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ABRUPT SEASONAL CHANGE OF ZONAL CIRCULATION OVER THE TIBETAN PLATEAU

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Abstract: The abrupt changes of zonal circulation in the Tibetan Plateau (TP) region and their likely causes are derived from National Centers for Environmental Prediction and the National Center for Atmospheric Research reanalysis data. The zonal circulation over the TP abruptly changed in summer (31st pentad) and winter (59th pentad). The switch from summer to winter circulation is characterized by a sudden northward shift of the westerlies and the zero-velocity curve and disappearance of the westerly jet. The winter–summer switch is characterized by the reverse pattern. Therefore, the circulation conversion between summer and winter can be judged from the position of the zero-velocity curve. Curves located north of 20 °N indicate summer circulation over the TP and vice versa. The abrupt change of zonal circulation is mainly caused by the thermodynamic effect of the TP. In June, this effect causes a huge monsoon circulation cell extending from the TP to low latitudes. Consequently, the westerlies jump to the north as easterlies develop. This process, which is enhanced by the strong northerly in Coriolis, establishes the summer circulation. In October, the Hadley cell recurs as the thermal effects of the TP diminish, the westerlies rush southward, and the winter circulation is established.

Key words: Tibetan Plateau; zonal circulation; abrupt change; thermodynamic effect; monsoon circulation
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1 INTRODUCTION

At medium and high latitudes, where the high altitude flow field and temperature field present significant seasonal changes, the weather and climate vary significantly between summer and winter. The meteorological community has long been concerned about abrupt changes of atmospheric circulation. First, Yin [1] associated the beginnings of the summer season with the sudden disappearance of westerly jets over the Himalayas in June. Further studies of the upper air circulation at Asian high altitude revealed the sudden establishment of the same jets in October 1945 (Yeh [2]). There were two westerly jets over Asia, at the north and south sides of the Tibetan Plateau (TP). The sudden appearance and retreat of the westerly jets at the south side strongly affected the weather processes in East Asia (Ye et al. [3]). Significant changes in atmospheric circulation have also been reported in the upper air wind fields of North America, the Middle East, and the Eastern Mediterranean region (Sutcliffe and Bannon [4]; Hsieh [5]). These abrupt changes are global phenomena and are accompanied by seasonal changes in June and October. They have been demonstrated in the northward and southward movements of Asian westerly jets (Ye et al. [6]). Remarkably, the East Asian circulations are unique because of the presence of the TP. The 500 hPa circulation in May and June, which represents the abrupt retreat of jets, is absent in other regions (Gu [7]). The westerly circulation changes over China was linked to abrupt surface temperature changes in June 1945 and October 1946 (Ye et al. [3]; Gao [8]).

The zonal circulation changes greatly affect the monsoon and Meiyu in China. The advent of the Meiyu season and the summer monsoon burst in the Yangtze River Basin in Asia correspond to abrupt locational changes of the westerly jets over Asia (Dong et al. [9]; Tao [10]). Meanwhile, abrupt changes in June cause abnormal East Asian summer monsoons and affect the precipitation distribution in East Asia

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(Zheng and Liang [11]). In the eastern part of China, these June changes significantly increase the precipitation in the south of the middle–lower reach of the Yangtze River (Zhu et al. [12]). Therefore, understanding the abrupt changes of zonal circulation in monsoon regions is essential for climate prediction.

Due to lack of earlier observations of the TP and upper air temperature data, few scholars have investigated zonal circulations in the TP region. Previous studies on the abrupt changes of westerlies were undertaken in typical years and the specific times of the abrupt changes were not defined. The present paper studies the characteristics and timings of the abrupt changes and the reasons for their seasonal switching. To this end, the zonal circulation and upper air temperature in the TP monsoon region are analyzed and discussed using long time series data. This work will assist the prediction of seasonal changes and the characterization of climate change in the TP region.

2 DATA AND METHODS

The study data included the daily data of the zonal wind velocity field, the temperature field and the vertical velocity field from 1951 to 2012 with a spatial resolution of 2.5° × 2.5° (latitude × longitude), which were reanalyzed by the National Centers for Environmental Prediction and the National Center for Atmospheric Research (NCEP/NCAR). Adopting the principle of 6 pentads per month and 72 pentads per year, climatic-season averages (pentad average data of 62 years) of the zonal wind velocity field, temperature field and vertical velocity field were constructed.

3 ABRUPT SEASONAL CHANGES OF ZONAL CIRCULATION

The abrupt transition of upper westerly structure is an important marker of seasonal changes. As earlier data are limited, most of the existing literature presents case studies of typical years (1945 and 1956). To analyze the evolution of the upper zonal circulation, the present paper analyzes the average data from 1951 to 2012. Specifically, it analyzes the seasonal evolution of the zonal circulation in the TP monsoon region, and identifies the abrupt transition time of the seasonal changes. The eastern and western boundaries of the TP monsoon region are located at 62.5° E and 115° E, respectively (Zhou et al. [13]).

