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Weather and Climate Effects of the Tibetan Plateau

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ABSTRACT

Progress in observation experiments and studies concerning the effects of the Tibetan Plateau (TP) on weather and climate during the last 5 years are reviewed. The mesoscale topography over the TP plays an important role in generating and enhancing mesoscale disturbances. These disturbances increase the surface sensible heat (SH) flux over the TP and propagate eastward to enhance convection and precipitation in the valley of Yangtze River. Some new evidence from both observations and numerical simulations shows that the southwesterly flow, which lies on the southeastern flank of the TP, is highly correlated with the SH of the southeastern TP in seasonal and interannual variability. The mechanical and thermal forcing of the TP is an important climatic cause of the spring persistent rains over southeastern China. Moreover, the thermodynamic processes over the TP can influence the atmospheric circulation and climate over North America and Europe by stimulating the large-scale teleconnections such as the Asian-Pacific oscillation and can affect the atmospheric circulation over the southern Indian Ocean. Estimating the trend in the atmospheric heat source over the TP shows that, in contrast to the strong surface and troposphere warming, the SH over the TP has undergone a significant decreasing trend since the mid-1980s. Despite the fact that *in situ* latent heating presents a weak increasing trend, the springtime atmospheric heat source over the TP is losing its strength. This gives rise to reduced precipitation along the southern and eastern slopes of the TP and to increased rainfall over northeastern India and the Bay of Bengal.

Key words: Tibetan Plateau, observation, weather, climate

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1. Introduction

The Tibetan Plateau (TP) is known for its significant mechanical and thermal effects upon the regional and global circulation and climate. Since the 1950s, numerous data analyses (e.g., Yeh, 1950; Yanai et al., 1992), theoretical studies (e.g., Zhu, 1957a, b; Wu, 1984), numerical modeling (e.g., Hahn and Manabe, 1975; Broccoli and Manabe, 1992), as well as rotating annulus studies (e.g., Yeh and Chang, 1974) have been performed to increase our insights in these fields. The mechanical forcing of a topography uplifts the impinging air flows, divides them into branches, and generates stationary lee waves (Charney and Elliassen, 1949; Yeh, 1950; Hoskins and Karoly, 1981). On the other hand, the heating effect of large-scale mountains also plays an important role in the hemispheric circulation patterns (Yeh and Gao, 1979). Numerical simulation studies show that the forcing of TP is of special importance in determining the Asian summer monsoon circulation (e.g., Hahn and Manabe, 1975; Li et al., 2001; Chou, 2003).

In the summer season, the TP serves as a huge heat source, with strong surface sensible heating (SH) and deep latent heating (LH) over the central and eastern regions (Yeh et al., 1957; Yeh and Gao, 1979; Yanai

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*Corresponding author: DUAN Anmin, amduan@lasg.iap.ac.cn et al., 1992). A shallow cyclonic circulation near the surface and a deep anticyclonic circulation exist over the TP throughout the whole summer season (Yeh and Gao, 1979), which can be regarded as a result of atmospheric thermal adaptation (Wu and Liu, 2000). Duan and Wu (2005) further implied that the thermal forcing of TP intensifies the East Asian monsoon to its east and the dry and hot desert climate in mid-Asia to its west.

After the Qinghai-Xizang Meteorology Experiment (QXMEX) in 1979 and the second Tibetan Plateau Atmosphere Science Experiment (TIPEX) in 1998, more and more field experiments have continued to overcome the shortage of observational data over the TP, especially in the remote areas, and some of them have become part of international coordination, including the Global Energy and Water Cycle Experiment (GEWEX); the Asian Monsoon Experiment on the Tibetan Plateau (GAME/Tibet); the Coordinated Enhanced Observing Period (CEOP) Asia-Australia Monsoon Project (CAMP) on the Tibetan Plateau (CAMP/Tibet); and the New Integrated Observational System over the Tibetan Plateau (NIOST, supported by the Chinese–Japanese joint international cooperation program).

A systematic review of the advances concerning the impact of the TP on climate during 2004–2007 in China has been documented by Liu et al. (2007); it focused mainly on the climate effects of the TP. In this review, a retrospective of the most recent observation experiments and studies related to weather and climate effects of the TP during the last 5 years (2006–2010) is presented. Section 2 describes some new findings from satellite data and some ongoing observational projects over the TP. Sections 3 and 4 summarize the impacts of TP forcing on the weather and climate, respectively. Research on trend in the climate and heat source over the TP is presented in section 5. Finally, in section 6, some important research issues regarding TP weather and climate dynamics are listed.

2. Observations over the TP

2.1 *Satellite data*

Based on monthly mean datasets of three-dimensional (3D) latent heating (LH) derived from Tropical Rainfall Measuring Mission Microwave Imager (TRMM TMI), Liu and Fu (2007) investigated the characteristics of horizontal distributions and vertical profiles of LH over the TP and compared the results with those of the adjacent regions (Fig. 1). Their results showed that three maximum centers of LH occur over the plateau area, and the unique LH profile with a single peak was revealed. When comparing the mean LH profile in the TP with those in the nearby areas, the LH profile over the TP is only similar to the upper part of LH profile over the Indian subcontinent. Additionally, from 6 km to the upper atmosphere, the LH at each level over the TP is generally greater than that over the eastern part of mainland China and the warm pool region of the western Pacific, implying that a significant heating source is located in the middle and upper troposphere over the TP.

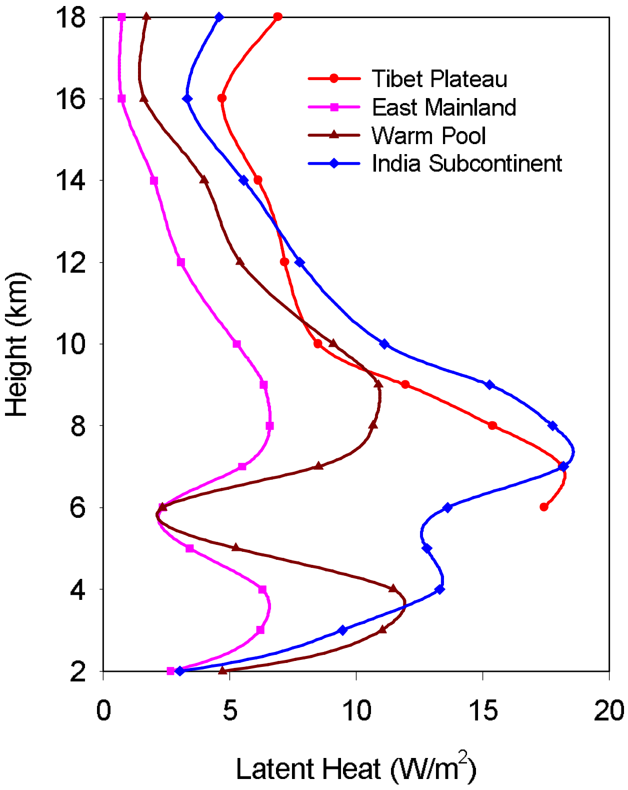

Fig. 1. The differences of latent heating profiles between over the TP and over the adjacent regions (cf., Liu et al., 2007).

