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Influence of the Tibetan Plateau on the Summer Climate Patterns over Asia in the IAP/LASG SAMIL Model

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ABSTRACT

A series of numerical experiments are carried out by using the Spectral Atmospheric Model of State Key Laboratory of Numerical Modeling Atmospheric Sciences and Geophysical Fluid Dynamics/Institute of Atmospheric Physics (SAMIL) to investigate how the Tibetan Plateau (TP) mechanical and thermal forcing affect the circulation and climate patterns over subtropical Asia. It is shown that, compared to mechanical forcing, the thermal forcing of TP plays a dominant role in determining the large-scale circulation in summer. Both the sensible heating and the latent heating over TP tend to generate a surface cyclonic circulation and a gigantic anticyclonic circulation in the mid- and upper layers, whereas the direct effect of the latter is much more significant. Following a requirement of the time-mean quasi-geostrophic vorticity equation for large-scale air motion in the subtropics, convergent flow and vigorous ascending motion must appear to the east of TP. Hence the summer monsoon in East China is reinforced efficiently by TP. In contrast, the atmosphere to the west of TP is characterized by divergent flow and downward motion, which induces the arid climate in Mid-Asia.

Key words: Tibetan Plateau, thermal forcing, climate pattern, numerical simulation

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1. Introduction

Since the 1950s and afterwards, the effect of the Tibetan Plateau (TP) in affecting the surrounding atmosphere circulation and weather and climate has been investigated in many aspects such as data analysis (e.g., Yeh,1950, Yanai et al.,1992), theoretical study (e.g., Zhu, 1957a,b; Wu, 1984), numerical modeling (Hahn and Manabe, 1975, Broccoli and Manabe, 1992), as well as rotating annulus (Yeh and Chang, 1974). The mechanical forcing of a topography uplifts the impinging air flows, divides them into branches, and generates stationary lee waves (e.g., Charney and Elliassen, 1949; Yeh, 1950; and 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; Liu et al., 2001, and many others). More and more numerical simulation studies indicate that the forcing of TP is of special importance in determining the Asian summer monsoon circulation (Hahn and Manabe, 1975; Li et al., 2001; Chou, 2003).

During the summer season, TP acts as a giant heat source with strong surface sensible heating (SH) and deep latent heating (LH) over the central and eastern regions (Yeh et al., 1957; Yanai et al., 1992). As a result of atmospheric thermal adaptation (Wu and Liu, 2000), a shallow cyclone in the surface and a deep anticyclone exist over TP, and such a circulation system can be detected in nature throughout the whole summer season in daily or monthly data (Yeh and Gao, 1979). The most recent study by Duan and Wu (2005) further implies that the effect of the TP thermal forcing is to generate and maintain a Gill type circulation (Gill, 1980) in the lower layers and an opposite circulation in upper layers. Under such a circulation background, airflows then converge and ascend over the eastern side of TP, and an opposite case with diver-

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*Corresponding author: WU Guoxiong, gxwu@lasg.iap.ac.cn gent airflows and subsidence is also created to the west of TP. Hence the thermal forcing of TP is to intensify the East Asian monsoon to its east and the dry and hot desert climate in Mid-Asia to its west. However, this hypothesis still need supports from numerical simulations.

The present work aims to explore the mechanism of TP thermal forcing in affecting the large-scale circulation and climate regime in summer season and qualitatively assess the relative importance of various components of diabatic heating over TP by using the spectral climate atmospheric general circulation model (SAMIL) developed in the Key Laboratory of Numerical Modeling Atmospheric Sciences and Geophysical Fluid Dynamics, Institute of Atmospheric Physics, Chinese Academy of Sciences (LASG/IAP/CAS). A brief review of the model and a description of experiments design are given in section 2. The impacts on general circulation due to the pure mechanical forcing of TP is examined and discussed in section 3. This is followed by an evaluation in section 4 on the thermal effect of the TP by regarding the main components of heat source. The physical mechanism of the thermal forcing in influencing the subtropical climate patterns in Asia is then discussed in section 5 by using the steady barotropic vorticity equation for large-scale air motions. Summary and discussions are presented in section 6.

2. The model and experiment design

The atmospheric general circulation model (AGCM) used in this investigation is developed from the atmospheric component of the Global Ocean-Atmosphere-Land System Model (GOALS) of IAP/LASG (Wu et al., 1997b) and now named as SAMIL. The horizontal direction of SAMIL is rhomboidally truncated at zonal wave number (R42), roughly equaling to a grid of 2.8125° longitude and 1.67° latitude. In this work the vertical 9-layer in σ-coordinate is adopted. The dynamical framework uses a "standard atmosphere reduction" scheme (Zeng, 1963; Philips, 1973). The radiation scheme is the K-distribution (Shi, 1981; Wang, 1996). The convection and condensation processes are parameterized by using the dry/moist convective adjustment (Manabe et al., 1965). The land surface process implemented here is the SSiB model (Xue et al., 1991; Liu and Wu, 1997). A more detailed description and recent improvements of this model can be seen in Zhou et al. (2005).

All experiments are perpetual July runs with mixed solar radiation and sea surface temperature on 15 July. Integration for each experiment is carried out for 15 months, and the results of last 10 months are averaged for diagnosing. In the topography sensitive experiment (referred to NTP in the following parts), all terrains across the eastern Northern Hemisphere (i.e., 0.829°–88.730°N, 0°–180°E) are decreased to 20% of the real case, which results in a 1 km peak of TP instead of a 5 km peak in control run. This designation keeps the topographic distribution in nature and remains the impacts of other large-scale terrains in the Northern Hemisphere such as the Rockies and Greenland. Moreover, in the thermodynamic equation, the contribution of the SH and LH flux to the air temperature at grids with height above 3 km within this domain is omitted (area of 27.5°–37.5°N, 75°–105°E is used to represent TP in this work), For NSH sensitive experiment, the topography remains unchanged but contribution to air temperature from SH is removed for grids within TP area. Similarly, we neglect the impacts of LH at those grids in the experiment named NLH. Finally, for the non-heating experiment NHT, both the influences of SH and LH are excluded at those TP grids. Comparison and goals these experiments are exhibited in Table 1. By comparing the results in these experiments with a control run (CON), the relative importance of the topography and the main components of diabatic heating of TP can be qualitatively assessed. Note that the radiation flux in summer over TP acts as a cooling term for the air temperature, and it is generally of less importance than the sensible and LH fluxes (Duan and Wu, 2005). Thus we do not consider its impacts in this work.

