Comparative analysis of meteorological and hydrological drought over the Pearl River basin in southern China
Kai Xu, Guangxiong Qin, Jie Niu, Chuanhao Wu, Bill X. Hu, Guoru Huang and Peng Wang

ABSTRACT
Drought is one of the major natural hazards with a possibly devastating impact on the regional environment, agriculture, and water resources. Previous studies have assessed the historic changes in meteorological drought over various regional scales but have rarely considered hydrological drought due to limited hydrological observations. Here, we use long-term (1960–2012) hydro-meteorological data to analyze the meteorological and hydrological drought comparatively in the Pearl River basin (PRB) in southern China using the standardized precipitation index (SPI) and the standardized runoff index (SRI). The results indicate a strong positive correlation between the SPI and SRI, and the correlation tends to be stronger at the longer timescale. The SPI is reliable to substitute for the SRI to represent the hydrological drought at the long-term scale (e.g., 12 months or longer). Trend analysis reveals a noticeably wetting trend mainly in the eastern regions and a significant drying trend mainly in the western regions and the downstream area of the PRB. The drought frequency is spatially heterogeneous and varies slightly at the interannual scale. Overall, the drought is dominated by noticeable cycles of shorter periodicity (0.75–1.8 years), and periodic cycles in the meteorological drought are mainly responsible for those in the hydrological drought.

INTRODUCTION
Drought is a hydro-meteorological phenomenon of a period from months to years with below-average moisture in a given region, generating prolonged shortages in water supply, atmospheric water, surface water, and groundwater (Mohamed et al. 2016). Compared with other natural disasters, drought is more extensive with higher frequency and longer duration and has become a grave threat to the environment, agriculture, energy production, public health, and ecosystem (EEA 2012; EM-DAT 2012; Zhang et al. 2015). In the past decade, extreme drought events have been reported worldwide, such as in North America (Cook et al. 2004, 2007; Herweijer et al. 2007; Seager et al. 2009a; Hoerling et al. 2014), Mexico (Seager et al. 2009b; Mendez & Magana 2010), Asia (Davi et al. 2006; Xin et al. 2006; Zhang et al. 2008; Fang et al. 2009; Chen et al. 2010; Qian et al. 2011), Africa (Touchan et al. 2008; Shanahan et al. 2009; Dutra et al. 2012; Arnell et al. 2013), and Australia (Kiem & Franks 2004; Nicholls 2004), which have caused substantial economic losses and casualties. To make matters worse, the risk of drought will most likely continue to increase throughout the 21st century (Dai 2011, 2013).

Droughts are generally classified into four categories: meteorological drought (WMO 1975), hydrological drought (Palmer 1965), agricultural drought (FAO 2002), and socioeconomic drought (AMS 2004). There are some differences between these four droughts, among which meteorological drought is initially induced by precipitation ($P$) deficits, and can result in soil moisture deficits (i.e., agricultural droughts).
drought) as well as the decrease of surface runoff and groundwater level (i.e., hydrological drought), and can also lead to crop loss, drinking water shortage, and socio-economic loss (i.e., socio-economic drought).

Substantial research efforts have been made to develop drought-monitoring indices to characterize different types of droughts by using a single impact factor or a combination of different hydro-meteorological variables (McKee et al. 1993; Karamouz et al. 2009; Núñez et al. 2014; Stagge et al. 2015). Among them, the standardized precipitation index (SPI) is the widely used meteorological drought index (McKee et al. 1993). In addition, some other drought indices have been developed and improved to better describe the specific features of drought, such as the Palmer drought severity index (PDSI; Palmer 1965), the US Drought Monitor (USDM; Svoboda et al. 2002), the rainfall anomaly index (RAI; van Rooy 1965), the Palmer hydrological drought severity index (PHDI; Heim 2002), the surface water supply index (SWSI; Shafer & Dezman 1982), the standardized precipitation evapotranspiration index (SPEI; Vicente-Serrano et al. 2010), the streamflow drought index (SDI; Nalbantis 2008), and the standardized runoff index (SRI; Shukla & Wood 2008). Each of them has its own strengths and weaknesses (Mishra & Singh 2010; Corzo Perez et al. 2011).