In contradiction to surface observations, statistics of rain types based on the standard TRMM PR algorithm show that most of the Tibetan summer rains are stratiform. Analyzing bright-band height determined by precipitation radar (PR), Fu and Liu (2007) found that these values are often below surface-level height over the plateau. It is suspected that the PR algorithm may have mistakenly regarded strong surface radar return as bright band. Because the PR-determined stratiform rain-rate profiles over the plateau have a pattern similar to those of convective rain-rate profiles in the nearby plains, most of the stratiform rains (as classified by PR algorithm) may actually have been weak convections.

2.2 *Observation on plateau–atmosphere–land interaction over a heterogeneous landscape*

The TP has the most prominent and complicated terrain on the globe, with an elevation averaging higher than 4000 m above mean sea level (ASL). It is often called the "Third Pole" because its geographic significance is similar to that of Antarctica and the Arctic. The huge TP dramatically impacts the world's environment and especially controls climatic and environmental changes in Asia and elsewhere in the Northern Hemisphere. It therefore provides a field laboratory for studying global change. The lack of quantitative understanding of interactions between the land surface and atmosphere makes it difficult to model the complete energy and water cycles over the TP and their effects on global climate change. Therefore, study of atmosphere–land interaction over the TP has increased in recent years (e.g., Xu et al., 2008; Ma et al., 2010). However, experiments have been limited by observational parameters, and most investigations have only been done in summer and at a few locations.

With support from various agencies in the People's Republic of China, a Tibetan Observation and Research Platform (TORP) is now focusing on the land-surface processes and environment over the TP, with an emphasis on atmosphere–land interaction. When it is complete, there will be 21 comprehensive observation and research stations and 16 additional observational sites in the TORP. Of these, 11 comprehensive observation and research stations and 10 observational sites will be configured for the study of atmosphere–land interaction (see Fig. 2) by the end of 2012. Each comprehensive observation and research station will include 20-m atmospheric boundary layer (ABL) towers (measuring wind speed, wind direction, air temperature, and humidity at five levels), a four-component radiation measurement system, a five-level soil moisture and soil temperature measurement system (SMTMS), a GPS radiosonde system, a wind profiler and radio acoustic sounding system (RASS), a sonic turbulent measurement system, and CO_2/H_2O flux measurement system, a precipitation monitoring system, and a soil heat flux measurement system. Each additional observational site will include a 10-m automatic weather station (AWS) (measuring wind speed, wind direction, air temperature, and humidity at three levels), a radiation measurement system, a SMTMS, a precipitation and snow depth system, and a soil heat flux system. All of the sites will monitor the atmosphere (from the stratosphere to the sur-

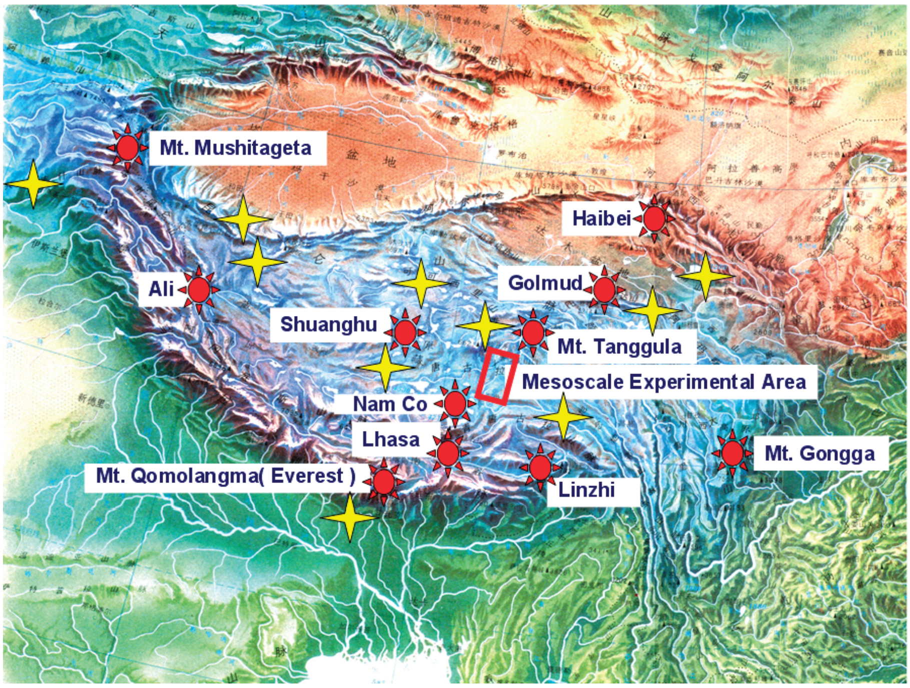

Fig. 2. The Tibetan Observation and Research Platform (TORP) for the study of atmosphere–land interaction on the Tibetan Plateau. (⊛ indicates comprehensive observation and research station; star indicates observational site; and □ indicates mesoscale experimental area of the GAME/Tibet and the CAMP/Tibet) (cf., Ma et al., 2008).

face layer) as well as ground-surface processes. Three comprehensive observation and research stations (Mt. Everest, Nam Co, and Linzhi) were established by the Institute of Tibetan Plateau Research (ITP) of the Chinese Academy of Sciences (CAS) in August 2005. The comprehensive observation and research stations of Haibei, Golmud, Lhasa, and Mt. Gongga were established by other institutes of CAS around the beginning of 2000. All of the established stations are working well now and have yielded a large amount of data. The Ali station and the station at Mt. Mushitageta were been established in 2008. Shuanghu station and Mt. Tanggula station will be established by ITP/CAS by the end of 2012, and all 10 observational sites will be set up by the end of 2012. One of the important parts of TORP is the mesoscale monitoring network. It worked successfully during the Global Energy and Water Cycle Experiment (GEWEX), the Asian Monsoon Experiment on the Tibetan Plateau (GAME/Tibet, 1996–2000), and the Coordinated Enhanced Observing Period (CEOP) Asia–Australia Monsoon Project on the Tibetan Plateau (CAMP/Tibet, 2001–2006). This monitoring network was established at the beginning of 1998 during GAME/Tibet, and more instruments were set up during CAMP/Tibet and will be continued in TORP. It covered a 150×250 km^2 area (30.7°–33.3°N, 91°–92.5°E), and many kinds of instruments have been deployed in the network. A large amount of data was collected during GAME/Tibet and CAMP/Tibet, which comprise the best dataset to date for TP hydrometeorology. Using the data, substantial research progress has been made in land and atmosphere processes, remote sensing, and land data assimilation. It is best to extend the observations as long as possible for the study of atmosphere–land interaction and climatic change over the TP and surrounding areas.

