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Seasonal Variation of Climatological Bypassing Flows around the Tibetan Plateau

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ABSTRACT

The present study investigated diagnostically the seasonal variation of the bypassing flows caused by the splitting effect of the Tibetan Plateau (TP). The relationships among the splitting bypassing flows around the TP to precipitation in China, the westerly jet stream, and the thermal status over the TP are revealed. The bypassing flows occur from the 1st to the 22nd pentad and from the 59th to the 73rd pentad, respectively, and they disappear from the 29th to the 58th pentad. They are strongest in winter from the 1st to the 22nd pentad and from the 59th to the 73rd pentad, respectively. During the rebuilding of the bypassing flows from mid-October to mid-February, they are the main cause of precipitation over southeastern China. The enhancement of the bypassing flow intensity in March can cause the precipitation to increase in the early stage of the persistent spring rain over southeastern China. From winter to summer, the seasonal transition of the bypassing flows in the lower troposphere precedes that of the westerly jet stream axis in the upper troposphere to the west of the TP by ∼4 pentads, while from summer to winter lags by ∼4 pentads. The seasonal variation of the thermal status over the TP plays an important role in the bypassing flows around the TP. The strengthening of the heating over the TP weakens the bypassing flows, and the increase in cooling over the TP is related to the rebuilding and strengthening of the bypassing flows.

Key words: Tibetan Plateau, bypassing flows, seasonal variation

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1. Introduction

The Tibetan Plateau (TP), with an average altitude of ∼4 km, occupies ∼15° latitude meridionally and > 30° longitude zonally. It occupies ∼25% of China's territory and reaches a height of ∼33% the troposphere. Such a huge obstacle is able to exert a significant dynamic effect on the atmospheric general circulation. In boreal winter and spring, obstructed by the TP, the westerly in the lower troposphere is split into two branches, forming bypassing flows around the plateau to the north and south sides, respectively. Yeh (1950) and Ye and Gu (1955) pointed out that the principal features of the general circulation over China are two belts of maximum westerlies, one flowing around the southern edge of the TP and the other around the northern edge of the TP. The bypassing westerlies around the TP mainly occur in the lower troposphere (Luo et al., 1985) and are affected by the mechanic barrier effect forced by the large-scale topography of the TP (Ding, 1992). Using an atmospheric general circulation model (GCM), Liang et al. (2005) showed that the northern branch of the bypassing flow strengthens the cold air moving southward to eastern Asia. In spring the intensity of the southern branch enhances when the heating over the TP weakens; the enhanced southern branch transports more moisture to the southern China.

Obvious and abrupt changes of the atmospheric general circulation occur over East Asia during seasonal transitions. In early summer, the westerly wave adjusts and the westerly jet moves northward abruptly.

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As discovered by Ye et al. (1958) and Yeh et al. (1959), the most distinct feature of the abrupt change of circulation is the westerly jet stream at 200 hPa moving northward or southward sharply. In general, in mid-June the westerly jet moves rapidly from 30°–32°N to north of 35°N, and the circulation in the Northern Hemisphere changes from a winter pattern to a summer pattern; the opposite change occurs in mid-October. Li and Luo (1983) demonstrated that this abrupt change is a kind of nonlinear and dissipation phenomenon caused by the forcing of various heating mechanisms and the interaction between thermal and dynamic processes.

The northward jump of the westerly jet stream is closely related to the onset and advance of the Asian summer monsoon during the seasonal transition from spring to summer. Zhu et al. (1990) and Kuang and Zhang (2006) indicated that the East Asian subtropical westerly jet stream is the most important circulation system in the upper troposphere; it affects the onset of South China Sea summer monsoon, mei-yu activity, and the onset of the Indian summer monsoon. By investigating the role of the TP in the seasonal transition, Zheng and Wu (1995) found that the thermal and dynamic effects of the TP accelerate the northward movement of the subtropical westerly jet stream and shifts it more northward by ∼7° latitude in ∼20 days. The thermal and dynamic effects also help the shifted jet stream remain around the northern periphery of the TP. The northward shifts of the East Asian westerly jet stream are closely related to Asian summer monsoon activities (Li et al., 2004), such as the onset of the South China Sea summer monsoon (Li and Wu, 2000), the duration of the mei-yu season in June and July (Tao et al., 1958), and the onset of Indian summer monsoon (Lau and Li, 1984; He et al., 1987).

These previous studies have revealed that the westerly in the lower troposphere is split into two branches forming bypassing flows around the TP in boreal winter and spring. However, the seasonal variation of the bypassing flows is still unclear. For example, it is not clear when the bypassing flows vanish during the transition from spring to summer and rebuild from summer to autumn climatologically. Although abrupt changes have been observed during the seasonal transition from spring to summer or from summer to autumn for the lower and upper tropospheric westerly systems, the behaviors of the bypassing flows during the seasonal transition remain unknown. To study these issues, using the data and method described in section 2, we investigated the seasonal evolution and intensity variation of the bypassing flows; we report our findings in sections 3 and 4, respectively. The association of the bypassing flows with precipitation in China is discussed in section 5. In section 6 we present the relationships among the bypassing flows, the westerly jet, and the thermal status of the TP. Conclusions are presented in section 7.

