Three-Dimensional Circulation Structure of Summer Heavy Rainfall in Central North China

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ABSTRACT

Based on daily rainfall observations and Japanese 25-year Reanalysis Project data during years 1981–2010, a three-dimensional circulation structure that formed before heavy summer rainfall in central north China (CNC) is revealed in this study. Composite analyses of circulation in advance of 225 heavy rain days show that the circulation structure is characterized by a remarkable upper-tropospheric warm anomaly (UTWA), which covers most of northern China with a center at 300 hPa. Under hydrostatic and geostrophic equilibriums, the UTWA contributes to the generation of an anticyclonic (cyclonic) anomaly above (below). The anticyclonic anomaly strengthens (weakens) westerly winds to the north (south) of the warm center and pushes the high-level westerly jet to the north. The cyclonic anomaly deepens the trough upstream of CNC and intensifies lower southwesterly winds to the mideast of the warm center. As a result, the northerly stretched high-level jet produces upper divergence in its right-front side and the intensified southwesterly winds induce lower moisture convergence in its left-front side, causing heavy rainfall in CNC. Correlation analyses further confirm the close connections between UTWA and circulation in the upper and lower troposphere. The correlation coefficients between UTWA and the upper geopotential height, upper westerly jet, and lower southerly flow reach 0.95, 0.70, and 0.39, implying that the two critical factors leading to intense rainfall in CNC, the high-level jet and the low-level southerly flow, are closely connected with the UTWA. Consequently, in the future analyses and forecasts of heavy rainfall over northern China, more attention should be paid to the temperature in the upper troposphere.

1. Introduction

Heavy rainfall has always been a major concern of society because of its disastrous impacts. The spatial distribution, changing trends, and formation mechanisms of heavy rainfall have drawn extensive attention among scholars (Chu et al. 2010; Li et al. 2013; Sun et al. 2013; Zhai et al. 2005). On the one hand, influenced by complex topography and diverse circulation systems, the forecast of intense rainfall is rather difficult in north China (NC). On the other hand, constituted by modern metropolises such as Beijing and Tianjin, NC is densely populated, especially in its central area. As a result, disastrous rainfall could cause immeasurable economic damages and casualties in NC. Meanwhile, water is scarce in NC, which makes heavy rainfall a significant water resource. Therefore, investigating
the impact and formation mechanism of heavy rainfall in central north China (CNC) has both a practical value in rainfall forecasting and disaster warning, and a scientific value for water resource utilization and economy development.

Many studies (e.g., Ding 2005, 315–336; Wang and Zhou 2005; You et al. 2011; Zhang et al. 2008) have demonstrated that the formation of heavy rainfall needs a massive supply of water vapor. However, local water vapor is relatively limited (Jiang et al. 2008; Simmonds et al. 1999), and thus heavy rainfall is commonly associated with large-scale circulation in favor of moisture transport. Back to the middle of the twentieth century, scholars have laid the foundation for research on the relation between heavy rainfall and circulation in NC. Xie (1956) analyzed the environment of heavy rainfall in relation between heavy rainfall and circulation in NC. Xie (1956) analyzed the environment of heavy rainfall in NC from a synoptic perspective, pointing out that the connection between general circulation in higher and lower latitudes could be investigated through the rainfall-producing process that is caused by cold (dry) air masses meeting warm (wet) ones (Xie et al. 1977). Through comparing the typical characteristics of circulation in drought and flood years, Bai and Su (1982) found out that the Okhotsk high has a significant correlation with the rainfall amount in Beijing, China. Zhou (1993) studied large-scale circulation from 50 regional strong rainstorms over NC, and classified the circulation patterns according to the features of the west Pacific subtropical high, the low pressure trough, and the cyclonic vortex.

Recently, heavy rainfall has become increasingly frequent in city clusters, represented by Beijing, Tianjin, and Hebei. This phenomenon brings further attention to the connection between general circulation and intense rainfall in NC. Based on case analyses, studies suggest that large-scale circulation has a significant impact on the formation and development of strong rainstorms (Sun et al. 2005; Wang et al. 2008; Zhao et al. 2013). Through climatological analyses, studies demonstrate that the spatial distribution and variation of heavy rainfall is highly correlated with the pattern and adjustment of circulation (Wang and Zhou 2005; Zhao et al. 2010; Zhu et al. 2011).