SAMIL can reproduce the mean large-scale climate pattern and the climate variability in various timescale to a considerable degree (Wu et al., 1997b). Figure 1 presents the July mean circulations and precipitation patterns simulated by SAMIL_R42L9 CON run. Near the surface of TP, strong inward airflows can be seen in the midst of TP, corresponding to the low pressure in TP and the surrounding cyclonic circulation. Meanwhile, the upper atmosphere over the area is characterized by a deep anticyclonic circulation and the South Asian High (SAH, or Tibetan High). All of these features are very similar to the observations. The SAH has long been regarded as an essential component of Asian summer monsoon system and covers a large partition of the Asian subtropics (roughly 25°–40°N, 70°–110°E). Consequently, to the western edge of TP, northerlies and southerlies prevail in the lower and upper atmosphere, respectively. In contrast, the eastern edge of TP is characterized by an opposite wind configuration in vertical with the southerly wind vector in the lower layers and the northerly wind vector in the upper layers (Figs. 1a–d). Clearly, the SAH is a fundamental circulation system in the upper troposphere over Asia during the summer. Flohn (1960) suggested

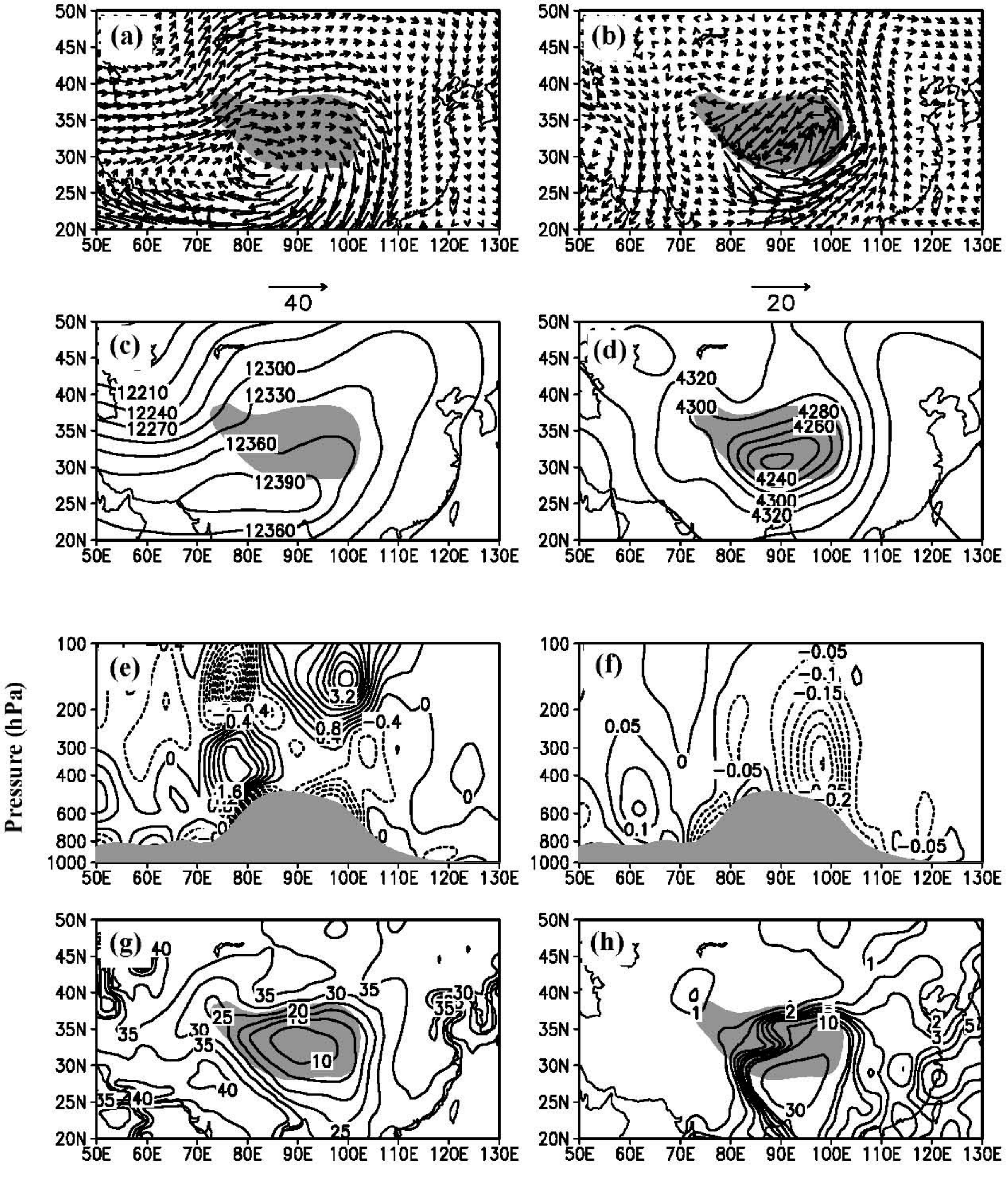

Fig. 1. July mean (a) 200 hPa wind field, (b) 600 hPa wind field, (c) 200 hPa geopotential height field, (d) 600 hPa geopotential height field, (e) longitude-pressure section of divergence along 32°N, (f) longitude-pressure section of vertical velocity along 32°N, (g) surface temperature field, and (h) precipitation field simulated by SAMIL. Units are in m s^{-1} for wind, gpm for geopotential height, 10^6 s^{-1} for divergence, Pa s^{-1} for vertical velocity, °C for surface temperature, and mm d^{-1} for precipitation. Shaded area denotes the TP with the average height more than 3000 m.

Table 1. Comparison among all numerical experiments design in this work.

