The Large-Scale Circulation Patterns Responsible for Extreme Precipitation Over the North China Plain in Midsummer

Yang Zhao1,2, Xiangde Xu1,2, Jiao Li3, Rong Zhang1, Yanzhen Kang4, Wubin Huang2, Yu Xia6, Di Liu6, and Xiaoyun Sun4

1State Key Laboratory of Severe Weather, Chinese Academy of Meteorological Sciences, Beijing, China, 2Department of Atmospheric and Oceanic Sciences, McGill University, Quebec, Canada, 3Henan Province Climate Center, Zhengzhou, China, 4College of Atmospheric Sciences, Lanzhou University, Lanzhou, China, 5Lanzhou Central Meteorological Observatory, Lanzhou, China, 6Nanjing University of Information Science and Technology, Nanjing, China

Abstract Extreme precipitation events over the North China Plain (NCP) in midsummer during 1979–2016 are classified into two types using objective cluster analysis: a northern pattern with heavy precipitation and a central–southern pattern with relatively moderate precipitation. The large-scale circulation patterns responsible for the midsummer extreme precipitation are then determined. In the northern NCP type, extreme precipitation accompanies a zonal gradient between an anomalous low-pressure system at high latitudes and the westward- and northward-extended western North Pacific subtropical high (WNPSH). Anomalous southwesterlies flow is driven by a trough that extended from the high latitudes to the northern NCP, where it encounters southeasterly wind flow induced by an anomalously northward-extended WNPSH and a southern low-pressure anomaly at low latitudes. Anomalous amounts of moisture are mainly transported from the tropical western Pacific by southeasterlies.

1. Introduction

Extreme precipitation has a profound impact on society, property, and human welfare around the world (Easterling et al., 2000; Greenough et al., 2001; Véronique et al., 2014; Xia et al., 2015) and can result in deadly and destructive natural disasters (Plummer et al., 1999; Jonkman, 2005; Potop et al., 2014). The North China Plain (NCP; 32°–40.5°N, 115°–121°E) is a politically and economically key region with a dense population and substantial grain production. However, the socioeconomic life of the NCP is remarkably vulnerable to the uncertainties of extreme precipitation, which costs the region billions of U.S. dollars each year. Research on extreme precipitation over the NCP not only facilitates precipitation forecasts and disaster warning but also benefits water resource utilization and societal development (Sun et al., 2015).

The NCP is located on the northern edge of the area influenced by the subtropical East Asian monsoon. Summer precipitation over the NCP has decreased with the weakening summer monsoon in recent decades (Ding et al., 2010; Liu et al., 2005). Despite this long-term decrease over the NCP, extreme intense precipitation has occurred more frequently in recent years (Tu et al., 2010). For instance, the torrential precipitation event in Beijing on July 21, 2012 (the “7.21” event) brought huge economic losses to China (Sun et al., 2013).

Much effort has been devoted to exploring the mechanism of extreme precipitation over the NCP (Wang et al., 2015; Jiang et al., 2016). Ding et al. (1980) divided circulation patterns for rainstorms over the NCP during 1958–1976 subjectively into three types: the first type has a steady meridional circulation system with a high to the east and low to the west; the second type has vortexes or a quasi-east-west-oriented shear line at low level; and the third type is the interaction of the first two types of circulation. Tao (1980) identified two main...
circulation patterns driving rainstorms over the NCP using historical extreme precipitation events: a steady meridional circulation accompanying a northward-extended western North Pacific subtropical high (WNPSH) with violent precipitation and a stable zonal circulation with moderate precipitation. Sun et al. (2005) further categorized the circulation systems driving summer extreme precipitation over North China during 1990–1999 into six groups. Zhao et al. (2013) classified circulation patterns driving extreme precipitation during 1951–2012 into nine types and found that circulation patterns including a westward-extended WNPSH, an intensified jet, an enhanced vertical wind shear, and anomalously abundant water vapor transport were responsible for the “7.21” torrential precipitation event in Beijing. Orsolini et al. (2015) reported that the Silk Road wave train and a polar wave train induced northward and westward extension of the WNPSH and, consequently, extreme precipitation in August 2010 over North China. Extreme precipitation over the central NCP is attributed to warm (cold) anomalies in the upper level via two different circulation patterns (Sun et al., 2015).

Numerous studies of extreme precipitation over the NCP have mainly looked at historical specific cases or subregions, and most have considered the factors favoring variously defined extreme precipitation over the NCP at a certain level while neglecting circulation structures at multiple levels. There is no systematic and comprehensive overview of the large-scale circulation patterns of extreme precipitation over the NCP. Furthermore, whether these circulation features are special to individual cases or common to all extreme precipitation events needs to be clarified. Objective classification criteria are more widely applicable than subjective groupings because they are independent of user expectations (Huth et al., 2008). Previous studies have conventionally focused on the circulation classifications associated with extreme precipitation over the NCP. However, classifications in terms of extreme precipitation distribution over the NCP remain insufficient. In this regard, objective classification with respect to extreme precipitation location over the NCP is essential to improve precipitation forecast skill over the NCP and identify the relevant climatic features in situ.

Objective classification has shown that regional extreme precipitation is closely linked to large-scale circulation (Cavazos, 1999; Freychet et al., 2015). Clustered extreme precipitation events can cause severe natural hazards. Li, Chen and Wang (2016), for example, revealed that the significant increase in clustered extreme precipitation over South China after 1992/1993 is attributed to the extensions of the WNPSH and westerly jet and abundant water vapor transport over East Asia. Hu et al. (2018) used hierarchical cluster analysis to identify three large-scale circulation patterns over the middle reaches of the Yangtze River and suggested that extreme precipitation events in this region are modulated by the South Asia High, low-level water vapor transport, and the westerly jet. The large-scale circulation at various heights was shown to drive persistent extreme precipitation over South China, with two circulation patterns identified by cluster analysis (Wu et al., 2016).

Following the northward advance of the East Asian summer monsoon, the most pronounced rainband over the NCP occurs mainly from mid-July to mid-August (Ding et al., 2007; Ding & Chan, 2005). Tao (1980) reported that extreme precipitation over the NCP extends mainly from the second half of July to the first half of August. Many other studies have also confirmed that most extreme precipitation events over the NCP are concentrated in the period from mid-July to mid-August (Li & Wang, 2017). The 30-day period from the second half of July to the first half of August is defined as midsummer over eastern China (Wang et al., 2017; Wang & Zuo, 2016). Thus, in this study, we define the period from 15 July to 15 August as midsummer to capture the most frequent period of extreme precipitation over the NCP.

