Objective Analysis of Circulation Extremes During the 21 July 2012 Torrential Rain in Beijing

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ABSTRACT

It has been reported that the heaviest rain event since 1951 hit Beijing on 21 July 2012 (henceforth referred to as the 721 case). The frequency and extreme attributes of the large-scale circulation patterns observed during the 721 case are explored by using obliquely rotated T-mode principle component analysis (PCA) and reanalysis data from NCEP/NCAR. The occurrence frequency of the 721-type circulation during the summers of 1951–2012 is 10.9%, while the frequency of torrential rain under this type of circulation is 4.51%. Relative to other rainstorms with similar large-scale circulations during the study period, the 721 case is characterized by a more westward extension of the subtropical high over the western North Pacific, a stronger low-level jet in the lower troposphere over the south of Beijing, a larger amount of ambient precipitable water, and a stronger vertical wind shear over Beijing. Among the 621 days with the 721-type circulation during the study period, the 721 case ranks the 54th in terms of the 925-hPa low-level jet south of Beijing, the 209th in terms of the local vertical wind shear, and the 8th in terms of the local precipitable water. The 721 case is particularly extreme with respect to the 925-hPa low-level jet south of Beijing and local precipitable water. Cases with similar circulations and equal or greater values of the 925-hPa low-level jet south of Beijing and local precipitable water have occurred thrice during the summers of 1951–2012 (i.e., once every 21 years).

Key words: torrential rain, circulation classification, low-level jet, vertical wind shear, precipitable water

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1. Introduction

A torrential rainfall event hit Beijing on 21 July 2012 (hereafter referred to as the 721 case). This event has produced the heaviest rainfall on record in Beijing since 1951, when comprehensive meteorological observations started in China. During the period of 1000 BT 21–0400 BT 22 July 2012 (BT denotes Beijing Time), the average precipitation throughout Beijing City was 170 mm. The maximum precipitation (460 mm) occurred in Hebei Town of Fangshan District. This torrential rainfall event caused 78 deaths and more than 10 billion RMB in economic loss (Sun Jisong et al., 2012). Several preliminary investigations on this torrential rainfall event have been performed. Fang et al. (2012) discussed the mesoscale convective conditions and the features of the convective system within the rainstorm. Their results indicated that the primary causes of the 721 case were abundant moisture, convective instability, low cloud base, and high precipitation efficiency. Upon investigating the synoptic structure of the storm, Sun Jisong et al. (2012) concluded that the 721 case exhibited an obvious "train-effect", in which the initial convection originated from

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both mesoscale convergence caused by the topographic forcing of the Taihang Mountains and wind velocity fluctuations enhanced by the low-level jet. Chen et al. (2012) analyzed the environmental conditions and the genesis and development of the mesoscale convective system, and found that the 721 case consisted of both warm region precipitation and frontal precipitation. Sun Jun et al. (2012) described the extreme precipitation associated with the 721 case in terms of precipitation efficiency, water vapor, and ascending motion. Studies of the 721 case have concentrated on local meteorological conditions and the contemporaneous features of the large-scale and mesoscale circulations. Given that the average precipitation in Beijing during the 721 case has been the largest observed since 1951, how frequently has the associated large-scale circulation pattern occurred over 1951–2012? How is the 721 case different from other rainstorms with the same circulation type? Is it possible to place the extremeness of the 721 case into a quantitative context?

Several studies concerning the circulation patterns associated with torrential rains have been conducted, but their focus is on the characteristics and evolution of specific torrential rain cases (Zhang et al., 2001), composites of several torrential rain cases (Lei, 1981), or subjective classification of circulation patterns on torrential rain days. These studies have largely neglected to explore whether the same circulation patterns can occur on non-torrential rain days as on torrential rain days. Previous classifications of circulation patterns associated with torrential rain cases are based on the features of the large-scale circulation or influencing systems. Tao (1980) divided the circulation patterns of rainstorms in China into three types: a stable meridional type, a stable zonal type, and a transitional type. Sun et al. (2005) classified severe heavy rainfall events in Beijing during the summers of 1990–1999 into 6 types with the following features in terms of the influencing systems: 1) remote interaction between a typhoon and a westerly trough (or vortex), 2) direct interaction between a vortex (or landing typhoon) and a westerly trough, 3) a standing or slow-moving landed typhoon impeded by a continental high pressure system, 4) a vortex in the lower-middle troposphere, 5) a shear line pushed by warm air, and 6) a cold front with a trough. The above methods are all subjective and tailored toward the classification of circulations with obvious differences. It is therefore difficult to use these methods to classify similar circulation types. Objective classification methods are more widely applied than subjective methods because they adopt a more uniform classification standard and are easily adapted to include additional circulation types.