Experements	Thermal forcing of TP	Topography in Europe-Asia	Objects
CON	Yes	Yes	Test the performance of SAMIL
NTP	None sensible or latent heating	Keep 20% topographic height	Test the role of mechanical forcing
NSH	None sensible heating	Yes	Test the role of sensible heating in TP
NLH	None latent heating	Yes	Test the role of latent heating in TP
NHT	None sensible or latent heating	Yes	Test the role of total thermal forcing of TP

that the formation of the huge anticyclone is a result of the elevated heating of the TP to the atmosphere.

In the corresponding longitude-pressure sections of divergence and vertical motion (Figs. 1e and f), the stoss slope of TP is characterized by a triple structure of divergence in the vertical, namely the shallow air convergence near the surface due to the uplifting effect of the topography, the other convergence center stands in the upper troposphere, with air divergence in the middle layers. The situation is similar in Mid-Asia with weaker magnitude, except there is almost no air convergence in the surface layers. Over the lee slope, however, strong air convergence in the lower and middle layers and air divergence in the upper troposphere coexist. Such a divergence configuration corresponds to the particularly strong ascending motion to the east of TP and descending motion to the west of TP. Therefore, the basic feature of the summer large-scale circulation over subtropical Asia can be summarized as the southward and descending airflows to the west of TP and the northward and ascending airflow to the east of TP, which further induces the fervent and arid climate in Mid-Asia, but also abundant monsoon rainfall in East Asia (Figs. 1g and 1h). However, systematic exaggerated surface temperature and precipitation amounts exist in the CON run. For example, more than 30 mm per day rainfall to the north of Bay of Bengal is more than that in the observation. This deficiency is directly related to the processing of the land boundary and the cumulus convective scheme in the exiting version of SAMIL.

Anyway, in view of the demonstrable capability of the model to mimic the large-scale circulation systems, we shall henceforth make use of the output from the CON and sensitive experiments to delineate the mechanism linking TP forcing to the formation of climate regimes in summer Asia. Imperfect performance of the model will not affect our study to qualitatively elucidate the mechanical and thermal forcing of TP on the mean general circulation and climate regimes.

3. Mechanical influence of TP

There are numerous studies concerning the effects of large-scale mountains on the atmospheric circulation. As a milestone, Hahn and Manabe (1975) first investigated the differences in Asian monsoon circulation with and without global larges-scale mountains by an AGCM. It is indicated that in the later case, the onset of Asian summer monsoon will be retarded by 10 to 15 days, and the north border of the southwesterly jet in the lower atmosphere will also be shifted southward about 10 degrees. Numerical simulation results given by Broccoli and Manabe (1992) further suggest that the widespread arid climate in the middle latitudes is induced by the large-scale mountains to a greater degree than that of the distant oceanic vapor source. A recent modeling study by Liu and Yin (2002) suggests that the East Asian monsoon seems to receive more influence from TP than the South Asian monsoon.

To explore the effect of pure mechanical forcing of the main terrain in the Euro-Asian continent on the atmosphere during the summer, Fig. 2 displays the difference fields between the NHT and NTP runs (i.e., NHT minus NTP). In the upper atmosphere (200 hPa), the most significant features are the cyclonic circulation centered above the midst of TP and strong northeasterlies over East China (Fig. 2a). At 600 hPa (Fig. 2b), the pure mechanical forcing tends to generate a surrounding cyclonic circulation and divergent flow within the TP domain (Fig. 2b). A more detailed structure can be seen in the corresponding latitude- and longitude-pressure sections of vertical circulation and air temperature along 32°N and 90°E, respectively (Figs. 2c, d). In the south slope of TP, air currents are elevated efficiently and then advected southward or northward when reaching the tropopause. As a result, the compensated descending motion occurs in the north slope of TP. Meanwhile, due to the very weak zonal wind in the summer subtropics, ascending motion near the west fringe of TP is limited in the lower layers only. For most parts of TP, descending motion prevails in a deep layer from the surface to 200 hPa nearby, which is in accord with the divergent flow in lower layers. Moreover, the mechanical forcing of TP results in a cold center near the tropopause and the underlying warm center in the upper troposphere just