The goal of this study is to identify the typical large-scale circulation patterns responsible for extreme precipitation over the NCP in midsummer using objective cluster analysis. A better understanding of the underlying causes of extreme precipitation over the NCP will help to mitigate regional natural disasters. This current research will allow us to better characterize extreme precipitation events and provide a robust scientific foundation for improving extended-range forecasts of extreme precipitation over the NCP.

2. Data and Methodology

2.1. Data

Daily precipitation data from 2010 gauge stations for 1979–2016 were released by the National Meteorological Information Center of the China Meteorological Administration (http://data.cma.cn/). The data set has undergone homogeneity and quality control processing (Ren et al., 2010; Zhang et al.,
Gauges are included if they have less than 10% missing values. There are 289 surface meteorological stations evenly distributed throughout the NCP (Figure 1, purple box). Daily atmospheric fields for 1979–2016 were acquired from the ERA-Interim reanalysis data set (http://apps.ecmwf.int/datasets/) produced by the European Centre for Medium-Range Weather Forecasts (Dee et al., 2011). This data set has a horizontal resolution of 0.75° × 0.75° and a 6-hr time interval. The variables used in this study are horizontal winds, specific humidity, and geopotential height. The daily records were converted to precipitation amounts for the 24 hr from 2000 Beijing time (BJT) of the previous day to 2000 BJT of the current day. As BJT is 8 hr ahead of Coordinated Universal Time (UTC), the large-scale circulation patterns responsible for extreme precipitation (Bernard et al., 2013; Park et al., 2014; Toreti et al., 2010; Zhao et al., 2017). Extreme precipitation is defined using different thresholds than using a fixed criterion (Manton et al., 2001; Plummer et al., 1999). Extreme precipitation is defined as exceeding a threshold percentile of the 24-hr precipitation amount at each gauge (Zhai et al., 2005; Zhang et al., 2008). The advantage of this method using different thresholds is that it can accurately represent extreme precipitation at diverse stations (Tian & Fan, 2013). Daily extreme precipitation at each gauge over the NCP is defined using an objective k-means clustering algorithm (Anderberg, 1973). In this study, the k-means clustering analysis is applied to classify extreme precipitation days over the NCP in midsummer (15 July to 15 August) collected from 289 observation gauges during the period 1979–2016.

2.2. Methodology

2.2.1. Extreme Precipitation Days

The relative threshold value is deemed to be more appropriate for investigating regional extreme precipitation than using a fixed criterion (Zhang & Zhai, 2011). The most widely applied international percentile method is chosen to define the extreme precipitation threshold (Manton et al., 2001; Plummer et al., 1999). Extreme precipitation is defined as exceeding a threshold percentile of the 24-hr precipitation amount at each gauge (Zhai et al., 2005; Zhang et al., 2008). The advantage of this method using different thresholds is that it can accurately represent extreme precipitation at diverse stations (Tian & Fan, 2013). Daily extreme precipitation at each gauge over the NCP is defined to be larger than the 90th percentile threshold of the 24-hr precipitation amount in midsummer (15 July to 15 August) collected from 289 observation gauges during the period 1979–2016.

2.2.2. Cluster Analysis

Both non-hierarchical and hierarchical cluster analysis have been extensively used to analyze the large-scale circulation patterns responsible for extreme precipitation (Bernard et al., 2013; Park et al., 2014; Toreti et al., 2010; Zhao et al., 2017). k-means clustering is a non-hierarchical centroid-based method. It determines the dominant extreme precipitation clusters based on the mean state (Hartigan & Wong, 1979). Precipitation clusters are identified using an objective k-means clustering algorithm (Anderberg, 1973). In this study, the k-means clustering analysis is applied to classify extreme precipitation days over the NCP in midsummer during the period 1979–2016.

The k-means clustering method is an iterative procedure used to identify clusters in a given data set. k-means clustering divides the n observations into k sets to minimize the within-cluster sum of squares. The basic algorithm works as follows:

First, we initialize k points, called means, randomly.

Second, we categorize each item to its closest mean and we update the mean’s coordinates, which are the averages of the items categorized in that mean so far.

Third, we repeat the process for a given number of iterations and at the end, and the clusters are selected.

Based on the previous studies, the core equation of k-means clustering analysis is as follows:

\[
\arg\min_m \sum_{i=1}^k \sum_{y \in m_i} \text{dis}(y, q_i) = \arg\min_m \sum_{i=1}^k \sum_{y \in m_i} \|y - q_i\|_2^2, \tag{1}
\]

\[
\sum_{y \in m_i} \|y - q_i\|_2^2 = \sum_{y \in m_i} \sum_{p=1}^m (y_p - q_i)^2. \tag{2}
\]

There are n data points in the study area (the NCP region has 289 points). The goal is to group points into different clusters obtained by minimizing the sum of squared distances (dis). The n data points are divided into k clusters. k-means clustering determines the positions \(q_i\) \((i = 1, 2, 3 \ldots k)\) of the clusters that minimize the data distance to the cluster, and there are m points in cluster \(i\). The norm \(y\) is the 90th percentile threshold of the observational 24-hr precipitation in midsummer in each station for each cluster \(y = [y_p| p = 1, 2, \ldots, m]\). However, the weakness of the k-means clustering method is that it does not determine the
optimal number of clusters. Zhang et al. (2001) divided all stations into two to six groups and used spatial consistency to determine the number of clusters. We use the same method here.

To consider the sufficient number of rainstorm days existing in each cluster, two clusters of extreme precipitation days over the NCP were finally selected.

2.2.3. Vertically Integrated Water Vapor Flux

The continuous supply of water vapor is an important factor for extreme precipitation (Li, Jiang, et al., 2016; Zhao et al., 2018; Zhao, Xu, Liu et al., 2019). To investigate the water vapor transport associated with extreme precipitation over the NCP in midsummer, the vertically integrated water vapor fluxes are calculated as follows:

\[
q_u = \frac{1}{g} \int_{P_s}^{P_t} q u dp,
\]

\[
q_v = \frac{1}{g} \int_{P_s}^{P_t} q v dp,
\]

where \( q \) is specific humidity; \( g \) is acceleration due to gravity; \( u \) and \( v \) are the zonal and meridional wind speeds, respectively; the \( P_s \) is the surface pressure, set to 1,000 hPa; the \( P_t \) is the top atmospheric pressure, set to 100 h Pa; and \( q_u \) and \( q_v \) are the zonal and meridional water vapor fluxes, respectively.

