

Current Progresses in Study of Impacts of the Tibetan Plateau on Asian Summer Climate*

WU Guoxiong (吴国雄), MAO Jiangyu (毛江玉), DUAN Anmin (段安民), and ZHANG Qiong (张琼)

State Key Laboratory of Atmospheric Science and Geophysical Fluid Dynamics (LASG), Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing 100029

(Received May 9, 2006)

ABSTRACT

The current progresses in the study of impacts of the Tibetan Plateau on Asian summer climate in the last decade are reviewed. By analyzing evolution of the transitional zone between westerly to the north and easterly to the south (WEB), it is shown that due to the strong heating over the Tibetan Plateau in spring, the overturning in the prevailing wind direction from easterly in winter to westerly in summer occurs firstly over the eastern Bay of Bengal (BOB), accompanied with vigorous convective precipitation to its east. The area between eastern BOB and western Indo-China Peninsula thus becomes the area with the earliest onset of Asian monsoon, which may be referred as BOB monsoon in short. It is shown that the summertime circulations triggered by the thermal forcing of the Iranian Plateau and the Tibetan Plateau are embedded in phase with the continental-scale circulation forced by the diabatic heating over the Eurasian Continent. As a result, the East Asian summer monsoon is intensified and the drought climate over the western and central Asian areas is enhanced. Together with perturbations triggered by the Tibetan Plateau, the above scenarios and the associated heating have important influences on the climate patterns over Asia. Furthermore, the characteristics of the Tibetan mode of the summertime South Asian high are compared with those of Iranian mode. Results demonstrate that corresponding to each of the bimodality of the South Asian high, the rainfall anomaly distributions over Asia exhibit different patterns.

Key words: the Tibetan Plateau heating, westerly-easterly-boundary (WEB), Asian monsoon onset, climate pattern over East Asia, bimodality of the South Asian high

1. Introduction

Most of previous studies focused on the mechanical impact of large-scale orography upon atmospheric circulation and climate before 1950s. Based on linearized equations, Queney (1948) proposed several critical scales to characterize mountain waves, and substantiated that the gravity wave, inertial gravity wave, and Rossby wave are induced when air flow undergoes the mountains with different spatial scale. In the early 1950s, Bolin (1950) and Yeh (1950) suggested that in winter, the Tibetan Plateau (TP) split the westerly flow into two branches, resulting in the generation of the Great Trough over East Asia. Gu (1951) argued that in winter the westerly jets in northern and southern sides of the TP converging over the downstream region lead to the formation of strong East

Asia jet. At that time, a newly developed atmospheric numerical model was only used to simulate the role of mechanical forcing by large-scale orography in the formation of westerly troughs and ridges (Charney and Eliassen, 1949).

In 1957, Yeh et al. and Flohn found, respectively, that in summer the TP is a heat source for atmospheric motion. Since then, many studies have been carried out on the temporal and spatial distributions of the heating field over the TP and its impacts on weather and climate, and resulted in the foundation of an important field in weather and climate research, Tibetan Plateau Meteorology, which focuses on the mechanical and thermal effects of the TP.

During the "Ninth five-year plan" and "Tenth five-year plan", on the basis of previous studies, Wu et al. (1997, 2000) applied the theory of Ertel's

*Supported by the National Basic Research Program of China under Grant No. 2005CB422004 and Natural Science Foundation of China under Grant Nos. 40375022, 40325015, and 40475027.

potential vorticity (Ertel, 1942) to the study on climatic effects of the TP. Based on the perspective of the potential vorticity and potential temperature (Hoskins, 1991), and using the newly released reanalysis data and numerical simulation, it was verified that the atmospheric motion driven by the TP heating similar to a huge air pump adjusts the Asian monsoon variability. It was demonstrated that the TP in summertime is not only a crucial heat source but also a crucial negative vorticity source (Liu et al., 2001). Such a negative vorticity source over the TP influences the atmospheric circulation anomalies in the Northern Hemisphere in the form of the Rossby wave trains (Wu, 2004).

It is well known that the onset of the Asian summer monsoon is accompanied with the significant adjustment in the structure of the subtropical anticyclone (Chen et al., 1991). The variations of the ridge-area of the subtropical anticyclone during seasonal transition from winter to summer are reviewed in Section 2. The impacts of the TP on Asian climate pattern and the possible mechanisms are addressed in Section 3. The thermal and dynamic effects of the TP on bimodality of the South Asian high in summer are shown in Section 4. Summaries and discussions are given in Section 5.

2. Relationship between the Tibetan Plateau heating and seasonal transition of the Asian monsoon

Ye et al. (1958) pointed out that the seasonal transition from winter to summer is characterized by the abrupt changes in general circulation. Mao et al. (2002a, b) associated the tilt of the ridgelines of the subtropical anticyclone with the meridional temperature gradient, and studied the relationship between the Asian monsoon onset and variations in configuration of the subtropical anticyclone. It was found that the ridgelines of the subtropical anticyclone, which is defined as the westerly-easterly boundary surface (WEB in brief), represents well the three-dimensional structure of the subtropical anticyclone belt based on theoretical and diagnostic analyses. It was substantiated

that the Asian summer monsoon firstly burst over the eastern Bay of Bengal (BOB) and western Indo-China Peninsula (Wu and Zhang, 1998; Mao et al., 2002a). Such a seasonal transition results from the earliest reversal of the land-sea thermal contrast due to the TP heating during spring along the longitudes of the eastern TP.

Under the thermal wind constraint, the WEB usually tilted toward the warmer zone in vertical. In the Asian monsoon area and in winter, the WEB tilted southward with increasing height. While in summer, the ridgelines of the subtropical anticyclone in the lower troposphere were discontinuous and the WEB in upper troposphere tilted northward. During the seasonal transition, the tilt of the WEB changed from southward to northward. When the WEB became perpendicular to the earth's surface or tilted northward, the summer monsoon was replaced by the winter monsoon. Figure 1 shows the projections of the WEB and evolutions of outgoing longwave radiation (OLR) during seasonal transition (Mao et al., 2004). In the fifth and sixth pentads of April, although the entire WEB kept the winter pattern, the ridgelines above 500 hPa were close together between 90°E and 100°E, implying that the extent of southward tilting of the WEB over 90°-100°E was less than that over other longitudes. Deep convection with OLR values less than 215 W m⁻² existed only south of 5°N and east of 80°E. Essential changes in the WEB started from the first pentad of May when the ridgelines in mid-upper troposphere formed two intersection points (C and D) situating 105°E and 90°E respectively, due to the northward (southward) migration of the upper (lower) ridgelines. Actually, the intersection points C and D were the seasonal transition axis (STA) defined by Mao et al. (2002a). The WEB between C and D exhibited northward tilting, indicating the establishment of summer type of the subtropical anticyclone. In lower troposphere, the 850 hPa ridgeline split completely into two segments over the BOB, and the BOB monsoon trough therefore formed. The tropical westerlies extended northward, then turned into southwesterlies, and connected with the subtropical westerlies. With the northward tilting of the