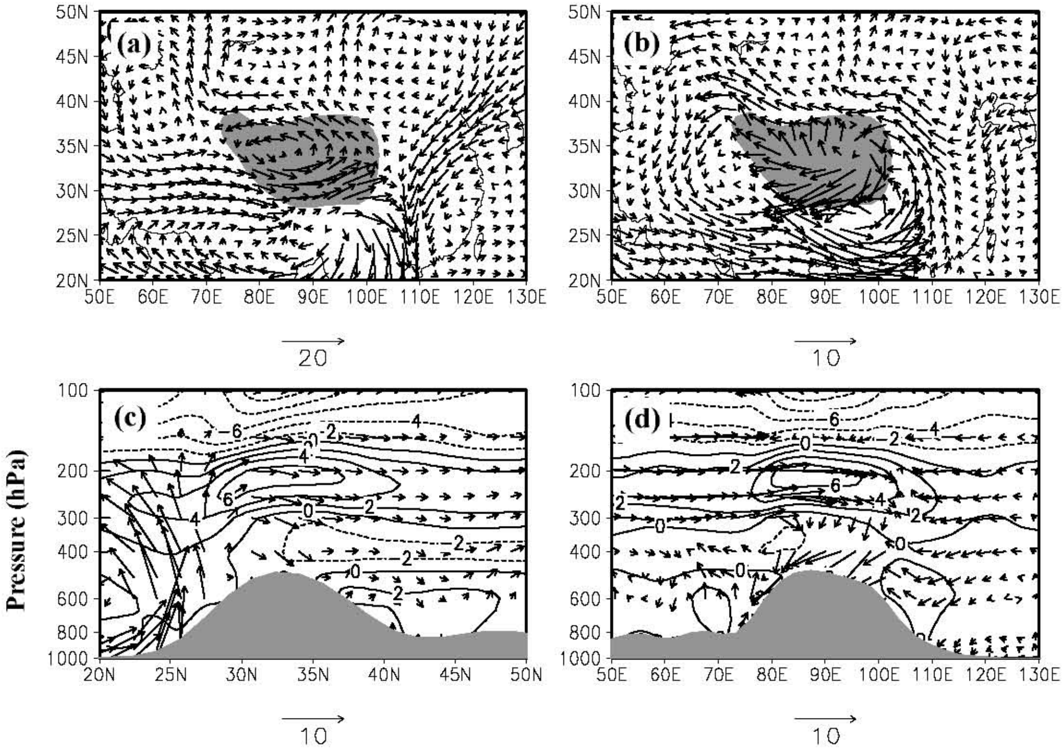

Fig. 2. Differences between the NHT and NTP runs (NHT minus NTP) in (a) 200 hPa wind field, (b) 600 hPa wind field, (c) latitude-pressure section of meridional circulation $[v\cdot(-40\times\omega)]$ and temperature (contours) along 90°E, and (d) longitude-pressure section of zonal circulation $[u\cdot(-40\times\omega)]$ and temperature (contours) along 32°N. Units are in m s^{-1} for wind, Pa s^{-1} for vertical velocity, °C for temperature. Shaded area is as same as Fig. 1.

above TP. It may be related to the absorbtion of more solar radiation in the elevated surface in NHT run. The warm air column to the north of TP in NHT is ascribed to the adiabatic descending warming effect.

The precipitation pattern related to the pure mechanical forcing of TP is estimated in Fig. 3a. During the summer monsoon period, active northward flows with abundant vapor from the Bay of Bengal or other distant large bodies of water ascend the steep south slope of TP and produce plentiful rainfall. The subsequent latent heat release in turn reinforces the lifting motion. Thus a positive feedback between the topography and precipitation appears. In addition, the precipitation in the northern Indo-China peninsula, Yunnan-Guizhou Plateau, Sichun Basin, and the eastern part of Northwest China are closely connected with topographic forcing. Reduced precipitation up to 3 mm d^{-1} in East China should be related to the westward shift of the low level jet due to the exist of TP and other mountains in southwest China. Whereas the precipitation in Mid-Asia suffers fewer impacts of topography, in the following section we will show that the in situ arid climate is a remote response to the TP thermal forcing. Another fact should be mentioned here that although terrains are uniformly reduced within the whole Euro-Asian continent in NTP run, almost all of the significant differences appear in the TP and surrounding areas. It denotes that TP serves as a primary role for large-scale circulation among all mountains in Europe-Asia.

4. Thermal influence of TP

4.1 *Sensible heating influence of TP*

The surface heating rate is of about 10 K d^{-1} (or 100 W m^{-2} SH flux) in summer over TP (Duan and Wu, 2005). Such a strong heat source acts as an air pump, enhancing the upward motion over TP, attracting ambient air to flow towards TP and converge there. The resultant rainfall and condensation latent heat release further intensify the divergent flow in the upper troposphere and maintain the SAH (Li et al., 2001; Wu et al., 1997a).

Numerical simulation results suggest that the sensible heat source plays a key role in determining the location of the upper circulation and its seasonal evolution in North America (Liu et al., 1999). Figure 4

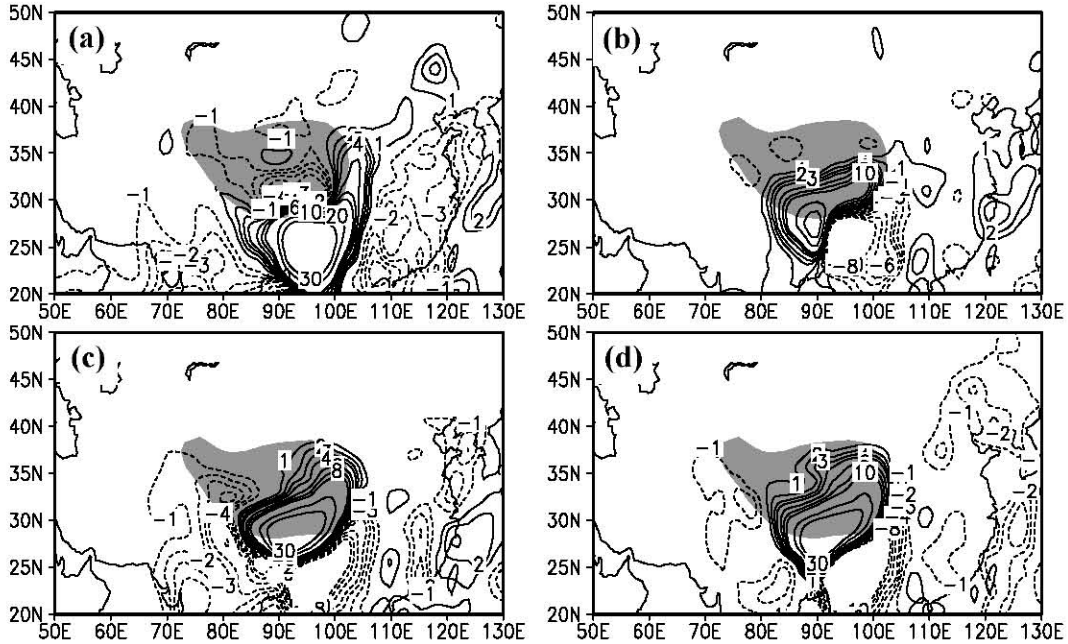

Fig. 3. Precipitation differences between (a) NHT and NTP, (b) CON and NSH, (c) CON and NLH, and (d) CON and NHT. Units are in mm d^{-1} and shaded area is as same as Fig. 1.

presents the differences between the CON and NSH runs. The SH of TP generates an anticyclonic circulation to the southwest of TP and the northerlies to the southeast. In lower layers, SH effect on circulation is almost opposite to the pure mechanical forcing of TP. This agrees well with other studies aforementioned, the surface warm low over TP in summer is an outcome of the strong surface SH. Since the air column over TP during the summer season is much warmer than surrounding areas, the isentropic surfaces intersect the slope of TP. It means that diabatic heating must exist when the air flows pass through the isentropic surfaces and converge in TP, and the SH in the surrounding borders may be more important than that of inner TP.

