Assessment of Regional Drought Trend and Risk over China: A Drought Climate Division Perspective

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ABSTRACT

A combination of Ward’s and k-means clustering was applied to a 3-month standardized precipitation index (SPI-03), and eight divisions of homogeneous drought variation throughout China were identified from the perspective of meteorological and agricultural droughts. A greater meridional gradient appeared over eastern China (six divisions) than over western China (two divisions).

The climate division facilitated the evaluating of not only regional but also widespread droughts. Trend evaluation showed that western north China (WNC) has become increasingly wet in recent decades, while northern northeast China (NNE) has become increasingly dry. The Yangtze River valley (YZ) tended to experience less and weaker drought after the late 1970s. Southern northeast China (SNE) and the southwestern China–Tibetan Plateau (SW-TP) showed a decreasing trend in long-term but not short-term SPIs, implying that long-term drought conditions might develop continuously, thus allowing the following droughts to develop more rapidly and with a stronger intensity. Examination of the drought risk under El Niño revealed that northern regions were likely to suffer from drought rather than flood in the developing phase and the reverse in the decaying phase. Southeastern China (SE) and the YZ were vulnerable to flood rather than drought in the mature and decaying spring, with SE subjected to drought in the decaying summer. Such a distinctive regional pattern of drought risks was closely connected with the abnormal moisture supply patterns modulated by ENSO in different phases.

1. Introduction

The climate in China differs throughout its vast territory because of differences in latitude, elevation, wind direction, and distance to oceans. A good understanding of how the climate varies by region is of great importance in a wide variety of applications. They include not only simply identifying regions with similar climate variability but also forecasting seasonal climate and applying hydrological measures, such as drought evaluation.

Many climate classification schemes have been put forward to account for spatial variability. The most popular one is the Köppen–Geiger scheme (Peel et al. 2007; Kottek et al. 2006), which divides climate into five categories according to temperature and precipitation (McKnight and Hess 2000), that is, tropical, dry, temperate, continental, and polar and alpine climates. This scheme proved to be effective and efficient in classifying climate-type zones throughout China. Unfortunately, it did not provide information on temporal variability, as only the general climatological characteristics, rather than consistently homogeneous climatic variability, were
considered (Shi and Xu 2007; Yang and Li 2008). To solve this problem, the rotated empirical orthogonal function (REOF) analysis is developed to construct the climate division. As the rotated spatial patterns are generally robust and the physical mechanisms underlying the patterns are simplified (Richman 1986), REOF is widely applied to isolate regions with similar temporal variability (e.g., Lian and Chen 2012; Yang and Li 2008; Yuan et al. 2010). However, there are still some problems embedded in the REOF method—for example, patterns derived from REOF analyses can be misleading at times and associated with very little climate physics. In recent years, the clustering methods, which could group the stations to identify regions with consistently homogeneous climatic variation objectively, are becoming more common in climate divisions (Fovell and Fovell 1993; Fovell 1997; Bieniek et al. 2012). It has been applied to construct the climate division in the United State (Fovell and Fovell 1993) and has been also been applied to diverse climates, such as Saudi Arabia (Ahmed 1997) and Turkey (Unal et al. 2003).

Drought is one of the costliest natural disasters affecting China, having substantial impacts on the environment, agriculture, economy, and society as a whole. A prolonged drought can span more than one season, such as the extreme drought over southwestern China from the autumn of 2009 to early spring of 2010 (Huang et al. 2012; Song et al. 2011). The extreme drought over southeastern China from 2003 to 2005 lasted even longer than 2 years (Lin et al. 2012). Besides being persistent, drought can also be widespread. Drought tends to vary from region to region during its evolution. To explore the drought variation, efforts had been made to construct the drought divisions throughout China in the past few years based on different methods and drought indices (Shi and Xu 2007; Yang and Li 2008; Yuan et al. 2010). On the basis of the drought climate division, the regional disparities in the interannual and decadal variations of the drought condition were well explored. During the past half century, an increasing wet trend dominates northwestern China, while the opposite dominates northeastern China and northern China in the annual mean perspective (Yang and Li 2008). From the perspective of the winter drought condition, the trend over northern China splits with the northern part getting drier while the southern part getting wetter (Yuan et al. 2010). Drought climate division also favors the investigation of the characteristics of the interdecadal turning of climate modes, which shows remarkable regional structures (Shi and Xu 2007). It is found that the interdecadal turnings of the climate over different regions tend to appear at different times. Based on Shi and Xu’s (2007) climate divisions, Liu and Jiang (2014) investigated the interdecadal change in extreme summer and winter droughts and found that extreme droughts increased over China and showed great regional diversity. Hence, it appears that drought climate division is vital for better understanding of the drought variation over the country’s vast territory.

