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Recent Progress in the Impact of the Tibetan Plateau on Climate in China

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ABSTRACT

Studies of the impacts of the Tibetan Plateau (TP) on climate in China in the last four years are reviewed. It is reported that temperature and precipitation over the TP have increased during recent decades. From satellite data analysis, it is demonstrated that most of the precipitation over the TP is from deep convection clouds. Moreover, the huge TP mechanical forcing and extraordinary elevated thermal forcing impose remarkable impacts upon local circulation and global climate. In winter and spring, stream flow is deflected by a large obstacle and appears as an asymmetric dipole, making East Asia much colder than mid Asia in winter and forming persistent rainfall in late winter and early spring over South China. In late spring, TP heating contributes to the establishment and intensification of the South Asian high and the abrupt seasonal transition of the surrounding circulations. In summer, TP heating in conjunction with the TP air pump cause the deviating stream field to resemble a cyclonic spiral, converging towards and rising over the TP. Therefore, the prominent Asian monsoon climate over East Asia and the dry climate over mid Asia in summer are forced by both TP local forcing and Eurasian continental forcing.

Due to the longer memory of snow and soil moisture, the TP thermal status both in summer and in late winter and spring can influence the variation of Eastern Asian summer rainfall. A combined index using both snow cover over the TP and the ENSO index in winter shows a better seasonal forecast.

On the other hand, strong sensible heating over the Tibetan Plateau in spring contributes significantly to anchor the earliest Asian monsoon being over the eastern Bay of Bengal (BOB) and the western Indochina peninsula. Qualitative prediction of the BOB monsoon onset was attempted by using the sign of meridional temperature gradient in March in the upper troposphere, or at 400 hPa over the TP. It is also demonstrated by a numerical experiment and theoretical study that the heating over the TP leads to a significant variability in the atmospheric circulation on a quasi-biweekly timescale, bearing much similarity to that found from observational studies. Finally, some important issues for further work in understanding the impacts of the TP are raised.

Key words: Tibetan Plateau, TP-dipole, cyclonic spiral, quasi-biweekly oscillation

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1. Introduction

The Tibetan Plateau (Qinghai-Xizang Plateau, abbreviated as TP hereafter) is not only a terrain obstacle to air flow, but also a strong heat source or sink, which intensifies the land-sea thermal contrast there. Therefore, the TP functions as an important modulator of regional climate over central and southern Asia; particularly, the South Asian monsoon climate to the south, the East Asian monsoon to the east, the unique China-Mongolia mid-latitude drought climate to the north, the central Asian desert and dry climates to the

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*Corresponding author: LIU Yimin, lym@lasg.iap.ac.cn west, and the unique plateau monsoon climate over the TP.

Before the 1950s, most studies concerned the influence of large-scale topography upon atmospheric circulation and climate, focusing on the mechanical aspects. Queney (1948) summarized studies on airflow over mountains and brought forward three critical scales to distinguish different mountain waves by using linearized equations. Yeh et al. (1957) and Flohn (1957) found that the TP is a heat source for the atmosphere in summer. Since then, the temporal and spatial distributions of the heating field over the TP and their impacts upon weather and climate have become an important research field in meteorology (Yeh et al., 1958; Yeh and Gao, 1979; Zhang et al., 1988; Wu et al., 1997, 2004). Recently, Yanai and Wu (2006) produced a thorough review of past studies concerned with the effects of the TP. The review summarized, from the 1950s on, research on the jet stream, the warm South Asian high, and early progress of TP research in China. The review also discussed the mechanical effects of the TP on large-scale motion, the winter cold surge, and the summer negative vorticity source over the TP, as well as the heating source Q_1 and Q_2 used by Yanai et al. (1973).

Field experiments over the TP have been a focus for TP studies for a long time in China. The Qinghai-Xizang Meteorology Experiment (QXPMEX) in 1979 and the second Tibetan Plateau Atmosphere Science Experiment (TIPEX) in 1998 were conducted in China. These were intensive in situ meteorological observations and land surface physical process observations over the Plateau (Zhang et al., 1988; Tao et al., 2000a,b,c; Zhou et al., 2000). During the last four years, such field experiments have continued and become part of an international coordination. These include: the Global Energy and Water Cycle Experiment (GEWEX); the Asian Monsoon Experiment on the Tibetan Plateau (GAME/Tibet); and the Coordinated Enhanced Observing Period (CEOP) Asia-Australia Monsoon Project (CAMP) on the Tibetan Plateau (CAMP/Tibet). Prominent progress has been subsequently achieved (Ma et al., 2006a).

This paper reviews recent advances (last four years) in TP research in China. Section 2 covers new observational facts about the TP. Sections 3 and 4 describe the impacts of TP forcing on the synchronous and time-lag climate, respectively. Research on heating over the TP and the Asian monsoon onset is presented in section 5. Section 6 is devoted to the relationship between heating over the TP and low-frequency oscillation of circulation. Finally, in section 7, some important issues for further research on understanding TP climate dynamics are raised.

2. Recent observations

2.1 *Precipitation, surface air temperature and their variation*

Based on the three-year Tropical Rainfall Measuring Mission (TRMM) precipitation radar data, Fu (2005) and Fu et al. (2006) revealed that a tower mast shape in the deep precipitation layer with a rain rate of more than 2 mm h^{-1} can be seen over the TP in summer (Fig. 1), with a very strong diurnal cycle. These authors' work also indicated that the TRMM algorithm might have misclassified weak convection as stratiform rain. The fact that the latent heat tower was well-lifted and well-penetrated into the middle troposphere confirms the earlier finding that convection heating is a dominant form of heating in summer over the TP (Yeh and Gao, 1979).

Utilizing the monthly mean data of the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR), Cai and Qian (2004) calculated the air column precipitable water (PW) and showed that in winter the minimum PW is over the TP, at only 3 mm—even lower than over North China and the eastern part of Northwest China. In summer, there is a maximum PW of 60 mm or more over the South and East Asian monsoon regions, while the PW over the TP is around 10 mm. However, the mean precipitation conversion rate of PW to real rainfall over the TP is double that over southern and eastern China, and is much greater than that in northern and northwestern China.

There is significant interannual and decadal variability in TP rainfall. Cai et al. (2003), Wei et al. (2003), Ma and Hu (2005), and Wu et al. (2005c) showed that the main trends of climate change are a rise in temperature and an increase in precipitation. Precipitation in most parts of the TP increases smoothly. The changes are detected in Qinghai and northwestern Sichuan in 1968, 1972 and 1986 separately (Ma and Hu, 2005; Duan et al., 2006). The increasing trends of annual mean temperature, and maximum and minimum temperature, have been confirmed by recent station data (Duan et al., 2006; Li et al., 2006b), as well as satellite data (Xu et al., 2005).