Figure 1 illustrates the vertical cross-section of the average zonal wind velocity in the 28–36th pentads. As seen in the figure, the zero-velocity curves before June located south of 20° N and a westerly jet appeared on the south and north side of the TP. In the 1st pentad of June (31st pentad), the zero-velocity curves visibly jumped to 20 °N. A vertical jump to approximately 400 hPa is also observed. The southern branch of the westerly jet suddenly disappeared and was replaced by a north-advancing easterly, completing the transition from winter to summer. The westerly then gradually moved northward, while the easterly was significantly reinforced and moved to the south side of the TP. Westerly and easterly jets stably persisted over the TP, establishing the summer circulation pattern. The zonal wind changes during the 52–60th pentads are shown in Fig. 2. The abrupt change was less drastic in October than in June. The circulation pattern over the TP in September were similar: easterly jets were still very salient and coexisted with westerly jets at the southern edge of the TP. The easterly flow diminished after the 1st pentad of October (55th pentad) and began retreating southward. The zero-velocity curve of the south side of the TP is located north of 20° N. The easterly flow of the 5th pentad of October (59th pentad) was very weak, and the easterly and westerly zero-velocity curves coalesced and began to cross the 20 °N latitude. The southern branch of the westerly jet reappeared at the south side of the TP, and coexisted with the northern branch of the westerly jet over the TP. Meanwhile, upper jets at high latitudes (over 55° N) appeared at 200–300 hPa. With the conjunction of the lower and upper jets, the westerly strengthened and advanced southward, thus establishing the winter circulation pattern.

This dynamic action was accompanied by a strong westerly on the north and south sides of the TP. The sudden retreat and appearance of the southern branch of the westerly jet is a distinct marker of the summer–winter alternations. Fig. 3 plots the temporal cross-section of the average annual 600 hPa zonal wind velocities. The westerly jets on the south side of the TP (20–30° N) were clearly disrupted in late May and were replaced by a strong westerly, which prevailed until the southern branch jet recurred in mid-October. The northern branch of the jet (40–50° N), which was weaker than the southern branch, persisted.

To more accurately determine the abrupt transition times of seasonal changes, the average latitudinal changes of the zero-velocity curves were determined by averaging the pentad data of the 600-hPa zonal wind in the TP monsoon region. As shown in Fig. 1, the two zero-velocity curves appearing in late May were disrupted by a vertical jump in early June and did not reappear until 4° latitude. After their reappearance, the two zero-velocity curves coalesced in mid-October. The latitudinal locations of the zero-velocity curves in the 72 pentads are presented in Table 1 (in June, where the zero-velocity curves were disrupted, the latitude is that of the lowest point of the curves in the vertical cross-section; see the underlined part). The northward latitudinal jump was analyzed from the zero-velocity curves of the north branch (near the south side of the TP). As observed in Table 1, the most evident northward jump in these curves was 17.79° N to 20.06° N in the 30th to 31st pentad. The magnitude of this jump (3 latitudes per pentad) is consistent with the timing of the abrupt change in Fig. 1. Therefore, the 31st pentad was considered to indicate the summer-to-winter change in the atmospheric circulation. The zero-velocity curves of the 35th and 36th pentads also jumped across almost 3 latitudes. This jump was attributed to the full establishment of the summer circulation pattern in which the easterly and westerly jets coexisted over the TP, driving the easterly jets toward the southern rim of the TP and the westerlies back to the north. The appearance of the strong easterly in late June (see the cross-section at 600 hPa in Fig. 3) supports this view. The abrupt change in October was less drastic than in June and the zero-velocity curves were relatively stable. The combined analyses show that the two zero-velocity curves coalesced in the 5th October pentad (59th pentad), when the circulation began to change. Meanwhile, as shown in Table 1, the zero-velocity curves jumped back to 19.28° N (south of 20° N). Therefore, the 59th pentad was regarded as time at which the atmospheric circulation switched from summer to winter. Moreover, the summer and winter circulations can be identified from the latitude of the 600 hPa zonal wind zero-velocity curve (>20° N in summer; <20° N in winter), providing a valuable indicator of the seasonal changes in China’s TP region.