The Pearl River basin (PRB) located in southern China is climatically humid with abundant P. However, the uneven spatiotemporal distribution of P can easily trigger extreme hydro-climatological events, such as floods and droughts. In the past few decades, the PRB has experienced serious droughts with high drought intensity and extended periods of water scarcity, such as extreme drought events in 2004, 2005, 2010, and 2011 (Xiao et al. 2012; Zhang et al. 2012). Recent studies have investigated the historic changes in meteorological drought in the PRB (Zhang et al. 2007a, 2012, 2013; Yu et al. 2014a, 2014b; Wu et al. 2016). For example, Zhang et al. (2009b) investigated the changes of drought/wetness episodes in the PRB by using SPI and aridity index and found that the PRB has become drier during the rainy season and wetter in winter. Fischer et al. (2011) observed decreasing numbers for rainy days and a tendency of longer dry periods and shorter wet periods in the PRB. Gemmer et al. (2011) analyzed the spatial and temporal characteristics of precipitation extremes in the PRB and found increasing tendencies of drier conditions and stronger precipitation intensities during the period 1961–2007.

Previous studies have made advances in assessing the dependence and relationship of meteorological drought (or climate change) and hydrological drought (Vicente-Serrano et al. 2012; Wong et al. 2013; Niu et al. 2015), and highlighted the importance of incorporating meteorological drought in hydrological drought characteristics (Van Lanen et al. 2013; Wong et al. 2013; Van Loon & Laaha 2015). As hydrological droughts often occur after a considerable long period of meteorological drought (Rimkus et al. 2013), the meteorological drought index may not be sufficient to represent the diversity of hydrological drought (Wanders et al. 2010). Therefore, exploiting the intrinsic relationship between meteorological and hydrological droughts would be of great value to the risk assessment of regional drought (Karamouz et al. 2009).

On the basis of long-term (1960–2012) gridded hydro-meteorological data, this study analyzes meteorological and hydrological droughts comparatively in the PRB using the SPI and SRI at four different timescales (1-, 3-, 6- and 12-month). The objectives of the study are: (1) to investigate historical changes in the trend and frequencies of meteorological and hydrological droughts at different timescales; (2) to analyze the temporal variability of meteorological and hydrological droughts; and (3) to provide a holistic evaluation of the interconversion between hydrological and meteorological drought. The results of this study will improve our understanding of the changing drought risk under the changing environment and will also help to improve drought hazards’ prevention and regulation in the PRB.

**STUDY AREA AND DATA**

**Study area**

The Pearl River is the second largest river in discharge and the third largest river in drainage area (102° 14’E–115° 53’E; 21° 31’N–26° 49’N) in China, with a drainage area of 4.42 × 105 km2 and including three major tributaries: the West River, the North River, and the East River (Figure 1). The PRB is located in the tropical and subtropical climate zones, with mean annual temperature ranging from 14 to
22 °C and mean annual precipitation of approximately 1,525 mm yr⁻¹ \( (Zhang \ et \ al. \ 2009a; \ Wu \ et \ al. \ 2013) \). The rainfall is mainly concentrated in the flood season (i.e., April–September), accounting for 70–80% of the total annual precipitation \( (Zhang \ et \ al. \ 2012) \). The water resources are unevenly distributed spatially and mainly located in the West River and the North River basins, which account for about 93.7% of the total area of the PRB \( (Zhang \ et \ al. \ 2015) \). The Pearl River is the key resource of drinking water for large cities (total population of 56 million) in the Pearl River delta region, such as Guangzhou, Zhuhai, Hong Kong, and Macau \( (Zhang \ et \ al. \ 2008) \). Due to recent climate warming, the climatic characteristics have become more changeable, resulting in higher risk of meteorological disasters (e.g., floods and droughts). In the past decade, the PRB has suffered several extreme drought events, such as in 2004, 2005, 2010, and 2011, causing serious negative impacts on the sustainable development of social economy in the study region.