2.2 *Ground temperature and its variation*

Usually, ground temperature (TG) is the 0 cm temperature measured by a mercury thermometer at weather stations. Li et al. (2006a) showed that in the last 30 years the TG trends in the northern and southern TP are different. The TG over the northern and northeastern TP has exhibited a significant increasing, while the TG over the middle and southeast TP has shown a decreasing trend. However, Jiang et al. (2006)

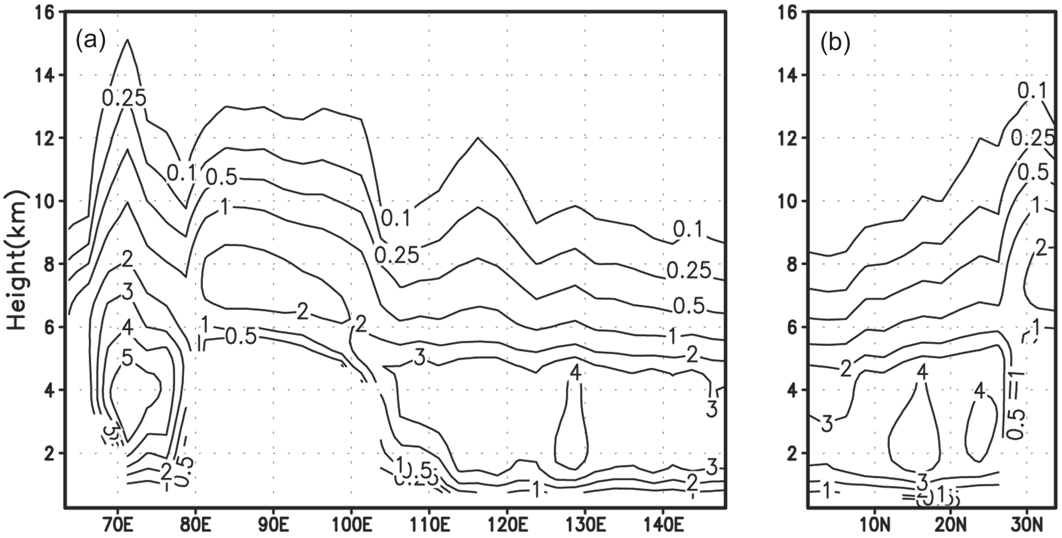

Fig. 1. Mean precipitation rate over the Tibetan Plateau, calculated from the TRMM received radar-reflectivity profiles by averaging rain-only bins at each level of the profiles. The averaging period covers June, July and August of three years from 1998–2000 (units: mm h^{-1}). (a) Height-longitude cross section averaged between 30°N and 35°N and (b) height-latitude cross section averaged between 85°E and 90°E. (from Fu et al., 2006).

indicated that the difference between the TG on the bare surface measured by a mercury thermometer and calculated by the radiation balance can be more than 4°C during daytime in summer, and around −2°C during the night. On densely vegetated surfaces, the highest difference during daytime can be over 16°C, and the negative difference at night can reach around −3°C. In this regard, the conclusion of Li et al. (2006a) should be considered qualitative and further verification is needed.

2.3 *Land-surface processes and the boundary layer*

The climatological average of the surface sensible heat flux (SH) over the Plateau from recent data does not show much in the way of new results over and above what has already been reported in previous studies. The SH appears as a weak negative value within a small range during winter, while it is positive during the rest of the seasons (Li et al., 2003a). In detail, the western part of the TP is a heating source in all seasons (Li et al., 2003c; Yu et al., 2004). The long-term variation in SH shows a decreasing trend in the northern and western parts of the Plateau and an increasing trend in the middle and eastern parts in winter. In summer, the SH in the main part of the TP and its eastern area increases year by year, but has an opposite trend in the western part (Li et al., 2003b).

Most of these studies are based on station data. A study by Wei and Li (2003) indicated that, using NCEP/NCAR reanalysis data, long-term variations in air temperature and radiation flux over the TP agree with observations, although the reanalyzed temperature was systematically lower than observed data due to the higher altitude of the Plateau in the reanalysis model. In the last four years, studies of diurnal to annual variation based on data from TIPEX and CEOP have been conducted and a parameterization method has been proposed to calculate the SH and determine the SH regional distribution over the TP (Gao et al., 2003b; Ma et al., 2003, 2006a,b).

A higher elevation of the atmospheric boundary layer (ABL) over the TP has been indicated from field observations. In 1998, it was as high as 3550 m above ground at Amdo in the central TP during the dry season, but 2300 m during the wet season (Zuo et al., 2005). In the Mt Qomolangma region of the Himalayan ranges, the ABL altitude reached as much as 4000 m during the dry season of 2005 (Li et al., 2006c). Moisture inversion phenomena were found over the TP during the TIPEX period (Liu et al., 2002a; Peng et al., 2005b), presenting a unique characteristic of the boundary layer over the TP (Bian et al., 2003).

3. TP forcing and the synchronous circulation and climate

Work regarding the temporal and spatial distributions of heating over the TP and their impacts on weather and climate has seen some advancements and achievements during the last four years.

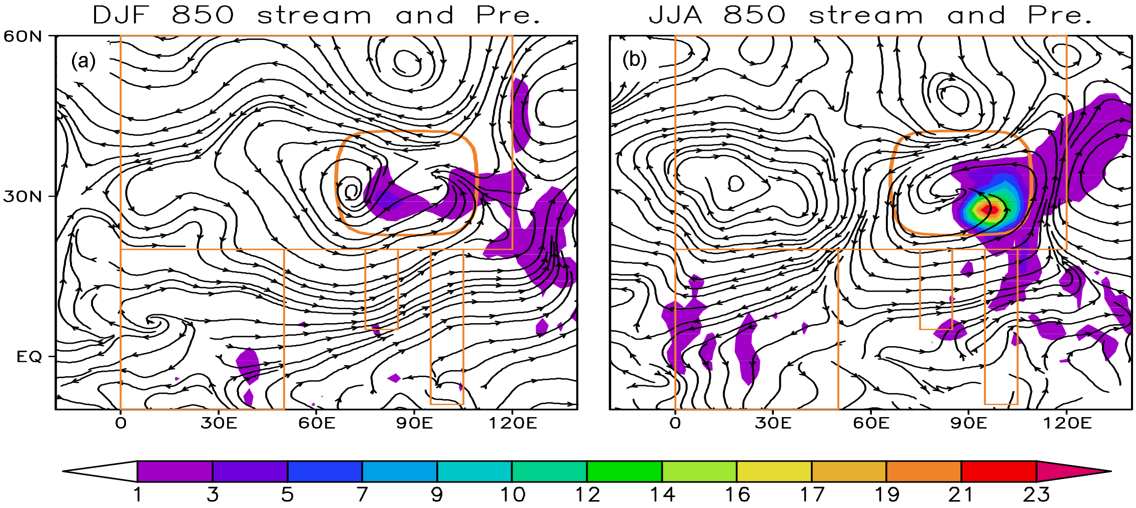

Fig. 2. The 850-hPa stream field difference between experiments with and without ellipsoidal orography, centred at (33°N, 90°E) with a maximum elevation of 5 km and a domain of 50° (lon)×30° (lat), mimicking the TP as marked by the heavy ellipse at the elevation of 100 m. The experiments use an idealised landmark to present the Africa-Eurasian continent, which is embedded on the aqua surface of the GOALS-SAMIL model. Both experiments were integrated for 10 years and the results from the last eight years are extracted for the calculation. (a) December–February; (b) June–August.

3.1 *TP forcing in winter and persistent rainfall in early spring in South China*

In winter, as a large obstacle, the TP together with the mountains to the north of it retard the westerly jet flow, deflecting it into northern and southern branches. The deviation stream flow then appears as an asymmetric dipole (TP-dipole), with the convergent entrance on its eastern flank and the divergent outgoing on its western flank (Wu et al., 2005a). Figure 2 shows the 850-hPa stream field differences between experiments with and without an idealized elliptical mountain, based on a spectral atmospheric GCM (GOALS-SAMIL) which has nine vertical layers and is truncated at wave-number 42 (Wang et al., 2004). Even in such a highly simplified experiment, the asymmetric dipole in December-January-February (DJF) is dominant. The huge anticyclonic deflected flow in the north has an important impact upon atmospheric temperature distributions due to its horizontal advection, making East Asia much colder than middle Asia at the same latitudes north of 35°N (Jian, 2003). Its cyclonic deflected flow in the south has an important impact upon the dry climate in South Asia and the moist climate in Southeast Asia and South China. In late winter and early spring over South China, the southward moving cold and dry air that flows along the northern anticyclonic circulation of the TP-dipole meets with the northward-moving warm and moist air that flows along the southern cyclonic circulation of the TP-dipole. Persistent rainfall in early spring therefore occurs over South China until the onset of the Asian monsoon (Wan and Wu, 2007) (Fig. 3). 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 (Wu et al., 2007).

