Precursor Circulation Features for Persistent Extreme Precipitation in Central-Eastern China

YANG CHEN

Department of Atmospheric Science, Nanjing University of Information Science and Technology, Nanjing, and State Key Laboratory of Severe Weather, Chinese Academy of Meteorological Sciences, China Meteorological Administration, Beijing, China

PANMAO ZHAI

State Key Laboratory of Severe Weather, Chinese Academy of Meteorological Sciences, China Meteorological Administration, Beijing, China

(Manuscript received 4 June 2013, in final form 7 October 2013)

ABSTRACT

Using a composite analysis, the typical precursor circulation configuration from the lower to the upper troposphere responsible for persistent extreme precipitation events (PEPEs) of double-blocking-high type in central-eastern China is identified. The potential of these precursors is further assessed based on the composites of normalized anomalies. The composite results reveal that at 500 hPa, about 2 weeks prior to the onset of PEPEs, a positive height anomaly progresses toward the Ural Mountains region from 30°E and another positive anomaly extends southwest from high latitudes toward the Sea of Okhotsk. Afterward, these two positive anomalies grow in magnitude in situ. The double blocking highs are finally well established with height anomalies of 2.4 and 1.8 standard deviations above normal, respectively. At 850 hPa, an anomalous anticyclone originating from the equatorial western Pacific migrates northwestward 1 week prior to the event occurrence, resulting in a greatly intensified moisture transport toward central-eastern China with a magnitude anomaly over four standard deviations above normal. In the upper troposphere, the eastward-extended South Asia high and the southward-displaced westerlies combine to provide favorable upper-level divergence for PEPEs.

These composites of the anomalies and normalized anomalies may offer forecasters some useful clues in recognizing significant weather events about 1–2 weeks in advance of an event.

1. Introduction

Extreme precipitation often brings catastrophic consequences, such as floods, urban waterlogging, and landslides. When these extremes persist for several days they are called persistent extreme precipitation events (PEPEs; Chen and Zhai 2013). These PEPEs have significant economic and human impacts due to both their intensity and areal coverage (Grumm and Hart 2001). For instance, a PEPE in 1998 triggered a severe flood in the Yangtze River valley, leading to the loss of more than 3000 lives and direct economic losses of 250 billion yuan renminbi (RMB; $40 billion U.S.) (Riyu 2000). It is therefore of the utmost importance to forecast such events accurately. However, while synoptic-scale mass-field forecasts (heights, sea level pressure, etc.) have improved dramatically over the past three or four decades, progress in quantitative precipitation forecasting (QPF) has come at a much slower rate, particularly for extreme precipitation (Bosart 1981; Roebber and Bosart 1998; Sisson and Gyakum 2004). Root et al. (2007) have reported that many high-impact precipitation events failed to be recognized in the model output by even experienced forecasters. It is therefore necessary that efforts be made to aid the local forecaster in identifying significant synoptic-scale structures and precursors associated with high-impact precipitation at a particular location (Grumm and Hart 2001).

Previous studies have indicated that persistent extreme precipitation is often caused by long-lived atmospheric...
circulation anomalies (Teixeira and Satyamurty 2007; Zhou et al. 2009; Lau and Kim 2012). Summertime PEPEs in southern China are closely associated with long-lived blocking highs in the mid- to high latitudes (Yihui and Chan 2005; Wang et al. 2000), unbroken water vapor transport related to southeasterlies from the southern flank of the western Pacific subtropical high (WPSH) and/or southwestlies from the Bay of Bengal (BOB) (Zhou and Yu 2005; Qian et al. 2004), and some instances of favorable upper-level divergence related to the anomalies in the South Asia high (SAH) and the westerly jet (Wang et al. 2000; Samel and Liang 2003). Though much attention has been paid to persistent extreme precipitation, the literature to date has mostly focused on case studies. Such studies are unable to address the extent to which their results are representative of other PEPEs. Encouragingly, some studies have noted that a large population of high-impact precipitation events in different regions of the world shared similar large-scale circulation patterns with some historical cases (Maddox et al. 1980; Müller et al. 2009; Martius et al. 2012). These similarities make pattern recognition and forecast analogs possible, which will offer forecasters paradigms to further improve the prediction accuracy of high-impact events. Based on similarities in large-scale circulation patterns, the circulation patterns of 25 PEPEs in central-eastern China (Chen and Zhai 2013) are mainly classified by Chen and Zhai (2014) into two typical types: a double-blocking-high type and a single-blocking-high type. These two pattern types account for 76% of the historical cases in central-eastern China during 1951–2010.