The SH source-related large-scale precipitation distributes mainly in the subtropical regions south to 35°N. In generally, it is in favor of precipitation in the eastern and southern TP but goes against that in the northern Indo-China peninsula. As for East China, it can increase rainfall up to 3 mm d^{-1} in the valleys of the Yangtze River and Huaihe River (Fig. 3b). This positive correlation between the SH source over TP and the precipitation in the Yangtze River and Huaihe River in summer agrees well with our previous study based on data diagnosis (Duan et al., 2005).

4.2 *Latent heating influence of TP*

For the average of the entire air column over TP, the primary component of the atmospheric heat source is the precipitation-induced LH. The integrated LH flux in TP domain is approximately 180 W m^{-2} in July (Fig. 3 in Duan and Wu, 2005). Since LH usually concentrates in the mid- and upper troposphere over TP due to deep convective activity, it can affect the upper atmosphere in the neighboring areas more efficiently. By comparing Fig. 5 with Fig. 4, one can see that the basic atmospheric response to LH over TP is similar to SH. Monsoon precipitation in TP heats the atmosphere and further enhances the surface heat low over TP and SAH. What is different is that the response to LH is much more significant especially in the mid- and upper atmosphere, and the center of SAH at 200 hPa also moves eastward somewhat.

In the corresponding precipitation difference field (Fig. 3c), the situation is very similar to that in Fig. 3b for most parts of East China. The heating effect of LH in TP produces two meridional rainfall belts downstream. One locates in Yunnan-Guizhou Plateau and the other extends from South China to East China. Precipitation between them (i.e., Mid-China) will be reduced by LH over TP. The reason for such rainfall patterns is not clear, but it is suggested to be related to the Rossby wave trains generated by TP diabatic heating (Liu et al., 2001). An interesting phenomenon is that the LH over TP alone can induce the descending motion and decreased rainfall in Mid-Asia instead of a remote response to the whole Asian summer monsoon heating (Rodwell and Hoskins, 2001).

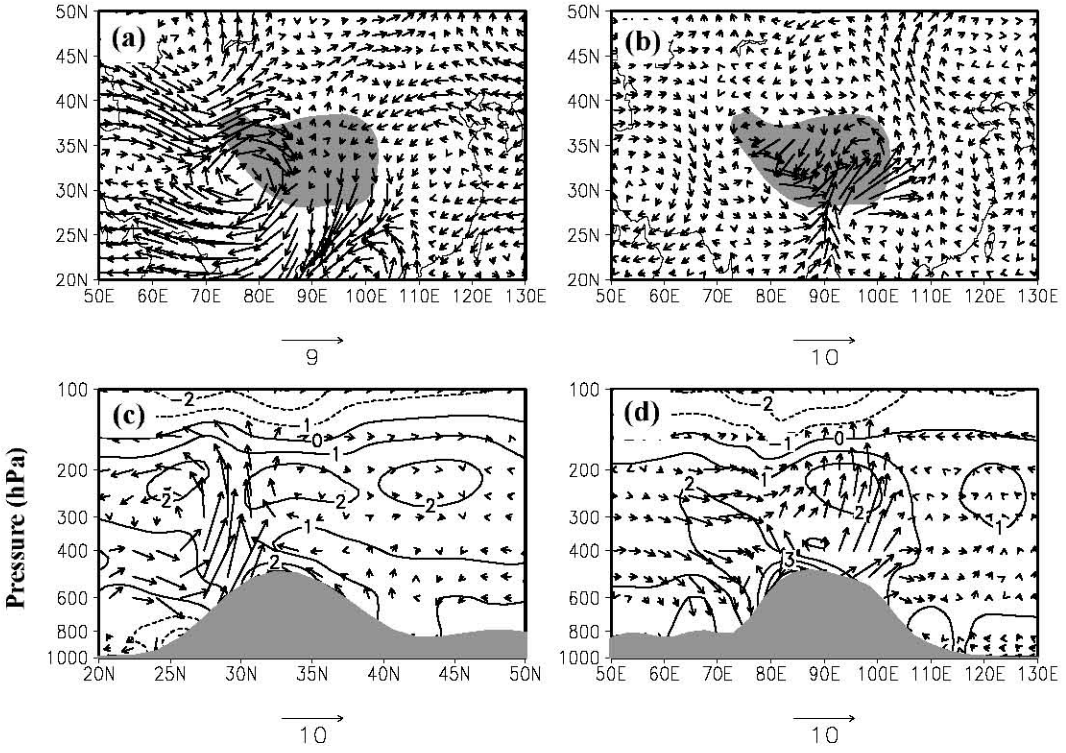

Fig. 4. Same to Fig. 2 but for differences between the CON and NSH runs.