3.2 *TP forcing in summer and the Asian climate pattern*

In summer, TP heating produces a large-scale cyclonic circulation in the lower troposphere. Such a forcing, in conjunction with the TP air pump (Wu et al., 1997), causes the deviation stream field to resemble a cyclonic spiral (Fig. 2b), converging towards and rising over the TP (Wu et al., 2007). Duan and Wu (2005) and Wu et al. (2005b) found that, since the TP acts as a strong heat source in summer with the strongest heating lying in the lower layers (Fig. 4), the thermal adaptation results in a shallow and weak cyclonic circulation near the surface and a deep and strong anticyclonic circulation above it (Fig. 5). As a consequence, large amounts of moisture flux are transported from the tropics to the eastern flank of the TP and to its east, resulting in plentiful rainfall. On the contrary, dry climate is forced to the west of the TP (Fig. 2b).

Moreover, with longwave radiation cooling (LO), sensible heating (SE), condensation heating (CO), and double heating (D) (LOSECOD) as the local dominant heating types appearing from west to east across each

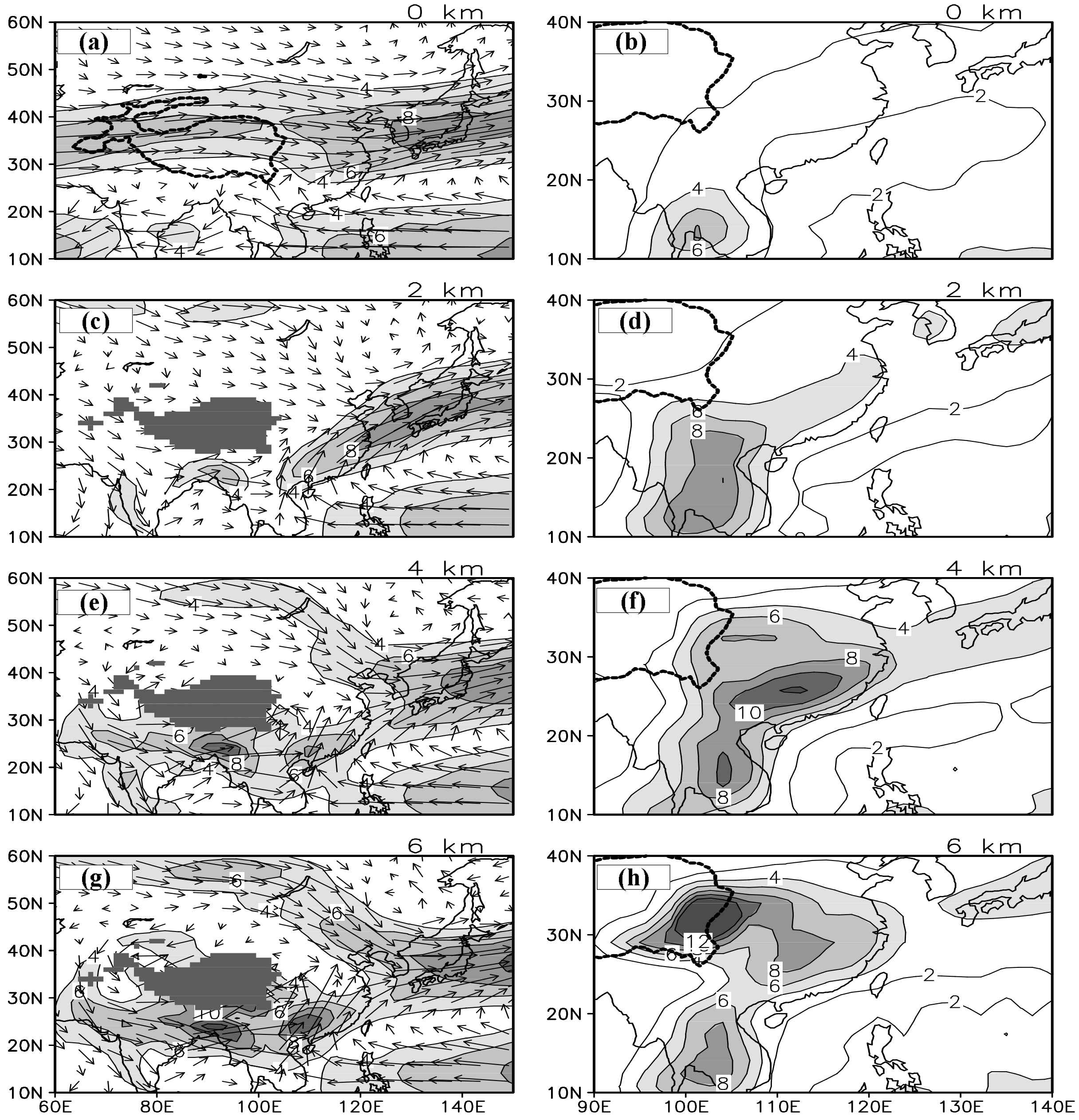

Fig. 3. Distributions of wind vector and isotach at 850 hPa (left panels: units: m s^{-1}; shading indicates in excess of 4 m s^{-1}), and rain (right panels: units: mm d^{-1}) in the perpetual spring sensitivity experiments with different TP elevations and averaged over 30 months using GOALS-SAMIL. Black shading in the left panels and the bold solid curve in the right panels are the main part of the TP. The TP maximum elevation is 0 km in (a) and (b), 2 km in (c) and (d), 4 km in (e) and (f), and 6 km in (g) and (h). (from Wan and Wu, 2007)

continent and its neighboring oceans, the continental-scale diabatic heating along the summer subtropics presents such quadruplet LOSECOD pattern (Wu and Liu, 2003; Liu et al., 2004). This LOSECOD quadruplet heating generates lower-layer cyclonic circulation and upper-layer anticyclone circulation over land areas (Cai and Qian, 2004). Therefore, the circulation pattern forced by the continental-scale heating over Eurasia is in phase with the circulation patterns forced by the thermal forcing of the TP and the Iran Plateau. Dry and hot climates in West and middle Asia, but strong monsoon and wet climates in East Asia are thus formed (Duan and Wu, 2005; Liang et al., 2005a, 2006).