In addition to drought evaluation, drought climate division also facilitates more accurate climate forecasting. In the United States, the climate divisions are currently used as the zones for the seasonal climatic predictions by considering the influence of climatic teleconnection indices in each division, which is highly valuable for seasonal climatic forecasting (Wolter et al. 1999; Budikova 2005). The El Niño–Southern Oscillation (ENSO) phenomenon, as an energetic interannual fluctuation over the tropical Pacific, exhibits remarkable influence on drought and flood conditions over China (e.g., Huang and Wu 1989; Zhang et al. 1996; Feng et al. 2010; Li et al. 2012). During the fall of a developing El Niño, southern and east-central China is subject to surplus rainfall while northern China is vulnerable to rainfall deficits. A vast region of East Asia stretching from southern China to the east of Japan undergoes wet conditions from the mature winter to the decaying spring–early summer (Wu et al. 2003; Wang et al. 2000). Other regions experience nearly the opposite risks of drought and flood, as ENSO affects different parts of China in different ways during its life cycle.

This study has two objectives. The primary objective is to identify drought divisions throughout China based on the temporal and spatial variability of drought. The second objective is to investigate the variation of drought in each division during the past few decades. The rest of this paper is organized as follows: The data and methods are described in section 2, followed by the results of the cluster analyses in section 3, in which the distinctive climatic characteristics in each division will be examined. In section 4, regional drought trends and risks, including the capacity of divisions to evaluate drought, drought trends in the past few decades, and the risk of drought or flood under El Niño conditions, will be investigated. A summary and discussion are given in section 5.

2. Data and methods

a. Data

Gauge-based daily precipitation data during 1961–2012 from 756 stations over China, collected and subjected to quality control procedures by the China Meteorological Administration (Bao 2007), were used to calculate the standardized precipitation index (SPI)
and the climatological monthly precipitation. To ensure that there were no missing values or isolated points in the cluster analysis, only 535 stations were enrolled. Additionally, the homogenized historical temperature dataset of China (Li and Yan 2009), including daily maximum/minimum temperatures from 549 stations during 1961–2011, were also employed.

The National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) Reanalysis 1 dataset during the period 1961–2012 were used to calculate the vertical integral of water vapor flux and its divergence (Kalnay et al. 1996). The variables employed included the horizontal wind and specific humidity data, with the horizontal resolution of 2.5° × 2.5° and the temporal resolution of four times daily. Historical El Niño episodes were identified using the 3-month running mean of ERSST.v3b SST anomalies in the Niño-3.4 region by the National Oceanic and Atmospheric Administration (NOAA)/Climate Prediction Center (CPC) (http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears_ERRSSTv3b.shtml). They were applied to study the risk of drought or flood in each division under El Niño. The 3-month SPI (SPI-03) represents an arbitrary but specific method of defining drought climate division will be constructed based on actual observation. Based on its definition, it can represent both dry and wet conditions simply and flexibly. The 3-month SPI (SPI-03) represents an arbitrary but typical time scale at which a precipitation deficit will affect soil moisture and harm agriculture directly. A drought climate division will be constructed based on the variation of SPI-03 in this study from the perspective of meteorological and agricultural drought.

b. Analysis methods

Cluster analysis is a plausible approach for defining climate divisions (Fovell and Fovell 1993; Unal et al. 2003). The commonly used clustering strategies are hierarchical and partition-based cluster analyses. In this study, both clustering strategies—Ward’s clustering and k-means clustering—which are both well-established techniques and superior to other clustering methods (Wilks 1995), are applied. Nevertheless, it is important to note that both have their own advantages and shortcomings. Use of both methods allows the comparison of their performance and the determination of the final cluster scheme.