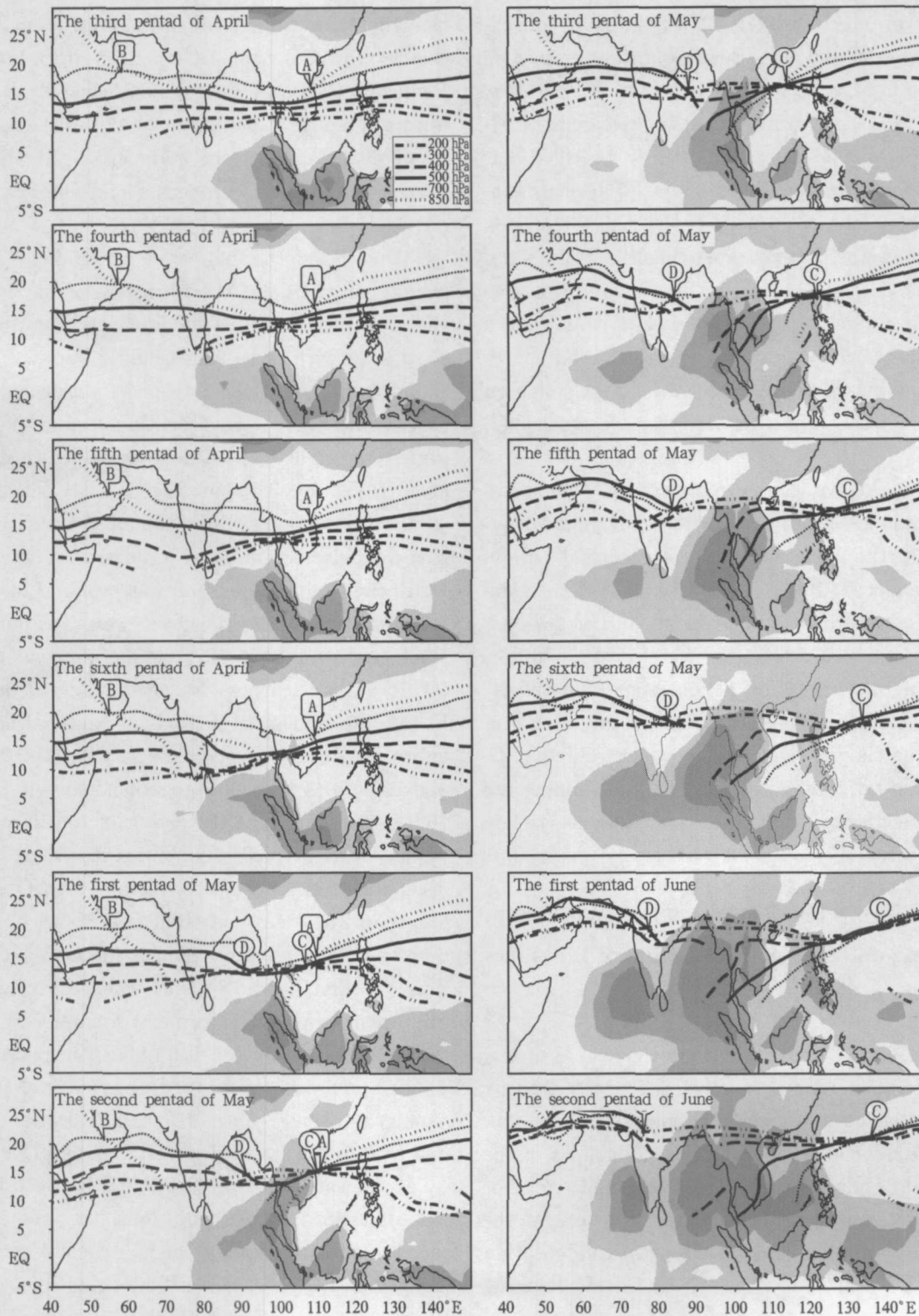


Fig.1. Projections (thick curves) of the WEB and OLR (shaded) from the third pentad of April to the second pentad of June. Thick curves denote the subtropical anticyclone ridgelines on various isobaric surfaces (indicated by the numbers in legend). Shaded areas indicate the regions with different OLR values in $W m^{-2}$: light (between 230 and 215), dark (between 215 and 200), and darker (<200).

increasing WEB, the BOB monsoon trough further deepened in the second pentad of May so that the 700-hPa ridgeline now split. At the same time, deep convection were developed all over the eastern BOB and the Indo-China Peninsula, indicating that the onset of the Asian summer monsoon firstly occurred over this region. It was noteworthy that the “connection” between the tropical westerlies and the subtropical westerlies happened to occur when the tilting of the WEB in the mid-upper troposphere over the eastern BOB overturned from southward to northward, which implied that the BOB monsoon onset depended on not only circulation abruptness in the lower troposphere but also the changes in the pressure and temperature structure in the mid-upper troposphere. Two pentads later (the fourth pentad of May), the STA at point C moved to the northeastern South China Sea (SCS) and the westernmost point of the 850-hPa ridgeline retreated abruptly eastward to 120°E, with the broken ridgeline at 400-hPa level. Meanwhile, the southwest-erlies along the monsoon trough entered into the SCS, with deep convection becoming active almost all over the area. When the STA at point D moved westward and reached the central and western India during the first two pentads of June, the South Asian summer

monsoon onset occurred, accompanied with the occurrence of active convection over the southern Indian Peninsula and the eastern Arabian Sea. In summary, each of the three stages when the Asian summer monsoon establishes over the eastern BOB and Indo-China Peninsula, SCS, and South Asia, respectively, closely corresponded to the change in the tilting of the WEB and the location of the STA. Therefore, another characteristic associated with the Asian summer monsoon onset is the overturning of the WEB and the initiation of the STA (Mao et al., 2003), in addition to a wind reversal at low levels and an increase of seasonal precipitation.

Figure 2 displays the cross sections (90°-100°E) of local temperature change and warm temperature ridge during the BOB monsoon onset from the sixth pentad of April to the third pentad of May (Mao et al., 2002c). It can be seen that the near-vertical warm ridge (200-500 hPa) suddenly jumps from south to north of the geopotential height ridge (namely STA) on the second pentad of May. Prior to the monsoon onset (from the fourth pentad to the sixth pentad), the warm ridge was located between 5°-10°N, with local temperature tendency being 0.05 K day⁻¹, in contrast to above 0.1 K day⁻¹ to its north over the TP. It is

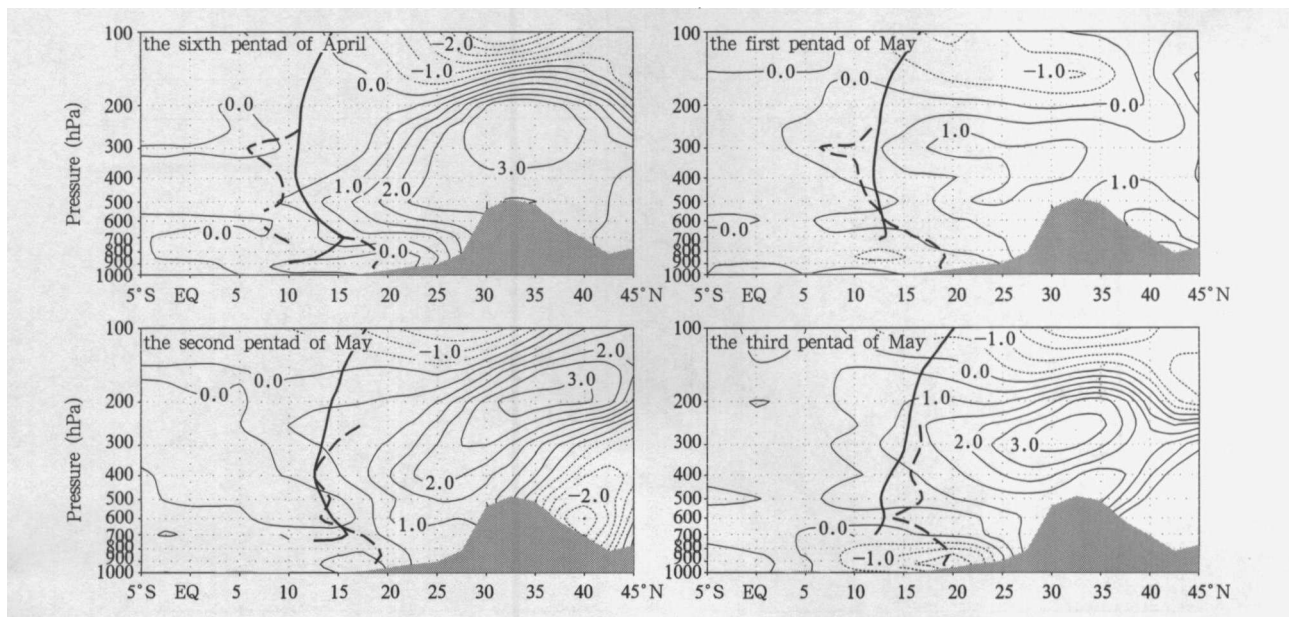


Fig.2. Pressure-latitude cross-sections (90°-100°E) of the local temperature tendency (0.1 K day⁻¹) and warm temperature ridge (right panels) during the BOB monsoon onset (from the sixth pentad of April to the third pentad of May). Thick solid line denotes geopotential height ridge, thick dashed line denotes warm temperature ridge, and shaded indicates orographic altitudes.

expected that the actual temperature in the north of the warm ridge would certainly exceed that at present, and then a new warm ridge occurred to the north of the present one in such a manner that the warm ridge shifted northward. The warm ridge in upper troposphere formed north of 18°N in the second pentad of May so that the STA tilted northward significantly. Afterwards, high temperature center was stagnated over the TP, and the STA thoroughly was located north of the warm ridge in the third pentad of May. It turned out that climatologically, the heating effect of the TP accelerated the abrupt change of the Asian monsoon circulation.