Besides thermal forcing, it has been revealed that orographic forcing can also contribute significantly to

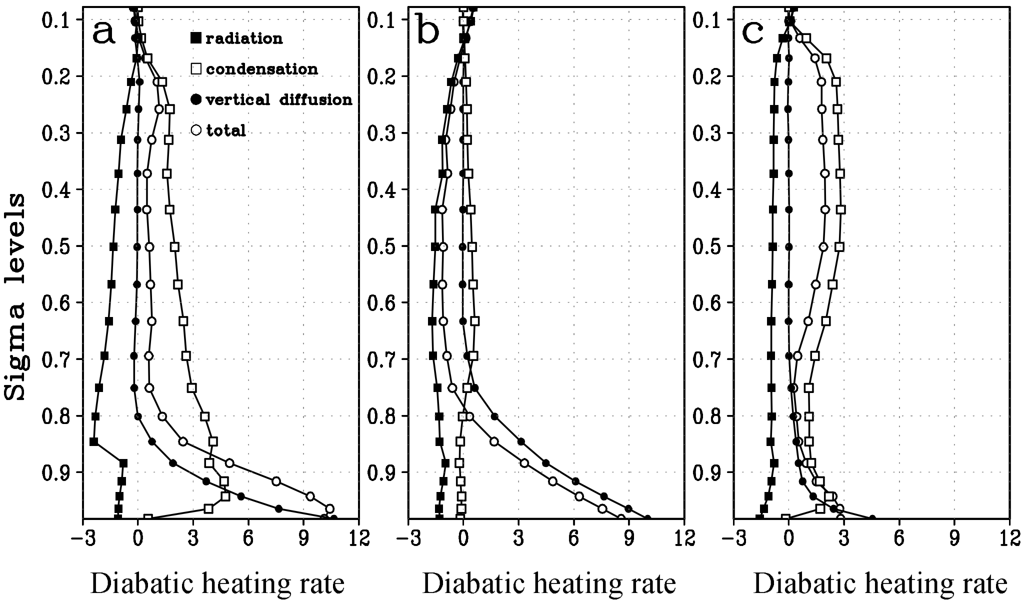

Fig. 4. July mean area-averaged profile of the total and individual diabatic heating rate over (a) TP region; (b) middle Asia region; and (c) East China region from NCEP/NCAR for 1980–1999. Units: K d^{-1}. (from Duan and Wu, 2005).

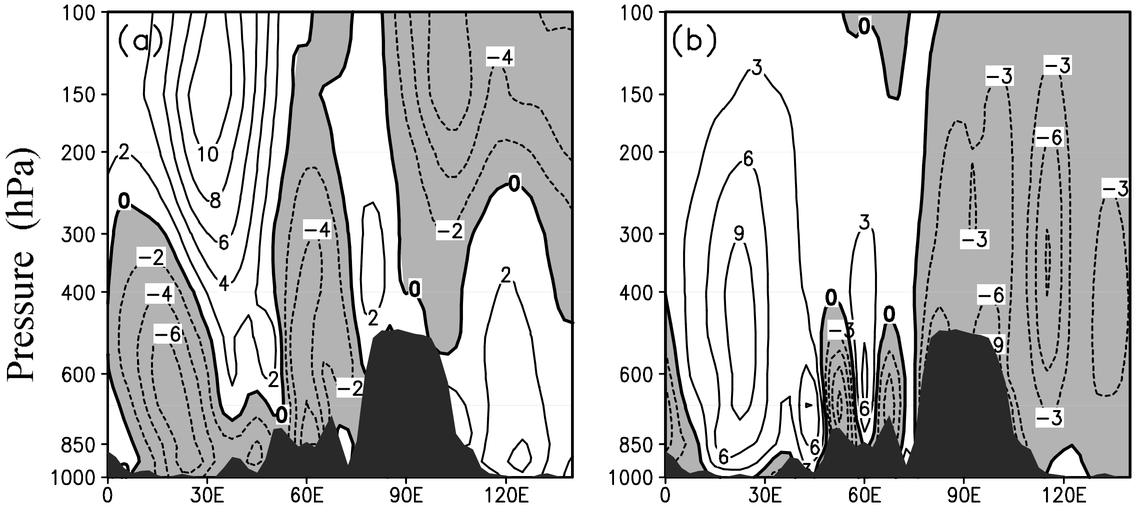

Fig. 5. Longitude-pressure cross sections along 32.5°N of the July mean meridional wind [(a), units: m s^{-1}] and vertical velocity in p-coordinates [(b), units: 10^{-1} Pa s^{-1}] from NCEP/NCAR for 1981–1999. (from Duan and Wu, 2005).

the configuration of the summer circulation. Previous studies have shown that in winter, when westerlies dominate in the mid latitudes and subtropical upper troposphere, orographic forcing plays a very important role. In summer, the zonal flow across the TP is weak and the zonal mean zero-westerly wind isoline at the upper troposphere is over the TP. The importance of its thermal forcing has been stressed (Yeh et al., 1957; Yanai and Wu, 2006). Little attention has been paid to the role of TP orographic forcing in Asian summer monsoon flow. Recently, Liu et al. (2007) investigated the influence on summer circulation over Asia of the orographic and thermal forcing of the TP using a sequence of idealized experiments based on a global primitive equation model. It was shown that there is some similarity between the responses to the separate orographic forcing and thermal forcing. The upper tropospheric Tibetan anticyclone is forced predominantly by the heating, but also weakly by the orography. In the lower troposphere, both forcings produce air desc-

