Multiscale variability of China’s historical flood/drought index and precipitation teleconnections with ENSO using wavelet analyses

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Abstract
Studies of the low-frequency variabilities of key climate variables are often handicapped by the limited length of available instrumental observations. To tackle this, the use of a set of historical flood/drought index (FDI) spanning from AD 1470 to 2000 for 120 sites in China has been made to investigate the multiscale temporal variability of annual precipitation by applying wavelet methods. The analyses reveal oscillating components of the FDI time series from the decadal to multi-decadal, and to the quasi-centennial range, as well as in the interannual range. Furthermore, the relationships of the FDI with the dominant mode of oscillations in the coupled ocean–atmosphere system, i.e., the El Niño-Southern Oscillation (ENSO) index, on a range of time scales have been probed by cross wavelet transform and wavelet coherence methods. Statistically significant coherence between FDI and ENSO index time series has been found for regions in eastern China south of the Yangtze River (inclusive) at the decadal to multi-decadal time scale (10- to 50-yr) after 1750, as well as for north China on the 10- to 30-year range in the eighteenth century. The FDI is less coherent with the ENSO index for other regions of China. The results of the present study may add to our understanding of the connections between long-term changes of annual precipitation and large-scale oscillations in the coupled ocean–atmosphere system, and provide a scientific basis for developing policies to adapt to future changes in water abundance.

1 Introduction
Floods and droughts, which are among the most seriously damaging natural hazards, can be viewed as consequences of inhomogeneities in the temporal distribution of precipitation. Excessive precipitation in a short period can cause floods, which may result in enormous damages to lives and properties, while prolonged shortage of precipitation may result in drought. Both severe floods and drought can lead to reductions in crop yields. For China, where resides nearly a fifth of the world’s population, floods and droughts continue to pose major threats to lives and welfare of people, in spite of the great disaster defense measures undertaken (Ministry of Water Resources of the People’s Republic of China 2021).

Periodicities in time series of climate or meteorological variables are often sought after for implications of predictability. Periodicities in the precipitation time series for China, which has been frequently plagued with floods and droughts, have been identified on a wide range of time scales in a number of previous studies. Within the interannual scale, quasi-periodic oscillations in annual precipitation were found on a few time scales for many parts of China between 1951 and 2002 (Hartmann et al. 2008). Power spectrum analyses of time series of AD 1470–1999 dryness/wetness index revealed several energy peaks ranging from the bi-decadal to the quasi-centennial scales (Song 2000). Quasi-periodic wetness variations spanning between 10- to 130-year scales were found in the historical period of AD 960–1992 in six regions of east China (Jiang et al. 1997). Analyzing two sets of precipitation records for the time intervals AD 1880–2002 and AD 1951–2004, Ding et al. (2008) identified a dominating oscillation of roughly 80-year period, as well as minor modes of oscillations on the 12-year and 30- to 40-year scales. The near 80-year oscillation has also been reported by several studies of northern China precipitation (Hameed 1983; Zhu and Wang 2001; Qian et al. 2012).
Most of China’s territory is under the influence of the East Asian Monsoons, and precipitation variability in China is critically dependent on the strengths of the monsoon systems (Ding 1994). The strength of the monsoon is closely related to the thermal contrast between the land and the ocean (Ding et al. 2008). In particular, the strength of the monsoon has been found to be sensitive to the tropical Pacific sea surface temperatures (SSTs) variations. Weaker monsoon circulation and delayed monsoon onset are observed in association with warm SSTs in the equatorial central and eastern Pacific Ocean (El Niño) (Ju and Slingo 1995). Drought conditions in northern China and flood conditions in central China are linked to an El Niño-like SST anomaly distribution in the tropical Pacific (Weng et al. 1995). The hydroclimatic trends of northern and central eastern China in the second half of the twentieth century have been attributed to the trends of forcing by the tropical SSTs (Yang and Lau 2004).

The El Niño–Southern Oscillation (ENSO) phenomenon, defined by the anomalies in the tropical Pacific SSTs, is the primary mode of oscillations in the coupled global ocean–atmosphere system (McPhaden et al. 2006). ENSO has profound impacts on the climate of regions far beyond the tropical Pacific, affecting water abundance nearly worldwide (Kundzewicz et al. 2019) via a myriad of teleconnecting mechanisms in the global ocean–atmosphere system. While trends and variability of precipitable water in the atmosphere are dominantly affected by the evolution of ENSO (Trenberth et al. 2005), studies show a very complex picture of ENSO’s influence on hydroclimate, which depends on the time and location, as well as the hydrological statistics studied (Ward et al. 2014a, 2014b, 2016; Emerton et al. 2017).