Dataset

A long-term (1960–2012) consistent and comprehensive hydro-meteorological gridded dataset, covering China with a 0.25° spatial resolution, is provided by Zhang \ et al. \ (2014). In this dataset, the daily \( P \) are derived from 756 monitoring stations of the Chinese Meteorological Administration (CMA). The surface runoff \( (R_s) \) and baseflow \( (B_s) \) are
simulated by the variable infiltration capacity (VIC) model, with the daily observation of \( P \), maximum/minimum temperature, and wind speed as the forcing data. An optimization algorithm of the multi-objective complex evolution from the University of Arizona (MOCOM-UA) was implemented for model calibration (Yapo et al. 1998). Zhang et al. (2014) indicated that the simulated monthly runoff (\( R \)) matches well with the observations at the large river basins over China. Particularly, the Nash–Sutcliffe efficiency between the simulation and observation is above 0.82 and the relative error is less than 7% at all hydrological stations in the PRB. Overall, the dataset provides a more reliable estimate of \( R \) at the large river basins over China compared with global products of a similar nature (Nijssen et al. 2001; Rodell et al. 2004; Adam et al. 2006; Sheffield et al. 2006; Sheffield & Wood 2007; Pan et al. 2012). Consequently, the data have been successfully used for the quantitative assessment of effects of climate and water storage change on the temporal variability of actual evapotranspiration in China (Wu et al. 2017). The data of \( P \), \( R_s \), and \( B_s \) for the total 618 grids covering the PRB are collected in this study. \( R \) for each grid is computed by summing up \( R_s \) and \( B_s \).

Using Sen’s trend slope estimator, the spatial distribution of the trend magnitudes of annual \( P \) and \( R \) are analyzed in the PRB during the period 1960–2012 (Figure 2). As seen, the trend magnitudes of annual \( P \) and \( R \) range from –47.36 to 48.8 mm decade\(^{-1}\) and from –42.16 to 40.24 mm decade\(^{-1}\), respectively. The trend pattern of \( P \) is generally similar to that of \( R \), that is, there is a significant decreasing trend (i.e., drying trend) in the western regions and a weak increasing trend (i.e., wetting trend) in the eastern parts of the study region.

Methods

Calculation of the SPI and SRI

In this study, the SPI recommended by the World Meteorological Organization (WMO) is used for assessing meteorological drought, and the SRI is employed for assessing hydrological drought. Compared with other drought indices, the SPI (SRI) is mostly valued for its unambiguous theoretical development, robustness, temporal flexibility, and simplicity in that it requires only \( P \) (\( R \)) data (Raziei et al. 2009; Zhai et al. 2010). The calculation of the SPI (SRI) mainly includes the following steps: (1) generate a monthly time series of \( P \) (\( R \)); (2) choose a frequency distribution to fit \( P \) (\( R \)) and form the cumulative distribution from the fitted frequency distribution; (3) transform the cumulative probability into a normal distribution, with zero mean and unity standard deviation. More detailed information for the calculation procedure of the SPI and SRI can be found in Mckee et al. (1993). In this study, the gamma probability function is used for fitting \( P \) (\( R \)):

\[
g(x) = \frac{1}{\beta^\alpha \Gamma(\alpha)} x^{\alpha-1} e^{-x/\beta}
\]

(1)

where \( \beta \) is a scale parameter, \( \alpha \) is a shape parameter, and \( \Gamma(\alpha) \) is the ordinary gamma function of \( \alpha \).