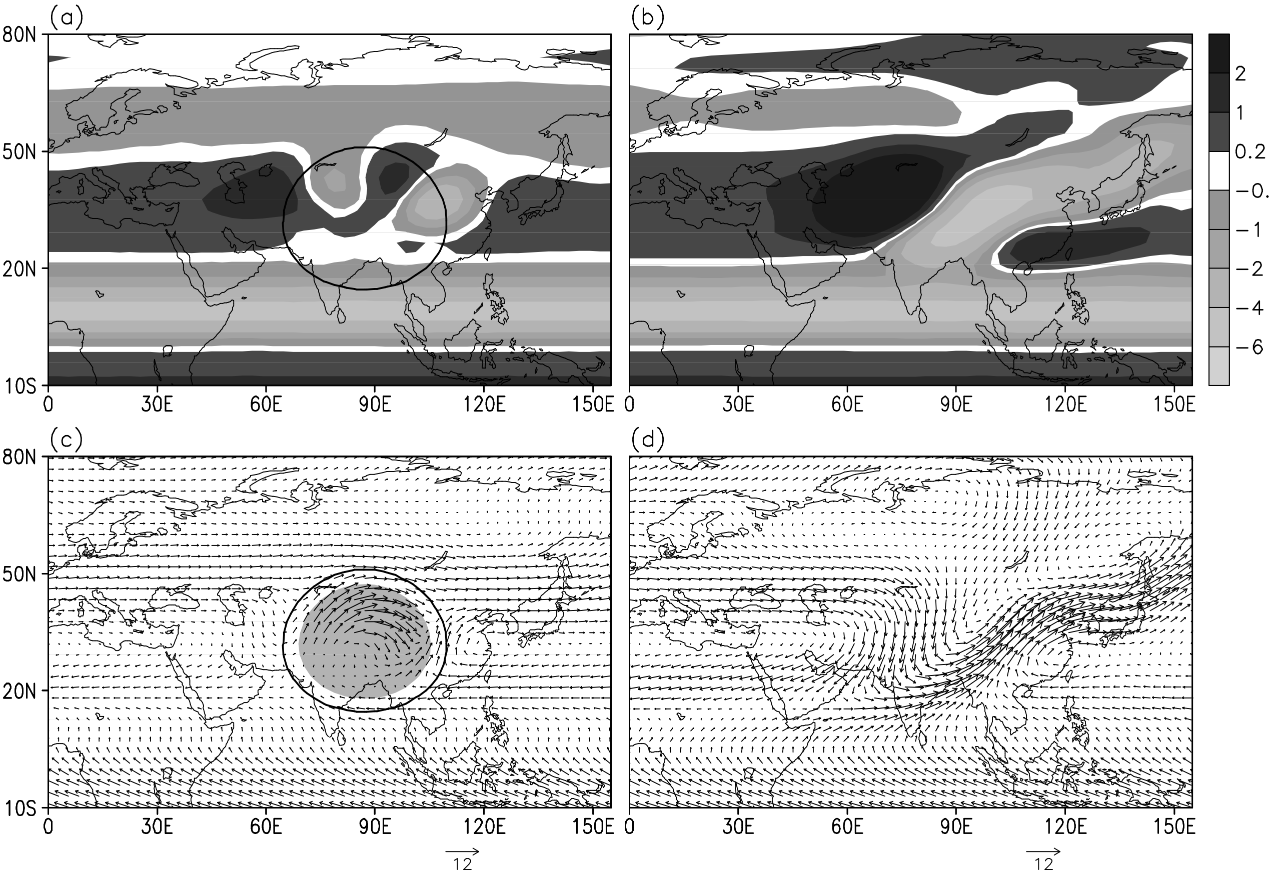

Fig. 6. Comparison of the mean of days 15–70 of the idealized orography experiment (right) and idealized heating experiment (right). (a) and (b) 400 hPa vertical velocity (units: 10^{-2} Pa s^{-1}), and (c) and (d) wind vectors at 850 hPa (units: m s^{-1}) based on a global primitive equation model. The maximum altitude of the idealised orography is 5580 m at (32°N, 87°E) and the height of 500 m is depicted by the bold contour in (a) and (c), and in (c) the region where the 850-hPa surface below ground is shaded. The idealised heating has the same horizontal distribution as the idealised orography. In the vertical it has a profile which is constant from σ=1.0–0.8 and then decreases linearly to zero at σ=0.2 (near 100 hPa over the highest topography). The maximum heating rate, near the surface at the centre, is 5 K d^{-1}. (from Liu et al., 2007)

ending down the isentropic surfaces in an equator ward anticyclonic circulation to the west and rising in a poleward circulation to the east (Fig. 6). These results explain why, in the experiments based on a complex GCM, the Asian monsoon precipitation in summer is greatly enhanced with the existence of the TP, compared to that without the TP (Liang et al., 2005a; Wu et al., 2007).

The China-Mongolia (CM) arid area is also influenced by the TP. Qian et al. (2001) showed that this arid area is associated with the summer mean vertical circulations over the TP and its vicinity. The TP thermally-inducing meridional cells exist not only along 90°E, but also along all of the meridians on the north side of the TP. In severe drought summers over the CM dry area, these meridional cells become intensified, whereas in wetter summers they are not clear.

3.3 *Variation of summertime TP heating and its impact on climate*

Hsu and Liu (2003) showed that the summer (June–July–August, JJA) column diabatic heating over the TP where the elevation is more than 3000 m shows an evident shift in the late 1970s. In the eight strong TP heating summers, the rainfall pattern exhibits a tripole structure over eastern China, ie. with a zonal-elongated positive anomaly in the Yangtze River and Huaihe River reaches, sandwiched by a negative anomaly in northern and southern China, and vice versa in the eight weak TP heating summers. Such a tripole pattern of rainfall distribution resembles the leading empirical orthogonal function (EOF) modes reported in earlier studies (e.g., Tian and Yasunari, 1992; Huang et al., 2003). The study also agrees with the findings that there is a closed link between TP heating and the East Asia summer rainfall (EASMR) (Bai et al., 2003a; Zhao et al., 2003; Jian et al., 2004; Zhang et al., 2006). To further understand the possible impacts of TP surface conditions on the EASMR, a suite of sensitivity experiments was performed with an atmospheric general circulation model (Bao et al., 2007). The land surface albedo was changed so that the TP land surface temperature was changed accordingly. The results showed that warmer surface temperature conditions over the TP tend to enhance the upper tropospheric South Asian high and the westerly jet stream to its north and the Indian monsoon to its south, while the moisture transport in the lower troposphere towards East Asia increases. The precipitation pattern in the case of a warmer TP surface is characterized by increasing rainfall over Northwest India and enhanced mei-yu and decreasing rainfall over the Bay of Bengal and in the regions under the control of the western Pacific subtropical high (Fig. 7). This agrees well with the result from the above data analysis.

The TP covers a broad area and features complicated topography. Thus, a single heating index is not enough to represent the geographic structure of heating over the TP. Based on the 1958–1999 monthly-averaged NCEP/NCAR reanalysis data, rotated EOF (REOF) analysis was applied to obtain the main spatial modes of normalized atmospheric heating sources over the TP in July (Duan and Wu, 2004). The results show that TP heating cannot be properly presented by only a few REOF components. However, since the reliability of the heating in reanalysis datasets is not certain, using new satellite data to validate all the above results and to reveal new facts is necessary.

4. TP thermal status and the time-lag circulation and climate

The TP thermal impact on the EASMR is not just during summer, but also in winter and spring due to the longer memory of the land.

4.1 *Snow accumulation, freeze-thaw processes and circulation and rainfall in summer*

The Impact of the TP winter snow cover on the EASMR has been studied by many Chinese scientists since the late 1970s (Chen and Yan, 1978). Recently, in more detail, Zhang and Tao (2001), and Wu and Qian (2000, 2003) showed that if the snow cover over the TP in winter is above normal, the TP heat source in the subsequent spring and summer is weakened, and so is the land-sea thermal contrast between the TP and the Pacific. As a result, the East Asian summer monsoon is weakened and more precipitation occurs in the Yangtze River valley and less poor rain is observed in northern South China; and vice versa in the lighter TP snow years. Similar results were also obtained by Huang and Li (2003) and Lu et al. (2003).

However, the relationship between the EASMR pattern and snow accumulation over the TP is not simple. First, snow is not unique and not the most important factor in determining the regional rainfall (Qian et al., 2003). Second, it has been found that the snow depth anomaly in winter over the Tibetan Plateau is relatively more important to regional precipitation in China than snow cover in winter and snow depth in spring. Liu et al. (2003) indicated that the relationship between TP snow cover and summer rainfall over China can be detected more appropriately under the background of the interdecadal variation of Asian monsoon circulation. Chen (2005) and Peng et al. (2005a) showed that in some areas of China the relationships between winter snow cover (and tropic Pacific SST) and summer rainfall is stronger at interdecadal scales than interannual scales. Furthermore, more or less winter-spring snow in the TP has been found to be well related to a stronger or weaker polar vortex over Europe and Asia and the subtropical anticyclone in winter (Wei et al., 2005).

Freezing and thawing processes in the TP are another aspect which may influence East Asian circulation. Wang et al. (2003a) showed that, in July, when the depth of frozen soil on the TP is lower, the South Asian high is stronger and shifts westward in location, and the 500-hPa subtropical high over the western Pacific is weaker and moves eastward. There are three belts where the correlation is significant between the mean frozen soil depth in the TP and precipitation in China in July. Therefore, the changes of moisture and heat associated with freeze-thaw processes in the TP could act as an external thermal forcing and influence East Asian climate. On the other hand, Gao et al. (2003a) and Nan et al. (2005) showed that the permafrost distribution over the TP is very sensitive to climate change.