Mao et al. (2002b) suggested that the thermal basis of the seasonal transition was the reversal of meridional temperature gradient (MTG) near the ridge-area of subtropical anticyclone, and proposed the area-averaged upper tropospheric (200-500 hPa) MTG in the vicinity of the WEB as a new index for measuring the Asian summer monsoon onset. Figure 3 shows the correlations between the BOB summer monsoon onset dates and the monthly temperature field at 400-hPa level (Mao, 2001). From February to April, positive correlations around the TP were very significant, with the coefficients in March reaching 0.8. These statistical facts indicated that the thermal anomalies over

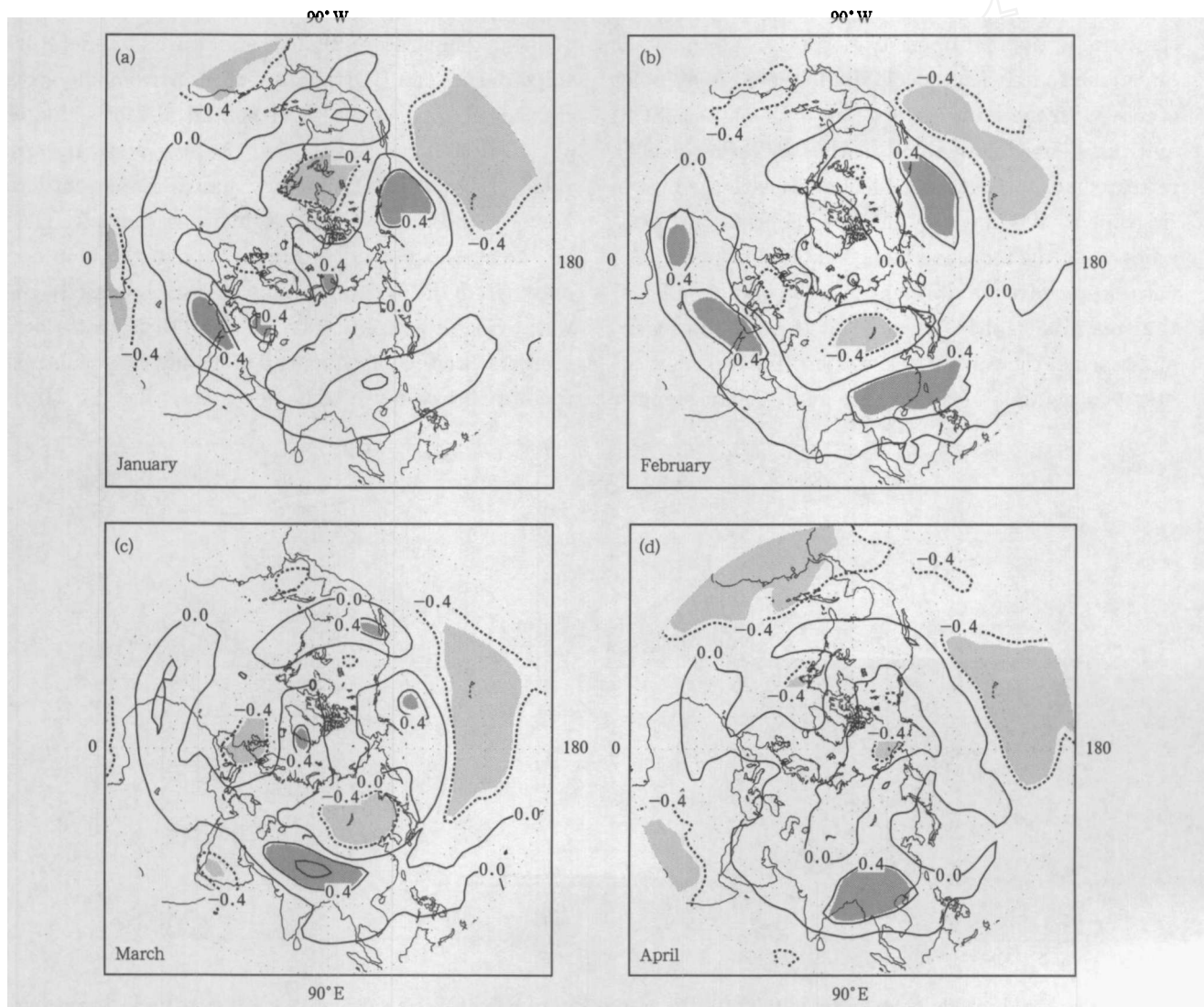


Fig.3. Lagged correlations between time series of the onset date of the BOB summer monsoon and monthly mean temperature at 400 hPa from January to April. The correlations are based on the period of 1980-1999. Critical positive (negative) values of the correlation at the 95% confidence level are shaded dark (light).

the TP were closely related to the BOB monsoon onset, and the TP heating anomalies during spring significantly affected the subsequent BOB monsoon onset.

3. Role of thermal forcing by the Tibetan Plateau in the climate pattern over subtropical Asia in summer

The role of mechanical forcing by large-scale mountain in winter atmospheric circulation has been revealed since the 1940s (e.g., Queney, 1948; Charney and Eliassen, 1949; Bolin, 1950; Yeh, 1950; Wu, 1984; Rodwell and Hoskins, 2001). However, the subtropical circulation in summer is largely affected by the TP thermal forcing, and the mechanism on the formation of subtropical circulation is more complicated as compared with other latitudes (Hoskins, 1987; Rodwell and Hoskins, 2001). Wu et al. (1999) suggested that the simplified potential vorticity equation be used to investigate the subtropical circulation because advection of the relative vorticity is very weak in the vicinity of the WEB. Since the terms on external forcing were expressed explicitly in Ertel's potential vorticity equation, which is convenient to study the climatic effect of the TP thermal forcing.

3.1 *Summertime diabatic heating pattern and the associated atmospheric circulation*

Figure 4 shows the height-longitude cross sections of diabatic heating and its components along 32.5°N (Duan, 2003). The vertical diffusion in low-layer over the TP was a dominant component with its maximum intensity being 10 K day⁻¹. It dropped sharply to zero near 500 hPa ($\sigma=0.8$ over the TP). However, latent heating was dominant almost in the entire troposphere over the TP. Over eastern China the maximum latent heating occurred preferably in the lower troposphere rather than in the middle and upper troposphere. These indicated that there were more active cumulus activities over the TP in summer. Moreover, radiation cooling over the TP was not sufficient to balance the sensible and latent heating, respectively, so that the air column over the TP became a strong heating source. Nevertheless, release of latent heating by condensation is scarce as rainfall is very small over

western Asia. As a result, the weak heating existed near land surface due to sensible heating, while cooling (heat sink) prevailed in mid-upper troposphere due to radiation cooling. The atmospheric heating source depended largely on latent heating by deep convection in the Asian monsoon region of the eastern TP, while the intensity of radiation cooling accounted for only half of that over the western Asia, with even less sensible heating there. Therefore, the summer cooling (heating) source existed over western (eastern) subtropical Asia, with maximum heating occurring over the TP. Sensible heating was a primary component of diabatic heating in the TP surface, while latent heating was a dominant component in the middle and upper troposphere.

Based on the thermal adaptation (Wu and Liu, 2000), this non-uniform diabatic heating over the TP can induce a shallow low in the lower troposphere and a deep South Asian high in the upper troposphere (Liu et al., 2001; Wu and Liu, 2003). Figure 5 displays summer mean meridional winds and vertical velocity along 32.5°N. The shallow cyclones (deep anticyclones) were observed over the surface (upper level) of the Iranian and Tibetan Plateaus. The two anticyclonic centers were located at 60°E and 90°E, respectively, representing the bimodality of the South Asian high (Zhang et al., 2002). Wu and Liu (2003) suggested that the atmospheric heating pattern over each subtropical continent and its adjacent oceans in summer exhibited a quadruple pattern of LO-SE-CO-D. The oceanic region to the west of the continent was characterized by strong longwave radiation cooling (LO), while the western and eastern portions of the continent were dominated by sensible heating (SE) and latent heating by condensation (CO), respectively. Furthermore, the oceanic region to the east of the continent was characterized by dual centers of dominant heating (D), with LO prevailing CO. Such a quadruple pattern of heating was generally accompanied with a distinct circulation, with cyclonic circulation over the continent near the surface and anticyclonic circulation in the upper troposphere. Over the continents east of 110°E and west of 30°E, the wind directions in the upper troposphere were opposite to those in the lower troposphere