1) WARD’S CLUSTERING

Ward’s minimum variance method is a hierarchical and agglomerative clustering technique widely used in climate research. Its performance tends to be superior to that of other procedures, especially in climate division (Kalkstein et al. 1987; Bieniek et al. 2012). In Ward’s method, the cluster distances are defined as the squared Euclidean distances between objects. Agglomeration starts with n clusters, with one object in each cluster, and merges the cluster pairs with a minimum between-cluster distance to form a new cluster at each step. This process continues until only one all-inclusive cluster is created. However, this technique has a tendency to form clusters with relatively equal numbers of objects (Kalkstein et al. 1987), which is a major drawback, since there is no reason to believe that the climate districts should contain approximately the same number of stations.

2) K-MEANS CLUSTERING

One of the best-known partition-based clustering methods is k-means clustering. In this method, the number of clusters k is specified in advance; the centers of k clusters are determined and each object is assigned to the nearest cluster center, so that the squared distances are minimized. Because of its operational simplicity and computational efficiency, k-means is an extremely popular method of cluster analysis (Hartigan and Wong 1979). However, when applied to climate division, the k-means method is likely to merge stations that are geographically far apart, which is obviously unreasonable. In consideration of this drawback, the climate division boundaries are drawn primarily based on the results from Ward’s clustering rather than k-means clustering; the results from k-means clustering allow comparison of performance and thus to decide the number of divisions and to amend the incorrect divisional memberships of some stations when experiencing Ward’s clustering.

3. Drought climate divisions over China

To construct the drought climate divisions over China, the two clustering methods were launched and the results were compared. The final division scheme is based mainly on Ward’s clustering, with the result from k-means clustering acting as a supplement to determine the number of divisions and to adjust the boundaries. When performing Ward’s clustering, the within-cluster sum of squares at each step was calculated and found to increase as the number of clusters decreases, indicating that the new merged cluster is relatively heterogeneous and contains units that are considerably different from each other. A good cluster solution shows a sudden jump in the within-cluster sum of squares with the cluster number before the jump offering the robust solution of division. Inspection of the change in the overall within-cluster sum of squares (Fig. 1) shows that the distance...
between clusters and their members begins to increase relatively fast after eight clusters. Though the jump after seven clusters might be even more robust, considering the good consistency between the results from Ward’s and \(k\)-means clustering in eight rather than seven clusters (Fig. 2), eight clusters were selected as the final division scheme. When seven divisions were drawn (Figs. 2a and 2c), discrepancies appear over northern China and northeastern China. In Ward’s method, northern China remained intact, while northeastern China was divided into two regions, implying that stations within northern China show greater similarity than those in northeastern China, while the result was the reverse with \(k\)-means clustering. When eight divisions were made (Figs. 2b and 2d), though the different memberships of some stations still occurred around the boundaries of the divisions, the divisions from the two methods showed consistent patterns. Hence, the drought climate over China was divided into eight sectors.