4.2 *TP thermal status in spring and climate anomalies in summer*

A simultaneous relationship between atmospheric circulation or rainfall over East Asia and the heating over the TP in summertime cannot be used for prediction. Zhao and Chen (2001) showed that the heating status over the TP in April can give a clue to predict the forthcoming weather over regions between the Yangtze River and the Huaihe River, as well as South China and North China. The number of days cov-

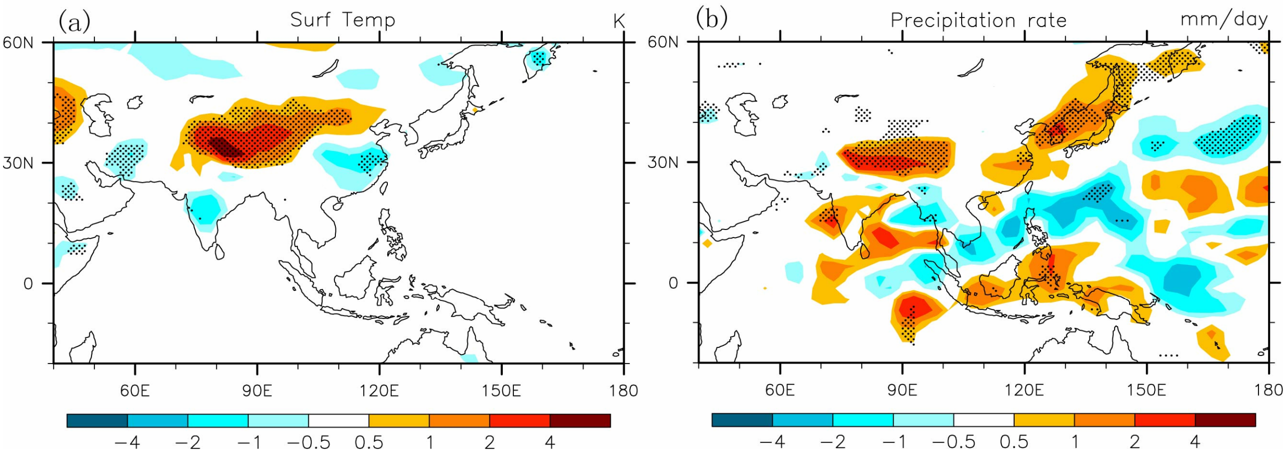

Fig. 7. Ensemble mean differences between sensitivity tests of the land surface albedo over the TP region being reduced 50% and increased with 150% using the ECHAM4 T42L19 model in boreal summer. (a) Surface temperature (K); (b) precipitation rate (mm d^{-1}). The stippling is the significant regions at the 0.05 level based on the student's *t*-test.

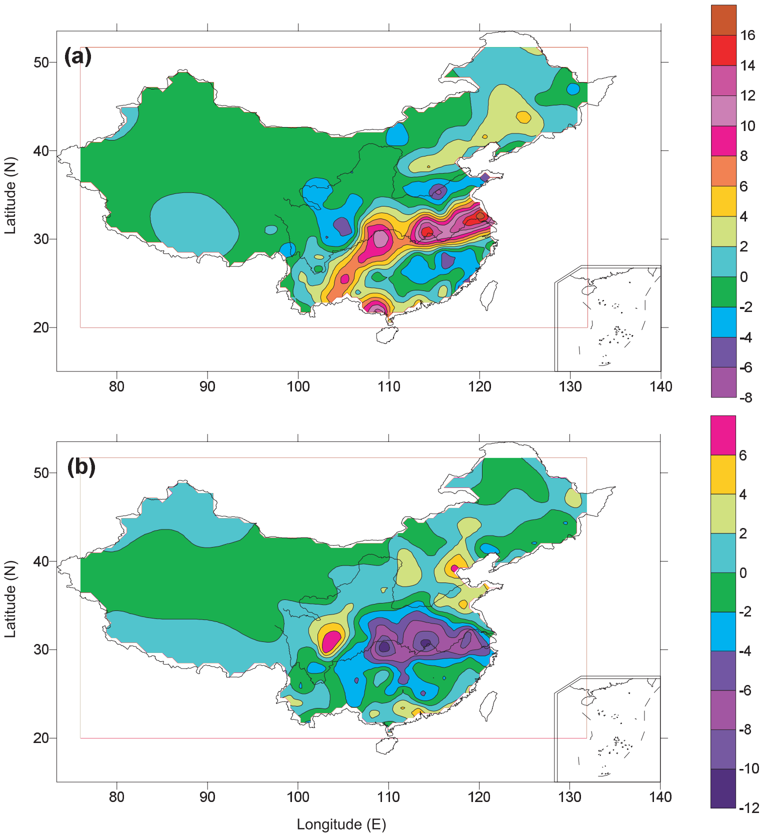

Fig. 8. Composite rainfall anomaly in July with (a) strong and (b) weak May sensible heating in the TP from NCEP/NCAR for 1981–1999. Units: mm d^{-1}. (from Duan et al., 2005).

ered by snow and snowfall over the TP have also been shown to have a good relationship with hemispheric extratropical atmospheric circulation and East Asian summer monsoon rainfall (Zhao et al., 2007). An increase in the number of spring (April–May) days covered by snow over the TP is associated with decreases in tropospheric temperature and geopotential height in the spring and early summer (June). These tropospheric anomalies over the TP are connected with changes in the hemispheric extratropical atmospheric circulation along the westerly jet stream that acts as a waveguide. Soil moisture in May–June might act as a bridge linking the spring snow anomaly and the subsequent summer monsoon.

The station data used in the above studies are mostly located in the eastern part of China. To further reveal the influence of the heating status over the TP before the East Asian summer monsoon onset upon the atmospheric circulation and rainfall in the forthcoming monsoon season, Duan et al. (2005) discussed sensible heat sources over the TP region from April, May and June and their influence upon the circulation and rainfall patterns in the subsequent July based on the NCEP/NCAR reanalysis after verifying their quality. The temporal variation of the April, May and June sensible heat source averaged over the TP is representative of the total diabatic heating, and their leading patterns during this period are almost the same. It was found that when the sensible heat source over the TP is abnormally strong (weak), there will be more (less) rainfall in July over the Yunnan-Guizhou Plateau and the middle reaches of the Yangtze River and Huaihe River (Fig. 8). Correspondingly, there is lower-layer convergence (divergence) of water vapor flux in these regions. All these were well explained in terms of the thermal adaptation theory, the large-scale quasi-stationary barotropic vorticity equation and the good persistence of the thermal status over the TP. These results are consistent with those presented in section 3.3, and also agree with other results derived from either data diagnoses or modeling (Li, 2003; Li et al., 2003a; Bai et al., 2003b; Bi et al., 2004; Ning and Qian, 2006). Therefore, the heating status over the TP during April, May and June can be used as a useful predictor for the early summer rainfall and atmospheric circulation over East Asia, especially over the valley between the Yangtze and Huaihe Rivers.

4.3 *TP thermal status and sand storm days in northern China*

Li et al. (2004) found that abnormal surface sensible heating (SH) on the TP in spring is significantly related to the number of sand storm days in the Northern China. The results indicated that, although individual sand storms may belong to different mesoscale weather processes, sand storms in different years have a good coherence in terms of spatial distribution. There are five natural sand sources: the Gansu Hexi-Corridor, the southern rim of the south Xinjiang basin, the Alashan Plateau, the Eerduosi Plateau, and the Hunshandake Sandlot. The trend of sand storm occurrence has been decreasing since 1964. The number of sand storm days in the 1990s was the least of the past five decades, but has shown a hoist from the end of the 20th Century to the beginning of the 21st Century. Moreover, the annual occurrence of sand storms in northern China is well related to TP surface heating. Zhong et al. (2004) decomposed the SH on the TP in winter and spring and showed that when the first EOF mode is positive in spring, the number of sand storm days in northern China is significantly above normal.

5. Heating over the TP and the onset of the Asian monsoon

In a review of the TP climate dynamics, Wu (2004) indicated that strong SH over the TP in spring contributes significantly to the abrupt seasonal transition of the East Asian circulation, resulting in the earliest Asian monsoon onset anchored over the eastern Bay of Bengal to the western Indochina Peninsula. Wu et al. (2004) showed that, due to surface cooling in winter and heating in summer, the air column over the TP descends strongly in winter and ascends strongly in summer. It acts as a huge air pump and regulates the seasonal evolution of lower-layer circulation over the surrounding areas, contributing to the occurrence of the monsoons over South Asia, the Bay of Bengal, the South China Sea, and the western Pacific (Mao et al., 2002a,b). However, without surface sensible heating, especially on sloping surfaces, such an air pump will not expel or suck the surface air flow (Wu et al., 2007).