All of the instruments in GAME/Tibet and CAMP/Tibet will continue long-term observations in TORP. The data collected in the TORP will be archived by the TORP data center in the ITP. The archived data will be available to the scientific community all over the world within 2 years after necessary measurements. The complete TORP dataset will be available in 2012. The data collected in TORP can be used for analysis of land and atmospheric processes, model/scheme development, model calibration, validation, and other tasks. Results from the process studies and parameterizations can be used as input to atmospheric models or for remote sensing and data assimilation studies. The results from the remote sensing and data assimilation can also be used as input for the atmospheric models. Using the atmospheric models, remote sensing, and data assimilation methodologies, the point or local-scale process studies and parameterizations can be scaled up to the TP scale. The plateau scale results can also be validated by the stations and sites data. In this way, we believe TORP can contribute to the study of impacts of the TP on the Asian Monsoon system and climatic change over China, East Asia, and the entire globe.

2.3 *The new integrated observational system over the Tibetan Plateau*

The New Integrated Observational System over the TP (NIOST), supported by the Chinese–Japanese joint international cooperation program, was initiated and has been implemented since 2005. The Chinese Academy of Meteorological Sciences (CAMS) of the China Meteorological Administration (CMA) is implementing the NIOST project. NIOST will provide a mechanism for transferring the research results from field experiments into a forecast capability, as well as for enhancing research activities by providing routinely available and long-term data sets. Based on these analyses, an observational network in two lines was designed: the east–west array of an observing network located on the south side of the TP, and the north–south array of an observing network located on the east side of the plateau. Although both observing networks focus on the TP, NIOST's coverage is also extended to several neighboring provinces of China to capture water-vapor downstream transport. In fact, the observational network covers most of the TP, a large portion of the Yunnan province (on the southeast side of Tibet), and some portions of Sichuang, Guangxi, and other provinces along the Yangtze River basin.

3. Weather effects of the TP

3.1 *Effect of mesoscale topography over the TP on summer precipitation in China*

The effect of mesoscale topography over the TP on downstream summer precipitation in China was studied using a regional atmospheric model (Shi et al., 2008). Two ensemble simulations with a 30-km model resolution were conducted for the 1998 summer monsoon season in China. The control simulation used the uniform resolution for both model atmosphere and topography. In the sensitivity simulation, the mesoscale feature in topography over the TP was smoothed out with the use of 120-km resolution topography over the TP. The results showed that the control simulation reproduced reasonably well, but the sensitivity simulation considerably underestimated the observed precipitation in the Yangtze River valley (YRV). Therefore, the mesoscale feature in topography plays an important role in generating and enhancing mesoscale disturbances over the TP. These disturbances enhance the SH over the TP and propagate eastward to enhance convection and precipitation in the YRV in China.

Observational evidence and numerical experiments with atmospheric general circulation models from Wang et al. (2008) show that atmospheric heating induced by the rising TP temperatures can enhance East Asian subtropical frontal rainfall. The mechanism of the linkage is found to be through two distinct Rossby wave trains and the isentropic uplift to the east of the TP, which deform the western Pacific Subtropical High and enhance moisture convergence toward the East Asian subtropical front. The model calculations suggest that the past changes in TP temperatures and East Asian summer rainfall may be linked, and that projected future increases in TP temperatures may lead to further enhanced summer frontal rainfall in East Asia region

3.2 *Mobile mesoscale convective systems over the TP and rainfall over eastern China*

Li et al. (2008) investigated the basic characteristics in terms of initiation, distribution, trajectory, development, life cycle, convective intensity, and precipitation of the summer convective system (CS) initiated over the TP using the International Satellite Cloud Climatology Project (ISCCP) deep convection database and associated TRMM precipitation for 1998–2001. They found that summer CSs have a dominant center over the Hengduan Mountain and a secondary center over the Yarlung Zangbo River valley. Precipitation associated with these CSs contributes >60% of total precipitation over the central-eastern area of the TP and 30%–40% over the adjacent region to its southeast. The average CS life cycle is ∼36 h; 85% of CSs disappear within 60 h of their initiation. Approximately 50% of CSs do not move out of the TP region, with the remainder split into eastward- and southward-moving components. The CSs moving out of the TP are generally larger, have longer life spans, and produce more rainfall than those staying inside the region. Convective system occurrences and associated rainfall present robust diurnal variations. The mid-afternoon maximum of CS initiation and associated rainfall over the plateau are mainly induced by solar heating linked to the unique TP geography. The delayed afternoon–late night peak of rainfall from CSs propagating out of this region is a combined outcome of multiple mechanisms working together. Results suggest that interactions of summer TP CSs with the orientation of the unique TP geography and the surrounding atmospheric circulations are important for the development, intensification, propagation, and life span of these CSs.

In a separate paper, Hu et al. (2008) examined the relationship between mobile mesoscale convective systems (MCSs) over the TP and the summer rainfall over China using the Deep Convection Tracking Database from ISCCP, reanalysis data from NCEP/NCAR, precipitation data from 138 stations. The results showed that most of the mobile MCSs in summer come from southeast of the TP, their generation periods have evident diurnal cycle characteristic, and they could move or propagate to most of China's eastern middle and South Asia region. Particularly, there is a significant correlation between mobile MCSs over the TP and the rainfall over China. The distribution of correlation coefficient appears in four zonal bands ("−+−+" from South to north), just like the regular pattern of rain bands over China. Further analysis suggests that the intensity of the South Asia High, the West Pacific Subtropical High, and the Northeast Cold Vortex might play roles in the environment, thus effecting the generation of mobile MCSs over the TP and rainfall over China.

3.3 *Influence of the TP on extreme weather in China*

Based on two groups of January perpetual runs with ECHAM4 (European Centre Hamburg Model of version 4) AGCM, Bao et al. (2010) discussed the roles of the TP warming in 2008 winter storm in China. According to the circulation differences with and without the TP warming, five major favorable conditions for this extreme winter storm are associated with the rising TP temperatures: the deepened South Asian trough, the enhanced lower level southwesterly anomaly over Southern China, the lower-level cyclonic shear with the southerly flow along the subtropical East Asian front, the inversion layer over central-southeastern China, and the strengthened Middle East jet stream (MEJS). Both the deepened South Asian trough and the enhanced lower-level southwesterly anomaly are linked to the continental large-scale cyclonic anomaly triggered by the increased surface temperatures over the TP; both the lower-level cyclonic shear with the southerly flow and the inversion layer are the secondary Rossby responses to the enhanced latent heating over southeastern China. All of these circulation anomalies induced by the TP warming favor the formation of freezing rain and heavy snow over central southern China (Fig. 3). The intensified MEJS is associated with the negative temperature advection to the northwestern flank of the TP caused by the rising TP surface temperature and the existence of a lower-level cyclonic anomaly with the quasi-barotropic structure.