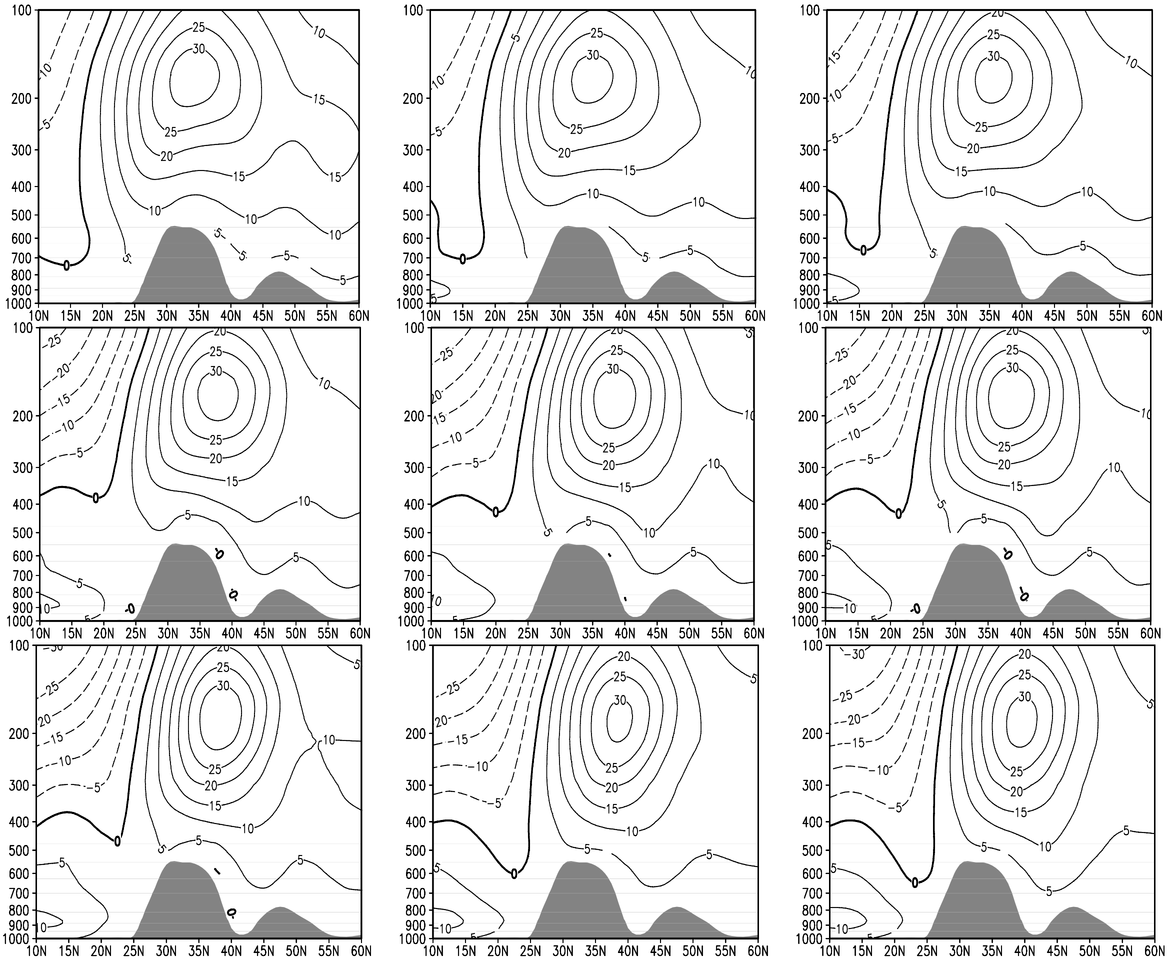

Figure 1. Vertical cross-section of average zonal wind velocity in the 28–36th pentads over 62 years.

