, observations on daily snow depths and snow cover appear to show increasing trends, concurrent with a deeper India–Burma trough, an intensified subtropical westerly jet and enhanced ascending motion over the TP. It is hard to reconcile this with other cryospheric changes, particularly the decrease in glacial extent. However snow cover shows more small-scale temporal and spatial variation, and maybe an unreliable indicator of long-term regional change.
 - (3) Increasing permafrost temperatures and permafrost degradation have occurred in the TP. Permafrost temperatures increased by 0.2–0.5 °C from the 1970s to 1990s over the hinterland of the TP. The area of permafrost has reduced by 100 000 km² over the same period. Significant changes in seasonally frozen ground have also been observed with active layer thicknesses increasing and seasonally frozen ground decreasing in layer thickness and duration.
- In the context of global warming, some new perspectives and unresolved issues concerning changes in the TP are summarized as follows.
- (1) Temperature extremes show patterns consistent with warming, with a large proportion of stations showing statistically significant trends, preferentially for extremes associated with minimum temperatures. Precipitation extremes are much less consistent, and often show contrasting trends in various sub-regions, or no trends at all. The consequences of possible intensification of the global hydrological cycle are yet to be evident in the TP.
 - (2) The use of reanalyses to represent climate variability in the TP is important because of sparse and incomplete surface data. However different reanalyses do not agree. ERA-40 has lower temperature trend magnitudes than surface stations, and NCEP fails to capture warming at all. Both reanalyses have cold biases. The ‘observation minus reanalysis’ trend is significantly increasing, with a rate of 0.63 °C/decade, which could be further evidence that surface changes, such as urbanization, have influenced climate change in the TP.
 - (3) There are conflicting signals over whether the future elevational dependency in warming, predicted by global climate models, is already evident in surface observations in the TP. Some studies have identified elevational dependency but others show no significant correlation between elevation and trend magnitudes (mean temperatures or temperature extremes). It may be that topographic type, local land use changes or the snow–ice feedback mechanism are more important than elevation on its own.
 - (4) Studies attempting to identify an anthropogenic signature to recent warming have shown that the DTR in autumn and winter is much stronger, especially in the central TP, which cannot be explained by a microclimatic effect. Interaction with anthropogenic aerosols may account for this, despite the TP being one of the most remote and clear regions in the world.

These studies have been made possible by the use of many difference surface, reanalysis, and satellite datasets combined with climate model output. Most of the datasets come from meteorological stations operated by the China Meteorological Administration. As with all global datasets these potentially include inhomogeneities resulting from relocation of stations and changes in the local environment. Thus data quality and homogeneity assessment are of great importance. It is critical to pay attention to data quality and homogenization when applying these datasets to examine change in the TP. In addition, a lack of observed data above 5000 m asl limits our understanding of surface climate change in the TP. Thus it is important to use other resources, such as remote sensing, reanalyses, and regional climate models to improve our ability to understand climate change in the TP. However, the remote mountains and complex topography are handled in reanalyses and climate models have a strong influence on the results obtained. More comparative studies between different types of data sources will help us to understand which effects are real, and which are an artifact of data production methods.

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