For most studies on the connection between circulation and heavy rainfall in NC, synoptic research has paid attention to the impacts of large-scale circulation on single rainfall events, and climatological research has placed an emphasis on the relation between changes in the circulation and monthly or annual rainfall amounts. Few studies have combined synoptic concepts with climatological perspectives. Moreover, previous studies focused mainly on the characteristics of low-level circulation, whereas less attention was paid to the upper levels, especially for temperature in the upper troposphere, which could affect both upper- and lower-level circulation. Synthesizing the above aspects, 30 yr of daily rain gauge records and reanalysis data over NC are used in this study to reveal a three-dimensional circulation structure that forms before heavy summer rainfall with a combination of synoptic and climatological perspectives. In particular, the role of upper-troposphere temperature in this circulation structure is discussed.

In the rest of this paper, the data description is given in section 2. Results are presented in section 3, in which the three-dimensional circulation structure is demonstrated first, and the connections between the upper-tropospheric warm anomaly (UTWA) and the circulation structure, as well as the causalties among the UTWA, the circulation structure, and the heavy rainfall, are further analyzed. The discussion and conclusions are given in section 4.

2. Data and method

This study is based on daily rain gauge records from 327 stations covering NC during the summers (June–August) of 1981–2010. The distribution of the 327 stations is shown by black dots in Fig. 1b. The dataset was collected and quality controlled by the National Meteorological Information Center of the China Meteorological Administration. It was initially obtained at 12-hourly intervals and further converted to daily records by adding up the rainfall amounts from 0800 Beijing time (BJT) of the present day to 0800 BJT of the next day. Large-scale circulation is described by the 6-hourly Japanese 25-year Reanalysis Project (Onogi et al. 2007) with the same period as the rain gauge data. The reanalysis dataset is 1.25° × 1.25° horizontally and contains 23 vertical levels.

The threshold of heavy rainfall is selected as the 90th percentile of historical summer rainfall. The spatial distribution of average total rainfall amount and heavy rainfall amount over NC are shown in Fig. 1. Although the distribution patterns of total and heavy rainfall are generally consistent (lower values to the northwest and higher values to the southeast), the heavy rainfall shows a stronger zonal gradient, which leads to heavy rainfall amounts above 30 mm day$^{-1}$ in Beijing, Tianjin, and Bohai, and below 22 mm day$^{-1}$ in most other regions. In this situation, observations in the Beijing–Tianjin–Bohai region are more capable of reflecting the heavy rainfall over NC. Therefore, we selected 41 stations around Beijing and Tianjin (−38.5°–40.5°N, −116°–118°E; white dashed rectangle in Fig. 1b) to represent the CNC, and all station altitudes are less than or equal to 100 m. The heavy rainfall days are defined as the dates when at least
five stations in CNC have rainfall beyond the 90th percentile. By this method, 225 heavy rainfall days are gathered over the 30 yr.

To investigate the precursor circulation signals associated with the heavy rainfall events, each circulation is described by the reanalysis data at 0800 BJT on heavy rainfall days, which is just in advance of the heavy rainfall in this study. For instance, the circulation at 0800 BJT 1 June 2001 corresponds to the rainfall amount from 0800 BJT 1 June to 0800 BJT 2 June 2001.

3. Results

To reveal the relation between heavy rainfall and circulation, the correlation coefficients on heavy rainfall days were first calculated. As presented in Fig. 2, the average heavy rainfall amount over CNC is significantly correlated with circulation variables at different levels. One common feature among them is that the most significant correlations are not located in CNC but, rather, are up- or downstream of CNC. Specifically, the 200-hPa zonal wind $U_{200}$ in the Inner Mongolia region (to the north of CNC) has a high positive correlation with heavy rainfall amounts in CNC (Fig. 2a), implying that the strengthening of the high-level westerly jet could increase the rainfall amount to its south (Cunningham and Keyser 2000; Shi et al. 2010). Meanwhile, the 700-hPa geopotential height $H_{700}$ to the west of 110°E has a significant negative correlation with heavy rainfall amounts in CNC (Fig. 2b), suggesting that the deepening of the low pressure trough could raise the rainfall amount in its downstream area (Liang et al. 2005; Zhao et al. 2007).

Correspondingly, the meridional wind at $-850–925$ hPa $V_{850–925}$ (Fig. 2c) and the specific humidity at $-850–925$ hPa $Q_{850–925}$ (Fig. 2d) to the south of CNC present high positive correlations with the heavy rainfall amount in CNC, which also reflects the contribution of upstream troughs to downstream rainfall. These results suggest that the environment around a rainfall area has a crucial impact on the rainfall, and large-scale circulation could be the key to creating such impacts.