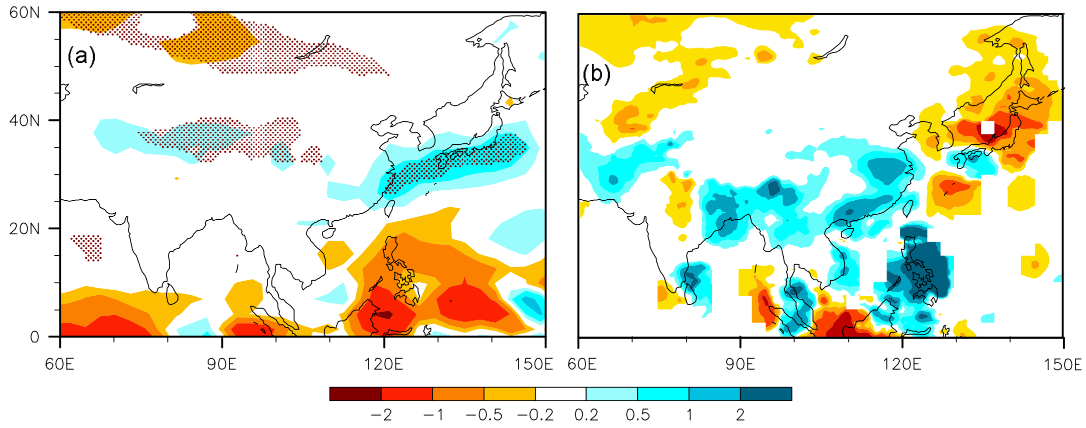

Fig. 3. (a) The difference of precipitation between the TP-W and CTRL experiments in January 2008 (the dotted regions indicate $p>0.05$ significance levels), and (b) the precipitation anomaly in January 2008 revealed from PREC/L (cf., Bao et al., 2010). Units: mm d^{-1}.

However, the anomalies with TP warming in simulation are basically confined to the surrounding and downstream regions of the TP. As such, the anomalies far away from the TP cannot be explained by the TP warming effects. For example, the strong lower-level southeasterly from the tropical western Pacific cannot be seen in the TP warming results; they might be linked to SST anomalies (e.g., the La Niña event in the winter of 2007–2008). In this sense, the TP warming is one of the important contributors to this 2008 winter storm, but not the only one. Further study by Li et al. (2010) suggests that during this period, the diabatic heating was centered in the tropical oceans, Central Asia, the TP, and the North Atlantic Ocean. Results from numerical experiments demonstrate that global diabatic heating anomalies are responsible for this extreme event. The diabatic heating anomalies in Central Asia and the TP could account for the extreme heavy snow event. Such anomalies generate anomalous air mass rising as well as southerly winds over South China. These features facilitate water vapor transportation and result in the heavy rain and snow. Meanwhile, an anomalous heating in the North Atlantic enhances the positive phase of North Atlantic Oscillation, which could contribute to the occurrence of this unusual snow event.

In December 2008 and January 2009, severe drought affected northern China, north of the YRV, a major wheat-planting area. In the core drought area, the number of severe drought days was significantly above average. Using the daily data of drought monitoring at 723 stations and the monthly means of atmospheric circulation, SST, and other fields, Gao and Yang (2009) have investigated the main characteristics of the drought and their associations with large-scale climate conditions. In October–November 2008, the temperature over the TP was higher than normal. The average temperature from 700 to 200 hPa was mostly above normal by 0.60°C or more. The surface temperature was also higher than normal. In spite of the negative value over 35°N, 97.5°E, the mean tropospheric temperature over 20°–40°N, 70°–100°E was 0.63°C above normal. As a result, the India-Burma trough was shallower and less active, weakening the moisture transportation from the Bay of Bengal to eastern China. This feature was possibly related to the less snow over the TP. Over most of the TP, the positive correlation values exceed the 95% confidence level. In addition, the coefficient of correlation between the severe drought days of December–January and the area-averaged 700–200-hPa temperature over the plateau of the previous October–November is 0.53, a highly significant value exceeding the 99% confidence level, suggesting that the autumn temperature over TP is a precursor of the winter drought. The strong temperature–drought relationship also suggests a possible connection between the drought and the snow condition over the TP.

4. Climate effects of the TP

Relative to earlier work, one of the most important processes in understanding TP climate impacts is its influence in different seasons (Liu et al., 2007). In winter, as a large obstacle, the TP retards the westerly jet flow and deflects it into northern and southern branches. The deflected stream flow then appears as an asymmetric dipole (TP-dipole), making East Asia much colder than the middle Asia at high latitudes. In late winter and early spring over South China, the TP-dipole circulation results in persistent rainfall in early spring over South China, until the onset of the

Asian monsoon. In late spring, TP heating also contributes to the establishment and intensification of the South Asian high and the abrupt seasonal transition of the surrounding circulations.

4.1 *Influence of the TP on the formation of the spring persistent rains over southeastern China*

The spring persistent rains (SPR) over southeastern China (SEC) are a unique synoptic and climatic phenomenon in East Asia. Wan and Wu (2007) reveals a possible mechanism responsible for the climatic cause of SPR formation through climatic mean data analysis and sensitive numerical model experiments. SEC is located downstream of the southwesterly velocity center which lies on the southeastern flank of the TP. As a result, there are both a strong southwesterly wind velocity convergence and a moisture convergence over SEC. This is the immediate climatic cause of SPR formation. In spring, the seasonal evolution of the southwesterly velocity coincides with the SH over the southeastern TP, indicating that the formation of SPR is related to not only the southwesterly wind of mechanical deflected flow of TP but also the southwesterly wind of thermal-forced cyclonic low circulation. Sensitive numerical experiments demonstrate that, without the TP, both southwesterly velocity center and the SPR rain belt would disappear. The southwesterly wind velocity increases almost linearly with the rising amount of the total diabatic heating over the TP. Therefore, southwesterly velocity center is the result of the mechanical and thermal forcing of the TP.