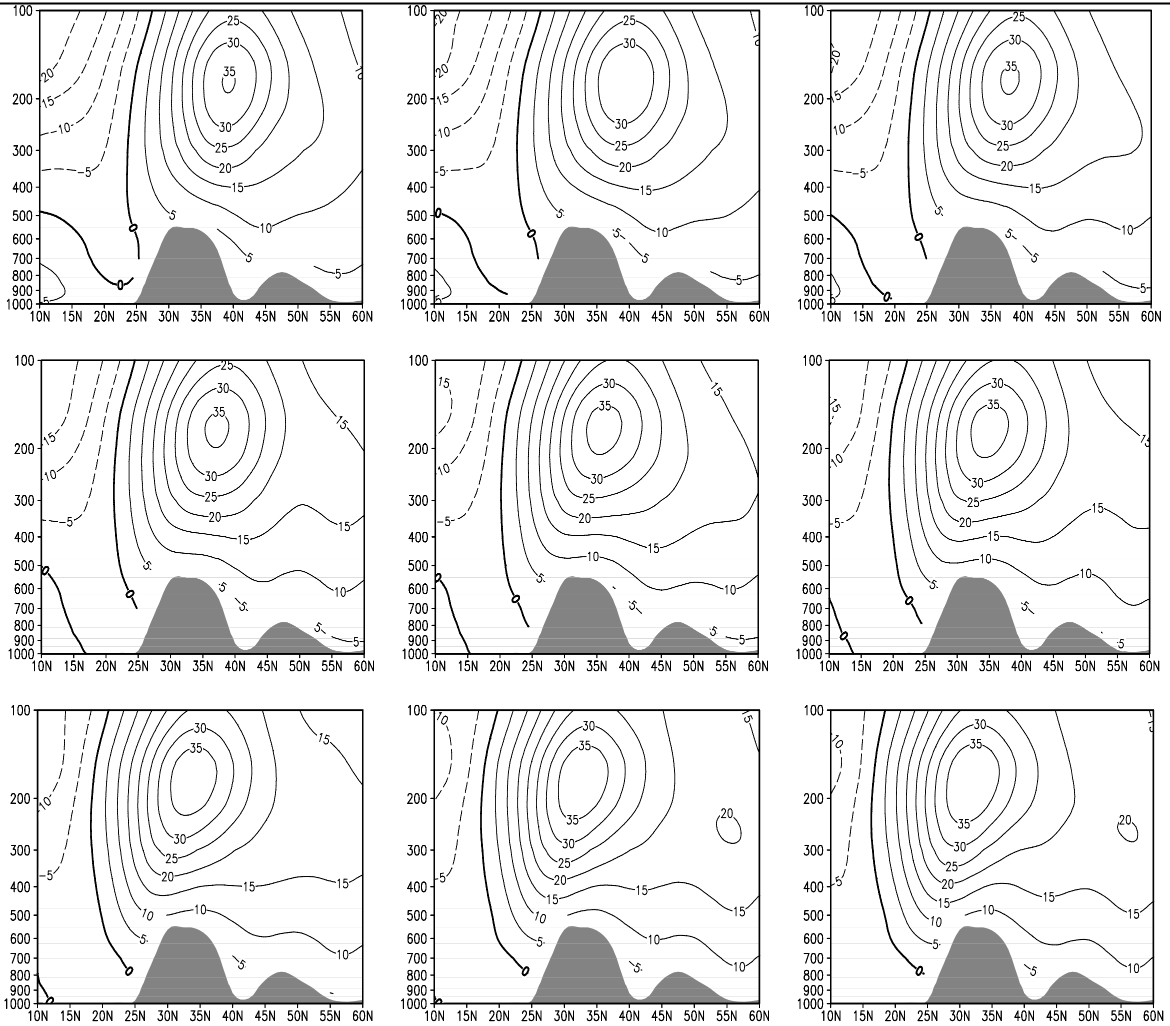

Figure 2. Vertical cross-section of average zonal wind velocity in the 52–60th pentads over 62 years.

Table 1. Average latitude of easterly and westerly zero-velocity curves in pentads 1–72 of 1962.

Time/ pentad	Latitude of zero-velocity curve on the north side (°N)	Latitude of zero-velocity curve on the south side (°N)	Time/ pentad	Latitude of zero-velocity curve on the north side (°N)	Latitude of zero-velocity curve on the south side (°N)	Time/ pentad	Latitude of zero-velocity curve on the north side (°N)	Latitude of zero-velocity curve on the south side (°N)
1	14		25	16.93		49	27.78	19.89
2	13.75		26	17.5		50	27.29	19.43
3	13.57		27	17.92		51	26	18.86
4	13.33		28	17.89	10	52	25.14	16.79
5	13.21		29	18.14	11.43	53	25.64	15.18
6	13.04		**30**	**17.79**	13.29	54	23.82	13.71
7	13		**31**	**20.06**		55	23.39	12.5
8	12.89		32	20.72		56	21.57	11.57
9	13.14		33	21.57		57	21.36	10
10	13.14		34	23.28		**58**	**20.79**	
11	13.68		35	22.5		**59**	**19.28**	
12	13.79		36	25.43	21.61	60	19.14	
13	13.96		37	25.64	21.86	61	19.04	
14	14.43		38	26.11	22.29	62	18.54	
15	14.64		39	26.5	22.11	63	18.18	
16	14.57		40	27	21.86	64	17.86	
17	14.79		41	28.11	21.75	65	17.36	
18	15.29		42	28.07	21.75	66	16.64	

19	15.43	43	28.93	21.11	67	16.68
20	15.71	44	29.23	20.93	68	16.25
21	16.36	45	28.68	21.07	69	15.82

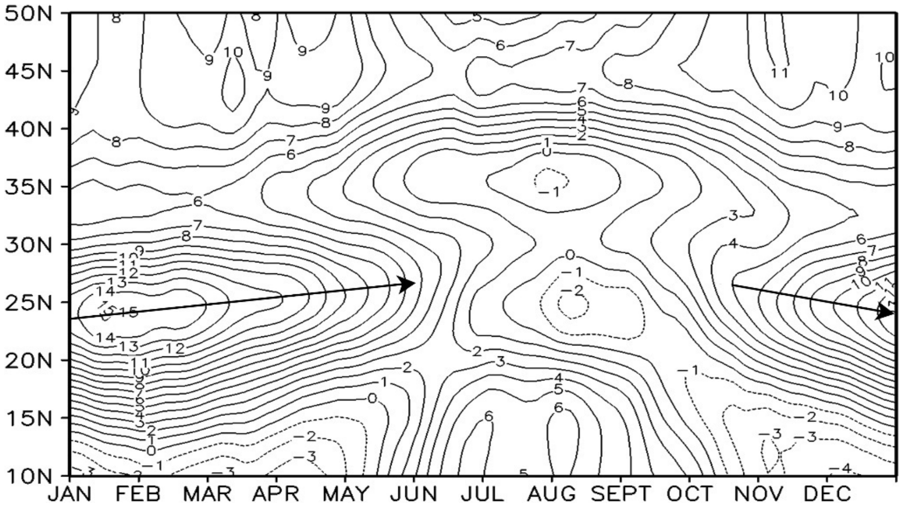

Figure 3. Time cross-section of average 600 hPa zonal wind velocity over 62 years.