Compared with considerable discussions about the large-scale circulation anomalies during PEPEs, little has been reported about the forecasting of these long-lasting high-impact events from the perspective of multi-day lead time. Some studies present monthly average meteorological fields, such as monthly average geopotential height and horizontal wind, to describe the circulation background prior to the high-impact events (Galarneau et al. 2012; Zhou et al. 2009; Hong et al. 2011). Although such studies are effective when analyzing the underlying mechanism of high-impact events, they cannot be used to depict the evolution of anomalous large-scale circulation patterns. Some other studies into 1-day extremes have reported that precursor features for extreme events can be identified up to 3 days prior to the events (Teixeira and Satyamurty 2007; Grotjahn and Faure 2008; Milrad et al. 2009; O’Hara et al. 2009; Warner et al. 2012); however, some long-lasting (more than 3 days) extremes were reported to be preceded by long-lived circulation anomalies. For example, both Dole et al. (2011) and Barriopedro et al. (2011) pointed out that during the Pakistan flood in 2010 (late July–early August), a long-lived blocking high that was well established in mid-June persisted for nearly 2 months over Europe and Russia. These long-lived precursors for PEPEs seem to be understudied and they may be of great help in identifying the evolving large-scale circulation patterns that are likely to spawn the occurrence of high-impact events in a particular region (Martius et al. 2008).

The main objective of this study is to identify common principal synoptic precursor circulation features from the lower to the upper troposphere responsible for PEPEs in central-eastern China (region shown in Fig. 1) within the period 1–2 weeks prior to the onset of PEPEs. This objective also matches well with the major goal of The Observing System Research and Predictability Experiment program (THORPEX; Shapiro and Thorpe 2004), which aims to accelerate improvements in the accuracy of 1-day to 2-week high-impact weather forecasts. Central-eastern China is selected as the study area because this region is one of the most populated as well, as the most economically developed, regions in China. The PEPEs in this region therefore have the potential to generate high-impact meteorological–sociological events. Further, this study will assess the potential of precursor circulation patterns in inducing high-impact precipitation events of long duration.

2. Data and method

a. Data

The PEPEs analyzed in this study are selected from the PEPEs over central-eastern China during 1951–2010, as defined by Chen and Zhai (2013). The details of these events are listed in Table 1. This definition ensures that only those events with substantial capability to trigger severe socioeconomic disasters are considered by demanding that rainstorms with daily precipitation amounts equal to or larger than 50 mm 1) be observed by at least three neighboring stations and 2) persist for at least 3 days at every station. Such a definition aims to identify persistent extreme precipitation events in one location rather than transient cases.

This study mainly focuses on the 10 typical cases of the double-blocking-high type (Chen and Zhai 2014), which are predominately characterized by the development of two blocking highs near the Ural Mountains and the Sea of Okhotsk, with a trough between them. This long-lived pattern continuously steers cold, dry air from the mid- to high latitudes toward central-eastern China, where it encounters warm, moist air from lower latitudes, conveyed by enhanced southeasterlies associated with the westward shift of the WPSH.
The daily reanalysis data are provided by the National Centers for Environmental Prediction and the National Center for Atmospheric Research (NCEP–NCAR). The reanalysis data are provided at a horizontal resolution of $2.5^\circ \times 2.5^\circ$ (Kalnay et al. 1996). The data used in this study include geopotential height (gpm), horizontal wind (m s$^{-1}$), and specific humidity (kg kg$^{-1}$).