Further study by Wan et al. (2009) found that the southwesterly flow is also highly correlated with the SH of the southeastern TP in interannual variability, in addition to having a high correlation in seasonal variability. These facts suggest that the thermal forcing of the TP is another important climatic cause of SPR. Numerical sensitivity experiments further verify that the mechanical and thermal forcings of the TP are the climatic causes of the formation of the SPR. On the other hand, the Nanling Mountains and Wuyi Mountains over southeastern China not only increase the SPR precipitation amount evidently, but also make the SPR rain belt move to the south by blocking the strong southwesterly flow.

4.2 *Tibetan heating on the Southern and Northern Hemispheric atmospheric circulations*

The observations and numerical simulations show that the spring and summer elevated Tibetan heating affects the Asian-Pacific Oscillation (APO) intensity (Nan et al., 2009; Zhou et al., 2009). With the Tibetan topography increasing, the summer elevated heating increases the tropospheric temperature over the Eurasian continent, with positive anomalies of tropospheric temperature deviation over the Eurasian continent. Meanwhile, the middle and upper tropospheric temperature decreases over the central and eastern North Pacific and the Atlantic Ocean during summer. Accordingly, a low-level anomalous anticyclonic circulation appears at the mid latitudes from North America to Europe, with significant negative anomalies of rainfall appearing at the mid latitudes of North America and Europe, indicating a decrease of rainfall over these regions.

The disturbance produced by the TP heating anomaly may affect the atmospheric circulation over the Southern Hemisphere across the equator. During summer, the anomalous ascending flow over the TP may go across the equator along the TP–southern Indian Ocean meridional circulation, entering into the southern Indian Ocean. The observations and simulations show that when the elevated TP summer heating strengthens, the tropospheric temperature increases over the Asian continent and the positive anomalies of temperature expand southward and upward from the Asian continent to the tropics and subtropics of the southern Indian Ocean, leading to increases of the tropospheric temperature over these regions. Meanwhile, the negative anomalies appear in the middle and lower layers of the troposphere at the mid and high latitudes of the southern Indian Ocean, with a wave train at the mid and high latitudes of the southern Indian and Pacific Oceans (Zhou et al., 2009).

4.3 *Effects of Tibetan heating on the Pacific ocean–atmosphere interactions*

Less TP snow cover often increases local heating, resulting in an increase of the overlying atmospheric temperature, while more TP snow cover often deceases the local heating, resulting in a decrease of the overlying atmospheric temperature (Zhao et al., 2007, 2010). Observations and numerical simulations show that in the theoretic frame of APO, the increasing Tibetan tropospheric temperature may cause a decrease of the tropospheric temperature in the subtropics of the central and eastern North Pacific (Fig. 4a) with the strengthening of the subtropical high over the eastern North Pacific and the anticyclonic anomalous circulation at the mid latitudes of the North Pacific (Nan et al., 2009), while decreasing Tibetan tropospheric temperatures may cause an increase of the tropospheric temperature, with the weakening of the subtropical high over the eastern North Pacific and the cyclonic anomalous circulation at the mid latitudes of

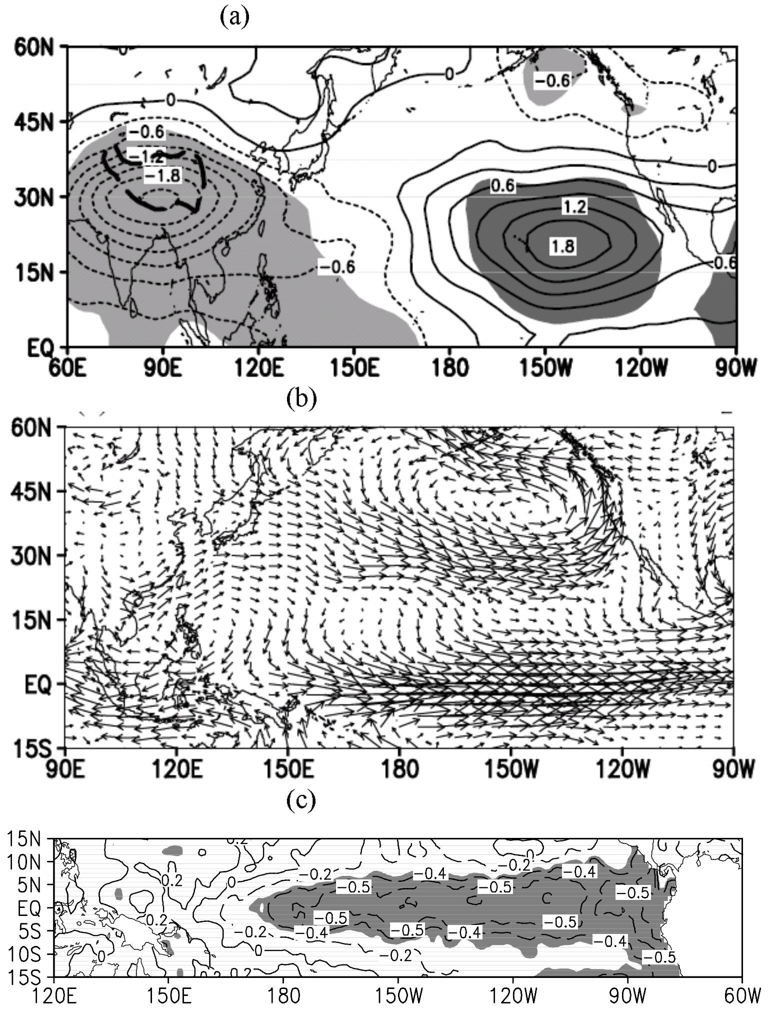

Fig. 4. (a) Composite difference of March–April–May 400–200-hPa averaged temperature deviation (°C) between low and high TP temperatures, (b) same as in (a) but for 850-hPa winds, and (c) correlation coefficients between the spring TP temperature and the synchronous SST during 1973–2007. The lightly shaded and heavily shaded areas are significant at the 95% confidence level for the negative and positive differences, respectively (cf., Zhao et al., 2010).

the North Pacific (Nan et al., 2009). Moreover, corresponding to a stronger Tibetan heating, the positive anomalies of geopotential height over the TP (while the negative anomalies of geopotential height over the TP corresponding to a weaker Tibetan heating), propagate eastward and westward along the westerly wind jet stream that acts as a waveguide, propagating eastward to the eastern North Pacific (Zhao et al., 2009). This result finally leads to the strengthening (or weakening) of the lower-tropospheric subtropical high over the North Pacific.