4 CAUSES OF ABRUPT SEASONAL CHANGES IN CIRCULATION

The dynamic and thermal activities over the TP simultaneously influence the atmospheric circulation of the northern hemisphere, which plays a decisive role in circulation formation. As revealed in numerous studies, thermal anomalies over the TP are directly implicated in abnormal circulation (Huang [14]; Song and Liu [15]; Wang et al. [16]). The formation of the East Asian monsoon circulation system depends more on atmospheric diabatic heating than on dynamic action (Luo and Zhang [17]). Numerical experiments have shown that diabatic heating over the TP affects the global atmospheric circulation and encourages the northward movement of the mid-latitude westerly during seasonal changes. Regions of volatile heating sources at the TP generate volatile temperatures over the TP (Hu and Zhu [18]; Zheng and Liang [11]). The changes of the temperature over the TP were adopted instead of the changes of the TP heat sources. The present study analyzes the times of abrupt changes in the heat sources from summer to winter using the pentad-averaged temperature data at 600 hPa during the 62 years from 1951 to 2012. The timings are compared with those of the abrupt changes in zonal circulation.

During the study period, the maximum temperature at 600 hPa was clearly centralized in the main TP region in summer, but moved out of the main TP region in winter. Fig. 4 illustrates the temporal changes in the maximum temperature at 600 hPa in the TP monsoon region. The maximum temperature steadily rose in May, at a rate of 0.5 K per pentad (see Fig. 4 a). In the 1st pentad of June (31st pentad), the maximum temperature suddenly increased from 276.4 K to 278.5 K, and thereafter steadily rose through June at a rate not exceeding 1 K per pentad. Although the changes in upper air temperature differ from the surface temperatures analyzed by Ye [3], the upper air temperature clearly jumped from one steady rise to another. In September (Fig. 4b), the maximum upper air temperature dropped at a rate of 0.8 K per pentad. The maximum temperature suddenly dropped by 2.2 K in the 1st pentad of October (55th pentad), and thereafter reduced by 1 K per pentad. This indicates that the temperature dropped more drastically after the abrupt fall in early October than before the change. These analyses reveal abrupt changes in the maximum temperature over the TP region during summer and winter; specifically, at the 31st and 55th pentads. To verify these timings of abrupt temperature change, the temperature differences in the TP region between two successive pentads in May and June, and in September and October, were comparatively analyzed. Panels a, b and c of Fig. 5 display the temperature differences between the 30th and 29th, the 31st and 30th, and the 32nd and 31st pentads, respectively. In Fig. 5a, the temperature change between the two pentads was significant only in the Yunnan–Guizhou Plateau region (difference = 0.6 K). In Fig. 5c, the change was significant only in the central and eastern parts of the TP and never exceeded 1 K between the two pentads. In Fig. 5b, the central and eastern part of the TP, northwest China and Inner Mongolia passed the significance test, with a maximum difference of 1.6 K. Moreover, the temperature differences in the main TP region were consistently higher than 1 K. This indicates that the temperature rose dramatically only in the 31st pentad; the changes before and after this period were insignificant. This finding is highly consistent with the maximum temperature trends in the TP region, as analyzed above. Both sets of results indicate that the upper air temperature abruptly rises in the 31st pentad, marking the transition from winter to summer. A similar analysis was applied to the temperature-difference chart during September and October. Panels a, b, and c of Fig. 6 display the temperature difference between the 54th and 55th, the 55th and 56th, and the 56th and 57th pentad, respectively. The contours in Fig. 6b are very steep, indicating large temperature differences between the 54th and 55th pentad all over the TP. The temperature difference was maximized at 2 K, and exceeded 1.4 K (i.e., passed the significance test) over almost the entire Plateau region. Therefore, a significant temperature drop occurred over the entire region. In Fig. 6a, the temperature drop is significant only in the south–east corner of the TP region, and is below 0.6 K in the TP monsoon region, meaning that the temperature change is insignificant in late September. In Fig. 6c, the temperature difference between the two pentads was approximately 1 K in the TP region, and was significant in the western and northern parts of the TP. This indicates that during the study period, the temperature changed more obviously in October than in September, thus verifying the advent of winter. Moreover, this result is consistent with the abrupt maximum temperature drop in October (see Fig. 4b). Therefore, the 55th pentad was regarded as the time at which the upper air temperature suddenly falls during the summer-to- winter transition.