Objective classification methods have a long history in meteorology and climatology. One of the most important applications of these methods is the classification of the atmospheric circulation. An objective classification method can be implemented by using one of two approaches: classification based on air mass or classification based on circulation. Air mass-based classification methods use multiple variables (e.g., air pressure, wind speed, and temperature) from a single site to define circulation types, while circulation-based classification methods use fields such as sea level pressure (SLP) or geopotential height to describe the atmospheric circulation (Huth et al., 2008). Local meteorological variables are also influenced substantially by the large-scale circulation, so circulation-based classification is preferable for classifying circulation types (Zhang et al., 2012). Many studies have used circulation-based classification methods to examine circulation patterns over Europe (Cahynová and Huth, 2010; Kyselý and Huth, 2008); however, few similar studies have been conducted in Asia, especially in China (Huth et al., 2008). By using an objective method of classifying the atmospheric circulation, this study assesses the frequency of circulation types with the same pattern of the 721 case during the summers of 1951–2012, explores the differences between the 721 case and other torrential rainfall cases with the same circulation pattern, and further quantitatively evaluates the extreme features of the 721 case.

2. Data and method

2.1 Gridded meteorological data

The gridded meteorological data used in this study include daily reanalyses of SLP, wind, geopotential height, and precipitable water produced by the National Centers for Environmental Prediction (NCEP) and the National Center for Atmospheric Research (NCAR). Data are analyzed during the summers (1 June–31 August) of 1951–2012. The horizontal resolution of the data is 2.5°×2.5°. Reanalyses of SLP are available at 0000, 0600, 1200, and 1800 UTC. This study focuses on reanalyses at 0000 UTC (0800 BT) because the radiosonde coverage is most comprehensive at this time. The timing of torrential rain events differs from event to event. Accordingly, the extreme features of the 721 case are analyzed by using daily mean values of wind, geopotential height, and precipitable water.

2.2 Precipitation data

Daily precipitation data of Beijing (station 54511) are used to identify torrential rain days during the summers of 1951–2012. The threshold for torrential rain is defined as 50 mm of rainfall in one day.

2.3 Circulation classification

The obliquely rotated T-mode principle component analysis (PCA) proposed by Huth (1993) is applied in this study. This method can reproduce predefined circulation types, yield results that are stable in time and space, and avoid the "snowballing" effects (i.e., one very common type is created along with a number of very uncommon types) common to other methods (Huth, 1996a, b). "T-mode" means that the columns of input data represent time observations while the rows correspond to grid points. The oblique rotation is utilized because it yields superior results (Richman, 1981; Compagnucci and Ruiz, 1992). This method has been made available within the framework of the COST733 Action (http://cost733.geo.uni-augsburg.de). A thorough description of COST733 circulation classification has been provided by Philipp et al. (2010).

3. The 721 circulation type

The 721 case occurred with the intersection of a cold air mass advected by a deep low vortex over Lake Baikal and Mongolia and a warm, moist air mass advected by the western North Pacific subtropical high. Positive vorticity advection by the low vortex over Lake Baikal and Mongolia established large-scale upward motion and favorable conditions for the generation and development of a severe convective system. The subtropical high extended westward and northward. Southeasterly flow along the southwestern boundary of the high provided a steady supply of water vapor, and the coupling between the low vortex in the lower troposphere and strong divergence in the upper troposphere promoted the further development of the rainstorm. A strong southerly low-level jet contributed an abundant supply of water vapor and unstable energy to the rainstorm area (Sun Jisong et al., 2012).

Figure 1 shows the spatial distribution of SLP at 0800 BT 21 July 2012. A center of high pressure is located to the east of China, with a center of low pressure over mainland China. A meridional circulation with a large horizontal gradient is located between the centers of the high and low pressure. Meanwhile, the spatial patterns of SLP during the summers of 1951–2012 are classified into 9 types by using obliquely rotated T-mode PCA (Fig. 2). These types can be compared with the subjective classification of rainstorms in Beijing carried out by Sun et al. (2005). The first type of circulation pattern in this paper corresponds to the "cold front with trough" type introduced by Sun et al. (2005). The second, third, and seventh types correspond to vortices in the lower-mid troposphere,

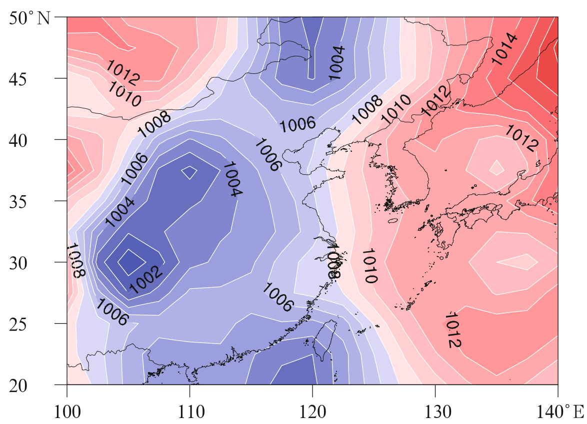

Fig. 1. Spatial distribution of SLP at 0800 BT 21 July 2012.