The SPI (SRI) can be designed to quantify the deficit of \( P \) (\( R \)) for multiple timescales, reflecting the impact of drought on the availability of different water resources. In this study, four different timescales (i.e., 1-, 3-, 6- and 12-month) are used for analyses, representing not only soil moisture conditions at the relatively short timescale but

![Figure 2](https://iwaponline.com/hr/article-pdf/50/1/301/524709/nh0500301.pdf)
also groundwater, streamflow and reservoir storage at the long-term scale. Based on the values of SPI/SRI, and according to McKee et al. (1995), the classifications of drought intensities are defined (Table 1). A drought event usually occurs during the period when SPI (SRI) is continuously negative and reaches or is below $-0.1$, and ends when SPI (SRI) becomes positive (McKee et al. 1993, 1995).

The time series of SPI and SRI in the PRB are presented at four different timescales (1-, 3-, 6-, and 12-month) during 1960–2012 (Figure 3). It is clear that remarkably dry or wet events with different magnitudes have occurred in different years. In general, there is a good agreement between SPI and SRI for all four timescales, especially for the longer one (e.g., 12-month). However, the variation of SPI is significantly greater than that of SRI during the drought episodes (i.e., the index value less than 0) at 1- and 3-month timescales, indicating an inconsistency in the assessment of drought when applying SPI and SRI to the short timescale. The differences between SPI and SRI decrease as the timescale increases. The time series of 6- and 12-month SPI and SRI show clear long-term changes in dryness and wetness, such as the dry periods in 1963, 1989, and 2004, which are in agreement with previous reports (Xiao et al. 2015; Zhang et al. 2012).

**Mann–Kendall test**

The Mann–Kendall (M-K) test is a nonparametric statistical trend test method, with the advantage of not providing any distribution for the data and without being affected by the

### Table 1 Classification of the SPI and SRI

<table>
<thead>
<tr>
<th>SPI/SRI values</th>
<th>Drought category</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.00 or more</td>
<td>Extreme wet</td>
</tr>
<tr>
<td>1.50 to 1.99</td>
<td>Severe wet</td>
</tr>
<tr>
<td>1.00 to 1.49</td>
<td>Moderate wet</td>
</tr>
<tr>
<td>0.0 to 0.99</td>
<td>Mild wet</td>
</tr>
<tr>
<td>0.0 to $-0.99$</td>
<td>Mild drought</td>
</tr>
<tr>
<td>$-1.00$ to $-1.49$</td>
<td>Moderate drought</td>
</tr>
<tr>
<td>$-1.50$ to $-1.99$</td>
<td>Severe drought</td>
</tr>
<tr>
<td>$-2.00$ or less</td>
<td>Extreme drought</td>
</tr>
</tbody>
</table>

**Figure 3** The time series of the SPI and SRI at (a) 1-month scale, (b) 3-month scale, (c) 6-month scale, and (d) 12-month scale in the Pearl River basin during 1960–2012.
interference of a few outliers (Mann 1945; Kendall 1975). It has been widely used in the research of hydro-meteorological trend test (Wu et al. 2014; Wang et al. 2015). In this study, we used the M-K trend test to detect the statistical significance of trends in the time series of SPI and SRI. The significance level for the trend analysis was set to 5%. Additionally, the non-parametric trend slope estimator developed by Sen (1968) was used to estimate the trend magnitudes of SPI and SRI.

Wavelet transform analysis

The wavelet transform is a powerful tool to characterize the frequency, time position, and duration of the variability of the data (Zhang et al. 2007b, 2008; Zhao et al. 2013). It can easily reveal the localized time and frequency information without the constraint that the time series be stationary as required by the Fourier transform and other spectral methods. Wavelet transform has been widely applied in the periodicity analysis of hydroclimatic series (Zhang et al. 2007b; Zhao et al. 2014; Wu & Huang 2015). In this study, continuous wavelet transform (CWT; Torrence & Compo 1998) is used to examine the variation of periodicities in SPI and SRI to investigate the possible linkage between meteorological drought and hydrological drought in the PRB.