Notably, as presented in Fig. 2e, there are significant positive correlations between heavy rainfall amounts and the 300-hPa temperature $T_{300}$ covering NC. The characteristics of the upper-troposphere temperature have been commonly ignored in the previous studies of rainfall, until Yu et al. (2004) discovered that there is a distinct decadal cold anomaly located over East Asia at 300 hPa during late summer. They pointed out that this upper-tropospheric cool anomaly contributes to the formation of the anticyclonic (cyclonic) anomaly below (above), and leads to the so-called southern flood and northern drought decadal rainfall pattern over China. To further support and confirm the conclusions of the decadal study, corresponding characteristics should be traced into single events. Therefore, whether there is a favorable circulation structure, which is characterized by upper-troposphere temperature, for heavy rainfall events in NC leads us to launch the following analysis.

a. Three-dimensional circulation structure of heavy rainfall

At different levels, we show the composite rainfall amount distributions and circulation characteristics of the summer climatology (Figs. 3a,d,g), heavy rainfall days (Figs. 3b,e,h), and anomaly fields (Figs. 3c,f,i). First, at 300 hPa, a weak cold trough is situated in NC climatology (Fig. 3a), while a warm ridge dominates across NC on heavy rainfall days (Fig. 3b), producing extensive warm anomalies over NC (Fig. 3c). The anomalous
center, which is 3°C higher than the climatological average, is located at ~42°N, 116°E. Controlled by hydrostatic equilibrium, the geopotential height at higher levels will be raised by the warm anomaly. As a result, a 200-hPa westerly (easterly) anomaly forms to the upper north (upper south) of the warm anomaly under the cooperation of the pressure gradient force and Coriolis force. Correspondingly, the high-level westerly jet stretches toward the northeast, with the eastern edge of the wind speed at 27 m s⁻¹ (boldface sienna contour; Figs. 3a,b) moving from 39°N, 110°E (in the climatology) to 42°N, 124°E (on heavy rainfall days). Many studies (Cunningham and Keyser 2000; Shi et al. 2010) have suggested that a westerly jet is commonly accompanied...
by an upper divergence to its southern area, which could promote the development of local convection.

Based on hydrostatic and geostrophic equilibriums, the warm anomaly also contributes toward the generation of a cyclonic anomaly in the lower levels. Accordingly, the anomaly field shows that northerly (southerly) anomalies at ~850–925 hPa dominate to the west (east) of the warm center (Fig. 3i), accompanied by a negative 700-hPa geopotential height anomaly center upstream of NC. Furthermore, CNC lies in the junction zone between the negative and positive centers, with prevailing southerly winds (Figs. 3f,i). Benefitting from this, broad wet anomalies cover NC with their center around CNC (Fig. 3i). Hence, on heavy rainfall days, a 700-hPa trough is located in the Great Bend of the Yellow River around 110°E with both strong low-level southwesterly flows at its front and a moist tongue covering ~105°–120°E below 850 hPa, while the geopotential height at 700 hPa and moisture below 850 hPa are relatively flat in the climatology.

The composite analyses above indicate that the heavy rainfall in CNC correspond to a distinct three-dimensional circulation structure characterized by the UTWA. To verify the typicality of this three-dimensional circulation, the probabilities of occurrence of the anomalous (relative to climatology) systems are calculated for the 225 heavy rainfall cases (Fig. 4). The positive (negative) anomalous systems are defined as the ones with anomalies higher (lower) than certain thresholds. The absolute values of the thresholds for temperature, geopotential height, and wind are 2°C, 10 gpm, and 2 m s⁻¹, respectively.

As illustrated in Fig. 4, the probability of occurrence is relatively high in each crucial anomalous system. Specifically, the probability of a 200-hPa westerly anomaly to the north of NC is over 70% (Fig. 4a), and the probability of a 300-hPa warm anomaly over NC reaches
above 65% (Fig. 4b). Meanwhile, the positive (negative) geopotential height anomaly downstream (upstream) of CNC possesses a probability beyond 70% (50%) at 700 hPa (Fig. 4c), and the southerly wind anomaly over NC has a probability around 60% at 850–925 hPa (Fig. 4d). These high probabilities suggest that the circulation characteristics obtained from the composite analyses exist steadily to a great extent, and thus the three-dimensional circulation structure that formed before the heavy rainfall in CNC is highly representative.