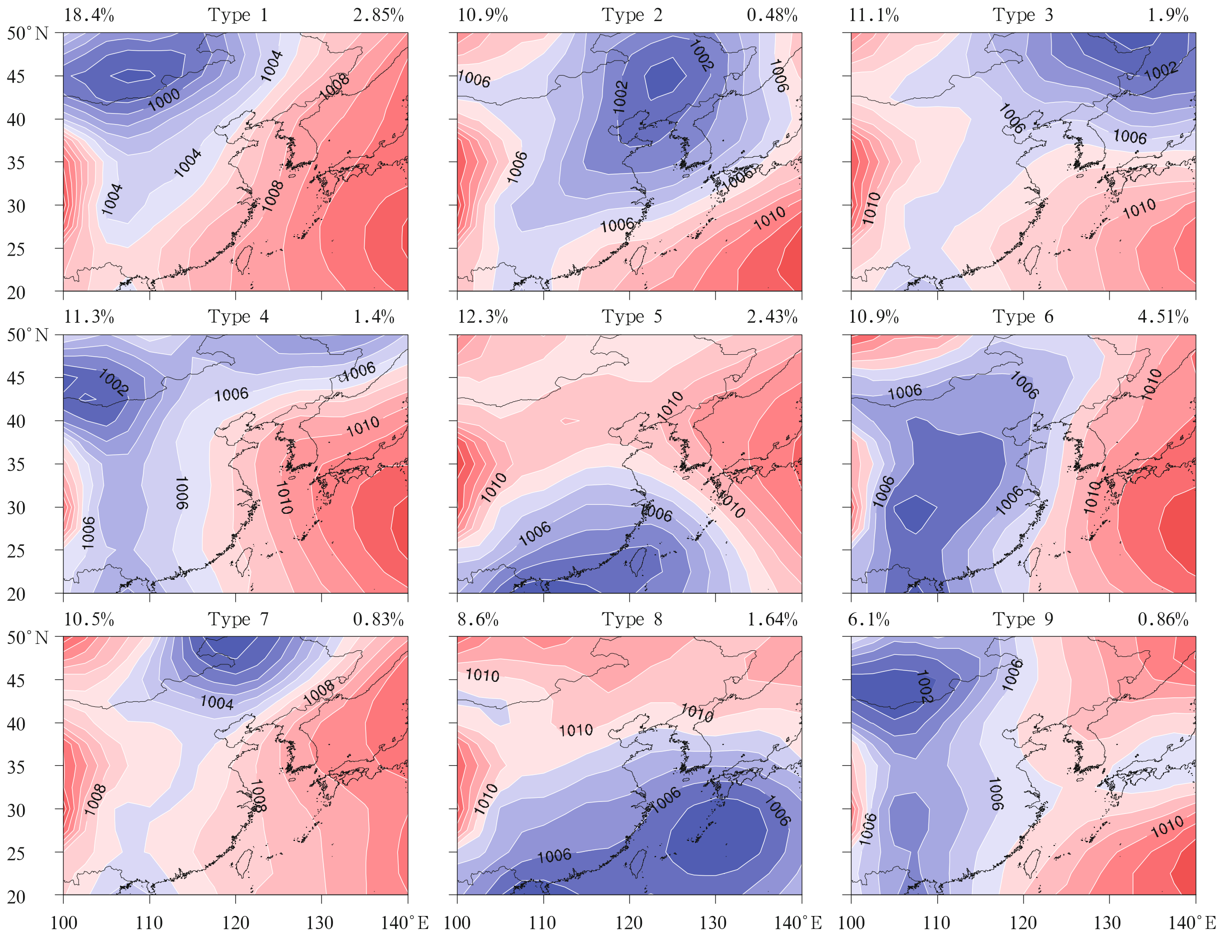

Fig. 2. SLP patterns associated with the 9 circulation types identified during the summers of 1951–2012. The occurrence frequency of each type is shown in the upper left and the frequency of torrential rain under each type is shown in the upper right of each panel.

while the fifth and eighth types correspond to remote interaction between a typhoon and a westerly trough (or vortex). The sixth and ninth types correspond to the meridional type introduced in a separate subjective classification by Tao (1980). The circulation associated with the 721 case belongs to the sixth type (hereafter referred to as the 721 type). The 721 type reflects the main features of the SLP field during the 721 case, with high pressure to the east of China, low pressure over mainland China, and a meridional circulation between the centers of the high and low pressure. The centers of the high and low pressure are stronger during the 721 case than during the general 721-type cases, and the horizontal gradient in SLP between the centers of the high and low pressure is therefore greater.

Among the 5704 days considered in this analysis, 621 days (10.9%) are classified as belonging to the 721 type. Of those same 5704 days, 115 are torrential rain days (based on daily precipitation during the summers of 1951–2012 from station 54511 with a threshold of 50 mm). The circulation types corresponding to these torrential rain days are obtained by using the same atmospheric circulation classification (e.g., 28 torrential rain days belong to the 721 type). The occurrence frequency of torrential rain under each of the 9 circulation types is then calculated (e.g., the occurrence frequency of torrential rain under the 721 type is 28 over 621, or 4.51%). The 721 type has the highest occurrence frequency of torrential rain among the 9 circulation types. These results show that the 721 type is not rare over the study period. Moreover, the 721 type results in torrential rains relatively more frequently.