2. Data and methods

In this study, we utilized both daily and monthly meteorological reanalysis data obtained from the National Center for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR; Kalnay et al., 1996), with global coverage (2.5° × 2.5° grid resolution) for the period 1951–2010. The daily precipitation data from 740 rain-gauge stations in China for the period 1951–2010 were obtained from the China Meteorological Administration (CMA).

The climatological daily and monthly data were calculated in terms of the averages in 1951–2010. The 5-day (pentad) averaged values were calculated from the climatological daily data. There are 73 pentads in each year. The first pentad is from 1 to 5 January and the last from 27 to 31 December.

To investigate the thermal status over the TP, we calculated the apparent heat source based on the method presented by Yanai et al. (1973). Following Zhou and Zhang (2005) and Zhang and Zhou (2009), the TP region was considered to be the area of 27.5°–37.5°N, 75°–105°E with altitude $>$ 3000 m.

3. Seasonal evolution of the bypassing flows around the TP

Figure 1 shows climatological wind fields at 700 hPa in winter (January) and summer (July), respectively. In winter (Fig. 1a), the westerlies to the west of the TP centered at ∼30°N split into two branches flowing around the TP. The meridional winds show divergence upstream of the TP, deflecting southward and northward, respectively, because of the splitting of the TP and convergence downstream to the east of the TP. The southwesterlies north of 30°N, upstream of the TP, flow around the northern periphery of the TP and form a ridge at ∼90°E, where the winds turn northwesterly and flow from high to low latitudes. The northwesterlies south of 30°N in the upstream of the TP flow around the southern periphery of the TP and form a trough in the north of the Bay of Bengal at ∼90°E, where the climatological southern branch trough is located (Wei et al., 2008; Suo and Ding, 2009).

From Fig. 1a we can see that the dynamic influence of the TP on the winds is the divergence of meridional winds upstream of the TP and convergence down-

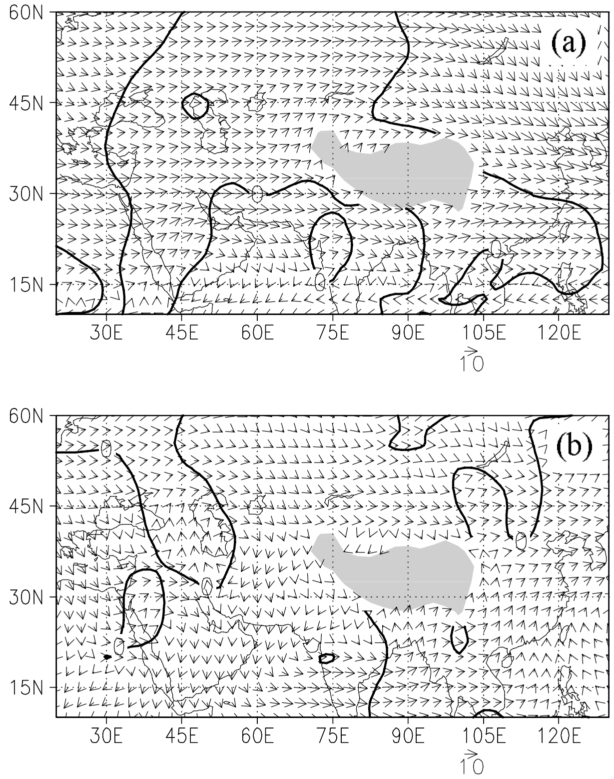

Fig. 1. Climatological winds (vectors, units: m s^{-1}) and 0 m s^{-1} contour line of meridional winds (solid lines) at 700 hPa for (a) January and (b) July. The climatology is calculated in terms of average in 1951–2010. The Tibetan Plateau above 3000 m is shaded.

stream. Therefore, the effect of the TP on splitting the westerlies can be displayed by the zero contour line of meridional winds, which we called the meridional wind divergence line (MWDL). In Fig. 1a we also show the climatological MWDL at 700 hPa for winter. The climatological location of the MWDL between 55°E and 70°E upstream of the TP is located at ~30°N, indicating that the meridional winds diverge there. The MWDL downstream of the TP, formed by the convergence of the two splitting branches of bypassing flows upstream of the TP, appears also at ~30°N.

In summer (Fig. 1b), the circulations around the TP are different from those in winter (Fig. 1a). Upstream of the TP, an anticyclone is centered at ~38°N, 39°E. The northerlies associated with the anticyclone prevail between the western periphery of the TP and 50°E. The westerlies shift to the north of ~40°N, and there are no westerlies to the west of the TP. Also, there are no systematic westerlies along the southern periphery of the TP (like those that appear in winter). A cyclone is located over northern India in association with the Indian summer monsoon. Downstream of the TP, the southerlies of the East Asian summer monsoonal flow occur. By examining the MWDL, neither the divergence of the meridional winds upstream of the TP nor the convergence downstream can be determined. Therefore, in summer the westerly splitting to the west of the TP and associated bypassing flows around the TP disappear. This is mainly a cyclonic circulation surrounding the TP because of the heating of the TP.