Corresponding to the strengthened subtropical high over the North Pacific, anomalous easterly winds prevail over the tropical Pacific, with the anomalous intertropical convergence zone over the eastern Pacific. Corresponding to the weakened subtropical high over the North Pacific, anomalous westerly winds prevail over the tropical Pacific (Fig. 4b). These variations lead to the strengthening (weakening) of the trade wind over the equatorial central and eastern Pacific, changing the thermocline and ocean currents. As a result, the upwelling in the cold tongue strengthens or weakens and SST according to the respective decreases or increases in the equatorial eastern Pacific, finally causing a significant negative correlation between the Tibetan temperature and the equatorial eastern Pacific SST (Fig. 4c) (Zhao et al., 2007; Nan et al., 2009). This correlation may persist through the subsequent autumn. Because the anomalous westerly wind over the tropical central and eastern Pacific does not originate from the Asian tropical monsoon region, the modulation of the Tibetan climate on El Niño-Southern Oscillation (ENSO) does not recur to the tropical monsoon processes instead of the extratropical atmospheric circulation in the Asian-North Pacific region (Nan et al., 2009).

Moreover, corresponding to the anomaly of the subtropical high over the North Pacific, the local anomalous surface sensible heat and latent heat fluxes and northward transport of warm water may lead to an increase or decrease of SST at the mid latitude of the western North Pacific, with a respective decrease or increase of SST on its east side (Zhou et al., 2009). These features are generally simulated through changing the elevated Tibetan summer heating in the ocean–atmosphere CCSM3 (the Community Climate System Model version 3) model (Zhao et al., 2009). Because the Pacific decadal oscillation (PDO) is an important mode of the SST variability in the extratropical North Pacific, the Tibetan effect on the extratropical Pacific SST possibly implies a modulation of the Tibetan climate on PDO.

5. Trend in climate and heat source over the TP

5.1 *Trend in temperature and precipitation*

Observational studies have shown that a striking climate warming occurred over the TP during the second half of the 20th century (e.g., Liu and Chen, 2000; Zhu et al., 2001; Niu et al., 2004; and Kang et al., 2010). However, most of them focus only on the phenomenon of climate warming, and the intrinsic reason of climate warming is particularly needed because it will provide further insight into the ongoing global change. One prominent feature of the TP climate is the much larger diurnal temperature range (DTR) compared to its adjacent plain regions at the same latitudes, which is due to its intense daytime solar radiation heating and nocturnal long-wave radiation cooling (Yeh and Gao, 1979). Duan et al. (2006) found that, during the past decades, the *in situ* climate warming is accompanied by a distinct decreasing trend of DTR (Fig. 5). In the upper atmosphere, there seems to be a coherent warming trend near the tropopause but a cooling trend in the lower stratosphere. Moreover, all these features can be reproduced in two coupled climate models forced by observed CO_2 concentration of the 20th century but cannot be reproduced by the fixed external conditions before the Industrial Revolution. These suggest that the recent climate warming over the TP primarily results from the increasing anthropogenic greenhouse gas emissions, and impacts of the increased greenhouse gas emissions upon climate change in the TP are probably more serious there than in the rest of the world.

Meanwhile, the low-level cloud amount over the plateau exhibits a significant increasing trend during the nighttime, leading to the enhanced atmospheric counterradiation, weakened effective terrestrial radiation, and the subsequently strong nocturnal surface warming. On the other hand, both the total and low-level cloud amounts during daytime display decreasing trends, resulting in more absorption of direct solar radiation at the surface and the associated surface warm-

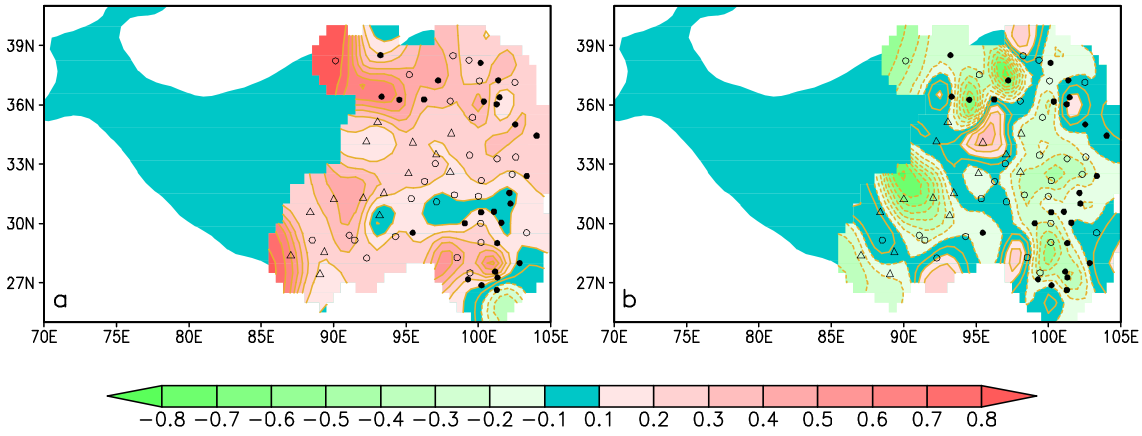

Fig. 5. Linear variation rates of (a) annual mean surface air temperature and (b) diurnal range of the surface air temperature (DTR) during 1961–2003 in units of °C per decade. Triangles, open circles, and solid circles denote stations ⩾4000, 3000, and 2000 m, respectively. The cyan area represents the TP area with the average altitude >2500 m. The station of Gulmud is located at 34°44′N, 101°36′E, with the height of 3501 m above sea level (cf., Duan et al., 2006).