b. Methods

This study is based on a composite analysis, which is a simple and effective method for identifying and typing synoptic-scale circulation patterns and precursors associated with extreme events (Sisson and Gyakum 2004; Milrad et al. 2009; Junker et al. 2008; Grotjahn and Faure 2008). Moreover, examining circulation anomalies in addition to the full composite fields allows the depiction of the significance of a particular feature with respect to climatology (Milrad et al. 2009). To identify common precursors within periods of 1–2 weeks prior to the occurrence of PEPEs, first, precursor circulation features from 3 weeks (21 days) prior to the occurrence of the third day after the occurrence are manually investigated day by day to ensure the similarity of large-scale patterns between different cases. This manual inspection guarantees that the composite results are only slightly smeared and this method is widely used in atmospheric science in synoptic typing (Milrad et al. 2009, 2010; Ladd and Driscoll 1980). Based on the similarity, composites are accumulated in difference cases for every day from 21 days prior to the occurrence to the third day after the occurrence.

Previous studies indicate that prior to and during extreme precipitation events, significant anomalies of different variables appear from the lower to the upper levels (Junker et al. 2008; Graham and Grumm 2010; Milrad et al. 2010). The predictors therefore cannot be considered individually, because only opportune coincidences make the synoptic situations excessively
dangerous (Müller et al. 2009). For PEPEs in central-eastern China, according to the study of Chen and Zhai (2014), more attentions should be paid to geopotential height at 500 hPa, horizontal wind and moisture transport at 850 hPa, and geopotential height and horizontal wind at 200 hPa.

Normalized anomalies are also composited following the method described by Hart and Grumm (2001). The composites of normalized anomalies are used to estimate how unusually large departures from normal in various meteorological parameters might be used as a tool for predicting high-impact precipitation events (Junker et al. 2008). These analyses may therefore offer forecasters some useful clues in assessing the potential of anomalous precursor features for persistent extreme precipitation events. The standard deviation is denoted by $\sigma$ in this study.

Moisture flux (MF) in this study is represented as the vector composition of the product of the specific humidity and the $u$ and $v$ components of the wind at each grid point. The normalized anomalies of MF are based on the departures from the mean of the latitude and longitude, and the maximum and minimum precipitation amounts observed by affected stations over the duration of the event.

## Table 1. Persistent extreme precipitation events of double-blocking-high type in central-eastern China (26°–34°N) between 1951 and 2010. The detailed information for each case includes the start and end dates, the duration, the number of affected stations, the affected area, the boundaries in latitude and longitude, and the maximum and minimum precipitation amounts observed by affected stations over the duration of the event.