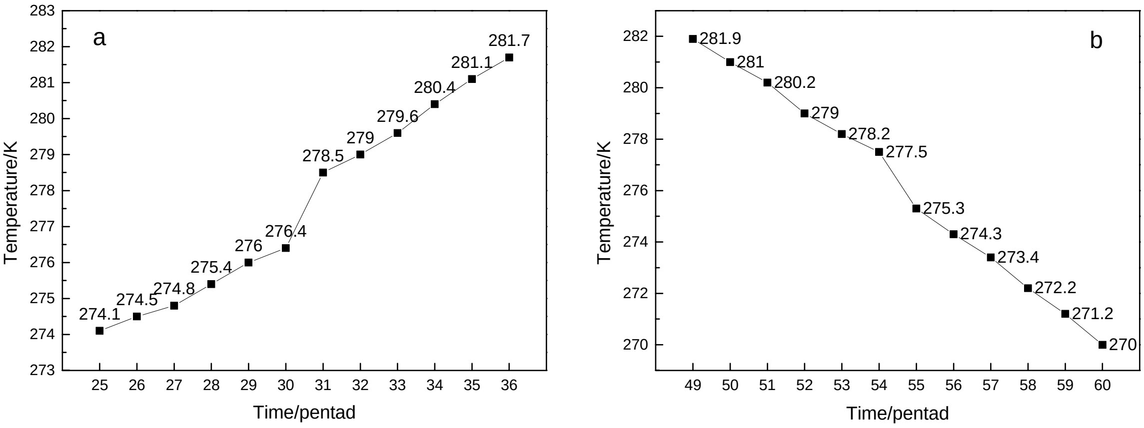

Figure 4. Temporal changes in maximum temperature at 600 hPa in the main Tibetan Plateau region over 62 years (a: May–June; b: September–October).

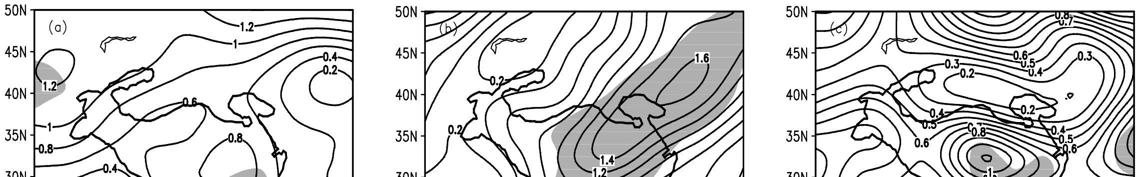

Figure 5. Average temperature differences at 600 hPa between two successive pentads over 62 years (a: 30th and 29th pentad; b: 31st and 30th pentad; c: 32nd and 31st pentad; shaded area passed 95% confidence test).

This result improves the conclusions of Ye et al. [3], and demonstrates that (assuming the same changes in the upper air and ground temperatures) the temperature suddenly rises in early June (31st pentad) and drops in early October (55th pentad), at least in the TP monsoon region. The change in the temperature field was essentially mirrored by changes in the high-altitude flow field, although the abrupt October change occurred four pentads earlier in the temperature field than in the flow field. If the circulation change was caused by TP thermal effects, then anti-Hadley (Hadley) circulation inevitably occurred in the south TP, reinforcing (weakening) the easterly flow over that region, forcing the northward (southward) retreat of the westerly jets, and completing the abrupt seasonal change of the zonal circulation. Whether the zonal circulation was actually caused by TP thermal effects was assessed from the cross-section of the average vertical velocities over the 62-year period (longitudinal averages of the eastern and western boundaries (62.5–115°E) of the TP monsoon region).