One of the limitations of hierarchical clustering is that once a station is classified into one cluster, it cannot be reclassified into others in the following steps, which might result in incorrect divisional memberships for some stations. To alleviate this problem, cross-correlation analysis between individual stations and the division averages was carried out to validate the final divisional memberships (Fig. 3). Roughly, most of the stations show higher correlation with their own division. Only 32 stations showed higher correlation with other divisions that were geographically adjacent to their own divisions. After both the correlation coefficients and divisional memberships from the \(k\)-means method were examined, 29 out of 32 stations were reclassified to the adjacent divisions that showed higher correlation, while the rest were retained in their original divisions. The validated membership and boundaries of each division are shown in Fig. 4. From south to north, eastern China was divided into six drought climate divisions showing mainly a meridional gradient, that is, southeastern China (SE), the Yangtze River valley (YZ), the Yellow–Huaihe River valley (YR-HHR), northern China (NC), southern northeast China (SNE), and northern northeast China (NNE). These might result from monsoon activity, as the...
variation in the northern edge of the summer monsoon and the southern edge of the winter monsoon dominates precipitation anomaly patterns and thus meteorological drought. In contrast, the drought condition over west China seemed more homogeneous; it was classified into two divisions—that is, southwestern China–Tibetan Plateau (SW-TP) and western north China (WNC)—with the boundary around the major terrain feature of the Tibetan Plateau. It is interesting to see that the east–west discrepancy over southern and northern China is different: the boundary is located much farther east over southern China, extending to around 110°E, but it is much farther west over northern China, extending to around 100°E.

There are great differences between the new climate divisions and the previous divisions proposed by Yang and Li (2008), who identified 11 regions throughout China based on drought grades derived by applying REOF analysis. To discover whether the differences are rooted in the methods, a REOF analysis based on the SPI-03 was also carried out. Based on North et al.'s (1982) significant test for the EOF analysis, only the first eight EOF modes of the SPI-03 throughout China are well separately from each other (figure not shown). Thus, the first eight EOF modes—occupying 41.6% of the total variance—are rotated and shown in Fig. 5, though their accumulated explained variances is much less than the suggested value of 85% (Wei et al. 2004). It was found that the divisions from REOF show great consistency with those from cluster analyses, with the highest eigenvector values of each mode located within the identified divisions and the sharp gradient of eigenvector values lying around the identified boundaries. Such highly consistent results from REOF and the cluster analyses, which are principally different methods, further verify our divisions. The differences between this study and that of Yang and Li (2008) may stem from the drought indices applied in the climate division. However, the SPI applied here is obviously superior to drought grades in analyzing drought variation, as it is more continuous and standardized among stations.

4. Regional drought trend and risk

To examine the variation in the drought regimes over China in the past few decades, the meteorological droughts in each division were identified using the regional SPI-03, which is calculated based on the regional mean precipitation in each subregion, that is, a period in which the SPI is continuously negative and reaches $≤ -1.0$ or less (McKee et al. 1993). Drought begins when the SPI first falls below zero and ends with a positive SPI value. Drought intensity was arbitrarily defined using the minimum SPI as moderate drought ($-1.0 ≤ SPI > -1.5$), severe drought ($-1.5 ≤ SPI > -2.0$), and extreme drought ($SPI ≤ -2.0$). Drought magnitude, which represents the impact of drought synthetically, was defined as the accumulated SPI during the drought period. The variation of the regional SPI-03 and the magnitude of droughts of different intensities are displayed in Fig. 6.

a. Good capacity for evaluating drought

The reasonableness of the drought climate divisions can be further examined by determining whether the
regional SPI-03 variation in each division accurately captures the occurrence of droughts in the past few decades.

In Fig. 6, several exceptional drought events are identified. The extreme drought over the YZ that lasted for 3 years from March 1978 to February 1980 had a magnitude reaching −24.8 and was the longest drought affecting the YZ since 1961. The extreme drought over SE during March 2003–February 2005, with a magnitude reaching −23.5, resulted in the lowest water levels over the main rivers and the saline water intrusion, seriously affecting the freshwater supply in the coastal cities (Ji et al. 2009). Another far-reaching extreme drought was over SW-TP during February 2009–May 2010, with an index reaching −19.2, and was one of the most serious meteorological disasters in the history of southwestern China, with more than 60 million people affected and the causes are still under investigation.