4. The extreme features of the 721 case

The occurrence frequency of the 721 type is 10.9% during the summers of 1951–2012, and 24.3% (28 days) of the total 115 torrential rain days over the study period occur under this type. What makes the 721 case so prone to intense rainfall?

Figure 3 shows the mean distributions of 500-hPa geopotential height patterns for the 721 case (Fig. 3a), for all 621 days classified under the 721 type (Fig. 3b), for the 28 torrential rain days under the 721 type (Fig. 3c), and for all non-torrential rain days under the 721 type (Fig. 3d). The mean distribution of 500-hPa geopotential height associated with the 721 type is consistent with that associated with non-torrential rain days under the 721 type. By contrast, the subtropical high is more intense with a more northward position on torrential rain days relative to non-torrential rain days. Moreover, the ridge of the subtropical high is extended toward the northwest with a trough upstream of Beijing. During the 721 case, the subtropical high is even more intense, its ridge is extended further toward the northwest, and the trough located upstream of Beijing is deeper than during typical 721-type torrential rain days.

Figure 4 shows the mean distributions of 925-hPa geopotential height and winds for the 721 case (Fig. 4a), for all 621 days classified under the 721 type (Fig. 4b), for the 28 torrential rain days under the 721 type (Fig. 4c), and for all non-torrential rain days under the 721 type (Fig. 4d). Compared to non-torrential rain days, the center of high pressure to the east of China and the center of low pressure over mainland China are both stronger on torrential rain days, with a sharper horizontal gradient in geopotential height between the centers of the high and low pressure. These differences are even more pronounced during the 721 case (Fig. 4a), for which the centers of the high and low pressure are even stronger and the horizontal gradient in geopotential height near Beijing is even sharper than for typical 721-type torrential rain days. Distributions of geopotential height on other vertical levels in the lower troposphere are similar (figures omitted), with sharper horizontal gradients corresponding to a stronger southerly low-level jet during the 721 case.

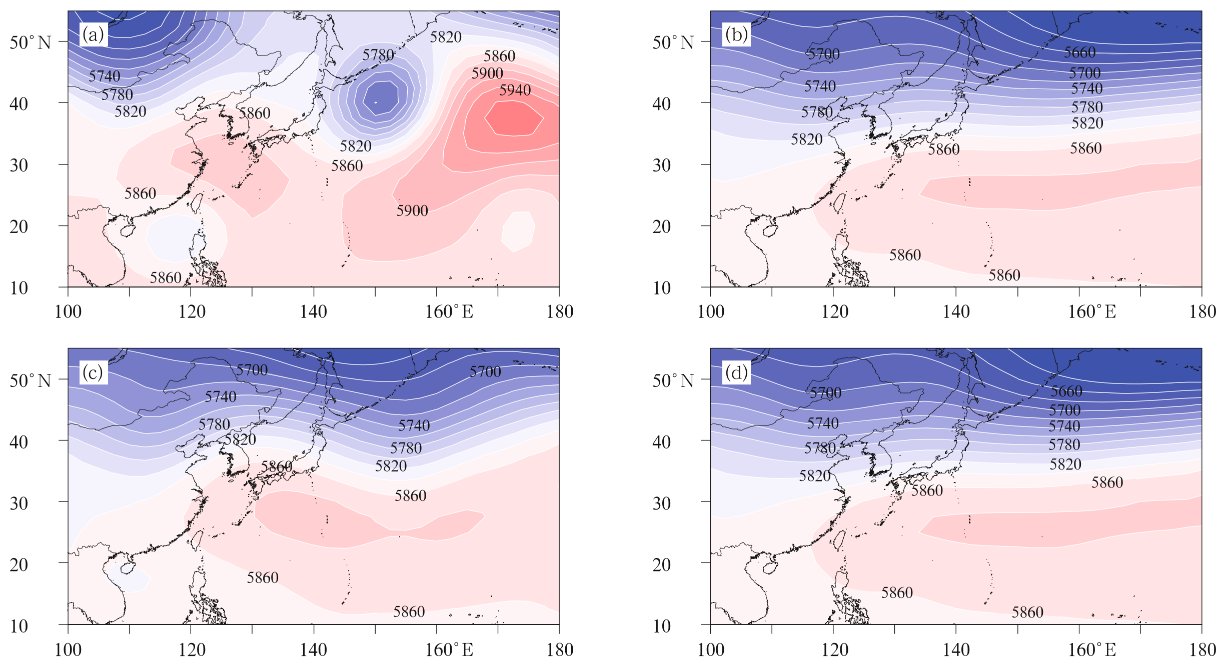

Fig. 3. Mean distributions of 500-hPa geopotential height for (a) the 721 case, (b) all days classified under the 721 type, (c) torrential rain days under the 721 type, and (d) non-torrential rain days under the 721 type.