<table>
<thead>
<tr>
<th>Year</th>
<th>Start date</th>
<th>End date</th>
<th>No. of days</th>
<th>No. of stations</th>
<th>Affected area ($10^4$ km$^2$)</th>
<th>North (°)</th>
<th>South (°)</th>
<th>West (°)</th>
<th>East (°)</th>
<th>Max precipitation (mm)</th>
<th>Min precipitation (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1954</td>
<td>4 Jul</td>
<td>7 Jul</td>
<td>4</td>
<td>3</td>
<td>3.23</td>
<td>32.55</td>
<td>32.10</td>
<td>115.37</td>
<td>117.23</td>
<td>430.20</td>
<td>265.40</td>
</tr>
<tr>
<td>1955</td>
<td>18 Jun</td>
<td>23 Jun</td>
<td>6</td>
<td>6</td>
<td>5.70</td>
<td>29.44</td>
<td>28.41</td>
<td>115.59</td>
<td>119.39</td>
<td>516.80</td>
<td>265.40</td>
</tr>
<tr>
<td>1974</td>
<td>14 Jul</td>
<td>17 Jul</td>
<td>4</td>
<td>3</td>
<td>2.59</td>
<td>30.08</td>
<td>29.18</td>
<td>117.12</td>
<td>118.17</td>
<td>279.50</td>
<td>238.70</td>
</tr>
<tr>
<td>1989</td>
<td>29 Jun</td>
<td>3 Jul</td>
<td>5</td>
<td>4</td>
<td>3.80</td>
<td>29.00</td>
<td>27.48</td>
<td>117.12</td>
<td>118.17</td>
<td>397.30</td>
<td>302.80</td>
</tr>
<tr>
<td>1991</td>
<td>1 Jul</td>
<td>11 Jul</td>
<td>11</td>
<td>9</td>
<td>9.05</td>
<td>32.52</td>
<td>30.21</td>
<td>112.09</td>
<td>120.19</td>
<td>742.20</td>
<td>369.90</td>
</tr>
<tr>
<td>1995</td>
<td>21 Jun</td>
<td>26 Jun</td>
<td>6</td>
<td>3</td>
<td>2.07</td>
<td>30.08</td>
<td>28.41</td>
<td>118.09</td>
<td>118.54</td>
<td>469.00</td>
<td>286.00</td>
</tr>
<tr>
<td>1996</td>
<td>29 Jun</td>
<td>2 Jul</td>
<td>4</td>
<td>4</td>
<td>2.77</td>
<td>30.21</td>
<td>29.43</td>
<td>118.09</td>
<td>120.10</td>
<td>619.90</td>
<td>291.20</td>
</tr>
<tr>
<td>1998</td>
<td>12 Jun</td>
<td>27 Jun</td>
<td>16</td>
<td>12</td>
<td>10.78</td>
<td>30.37</td>
<td>23.48</td>
<td>113.32</td>
<td>118.59</td>
<td>1053.90</td>
<td>283.60</td>
</tr>
<tr>
<td>1999</td>
<td>24 Jun</td>
<td>1 Jul</td>
<td>8</td>
<td>7</td>
<td>4.84</td>
<td>31.09</td>
<td>29.37</td>
<td>113.55</td>
<td>120.10</td>
<td>813.50</td>
<td>313.80</td>
</tr>
<tr>
<td>2006</td>
<td>4 Jun</td>
<td>7 Jun</td>
<td>4</td>
<td>5</td>
<td>3.47</td>
<td>28.04</td>
<td>26.55</td>
<td>116.39</td>
<td>119.08</td>
<td>421.10</td>
<td>219.00</td>
</tr>
</tbody>
</table>

3. Results

In this study, only the composite results on those days are presented, when the anomalous large-scale circulation signals are steadily enhanced in magnitude and match well with the circulation pattern of most (more than 80%) of individual cases used in the composite. Day 0 represents the occurrence of PEPEs, and day $d$ refers to the $d$th day prior to (negative) or after (positive) the occurrence of PEPEs.

### a. 500-hPa geopotential height

For geopotential height at 500 hPa (Fig. 2), from day $-12$ to day $-7$, a positive anomaly (shading) originated from 30°E progressed toward the Ural Mountains region with increasing magnitude, corresponding to the development and eastward shift of the Ural blocking high. Another positive anomaly originated from the high latitudes in East Asia and extended southwestward where it gradually combined with the positive anomaly to the south of Lake Baikal, corresponding to the establishment and development of the East Asia blocking high. A negative anomaly is sandwiched between these two positive anomalies with little variation in either magnitude or position. Correspondingly, the trough is restricted at high latitudes due to the existence of the positive anomaly in its south. During this period, the WPSH [denoted by the 588-dagpm contour (1 dagpm = 10 gpm)] extends westward and to grow in magnitude. Likewise, a well-defined $\Omega$ blocking pattern is established near the Sea of Okhotsk. Due to the dissipation of the positive anomaly near Lake Baikal, the trough extends to the south of 45°N. As a matter of fact, the positive anomaly to the south Lake Baikal is merged into the positive anomalies near the Ural Mountains and East Asia, which is conducive to a strengthening of the double blocking highs. The WPSH continues to shift westward at a low speed. From day $-3$ to day $-1$, the positive anomaly in the west grows in magnitude greatly and extends into the high latitudes, corresponding to a well-defined $\Omega$ blocking pattern near the Ural Mountains. The deepening trough sandwiched between the double blocking highs intrudes southwestward into the region south of 40°N, steering the cold, dry air necessary for frontogenesis that piles up to...
Fig. 2. Composite of 500-hPa geopotential height (black contours) and anomalies (shadings). The gray hatched lines indicate that anomalies are significant at the 5% level. The number above each panel refers to the $d$th day prior to (negative) and after (positive) the occurrence of the PEPEs. The contour interval and shading interval are 4 dagpm and 20 gpm, respectively.
the immediate north of central-eastern China. By day −3, the WPSH jumps to the west of 120°E and keeps progressing westward. This abrupt westward shift of the WPSH is associated with the arrival of a northwestward-propagated anomalous anticyclone from the equatorial western Pacific (Yang et al. 2010). On day 0, the typical double-blocking-high pattern forms and stays stationary through the first 3 days during PEPEs. This pattern of geopotential height anomalies favors the continuous southward intrusion of cold and dry air into central-eastern China along the trough in the north, together with northward advection of warm and moist air associated with the westward extension and intensification of the WPSH in the south. This confluence of cold, dry air and warm, moist air over the Yangtze–Huai River valley (YHRV) enhances the gradients of both the temperature and specific humidity, which is conductive to the formation and maintenance of the mei-yu front (Ninomiya and Shibagaki 2007). The strong ascending motion of the warm, moist air along the quasi-stationary mei-yu front finally contributes to persistent extreme precipitation.