3. Two Types of Extreme Precipitation Events Over the NCP

3.1. Spatial and Temporal Distributions of Extreme Precipitation Days

Figure 1 depicts the spatial distributions of the 90th percentile daily extreme precipitation at each station over mainland China and the integrated column water vapor flux over mainland China and its surrounding regions in midsummer during 1979–2016. The red box indicates the North China Plain (NCP; 32°–40.5°N, 115°–121°E). Arrows denote the daily average of integrated column water vapor flux (unit: g·m\(^{-1} \cdot \)s\(^{-1} \)) in midsummer from 1979 to 2016.

Figure 1. Spatial distributions of the 90th percentile daily extreme precipitation (unit: mm) at each station over mainland China in midsummer during 1979–2016. The red box indicates the North China Plain (NCP; 32°–40.5°N, 115°–121°E). Arrows denote the daily average of integrated column water vapor flux (unit: g·m\(^{-1} \cdot \)s\(^{-1} \)) in midsummer from 1979 to 2016.
frequency of extreme precipitation increased from 1997 to 2016 over the NCP, consistent with the results of Zhou et al. (2013).

The regional mean value of the 90th percentile daily extreme precipitation across the entire NCP in midsummer is 17.4 mm. Hereafter, an extreme precipitation day over the NCP is defined as when the regional mean of the daily precipitation amount exceeds 17.4 mm. Finally, this gave 65 days of extreme precipitation in midsummer over the entire NCP from 1979 to 2016.

3.2. Diagnosis of the Climatological Circulation Patterns

To identify the atmospheric circulation in the troposphere over the NCP, the climatological geopotential height and wind fields in midsummer during 1979–2016 are shown in Figures 3a and 3b. At 500 hPa, the 5,860 geopotential-meter (gpm) contour is located over the east coast of China (Figure 3a). The NCP is in front of a weak trough east of the Loess Plateau, resulting in westerly and southwesterly winds over the NCP (Figure 3a). As water vapor content is generally maintained at low levels, the corresponding circulation at 850 hPa is also shown in Figure 3b. The low-level southwesterly flow over the NCP carries the water vapor from the Bay of Bengal and South China Sea to the NCP.

3.3. Classification of Extreme Precipitation Over the NCP

The above analysis has provided a preliminary diagnosis of the climatological circulation over the NCP in midsummer, revealing the general patterns over the NCP. However, circulation features with respect to extreme precipitation events over the NCP are still missing. Chen and Zhai (2014) emphasized the
importance of determining whether the circulation patterns differ between events or are common to all extreme precipitation events. Classification is a useful method in synoptic climatology for investigating extreme precipitation and associated large-scale circulation variation (Liu et al., 2015). Clustered extreme precipitation events cause more severe natural disasters such as floods and landslides than do general extreme precipitation events (Li, Chen, & Wang, 2016). Thus, cluster analysis using objective criteria was adopted here to categorize 65 extreme precipitation days over the NCP in midsummer during 1979–2016 into two dominant clusters and to determine the actual extreme precipitation distribution.

Figure 4 displays the spatial patterns of the composite 90th percentile daily extreme precipitation amount (color shading; unit: mm) over the NCP in midsummer in Cluster 1 (accounting for 30 days of the total extreme precipitation days), extreme precipitation is mainly confined to the northern NCP. Extreme precipitation over the northern NCP forms an intense northeast–southwest-oriented belt with a daily mean precipitation of 25.5 mm and daily precipitation peak exceeding 65 mm. In contrast, extreme precipitation in Cluster 2 (representing 35 days of extreme precipitation days) occupies the central–southern part of the NCP. This area receives relatively moderate precipitation with a daily mean precipitation of 19.0 mm. A line drawn at about 36.5°N divides the extreme precipitation distribution into two types, referred to as Clusters 1 and 2. The two types share distinct regional differences with respect to the location and intensity of extreme precipitation. Hereafter, Type 1 represents the “northern NCP” pattern, and Type 2 denotes the “central–southern NCP” pattern.

The large body of literature on extreme precipitation over the NCP mainly considered the grouping of circulation patterns (Liang et al., 2011; Sun et al., 2018). In this study, the objectively cluster analysis method that initially divides extreme precipitation over the NCP into a northern distribution with intense rainfall and a central–southern pattern with relatively moderate rainfall is expected to improve regional precipitation forecast skill. To further highlight and analyze the typical comprehensive large-scale circulation conducive to extreme precipitation for these two types, the top 10 days with the highest extreme precipitation for each type were selected from 65 days of the 90th percentile daily extreme precipitation. We focus on the top 10 days with the highest extreme precipitation, as they are expected to represent the most typical extreme precipitation of each type over the NCP (Table 1).

| Northern Type 1 | Central–Southern Type 2 |
|-----------------|--------------------------|
| Year | Date | Precipitation (mm) | Year | Date | Precipitation (mm) |
| 1984 | 8 Aug | 47.7 | 1982 | 21 Jul | 18.2 |
| 1988 | 17 Jul | 20.0 | 1983 | 18 Jul | 18.4 |
| 1990 | 28 Jul | 18.3 | 1986 | 17 Jul | 18.3 |
| 1991 | 27 Jul | 34.3 | 1990 | 16 Jul | 22.3 |
| 1994 | 5 Aug | 20.5 | 1996 | 16 Jul | 19.9 |
| 1996 | 4 Aug | 32.4 | 1997 | 16 Jul | 17.0 |
| 2009 | 16 Jul | 18.2 | 2001 | 29 Jul | 17.6 |
| 2010 | 18 Jul | 29.0 | 2003 | 20 Jul | 18.6 |
| 2012 | 21 Jul | 29.8 | 2007 | 18 Jul | 18.9 |
| 2012 | 31 Jul | 22.1 | 2008 | 22 Jul | 22.3 |
4. Related Circulation

4.1. Low-Level Circulation Patterns of Extreme Precipitation for the Two Types

The spatial distributions of extreme precipitation selected from the top 10 days with the highest extreme precipitation for each type over the NCP are illustrated to examine whether it is identical to the clustered results. In Type 1, extreme precipitation shows a remarkable northeast–southwest-oriented pattern over the northern NCP with a large amount of precipitation above 65 mm (Figure 5a). In contrast, in Type 2, the central–southern NCP is covered by relatively moderate precipitation (Figure 5b). The spatial patterns of these highest extreme precipitation days are quite similar to the clustered results. These highest extreme precipitation days for each type capture the typical extreme precipitation over the NCP and ensure that the corresponding circulation reflects the actual circulation characteristics of extreme precipitation over the NCP.

Although Tao (1980) identified the main circulation patterns driving two rainstorm types over the NCP subjectively, the comprehensive circulation patterns leading to extreme precipitation over the NCP in the two objectively categories remain unclear. Therefore, it is necessary to address the large-scale circulation patterns associated with extreme precipitation for the two types over the NCP.