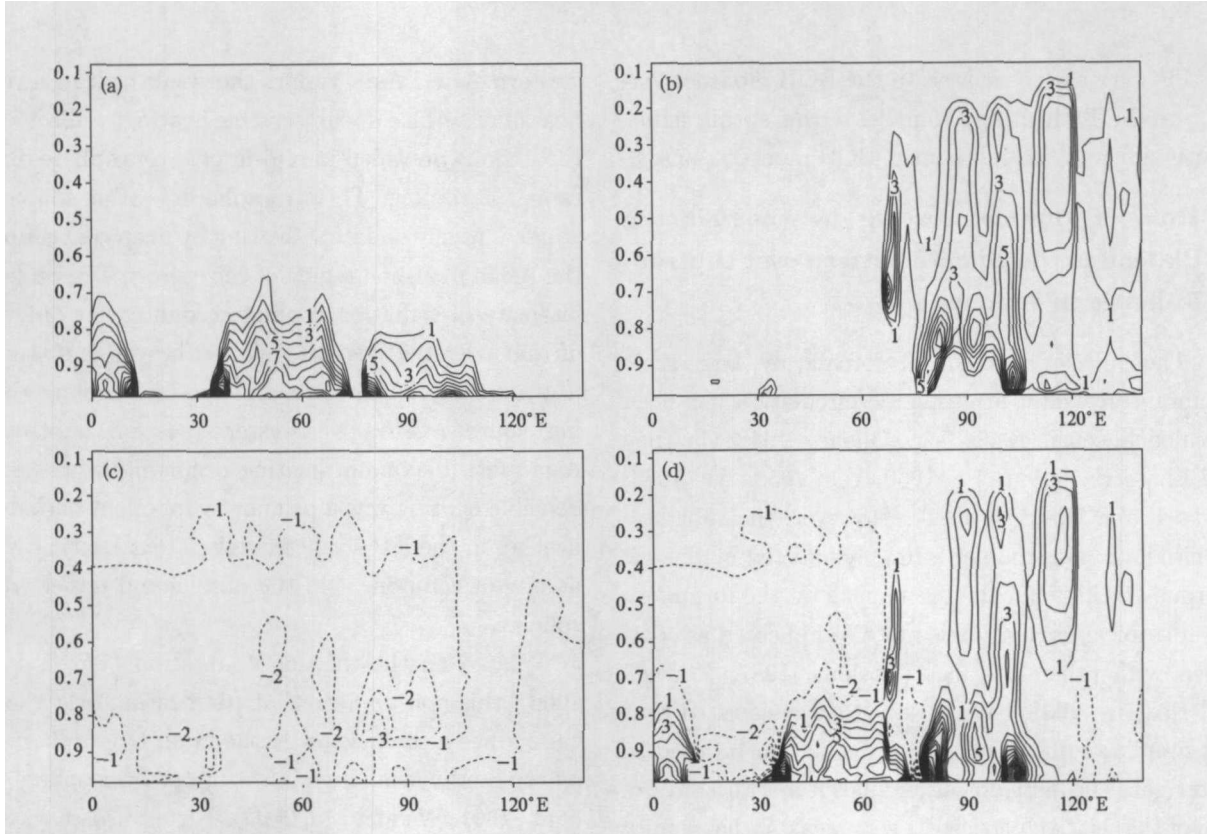


Fig.4. July mean profile of the individual and total diabatic heating rate along 32.5°N . (a) Sensible heating; (b) latent heating; (c) radiation cooling; and (d) total diabatic heating. The contour intervals are 1 K day^{-1} without zero lines. The layers $\sigma=0.9$ and $\sigma=0.1$ represent about 540 hPa and 60 hPa, respectively, over the TP.

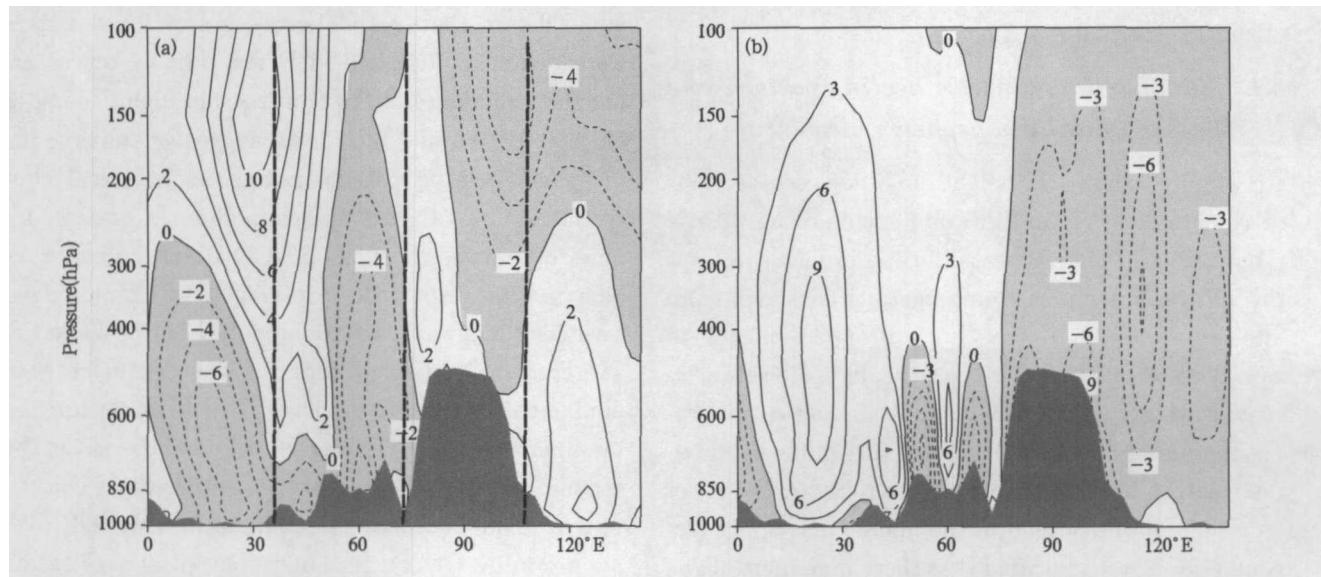


Fig.5. Longitude-pressure cross-section of mean (a) meridional wind and (b) vertical velocity in July along 32.5°N . The contour intervals are 2 m s^{-1} in (a) and $3 \times 10^{-2} \text{ Pa s}^{-1}$ in (b). The terrain is shown in shaded areas.

(Fig.5a), suggesting that summer subtropical circulation in Asia be regarded as the thermal circulation induced by the Iranian and Tibetan Plateaus that are embedded in the Asian continental-scale thermal

circulation. These two scales of thermal circulations were all characterized by low-layer cyclones and upper-layer anticyclones. Maximum velocities of low-layer northerly and upper-layer southerly occurred around

20°N and the western border of the Asian Continent, with the secondary center existing around 60°E and the western TP. On the other hand, maximum velocities of low-layer southerly and upper-layer northerly were observed around 115°E and eastern border of the Asian Continent, with the secondary one found around 110°E and the eastern TP (Fig.5a). Because of very small vorticity advection ($\mathbf{V} \cdot \nabla \xi$) near the ridgeline of the subtropical anticyclone, the equation describing stationary vorticity budget can be written as

$$\beta v + (f + \xi) \nabla \cdot \mathbf{V} \approx 0, \quad (1)$$

where \mathbf{V} is three-dimensional winds, ξ the vertical component of vorticity, v the meridional wind, f the Coriolis parameter, and β the meridional gradient of f . In the eastern thermal circulation, the lower troposphere is an area of convergence ($\nabla \cdot \mathbf{V} < 0$), while the upper troposphere a region of divergence ($\nabla \cdot \mathbf{V} > 0$), according to the above equation. Both lower tropospheric sinking and upper tropospheric divergence resulted in an enhanced ascending motion here and much rainfall over there (Fig.5b). The opposite was also true in the western thermal circulation. Corresponding to three mountains, three descending-ascending dipoles were present over 50°, 70°, and 90°E, respectively, with centers of maximum wind speed near surface. Moreover, the descending (ascending) motion existed over the larger area in west of 30°E (east of 110°E). Such a continental-scale descending/ascending motion became more intense due to its coupling with the descending/ascending motion forced by large terrain. Therefore, the hot and dry climate was resulted in over North Africa and West Asia, while the cool and wet monsoon climate was formed over East Asia.

3.2 The effect of adjustment by mountain wave on local climate pattern

Figure 6 shows the winds at 500 hPa, precipitation, and pressure-longitude cross section of potential temperature as well as vertical velocity along 32.5°N. At 500 hPa, four ascending centers were located over the southwestern TP (85°E), southeastern TP (100°E), eastern China (115°E), and south of Japan (130°E), respectively, in subtropical Asia (Fig.6a). The distance between two ascending cen-

ters was approximately 15° longitude, and each center corresponded well to maximum precipitation (Fig.6b) and wave peak (Fig.6c). Duan (2003) demonstrated that the amplitude of the wave forced by surface heating decreased with increasing height (Figs.4 and 6c), while maximum amplitude of the wave induced by deep convection occurred in free atmosphere. Thus the summer heating distributions associated with the TP have important effects of adjusting local climate pattern around the TP and the downstream region.