Obviously, the development of the double blocking highs is crucial to the formation and maintenance of the anomalously intensified meridional circulation in the mid- to high latitudes, especially after day −6. Additionally, the East Asia blocking high has been reported to impede the eastward progression of short-wave troughs along the northern periphery of the Tibetan Plateau, and to steer these transient disturbances into central-eastern China (Yihui and Reiter 1982; Yihui 1993), which consequently enhances the local rainfall (Samel et al. 1995, 1999; Samel and Liang 2003).

With the exception of the characteristics presented in Fig. 2, the composite of normalized anomalies of geopotential height (Fig. 3) can depict quantitatively the extent of the departures from normal. From day −12 to day −9, the height anomalies near the Ural Mountains and East Asia are more than 1.2 σ above normal and the negative anomalies between them are about 1 σ below normal. From day −8 to day −5, due to the merger of the positive anomaly to the south of Lake Baikal, the two positive anomalies both grow in magnitude. In particular, the positive anomaly near the Ural Mountains develops to be 1.8 σ above normal. Accompanied by the southward extension, the negative anomaly near Lake Baikal weakens. From day −4 to day −1, the positive anomalies near the Ural Mountains and over East Asia develop to be 2.4 σ above normal and 1.5 σ above normal, respectively, while at the same time the negative anomaly between them grows to be 2.1 σ below normal. The westward-shifted positive anomaly related to the WPSH is more than 1.2 σ above normal during the whole period. It is also detected that a negative anomaly of more than 1.2 σ below normal moves southwestward, accompanying the progression of the positive anomaly in East Asia, and finally is anchored in the south of the positive anomaly (days 1 and 2). The pairing of a positive anomaly in the north and a negative anomaly in the south in the mid- to high latitudes constitutes the “dipole blocking,” indicating the maturity and persistence of the blocking high (Yihui and Reiter 1982; Huang et al. 2007). A robust dipole blocking pattern also appears over the Ural Mountains region (from day −5 to day 2). These long-lived mature blocking highs play an important role in maintaining the extreme precipitation (Carrera et al. 2004; Hong et al. 2011).