To investigate the seasonal variation of westerly flows splitting to the west of the TP, we calculated the climatological MWDL for each month (Fig. 2). From January to March (Fig. 2a), the MWDL in all 3 months steadies at ~30°N upstream of the TP. In April the MWDL moves northward to ~34°N (Fig. 2b); it jumps northward significantly up to near 45°N in May and disappears in June. From July to September (Fig. 2c), the MWDL continues to vanish. It rebuilds in October and shifts southward continuously from November to December when it reaches ~30°N again (Fig. 2d). The MWDL upstream of the TP feature shows obvious seasonal variation from October to May and vanishes from June to September. Because the MWDL represents the splitting of westerlies into two branches of bypassing flows around the TP, climatologically the dynamic role played by the TP in splitting westerlies mainly exists from October to May.

To understand the variance of the winds at 700 hPa, the standard deviation of zonal and meridional winds at 700 hPa, respectively, were calculated using the climatological daily data in terms of averages in 1951–2010 (Fig. 3). Around the TP there are three maximum centers of the zonal wind standard deviation with the standard deviation exceeding 4.0: to the west of the TP and the Arabian Peninsula, northern India, and south of the Yangtze River of China (Fig. 3a). The appearance of the maximum standard deviation centers around the western and southern peripheries of the TP reflects significant seasonal variation of the southern branch of the bypassing flow in these areas, which is in good agreement with the seasonal variation of the MWDL (Fig. 2). For the standard deviation of the meridional winds (Fig. 3b), a maximum center can be found to the west of the TP, indicating strong seasonal variation of the meridional winds there, which is in accordance with the seasonally vanishing and rebuilding of the MWDL (Fig. 2).

Because of the close connection of the MWDL to the west of the TP with the splitting effect of the TP on the westerlies, the MWDL to the west of the TP can represent the appearance of the bypassing flows around the TP caused by the splitting effect of the TP on the westerlies. Using the climatological daily winds at 700 hPa, we selected the zero meridional wind