Besides regional droughts, widespread droughts can also be well identified using the SPI-03 in the classified climate divisions. One exceptional case is the extreme drought over northern China during 1998–2001. It started during August 1998–January 2000, with a magnitude reaching −19.2 and a peak SPI-03 reaching −3.4 in February 1999, making it the most serious drought over NE over the past half century. It concurred with severe droughts in both NNE and SNE. Extreme drought evolved into SNE (strength: −2.2), with severe drought affecting NC (−1.8) and NNE (−1.6) during the following summer. Subsequently, the extreme drought persisted over SNE and expanded to NNE (−2.0) and YR-HHR (−2.5) in 2001. These were three outstanding consecutive drought years in the historical record. Over 20.7 and 23.7 × 10^6 ha were affected throughout China in 2000 and 2001, respectively, resulting in around 20%–30% losses in crop yields. The water level of the Songhua River at Haerbin station reached its lowest value in the hydrological record and the Liao River broke its record in 2001 (Wei et al. 2004).
Fig. 6. Drought events evaluated by the regional SPI-03 over the eight divisions. The top panel of each pair of graphs shows the time series of the regional SPI-03 with SPI $> 1$ and SPI $< -1$ shaded in blue and red, respectively. The bottom panel shows the magnitudes of the moderate (SPI $\leq -1.0$), severe (SPI $\leq -1.5$), and extreme (SPI $\leq -2.0$) drought events.
Another widespread drought event occurred in 2011. Four of the eight divisions—the YR-HHR, YZ, SE, and SW-TP—suffered from extreme droughts, with the YZ experiencing the worst in April 2011 (−3.7). This drought first emerged in the YR-HHR in late fall of 2010 and then developed rapidly and reached its peak at the end of the year. In early 2011, it spread southward to the YZ and SE and strengthened up to −3.7 and −2.3, respectively, by midspring. It terminated over the YZ in early summer but persisted over SE until midfall. This drought also spread to SW-TP when it reached its peak in the YZ and SE, and persisted until the end of that year. The precipitation deficit during this drought reduced not only the crop yield but also the water level in several big lakes, including Tai Lake, Hongze Lake, and Dongting Lake, which severely impacted the fisheries and the freshwater supply for livestock and people. In the most seriously affected region, the YZ, over $3.7 \times 10^8$ ha of growing area suffered from a water deficit and $0.2 \times 10^8$ ha suffered crop failure, with the total losses reaching RMB14.9 billion (Jin et al. 2013).

Hence, the climate division based on the monthly SPI-03 is reasonable and meaningful, as it facilitates the evaluating of not only regional drought but also more widespread drought that covers several regions.

**b. Drought trend in each division**

The trend of the drought regime over China is a popular topic because of not only its high impact but also the dramatic long-term precipitation variation throughout China. In some studies, this variation has been proposed as climate trend. Northern China has become increasingly dry, while southern China has become increasingly wet, and the precipitation has been more concentrated under global warming, thus increasing both flooding and drought disasters (Gong and Ho 2002; Yu et al. 2004; Li et al. 2012). However, other studies have described this variation as decadal variation rather than climate trend, as the southward-shifted summer rain belt has tended to shift northward again in recent years (Hu and Ding 2009). To address these questions, the drought trends in the eight divisions are investigated using four indicators, that is, SPI-03, SPI-06, SPI-12, and SPI-24, which represent arbitrary but typical time scales for a precipitation deficit to affect soil moisture, groundwater, snowpack, and streamflow (McKee et al. 1993) (Table 1).

The increasing trends in the SPI (SPI-03, SPI-06, SPI-12, and SPI-24) in WNC are the most remarkable. The coefficients [7.5, 8.8, 12.3, and 11.5 $\times 10^{-2}$ (10 yr$^{-1}$)] are significant at the 99.9% confidence level; even though the most moderate SPI-03 has increased by 0.4 (σ is standard deviation) in the past 62 years. Drought conditions over WNC, no matter at which time scale, have weakened in recent decades. Figure 6 also shows that most of the severe and persistent droughts over WNC occur before the mid-1970s and almost no droughts occur after 2000 except for three short and weak moderate droughts. WNC has become increasingly wet in recent decades, with the number of drought months (SPI ≤ −1.0) decreasing and the number of flood months (SPI ≥ 1.0) increasing (Fig. 7). Considering the climatologically south–north and east–west gradient of the dry–wet condition over China, the west–east gradient of the dry–wet condition over the northern China is decreasing, as the WNC tends to experience less and less drought, while a similar variation is not expected over southern China.