Wu and Zhang (1998) showed that it is due to mechanical as well as thermal forcing of the TP that the onset of the Asian monsoon is composed of three consequential stages: the earliest over the eastern Bay of Bengal to the western Indochina Peninsula in early May. The Bay of Bengal monsoon onset creates favorable conditions for the Southern China Sea monsoon onset in mid May (Liu et al., 2002b). This leads to great changes in both large-scale circulation and diabatic heating over Asia. Finally, the onset of the Indian monsoon appears in early June. A numerical simulation by Liang et al. (2005b) proved that TP heating in late spring greatly intensifies the southern branch of the wintertime dipole of the 850-hPa stream field. This intensified southern branch of the dipole enhan-

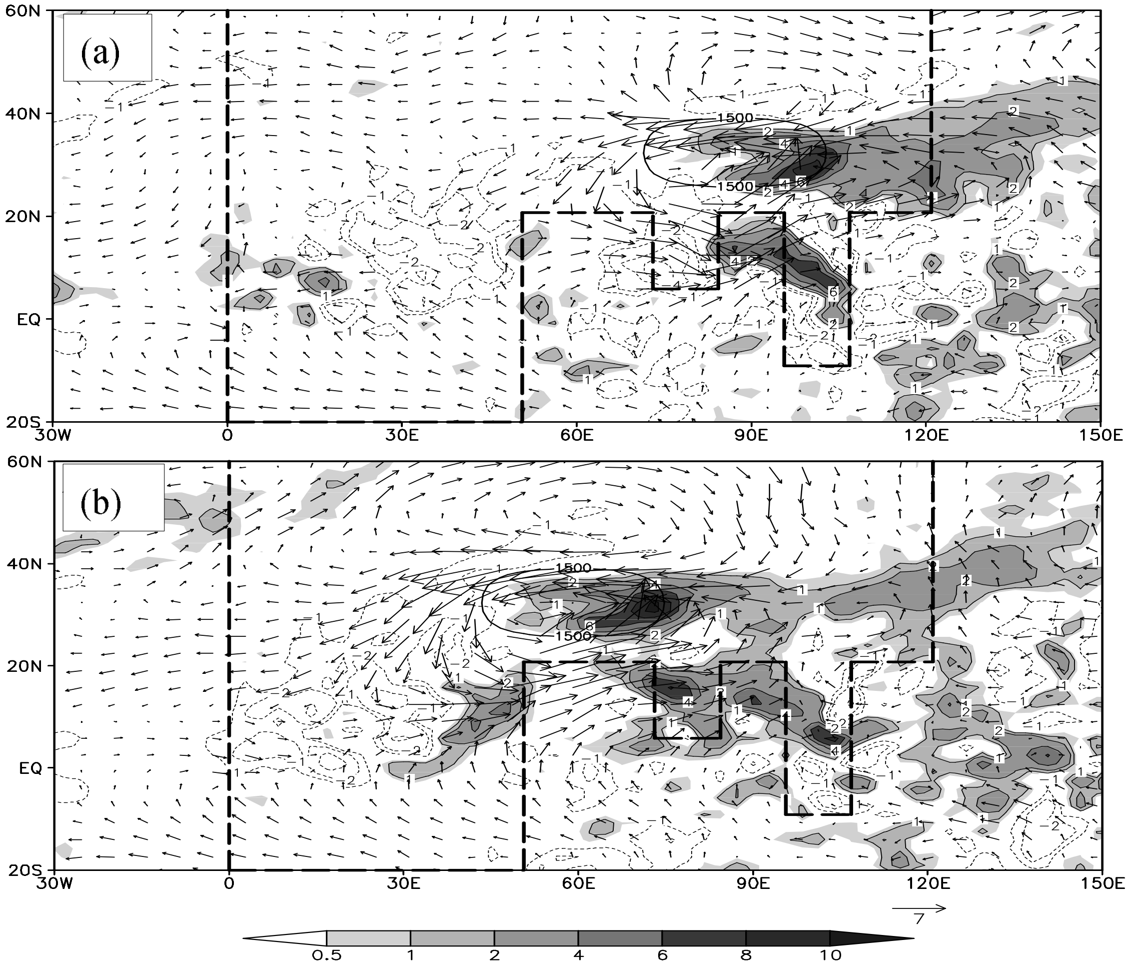

Fig. 9. Differences in precipitation (mm d^{-1}) (shading) and wind vector (m s^{-1}) at 850 hPa with and without TP experiments during the Asian summer monsoon onset time. (a) "TP" is centred at (33°N, 90°E), and (b) "TP" is centred at (33°N, 60°E) by using the GOALS-SAMIL model. (from Liang et al., 2005b).

ces the southerlies to the southeast of Tibet and brings heavy rainfall and more latent heating over the eastern Bay of Bengal and to its east, as well as prevailing northerlies to the southwest of Tibet, resulting in less rainfall and more sensible heating over the Indian subcontinent. Therefore, the TP anchors the onset site of the Asian summer monsoon, which often takes place over the eastern coastline of the Bay of Bengal, to the south of the TP (Fig. 9). It is also found that stronger surface sensible heating on the TP in spring leads to an earlier seasonal transition in eastern Asia (Wang et al., 2003b; Duan et al., 2004; Mao and Duan, 2005).

6. Heating over the TP and low-frequency oscillation of circulation

Tao and Zhu (1964) demonstrated that zonal shifting of the South Asian high over the TP in summer leads to the east-west movement of the 500-hPa subtropical anticyclone over the western Pacific (SAWP) for a few days. Krishnamurti and Bhalme (1976) showed that sub-seasonal oscillations of summer rainfall, which lead to the active and break monsoon, are related to a quasi-biweekly oscillation of the monsoon system, including the Tibetan high. Liu et al. (2007) analyzed the transient behavior of circulation from a sequence of idealized experiments based on a global primitive equation model. It was found that heating over the TP leads to a potential vorticity (PV) minimum over the TP in the upper troposphere. It was further shown that if the heating is sufficiently strong, the background flow becomes unstable and a quasi-biweekly oscillation is produced (Fig. 10). During this oscillation, the Tibetan anticyclone in the upper troposphere changes between a single centre over the southwestern side of the TP and a split/double-center

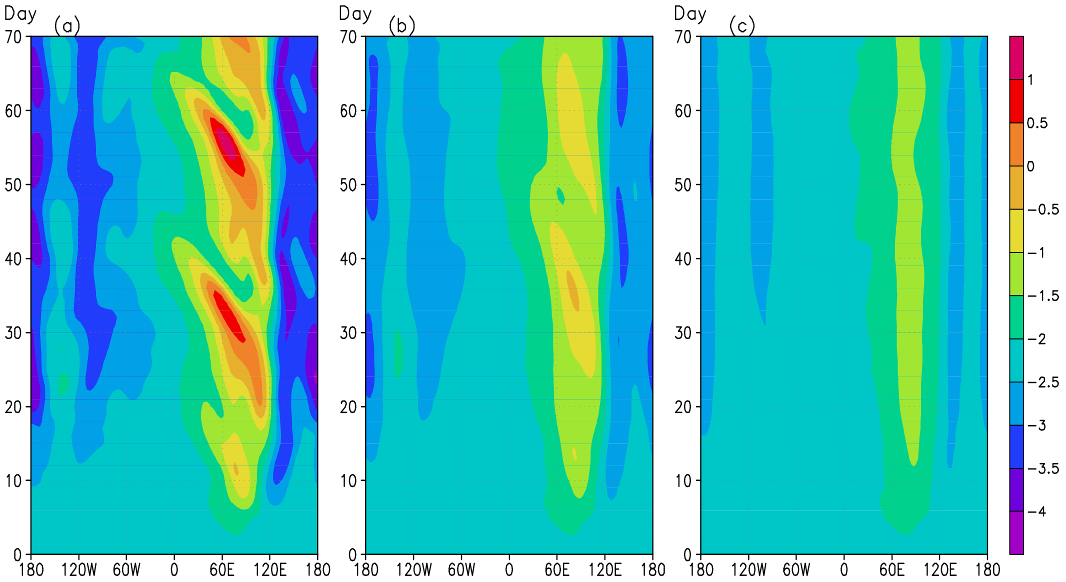

Fig. 10. Time-longitude cross section of 25°–35°N-averaged 200-hPa streamfunction (units: 10^7 m^2 s^{-1}) for (a) the experiment with idealized orography and heating; (b) as in (a) but with the magnitude of the idealized heating reduced by a factor of two; and (c) as in (a) but with the magnitude of the idealized heating reduced by a factor of four. (from Liu et al., 2007).