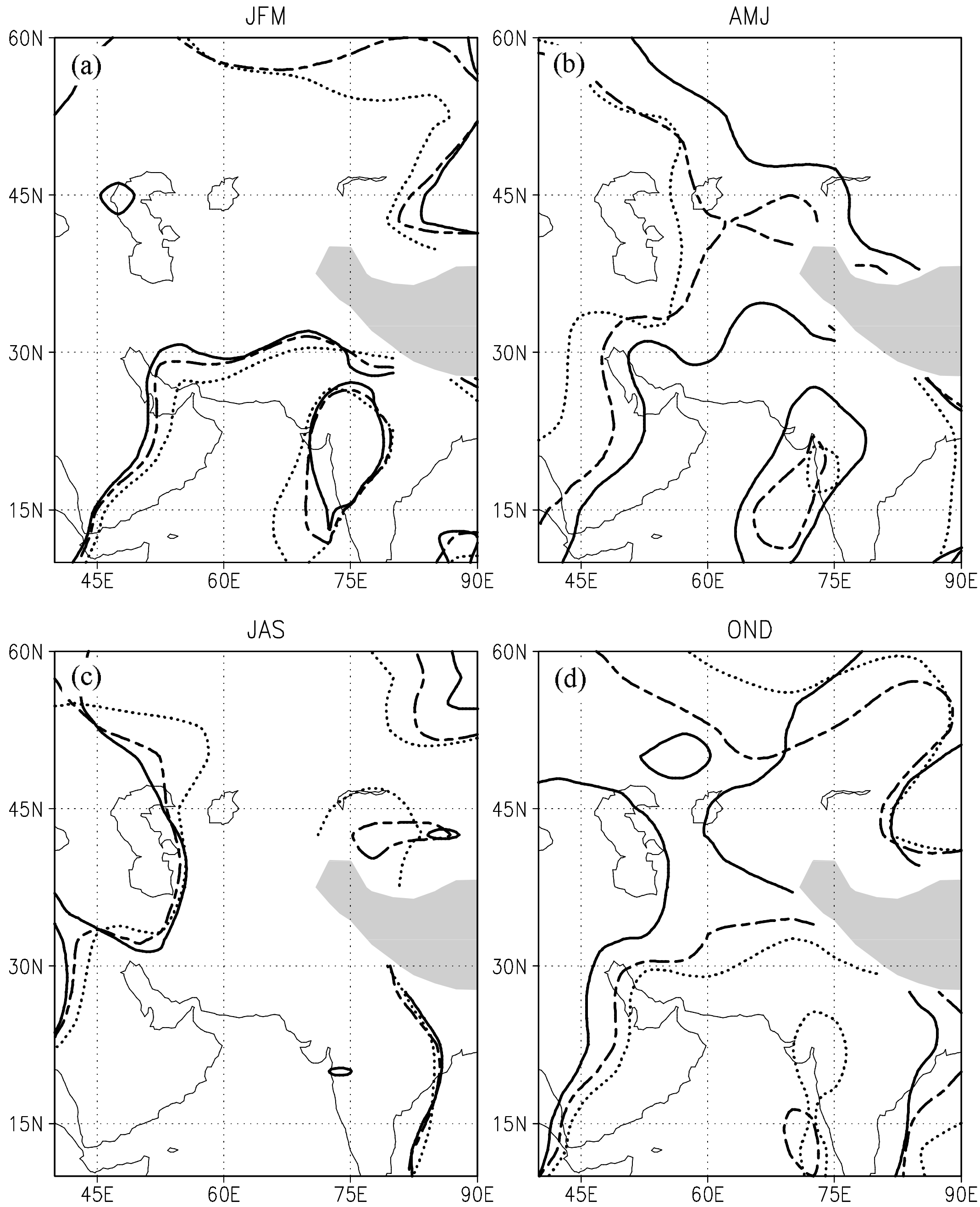

Fig. 2. Climatological monthly 0 m s^{-1} contour lines of meridional winds at 700 hPa for (a) January–March, (b) April–June, (c) July–September, and (d) October–December. Solid lines stand for January, April, July, and October, respectively; dashed lines for February, May, August and November; and dotted lines for March, June, September and December.

at the grid points between 55°E and 70°E upstream of the TP. Because the data has 2.5° grid resolution, there is a total of seven grids between 55°E and 70°E. If the zero meridional winds appear in more than four grids, we considered them to represent bypassing flows around the TP. Under this definition, the occurrence of the bypassing flows can be expressed by the MWDL when the zero meridional winds at more than four grids between 55°E and 70°E.

We calculated the pentad MWDL at 700 hPa using climatological daily data. To investigate the seasonal variation of the bypassing flows, we calculated the time evolution of the averaged latitude of the zero meridional wind grids when the zero pentad merid-

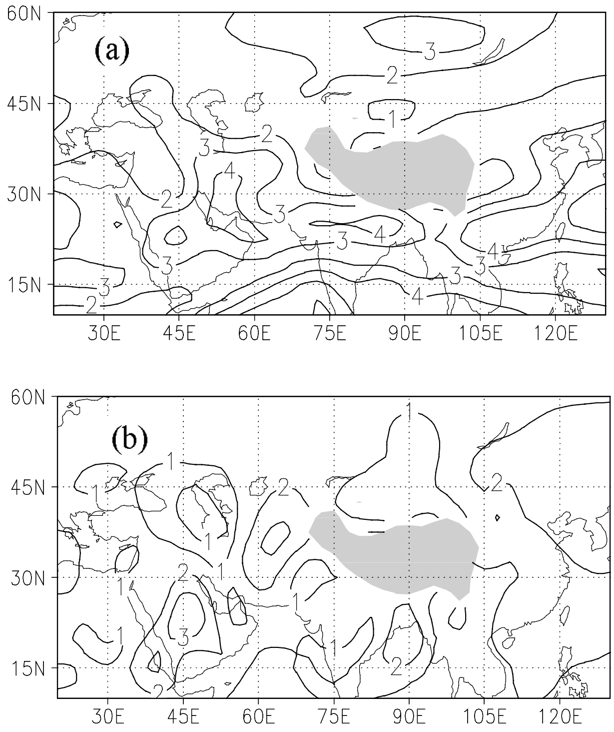

Fig. 3. Standard deviation for (a) zonal and (b) meridional winds at 700 hPa calculated using climatological daily data in terms of average in 1951–2010. The Tibetan Plateau above 3000 m is shaded.

ional winds between 55°E and 70°E appear at more than four grids (called the pentad MWDL-WTP hereafter). As shown in Fig. 4, the pentad MWDL-WTP remains around 30°N from the 1st to the 22nd pentad when an obvious northward jump occurs. The pentad MWDL-WTP shifts northward rapidly from 30°N at the 22nd pentad to 37°N at the 28th pentad. The pentad MWDL-WTP disappears from the 29th to the 58th pentad. During the transition season between summer and winter, the pentad MWDL-WTP rebuilds at the 59th pentad. From then on, the pentad MWDL-WTP moves southward rapidly from 37°N to 30°N at the 62nd pentad. As pointed out by Kuang et al. (2008), the rebuilding time of the pentad MWDL-WTP at the 59th pentad is associated with the seasonal transition of the general circulation from autumn to winter, during which time a signal can be found primarily in the surface temperature over the TP. At the 56th pentad, the seasonal transition of the surface temperature first appears in the vicinity of central TP at ~80°E then expands to the neighboring area. Here we can see that the splitting effect of the TP on the westerlies happens from the 1st to the 22nd pentad and from the 59th to the 73rd pentad, respectively, during which time the splitting bypassing flows around the TP prevail. From the 29th to the 58th pentad, the splitting bypassing flows around the TP and the splitting effects disappear.