In contrast, drought conditions over NNE have become increasingly severe, opposite to those over WNC. Of the four time scales, the decreasing trend of SPI-24 is the most significant, indicating that the streamflow over NNE has been reduced in recent decades. This implies that NNE is vulnerable to drought and droughts might develop rapidly and reach an extreme intensity easily, as can be confirmed in Fig. 6. Since the mid-1990s, droughts over NNE have tended to occur with a stronger intensity and longer duration; both of the top two extreme droughts, with magnitudes of over −10.0, appeared after 2000.

Another significant feature is the increasing trend of the SPI-03 over the YZ. It is found that droughts tend to occur with a weaker intensity and lower frequency after the extreme drought in the late 1970s over the YZ. This is quite consistent with the increasing precipitation shift over the YZ after the late 1970s (Yu et al. 2004).

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**Table 1. Trends of negative regional SPI-03, SPI-06, SPI-12, and SPI-24 [SPI < 0; $10^{-2}$ (10 yr$^{-1}$)] over the eight divisions. The boldface type indicates values significant at the 95% confidence level.**

<table>
<thead>
<tr>
<th>Division</th>
<th>SPI-03</th>
<th>SPI-06</th>
<th>SPI-12</th>
<th>SPI-24</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) SE</td>
<td>1.9</td>
<td>−1.9</td>
<td>−0.9</td>
<td>3.5</td>
</tr>
<tr>
<td>2) YZ</td>
<td>5.5$^a$</td>
<td>1.7</td>
<td>4.7</td>
<td>3.9</td>
</tr>
<tr>
<td>3) YR-HHR</td>
<td>−3.2</td>
<td>−4.7</td>
<td>−3.2</td>
<td>2.2</td>
</tr>
<tr>
<td>4) NC</td>
<td>2.7</td>
<td>4.6</td>
<td>14.8$^b$</td>
<td>−1.2</td>
</tr>
<tr>
<td>5) SNE</td>
<td>0.2</td>
<td>1.3</td>
<td>−3.9</td>
<td>−8.6$^b$</td>
</tr>
<tr>
<td>6) NNE</td>
<td>−5.3$^a$</td>
<td>−4.9</td>
<td>−6.6$^b$</td>
<td>−11.1$^b$</td>
</tr>
<tr>
<td>7) SW-TP</td>
<td>−1.5</td>
<td>−5.3</td>
<td>−17.3$^b$</td>
<td>−25.1$^b$</td>
</tr>
<tr>
<td>8) WNC</td>
<td>7.5$^b$</td>
<td>8.8$^b$</td>
<td>12.3$^b$</td>
<td>11.5$^b$</td>
</tr>
</tbody>
</table>

$^a$Values significant at the 99% confidence level.

$^b$Values significant at the 99.9% confidence level.
It is important to note that though the short-term SPIs (SPI-03 and SPI-06) showed no significant trend, the long-term SPIs (SPI-12 and SPI-24) decreased significantly over both SNE and SW-TP, implying that long-term drought might develop continuously even if short-term drought is terminated. The accumulated precipitation deficit still persists, and thus the following droughts tend to develop rapidly and with a stronger intensity. This was the case with the three recent consecutive extreme droughts over southwest China during 2009/10, 2011, and 2012/13. The huge accumulated deficits in most rivers, reservoirs, and snowpacks made complete drought recovery even more difficult. It is found that the drought trend over SE is not significant at all; the extreme drought during 2003–05 over SE seems to be just an exceptional case, rather than the beginning of a drought era.