Tian and Fan (2013) documented that atmospheric circulation anomalies can lead to extreme precipitation events. Hu et al. (2018) suggested that summer extreme precipitation cases over East Asia are mainly caused by anomalous circulation rather than the climatological circulation. Hereafter, we investigate the
geopotential height anomalies of extreme precipitation days in the lower troposphere over the NCP for the two types in midsummer. In Type 1, a significant anomalous low-pressure system extends along a north–south-orientated belt from Lake Baikal to the eastern periphery of the Tibetan Plateau (TP). An anomalous high-pressure system is located over the western North Pacific, near Japan and the Korean Peninsula. The NCP lies in the area with a sharp zonal gradient of low- and high-pressure system anomalies at middle–high latitudes. There are also low-pressure systems north of Lake Balkhash and over the Bay of Bengal and the South China Sea (Figure 5c).

In Type 2, there are prominent anomalous low-pressure systems over all of northern China with centers over the Sichuan Basin and northeast China. Concurrently, a weaker anomalous high-pressure system dominates the southeast coast of China at low latitudes. Different from the sharper zonal gradient of geopotential height anomalies at middle–high latitudes of Type 1, the NCP in Type 2 is influenced by the meridional structure of two isolated northern low-pressure anomalies at middle latitudes and the southern anomalous high-pressure system at lower latitudes (Figure 5d).

To check that the composite results are representative and not affected by a single extreme case, the frequency of dominant high- and low-pressure systems is calculated for all extreme precipitation days to examine their consistency. The criterion for consistency of high (low) pressure systems is that their geopotential height is always 10 gpm higher (lower) than the climatology. Through manual examination of all the selected extreme precipitation days in Table 1, the location where the anomalous high-pressure system appears on 80% of event days in each category is identical to the center of the maximum composite height anomaly (red dots in Figures 5c and 5d). This signifies that the anomalous high-pressure systems in each category are shared by most extreme precipitation days within the categories rather than being decided by specific days. The anomalous low-pressure system that occurs on 80% of all event days is consistent with the center of the minimum composite height anomaly (red dots in Figures 5c and 5d), indicating a fairly robust relationship between the anomalous low-pressure system and extreme precipitation. Our results reflect that the particular consistent low- and high-pressure system anomalies are responsible for extreme precipitation over the NCP in the corresponding type.

A large supply of water vapor is a necessary condition for torrential rainfall formation (Freychet et al., 2015). Zhang (1999) discussed the relationship between summer precipitation over northern China and water vapor transport of the Indian summer monsoon. The composite anomalies of horizontal winds and specific humidity at 700 hPa in the two types during midsummer are shown in Figure 6. In Type 1, a westward–and northward-extended anticyclonic anomaly is located over Japan and the Korean Peninsula. The NCP is located beneath the western edge of this anomalous anticyclone, accompanied by southerly flow. At the same time, an anomalous cyclone is located over the southeast coast of China. As shown in Figure 6a, the intensified southerly flow towards the NCP coincides with the increased northward transport of anomalous moisture that originates mainly from the western North Pacific (Figure 6a).

In Type 2, there are two cyclonic centers over northern China: one anomalous vortex to the southwest over the Sichuan Basin and the other vortex over northeast China. At low latitudes, an anomalous anticyclone is located over the southeast coast of China. Previous studies have described a circulation type driving torrential rainfall over the NCP that features a northeast cold vortex, a southwest vortex, or an east–west-oriented shear line at low levels (Ding et al., 1980; Luo et al., 2016). The central–southern NCP is situated at the confluence core of low-level northerly flow associated with the anomalous northeast vortex and southwesterlies driven by both the anomalous anticyclone over the southeast coast of China and the anomalous vortex to the southwest.

As a result of the southward shift of the anomalous anticyclone relative to its position in Type 1 extreme precipitation, the anomalous moisture for extreme precipitation in Type 2 originates mainly from the South China Sea and the Bay of Bengal. Moisture converges over the Sichuan Basin, crosses central China, and then reaches the southern NCP via southwesterlies (Figure 6b). Thus, the anomalous moisture supplying Type 1 is primarily from the western North Pacific. The anomalous moisture for Type 2 originates mainly from the South China Sea and the Bay of Bengal.

As an important component of the East Asian monsoon circulation system, the strong southwesterly low-level jet (LLJ) has a close relationship with extreme precipitation over the NCP (Wang & Liu, 2017). Wang et al. (2014) suggested that the water vapor transport responsible for a rainstorm case over the NCP...
during midsummer 2011 was conveyed mainly by the southwesterly LLJ. The southwesterly LLJ is found to make a major contribution to summertime convective initiation over North China from both observations and climate models (Chen & Tomassini, 2015).

The criterion of the southwesterly LLJ is defined in this study: The wind speed at 700 hPa is larger than 12.0 m·s\(^{-1}\), and the wind direction is southwesterly wind. To investigate the impact of the southwesterly LLJ on extreme precipitation over the NCP, the composite horizontal winds and the composite positive anomalies of the southwesterly LLJ at 700 hPa during midsummer for the two types are shown in Figures 6c and 6d. In Type 1, there is no obvious southwesterly LLJ over the areas surrounding the NCP (Figure 6c). In Type 2, there is an anomalous maximum core of the strong southwesterly LLJ from southwest China to the southern NCP. The rainstorm center over the central-southern NCP is directly to the left of this anomalous southwesterly LLJ (Figure 6d). Sun and Zhai (1980) reported that heavy rainstorms and their related vortexes occur frequently to the left of the southwesterly LLJ. Sun et al. (2012) found that the convective systems responsible for a severe rainstorm in July 2012 in Beijing propagated along the left side of the southwesterly LLJ axis.

To further analyze the possible cause of the southwesterly LLJ on extreme precipitation over the central-southern NCP, we compare the anomalous specific humidity distribution in Figure 6b and the anomalous southwesterly LLJ in Figure 6d. The spatial distributions of the strongest specific humidity and the intensified southwesterly LLJ anomalies share a great similarity. The increased specific humidity corresponds to the intensified southwesterly LLJ and results in more vigorous precipitation over the central-southern NCP that is located at the southwesterly LLJ outflow area. This reveals that the southwesterly LLJ acts as...
a channel to transport moisture mainly from the South China Sea and the Bay of Bengal, through the LLJ entrance towards the LLJ exit, finally reaching the central–southern NCP. The southwesterly LLJ can also provide dynamic forcing for extreme precipitation development (Wang et al., 2013). To the left of the southwesterly LLJ, there is positive vorticity produced by the anomalous southwest vortex over Sichuan Basin. Meanwhile, the significant anomalous convergence distributed along the left side of the strong southwesterly LLJ corresponds to precipitation locations over the central–southern NCP (dots in Figure 6d).