In addition to the climatological mean seasonal evolution of the bypassing flows, we also investigated their interannual and interdecadal variability. As seen in Fig. 4, the MWDL-WTP is steadily situated at ~30°N from the 1st to the 22nd pentad and shifts northward thereafter. We thus calculate the mean latitude of the MWDL-WTP in the period from the 1st to the 22nd pentad for each year. The time evolution of the yearly averaged MWDL-WTP from 1951 to 2010 is shown in Fig. 5. Interannual variability is obvious. The northernmost and southernmost positions of the yearly averaged MWDL-WTP are 35°N in 1962 and 24.4°N in 1992, respectively. Although no clear climate trend for the yearly averaged MWDL-WTP was revealed, the interdecadal variability can be observed. We calculated the MWDL-WTP positions

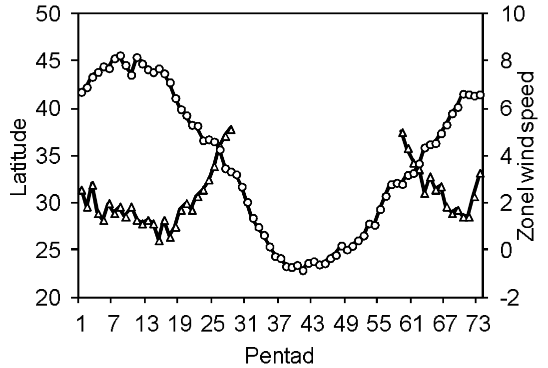

Fig. 4. Time evolution for the latitudes of the pentad MWDL-WTP (triangle line, units: °N) and climatological pentad zonal winds averaged over 25°–37.5°N, 50°–70°E at 700 hPa (circle line, units: m s^{-1}).

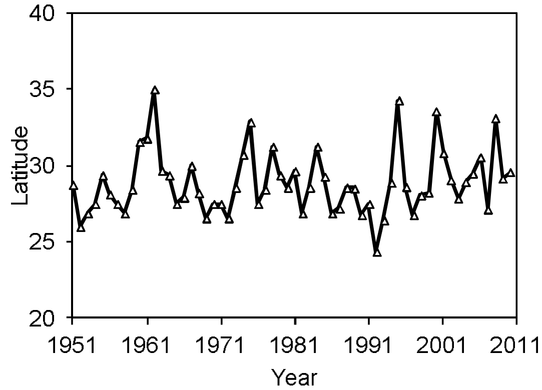

Fig. 5. Time evolution of the yearly averaged mean MWDL-WTP between the 1st and the 22nd pentad. (units: °N)

for each decade. The average position was 28.10°N in 1951–1960, 29.35°N in 1961–1970, 29.13°N in 1971–1980, 28.35°N in 1981–1990, 28.68°N in 1991–2000, and 29.58°N in 2001–2010. The positions of the decadal MWDL-WTP were located to the south of 29°N in 1950s, 1980s, and 1990s, and to the north of 29°N in 1960s, 1970s, and 2000s, respectively.

4. Seasonal intensity variation of the bypassing flows around the TP

As mentioned in section 3, the bypassing flows around the TP appear and vanish seasonally in terms of the latitudes of the pentad MWDL-WTP. We investigated the seasonal intensity variation of the bypassing flows and its relation to the latitudes of the pentad MWDL-WTP. Because the bypassing flows originate from the westerlies to the west of the TP, the intensity of the bypassing flows can be judged by the zonal winds upstream of the TP. Figure 4 shows the climatological pentad zonal winds at 700 hPa averaged over 25°–37.5°N, 55°–70°E to the west of the TP. The intensity of the pentad zonal winds is generally correlated negatively with the latitudes of the pentad MWDL-WTP. The more northward the pentad MWDL-WTP is located, the weaker the zonal winds. The zonal winds are strong in winter and weak in summer; the maximum appears in February and the minimum in July. From the 29th to the 58th pentad, when the bypassing flows vanish, the intensity of zonal winds decreases to <3 m s^{-1}, and even the easterly flow prevails from the 36th to the 47th pentad over the area west of the TP (25°–37.5°N, 55°–70°E).

The latitudinal shift of the pentad MWDL-WTP to the west of the TP is closely related to the intensity of the bypassing flows. The bypassing flows are strongest in winter from the 1st to the 22nd pentad and from the 59th to the 73rd pentad, respectively. The northward rapid shift of the pentad MWDL-WTP in the transition period between spring and summer from the 22nd to the 28th pentad and the southward shift between summer and autumn from the 59th to the 62nd pentad correspond to the weakening and strengthening of the bypassing flows, respectively. During the period from the 29th to the 58th pentad of very weak westerlies or even easterlies to the west of the TP, the bypassing flows vanish.

5. The bypassing flows around the TP and precipitation in China

Figure 6 shows the climatological precipitation over China in January. Precipitation is mainly concentrated in the southeastern part of China downstream of the TP. The maximum precipitation centers (>60 mm) arise between 25°N and 30°N in southeastern China. As shown in Fig. 1a, in January the zero contour line of the meridional winds appears at ∼30°N downstream of the TP, formed by the convergence of the two splitting bypassing flows around the TP. The major precipitation occurs to the south of the zero contour line of the meridional winds, where the southerlies prevail. Zhao et al. (2007) indicated that in late winter and early spring, the northern extent of precipitation in southeastern China coincides with that of the southerlies, which bring warm and moist air from the south. Because the southern branch of the bypassing flows to the south of the zero contour line transport warm and moist air downstream of the TP, obviously precipitation occurs mainly in southeastern China.

To investigate the seasonal features of the relationship between the bypassing flows and the precipitation in East China, we calculated the time-latitude cross section of the climatological daily MWDL in the upstream of the TP, zero contour line of the meridional winds in the downstream of the TP and the climatological daily precipitation over East China, respectively (Fig. 7). In general, precipitation is mainly located to the south of the zero contour line where the southerlies prevail. The precipitation amount is smallest in winter and is asymmetric in spring and autumn, with more precipitation in spring and less in autumn. Precipitation that is >4 mm d^{-1} jumps northward in middle June together with the zero contour line, which shifts sharply southward in early September.