It can be observed in Fig. 2 that the blocking highs and trough basically develop in situ, especially after day −9 (Fig. 2). A time–longitude plot of the anomaly of the meridional wind (υ) at 500 hPa is presented (Fig. 4) to diagnose the downstream dispersion of the Rossby wave energy responsible for the development of the double-blocking-high pattern. It is implied here that the downstream-propagation of Rossby wave energy is evident prior to the occurrence, as each 500-hPa meridional wind anomaly maximum lags the previous anomaly maximum in time (Milrad et al. 2009). It is found that the double blocking highs (30°–75°E and 120°–150°E) nearly stay stationary, with a maximum phase velocity of about 4° longitude per day. The energy responsible for the development of the East Asia blocking high can be traced back to the region around 120°W, 20 days prior to occurrence. The growth in magnitude of the Ural blocking high may be attributed to the energy dispersion that originated from the upstream region around 60°W, 10 days prior to occurrence. The group velocity is about 15°–25° longitude per day, much faster than the phase velocity. The arrival of the dispersed energy from upstream corresponds well with the manifest enhancement of double blocking highs. A subjective comparison of a Hovmöller diagram (Hovmöller 1949) of the meridional wind anomaly at 500 hPa between the composite and the individual cases constituting the composites finds that the composite result represents the individual cases reasonably well. The wave activity flux defined by Takaya and Nakamura (2001) also portrays similar downward energy propagation in the mid- to high latitudes (figure not shown). Similar strong amplification of the Rossby wave packet across Eurasia prior to the formation of blocking highs can be also found in the study of Cheung et al. (2013). It is not surprising then that the energy can be traced back to such a remote region and at such a long time prior to occurrence. Grazzini and Van der Grijn (2003) reported that the downstream dispersion of energy that originated from Japan played a key role in trigging and maintaining the
FIG. 3. Composite of the 500-hPa normalized geopotential height anomalies. The red (blue) contours represent positive (negative) anomalies. Contour values of $\pm 0.9$, $\pm 1.8$, $\pm 2.7 \sigma$ are shown in boldface. The gray shadings indicate that the normalized anomalies are significant at the 5% level or greater. The number above each panel is as in Fig. 2. The contour interval is 0.3 $\sigma$. 
extreme precipitation that induced severe flooding (on the scale of a 500-yr return period) in central Europe during August 2002. It seems that the utility of the Hovmoller diagrams in identifying the precursors for the extreme events of long duration is underestimated (Tao et al. 2010).

b. 850-hPa wind and moisture flux

Figure 5 shows the anomaly of the horizontal wind and normalized anomaly of the magnitude of the total MF. From day −7 to day −6, an anomalous cyclone is observed to the immediate south of the Yangtze River valley, with anomalous northeasterlies prevailing in its northwestern quadrant. In the meantime, a weak anomalous anticyclone could be identified near the equatorial western Pacific. By day −5, the anomalous cyclone weakens and dissipates, and the anomalous anticyclone is slightly enhanced accompanied by a westward migration. The dissipation of an anomalous cyclone may be related to the increased static stability associated with the adiabatic cooling (Tsou et al. 2005). Afterward, the anomalous anticyclone further enhances with an MF anomaly of about 2 σ above normal along its northwestern flank (day −4). Meanwhile, the anticyclone progresses a large distance westward and arrives at the eastern edge of the Philippines. From day −3 to day −2, the anomalous anticyclone progresses northward with an increasing magnitude and a larger areal coverage, contributing to the westward extension of the WPSH to 120°E at 850 hPa. By day −2, the anomalous anticyclone dominates the South China Sea (SCS) and an anomalously enhanced southwesterly is observed along its north flank, resulting in a zonally oriented anomalously intensified moisture transport with a normalized MF anomaly of 2.5 σ above normal. By day −1, the anomalous anticyclone moves northward slightly but enhances greatly, resulting in a further intensification of the WPSH. On this day, a large quantity of anomalous moisture is conveyed toward the Yangtze River valley with an MF anomaly of more than 4 σ above normal. Correspondingly, during this period, the WPSH advances northward slightly and enhances greatly. The typical circulation pattern at 850 hPa responsible for the PEPEs described by Chen and Zhai (2014) has been well established at that time. After the occurrence of PEPEs, the anomalous anticyclone remains stationary in the northern SCS, with a highly enhanced westerly along its north flank, resulting in an enhancement of low-level convergence along the mei-yu front in central-eastern China (Chen et al. 2005). In addition to providing water vapor and convergence necessary for the long-lasting extreme precipitation, the enhanced MF also results in a decrease in convective stability around central-eastern China by advecting large quantities of warm and moist air persistently at lower levels (Chen et al. 1998; Chen et al. 2005). The MF with an anomaly of more than 4 σ (even 5 σ on day 0) above normal during PEPEs clearly illustrates the extremity of the PEPEs.