For China, ENSO has been thought of as a key factor modulating the temporal variation of precipitation (Ding 1994; Ding et al. 2009), and thus an important factor related to occurrences of floods and droughts. The relationship between precipitation, or related hydrological variables, and the ENSO index has been extensively studied. By analyzing proxy records, Lu et al. (2019) identified an influence of ENSO as a cause of rapidly decreasing precipitation in northern China and anomalously increasing rainfall in southern China during the late Holocene. An analysis of δ18O of tree-ring cellulose in the north China Plain revealed close links of summer hydroclimate with ENSO since AD 1784 (Li et al. 2011). The response of East Asian monsoon rainfall to El Niño was found to be robust but variable since the second half of the last century (Wang et al. 2017). The picture is further complicated by the different impacts of the different regimes and phases of ENSO on precipitation regimes in China (Cao et al. 2017; Lv et al. 2019). There are, in addition, numerous studies on the relationship of individual flood/drought events with ENSO (e.g., Ma et al. 2018). The relationship of precipitation with ENSO is characterised with marked difference for different regions of China (cf. a recent review by Kundzewicz et al. 2020).

The relationship between precipitation and ENSO is not stationary over time. This is mirrored by the fact that the strength of the relationships of between ENSO and annual floods of major rivers around the world was not stationary over the period 1958–2000 (Ward et al. 2014a). An investigation of rainfall proxies in the eastern hemisphere for the last five centuries revealed a change in the teleconnecting relationship of rainfall with ENSO around 1750 (Whetton and Rutherfurd 1994). The relationship between ENSO and summer precipitation in China has weakened during the period 1951–2003 (Gao et al. 2006), and some theory was proposed to explain the decadal shift in El Niño influences on East Asian climate in the 1970s (e.g., Xie et al. 2010).

Many of the nationwide investigations in China are limited to time spans starting as early as the second half of the last century, due to the scarcity of systematic instrumental observations undertaken prior to ca. 1950. However, time series longer than a century are often required to study oscillations at multi-decadal scales. For the case of China, although the precipitation time series obtained by instrumental observations are sufficiently long to study the temporal variabilities in the interannual to bi-decadal range, it is handicapped to study the oscillations in the multi-decadal to quasi-centennial range due to the limited length of instrumental records.

By statistically analyzing an atlas of historical flood/drought index (FDI) in China spanning 531 years since AD 1470 and investigating their relationships with historical ENSO index time series, the present study aims: (a) to extend the analysis of precipitation variabilities to longer time scales (up to the quasi-centennial scale), which correspond to low-frequency oscillations, by using more than five centuries of historical records, and (b) to probe if there existed statistically significant relationship between the time series of annual precipitation and ENSO index and, if such relationship did exist, to investigate how the relationships of annual precipitation and ENSO evolved with time in a historical context. The regional differences of precipitation characteristics are considered by dividing the 120 stations in the atlas into several regions. The temporally oscillating features of the time series of both the FDI for each region and an ENSO index are studied using continuous wavelet transform, and then the relationship between each pair of the two time series is investigated using cross wavelet transform and wavelet coherence.

The data and methods used are described in Sections “2 Data” and “3 Method,” respectively. In Section “4 Results” the features of the time series are described and the time-varying relationships between the FDI and ENSO index time series on multiple time scales are investigated. Section “5 Concluding remarks” concludes with a discussion.
2 Data

The precipitation data set used in this study is based on an atlas of historical flood/drought index (FDI) spanning from AD 1470 to 1979, as the outcome of extensive efforts by climatologists who compiled the atlas from more than 2200 local chronicles into 120 regions (prefectures) across China (Chinese National Meteorological Administration 1981). By incorporating instrumental observations of the second half of the twentieth century (Zhang and Liu 1993; Zhang et al. 2003), the atlas has been further extended to 2000, constituting a coherent data set spanning 531 years long in total.

Historical documents are a unique source of information about the climate of the past, especially under the circumstances in which instrumental observations are not sufficient, or even absent, to infer variabilities of key climate variables. The use of documentary materials in historical climate studies was recently reviewed by Brázdil et al. (2018) and Nash et al. (2021). The historical FDI atlas used in the present study has been previously used in many studies. Song (2000) used this data set to study the dryness/wetness trends in many regions of China in the last five centuries. Spatio-temporal variations of the FDI were studied using rotated empirical orthogonal functions (REOF) analysis (Qian et al. 2003). The relationship between precipitation in the Yangtze River basin and ENSO was studied using a part of this atlas (Jiang et al. 2006). Historical droughts of a region in north China were analyzed using a subset of this data set (Qian et al. 2012). Flood and drought disasters increased in the period of 1500–2000 in southwest China, based on Ji et al. (2015) analysis of this data set.