From November to middle February, the daily MWDL and zero contour line appear simultaneously, indicating that the formation of the zero contour line in East China is the result of the bypassing flows

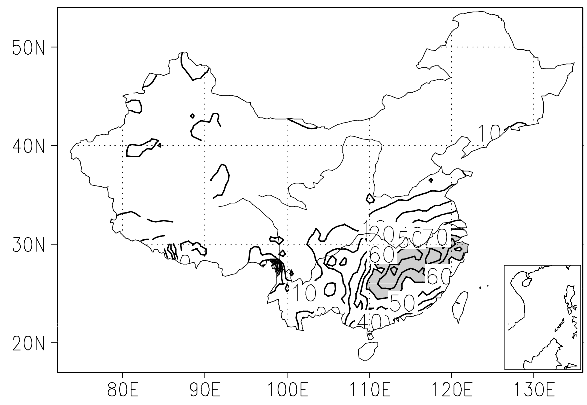

Fig. 6. Climatological precipitation over China in January (units: mm). The climatology is calculated in terms of the average in 1951–2010. Precipitation > 60 mm d^{-1} is shaded.

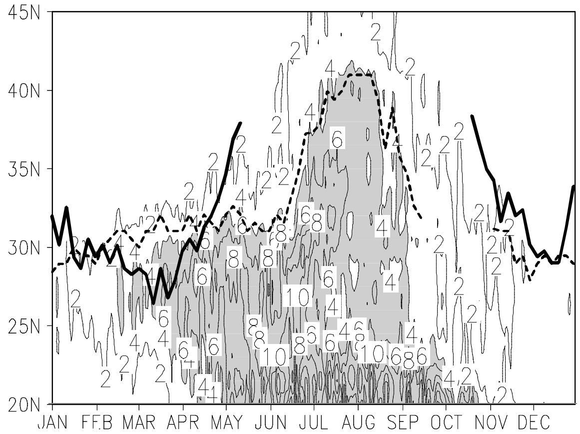

Fig. 7. Time-latitude cross sections of the climatological daily MWDL averaged between 55°E and 70°E in the upstream of the TP (thick solid lines), zero contour line of the meridional winds averaged between 100°E and 120°E in the downstream of the TP (dashed lines) and the climatological daily precipitation averaged over eastern China between 100°E and 120°E (contours; units: mm d^{-1}). The climatological daily precipitation >4 mm d^{-1} is shaded.

around the TP, which is the main cause of precipitation that is $\leqslant 2$ mm d^{-1} over Southeast China. In March, the daily MWDL shifts more southward than in January and February and the precipitation over Southeast China increases, reaching to > 4 mm d^{-1} between 25°N and 30°N. The southward shift of the MWDL corresponds to the enhancement of the bypassing flow intensity, which is possibly responsible for the increase of the precipitation in southeastern China. In April, the MWDL moves northward rapidly, indicating the weakening of bypassing flows and their effect on the precipitation in southeastern China. Although precipitation is continuously increasing from the spring to summer, the role of the bypassing flows in the formation of southerlies south of the zero contour line become less important because of the weakening of the bypassing flows. In fact, in spring, persistent rain (Tian and Yasunari, 1998) prevails in southeastern China. In addition, the mechanical effect of the TP, the thermal effect of the TP on the persistent spring rain becomes more dominate (Wan and Wu, 2007; Jiang et al., 2009). In addition to the role played by the bypassing flows because of the splitting effect of the TP, the southerlies in southeastern China also arise from the enhancement of the springtime subtropical tropospheric temperature gradient between the southwestern China and the western North Pacific (Zhao et al., 2007). In May, the daily MWDL disappears completely. Therefore, because of the weakening and even vanishing of bypassing flows in late spring, the strengthening of the southerly winds over southeastern China is mainly associated with both the thermal effect of the TP and the zonal gradient of the tropospheric temperature over East Asia between land and ocean in the subtropics. The southerlies are favorable for transporting warm and wet air to southern China and cause heavy rainfall there.

In middle June, both the zero contour line and the front of the precipitation that is >4 mm d^{-1} shifts rapidly northward. In July and August, they reach a latitude exceeding 40°N. The southerlies south of the zero contour line in summer result from the flow of the East Asian summer monsoon, which transports water vapor to East China from both the Indian summer monsoon region and the western tropical Pacific (Zhang, 2001). The zero contour line disappears from middle September to the end of October, forming a unique period without a zero contour line. This period is within the time during which the East Asian summer monsoon retreats and the MWDL rebuilds; therefore it is unfavorable for the southerlies to meet the northerlies in East China to form the zero contour line of meridional winds. Because the formation of the precipitation in East China needs both the dry and cold air from the north and the wet and warm air from the south, the disappearance of the zero contour line means that such conditions are not satisfied and thus precipitation sharply weakens over East China. As shown in Fig. 7, the precipitation in autumn is less than in spring, obviously. In mid-October the MWDL rebuilds and shifts southward rapidly, indicating the strengthening of the bypassing flows. The bypassing flows affect the southerlies in southeastern China again and bring precipitation there in winter.