RESULTS

Trends in drought

Meteorological drought

Using the M-K trend test, the trend analysis for SPI was conducted at four timescales (e.g., 1-, 3-, 6- and 12-month). The M-K values of SPI are spatially interpolated using the inverse distance-weighted (IDW) method. As seen, the M-K values of the SPI range from -3.04 to 1.56 at the 1-month scale, from -4.58 to 2.89 at the 3-month scale, from -7.27 to 3.58 at the 6-month scale, and from -11.92 to 5.09 at the 12-month scale during the period 1960–2012 (Figure 4(a)–4(d)). The results suggest that the trend in SPI tends to be more significant with the increased timescales, indicating a more significant drying/wetting trend in the PRB at the longer timescales. Generally, a similar trend pattern of SPI is identified for all four timescales. A noticeable increasing trend of SPI (wetting trend) is observed in the North River and East River basins and the central parts of the West River basin, while a significant decreasing trend (drying trend) is detected mainly in the western parts of the West River basin.

Hydrological drought

Similar to SPI, the trend analysis for the SRI was also conducted at 1-, 3-, 6-, and 12-month timescales. As seen in Figure 4(e)–4(h), the spatial M-K values of SRI range from -5.83 to 2.36 at the 1-month scale, from -6.84 to 3.28 at the 3-month scale, from -8.74 to 4.19 at the 6-month scale, and from -12.21 to 5.55 at the 12-month scale. A more significant trend of SRI occurs at the longer timescale, which is similar to that of SPI. Spatially, SRI shows a significant decreasing trend (drying trend) mainly in the western regions and the downstream area of the West River basin. In contrast, a significant increasing trend (wetting trend) mainly occurs in the eastern regions, such as the upstream area of the North River and the downstream area of the PRB. Compared with the SPI (Figure 4(a)–4(d)), the trend of the SRI tends to be more significant at all four timescales.

Changes in the frequency of drought

Meteorological drought

We conducted a statistical analysis of the frequency of meteorological drought over the PRB during the period 1960–2012. The frequencies (%) of meteorological drought events, including extreme drought, severe drought, moderate drought, and mild drought at four timescales, are shown in Figure 5. Overall, the frequency of meteorological drought events is spatially heterogeneous and ranks from high to low as: mild drought (≤41.44%), moderate drought (≤14.88%), severe drought (≤8.32%), and extreme drought (≤5.21%). Extreme drought events occur more frequently in the southwest and eastern regions at the 1- and 3-month scales, in most parts of the West River basin at the 6-month scale, and in the western and eastern regions at the
Figure 4 | Spatial distributions of the trend of SPI at (a) 1-month scale, (b) 3-month scale, (c) 6-month scale, and (d) 12-month scale, and the trend of SRI at (e) 1-month scale, (f) 3-month scale, (g) 6-month scale, and (h) 12-month scale during the period 1960–2012. The trend magnitudes calculated are expressed in the unit of year$^{-1}$. Up/down triangles stand for statistically significant positive/negative trends (significant at the 0.05 level).
12-month scale. The frequency of severe drought tends to be larger in the western region at the 1-month scale, in the northern region at the 3-month scale, and in the West River basin at the 6- and 12-month scales. In contrast, moderate drought is more frequent in most parts of the West River basin at the 1-month scale, in the southwest and eastern regions at the 3-month scale, and in the central and northern regions at the 6- and 12-month scales. Mild drought occurs more frequently in the northwest region at the 1-month scale, in the eastern region at the 3- and 6-month scales, and in the central and northern regions at the 12-month scale. Overall, extreme drought is more frequent at the shorter timescale, while the other kinds of drought (i.e., severe drought, moderate drought, and mild drought) tend to be more frequent at the longer timescale (Table 2).