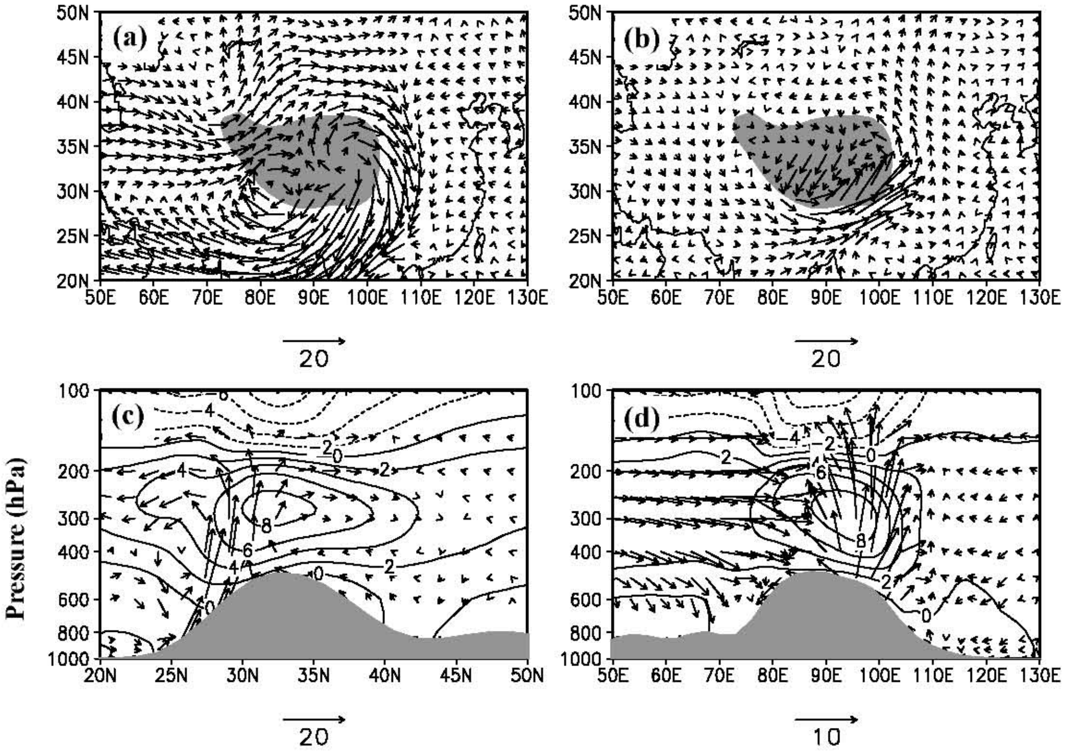

Fig. 5. Same to Fig. 2 but for differences between the CON and NLH runs.

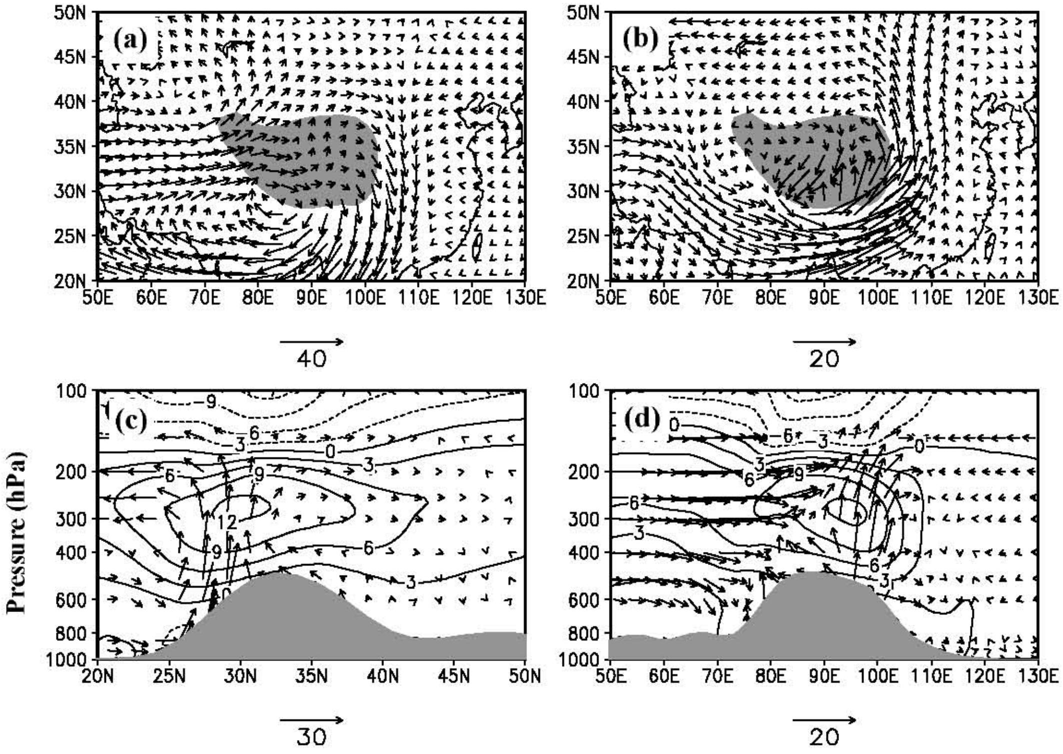

Fig. 6. Same to Fig. 2 but for differences between the CON and NHT runs.

4.3 *Combined heating influence of TP*

The combined heating effect of TP can be qualitatively assessed by the differences between the CON and NHT runs shown in Fig. 6. By comparing it with Figs. 2, 4, and 5, we find that the influence of the total diabatic heating over TP is more significant than the topography, SH, or LH alone. It suggests that there is a nonlinear amplification among topography and diabatic heating over TP. As explained in section 2, the thermal forcing of TP induces the prominent monsoon meridional cell to the south of TP and a relative weak positive thermal cell to the north of TP. Furthermore, it reinforces the thermal contrast not only between TP and the ambient areas but also between the whole land and sea especially in the lower layers. All these facts verify the fact that the thermal forcing of TP exerts an imperative role in maintaining and regulating the Asian summer monsoon system.

5. Mechanism of thermal influence of TP

By using the related PV-θ (i.e., isentropic potential vorticity) view, Hoskins (1991) interprets the atmospheric response to a given thermal forcing as the formation of lower layer cyclonic circulation and upper layer anticyclonic circulation. The vertical scale of such a solely thermal response depends greatly on the vertical scale of diabatic heating. The thermal adaptation theory developed by Wu and Liu (2000, also Wu et al., 2004). They extends the PV-θ view of Hoskins by taking into account the impacts of surface friction. For a near surface heating source, its warming to the atmosphere causes the intersection with the earth's surface of the lower-layer isentropic surfaces. Negative vorticity induced by surface friction is pumped into the air column, diluting the lower layer positive vorticity due to heating and extending the anticyclonic circulation aloft to the upper troposphere.