6. Relation of bypassing flows to westerly jet stream and thermal status of the TP

During the seasonal transition, the most obvious feature in atmospheric general circulation is the north–south shift of the westerly jet stream axis. Because the bypassing flows are also characterized by obvious seasonal variation, we calculated time evolutions of the latitudes for the climatological pentad MWDL-WTP at 700 hPa and westerly jet stream axis at 200 hPa averaged between 55°E and 70°E to the west of the TP (Fig. 8). The westerly jet stream axis remains at ~27.5°N from the 1st to the 24th pentad and then shifts northward. From the 36th to the 48th pentad, the westerly jet stream axis reaches its northernmost latitudes around 42.5°N and 45°N then moves southward to ~30°N at the 60th pentad. Generally, the seasonal latitudinal variation of the pentad MWDL-WTP in the lower troposphere is in accordance with that of the westerly jet stream axis in the upper troposphere. The seasonal transition of the pentad MWDL-WTP is earlier than that of the westerly jet stream axis from winter to summer and later from summer to winter. When the westerly jet stream axis situates north of 32.5°N, the pentad MWDL-WTP disappears and no bypassing flows occur.

During the seasonal transition from winter to summer, the pentad MWDL-WTP begins to shift northward at the 17th pentad, while the westerly jet stream axis sustains at ~27.5°N. Until the 24th pentad, the westerly jet stream axis begins to shift northward when the pentad MWDL-WTP reaches at ~32.5°N. The pentad MWDL-WTP disappears at the 28th pentad and the westerly jet stream axis continues to shift further northward. During the seasonal transition from summer to winter, the rebuilding of the pentad MWDL-WTP is at the 59th pentad at ~37.5°N when the westerly jet stream axis has shifted to ~32.5°N. From winter to summer, the seasonal transition of the bypassing flows in the lower troposphere precedes that of the westerly jet stream axis in the upper troposphere by ~4 pentads. This phenomenon also occurs in other weather systems over East Asia. For example, during the onset of the Asian summer monsoon, the seasonal transition exhibits a reversal of the meridional temperature gradient in the vicinity of the subtropical high ridge, which appears earlier in the lower troposphere than in the middle and upper troposphere (Mao et al., 2002). However, here we can also see that from summer to winter, the seasonal transition is opposite that from winter to summer. The seasonal transition of the bypassing flows lag that of the westerly jet stream axis by ~4 pentads, indicating a later seasonal transition in the lower troposphere than in the upper troposphere.

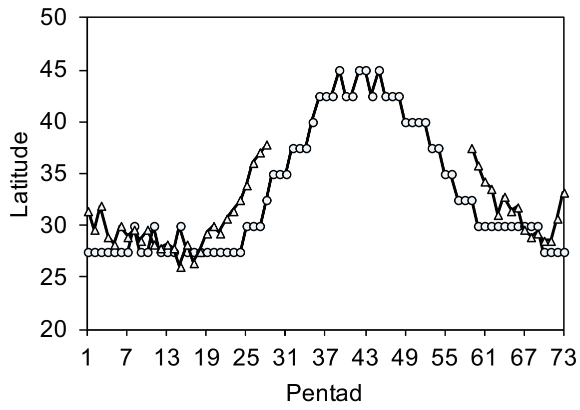

Fig. 8. Time-latitude cross sections for the climatological pentad MWDL-WTP at 700 hPa (triangle line) and westerly jet stream axis at 200 hPa (circle line) averaged between 55°E and 70°E.

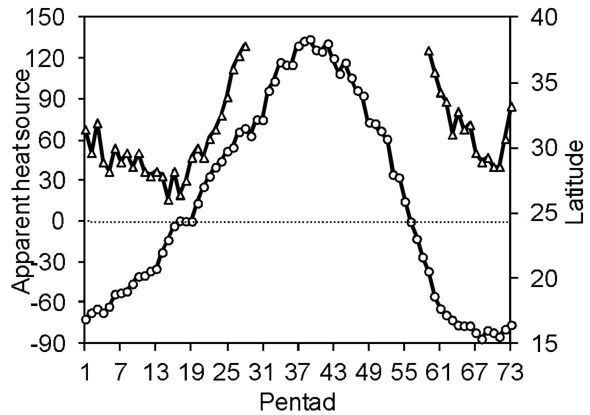

Fig. 9. Time evolution of the climatological pentad apparent heat source averaged in the area 27.5°–37.5°N, 75°–105°E over the TP (circle line; units: W m^{-2}) and the latitude of the climatological pentad MWDL-WTP (triangle line).