The frequencies of meteorological drought events in five different sub-periods (1960–1969, 1970–1979, 1980–1989, 1990–1999, and 2000–2010) are shown in Figure 6(a)–6(d). Generally, meteorological drought shows a small variability of frequency among the five decades, with the average frequency ranked from high to low as: mild drought, moderate drought, severe drought, and extreme drought. At the 1-month scale, mild drought is more frequent in the 1980s, while moderate, severe, and extreme droughts
occur more frequently in the 1960s. At the 3-month scale, the frequency of mild, moderate, severe, and extreme droughts are larger in the 2000s, 1980s, 1990s, and 1960s, respectively. At the 6-month scale, mild, moderate, and severe droughts tend to be more frequent in the 2000s, while extreme drought occurs more frequently in the 1960s. At the 12-month scale, mild drought increases from the 1960s to 1980s and decreases in the 1990s; moderate and severe droughts occur more frequently in the recent decade (2000s); the frequency of extreme drought is significantly large in the 1960s (~4.32%).

**Hydrological drought**

The frequencies (%) of hydrological drought events (extreme drought, severe drought, moderate drought, and mild drought) at four timescales during the period 1960–2012

<table>
<thead>
<tr>
<th>Timescale</th>
<th>Extreme drought</th>
<th>Severe drought</th>
<th>Moderate drought</th>
<th>Mild drought</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-month</td>
<td>3.70</td>
<td>3.65</td>
<td>6.43</td>
<td>32.22</td>
</tr>
<tr>
<td>3-month</td>
<td>3.08</td>
<td>3.66</td>
<td>7.12</td>
<td>34.51</td>
</tr>
<tr>
<td>6-month</td>
<td>2.74</td>
<td>3.65</td>
<td>7.83</td>
<td>35.05</td>
</tr>
<tr>
<td>12-month</td>
<td>2.59</td>
<td>4.52</td>
<td>8.77</td>
<td>33.63</td>
</tr>
</tbody>
</table>
are shown in Figure 7. Overall, the frequency of hydrological drought can be ranked from high to low as: mild drought (24.16%–42.08%), moderate drought (2.40%–15.2%), severe drought (0.96%–10.08%), and extreme drought (0.32%–5.92%). The ranking is similar to that of meteorological drought. Specifically, extreme hydrological drought events are concentrated in some parts of the West River and East River basins at the 1-, 3-, and 6-month scales and in the western and southern regions at the 12-month scale. In contrast, the frequency of severe drought events is uneven over the study area, with the percentage ranging from 2.2% to 6.6% at the 1-month scale, from 2.21% to 6.31% at the 3-month scale, from 1.9% to 6.34% at the 6-month scale, and from 0.96% to 10.08% at the 12-month scale. Similarly, the uneven spatial pattern of the frequency is also identified for mild and moderate droughts. Table 3 shows the average frequency of hydrological drought over the PRB at four timescales. The results suggest that extreme drought events are more frequent at the longer timescale, while mild drought events are more frequent at the shorter timescale.

The frequencies of hydrological drought events in five sub-periods: 1960–1969, 1970–1979, 1980–1989, 1990–1999, and 2000–2010 are shown in Figure 6(e)–6(h). Overall, the frequency variability of hydrological drought is similar to that of meteorological drought, with the largest and smallest frequencies in mild and extreme droughts, respectively. At both 1- and 3-month scales, mild and extreme droughts are more frequent in the 2000s, while moderate and severe droughts are more frequent in the 1980s. At the 6- and 12-month scales, mild drought occurs more frequently in the 1980s, while moderate and severe droughts occur more frequently in the 2000s. Particularly, the frequency of 12-month extreme hydrological drought is significantly large in the 1960s (5.37%), which is similar to that of extreme meteorological drought (Figure 6(a)–6(d)).