The above results imply that the southwesterly LLJ contributes to Type 2 by transporting moisture and supporting low-level dynamic convergence to strengthen upward motion in the region, while type 1 has no apparent association with the southwesterly LLJ.

4.2. Middle-Level Circulation Patterns of Extreme Precipitation for the Two Types

Figure 7 displays the composite anomalies of horizontal wind fields and geopotential height for the two types over the NCP at 500 hPa during midsummer. In Type 1 (Figure 7a), an anomalous high-pressure system develops north of Lake Balkhash, and a northeast–southwest-oriented anomalous low-pressure system is found near Lake Baikal with a trough stretching towards the northern flank of the TP. The anomalous high-pressure system north of Lake Balkhash facilitates deepening of this trough. The northern part of the NCP is anchored in front of this deep trough. At middle latitudes, the westernmost point of the 5,880-gpm contour extends to about 115°E with an ~20° westward displacement relative to the climatological mean location (Figure 3a) in midsummer. At the same time, a ridge of the 5,880-gpm contour is located at ~32°N, about 5° north of the climatological mean position (Figure 3a). The corresponding WNPSH is extended northward and westward and dominates the Korean Peninsula and Japan. Zhu (2007) reported that the rainband generally occurs 6°–10° north of the WNPSH ridge. As shown in Figure 7a, the northern NCP with intense precipitation extending from ~36.5° to 40.5°N lies north of the WNPSH ridge, consistent with previous finding (Zhu, 2007). There is a low-pressure system with an anomalous cyclone over the southeast coast of China at low latitudes. The meridional dipole pattern along with the northern WNPSH in middle latitudes and the southern low-pressure system at low latitudes ensures a continuous southeasterly flow into the NCP. These flows, along with the southwesterly flow with a trough at high latitudes, meet over the northern NCP. Zhao et al. (2013) found that a pronounced horizontal gradient between the westward-extended WNPSH and the trough from Lake Baikal to northern China was responsible for the “7.21”-type torrential rainfall in Beijing in the northern NCP; this is similar to our result. The coupling of zonally aligned pressure systems at high latitudes with meridionally elongated pressure systems at middle–low latitudes is conducive to Type 1 extreme precipitation.

The composite anomalies of horizontal wind fields and geopotential height for Type 2 are presented in Figure 7b. At middle latitudes, significant low-pressure anomalies completely cover all of northern China.
with two isolated centers developing over Sichuan Basin and northeast China. At low latitudes, the WNPSH is displaced by ~20° westward and 2° southward over the southeast coast of China from its climatological mean location (Figure 3a). The prevailing southwesterly flow due to the combined effects of the anomalous low-pressure system over the Sichuan Basin and the WNPSH encounters the steady northerly flow tied to the anomalous low-pressure system over northeast China. This confluence of northerly and southwesterly flows over the central–southern NCP provides convergence conditions favorable for Type 2.

Types 1 and 2 differ in that Type 1 is driven by the coupling of zonally aligned pressure systems at high latitudes with meridionally elongated pressure systems at middle–low latitudes, whereas Type 2 is mainly attributed to the interaction of the WNPSH at lower latitudes and low-pressure systems at middle latitudes.

### 4.3. Upper-Level Circulation Patterns of Extreme Precipitation for the Two Types

The upper tropospheric circulation systems tend to be steadier, more persistent, and more predictable than circulation patterns in the middle–lower troposphere (Zhang & Wu, 2001). The South Asian High (SAH) and the East Asian subtropical westerly jet are the planetary-scale systems with major impacts on summer precipitation over North China (Shi & Zhang, 2008; Xie et al., 2015). By considering two major groups of northward jumps of upper-tropospheric jets in midsummer (Lin & Lu, 2008), Lin (2013) claimed that a weakened westerly jet axis could induce westward and northward displacements of the WNPSH and thereby enhance precipitation over the NCP. The zonal and meridional displacements of the SAH might exert combined effects on summer precipitation over North China (Wei et al., 2013).

In this study, the extent of the SAH is characterized by the 12,500-gpm geopotential height contour (Wei et al., 2015), and the jet is defined as having zonal wind velocity greater than 28 m·s⁻¹. The composite circulation anomalies at 200 hPa are shown in Figure 8. For Type 1, the SAH measured by the 12,500-gpm contour is displaced northward by 5° latitude across the northern part of NCP relative to its climatological mean position.
position. The westerly jet gradually develops along the north side of the SAH. The westerly jet in Type 1 is dramatically extended eastward to ~125°E compared with the easternmost boundary of the climatological westerly jet at ~105°E. The core of the strengthened westerly jet characterized by the positive anomalies of zonal wind velocity is located over northeast China. In this situation, the northern NCP is typically positioned at the right entrance of this strong anomalous westerly jet stream, which implies a strong upper-level

Figure 9. Latitude–pressure cross-sections of meridional wind (unit: m·s⁻¹) and vertical motion (unit: hPa·s⁻¹) between 115°E and 121°E for Type 1 (left) and Type 2 (right) over the NCP in midsummer. The area between the two dashed lines in each panel is the latitude range of the NCP. Black shaded areas indicate the terrain.

Figure 10. Schematic of large-scale circulation patterns conducive to extreme precipitation over the NCP for the two types. “H” and “L” denote positive and negative anomalies of geopotential height, respectively. The intensification of the westerly jet stream at 200 hPa that contributes to the ascending motion and the anomalous flow at 700 and 500 hPa is indicated by red arrows. The dark blue arrows at 700 hPa in Type 2 denote the southwesterly LLJ. The red dashed line indicates the SAH extent. The upward black arrow denotes rising motion. Gray shading denotes the main body of the TP.
divergence in this region. In addition, a prevailing anomalous anticyclone exists over the NCP (Figure 8a). There is a pronounced center of anomalous divergence above the northern NCP (Figure 8c).

In Type 2, the SAH indicated by the 12,500 gpm contour passes along the southern edge of the NCP, and the westerly jet represented by the positive anomalies of zonal wind velocity flows along the north of the SAH. As a consequence, the entire NCP is located directly underneath the accelerated westerly jet belt (Figure 8b). The maximum center of anomalous divergence in Type 2 is displaced slightly southward over the southern NCP, which is not the case for Type 1 (Figure 8d). Compared with Type 2, the upper-tropospheric system of Type 1 plays a much more critical role by establishing multiple divergence conditions for the anomalous anticyclone and displacing the westerly jet and the SAH.