Cautions must be paid that the drought trend analyzed here is only based on the time span of 1961–2012. A different conclusion might be drawn if a different time span is considered. For SNE, an increasing drought trend is detected in the study of Yang and Li (2008) with the time span of 1974–2006 but not in this study. This is because the serious drought condition over SNE is relieved after the mid-1970s, but it is worsened from 1980s to early 2000s and is relieved again afterward. For NC and YR-HHR, increasing drought trends in recent decades are detected in the study of Zhai et al. (2005), which ends in 2000. However, this might result from the strongest drought over NC during 1999/2000 and several extreme droughts over YR-HHR in 1997, 1998/99, and 2000 (Fig. 6). If the weak drought condition in the 2000s is considered, then the drought trends over these two regions are not convincing. Similarly, the decreasing drought trend over SE disappears if the strong drought condition in the 2000s is considered. Hence, it is the decadal variation instead of the trend variation of the drought condition that is detected over SNE, NC, YR-HHR, and SE during the past half century.

### c. Drought risk under El Niño

The ENSO phenomenon, an energetic interannual fluctuation over the tropical Pacific, has been regarded as a crucial driver of dry and wet conditions throughout China by modulating the atmospheric circulation, and thus the rainfall anomalies, during its different stages (e.g., Huang and Wu 1989; Zhang et al. 1996; Feng et al. 2010; Li and Zhou 2012). It is important to clarify how the ENSO signal affects drought and flooding over China in different stages and what the differences among all the divisions are. To address this, a non-parametric kernel approach, which is widely used in theoretical and applied statistics (Bowman and Azzalini 1997), was employed to determine the risk of drought or flood under ENSO—simply, the ratio of the probability of the SPI $\leq -1.0$ and SPI $\geq 1.0$ under ENSO to that under all conditions [Eqs. (1) and (2)]:

\[
\text{Drought Risk} = \frac{P(\text{SPI} \leq -1.0 | \text{ENSO})}{P(\text{SPI} \leq -1.0)} \quad \text{and} \quad (1)
\]

\[
\text{Flood Risk} = \frac{P(\text{SPI} \geq 1.0 | \text{ENSO})}{P(\text{SPI} \geq 1.0)} \quad (2)
\]

Here, the historical ENSO episodes were selected using the December–February (DJF) Niño-3.4 SSTAs. The monthly regional SPI-03 is used to calculate the monthly risk first, and then the seasonal risk is calculated as the 3-month mean of the monthly risk. A value larger and less than 1.0 indicates a higher-than-normal risk and a lower-than-normal risk, respectively. The farther the risk is away from 1.0, the larger the likelihood of the anomaly. The risks of drought or flood over each division during the developing fall to the decaying summer of El Niño are displayed (Figs. 8a–d). In the developing fall of El Niño, western China (WNC and SW-TP) and northern China (NC and YR-HHR) experience a high drought risk and a low flood risk, especially in NC.
where the drought potential is double and the flood potential is reduced by half, indicating that these divisions tend to be drier than normal, which is consistent with Wu et al. (2003) that North China tends to receive less rainfall in the developing fall of El Niño. In contrast, NNE tends to have a low drought risk and a high flood risk. The risks of both drought and flood increase slightly over SE and SNE, implying that drought and wet conditions over these regions tend to be highly variable and vary from case to case under El Niño, while the reverse is true over the YZ. The influence of El Niño on the risk of drought or flood throughout China changes when it comes to the mature winter. Lower-than-normal drought risk dominates all divisions, indicating that drought conditions are likely to be alleviated during a mature El Niño. Consistently, multiple divisions (YZ, SE, WNC, and SW-TP) tend to experience more flooding. Over SE, the drought potential is only 30% of normal, while the flooding potential is twice normal. Similar results were also found in other studies (Wang et al. 2000; Wu et al. 2003; Sun and Yang 2012). The drought or flood conditions over the YR-HHR and NC are mild, with reduced risks of both drought and flood. In the following spring, the influence of El Niño in each division is homogeneous. Except in SW-TP, where a high risk of drought dominates, other divisions experience a greater chance of experiencing flooding than drought. In the decaying summer, the situation continues over all regions except SE, where the risk of flooding decreases. The flood risk over YR-HHR is as high as 1.8, nearly twice normal, indicating the Yangtze River tends to experience a high risk of flooding in the decaying summer of El Niño. The severe flood over the Yangtze River valley in the summer of 1998 is a most convincing example (Lau and Weng 2001).