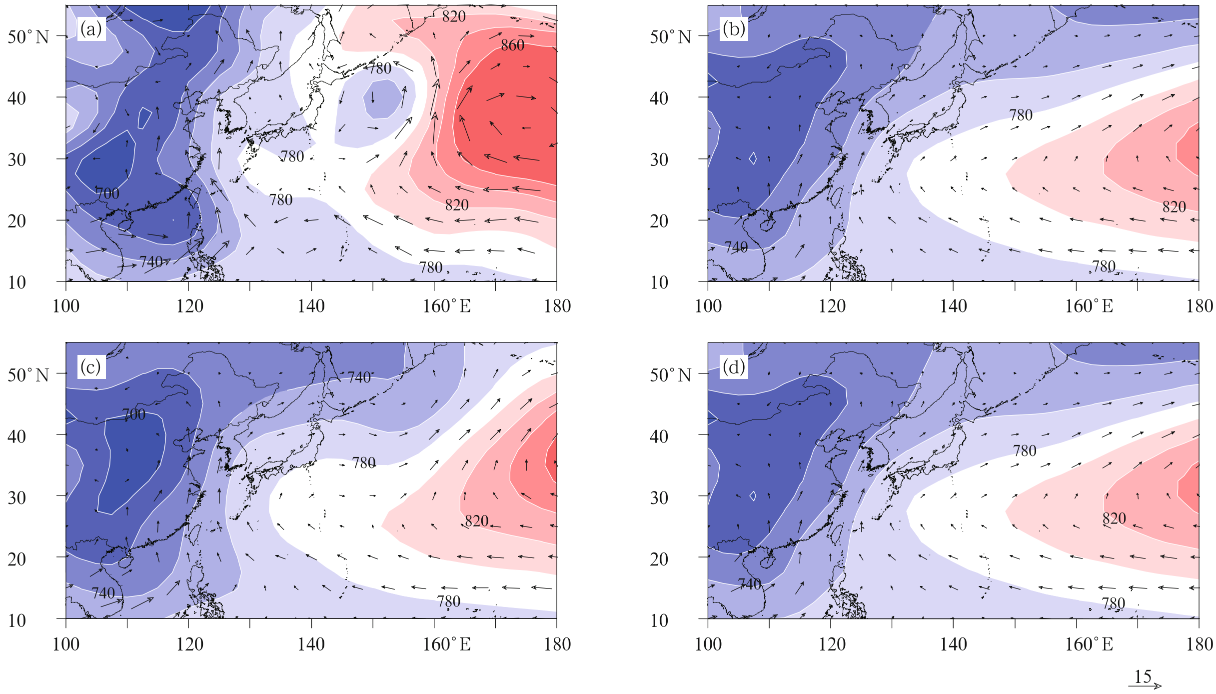

Fig. 4. As in Fig. 3, but for mean distributions of 925-hPa geopotential height (shaded) and winds (vectors).

This distribution of geopotential height provides a steady supply of water vapor to the Beijing region and promotes the construction of an unstable layer, triggering the release of unstable energy and strengthening mesoscale upward motion (Sun and Zhai, 1980).

Strong upward motion and a plentiful supply of water vapor are necessary conditions for the occurrence of torrential rains (Zhu et al., 2007). The average vertical wind shear (500-hPa wind vector minus 1000-hPa wind vector; see Fig. 5) over Beijing associated with the 721 circulation type is 9–10 m s^{-1}. This value is consistent with the value for non-torrential rain days under the 721 type. By contrast, the average value over Beijing is 10–11 m s^{-1} on torrential rain days under the 721 type and 12–13 m s^{-1} during the 721 case. Values of wind shear during the 721 case have exceeded 12 m s^{-1} over a large area around Beijing. A large vertical wind shear increases the baroclinic instability of the atmosphere (Lu et al., 2004). In addition, the vertical wind shear during the 721 case is clockwise, corresponding to warm advection between 1000 and 500 hPa. Warm advection at low levels destabilizes the atmosphere (Sheng et al., 2003), facilitating the development of strong convection from an initial disturbance. Large vertical wind shear also leads to a tilt in convection. Suppression of upward flow by downward flow is then inefficient, so the convection becomes well organized with a more persistent upward flow (Tao, 1980).

Figure 6 shows distributions of mean precipitable water for the 721 case (Fig. 6a), all days classified under the 721 type (Fig. 6b), torrential rain days under the 721 type (Fig. 6c), and non-torrential rain days under the 721 type (Fig. 6d). The mean precipitable water over Beijing is about 10 g m^{-2} higher on torrential rain days than on non-torrential rain days, while the precipitable water over Beijing during the 721 case is about 10 g m^{-2} higher than the mean for torrential rain days. Specific humidity is consistently higher throughout the lower atmosphere during the 721 case than on typical torrential rain days under the 721 type. Values of precipitable water over the areas south of Beijing during the 721 case are also higher than the average values for torrential rain days under the 721 type. Winds on the 925- and 850-hPa levels are directed from south to north through this area.