In this data set, the levels of precipitation abundance are categorized into 5 grades: severe flood, moderate flood, normal, moderate drought, and severe drought, which are labeled with grades from 1 to 5, respectively (Table 1; Chinese National Meteorological Administration 1981; Zhang and Liu 1993; Zhang et al. 2003). In order to facilitate analysis, the 120 stations across China are divided, based on the types of regional climate, into 7 groups (regions) as shown in Fig. 1: northern part of north China (NN), north China (NC), middle and lower Yangtze River region (YR), south China (SC), southwest China (SW), northwest China (NW), and northeast China (NE). Flood/drought indices of the stations within each region are averaged to obtain one FDI time series representing the corresponding region (Fig. 2). An ENSO index time series of 1525–1982 (Fig. 3a) reconstructed from multiple proxies collected from several locations spanning a broad area of the Pacific basin is used (Braganza et al. 2009).

3 Method

Wavelet analysis has been extensively applied in time series analysis in the realm of geosciences thanks to its advantageous capability in identifying localized intermittent periodicities by analyzing the time series in time–frequency space. As bivariate extensions of univariate wavelet analysis, cross wavelet transform and wavelet coherence have been developed to study the relationship between two time series of speculated links.

3.1 Continuous wavelet transform (CWT)

The continuous wavelet transform (CWT) has been widely used to identify oscillatory features of time series in time–frequency space. The key idea of CWT is to find localized intermittent periodicities by convolving the time series with a wavelet, a function designed to suit specific applications. The Morlet wavelet (Morlet et al. 1982a, 1982b) is
Fig. 2  Historical flood/drought index (FDI) time series for the seven regions of China (see Fig. 1 for geographical division)

Fig. 3  a Multi-proxy reconstructed historical ENSO index time series (Braganza et al. 2009) and b the real part of the corresponding Morlet wavelet transform. Regions of greater than 95% confidence against the null hypothesis of a red-noise process are enclosed by the thick contour and regions possibly distorted by edge effect are masked with a lighter shade
used in the present study, as in many studies in geophysics. The Morlet wavelet function \( \psi_0 \) can be expressed as a function of dimensionless time \( \eta \) by (Eq. (1); e.g., Torrence and Compo 1998):

\[
\psi_0(\eta) = \pi^{-1/4} e^{i\omega_0 \eta} e^{-\frac{1}{2} \eta^2}
\]

(1)

in which the dimensionless frequency \( \omega_0 \) is chosen to be 6 to strike a balance between time and frequency localization, as is often done in many wavelet studies of climatic time series. For a time series \( X_n \) consisting of \( N \) observations taken at even time intervals \( \delta t \), its CWT on the wavelet scale \( s \) can be expressed as in Eq. (2):

\[
W_n^X(s) = \frac{1}{\sqrt{s}} \sum_{n'=0}^{N-1} x_{n'} \psi_0^* \left[ (n' - n) \frac{\delta t}{s} \right]
\]

(2)

where the asterisk (*) denotes the complex conjugate. The wavelet power is defined as \( |W_n^X(s)|^2 \), and the local phase can be found from the complex argument of \( W_n^X(s) \).

The distribution of the wavelet power normalized by the standard deviation of time series \( X_n \) with background power spectrum \( P_X^k \), is given by Eq. (3):

\[
\frac{|W_n^X(s)|^2}{\sigma_X^2} \Rightarrow \frac{1}{2} P_X^k \chi_2^2
\]

(3)

In this study, we are interested in identifying wavelet power being significant on the 5% level against a background spectrum of red noise.

### 3.2 Cross wavelet transform (XWT)

The cross wavelet transform (XWT) analysis is a statistical approach designed, by analyzing the CWTs of two time series with speculated links, to identify regions of high coherence, even in the absence of high common power in XWT. Following Torrence and Webster (1999), WTC is defined as in Eq. (5):

\[
R_n^2(s) = \frac{\langle (s^{-1} W_n^{XY}(s)) \rangle^2}{\langle (s^{-1} W_n^X(s)) \rangle \cdot \langle (s^{-1} W_n^Y(s)) \rangle}
\]

(5)

where \( \langle \cdot \rangle \) is a smoothing operator denoting smoothing in both time and scale. The smoothing is necessary because without such smoothing WTC would be identically 1, as pointed out by Liu (1994). The statistical significance level of WTC can be tested against null hypotheses by using Monte Carlo simulations (Torrence and Webster 1999; Grinsted et al. 2004).