Relationship between meteorological and hydrological drought

Correlation analysis

The correlation coefficient between SPI and SRI is computed for each of the 618 grids at the 1-, 3-, 6-, and 12-month timescales. The results of spatial correlation across the PRB are shown in Figure 8. In general, SPI is strongly correlated with SRI, with the correlation coefficients in the range of 0.53–0.94, 0.69–0.96, 0.76–0.97, and 0.87–0.98 at the 1-, 3-, 6-, and 12-month scales, respectively. For the 1-month scale, the correlation between SPI and SRI is generally stronger in the North River basin (up to 0.94) and weaker in the central parts of the West River basin (down to 0.53), probably due to the influences of local topographic features. For 3-, 6-, and 12-month scales, the correlation is found to be larger (up to 0.98) and smaller (down to 0.69) mainly in the eastern region and some parts of the western region, respectively. The comparisons of the time series of SPI and SRI for all 618 grids over the PRB during the period 1960–2012 are shown in Figure 9. It is clear that the correlation tends to be larger at the longer timescale, with the correlation coefficient increasing from...
0.69 to 0.95 from 1- to 12-month scale. This suggests that the SPI can be used as a substitute for SRI to represent the hydrological drought at the long-term scale (e.g., 12-month or longer).

**Period analysis**

The results of CWT for the average time series of SPI and SRI at four timescales are shown in Figure 10. As seen, the periods of 0.75, 1, 2, and 5 years exist in the 1-month SPI during the period 1960–2012, with 0.75 year as the main oscillation period, significantly above the 95% confidence level. For the 1-month SRI, there are periods of 0.75, 1.8, and 6 years, also with 0.75 year as the main oscillation period. At the 3-month scale, the periods of 1.8, 2, and 6 years are observed in SPI and SRI, and the 1.8-year period is considered as the primary period. At the 6-month scale, the 1.8- and 4-year periods of SPI and SRI are identified in the periods 1980–2010 and 1965–2010, respectively. In contrast, the 12-month SPI and SRI show the main oscillation periods of 4 and 7 years during the periods 1965–2005 and 1970–2005,

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**Figure 7** Spatial distribution of the frequency (%) of hydrological drought events at four timescales in the Pearl River basin during the period 1960–2012: (a1) to (a4) are extreme drought, severe drought, moderate drought, and mild drought at the 1-month scale; (b1) to (b4) are extreme drought, severe drought, moderate drought, and mild drought at the 3-month scale; (c1) to (c4) are extreme drought, severe drought, moderate drought, and mild drought at the 6-month scale; (d1) to (d4) are extreme drought, severe drought, moderate drought, and mild drought at the 12-month scale. (Continued.)
respectively. Overall, the periods of 0.75–7 years are detected from 1-month to 12-month scale. Moreover, the periodic oscillation pattern of SRI becomes more similar to that of SPI with increased timescale, which is in good agreement with the stronger correlation between SPI and SRI at the longer timescale.

**DISCUSSION AND CONCLUSIONS**

On the basis of long-term (1960–2012) gridded precipitation and runoff data, this study conducted a comparative analysis of meteorological and hydrological drought in the PRB using SPI and SRI. The M-K method and wavelet analysis were used to explore the variability properties of meteorological and hydrological drought. The relationship between meteorological drought represented by the SPI and hydrological drought represented by the SRI over various timescales was discussed.

The results indicated that SRI is strongly correlated (correlation up to 0.98) with SPI over the PRB, especially for the eastern regions. Changes in precipitation are directly responsible for changes in runoff, particularly at the long-term scale, where SPI is reliable to be used as a substitute for SRI to represent the hydrological drought. This is consistent with the findings of Zhang et al. (2008) and Fischer
et al. (2013), which indicated that long-term changes of annual runoff are mainly controlled by precipitation variation in the PRB. However, at the short timescale (e.g., 1- and 3-month), the variation of SRI is significantly less than that of SRI during the drought episodes where the index value is less than zero (Figure 3), which is supported by the studies of Shukla & Wood (2008) and Niu et al. (2015). Furthermore, the correlation between SPI and SRI tends to be weaker at the shorter timescales (Figure 8). This is possibly due to the buffer behavior of land surface to the variability of precipitation, which results in a lower drought severity in hydrological drought compared with that of meteorological drought (Niu et al. 2015).