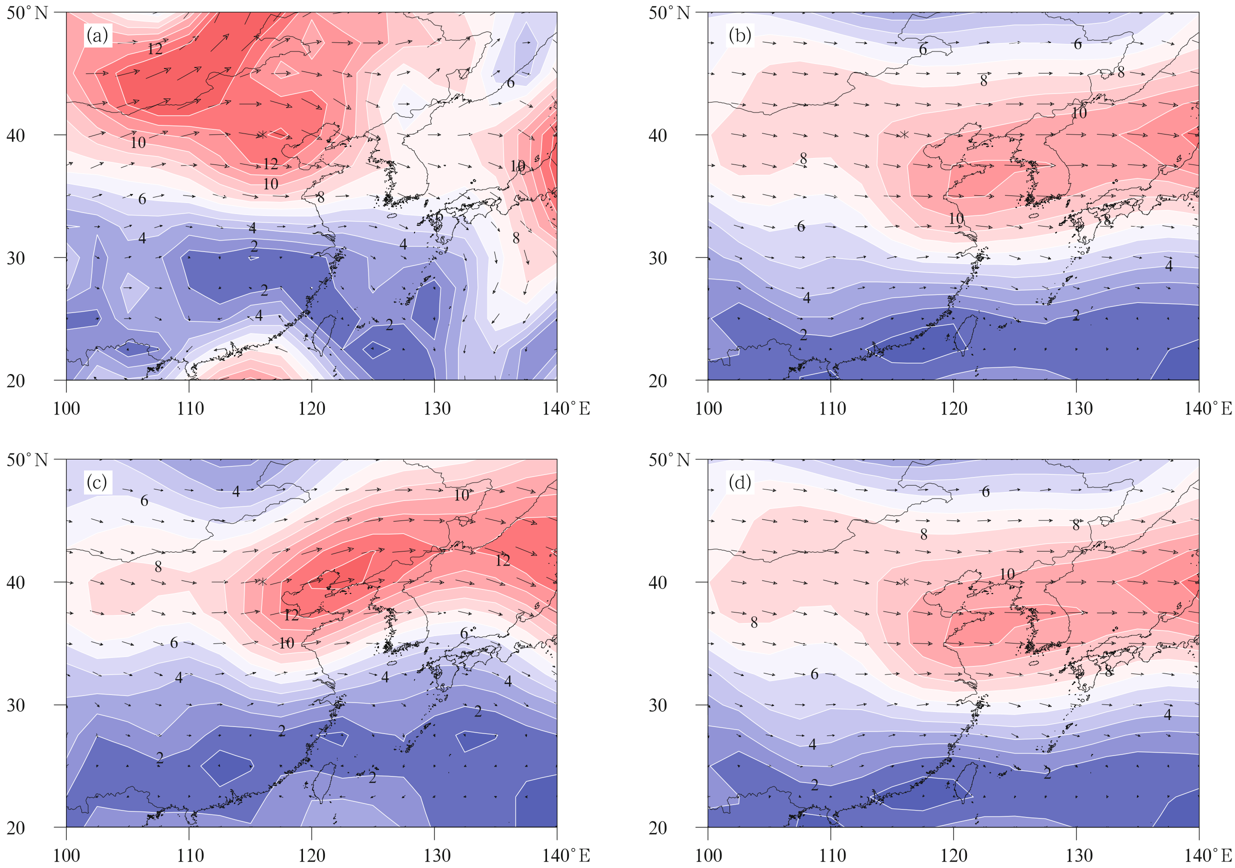

Fig. 5. As in Fig. 3, but for mean distributions of vertical wind shear.

The existence of this region of high specific humidity to the south of Beijing therefore corresponds to additional water vapor transport toward Beijing during the 721 case.

Figure 7 shows probability distributions of mean 925-hPa wind speed at four grid points south of Beijing (37.5°N, 117.5°E; 37.5°N, 120°E; 40°N, 117.5°E; and 40°N, 120°E), as well as probability distributions of vertical wind shear and precipitable water at the grid point closest to Beijing (40°N, 115°E). Separate probability distributions are derived for the 621 days classified under the 721 type and the 28 torrential rain days among these 621 days. The probability distribution for the 621 days under the 721 type is just the statistical result according to the definition of probability, and for the 28 torrential rain days it is verified to follow normal distribution and the probability distribution is then fitted. The maximum of the probability distribution of 925-hPa wind speed south of Beijing is 4.2 m s^{-1} for the 621 days classified as 721 type and 7.7 m s^{-1} for the 28 torrential rain days. The 925-hPa wind speed south of Beijing is 9.3 m s^{-1} for the 721 case. The maximum of the probability distribution of vertical wind shear over Beijing is 10.2 m s^{-1} for the 621 days of the general 721 type and 11.3 m s^{-1} for the 28 torrential rain days. The vertical wind shear during the 721 case is 12.8 m s^{-1}. The maximum of the probability distribution of precipitable water over Beijing is 27.7 g m^{-2} for the general 721 type and 37.5 g m^{-2} for the 28 torrential rain days. The precipitable water over Beijing during the 721 case is 50.5 g m^{-2}. The values of vertical wind speed south of Beijing and wind shear and precipitable water over Beijing during the 721 case are all higher than the mean values for the 28 torrential rain days under the 721 type, which are in turn higher than the mean values for the 621