In a time–frequency representation of wavelet analysis result, the regions subject to possible distorting effects of zero-padding at both ends of the time series are indicated by the cone of influence (COI), which is marked by an area with a lighter shade enclosed by a thick cone-shaped line in the plots. In a time–frequency diagram of the XWT or WTC analysis, the phase differences of the two time series are indicated by the direction of the arrows. The arrows point to the right when the two time series are in phase, and point to the left when they are out of phase. The arrows point straight down when \( X_n \) leads \( Y_n \) by a quarter period, while the arrows point straight up when \( Y_n \) leads \( X_n \) by a quarter period.

### 4 Results

#### 4.1 Multiscale variability of ENSO index

The real part of the Morlet wavelet transform of the reconstructed ENSO index time series from 1525 to 1982 (Braganza et al. 2009) in time–frequency space is shown in Fig. 3b. Rich time-varying features of oscillations at multiple time scales can be seen in this figure. Significant variabilities of the ENSO index were evident not only in the canonical
2- to 8-year range of ENSO variability (e.g., Torrence and Webster 1999), but also on longer time scales, spanning from the decadal to the quasi-centennial scales. A notable feature is that the major oscillations of the ENSO index were not stationary in frequency over time and were subject to amplitude and frequency modulations. Two trains of oscillations with an initial period of about 30 years, one starting from the 1540s, and the other starting near the beginning of the eighteenth century experienced decreases in period to about 16 years in about two centuries. The former (latter) merged and bifurcated with the oscillations in the decadal range in 1620–1670 and 1710–1760 (1780–1830 and 1850–1920). Such frequency modulation might originate from changes in some fundamental physical aspects of the coupled ocean–atmosphere system (Lau and Weng 1995).

Strong low-frequency oscillations on the 50- to 120-year scale in the second half of the sixteenth century bifurcated into two wave trains. The first train of waves are characterised with quasi-steady period of about 120 years, persisting to the end of the time series. The second wave train with slowly decreasing period merged with the aforementioned oscillations in the bi-decadal range in the 1930s.

### 4.2 Multiscale variability of the FDI time series

Figure 4 depicts the real part of the Morlet wavelet transform of the FDI time series for the 7 regions. In all studied regions, sporadic short time intervals of high variance appear in the interannual band. The high variance coincides with the band of vigorous ENSO variability, indicating ENSO’s direct impact on annual precipitation in China. On time scales longer than the decadal one, variabilities are concentrated on a few bands (with cycle length varying along with time). Furthermore, the time scales of the bands of high variance differ for each region, and this difference might originate from the different teleconnecting mechanisms for each of the regions.

#### 4.2.1 Northern part of north China (NN)

Wavelet power plot of the FDI time series for the northern part of north China (NN) is characterized with two distinct bands of oscillations (Fig. 4a), one in the decadal to bi-decadal range and the other in the multi-decadal range (20- to 50-year range). Both trains of oscillations were subject to amplitude and frequency modulations. Oscillations in the decadal to bi-decadal range were strong before 1750 and were punctuated after 1750, and reappeared since 1800. Strong oscillations in the 100- to 120-year range also existed prior to 1630. The trains of oscillations were interfered by abrupt shifts in wetness conditions, which are manifest as cone-shaped structures in the wavelet power plot (Lau and Weng 1995). For example, there was a cone-shaped region of high variability spanning a wide range from 8- to 128-year period centered at around 1640 (Fig. 4a). This represents the sudden transition of the NN region from the long-lasting drought of 1637–1641(one of the longest drought episode in China’s history) to a wet spell immediately thereafter (Domrös and Peng 1988; Shen et al. 2007; Qian et al. 2012). Two other abrupt changes with smaller magnitude of shift occurred around 1818 and 1874 (Fu and Zeng 2005), with the former transitioning from very dry to very wet, while the latter from very wet to very dry conditions.

Scattered intervals with high common power in the ENSO index and FDI time series in the interannual range (2- to 8-year period) can be seen in the cross wavelet power plot for the northern part of north China (Fig. 5a). A notable feature is that there were a few time intervals of several decades long with cross wavelet power significant on the 95% confidence level in the decadal to bi-decadal range, including the intervals of 1590–1660, 1720–1750, 1800–1830, and 1850–1880. High common power appeared also near the 30-year scale between 1880 and 1950, as well as on the range of 40 to 50 years between 1525 and 1750. High common power in the FDI and ENSO index time series near the centennial scale persisted from 1525 to the second half of the nineteenth century, but the 95% level of confidence was only exceeded near the 100-year scale between 1540 and 1650, which lies within the COI. We therefore cannot cast as much confidence in these regions as in those outside the COI.