A distinct cycle of several years is detected for dry and wet periods in the PRB. Both SPI and SRI are dominated by significant cycles of shorter periodicity (0.5–7 years), with the main oscillation period of 0.75–1.8 years. Similar periodicities have been found in the West River basin by Fischer et al. (2013), who pointed out that the precipitation and runoff of the West River are dominated by significant cycles of shorter periodicity (2.8–7.3 years). In addition, Niu et al. (2014) indicated that the anomalies of monthly runoff and soil moisture in the PRB exhibit the variability properties at 49 timescales ranging from 2 months to 9 years during the period 1952–2000. Overall, the periodic oscillation pattern of SRI is similar to that of SPI, especially at the long-term timescale. Due to the strong correlation between the SPI and SRI, we conclude that periodic cycles in SPI are mainly responsible for periodic cycles in SRI in the study region.

A noticeable drying (wetting) trend is most commonly observed in the western regions and the downstream area of the PRB (eastern region), mainly due to the decreases (increases) in annual precipitation and runoff in most parts of the western (eastern) region (Figure 2). This result is generally in agreement with the findings of Zhang et al. (2009b) and Deng et al. (2018), which indicated higher risk

<table>
<thead>
<tr>
<th>Timescale</th>
<th>Extreme drought (%)</th>
<th>Severe drought (%)</th>
<th>Moderate drought (%)</th>
<th>Mild drought (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-month</td>
<td>2.04</td>
<td>4.16</td>
<td>8.97</td>
<td>35.65</td>
</tr>
<tr>
<td>3-month</td>
<td>2.41</td>
<td>4.31</td>
<td>8.47</td>
<td>34.28</td>
</tr>
<tr>
<td>6-month</td>
<td>2.80</td>
<td>4.02</td>
<td>8.11</td>
<td>33.81</td>
</tr>
<tr>
<td>12-month</td>
<td>2.89</td>
<td>4.34</td>
<td>8.21</td>
<td>32.96</td>
</tr>
</tbody>
</table>

Table 3 | Frequency (%) of hydrological drought (SRI) for the Pearl River basin during the period 1960–2012

Figure 8 | Spatial correlation between the SPI and SRI over the Pearl River basin at (a) 1-month scale, (b) 3-month scale, (c) 6-month scale, and (d) 12-month scale during the period 1960–2012.
of drought in the upper reaches of the PRB. However, Zhang et al. (2013) observed higher drought risk in the lower PRB and lower drought risk in the upper PRB, while Chen et al. (2016, 2017) indicated higher risk of drought in the southeast part of the PRB, especially in the Pearl River delta. These disparities can be explained by the differences in time duration of the data used, which highlights the uncertainty inherent in the assessment of drought. The results also indicated a large spatial heterogeneity in the frequency of meteorological and hydrological droughts over different timescales. Overall, extreme drought occurs more frequently in the 1960s, while moderate and severe droughts become more frequent in the recent decade (2000s).

It should be noted that the influences of basin characteristics (e.g., topography and slope) are overlooked in the assessment of drought evolution. The PRB is generally characterized as high in the west and low in the east (Figure 1). In this case, local topographic features can be an important factor to regulate the spatial and temporal processes of drought evolution. Niu et al. (2015) indicated that the hydrological drought severity is generally less than meteorological drought severity for the region with high elevation during the drought developing period, mainly due to lower temperature and limited soil moisture availability. On the other hand, human activities, such as drawdown of reservoirs, can also worsen hydrological droughts. Therefore, future research is needed to explore the underlying causes of hydrological drought in the PRB by considering the impacts of basin characteristics and human activities. Additionally, drought behaviors have possible teleconnections with climatic patterns, especially for the PRB which is located in the tropical and subtropical climate zones. Recent studies have highlighted the potential effects of global climate indices, such as the El Niño Southern Oscillation, North Atlantic Oscillation, Indian Ocean Dipole, and Pacific Decadal Oscillation, on the changing patterns of dryness/wetness and hydrological processes over the PRB (Cai et al. 2011; Niu et al. 2014; Xiao et al.)
A thorough investigation of the teleconnections between large-scale climatic patterns and drought behaviors at various timescales should be considered in future research.

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