It can be concluded based on Fig. 5 that regardless of whether it was prior to or after the occurrence, the anomalously abundant water vapor is mainly transported by the anomalous anticyclone that originated from the equatorial western Pacific, which is responsible for the westward extension of the WPSH. However, the moisture transported by the southwesterlies that originated from the BOB shows no obvious difference from normal. The northwestward progression of the anomalous anticyclone may be related to the northwestward propagation of a wavelike intraseasonal oscillation, which is deemed to be an important contributor to the...
FIG. 5. Composite of the 850-hPa horizontal wind anomaly (vectors, m s$^{-1}$) and the normalized anomaly of the total moisture flux magnitude (shading). Only vectors that are significant at the 5% or greater level are shown. The number above each panel is as in Fig. 2. The shading interval is 0.5 $\sigma$. The letters A and C represent anticyclone and cyclone, respectively. The black dashed lines show the westward propagation of the anomalous anticyclone.
intraseasonal nature of the WPSH and East Asia summer monsoon patterns (Mao et al. 2010; Yang et al. 2010).

c. 200-hPa wind and geopotential height

In the upper troposphere, the displacements of the SAH and westerly jets are reported to be more important than the magnitude variation in providing divergences for extreme precipitation (Lin and Riyu 2005; Yihui and Chan 2005; Chen and Zhai 2014). The composite of full fields rather than anomaly fields of horizontal wind and geopotential height are therefore presented in Fig. 6 to depict the variations in the positions of the SAH and westerly jet.

From day $-7$ to day $-1$, the SAH (denoted by the 12 500-gpm contour, black solid line in Fig. 6) keeps progressing eastward, and by day $-1$ it has already arrived to the east of 120°E, about 10° east from the original position on day $-7$. This eastward extension of the SAH is a necessity for the formation and maintenance of the mei-yu front (Wang et al. 2000; Yihui and Chan 2005). A westerly jet along the north flank of the SAH also progresses eastward (from day $-7$ to day $-1$). This mainly results from the intensification of the height gradient due to the eastward extension of the SAH. During the first 3 days (days 0–2) of the PEPEs, the SAH nearly stays stationary, with an enhanced westerly pattern in its northeast quadrant. Another great acceleration of westerlies appears from eastern China to the Sea of Japan. The southward displacement of the westerly jet axis to the immediate north of central-eastern China makes the study area well located beneath the southern section of the westerly jet entrance region, where strong divergence usually exists (Uccellini and Kocin 1987). The upper-level divergence is further enhanced by the separation of westerlies and northeasterlies in the northeast quadrant of the SAH, which is located over the upper reaches of the YHRV. Accordingly, strong divergence (red solid line) appears above the study area by day $-2$ (red contours). Afterward, accompanied by a farther southward displacement of the westerly jet axis and a further eastward extension of the SAH, the divergence intensifies greatly and persists through the PEPEs. These multiple sources of upper divergence establish conditions conducive to the initiation and maintenance of PEPEs.

4. Conclusions and discussion

Based on the manual analyses and composites of 10 persistent extreme precipitation events (PEPEs) of double-blocking-high type, the precursor circulation features from the lower to the upper troposphere during the period 1–2 weeks prior to the occurrence of the events are investigated. The main conclusions are summarized as follows:

1) At 500 hPa, significant precursor signals can be detected about 2 weeks prior to the occurrence of PEPEs. During the period from day $-12$ to day $-9$, a positive anomaly progresses toward the Ural Mountains from 30°E and another positive anomaly moves toward the Sea of Okhotsk from the high latitudes. Afterward, the double blocking highs stay quasi-stationary and grow in magnitude in situ. Such a development actually results from the Rossby wave energy dispersion upstream. After day $-6$, the trough between the double blocking highs extends southward and arrives in the region south of 40°N. The WPSH keeps extending westward and jumps to the west of 120°E by day $-3$. The positive anomalies related to the development of blocking highs develop to be about two standard deviations ($\sigma$) above normal near the occurrence of PEPEs. And an anomaly of more than 1.2 $\sigma$ above normal indicates the intensification and westward extension of the WPSH.