4.4. Cross-Section Circulation Patterns of Extreme Precipitation for the Two Types

Figure 9 shows a latitude–pressure cross-section of meridional wind and vertical motion over the NCP for each type. For Type 1, this figure clearly demonstrates that active upward motion is located over the area between 36.5°N and 40°N, corresponding to the northern NCP as defined in this study. The intense upward motion extends from near the surface to 150 hPa in Type 1. For Type 2, the strong ascending motion that spans from low levels to the upper atmosphere at 150 hPa is concentrated south of ~36.5°N. The results also demonstrate that southerly flows provide sufficient moisture originating in tropical oceans for both types.

5. Conclusions and Discussion

This study reveals the comprehensive large-scale three-dimensional circulation patterns of two types of extreme precipitation over the NCP in midsummer during the period 1979–2016 using objective classification. The conclusions are summarized as follows.

Unlike previous classifications of the circulation patterns of extreme precipitation over the NCP, extreme precipitation over the NCP in midsummer is initially divided into Type 1, a northern pattern of (30 days) with intense precipitation and Type 2, and a central–southern pattern (35 days) with relatively moderate precipitation, using objective cluster analysis.

The key systems driving extreme precipitation over the NCP in the two categories have been demonstrated in Figure 10, and thorough comparisons of the circulation characteristics are made between the two types. In Type 1, the WNPSH at middle levels is extended northward and westward and dominates the Korean Peninsula and Japan. The meridional dipole pattern with the northern WNPSH at middle latitudes and the southern low-pressure system at low latitudes ensures continuous southeasterly flows into the NCP. These flows, along with the sustained southwesterly flow into the northern NCP driven by an anomalous low-pressure system at high latitudes, meet over the northern NCP. The above pressure systems at lower-middle-high latitudes are conducive to extreme precipitation of Type 1. In Type 2, remarkable anomalous low-pressure systems control all of northern China with two isolated centers over the Sichuan Basin and northeast China at middle latitudes. The WNPSH is displaced southward compared with that of Type 1. Type 2 is mainly attributed to the interaction of the WNPSH at lower latitudes and low-pressure systems at middle latitudes.

As moisture mainly occupies the lower troposphere, the anomalous moisture supplying Type 1 is primarily from the western North Pacific. Unlike the case for Type 1, a strong southwesterly LLJ is the key contributor to Type 2, transporting moisture primarily from the Bay of Bengal and the South China Sea and providing dynamic convergence that favors active ascending motion.

In the upper troposphere, the northern NCP in Type 1 is directly anchored over the right entrance of the westerly jet along the north of the SAH. The westerly jet acts to produce strong upper-level divergence over the northern NCP. In Type 2, the SAH is displaced to the south from its position in Type 1, and hence, the westerly jet passes across the entire NCP. The maximum center of anomalous upper-level divergence in Type 2 moves slightly southward relative to that of the Type 1 and occupies the southern NCP. Nevertheless, the upper-tropospheric divergence plays a more dominant role in Type 1, and type 2 tends to be influenced primarily by the southwesterly LLJ at lower levels.

A cross-section of wind fields over the NCP shows strong upward motions spanning from low levels to the upper atmosphere of both types (dashed arrow in Figure 10). Our research also demonstrates that the
wind fields in the cross-section provide sufficient moisture originating in the tropical oceans for both types, implying that the consistent vertical ascending motion is responsible for each type over the NCP.

Although some studies have identified the major circulation structures leading to summer rainstorms over the NCP using an objective method, these findings only focused on only a particular part of the NCP (Sun et al., 2015; Yan et al., 2018; Zhao, Xu, Zhao, et al., 2019). There are also some studies analyzing the circulation structure of extreme precipitation over the NCP based on a single rainstorm case (Jiang et al., 2014; Zhong et al., 2015), but the results may not be representative of the main types of extreme precipitation over the NCP. Our study applies objective classification according to the spatial distribution of extreme precipitation over the NCP and analyzes the related comprehensive large-scale circulation patterns from 1979 to 2016. The results identify two extreme precipitation types and their corresponding three-dimensional circulation patterns and have important implications for a better understanding of heavy precipitation events and accurate forecasts of regional extreme precipitation over the NCP.

This study identifies the circulation patterns responsible for two types of extreme precipitation over the NCP during 1979–2016. However, the large-scale circulation regime over East Asia has undergone significant interdecadal transitions since the end of the 1970s (Wang, 2001; Li et al., 2018). Thus, further research is required to determine whether the present results are applicable to extreme precipitation events before the 1970s or to future events. In addition, only reanalysis and historical observational data were used to diagnose the circulation driving heavy precipitation days. In future work, it will be necessary to adopt climate models to gain a full understanding of these circulation patterns, and high-resolution numerical simulations of typical extreme precipitation cases are also required.

References

Anderberg, M. R. (1973). Cluster analysis for applications. Academic Press.

Bernard, E., Naveau, P., Vrac, M., & Olivier, M. (2013). Clustering of maxima: Spatial dependencies among heavy rainfall in France. Journal of Climate, 26(20), 7929–7937.

Cavazos, T. (1999). Large-scale circulation anomalies conducive to extreme precipitation events and derivation of daily rainfall in northeastern Mexico and southeastern Texas. Journal of the Atmospheric Sciences, 72(10), 3871–3890.

Chen, Y., & Zhai, P. M. (2014). Two types of typical circulation pattern for persistent extreme precipitation in Central-Eastern China. Quarterly Journal of the Royal Meteorological Society, 140(662), 1467–1478.

Ding, Y. H., & Chan, J. C. L. (2005). The East Asian summer monsoon. Monsoon Region. Journal of the Atmospheric Sciences, 72(10), 3871–3890.

Ding, Y. H., Liu J. J., Sun Y., Liu, Y.J., He, J.H., & Song, Y.F. (2007). A study of the synoptic–mesoscale systems producing heavy rainfall in north China. Meteorology and Atmospheric Physics, Chinese Academy of Sciences, 91(3–4), 111–115.

Ding, Y. H., Li, J. S., & Sun, S. Q. (1980). The analysis on mesoscale systems producing heavy rainfall in north China. Papers of Institute of Atmospheric Physics, Chinese Academy of Sciences, 9, 1–13. (in Chinese).

Ding, Y. H., Liu J. J., Sun Y., Liu, Y.J., He, J.H., & Song, Y.F. (2007). A study of the synoptic–mesoscale systems producing heavy rainfall in north China. Papers of Institute of Atmospheric Physics, Chinese Academy of Sciences, 9, 1–13. (in Chinese).