Figure 5a shows the composite meridional–vertical section of the anomalous circulation over CNC on heavy rainfall days. A warm anomaly dominates over the heavy rainfall area (CNC) below 200 hPa, and the anomaly center is situated between 300 and 400 hPa. In the upper north (upper south) of the warm core, a positive (negative) center of the zonal wind anomaly appears at 200 hPa. In this situation, upper divergences could be created by the upper anticyclonic anomaly, contributing to strong updrafts around 36°–44°N (vectors in Fig. 5a), and vertical wind shears covering 40°–55°N are intensified by the westerly anomaly in the upper troposphere. Meanwhile, southerly anomalies prevail to the south of 40°N (vectors in Fig. 5a), bringing deep wet anomalies covering ~600–1000 hPa to areas around ~36°–44°N (black contours in Fig. 5a).

Based on a synoptic study, Ding (2005, 315–336) concluded that in addition to the basic conditions including moisture, energy, and convection for generating common convective systems, strong convective systems have two more conditions to be satisfied: the reinforcement and the conversion condition. According to Ding (2005) the reinforcement condition includes topographic effects and upper divergence, and the conversion condition mainly refers to a strong vertical wind shear. Based on this study, it is known that the circulation on heavy rainfall days not only fulfills the reinforcement condition, as UTWA creates the upper divergence, but it also satisfies the conversion qualification, as UTWA intensifies the vertical wind shear.

Furthermore, to better understand the convection that directly contributes to heavy rainfall, we display the zonal–vertical cross section of the circulation characteristics with positive vorticity advection (Fig. 5b) and warm advection (Fig. 5c). It is shown that the negative (positive) geopotential height anomaly dominates at the bottom and to the west (the top and the east) of the warm core. Situated between the negative and the positive geopotential height anomalies, CNC (~114°–119°E) is
accompanied by positive vorticity advection, which increases with height from 1000 to 200 hPa (Fig. 5b). Meanwhile, warm advection covers CNC from the top to bottom level (Fig. 5c). According to the omega equation, ascending motions are motivated by the increasing positive vorticity advection with height and the warm advection. This result lays the physical foundation for the ascending motion around CNC (Figs. 5b,c), indicating that the circulation structure characterized by UTWA is in favor of strong convection around heavy rainfall areas.

Synthesizing the vertical and horizontal structures illustrated by Figs. 5 and 3, there are two important systems that constitute the anomalous circulation structure. One is the lower trough to the west of 110°E, which possesses southerly flows in its front. The other is the upper anticyclone to the east of 110°E, which is accompanied by southerly updraft inflows from the southwest. These two important systems meet at ~110°E, constituting strong southerly updraft flows that provide the moisture and dynamic conditions necessary for heavy rainfall in CNC. According to previous analyses, both systems are regulated by the UTWA. Therefore, based on the synoptic concepts and climatological analyses above, it is known that UTWA has great significance for heavy rainfall in CNC.

**FIG. 5.** (a) Composite meridional–vertical section (along 117°E) and (b),(c) zonal–vertical section (along 40°E) of circulation characteristics on heavy rainfall days. Green contours in (a) denote the specific humidity anomaly (g kg$^{-1}$). Blue contours in (b) denote positive vorticity advection ($10^{-10}$ s$^{-2}$). Green contours in (c) denote positive warm advection ($10^{-5}$ K s$^{-1}$). Gray contours in (a)–(c) denote the zonal and meridional wind anomaly (m s$^{-1}$). Vectors in (a)–(c) denote the zonal–vertical and the meridional–vertical anomalous wind fields (m s$^{-1}$), and vertical winds are amplified by 40 times. Shading denotes the temperature anomaly (°C).
In conclusion, the three-dimensional circulation structure that formed before the heavy rainfall in CNC may be summarized as follows. A remarkable UTWA covers NC, with the warm core at \( \sim 300 \) hPa. Under hydrostatic and geostrophic equilibriums, the UTWA contributes to the generation of an anticyclonic (cyclonic) circulation anomaly above (below). The anticyclonic anomaly strengthens (weakens) the westerly winds to the north (south) of the warm center and pushes a high-level westerly jet to the north. The cyclonic anomaly deepens the trough upstream of NC and intensifies lower southwesterly winds to the mideast of the warm center. As a result, the northerly stretched high-level jet produces an upper divergence along its right-front side and the intensified southwesterly wind induces lower moisture convergence along its left-front side, causing heavy rainfall in CNC.