Figure 7 illustrates the vertical velocity evolution from the TP to lower latitudes. As the TP thermal effects increased, updrafts occurred above the TP during the 1st pentad of April (19th pentad), establishing an anti-Hadley cell between 500–300 hPa over the southern Plateau, and diminishing the original Hadley cell extending from the equator to the TP (Fig. 7a). Meanwhile, a pre-monsoon circulation cell developed below 600 hPa on the south side of the TP (between 11° and 27° N). During the 1st pentad of May (25th pentad), the TP thermal effects increased while the updrafts over the TP extended and coalesced into the lower anti-Hadley cell on the south side of the TP. The ascending and descending branches were located over the TP and at approximately 15° N, respectively (Fig. 7b). During the 6th pentad of May (30th pentad), all of the flows from the TP to the south Plateau (20° N) were consistent updrafts, and the downdrafts on the south side of the TP gradually diminished (Fig. 7c). During the 1st pentad of June (31st pentad), the updrafts on the south side of the TP disappeared, and were replaced by a huge monsoon circulation cell (anti-Hadley). At this time, all of the flows in the TP region to south of 10° N were updrafts, and the descending branch was located south of 10° S (Fig. 7d). Driven by the Coriolis force, the strong northerly reinforced the easterly jets and forced the northward retreat of the westerly jets at the south Plateau, completing the winter-to-summer circulation pattern. Fig. 7e and 7f illustrate the vertical velocity distribution in the 6th pentad of September (54th pentad) and the 2nd pentad of October (56th pentad), respectively. In late September, the updrafts and monsoon circulation in the TP and its southern parts persisted but were weaker than in June. During the 56th pentad, downdrafts occurred over the TP and its south side, and the Hadley cell recurred above 500 hPa, extending from the TP to the equatorial region. Again driven by the Coriolis force, the southerly reinforced the easterly jets, gradually driving them southward. As the easterly jets diminished and retreated southward, the zonal circulation completed the summer-to-winter conversion of its circulation pattern. The times of abrupt changes in the establishment of the anti-Hadley cell in summer and the anti-Hadley cell in winter were fairly consistent with the seasonal variations of the upper air temperature. The thermal changes over the Plateau in October preceded the abrupt change of zonal circulation, possibly because the atmospheric circulation was abruptly altered by the retreat of the Indian southwest monsoon. It may be worthwhile to remark that the atmospheric circulation abruptly changes across the globe [6], and that the winter-to-summer transition (or *vice versa*) in the circulation pattern is drastic. Abrupt seasonal changes in zonal circulation were evident in East Asia and the south Plateau. Moreover, these changes were consistent in time and were accompanied by the advent and retreat of monsoon and severe weather processes. In East Asia, these seasonal transitions were accompanied by the outbreak and retreat of the East Asian monsoon, and the abrupt changes over the TP were accompanied by the appearance and disappearance of the monsoon circulation in the south Plateau to the low-latitude monsoon circulation cell (that is, the Indian southwest monsoon).

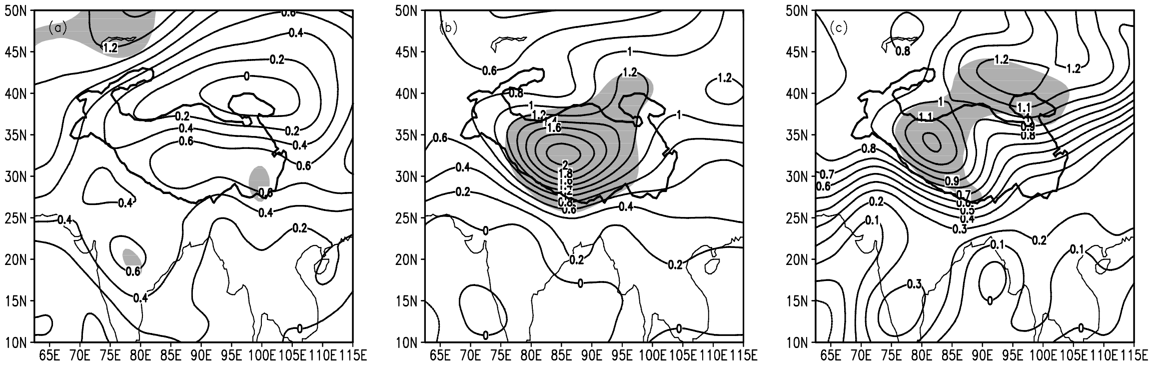

Figure 6. Average temperature differences at 600 hPa between two successive pentads over 62 years (a: 54th and 55th pentad; b: 55th and 56th pentad; c: 56th and 57th pentad; shaded area passed 95% confidence test).