For La Niña, the pattern of the risks of drought or flood throughout China is similar but opposite to that during El Niño (Figs. 8e–h); thus, it is not discussed in detail here. However, caution still needs to be paid attention to as the strength of the risks of drought or flood in El Niño and La Niña is asymmetric to some extent. For example, the risk of flood (drought) during El Niño is much stronger than the risk of drought (flood) during La Niña over SE and YZ in the mature winter (figure not shown), which is consistent with Zhang et al. (1996).

To illustrate briefly how ENSO leads to different drought risks throughout China in different phases, the water vapor supply anomalies are regressed (Fig. 9). In the developing fall, the moisture supply to most of China is weakened, as an anticyclone dominates the water vapor transport over the South China Sea. Stronger moisture divergence increases the drought risk throughout China. In the mature winter, abundant moisture is transported into southeastern China by the southwesterly peripheral flow of the Philippine Sea anticyclone. Strong moisture convergence increases the risk of flooding and reduces the risk of drought over SE and the YZ. In the decaying spring, the enhanced moisture convergence extends northward and reduces the drought risk over all of eastern China, while the abnormal moisture divergence dominates SW-TP and increases the drought risk there. In the coming summer, abnormal moisture divergence dominates SE, with convergence to the north over the YZ, YR-HHR, SNE, and NNE resulting from the southwestward shift of the western Pacific subtropical high. A distinctive pattern of drought risk appears throughout China. Abnormalities in the moisture supply, dominated by the atmospheric circulations that are remotely forced by ENSO, result in different patterns of drought and flood risks in different regions of China.

Overall, El Niño tends to increase the drought risk and decrease the flood risk over China in the developing phase, while the reverse is true in the mature and decaying phases, which is in general agreement with the aforementioned studies. However, division-to-division differences still occur across the country. It might be that the different impacts of climate signals on different regions cause the climate diversity throughout China and hence make the climate classification necessary.

5. Conclusions

On the basis of monthly SPI-03 throughout China, a combination of Ward’s and k-means cluster analysis has been applied to identify eight divisions of homogeneous drought variation, that is, southeastern China (SE), the Yangtze River valley (YZ), the Yellow–Huaihe River valley (YR-HHR), northern China (NC), southern northeast China (SNE), northern northeast China (NNE), southwestern China–Tibetan Plateau (SW-TP), and western north China (WNC). The division boundaries were drawn with additional reference to the cross-correlation analysis. Drought conditions over eastern China (six divisions) show a greater meridional gradient than those over western China (two divisions), and the east–west boundaries lie much farther east in the south and farther west in the north.

The climate division facilitates the evaluation of not only regional but also widespread drought. Drought conditions have significantly weakened over WNC and intensified over NNE at all time scales in the past few decades. Droughts tend to occur with a weaker intensity and lower frequency over the YZ after the late 1970s. Though the short-term SPIs show little trend, the long-term SPIs decrease significantly over both
Fig. 8. Drought and flood risks (drought/flood) in the eight divisions under (a)–(d) El Niño and (e)–(h) La Niña in different phases: developing fall [AUT (0)], mature winter [WIN (0)], decaying spring [SPR (+1)], and decaying summer [SUM (+1)].
SNE and SW-TP, implying that long-term drought might develop continuously and lead to a stronger and more rapid evolution of the following short-term droughts.

Evaluation of the impact of El Niño on the drought and flood risks reveals that El Niño is likely to increase the drought risk and decrease the flood risk over China in the developing fall, with the reverse being the case in the mature and decaying phases via its modulation of the water vapor supply. However, regional diversity can still be found. Such distinctive modulation from the oscillation signals causes the drought climate to vary considerably from region to region.

It is important to point out that the SPI-03 is just one of the many indices for conducting climate division (Keyantash and Dracup 2002). It is chosen by considering its flexibility, simplicity, and wide application in actual observation; at the same time, it can reflect soil moisture conditions that might harm agriculture effectively (McKee et al. 1993).

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