The plot of the WTC shows several spells in which the two time series were coherent (Fig. 5b), and many of the coherent spells appeared in the interannual range for WTC between FDI for the NN region and the ENSO index time series. A prominent feature is that at the 10- to 30-year scale there was a long period (1700–1820) in which precipitation variability in the northern part of north China was coherent with that of ENSO. This spell of coherence was characterized by not only a high coherence value of greater than 0.8 and being significant on the 95% confidence level, but also the slowly varying phase difference between the two time series. This interrelation is corroborated by the high common power in the XWT plot (Fig. 5a). The directions of the arrows of the phase difference between the two time series lie between being right and being up, indicating that the FDI time series of the northern part of north China was just in phase with the ENSO index time series, or the former lead the latter by within a quarter period. This indicates that dry spells were connected with intervals of active El Niño events, or lead such intervals by no more than a quarter period, whereas wet spells were associated with intervals of active La Niña events, or lead such intervals by up to a quarter period.
4.2.2 North China (NC)

Long-lasting quasi-periodic oscillations are conspicuous in the wavelet power plot for north China in three bands (Fig. 4b): near the 30-year scale, near the 50-year scale, and in the 80- to 120-year range. The 30-year oscillations were significant on the 95% confidence level between 1550 and 1670, whereas the 50-year oscillations were evident only prior to 1720. The 80- to 120-year oscillations persisted the entire time series for north China, with period decreasing from 120 years in the 1500s to 80 years in the 1990s. This quasi-centennial periodicity is consistent with that found...
by an analysis of tree-ring width collected in the Southern Taihang Mountains in north China (Zhang et al. 2017). In addition, variability at the decadal scale was significant on the 95% confidence level during the spells of 1580–1640 and 1820–1850. There were several drastic shifts between extremely wet and extremely dry conditions between 1565 and 1650 (Fig. 2b), and these shifts were marked by high variability in the range of 10 to 30 years in the CWT plot (Fig. 4b). The flooding years of 1569–1570, 1593, 1613, and 1647–1648, and the drought events of 1585–1587, 1609, 1615–1617, and 1637–1641 (Domrós and Peng 1988; Shen et al. 2007; Qian et al. 2012; Yi et al. 2012), were enclosed in this period of high variability. Another region of high variability appeared between 1845 and 1890 near the 30-year scale, encompassing the 2-year long drought of 1877–1878, which was preceded and followed by moderately wet conditions.

There were sporadic short spells of significant common power in the interannual range between the FDI for north China and ENSO index time series (Fig. 6a), but only between 1630 and 1670 the cross wavelet power was significant on the 95% confidence level for a period of considerable length. In the decadal to bi-decadal range, there were intervals with significant common power in 1580–1650, 1720–1750, 1780–1800, 1820–1830, 1850–1880, 1890–1920, and 1960–1970. The presence of several periods of significant common power in the bi-decadal range suggests that the FDI is more closely correlated with ENSO at this time scale than in the interannual range. Between 1570 and 1650, there was also high common power in the 20- to 30-year range. High common power, but not significant on the 95% confidence level, persisted for one and a half centuries (1700–1850) in the 30-year range. High common power can also be found on the 40-year range between 1540 and 1620, and on the 60- to 120-year scale between 1525 and 1940, though the common power did not exceed the 95% confidence level and part of these periods were within the COI.

Among the intervals with significant common power as shown in the XWT plot (Fig. 6a) and discussed in the preceding paragraph, there were several lasting intervals of significant coherence (on the 95% confidence level) for different timescale ranges, including 1630–1670 in the 5- to 8-year range, 1690–1730 near the 16-year scale and 1730–1800 near the 20-year scale (Fig. 6b). Within each of the above-mentioned time intervals, the phase difference between the
two time series only varied slightly around being upper-right along with time. This suggests that the FDI series lead ENSO by about 45°. It is thus indicated that in general dry spells lead intervals of active El Niño events by about 1/8 period, whereas wet spells lead intervals of active La Niña events by about 1/8 period. In addition, the corresponding cross wavelet power was high during these intervals (Fig. 6a). Hence, it seems reasonable to state with some confidence that precipitation variability in north China was related to ENSO index on these specific time scales during the time intervals discussed. There also existed significant coherence between the two time series from 1540 to 1600 near the 30-year scale, but part of this coherent region was inside the COI, and the confidence was therefore discounted by the possible edge effects.