structure with one center over East China and the other over the Middle East (Fig. 11). These characteristics are quite similar to the observed variability in the area. It has been shown that the origin of such variability is due to the zonally-extended PV minimum on a θ-surface, as proposed by Hsu and Plumb (2000), as well as due to the tendency to reduce the PV above the heating over the TP, and to advection by the consequent anticyclone of high PV from the east and low PV to the west.

The above JJA numerical simulation results are consistent with those from data diagnoses. Gong et al. (2004, 2006) found that there are evident differences in rainfall over the TP between weaker monsoon summers (e.g., 1993) and stronger monsoon summers (e.g., 1994). During the weaker monsoon summer of 1993, TP rainfall concentrated in July and August and possessed the feature of quasi-biweekly variation. The western Pacific subtropical high also presented a quasi-biweekly southward/northward oscillation during its northward shift from May to August. In contrast, in 1994, precipitation over the TP was stronger in May and June but weak in July and August, and the main variability was associated with 30–60-day tropical oscillations.

7. Concluding remarks

Studies of TP meteorology and climate dynamics in the last four years in China have been reviewed. The huge TP mechanical forcing and extraordinary elevated thermal forcing have a large influence on regional as well as global climate. The TP is a weak heat sink in winter but a strong heat source in summer. It was found that the converging impact of the TP on atmospheric circulation in summer is stronger than its diverging impact in winter, as in the summer months there is a Conditional Instability of the Second Kind (CISK)-like positive feedback between small-scale convection over the TP and the large-scale convergent spiral of the lower tropospheric circulation in the surrounding area (Wu et al., 2007). The analysis of the TRMM data proves that precipitation over the TP is dominated by deep convection.

Relative to earlier work, one of the most important processes in understanding TP climate impacts is its influence in different seasons. 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. In summer, TP heating in conjunction with the TP air pump generate a zonal

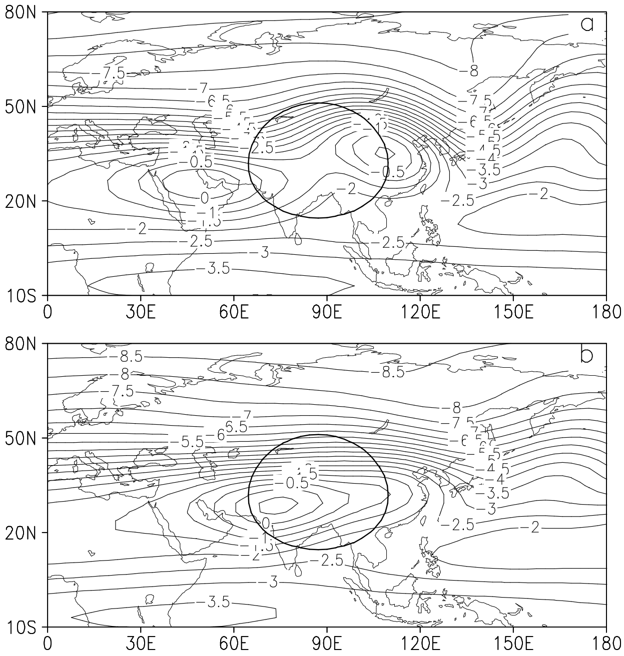

Fig. 11. For the idealised TP orography and idealised TP heating experiment, composites of the 200-hPa streamfunction for (a) the split/double mode (average of days 21, 38, 58, and 76); and (b) the single mode (average of days 12, 32, 53 and 70). Units: 10^7 m^2 s^{-1} d^{-1}. (from Liu et al., 2007).

deviation stream field to resemble a cyclonic spiral, converging towards and rising over the TP.

Together with the Iran Plateau, the TP is located in central and eastern parts of the Eurasian continent. The meridional and vertical motions generated by the Eurasian continental-scale heating are in phase with those generated by the TP local-scale forcing over Asia. The rising of the southerly flow over East Asia and the sinking of the northerly flow over middle Asia therefore becomes enhanced. The East Asian monsoon climate and the middle Asia dry climate in summer are intensified by TP mechanical and thermal forcing.

It has been shown that the variation in Eastern Asian summer rainfall is closely related to the TP thermal status both in summer and in late winter and spring. Generally corresponding to stronger TP heating in summer, more rainfall tends to occur along the Yangtze River and the Huaihe River and less rainfall in northern and southern China. An index combining both snow cover over the TP and the ENSO index has been proposed and has shown better ability for seasonal climate forecasting.

The influence of the TP on the onset of the Asian monsoon is another important issue that has received intensive study during the past four years. Strong sensible heating over the TP in spring contributes significantly to the abrupt seasonal transition of the East Asian circulation, resulting in the earliest Asian monsoon onset being anchored over the eastern Bay of Bengal and the western Indochina Peninsula. Moreover, since the essence of summer monsoon onset is a result of the change in land-sea thermal contrast, a qualitative prediction of the Bay of Bengal monsoon onset was attempted based on the thermal-wind balance and using the sign of meridional temperature gradient in the upper troposphere or at 400 hPa over the TP. However, the climate system is a nonlinear, dissipative and open system, and the timing and location of the Asian monsoon onset is influenced not only by TP heating, but also by other persistent external forcings and the low frequency oscillations in the atmosphere, including the Madden-Julian oscillation. Thus, continuous efforts are needed to improve monsoon prediction.

Numerical experiments have shown that heating over the TP can lead to a significant variability of atmospheric circulation on a quasi-biweekly timescale that bears much similarity to those discussed in observational studies.

In this paper, we have mainly reviewed studies of the TP impacts upon climate, not including its influence on weather systems such as local torrential rain (Chen and Li, 2005) and the TP vortex (Liu and Li, 2006). These are very important and should be reviewed separately.

Despite great efforts, many aspects are still unclear. Most of the conclusions summarized here are still qualitative in nature. Unresolved questions include: How do radiation processes affect the thermal state of the TP? What is the role of the aerosol-cloud-radiation-monsoon circulation feedback? How do air-sea exchange processes interact with such feedback? And how does the TP air pump, in conjunction with the thermal state over the Indian Ocean and Australia, affect the Asia-Australia monsoon? On the other hand, 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 the study. Large errors still exist in surface momentum flux, energy budget, cloud, and precipitation in the reanalysis data. Up to now, there have been no continuous observations of temporal and spatial variation in land processes. 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 areas that require improvement in the next few years are more field observation experiments and numerical modeling efforts. Further advances in the study of the TP require cooperation among scientists all over the world.

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