4. The thermal and dynamical effects of the Tibetan Plateau on bimodality of the South Asian high in summer

South Asian high (SAH) is a planetary scale high-pressure system in the upper troposphere and lower stratosphere over the Tibetan Plateau and its surrounding area. A significant characteristic of the SAH during summer was the east-west oscillation, which is characterized by the longitudinal shifting of the SAH towards or away from the TP (Tao and Zhu, 1964). Luo et al. (1982) further classified the SAH into the eastern pattern, western pattern, and the belt-type pattern. They found that the flood or drought occurrences over East China were closely related to the different SAH circulation patterns. Based on the different impacts of the SAH at different longitudes on convective activities over the TP as well as the Indian Monsoon rainfall, Zhu and Song (1981) further categorized the SAH into the eastern and the western TP pattern according to critical longitude of 90°E.

Two viewpoints have been suggested to explain the mechanisms for east-west oscillation of the SAH. One was to emphasize the thermal forcing. The huge sensible heating of the TP led to adjustment of the subtropical circulation, with the effects of the latent heating over the eastern China, further reinforcing the east-west oscillation (Liu and Wei, 1987). The other stressed dynamical interactions between different circulations. Based on dishpan experiments, Zhang et al. (1977) suggested that the formation of the SAH be mainly initiated by thermal forcing, while its shifting depended largely on external circulation impacts.

Recently, statistical results from both the 40-yr

monthly mean and 15-yr pentad mean NCEP/NCAR reanalysis data manifested that the main climate characteristics of the SAH during summer were the bimodality in its longitudinal location (Zhang et al., 2002). It was observed that the SAH centers possessed

two preferable locations corresponding to the location of the TP to the east and Iranian Plateau to the west (Fig.7a), but scarcely appeared near 70°-80°E, where the center of the climate mean SAH is located. According to its preferable location, the SAH was then

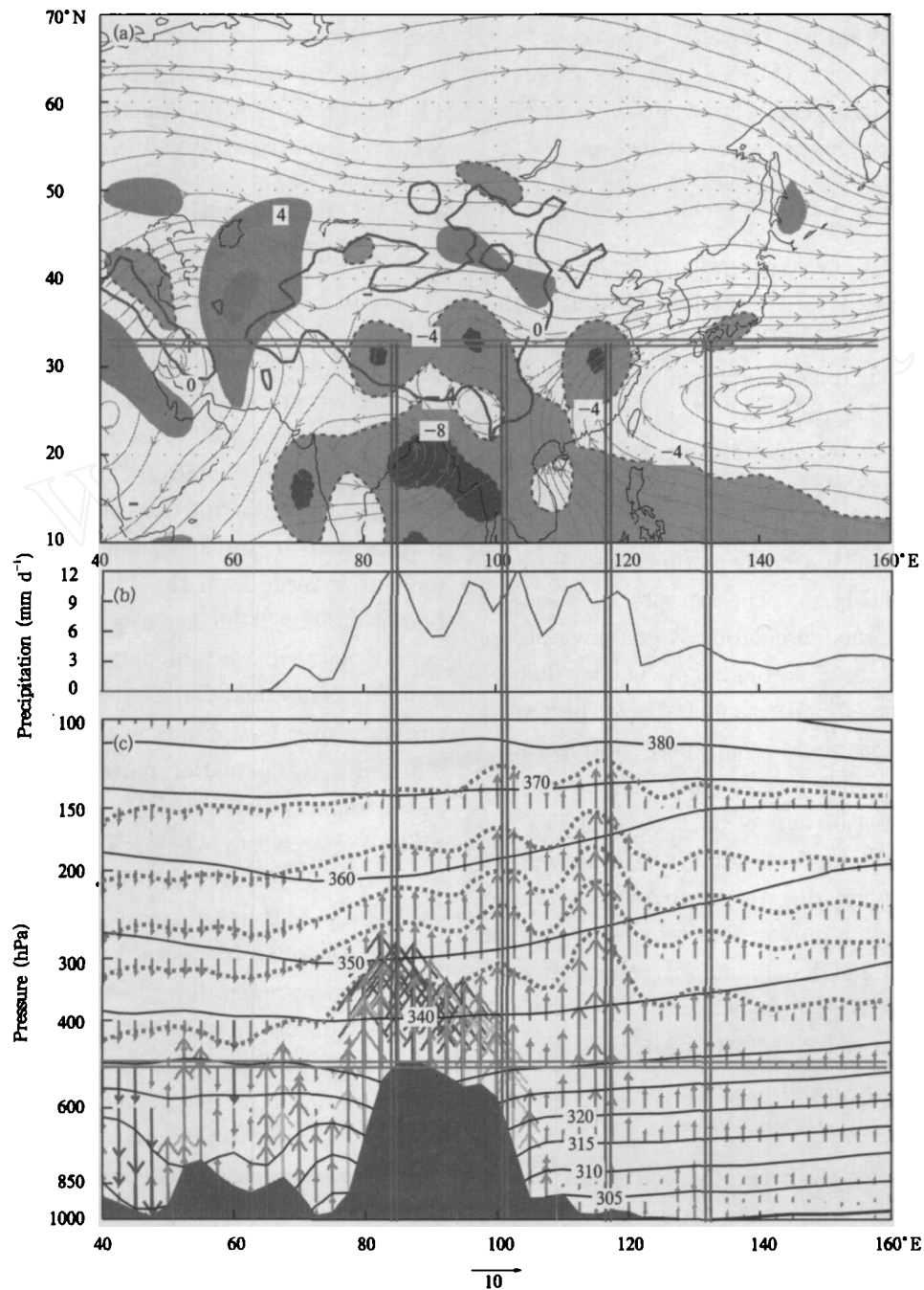


Fig.6. The monthly mean in July (a) streamline and vertical velocity fields at 500 hPa; (b) precipitation along 32.5°N; and (c) pressure-longitude sections of potential temperature and steady atmospheric wave denoted by vertical velocity along 32.5°N. Vertical velocity is in unit of 10^{-2} Pa s⁻¹, and precipitation is in unit of mm day⁻¹. Orography in the bottom panel is denoted by shaded area.

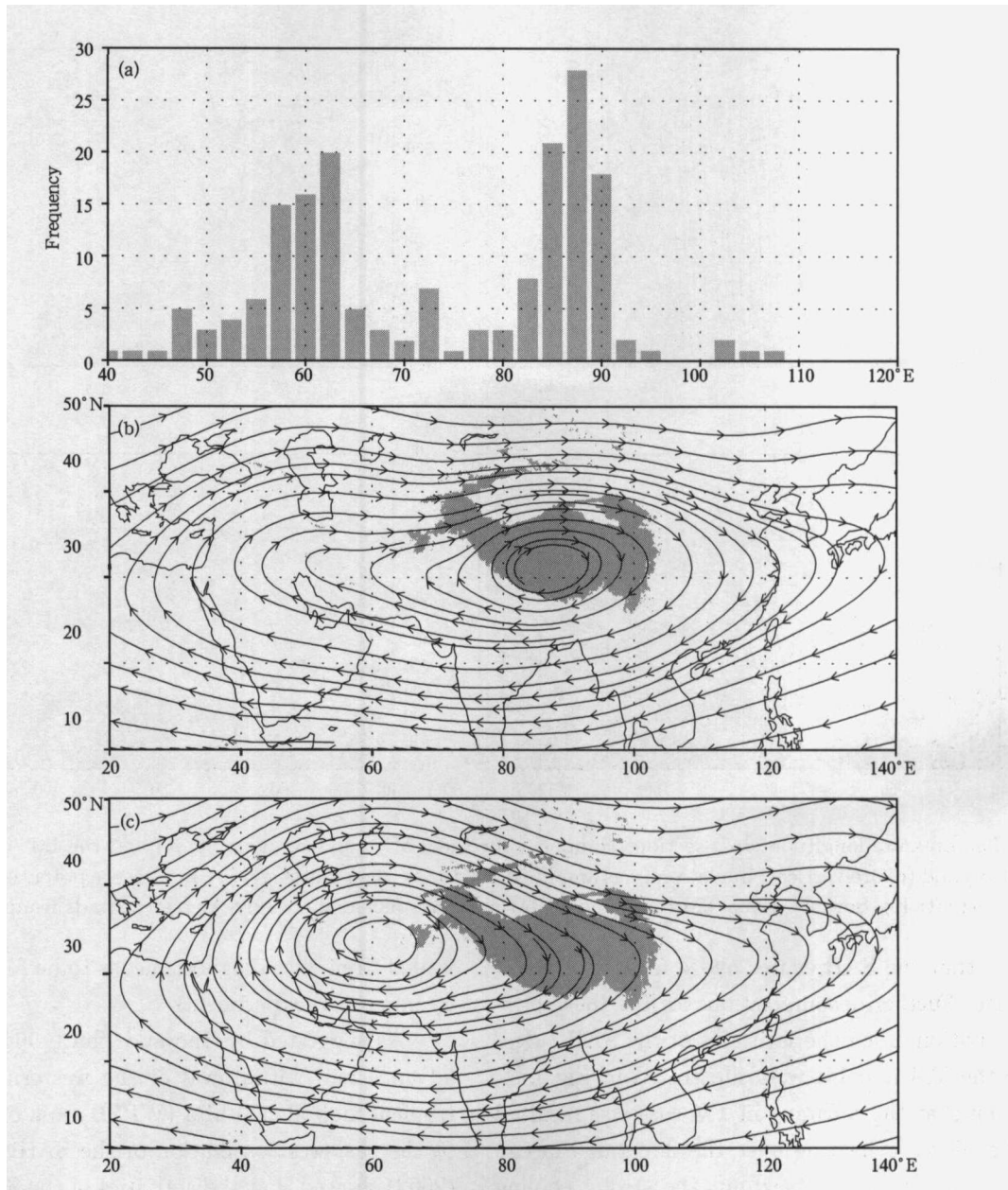


Fig.7. (a) The longitude-frequency distribution of the SAH major center during mid-summer from the pentad mean data. In the 15 summers there are totally 180 pentads involved in the statistics. The 100-hPa streamline composite corresponding to the Tibetan Mode (TM, b) and the Iranian Mode (IM, c). Seventy-seven TM cases and 62 IM cases are included on July-August pentads from 1980-1994.