### 4.2.3 Middle and lower Yangtze River region (YR)

Periodic oscillations of the FDI time series for the middle and lower Yangtze River region were strong in the decadal to bi-decadal range prior to 1750, with significant bi-decadal variability between 1490 and 1540 (Fig. 4c). After 1750 such variability split into two bands: one near the bi-decadal scale and the other on the 40-year scale. And this is consistent with the finding that the dominant modes of inter-decadal precipitation variability in the middle and lower Yangtze River are 20- and 40-year oscillations based on analyses of precipitation records between 1880 and 2002 (Ding et al. 2008). 50-year oscillations were strong in the sixteenth and seventeenth centuries. Regions with clumped high variabilities in the CWT plot were generally associated with occurrences of extremely wet or dry conditions. The 1588–1589 extraordinary drought (Fig. 2c) (Domrös and Peng 1988; Shen et al. 2007) was evident as a sharp cone of high variability in the CWT plot (Fig. 4c). Another cone-shaped structure centered ca. 1640 across the range of 10 to 130 years was a manifest of the exceptional drought of 1640–1641 (Domrös and Peng 1988; Shen et al. 2007). High variabilities in the decadal range between 1820 and 1855 resulted from the extraordinary 1835 drought and 1849 flood in this region. Another interval of high variability in the decadal range was between 1950 and 1980, during which interval the 1954 flood, and 1966 and 1978 droughts took place.

The cross wavelet power between the FDI time series for the middle and lower Yangtze River region and ENSO index are characterized with sporadic short spells of significant common power in the 2- to 8-year range, many of which appeared after the 1780s (Fig. 7a). Significant common power exceeding the 95% confidence level was also found in the 10- to 14-year range between 1590 and 1620, and near the 10-year scale between 1715 and 1735. After 1750 there was high common power on the multi-decadal range (20 to 50 years), but it was not significant on the 95% confidence level. There was significant common power near the 50-year scale between 1550 and 1600, and near the 100-year scale between 1535 and 1635. However, these intervals were inside the COI, and thus the confidence was discounted.

The WTC plot of the two time series is characterized by intervals of high coherence in the interannual range, notably 1585–1610, 1625–1640, 1875–1895, as well as many short spells of significant coherence (Fig. 7b). The two time series were significantly coherent on the 10-yr scale between 1705 and 1725, and on the 20-year scale between 1685 and 1705. As a salient long-lasting feature, the coherence was significant on the 95% confidence level on the 30- to 50-year scale between 1790 and 1880. This significant coherence coincided with high wavelet power in both time series (Figs. 3b and 4c), as well as high common power between the two time series (Fig. 7a), suggesting that the FDI for the middle and lower Yangtze River region was closely related to the ENSO index during this time interval. The arrows of the phase difference pointed to the left inside the region of significant coherence, indicating that the two time series were out of phase. In other words, low FDI index was connected with high ENSO index, suggesting that floods were associated with El Niño events, whereas high FDI index...
was associated with low ENSO index, suggesting droughts were linked to La Niña events. This is in agreement with the finding of Jiang et al. (2006). Significant coherence also existed in the second half of the twentieth century on the 10- to 30-year scale, and the corresponding cross wavelet power was significantly high, but this interval was inside the COI, thus discounting the confidence. The coherence was not quite high near the 50-year scale between 1550 and 1600, nor near the 100-year scale between 1535 and 1635, indicating that it is likely that the significant common power of these intervals shown in the XWT analysis (Fig. 7a) occurred merely by chance.

4.2.4 South China (SC)

In the CWT plot for south China, the interannual range (2 to 8 years) was characterized by many short spells of high variability (Fig. 4d), some of which are significant on the 95% confidence level. Decadal oscillations were significant on the 95% confidence level in the intervals of 1480–1520 and 1760–1800. There was a train of oscillations with varying periods between 10 and 20 years, persisting the entire FDI time series. An abrupt shift at around 1580 was evident as a cone-shaped structure with its base extending to the 80-year range. Another train of multi-decadal oscillations began from the 1780s with a period of 40 years and gradually decreased the period to 30 years at the end of the time series.

Short periods of significant common power can be seen in the 2- to 8-year range in the XWT plot for south China (Fig. 8a). There was significant common power on the 12- to 16-year scale between 1580 and 1620, and on the 8- to 14-year scale between 1775 and 1795. Common power was high in the 20- to 40-year range since the 1780s, but was significant on the 95% level only after the 1930s, and thus much of the significant common power was inside the COI. In the low-frequency range (periods longer than 50 years), the XWT plot was characterized with high common power, but much of this high common power was inside the COI, and was not significant except the time segment prior to 1620 in the 50- to 80-year range.