The thermal effect of the TP always plays an important role in the seasonal transition of the atmospheric general circulation over Eurasia (Wu et al., 2002). To investigate the thermal effect of the TP on the bypassing flows, we calculated the apparent heat source in the area 27.5°–37.5°N, 75°–105°E over the TP with altitude > 3000 m. Figure 9 shows a heat sink over the TP from the 1st to the 19th pentad and from the 55th to the 73rd pentad, respectively, and a heat source from the 20th to the 54th pentad. The heat sink over the TP becomes a source at the 20th pentad, which is earlier than the disappearance of the pentad MWDL-WTP by eight pentads. It becomes a heat sink over the TP again at the 55th pentad, which is also earlier than the rebuilding of the pentad MWDL-WTP. Ye and Gao (1979) pointed out that the heating over the TP can produce a thermal low and cyclonic circulation in the lower troposphere around the TP. The transition of the apparent heat source from negative to positive in spring and the strengthening of the heating over the TP thereafter are favorable for the cyclonic circulation around the TP in the lower troposphere. As seen in Fig. 1b, the cyclonic circulation produces northerlies to the west of the TP and leads to the northward movement of the pentad MWDL-WTP, which weakens the westerlies to the west of the TP and the bypassing flows and corresponds to the northward shift of the westerly jet stream (Wu et al., 2002). Meanwhile, to the west and southwest of the TP, there exist northerlies in association with the cyclonic circulation arising from the heating over the TP (Fig. 1b). The southward flows also tend to slow down the bypassing flow under the effect of Coriolis force. The transition of the apparent heat source from positive to negative in autumn and the increase of cooling over the TP thereafter are related to the rebuilding of the pentad MWDL-WTP and its southward shift, implying the rebuilding and strengthening of the bypassing flows. Therefore, the seasonal variation of the thermal status over the TP plays an important role in the bypassing flows by affecting the atmospheric general circulation in the vicinity of the TP.

7. Discussion and conclusions

Because of the splitting effect of the TP on the westerlies in the lower troposphere, the meridional winds at 700 hPa show divergence in the upstream of the TP, deflecting southward and northward, respectively, to form two branches of bypassing flows around the TP. The bypassing flows around the TP show an obvious seasonal variation. Climatologically the dynamic role played by the TP in forming the bypassing flows mainly exists from October to May. The splitting effect of the TP on the westerlies happens from the 1st to the 22nd pentad. From the 29th to the 58th pentad, there is no splitting effect, and the splitting bypassing flows disappear. At the 59th pentad, the splitting effect of the TP on the westerlies appears again; the bypassing flows rebuild and remain to the 73rd pentad.

The intensity of the bypassing flows also exhibits obvious seasonal variation. The bypassing flows are strongest in winter from the 1st to the 22nd pentad and from the 59th to the 73rd pentad, respectively. They become weaker from the 22nd to the 28th pentad in the transition period between spring and summer, and they become stronger from the 59th to the 62nd pentad between summer and autumn. During the period from the 29th to the 58th pentad, the bypassing flows vanish.

The bypassing flows are associated with the southerlies in southeastern China, which transport warm and moist air from the south and thus bring precipitation there. From the rebuilding of the bypassing flows in mid-October to mid-February, the bypassing flows around the TP are the main cause of precipitation that is $\leqslant$2 mm d^{-1} over Southeast China. The enhancement of the bypassing flow intensity in March can increase precipitation that is $>$ 4 mm d^{-1} in the early stage of the persistent spring rain over Southeast China.

From winter to summer, the seasonal transition of the bypassing flows in the lower troposphere precedes that of the westerly jet stream axis in the upper troposphere averaged between 55°E and 70°E to the west of the TP by ∼4 pentads, while from summer to winter the seasonal transition lags the westerly jet stream by ∼4 pentads, indicating a later seasonal transition in the lower troposphere than that in the upper troposphere.

Based on the calculated apparent heat source over the TP, a heat sink occurs over the TP from the 1st to the 19th pentad and from the 55th to the 73rd pentad, respectively, and it becomes a heat source from the 20th to the 54th pentad. The transition of the apparent heat source from negative to positive in spring and the strengthening of the heating over the TP thereafter weaken the bypassing flows by increasing the northerlies and weakening the westerlies to the west of the TP in the lower troposphere. In addition, the bypassing flows are also slowed down under the effect of Coriolis force on the southward flows to the west and southwest of the TP. The transition of the apparent heat source from positive to negative in autumn and increasing cooling over the TP thereafter are related to the rebuilding and strengthening of the bypassing flows. Therefore, the seasonal variation of the thermal status over the TP plays an important role in the bypassing flows by affecting the atmospheric general circulation in the vicinity of the TP.

Our study mainly focused on the climatological features for seasonal variations of the bypassing flows around the TP. In addition to the climatological features, we also determined that the bypassing flows vary obviously on interannual and interdecadal time scales. It is important to understand the interannual and interdecadal variability of the bypassing flows and their mechanisms; we will investigate them in our future research. In our present study we illustrated the possible role played by the bypassing flows in the climatological variation of the seasonal precipitation over southeastern China, especially increasing the precipitation in the early stage of the persistent spring rain. Previous studies have shown that the spring precipitation over southeastern China is affected by many factors, such as western Pacific subtropical high (Wen et al., 2004), sea surface temperatures (Yang and Lau, 2004), Eurasian snow cover (Wu and Kirtman, 2007; Zuo et al., 2012), El Niño events (Zhang et al., 1999; Zhang and Sumi, 2002). The quantitative comparison of the variance percentage explained by the bypassing flows with those of other factors that contribute to spring rainfall over southeast China is another important topic for our future investigation.

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