2) At 850 hPa, an anomalous anticyclone that originated from the equatorial western Pacific progresses northward beginning on day $-7$. At the same time, the anomalous cyclone that previously dominated the Yangtze River valley weakens and begins to dissipate. By day $-2$, the anomalous anticyclone has already arrived at the South China Sea (SCS), with greatly enhanced southwesterlies along its northern flank. Afterward, the anomalous anticyclone is anchored in the SCS with a continuously intensifying westerly to its north. This results in a highly intensified moisture flux of a magnitude anomaly of over $4 \sigma$ above normal. The greatly intensified westerly around the north flank of this anomalous anticyclone advects warm and moist air toward central-eastern China, maximizes convergence there, and favors the establishment of a convectively unstable environment.

3) At 200 hPa, the South Asia high (SAH) begins to moves eastward starting on day $-7$, accompanied by accelerated westerlies along its north flank. By day $-2$, the SAH extends into the region east of 120°E and keeps progressing eastward. Meanwhile, the jet axis is located to the immediate north of central-eastern China and continues to be displaced southward. Accordingly, the separation between the westerlies and northerlies in the northeast quadrant of the SAH and the acceleration of the westerlies in the southern section of the jet entrance region exert a joint divergence above central-eastern China, which is conductive to the development and maintenance of rising motion.
It seems that the 500-hPa height anomalies related to the individual key elements in this study are not as large as that of a single element, such as troughs and ridges, in some specific case studies of 1-day extremes (e.g., Junker et al. 2008; Graham and Grumm, 2010). Near the occurrence (day −3 to day −1) of PEPEs, from the perspective of a regional average (Fig. 2), the normalized anomaly is about 1.8 $\sigma$ above normal for the Ural blocking region (45°–65°N, 30°–75°E) and 1.5 $\sigma$ above normal for the East Asia blocking region (45°–65°N, 120°–150°E).
For the WPSH (15°–27.5°N, 110°–130°E), the normalized anomaly is only about 1.2 σ above normal. As presented in Fig. 7, the precursor anomalies of 1.8 and 1.5 σ above normal represent the upper 5th and 10th percentiles in the Ural Mountain and East Asian regions, respectively, during June–July 1951–2010 (total days: 60 × 61 = 3660 days). This means that there are 183 and 366 days with height anomalies of more than 1.8 and 1.5 σ above normal in these two regions, respectively. For the WPSH, the anomaly of 1.2 σ above normal represents the upper 20th percentile, meaning that there are about 732 days with height anomalies of more than 1.2 σ above normal in this area. However, there are only 90 days with height anomalies more than 1.0 σ above normal in all three key regions simultaneously. And these days correspond well with the days used for the composites. Thus, it is these combinations of precursor anomalies with magnitudes that result in the probability of PEPE occurrence to be very low (less than 2.4%). Moreover, it is the accompanying low-level moisture flux with anomalies over 4 σ above normal and strong upper-level divergence that even makes these PEPEs rare.

The configuration of precursor circulation features from the lower to the upper troposphere and the analyses of normalized anomalies are summarized in Fig. 8. The applicability of the precursors presented in Fig. 8 based on the PEPEs during 1951–2010 needs to be further justified by large numbers of future PEPEs after
2010. These conclusions and schematics can probably offer local forecasters benchmarks, in addition to available forecast models, to improve the prediction of such long-lasting high-impact precipitation events.

Acknowledgments. This study was supported by the National Key Basic Research Program of China (Grant 2012CB417205). The authors are grateful to Editor Dr. Yuqing Wang and three anonymous reviewers for their invaluable and constructive suggestions and comments that helped improve the manuscript.

REFERENCES


Grazzini, F., and G. Van der Grijn, 2003: Central European floods during summer 2002. ECMWF Newsletter, No. 96, ECMWF, Reading, United Kingdom, 18–28.