classified into the Tibetan mode (TM) and the Iranian mode (IM), as shown in Figs.7b and 7c, respectively. Zhang et al. (2002) indicated that the bimodality of the SAH was substantially different from the previous east-west oscillation (Tao and Zhu, 1964; Luo et al., 1982) in different domain, timescale as well as physical features.

Figure 8 displays some vertical structures for the

TM and IM. It was shown that the cold SAH center at 100 hPa corresponded to the anomalous warm column up to 200 hPa (Fig.8b), accompanied with the strong ascending motion right over the central Tibetan Plateau (Fig.8a). In the case of the IM, a similar anomalous warm column was observed over the Iranian Plateau (Fig.8d), but accompanied with the descending motion over the region (Fig.8c). It is

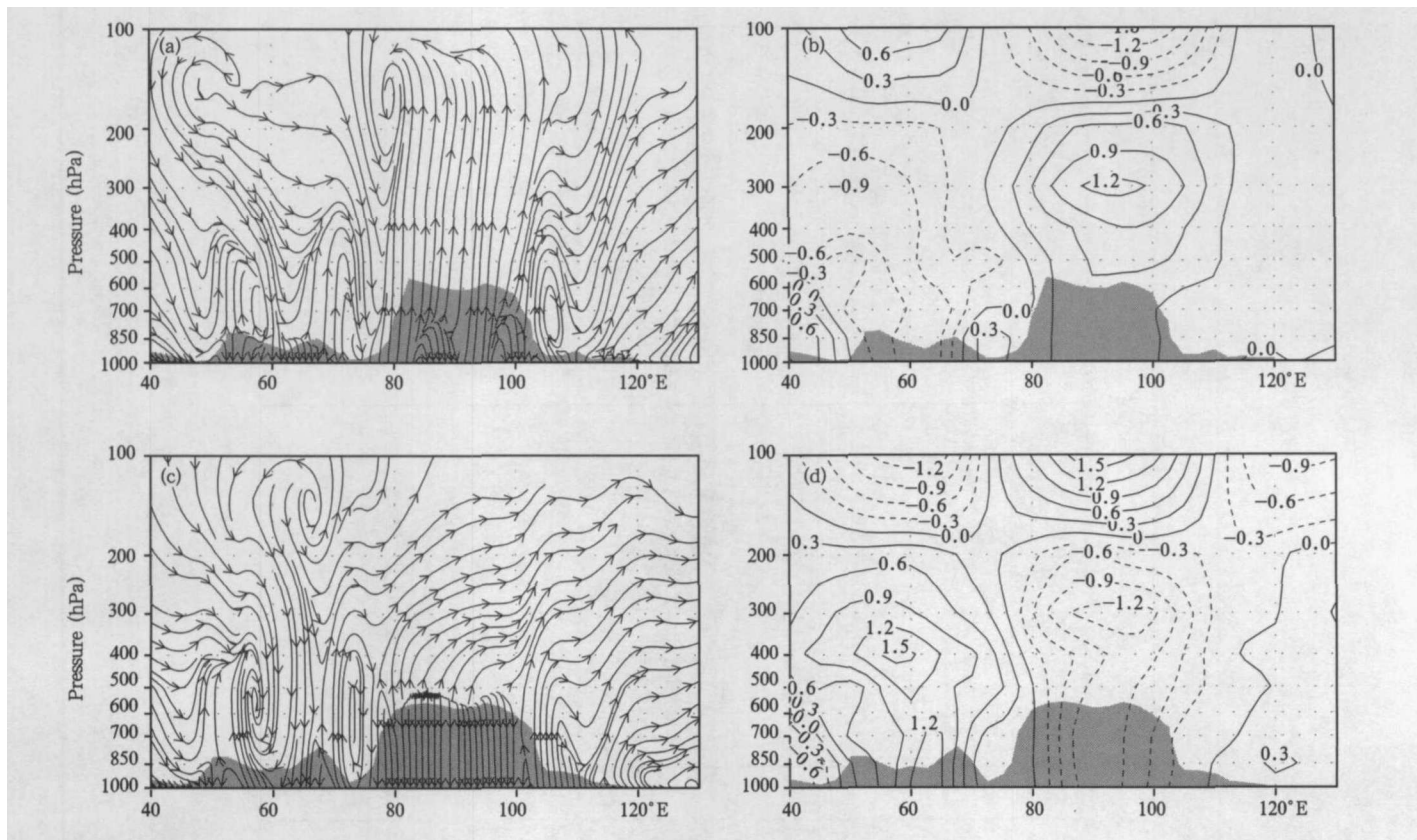


Fig.8. The pressure-longitude cross-sections composed for the TM (a and b, along 30°N) and the IM (c and d, along 32.5°N). (a) and (c) are vertical circulation (w is amplified 150 times when plotting); (b) and (d) are potential temperature anomalies (unit: K). Seventy-seven TM cases and 62 IM cases are included on July-August pentads from 1980-1994.

indicated that the SAH center had a feature of warm preference. Further decompositions for the thermodynamic equation along the latitudes of the SAH ridge-line for the TM and IM were illustrated in Fig.9. It was shown that the warming in TM case was resulted from the diabatic heating over the Tibetan Plateau (Fig.9a), while to a great extent, the strong cooling due to ascent over the Plateau shown in Fig.9b compensated the diabatic heating. In the IM case, warming over the Iranian Plateau in the lower troposphere was mainly due to the local surface heating (Fig.9d), while in the middle troposphere warming over the Iranian Plateau (Fig.9a) was mainly due to the local adiabatic heating (Fig.9c) with compensation by the horizontal advection (figure omitted) and diabatic cooling (Fig.9d). Therefore, maintenance of the SAH over the certain region depended mostly on the thermal effect of the atmosphere over that region. The above mechanism on maintenance of the SAH bimodality as re-

vealed from data diagnosis needs to be further verified by numerical experiments.

As suggested by Tao and Zhu (1964), significant advance and withdrawal of the western Pacific subtropical high at 500 hPa (WPSH) was closely related to the east-west oscillation of the SAH. Zhang et al. (2002) showed that the activities of the SAH bimodality at 100 hPa and the WPSH at 500 hPa were consistent with those in Tao and Zhu (1964), i.e., following the eastward (westward) shifting of the SAH at 100 hPa, the WPSH at 500 hPa behaved westward advancing (eastward withdrawing). Corresponding to the SAH bimodality and the extending-withdrawing of the WPSH at 500 hPa, the climate anomalies over the Asian-Australian monsoon region exhibited distinct patterns. Figure 10 shows the precipitation anomalies over the Asian-Australian monsoon region in both the TM and the IM cases (Zhang and Wu, 2001). In the TM case, due to westward extension of the WPSH