WTC analysis shows that on the interannual scale, among many short spells of significant coherence, there was a relatively long interval with significant coherence between the FDI series for the SC region and the ENSO index in the 4- to 6-year range between 1745 and 1770 (Fig. 8b), whereas the corresponding common power between the two time series was only moderately high (Fig. 8a). Wavelet coherence between the two time series was in general higher on longer time scales. Distinctively long intervals with significantly high wavelet coherence were found on the 25- to 40-year scale between 1560 and 1630, on the 12- to 30-year scale between 1760 and 1820, and on the 30- to 40-year scale between 1830 and 1960. These three intervals were also characterised with high common power as revealed by the XWT analysis (Fig. 8a), indicating that the FDI fluctuated in connection with the ENSO index on the respective time scale. The arrows of phase difference within these regions of significant coherence point to the upper-left, suggesting that the FDI series lead ENSO by about 135°, or 3/8 period. This suggests that wet spells lagged intervals of active El Niño events by about 1/8 period, whereas dry spells lagged intervals of active La Niña events by about 1/8 period.

4.2.5 Southwest China (SW)

Despite that the FDI time series for southwest China only started in 1761 due to the lack of continuous documented records, interesting features, such as two trains of persisting oscillations, can still be found via CWT analysis of the FDI time series (Fig. 4e). One train of oscillations appeared within the decadal to bi-decadal range, being significant on the 95% confidence level between 1830 and 1870, while another occurred within the multi-decadal range of 30 to 70 years, being strong in the first half of the twentieth century. The two trains interfered with each other after the
1880s. Several abrupt changes of dry/wet conditions were also evident in the CWT plot, and these abrupt changes took place around the years 1778, 1816, 1832, 1899, and 1992 (Fig. 2e).

Sporadic short spells of significant common high power can be seen in the 2- to 8-year range in the XWT plot (Fig. 9a). There was significant common power in the 12- to 16-year range for 1850–1870, as well as in the 8- to 12-year range for 1895–1920. The significant common power in the 16- to 28-year range appeared between 1945 and 1960, and part of this time interval intruded into the COI. The coherence between the two time series was significant on the 12-year scale between 1845 and 1880, and on the 16- to 30-year scale for a long period of 1880–1970 (Fig. 9b). Such coherence was accompanied by high common power (Fig. 9a), suggesting that the FDI of southwest China was related to the ENSO index time series on the respective time scale. The arrows of phase difference within the regions of significant coherence point up in general, suggesting that the FDI series lead ENSO by about 90°, or a quarter period. This indicates that wet spells lagged intervals of active El Niño events by about a quarter period, whereas dry spells lagged intervals of active La Niña events by about a quarter period.

### 4.2.6 Northwest China (NW)

The most prominent feature of the CWT plot for northwest China FDI time series is that the greatest variability was near the 80-year range between the 1630s and the 1800s (Fig. 4f). The 80-year oscillations were significant on the 95% confidence level before 1800, and thereafter evolved with decreasing amplitude and increasing frequency. 30-year oscillations were strong during the intervals 1670–1750 and 1820–1950. The interval between 1620 and 1670 was characterized with strong variability in the decadal to bi-decadal range, and between 1670 and 1850 it was rich in variabilities in the interannual range. Decadal to bi-decadal variability revived from ca. 1870 and persisted until the 1970s, and interannual variability was sporadically strong during the twentieth century.

XWT reveals high common power near the decadal scale for the time intervals of 1730–1760, 1775–1800, and 1890–1920, and some short spells of high common power.
on time scales shorter than 10 years (Fig. 10a). High common power in the 60- to 100-year range persisted from the beginning of the FDI time series for northwest China (1612) until the 1870s, but was only significant on the 95% confidence level from 1612 to 1675, which was inside the COI.

Significant coherence was found on the 10-year scale during the intervals of 1650–1670, 1700–1720, 1890–1920, and 1955–1975 (Fig. 10b), and these four intervals were accompanied by significant common power as shown in the XWT plot (Fig. 10a). Another prominent feature is the significant 2- to 8-year coherence between 1775 and 1820, and again the relation between the two time series was corroborated by the significant common power revealed by XWT analysis (Fig. 10a). There was also significant coherence in the interannual range in the intervals of 1865–1885, and 1895–1910, but high common power was not found in these regions by the XWT analysis.