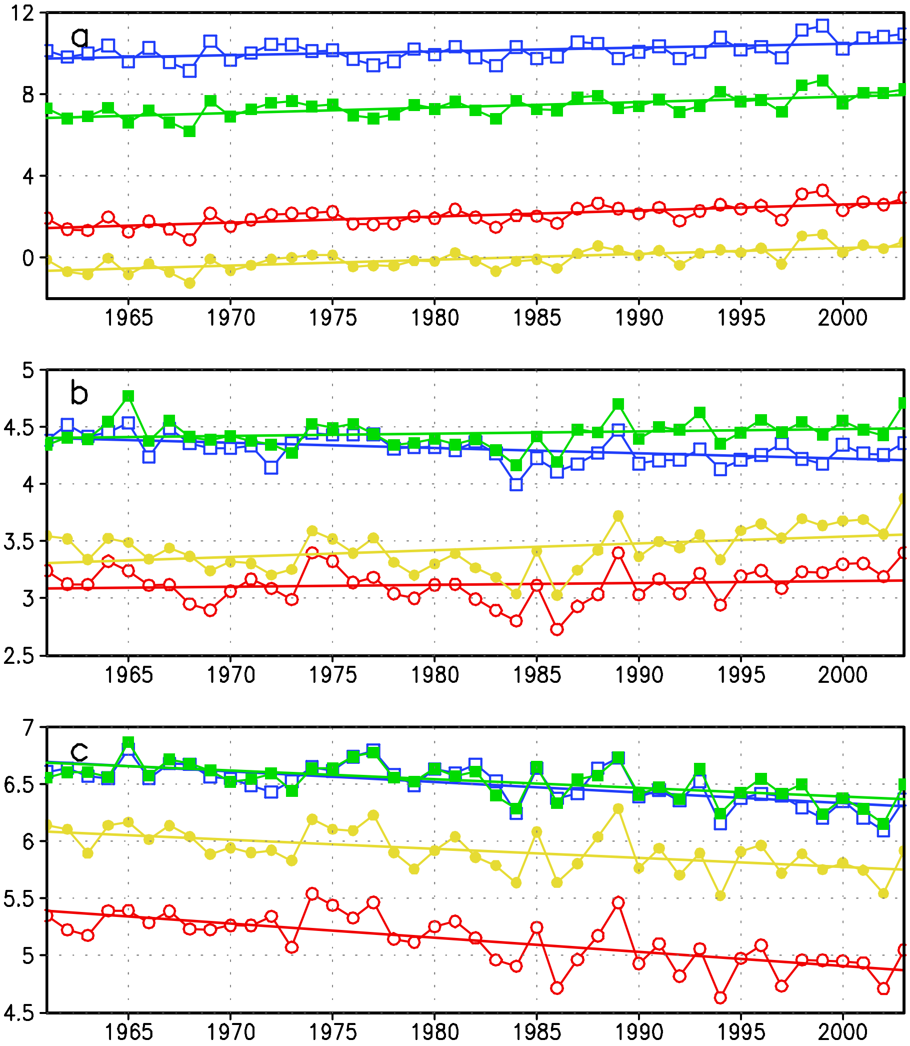

Fig. 6. Annual mean times series of the 71-station averaged (a) surface air temperature, (b) low-level cloud amount, and (c) total cloud amount in the period 1961–2003. Temperature is in units of °C. Cloud amount varies from 0 to 10 tenths of sky cover. Red, yellow, blue, and green curves denote 0000 LST, 0600 LST, 1200 LST, and 1800 LST, respectively. Heavy lines denote linear trend (cf., Duan et al., 2006).

ing (Fig. 6). Because the increase in nocturnal low-level cloud is more than the decrease of daytime low and total cloud amount, such changes of cloud amount also contribute to the increased surface air temperature and its diminished DTR on TP (Duan and Wu, 2006). However, for the data quality, the exact magnitude of the trend in these variables needs a further investigation.

5.2 *Trend in climate extremes*

You et al. (2008a, b) analyzed the changes in indices of climate extremes on the basis of daily maximum and minimum surface air temperature and precipitation in the eastern and central TP during 1961–2005. Twelve indices of extreme temperature and nine indices of extreme precipitation are examined. Temperature extremes show patterns consistent with warming during the studied period, with a large proportion of stations showing statistically significant trends for all temperature indices. Stations in the northwestern, southwestern, and southeastern TP have larger trend magnitudes. The regional occurrence of extreme cold days and nights has decreased by −0.85 and −2.38 days per decade, respectively. Over the same period, the occurrence of extreme warm days and nights has increased by 1.26 and 2.54 days per decade, respectively. The extreme temperature indices also show statistically significant increasing trends, with larger values for the index describing variations in the lowest minimum temperature. Most precipitation indices exhibit increasing trends in the southern and northern TP and decreasing trends in the central TP. On average, regional annual total precipitation, heavy precipitation days, maximum 1-day precipitation, average wet days (precipitation), and total precipitation on extreme wet days show insignificant increases. Decreasing trends are found for maximum 5-day precipitation, consecutive wet days, and consecutive dry days, but only the last trend is statistically significant.

5.3 *Trend in atmospheric heat source*

The climate warming over the TP should be accompanied by a change in the atmospheric heat source, not only its intensity but also its diurnal variation and seasonal evolution. Zhang et al. (2004) found that the snow depth over the TP exhibits a sharp increase during spring (March and April) after the 1970s, which implies excessive precipitation and land surface cooling. Using historical records, Duan and Wu (2008) have demonstrated that both SH and radiative cooling (RC) over the plateau underwent pronounced changes when a striking climate warming occurred there during the last two decades. The linear tendency of 71-station-averaged SH during 1980–2003 is -3.8 W m^{-2} per decade with a relatively decreasing rate of -14%. The largest decreasing trend occurs at local noon and in spring when SH reaches the daily and annual maxima. It in turn leads to the reduction in both the diurnal and annual ranges of SH. Meanwhile, a relatively weaker increasing trend in LH (0.7 W m^{-2} per decade) during 1980–2003 and a stronger decreasing trend in RC (-11.2 W m^{-2} per decade) during 1984–2003 has also been detected. The combination of these changes leads to a weakened atmospheric heating in spring and summer and an enhanced cooling in autumn and winter over the central and eastern TP. The annual-mean atmospheric heat source over the western TP has also been shown to decline (-4.2 W m^{-2} per decade) mainly because of the weakened SH in spring and summer and the enhanced RC in summer and autumn (Table 1). The decreasing trend in SH over the TP is induced mainly by the reduced surface wind speed and is also influenced to a certain degree by the diminished ground–air temperature difference. Furthermore, the reduced surface wind speed occurs when there are changes of temperature, geopotential height, and wind speed in the troposphere as well as in the lower stratosphere.

A subsequent work by Duan and Wu (2009) analyzed the mechanism of such a change, and in particular its relationship with the large-scale circulation shift under the background of the 20th-century global warming, is further investigated in this paper. In addition, a multi-model intercomparison was conducted to verify the diagnosis results. During the period 1979–2003, substantial warming in the mid and high latitudes over eastern Eurasia led to decreased meridional temperature and pressure gradients over the subtropics to the south. As a consequence of the geostrophic balance relationship, the East Asian subtropical westerly jet stream (EASWJ) exhibited a significant decreasing trend throughout most parts of the year. Because the near-surface wind over the TP depends mainly on the mid-tropospheric EASWJ, which straddles the TP in all seasons except summer, the declined wind speed and the suppressed spring heating source over the TP are closely related to the decreasing trend in EASWJ. Meanwhile, the local Ferrel cell over EA shows a coherent weakening trend, with anomalous descending motion by 60°N but anomalous ascending motion around 40°N. The change of the spring local Hadley cell shows an almost opposite signal to its climate mean, represented by a clear weakening trend in its equatorial ascending branch. Nevertheless, only several of the 16 climate models in for the Intergovernmental Panel on Climate Change Fourth Assessment Report (IPCC AR4) can successfully reproduce the observed change in air temperature

Table 1. Trend in the atmospheric heat source/sink E and its components over the central and eastern Tibetan Plateau (CE-TP) and the western Tibetan Plateau (W-TP) in units of W m^{-2} per decade. Analysis period for surface sensible heat (SH) and latent heat (LH) is 1980–2003 and for radiative cooling (RC) is 1984–2004 (cf., Duan and Wu, 2008). MAM (March–April–May); JJA (June–July–August); SON (September–October–November); DJF (December–January–February); E means the total atmospheric heat source.