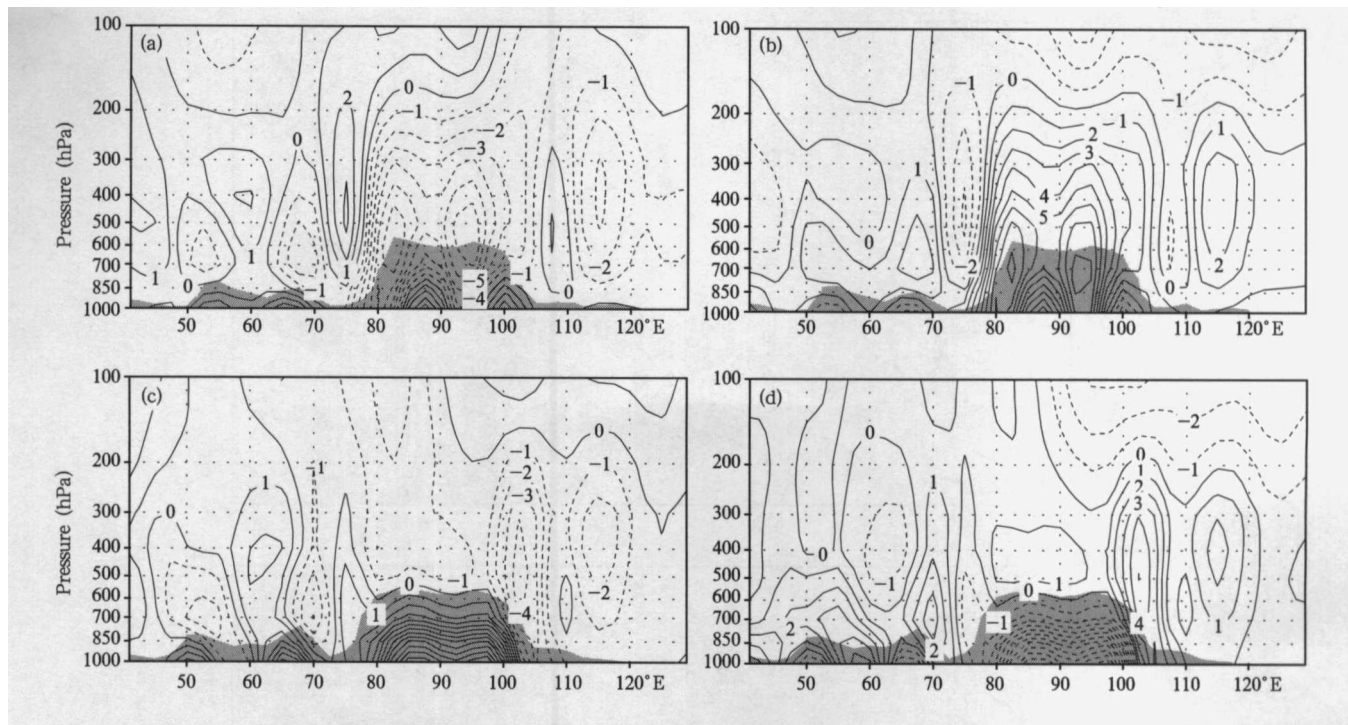


Fig.9. The pressure-longitude cross sections composed for the vertical advection (a, c) and diabatic heating (b, d) terms in thermodynamic equation along 30°N for the TM case (a, b) and IM case (c, d) (unit: K day^{-1}). Seventy-seven TM cases and 62 IM cases are included on July-August pentads from 1980-1994.

at 500 hPa, more precipitation was observed along the northwest part of the subtropical high. Therefore, the enhanced precipitation occurred over the BOB, southern TP, Yangtze River Basin and south of Japan (Fig.10a). In the IM case, however, the WPSH retreated eastward, and the distributions of precipitation anomalies were opposite to those in the TM situation (Fig.10b).

5. Conclusions and discussions

In winter, the transitional boundary from easterly to westerly (WEB) exhibited a relatively zonal structure in subtropics. During the Asian monsoon onset, the ridgelines of the WEB in the low-levels became discontinuous, the westerly trough appeared over this intermittent region, and enhanced rainfall occurred over eastern trough due to the southwesterly winds transporting lots of moisture. Thus, the winter easterlies were replaced by the westerlies from the tropics, resulting in reversal of the prevailing winds. Climatologically, the Asian summer monsoon was initially burst over the eastern BOB and western Indo-China Penin-

sula during the first ten days of May, then over the South China Sea during the second ten days of May, and finally over the western Indian during the first ten days of June. The earliest occurrence of the summer monsoon onset over the eastern BOB was intimately related to the heating over the TP in spring. Because the monsoon onset was affected by various factors, especially atmospheric intraseasonal oscillations, the interannual differences existed in onset dates and sites.

In summer, diabatic heating over the subtropical continent resulted in occurrence of cyclone in the lower troposphere and anticyclone in the upper troposphere. Therefore, the eastern continent was controlled by ascending, while the western continent was dominated by descending. Likewise, strong sensible heating over the TP surface led to presence of the shallow low pressure in near surface and high pressure in mid-upper levels. As a result, ascending prevailed over the TP and the adjacent region to its east, while descending dominated over the west of the TP. Consequently, the subtropical circulation manifested as continental-scale thermal circulation coupled with the in-phase thermal circulation induced by the TP, reinforcing both the

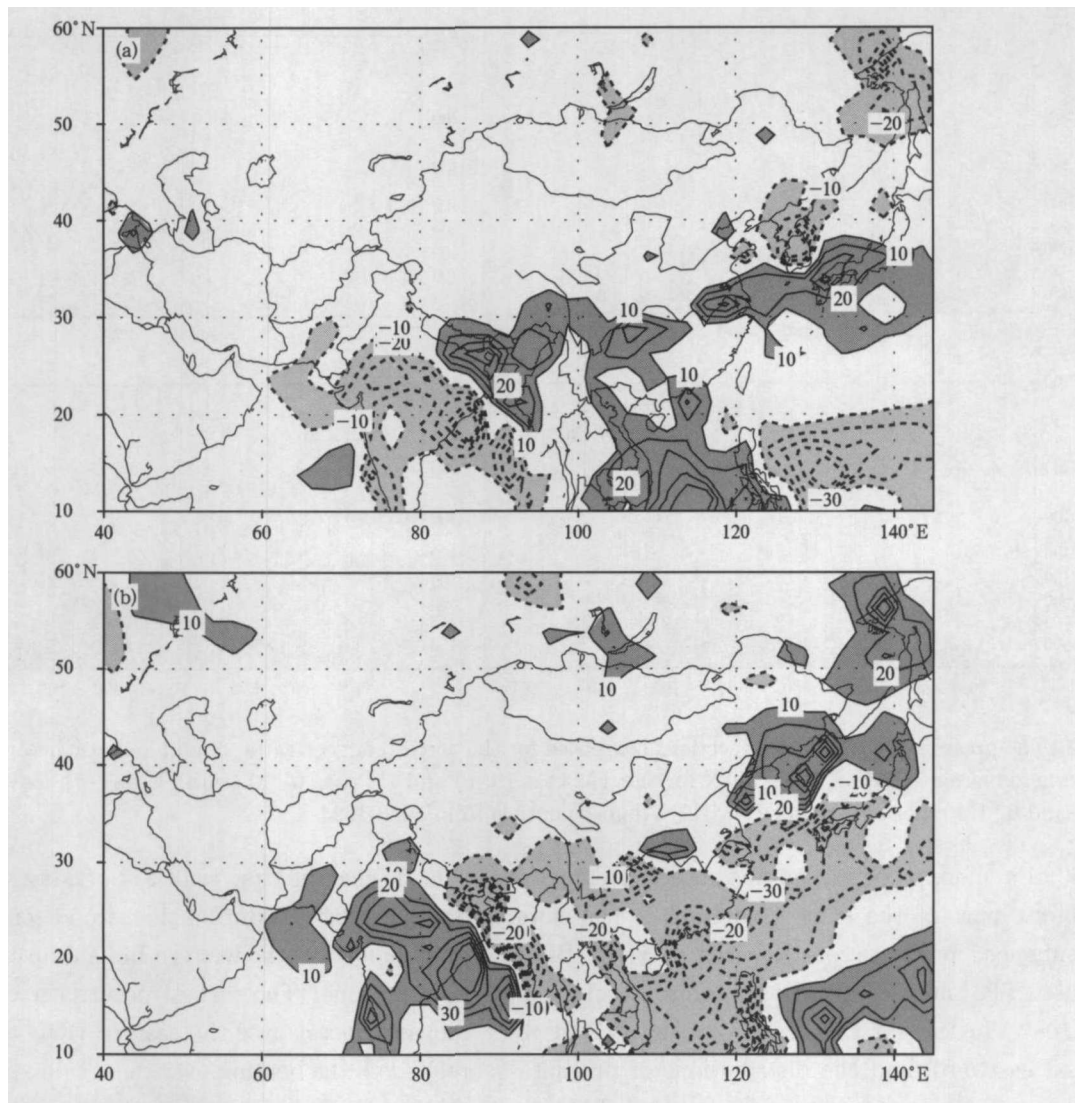


Fig.10. Composition of the precipitation anomalies for the TM (a) and the IM (b). Seventy-seven TM cases and 62 IM cases are included on July-August pentads from 1980-1994.

East Asian summer monsoon and the hot and dry climate in West Asia.