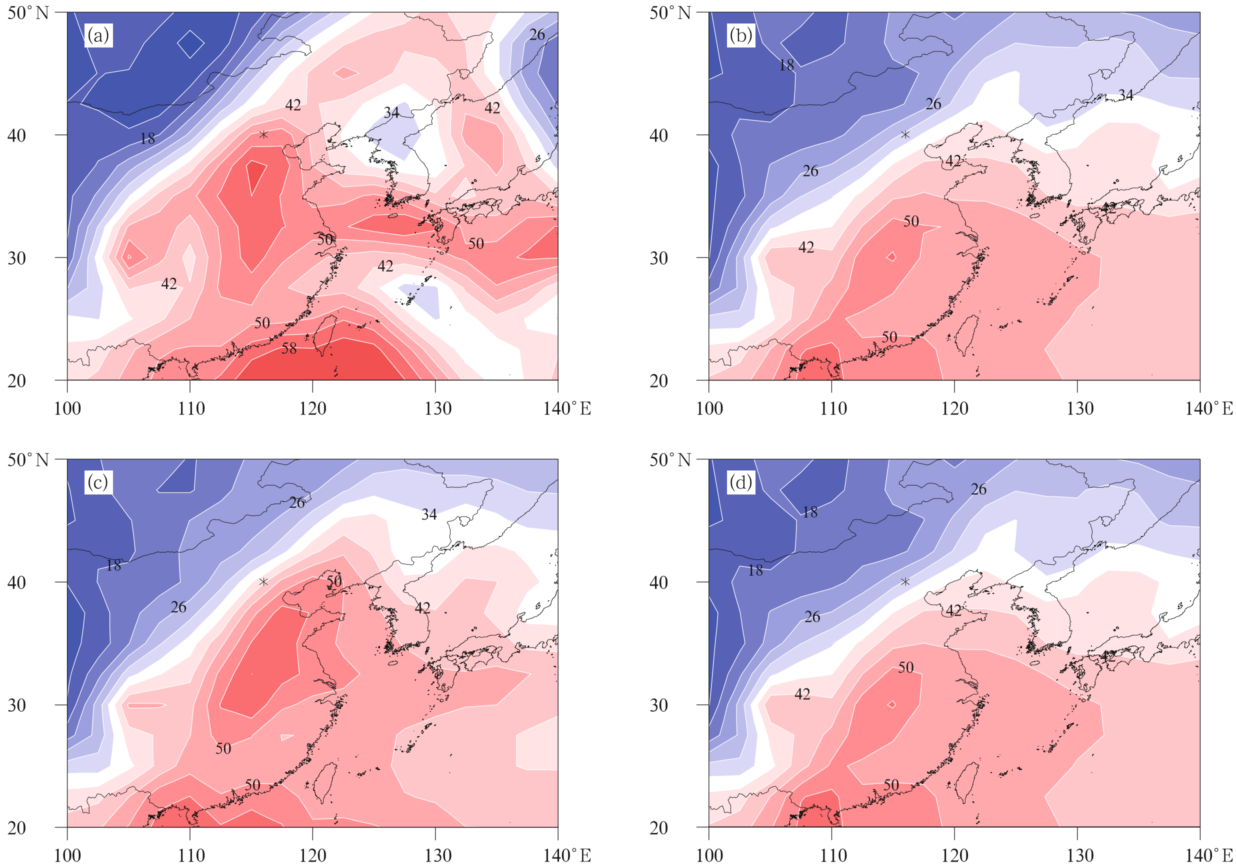

Fig. 6. As in Fig. 3, but for mean distributions of precipitable water.