Greenough, G., Mcgeehin, M., Bernard, S. M., Trtrnj, J., Riad, J., & Engelberg, D. (2001). The potential impacts of climate variability and change on health impacts of extreme weather events in the United States. Environmental Health Perspectives, 109(2), 191–198.

Hartigan, J. A., & Wong, M. A. (1979). A K-means clustering algorithm. Applied Statistics, 28, 100–108.

Hu, Y., Deng, Y., Zhou, Z. M., Cui, C. G., & Dong, X. Q. (2018). A statistical and dynamical characterization of large-scale circulation patterns associated with extreme summer precipitation over the middle reaches of Yangtze river. Climate Dynamics, 52(9–10), 6213–6228. https://doi.org/10.1007/s00382-018-4501-z

Huth, R., Beck, C., Philipp, A., Demuzere, M., Ustrnul, Z., Calvayrac, M., et al. (2008). Classifications of atmospheric circulation patterns: Recent advances and applications. Annals of the New York Academy of Sciences, 1146, 105–152. https://doi.org/10.1196/annals.1446.019

Jiang, N., Qian, W. H., Du, J., Grumm, R. H., & Fu, J. L. (2016). A comprehensive approach from the raw and normalized anomalies to the analysis and prediction of the Beijing extreme rainfall on July 21, 2012. Natural Hazards, 84(3), 1551–1567.

Jiang, X., Yuan, H., Xue, M., Chen, X., & Tan, X. G. (2014). Analysis of a heavy rainfall event over Beijing during 21–22 July 2012 based on high resolution model analyses and forecasts. Journal of Meteorological Research, 28(2), 199–212.

Jonkman, S. N. (2005). Global perspectives on loss of human life caused by natural disasters. Natural Hazards, 34(2), 151–175.

Li, H. X., Chen, H. P., & Wang, H. J. (2016). Changes in clustered extreme precipitation events in South China and associated atmospheric circulations. International Journal of Climatology, 36(9), 3226–3236.

Li, J., Ding, R. Q., Wu, Z. W, Zhong, Q. F., Li, B. S., & Li, J. P. (2018). Inter-decadal change in potential predictability of the East Asian summer monsoon. Theoretical & Applied Climatology, 136(1–2), 403–415. https://doi.org/10.1007/s00704-018-2482-9

Acknowledgments

Acknowledgments We sincerely thank two anonymous reviewers whose comments greatly improved the manuscript. We acknowledge the National Meteorological Information Center of the China Meteorological Administration for providing the observational daily precipitation data set (http://data.cma.cn/) and the European Centre for Medium-Range Weather Forecasts to support reanalysis data (http://apps.ecmwf.int/datasets/).

This work was supported by The Second Tibetan Plateau Scientific Expedition and Research (STEP) program (grant 2019QZKK0105), the Major Program of the National Natural Science Foundation of China (91644223, 91370000), and the Jiangsu Postgraduate Research Innovation Program (KYCX17_0869).
Li, J., & Wang, B. (2017). Predictability of summer extreme precipitation days over eastern China. *Climate Dynamics*, 51, 4543. https://doi.org/10.1007/s00382-017-3848-x

Li, W., Jiang, Z. H., Xu, J. J., Li, L., & L. (2016). Extreme precipitation indices over China in CMIP5 models. Part II: Probabilistic projection. *Journal of Climate*, 29(24), 8989–9004.

Li, Z. D., & Lu, R. Y. (2008). Abrupt northward jump of the East Asian upper-tropospheric jet stream. *Journal of the Meteorological Society of Japan*, 86(6):857-866.

Lin, D. (2013). Impacts of two types of northward jumps of the East Asian upper-tropospheric jet stream in midsummer on rainfall in eastern China. *Advances in Atmospheric Sciences*, 30(4), 1224–1234.

Liu, B. H., Xu, M., Henderson, M., & Qi, Y. (2005). Observed trends of precipitation amount, frequency, and intensity in China, 1960–2000. *Journal of Geophysical Research Atmospheres*. https://doi.org/10.1029/2004JD004864

Liu, W. B., Wang, L., Chen, D. L., Tu, K., Ruan, C. Q. & Hu, Z. Y. (2015). Large-scale circulation classification and its links to observed precipitation in the eastern and central Tibetan Plateau. *Climate Dynamics*, 46(11-12):1-17.

Luo, Y. L., Wu, M. W., Ren, F. M., Li, L. J., & Wong, W. K. (2016). Synoptic situations of extreme hourly precipitation over China. *Journal of Climate*. https://doi.org/10.1175/JCLI-D-16-0057.1

Manton, M. J., Della-Marta, P. M., Haylock, M. R., et al. (2001). Trends in extreme daily rainfall and temperature in Southeast Asia and the South Pacific: 1961–1998. *International Journal of Climatology*, 21(3), 269–284.

Orsolini, Y. J., Zahn, L., Peters, D. H. W., Fraedrich, K., Zha, X. H., Schneideri, A., & Hurk, B. V. D. (2015). Extreme precipitation events over north China in August 2010 and their link to eastward-propagating wave-trains across Eurasia: Observations and monthly forecasting. *Quarterly Journal of the Royal Meteorological Society*, 141(691), 3097–3105.

Park, T.W., Ho, C.H., & Deng, Y. (2014). A synoptic and dynamical characterization of wave-train and blocking cold surge over East Asia. *Climate Dynamics*, 42(1-2):183-202.

Potop, V., Zahra, I., Turkott, L., Stepanek, P., & Soukup, J. (2014). Risk occurrences of damaging frosts during the growing season of vegetables in the Elbe River lowland, the Czech Republic. *Natural Hazards*, 71(1), 1-19.

Ren, Z.H., Zhao, P., Zhang, Q., Zhang, Z.F., Cao, L.J., Yang, Y.R., et al. (2010). Quality control procedures for hourly precipitation data from automatic weather stations in China. *Climatic Meteorological Month*, 36(7): 123-132(In Chinese).

Shi, Y.Y., & Zhang, Y.C. (2008). The impacts of intensity variations of the East Asia Subtropical Westerly Jet on summer precipitation in North China. In: *Proceedings of the 25th Chinese Meteorological Society annual meeting*, pp 625-634.