Following a simple vorticity balance argument, considering the fact that the advection of relative vorticity in the summer subtropics is weak, the time-mean quasi-geostrophic vorticity equation for large-scale air motion in the subtropics can be written as

$$\beta v + (f + \zeta)\nabla \cdot \boldsymbol{V} = 0\,, \tag{1}$$

in which β and f are Rossby and Coriolis parameter, v is meridional wind speed, ζ relative vorticity, and $\nabla \cdot \boldsymbol{V}$ air divergence. The vertical structure of the circulation produced by heating should have lower-layer convergence and upper-layer divergence on its eastern side, and lower-layer divergence and upper-layer divergence on its western side. Following a continuity requirement argument, therefore, the vertical shear of meridional wind over a heating source in the subtropics should correspond to ascending motion on its east and descending motion on its west. This is the case as

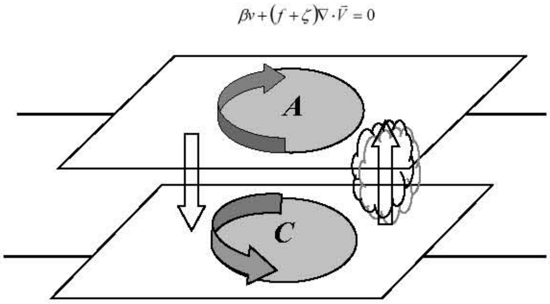

Fig. 7. Schematic diagram for the influence of the TP thermal forcing on the summer climate patterns. A and C denote the anticyclonic in the upper atmosphere and cyclonic circulation in surface layers, respectively. Upward (downward) arrow represents ascending (descending) motions.

presented in Figs. 4–6. Corresponding to the mountain crests at 50°E, 70°E, and 90°E, pairs of descent/ascent exist in the lower troposphere with ascent over the crests and their eastern sides.

The mechanism of the thermal forcing of TP in influencing the Asian summer climate patterns can be summarized by a schematic diagram shown in Fig. 7. Because TP is a huge elevated heating source with the strongest heating in the surface layers in summer, the thermal adaptation results in a shallow cyclonic circulation near the surface and a deep anticyclonic circulation above it. According to the steady barotropic vorticity equation for large-scales, airflows must converge in the lower layers and diverge in the high layers over the eastern side of TP. However, the western side of TP is characterized by a reversed structure, i.e., divergence in lower layers but convergence in high layers. Hence pumping and sucking processes bring in upward and downward movement over the east and west sides of TP, respectively. The continental scale vertical motion also corresponds to ascent on the east and descent on the west (Wu and Liu, 2003). The ascending motion over the eastern continent and the descending over its west induced by continental heating are at least partly overlapped with those induced by large-scale orographic thermal forcing. Therefore the existence of the Tibetan Plateau reinforces the East Asian monsoon rainfall to their east and enhances the dry and hot climate in central and western Asia to their west. These results are in agreement with those based on sensitivity numerical experiments with and without TP (e.g., Hahn and Manabe, 1975; Li et al., 2001).

6. Summary and conclusions

Based on a series of numerical simulations by using the IAP/LASG SAMIL climate model, the present study demonstrates that, compared to the pure mechanical forcing, the thermal forcing of TP plays a dominant role in determining the large-scale circulation in summer. Both the strong surface SH and the higher deep LH in TP tend to generate a surrounding surface cyclonic circulation and a gigantic anticyclonic circulation in the mid- and upper layers. Following a requirement of the time-mean quasi-geostrophic vorticity equation for large-scale air motion in the subtropics, air convergence and vigorous ascending motion must appear to the east of TP. In contrast, central Asia to the west of TP is characterized by air divergence and downward motion. On the other hand, the effect of pure mechanical forcing of TP on the atmospheric circulation is almost adverse. It makes a divergent air flow in the surface and a cyclonic circulation in the upper layers.

As discussed by Duan and Wu (2005), the adiabatic descent over central Asia will inhibit local convective heating and increase long-wave cooling, thus leading to a local "diabatic enhancement" (Rodwell and Hoskins, 2001). Similarly, deep convective heating over East China is in favor of the in situ ascending motion. Thus there could be positive feedback between the vertical motion and local diabatic heating. Moreover, the continental-scale diabatic heating along the summer subtropics generates lower layer cyclonic circulation and upper layer anticyclonic circulation over land areas (Wu and Liu, 2003). The circulation pattern forced by the continental-scale heating over Eurasia is in phase with the circulation patterns forced by the thermal forcing of TP and Iran Plateau. Therefore, the subsidence over the western continent and the upward motions over its east are enhanced greatly, resulting in a dry and hot climate in West and Middle Asia but a strong monsoon and wet climate in East Asia.

Thermal effects of large-scale mountains are closely connected with their mechanical counterparts (e.g., Zhu, 1957a,b; Hahn and Manabe, 1975). For example, the elevated land surface of TP obviously enhances the effect of the atmospheric heating source in summer. This is the oneness of the thermal and mechanical effects of large-scale orography on the atmospheric general circulation, and these two aspects are closely connected with each other through dynamical processes.

To completely understand the effect of large-scale mountains in the climate system, some improved numerical experiments based on a land-sea-air coupled GCM will be conducted in our future work.

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REFERENCES

Broccoli, A. J., and S. Manabe, 1992: The effects of orography on mid-latitude Northern Hemisphere dry climates. *J. Climate*, **5**, 1181–1201.

Charney, J. G., and A. Elliassen, 1949: A numerical method for predicting the perturbations of the middle latitude westerlies. *Tellus*, **1**, 38–55.

Chou, C., 2003: Land-sea heating contrasts in an idealized Asian summer monsoon. *Climate Dyn.*, **21**, 11–15.

Duan, A. M., and G. X. Wu, 2005: Role of the Tibetan Plateau thermal forcing in the summer climate patterns over subtropical Asia. *Climate Dyn.*, **24**, 793–807.

Duan, A. M., Y. M. Liu, and G. X. Wu, 2005: Heating status of the Tibetan Plateau from April to June and rainfall and atmospheric circulation anomaly over East Asia in mid-summer. *Science in China (D)*, **48**, 250–257.

Flohn, H., 1960: Recent investigation on the mechanism of the "summer monsoon" of southern and eastern Asia. *Proc. Symp. Monsoon of the World*, New Delhi, Hind Union Press, 75–78.

Gill, A. E., 1980: Some simple solutions for heat-induced tropical circulation. *Quart. J. Roy. Meteor. Soc.*, **106**, 447–462.

Hahn, D. G., and S. Manabe, 1975: The role of mountain in the south Asian monsoon circulation. *J. Atmos. Sci.*, **32**, 1515–1541.

Hoskins, B. J., and D. J. Karoly, 1981: The steady linear response of a spherical atmosphere to thermal and orographic forcing. *J. Atmos. Sci.*, **38**, 1176–1196.