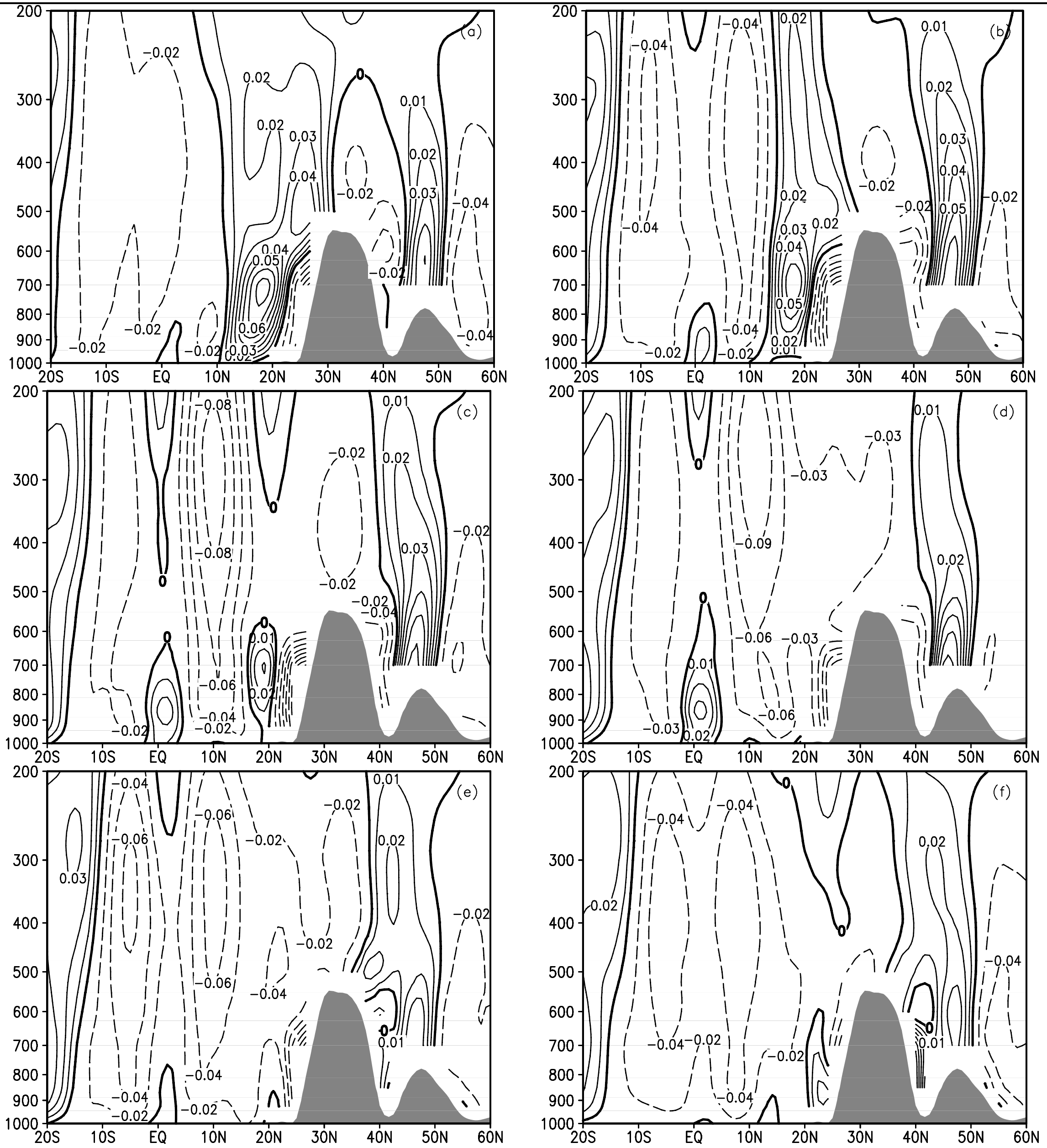

Figure 7. Vertical cross-sections of average vertical velocities over 62 years (a: 19th pentad, b: 25th pentad, c: 30th pentad, d: 31st pentad, e: 54th pentad, f: 56th pentad).

5 DISCUSSION AND CONCLUSIONS

Applying statistical methods to the daily data reanalyzed by NCEP/NCAR, this study determined the abrupt seasonal changes of zonal circulation in the TP region. The following conclusions were drawn from the study:

(1) Abrupt seasonal changes of zonal circulation were obvious over the TP region. The winter-to-summer transition in the circulation pattern manifested as an abrupt northward jump in the zero-velocity curves, the northward movement of a continuously reinforced easterly, the sudden disappearance of westerly jets, and the southward movement of westerly flows. A summer-to-winter transition induced the opposite effects in the circulation pattern, but the changes were less drastic than in the winter-to-summer transition.

(2) The latitude of the 600 hPa zonal wind zero-velocity curves is a useful indicator of summer and winter conversions. Curves located north and south of 20° N denoted a summer and winter circulation over the TP, respectively. After averaging the data, the times of abrupt change in the atmospheric circulation were pinpointed as the 1st pentad of June (31st pentad, marking the onset of summer) and the 5th pentad of October (59th pentad, marking the onset of winter). This finding enhances our understanding of the seasonal changes in China’s TP region.

(3) The abrupt seasonal change of the zonal

circulation over the TP region was associated with TP thermal effects. In June, the increasing thermal effects reinforced the updrafts in the TP and its southern part, leading to a huge monsoon circulation cell extending from the TP to low-latitude areas. Under the Coriolis force, the strong northerly in the south of the TP reinforced the easterly jets and drove the northward retreat of the westerly jets, completing the winter-to-summer change in the circulation pattern. Conversely, under the diminishing thermal effects in October, the Hadley cell recurred, the westerly jets over the TP were gradually reinforced and advanced southward, and the zonal circulation altered from its summer to its winter circulation pattern.

The abrupt seasonal transitions of zonal circulation were reasoned from the perspective of the TP thermal effects. The transitions may be associated with the TP dynamics, the positional variations of South Asian high, and the heating of the Indian Ocean. To reveal and deeply understand the underlying causes and the mechanism of the abrupt circulation changes, further investigations are required. In addition, heating of the TP is thought to largely change the atmospheric temperature and pressure fields over the TP. The regions of greater changes in air temperature were also the regions of greater volatility of the air temperature over the TP. Therefore, the changing air temperature over the TP might largely reflect the heating of the TP. The TP heat source is a comprehensive physical quantity embodying the sensible heat, latent heat, and net radiation. Therefore, there are certain constraints in the use of the air temperature over the TP as a proxy for the TP heat source.

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