Sun, J. H., Zhang, X. L., & Wei, J. A. (2005). Study on severe heavy rainfall in North China during the 1990s. *Climatic & Environmental Research*, 10(3), 92–506. (in Chinese)

Sun, J. H., Zhao, S. X., & Pu, S. M. (2013). Multi-scale characteristics of record heavy rainfall over Beijing area on July 21, 2012. *Chinese Journal of Atmospheric Sciences*, 37(3), 705-716. (in Chinese)

Sun, J.S., Wang G.R., He, N., Wang, G.R., Liao, X.N., & Wang, H. (2012). Preliminary analysis on synoptic configuration evolvement and mechanism of a torrential rain occurring in Beijing on 21 July 2012. *Tropical Rain and Disasters*, 3(1): 218-225 (in Chinese).

Sun, S. Q., & Zhai, G. Q. (1980). On the instability of the low level jet and its trigger function for the occurrence of heavy rainstorm. *Journal of Atmospheric Sciences*, 37(11): 1979-1985.

Tao, S. Y. (1980). *Heavy rainfall in China*. Beijing: Science Press, 251pp. (in Chinese)

Tian, B., & Fan, K. (2013). Factors favorable to frequent extreme precipitation in the upper Yangtze River Valley. *Meteorology and Atmospheric Physics*, 123(3-4), 189–197.

Toreti, A., Xoplaki, E., Maraun, D., Kuglitsch, F. G., Wanner, H., & Luterbacher, J. (2010). Characterisation of extreme winter precipitation in Mediterranean coastal sites and associated anomalous atmospheric circulation patterns. *Natural Hazards and Earth System Science*, 10(5), 1037–1050.

Tu, K., Yan, Z. W., & Dong, W. J. (2010). Climatic jumps in precipitation and extremes in drying north China during 1954-2006. *Journal of the Meteorological Society of Japan*, 88(1), 29–42.

Véronique, D., Braud, I., Davolio, S., et al. (2014). HYMEX-SOPi The field campaign dedicated to heavy precipitation and flash flooding in the Northwestern Mediterranean. *Bulletin of the American Meteorological Society*. https://doi.org/10.1175/BAMS-D-12-00244.1

Wang, C. X., Gao, S. T., Liang, L., Deng, D. F., & Gong, H. N. (2014). Multi-scale characteristics of moisture transport during a rainstorm process in North China. *Atmospheric Research*, 145-146, 189–204.

Wang, D., Zhang, Y., & Huang, A. (2013). Climatic features of the south-westerly low-level jet over southeast china and its association with precipitation over east China. Asia-pacific Journal of Atmospheric Sciences, 49(3), 259–270.

Wang, H. J. (2001). The weakening of the Asian monsoon circulation after the end of 1970s. *Advances in Atmospheric Sciences*, 18, 376–385.

Wang, J., Feng, J., & Yan, Z. (2015). Potential sensitivity of warm season precipitation to urbanization extents: Modeling study in Beijing-Tianjin-Hebei urban agglomeration in China. *Journal of Geophysical Research: Atmospheres*, 120(18), 9408–9425.

Wang, S., & Zuo, H. (2016). Effect of the East Asian westerly jet's intensity on summer rainfall in the Yangtze River Valley and its mechanism. *Journal of Climate*, 29(7), 2395–2406.

Wang, S. X., Zuo, H. C., Zhao, S. M., Zhang, J. K., & Lu, S. (2017). How East Asian westerly jet's meridional position affects the summer rainfall in Yangtze-Huaihe River Valley? *Climate Dynamics*, 2017(22), 1–13.

Wang, X. M., & Liu, Y. (2017). Causes of extreme rainfall in May 2013 over Henan Province: The role of the southwest vortex and low-level jet. *Theoretical & Applied Climatology*, 129(1-2), 1–9.

Wei, W., Wang, R. H., Wen, M., Kim, B. J., & Nam, J. C. (2015). Intereventation variation of the South Asian high and its relation with East Asian summer monsoon rainfall. *Journal of Climate*, 28(7), 2623–2634.

Wei, W., Zhang, R. H., Wen, M., Rong, X. Y., & Li, T. (2013). Impact of Indian summer monsoon on the South Asian high and its influence on summer rainfall over China. *Climate Dynamics*. https://doi.org/10.1007/s00382-013-1936-y

Wu, H., Zhai, P., & Chen, Y. (2016). A comprehensive classification of anomalous circulation patterns responsible for persistent precipitation extremes in South China. *Journal of Meteorological Research*, 30(4), 483–495.
Xia, F., Liu, X., Xu, J., Wang, Z., Huang, J., & Brookes, P. C. (2015). Trends in the daily and extreme temperatures in the Qiantang River basin, China. *International Journal of Climatology, 35*(1), 57–68. https://doi.org/10.1002/joc.3962

Xie, Z., Du, Y., & Yang, S. (2015). Zonal extension and retraction of the subtropical westerly jet stream and evolution of precipitation over East Asia and the Western Pacific. *Journal of Climate, 28*(17), 15070143658007.

Yan, Y., Miao, Y. C., Guo, J. P., Liu, S. H., Liu, H., Lou, M. Y., et al. (2018). Synoptic patterns and sounding-derived parameters associated with summertime heavy rainfall in Beijing. *International Journal of Climatology*. https://doi.org/10.1002/joc.5895

Zhai, P. M., Zhang, X. B., Wan, H., & Pan, X. H. (2005). Trends in total precipitation and frequency of daily precipitation extremes over China. *Journal of Climate, 18*(7), 1096–1108.

Zhang, D. Q., Feng, G. L., & Hu, J. G. (2008). Trend of extreme precipitation events over China in last 40 years. *Chinese Physics B, 17*(2):736.

Zhang, H., & Zhai, P. M. (2011). Temporal and spatial characteristics of extreme hourly precipitation over eastern China in the warm season. *Advances in Atmospheric Sciences, 28*(5), 1177.

Zhang, Q., & Wu, G. X. (2001). The large area flood and drought over Yangtze River valley and its relation to the south Asia high. *Acta Meteorologica Sinica, 59*(5):569-577 (in Chinese).

Zhang, Q., Zhao, Y., & Fan, S. (2016). Development of hourly precipitation datasets for national meteorological stations in China. *Torrential Rain & Disasters, 35*(2), 182–186. (in Chinese)

Zhong, L., Zhang, Z., Chen, L., Yang, J. H., & Zou, F. L. (2016). Application of the Doppler weather radar in real-time quality control of hourly gauge precipitation in eastern China. *Atmospheric Research, 172–173*(173), 199–218.

Zhou, T., Song, F., Lin, R., & Chen, X. D. (2013). The 2012 North China Floods: Explaining an extreme rainfall event in the context of a longer-term drying Tendency. *Bulletin of the American Meteorological Society, 94*(9), S49–S51.

Zhu, Q. G. (2007). *Principle of synoptic meteorology*. China Meteorological Press. 344 pp. (in Chinese)