The SAH in upper troposphere over the Asian Continent exhibited bimodality: the TM and IM. The TM of the SAH was characterized by ascending and diabatic heating, while the IM was distinctly marked by descending and adiabatic heating. The TM corresponded to enhanced precipitation appearing over the BOB, the southern TP, the Yangtze River Basin, and the south of Japan, while the IM matched the distributions of precipitation that are opposite to those in the TM.

Up to now, most of studies on the impacts of

the TP on weather and climate have been qualitative. Because of inadequate understanding on the Ocean-Atmosphere-Land interactions, how the TP heating influences local weather and climate as well as global circulation is still a subject to further examination. Many uncertainties still existed when the TP heating state was applied to climate prediction. Moreover, it is insufficient to study the thermal characteristics of the TP in other seasons and their relations to atmospheric circulation, the impact of the TP on global change, and so on. The important task that meteorologists will continue to carry out in the future is to understand and develop thoroughly the climate

dynamics of the TP, and improve weather and climate predictions.

REFERENCES

- Bolin, B., 1950: On the influence of the Earth's orography on the general character of the westerlies. *Tellus*, **2**, 184-195.
- Charney, J. G., and A. Eliassen, 1949: A numerical method for predicting in the perturbation of the middle latitude westerlies. *Tellus*, **1**, 38-54.
- Chen Longxun, Zhu Qiangen, Luo Huibang, et al., 1991: *East Asian monsoon*. China Meteorological Press, Beijing, 362 pp. (in Chinese)
- Duan Anmin, 2003: The influence of thermal and mechanical forcing of the Tibetan Plateau on the climate pattern over East Asia. Ph.D. thesis, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, 161 pp. (in Chinese)
- Ertel, H., 1942: Ein neuer hydrodynamische wirbelsatz. *Meteorology Z. Braunschweig*, **59**, 277-281.
- Flohn, H., 1957: Large-scale aspects of the summer monsoon in South and East Asia. *J. Meteor. Soc. Japan*, **75**, 180-186.
- Gu Zhenchao, 1951: On the importance of the dynamical influence of Tibetan Plateau on the circulation over East Asia. *Science in China*, **2**, 283-303. (in Chinese)
- Hoskins, B. J., 1987: Diagnosis of forced and free variability in the atmosphere. *Atmospheric and oceanic variability*. James Glaiser House, UK, 57-73.
- Hoskins, B. J., 1991: Towards a PV- θ view of the general circulation. *Tellus*, **43AB**, 27-35.
- Li Weiping, Wu Guoxiong, and Liu Yimin, 2001: How the surface processes over the Tibetan Plateau affect the summertime Tibetan anticyclone: Numerical experiments. *Chinese J. Atmos. Sci.*, **25**(6), 809-816. (in Chinese)
- Liu Fuming and Wei Shuhua, 1987: The east-west oscillation of the 100 hPa South Asian high and its forecasting. *The effects of the Tibetan Plateau on weather of China during summer*. Science Press, Beijing, 111-117. (in Chinese)
- Liu Yimin, Wu Guoxiong, Liu Hui, and Liu Ping, 2001: Condensation heating of the Asian summer monsoon and the subtropical anticyclone in the Eastern Hemisphere. *Clim. Dyn.*, **17**, 327-338.
- Luo Siwei, Qian Zhengan, and Wang Qianqian, 1982: The study for 100 mb South Asian high and its association with climate of East China. *Plateau Meteorology*, **1**(2), 1-10. (in Chinese)
- Mao Jiangyu, 2001: Variation in the configuration of the subtropical anticyclone during seasonal transition and the mechanism of the Asian monsoon onset. Ph.D. thesis, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, 139 pp.
- Mao Jiangyu, Duan Anmin, Liu Yimin, and Wu Guoxiong, 2003: Change in the tilting of the ridgeline surface of the subtropical anticyclone and the predictability of the onset of the Asian summer monsoon. *Chinese Science Bulletin*, **48**(Supp. II), 18-23.
- Mao Jiangyu, J. C. L. Chan, and Wu Guoxiong, 2004: Relationship between the onset of the South China Sea summer monsoon and the structure of the Asian subtropical anticyclone. *J. Meteor. Soc. Japan*, **82**, 845-859.
- Mao Jiangyu, Wu Guoxiong, and Liu Yimin, 2002a: Study on modal variation of subtropical high and its mechanism during seasonal transition. Part I: Climatological features of subtropical high structure. *Acta Meteorologica Sinica*, **60**(4), 400-408. (in Chinese)
- Mao Jiangyu, Wu Guoxiong, and Liu Yimin, 2002b: Study on modal variation of subtropical high and its mechanism during seasonal transition. Part II: Seasonal transition index over Asian monsoon region. *Acta Meteorologica Sinica*, **60**(4), 409-420. (in Chinese)
- Mao Jiangyu, Wu Guoxiong, and Liu Yimin, 2002c: Study on modal variation of subtropical high and its mechanism during seasonal transition. Part III: Thermodynamic diagnoses. *Acta Meteorologica Sinica*, **60**(6), 647-659. (in Chinese)
- Queney, P., 1948: The problem of air flow over mountains: A summary of theoretical studies. *Bull. Amer. Meteor. Soc.*, **29**, 16-29.
- Rodwell, M. J., and B. J. Hoskins, 2001: Subtropical anticyclones and summer monsoons. *J. Climate*, **14**, 3192-3211.
- Tao Shiyan and Zhu Fukang, 1964: The variation of 100 mb circulation over South Asia in summer and its association with march and withdraw of West Pacific subtropical high. *Acta Meteorologica Sinica*, **34**, 385-395. (in Chinese)
- Wu Guoxiong, 1984: The nonlinear response of the atmosphere to large-scale mechanical and thermal forcing. *J. Atmos. Sci.*, **41**, 2456-2476.

- Wu Guoxiong, 2004: Recent progress in the study of the Qinghai-Xizang Plateau climate dynamics in China. *Quaternary Sciences*, **24**(1), 1-9. (in Chinese)
- Wu Guoxiong and Liu Yimin, 2000: Thermal adaptation, overshooting, dispersion, and subtropical high. Part I: Thermal adaptation and overshooting. *Chinese J. Atmos. Sci.*, **24**(4), 433-436. (in Chinese)
- Wu Guoxiong and Zhang Yongsheng, 1998: Tibetan Plateau forcing and the timing of the monsoon onset over South Asia and the South China Sea. *Mon. Wea. Rev.*, **126**, 913-927.
- Wu Guoxiong, Li Weiping, Guo Hua, et al., 1997: Sensible heating pump over the Tibetan Plateau and Asian summer monsoon. *Selected Papers in Commemoration of Professor Zhao Jiuzhang*. Science Press, Beijing, 116-126. (in Chinese)
- Wu Guoxiong and Liu Yimin, 2003: Summertime quadruplet heating pattern in the subtropics and the associated atmospheric circulation. *Geophys. Res. Lett.*, **30**(5), 1201, doi: 10.1029/2002GL016209.
- Wu Guoxiong, Liu Yimin, and Liu Ping, 1999: The effect of spatially nonuniform heating on the formation and variation of subtropical high. Part I: Scale analysis. *Acta Meteorologica Sinica*, **57**(3), 257-263. (in Chinese)
- Ye Duzheng, Tao Shiyan, and Li Maicun, 1958: The abrupt change of circulation over Northern Hemisphere during June and October. *Acta Meteorologica Sinica*, **29**(4), 249-263. (in Chinese)
- Yeh, T. C., 1950: The circulation of the high troposphere over China in the winter of 1945-1946. *Tellus*, **2**(3), 173-183.
- Yeh T. C., Luo Siwei, and Zhu Baozhen, 1957: The Structure of atmospheric circulation over the Xizang (Tibet) Plateau and its neighborhood and heat balance in troposphere. *Acta Meteorologica Sinica*, **28**(2), 108-121. (in Chinese)
- Zhang Kesu, Chen Zhangzhao, Zhou Mingyu, et al., 1977: Simulation of the movements of the Tibetan high and the application on summer prediction. *Science in China*, **4**, 360-368. (in Chinese)
- Zhang Qiong and Wu Guoxiong, 2001: Relationships between the South Asian high and the flood/drought events over the Yangtze valley. *Acta Meteorologica Sinica*, **59**(5), 569-577. (in Chinese)
- Zhang Qiong, Wu Guoxiong, and Qian Yongfu, 2002: The bimodality of the 100 hPa South Asian high and its relationship to the climate anomaly over East Asia in summer. *J. Meteor. Soc. Japan*, **80**(4), 733-744.
- Zhu Baozhen and Song Zhengshan, 1981: The information process of the Tibetan high and its oscillation-the observation analysis. *Collection papers on the Tibetan Plateau Meteorology Experiments (No.1)*. Science Press, 303-313. (in Chinese)