Region	Component	MAM	JJA	SON	DJF	Annual
CE-TP	SH	−5.4	−3.1	−2.6	−2.3	−3.4
	LH	1.5	0.5	0.4	0.3	0.7
	RC	−8.1	−9.7	−14.4	−12.7	−11.2
	E	−12.0	−12.3	−16.6	−14.7	−13.9
W-TP	SH	−3.0	−6.1	0.2	1.1	−2.0
	LH	−1.4	1.3	−1.6	0.4	0.3
	RC	4.5	−3.6	−7.0	−1.4	−1.8
	E	0.1	−8.4	−8.4	0.1	−4.2

and the EASWJ when driven by historical natural and anthropogenic forcings during the 20th century. Intercomparison of results among these models suggests that sulfate aerosol (indirect effects) and ozone may be important for reproducing the weakening trend in the EASWJ. The performance of these models under the Twentieth Century Climate in Coupled Models (20C3M) scenario seems to have no direct relationship with the model resolution. Instead, whether they are able to reproduce the observed spatial distribution of the large-scale air temperature change is vital to simulate the observed trend in the EASWJ.

To clarify the thermal forcing of the TP, long-term, coarse temporal-resolution data from the China Meteorological Administration has been widely used to estimate surface sensible heat flux by bulk methods in many previous studies; however, these estimates have seldom been evaluated against observations. Yang et al. (2009) evaluated three widely used bulk schemes against TP flux data. The evaluation showed that large uncertainties exist in the heat flux estimated by these schemes; in particular, upward heat fluxes in winter may be significantly underestimated because diurnal variations of atmospheric stability were not taken into account. To improve the estimate, a new method has been developed to disaggregate coarse-resolution meteorological data to hourly according to statistical relationships derived from high-resolution experimental data, and then SH is estimated from the hourly data by a well-validated flux scheme. Evaluations against heat flux observations in summer and against net radiation observations in winter indicate that the new method performs much better than previous schemes, and therefore it provides a robust basis for quantifying the TP surface energy budget.

Serving as a strong forcing source, the weakened SH source over the TP in turn contributes to reduced monsoon precipitation over the southern and eastern slopes of the TP and to increased precipitation over northeast India, Bangladesh, and the Bay of Bengal. However, variations in the EASM and SASM indices, which represent the overall circulation intensity for a large domain, show a clear multiscale variability, rather than a persistent trend, after the 1980s. There is no stable and significant correlation between the spring SH index over the TP and EASM or SASM indices on an interdecadal time scale (Duan et al., 2011).

6. Summary and conclusions

Studies of TP meteorology and climate dynamics, together with new observational facts and experiments during the last 5 years in China have been reviewed.

In recognizing the important roles of the TP in the regional and global energy and water cycles, the Chinese government has recently mobilized resources for two important projects on the TP and its adjacent areas. The CMA and the CAS, joined by several other related government agencies, have developed two comprehensive observational systems over the TP. The first project aims to establish an operational observing network, i.e., NIOST. TORP is another project funded by several central and local Chinese government agencies that focuses predominantly on research on the TP land surface, land–atmosphere interactions, and environmental processes. TORP will provide a set of surface and near-surface hydrometeorological observations. In addition to the basic surface meteorological variables mentioned above for NIOST, soil moisture and temperature, the surface energy budget, and PBL turbulence are also measured. Although both observation networks focus on the TP, NIOST's coverage is also extended to several neighboring provinces of China to capture downstream water-vapor transport.

The mesoscale feature in topography plays an important role in generating and enhancing mesoscale disturbances over the TP. These disturbances enhance the surface SH flux over the TP and propagate eastward to enhance convection and precipitation in the YRV in China. Interactions of summer TP CSs with the orientation of the unique TP geography and the surrounding atmospheric circulations are important for the development, intensification, propagation, and life span of these CSs. Furthermore, most of the mobile MCSs in summer come from southeast of the TP; their generation time have evident diurnal cycle characteristics; and they could move or propagate to most of China's eastern middle and South Asia regions.

Under the unique influence of the underlying surface conditions on the TP, the local heating exhibits the interannual and interdecadal variability. Moreover, the TP heating anomaly stimulates the extratropical large-scale teleconnection over the Northern Hemisphere (such as APO) by affecting the Northern Hemispheric extratropical zonal circulation, further affecting rainfall over North America and Europe. Along the TP–southern Indian Ocean meridional circulation, the anomaly produced by the TP heating may cross the equator and affect the atmospheric circulation over the Southern Hemisphere. Thus, meridional circulation is likely an important passage of the interactions between the Southern and Northern Hemispheres.

Estimating the trend in the atmospheric heat source over the TP indicates that in contrast to the strong surface and troposphere warming, the SH over the TP exhibits a significant decreasing trend since the mid-1980s. The subdued surface wind speed contributes most to the decreasing trend. Meanwhile, the radiative cooling effect in the air column enhances persistently. Despite the *in situ* latent heating presents a weak increasing trend, the springtime atmospheric heat source over the TP loses its strength. The steady declining trend in the surface wind speed over the TP after the 1970s arises mainly from the zonal component. Overall, the substantial tropospheric warming in the mid- and high-latitudes to the north of the TP resulted in a decrease of the meridional pressure gradient in the subtropics and the resultant decelerated surface winds over the TP. The weakened SH source over the TP in turn contributes to reduced monsoon precipitation over the southern and eastern slopes of the plateau, and to increased precipitation over northeast India, Bangladesh, and the Bay of Bengal.

An entirely comprehensive review of research concerning the weather and climate effects of the TP is not possible within the limited length of this article. Despite great progress, many questions are still unresolved. For example, how does the TP air pump, in conjunction with the thermal state over the Indian Ocean and Australia, affect the Asia–Australia monsoon? In addition, owing to its broad coverage and complicated topography, the precision, content and coverage of satellite data and *in situ* observations still do not satisfy the requirements of current studies. Large errors still exist in surface momentum flux, energy budget, cloud, and precipitation in the reanalysis data. The reliability of numerical simulations is still limited by uncertainties in models of cloud-radiation feedback, schemes of convection, and land processes. Therefore, the priority in the next few years must be given to those research efforts that involve numerical modeling efforts.

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