Hoskins, B., 1991: Towards a PV-θ view of the general circulation. *Tellus*, **43**, 27–35.

Li, W. P., G. X. Wu, Y. M. Liu, and X. Liu, 2001: How the surface processes over the Tibetan Plateau affect the summertime Tibetan anticyclone—Numerical Experiments. *Chinese J. Atmos. Sci.*, **25**, 809–816. (in Chinese)

Liu, H., and G. X. Wu, 1997: Impacts of land surface on climate of July and onset of summer monsoon: A study with an AGCM plus SSiB. *Adv. Atmos. Sci.*, **14**, 289–308.

Liu, X., G. X. Wu, and W. P. Li, 2001: Heating of the Tibetan Plateau and the large-scale thermal adaptation in summer. *Progress in Natural Sciences*, **11**, 33–39.

Liu, X. D., and Z. Y. Yin, 2002: Sensitivity of East Asian monsoon climate to the Tibetan Plateau uplift. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **183**, 223–245.

Liu, Y. M., H. Liu, P. Liu, and G. X. Wu, 1999: The effect of spatially nonuniform heating on the formation and variation of subtropical high. Part II: Land surface sensible heating and east Pacific Subtropical High. *Acta Meteorologica Sinica*, **57**, 385–396.

Manabe, S., J. Smagorinsky, and R. F. Strickler, 1965: Simulated climatology of a general circulation model with a hydrological cycle. *Mon. Wea. Rev.*, **93**, 769–798.

Philips, N. A., 1973: Principles of large-scale numerical weather prediction. *Dynamics Meteorology*, P. Morel, Ed., D. Reidel Publishing Company, Dordrecht, Holland, 1–96.

Rodwell, M. J., and B. J. Hoskins, 2001: Subtropical anticyclones and summer monsoons. *J. Climate*, **14**, 3192–3211.

Shi, G. Y., 1981: An accurate calculation of the infrared transmission function of the atmospheric constituents. Ph. D. dissertation, Department of Meteorology, Tohoku University of Japan, 191pp.

Wang, B., 1996: On the radiation transfer models for climate simulation. Ph. D. dissertation, Institute of Atmospheric Physics, Chinese Academy of Sciences, 92pp. (in Chinese)

Wu, T. W., P. Liu, and Z. Z. Wang, 2003: The performance of atmospheric component model R42L9 of GOALS/LASG. *Adv. Atmos. Sci.*, **20**, 726–742.

Wu, G. X., 1984: The nonlinear response of the atmosphere to large-scale mechanical and thermal forcing. *J. Atmos. Sci.*, **41**, 2456–2476.

Wu, G. X., and Y. M. Liu, 2000: Thermal adaptation, overshooting, dispersion, and subtropical high. Part I: Thermal adaptation and overshooting. *Chinese J. Atmos. Sci.*, **24**, 433–436. (in Chinese)

Wu, G. X., and Y. M. Liu, 2003: Summertime quadruplet heating pattern in the subtropics and the associated atmospheric circulation. *Geophys. Res. Lett.*, **30**, 1201.

Wu, G. X., W. P. Li, and H. Liu, 1997a: Sensible heating-driving air pump of the Tibetan Plateau and the Asian summer monsoon. *Memorial Volume of Prof. J. Z. Zhao, D. Z. Ye*, Ed., Science Press, Beijing, 126pp. (in Chinese)

Wu, G. X., and Coauthors, 1997b: Global ocean-atmosphere-land system model of LASG (GOALS/LASG) and its performance in simulation study. *Quart. J. Appl. Meteor.*, **8**(Suppl.), 15–28. (in Chinese)

Wu, G. X., Y. M. Liu, and J. Y. Mao, 2004: Adaptation of the atmospheric circulation to thermal forcing over the Tibetan Plateau. *Observation, Theory and Modeling of Atmospheric Variability*, X. Zhu, Eds., World Scientific Press, London, 92–114.

Xue, Y. K., P. J. Sellers, J. L., Kinter, and J. Shukla, 1991: A simplified biosphere model for global climate studies. *J. Climate*, **4**, 345–364.

Yanai, M., and G. X. Wu, 2006: Role of the Tibetan Plateau on Asia monsoon. *The Asian Monsoon*, B. Wang, Ed., Springer, Chichester, 513–629.

Yanai, M., C. Li, and Z. Song, 1992: Seasonal heating of the Tibetan Plateau and effects of the evolution of the Asian summer monsoon. *J. Meteor. Soc. Japan*, **70**, 189–221.

Yeh, T. C., 1950: The circulation of the high troposphere over China in the winter of 1945–1946. *Tellus*, **2**, 173–183.

Yeh, T. C., and C. C. Chang. 1974: A preliminary experimental simulation on the heating effect of the Tibetan Plateau on the general circulation over Eastern Asia in China. *Science in China* (*D*), **XVII**, 397–420.

Yeh, T. Z., and Y. X. Gao, 1979: *Meteorology of the Qinghai-Xizang* (*Tibet*) *Plateau*. Science Press, Beijing, 278pp.

Yeh, T. Z., S. W. Lo, and P. C. Chu, 1957: On the heat balance and circulation structure in troposphere over Tibetan Plateau. *Acta Meteorologica Sinica*, **28**, 108–121. (in Chinese)

Zeng, Q. C., 1963: Characteristic parameter and dynamical equation of atmospheric motions. *Acta Meteorologica Sinica*, **33**, 472–483. (in Chinese)

Zhou, T. J., R. C. Yu, and Z. Z. Wang, 2005: *The Atmospheric General Circulation Model SAMIL and Its Coupled Climate Model GOALS-s*. China Meteorological Press, Beijing, 288pp.

Zhu, B. Z., 1957a: The influences of large-scale heat source or heat sink and terrain on the steady disturbance in westerlies (Part A). *Acta Meteorologica Sinica*, **28**, 122–140. (in Chinese)

Zhu, B. Z., 1957b: The influences of large-scale heat source or heat sink and terrain on the steady disturbance in westerlies (Part B). *Acta Meteorologica Sinica*, **28**, 198–211. (in Chinese)