**b. Connections between the UTWA and the three-dimensional circulation structure**

As the above analyses have qualitatively described the importance of UTWA in the three-dimensional circulation structure, this section focuses on statistically demonstrating the connections between UTWA and circulation patterns in the upper and lower troposphere. For the 225 heavy rainfall days covering 30 yr, all linear trends have been removed from the following correlation analyses.

Figure 6 displays the distributions of the correlation coefficients between 300-hPa temperature averaged over NC (red dashed rectangle) and (a) 200-hPa geopotential height, (b) 200-hPa zonal wind, and (c) \( \sim 850–925 \)-hPa meridional wind on 225 heavy rainfall days. The light and dark shading denotes the correlation areas that are significant at the 95% and 99% levels, respectively.
verified by a significance test at the 99% level, demonstrating that when 300-hPa temperatures become warmer, geopotential heights above the warm center will rise significantly, and an anomalous anticyclonic circulation will appear above the warm center. Therefore, considering that the westerly anomalies to the north of the warm center could promote the development of the high-level jet, it is reasonable to believe that the UTWA has an important effect on the formation of the high-level jet.

Paying attention to the impacts at the low levels, 300-hPa temperature is positively correlated with the 850–925-hPa meridional wind to the south of CNC. The correlation is also verified by a significance test at the 99% level with coefficients of 0.95, 0.70, 0.39, and 0.20. After processing the data with a 5-point smoother, the results clearly show that the variations of the four variables are in high accordance with the temperature at 300 hPa, especially for geopotential height and zonal wind at 200 hPa. The correlation analyses further confirm the close connections between UTWA and circulation in the upper and lower troposphere. On the one hand, UTWA contributes to generating an anticyclonic anomaly in the upper layer, pushing a westerly high-level jet to the north. On the other hand, accompanying the UTWA, a cyclonic anomaly appears in the lower layer, strengthening the southerly winds to the south of CNC. The stretched high-level jet and the enhanced low-level southerly flows are two critical factors leading to intense rainfall, and thus the UTWA has great significance for heavy rainfall in NC.

Fig. 7. Standardized time series between 300-hPa temperature (red line) over NC and (a) 200-hPa geopotential height (blue line) to the south of CNC, (b) 200-hPa zonal wind (blue line) to the north of CNC, (c) 850–925-hPa meridional wind (blue line) to the south of CNC, and (d) heavy rainfall amount (blue line) over CNC on 225 heavy rainfall days. The temperature and geopotential height are averaged in the red dashed rectangle in Fig. 6. The zonal wind is averaged over ~46°–54°N, ~110°–125°E. The meridional wind is averaged over ~32°–38°N, ~114°–120°E. The rainfall amount is averaged in the white dashed region in Fig. 1b. The solid and dotted lines denote the original and five-point-smoothed results, corresponding to the left and right y axes, respectively.
c. Causalities among the UTWA, the circulation structure, and heavy rainfall

Having illustrated the connections between the UTWA and the circulation structure, an important issue that remains to be further addressed is the causality between them. First, classical dynamic theory ensures the definite solution of the circulation field when the temperature field is given. Under hydrostatic equilibrium, temperature directly controls the geopotential height. According to geostrophic adjustment theory, the height field determines the wind field in large-scale motions. Meanwhile, based on theoretical analyses and model experiment, studies (Hoskins 1987; Liu et al. 1999a,b; Wu and Liu 2003; Wu et al. 1999; Zhang 1980) have demonstrated the adjustment process circulation of wind field to temperature field from different perspectives. Second, the influence of upper-tropospheric temperature on circulation has been specifically demonstrated by Xin et al. (2008), who performed two model experiments to confirm that a cyclonic (anticyclonic) anomaly is generated above (below) the imposed upper-tropospheric cooling. Their results display an opposite phase characteristic to that found in this paper, which includes a warm core in the upper troposphere and an anticyclonic (cyclonic) anomaly above (below).

Third, we conducted a sensitivity experiment with the Community Atmosphere Model, version 5 (CAM5), imposing UTWA in the perturbation (referred to as Perturb) run and keeping all of the other circulation conditions the same as the control run (referred to as Control; driven by the climatology mean). The configuration and corresponding results of the experiment are presented in Table 1 and Figs. 8 and 9. It is shown that the upper positive (lower negative) height anomaly appears 1 h after the UTWA was imposed, and a relatively complete upper-anticyclonic (lower cyclonic) anomaly forms in another 4 h (Fig. 8).