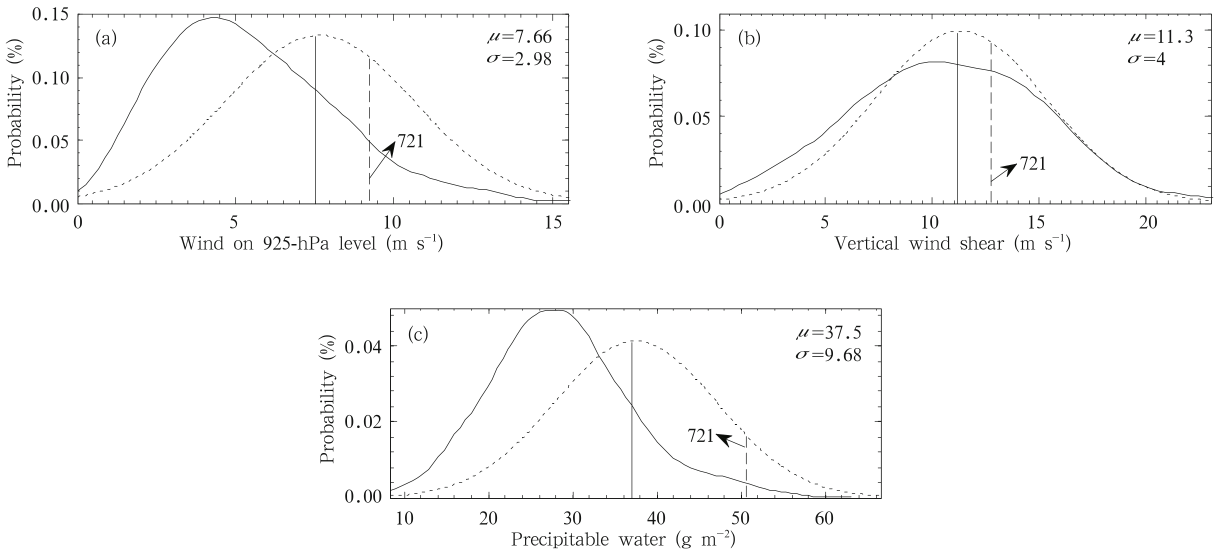

Fig. 7. Probability distributions of (a) average 925-hPa wind speed at four grid points south of Beijing (37.5°N, 117.5°E; 37.5°N, 120°E; 40°N, 117.5°E; and 40°N, 120°E), (b) vertical wind shear at the grid point nearest to Beijing (40°N, 115°E), and (c) precipitable water at the grid point nearest to Beijing. Separate distributions are shown for all days classified as the 721 type (solid curve) and the 28 torrential rain days under the 721 type (dashed curve). The solid vertical line indicates the mean value for the 28 torrential rain days, and the dashed vertical line indicates the value for the 721 case. The values listed for μ and σ are the mean and standard deviation for the 28 torrential rain days.

days classified as the 721 type. These relative differences are especially prominent for 925-hPa winds south of Beijing and precipitable water over Beijing. The probability distributions of 925-hPa wind speed and precipitable water for the 28 torrential rain days are shifted substantially toward the positive tail of the corresponding probability distributions for all days classified as the 721 type. By contrast, the probability distributions for vertical wind shear over Beijing are very similar. This result is consistent with the idea that the "occurrence of torrential rain requires certain vertical wind shear, but too large vertical wind shear is detrimental to the occurrence of torrential rain" (Tao, 1980). Among the 621 days classified as the 721 type during the study period, the 721 case ranks the 54th in terms of the strength of the low-level jet south of Beijing, 209th in terms of vertical wind shear over Beijing, and 8th in terms of precipitable water over Beijing. These ranks indicate that the low-level jet and precipitable water during the 721 case are extreme, where extreme values are defined to be values within the 90th percentile (Huang et al., 2010). The speed of the low-level jet south of Beijing and the values of precipitable water over Beijing equal to or greater than those during the 721 case happen on only 3 (inclusive of the 721 case) of the 621 days classified as the 721 type during the summers of 1951–2012. This result suggests that this type of extreme event occurs once every 21 years.

5. Summary

Daily SLP fields during the summers of 1951–2012 have been used to classify circulation patterns into 9 types using obliquely rotated T-mode PCA. The frequency of the circulation pattern observed during the 721 case (the 721 type) during the study period has been identified, and the extremity of the 721 case has been quantitatively evaluated. The conclusions are summarized as follows.

(1) The 721 circulation type occurs with a frequency of 10.9% during the summers of 1951–2012. The frequency of torrential rain associated with the 721 type is 4.51%.

(2) Relative to other rainstorms under the 721 type during the study period, the 721 case is characterized by a stronger subtropical high that has extended further toward the west over the western North Pacific, a deeper trough upstream of Beijing, a stronger low-level jet south of Beijing, a greater amount of ambient precipitable water, and a stronger vertical wind shear over Beijing.

(3) Among the 621 days classified under the 721 type during the study period, the 721 case ranks the 54th in terms of the speed of the low-level jet south of Beijing, 209th in terms of vertical wind shear over Beijing, and 8th in terms of precipitable water over Beijing. The low-level jet and precipitable water during the 721 case are both extreme (top 10% of all days with the 721 type).

(4) Over the study period, only 3 cases classified under the 721 type have equal or greater magnitudes of wind speed at 925 hPa and precipitable water over Beijing than the 721 case. This translates to an occurrence frequency of once every 21 years.

This paper provides a reference point for predicting extreme precipitation in Beijing. This reference is limited by time coverage and the use of daily precipitation data from only one location (station 54511) to identify torrential rain days. The analysis of the extremity of the 721 case is preliminary, and further verification should be performed by using a high-resolution numerical model.

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