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<th>Table 1. Configuration of the sensitivity experiment.</th>
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<td>Control run</td>
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<td>Circulation conditions</td>
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<td>Temperature from 1000 to 100 hPa</td>
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<td>225 heavy rainfall days averaged</td>
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![Fig. 8](image-url)
Viewing the anomalous circulation of the sensitivity experiment from a meridional–vertical section (Fig. 9), the results are basically consistent with the practical situation (Fig. 5a): a westerly (easterly) anomaly appears in the upper north (upper south) of the warm core; a strong ascending anomaly and deep wet anomaly appear below the warm core. Therefore, both the qualitative analyses and the sensitivity experiment demonstrate that the UTWA plays an important role in contributing to the formation of the circulation’s structure.

For the central value of this study, the forecasting significance of the UTWA circulation structure to the heavy rainfall in CNC, the demonstration could be more convincing by presenting the evolution of the circulation structure. As shown in Fig. 10, the UTWA and its corresponding wind anomaly reach maximums right before the heavy rainfall (0 day), and then move eastward and weaken gradually from 1 to 3 day. These results explicitly indicate that the circulation structure characterized by UTWA was formed before the heavy rainfall, and thus the UTWA could serve as an important precursor signal for the heavy rainfall. Therefore, in future analyses and forecasts of heavy rainfall over NC, it is necessary to pay more attention to temperatures in the upper troposphere.

4. Discussion and conclusions

Using daily rainfall observation and reanalysis data over 30 yr, a three-dimensional circulation structure that formed before heavy rainfall in CNC has been revealed. Major conclusions of this research are summarized below.

1) A three-dimensional circulation structure characterized by UTWA is found before heavy rainfall in CNC. Under hydrostatic and geostrophic equilibriums, the UTWA contributes to generating an anticyclonic (cyclonic) anomaly above (below). The upper anomaly strengthens (weakens) the westerly winds to the north (south) of the warm center and pushes the high-level westerly jet to the north. The lower anomaly intensifies the low-level southwesterly winds to the mideast of the warm center. As a result, the northerly stretched high-level jet produces upper-air divergence on its right-front side and the intensified southwesterly winds induce lower moisture convergence on its left-front side, causing heavy rainfall in CNC.

2) Three-dimensional analyses further indicate that UTWA has great significance for heavy rainfall in CNC. On the one hand, dominating 300–400 hPa, UTWA contributes to the formation of the positive (negative) zonal wind anomaly center in its upper north (upper south) at 200 hPa. With the 200-hPa anomalous anticyclone, upper divergences appear over CNC, inducing strong updrafts at 36°–44°N. On the other hand, with the promotion of the UTWA to the lower cyclonic anomaly, intense southerly flows prevail in southern CNC, bringing deep wet anomalies covering 600–1000 hPa to the area 36°–44°N.

3) Moreover, using correlation analyses, the close connections between UTWA and circulation in the upper and lower troposphere are statistically confirmed. Significant correlations are found between UTWA and the upper geopotential height, upper westerly jet, as well as lower southerly flow with coefficients of 0.95, 0.70, and 0.39, implying that both of the critical factors leading to intense rainfall, the developed high-level jet and the enhanced low-level southerly flows, are closely connected with the UTWA.
To compare with the decadal analysis results of Yu et al. (2004), we calculated the mean ratio and the correlation coefficient between the annual accumulated heavy daily rainfall amount and the total summer rainfall amount during ~1981–2010 at each station. Taking Beijing station as an example, the ratio above is 0.46, implying that nearly 50% of the total summer rainfall amounts are contributed by heavy daily rainfall. Meanwhile, the correlation above passes a significance test at the 99% level with a coefficient of 0.89 at the Beijing station, indicating that the variation of the annual total summer rainfall amount is closely connected with the change in heavy daily rainfall. Similarly, the average ratio and correlation coefficient over the 41 stations in CNC reach 0.45 and 0.89, respectively. These calculations demonstrate the close connection between decadal rainfall changes and heavy rainfall events in CNC, and thus the conclusions of this study could be seen as an extension and validation of the decadal analysis of Yu et al. (2004); that is, when a UTWA is over NC, an anticyclonic (cyclonic) anomaly could appear in the upper (lower) troposphere, and NC would have heavy rainfall events.

Further research could be concentrated on the dynamics and source of UTWA. For possible causes of the upper-tropospheric temperature anomaly, several studies (Xin et al. 2006; Yu et al. 2004) have provided potential research directions, including oscillations in the atmosphere and interactions between the troposphere and stratosphere. In addition, how the UTWA...
circulation structure would affect the characteristics of rainfall events also deserves further investigation.

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