4.2.7 Northeast China (NE)

Strong 2- to 8-year scale variability in the FDI time series for northeast China can be found in the periods of 1480–1550 and 1600–1640, but such variability in the interannual range diminished after 1700 (Fig. 4g). Decadal variability in the 6- to 12-year range was significant on the 95% confidence level during 1580–1620 and 1670–1690. In the decadal to bi-decadal range, oscillations initiated in the 1500s and diminished in the 1830s, and during their evolution they were subject to interferences from both shorter and longer period oscillations. After the 1830s major oscillations were in the 28- to 30-year range, and were significant on the 95% confidence level between 1860 and 1935. In the multi-decadal range, 40- to 100-year oscillations were strong between 1490 and 1730 and, outside the COI, were significant on the 95% confidence level between 1615 and 1725 near 50-year period.

Scattered intervals with high common power in the interannual range (2- to 8-year period) can be seen in the XWT of ENSO and FDI time series for northeast China (Fig. 11a), and among these intervals, some were significant on the 95% confidence level. In the decadal to bi-decadal range, there were three spells of high common power: 1530–1680, 1710–1780, and 1830–1880. The common power in the 28- to 32-year range was significant on the 95% level from 1925 to 1955, but some latter portion of the interval was subject to possible interference by the edge effect. There was high common power in the range of 50- to 120-year from 1530 to 1650, though this was completely within the cone of influence. In the WTC, there was little region in which the coherence between ENSO and FDI time series was significant (Fig. 11b), suggesting that northeast China precipitation was least affected by ENSO among the 7 regions investigated in this study.

5 Concluding remarks

This paper, to our best knowledge, presents the first attempt to study the time-varying relationships of the oscillatory aspects between annual precipitation in China nationwide and ENSO in a historical context on multiple time scales. The long time period of the data set makes it possible to extend the analysis to multi-decadal and quasi-centennial scales, which have not been well studied previously. Although many studies showed that there exist robust relations of variabilities in precipitation for individual sites or selected regions of China and ENSO index, the present study shows, based on wavelet analyses of historical FDI and ENSO index time series, that the relationship is not spatially uniform and is time-varying.

Sustained time intervals with statistically significant coherence between FDI and ENSO index time series have been found for 6 out of the 7 regions investigated in this
study. For central and south China, including the middle and lower Yangtze River region, and the south and southwest China (YR, SC, and SW in the present study), statistically significant coherence was present on the decadec to multi-decadal range (10- to 50-year scales), and was strong after the 1750s (Table 2). FDI was out of phase with ENSO in the middle and lower Yangtze River region (YR), indicating above-average precipitation was associated with warm ENSO phase. This revealed correlation is consistent with that previously found by Zhang et al. (2007). However, the phases of the two time series differed by a quarter cycle for the upper Yangtze River region (included in the SW region), indicating regional dependence of phase difference. For north China including its northern part (NC and NN in the present study), coherence was found in the 10- to 30-year range in the eighteenth century (Figs. 5b and 6b). The coherence was stronger for the NN region than for NC, despite that NC is geographically closer to the tropical oceans of vigorous ENSO variability than is NN. The phase difference between ENSO and FDI fell within the range of 0–90°, suggesting that wet spells in north China tend to be more linked to La Niña than to El Niño. FDI for the NW region is significantly coherent with the ENSO index for an interval of about a half century long around 1800 on the 2- to 8-year scale, which coincides with the canonical interannual ENSO variability. Few long intervals of significant coherence have been found between FDI and ENSO index time series for the NE regions beyond the interannual time scale. This suggests that historically ENSO’s impact on the multi-decadal variability of precipitation was trivial for this region, which is very distant from the tropical oceans of core ENSO variability.

There have been several studies (e.g., Hameed et al. 1983; Jiang et al. 1997; Zhu and Wang 2001; Ding et al. 2008; Qian et al. 2012), showing that there existed near 80-year oscillations in FDI for a region approximately corresponding to the NN region in the present study. Even though the near 80-year oscillations failed to reach a statistical significance of 5% outside the COI in XWT and WTC analyses in the present study (Figs. 5a and b), persistent high common power and high coherence near the 80-year scale suggests that these FDI oscillations are likely to be correlated with the ENSO index to some extent on this time scale.

In the absence of a systematic network of instrumental observations, the use of documentary sources of historical climate variability elongates the available time series of climate variables into the pre-instrumental era and makes it possible to study the long-term oscillations. In addition, wavelet analysis methods for bivariate time series are applied, making time–frequency representation and analyses of the covariability of two time series possible. The time-dependent correlations of historical precipitation in China and ENSO index on multiple time scales cannot be revealed without these two practices.

The time series studied in this paper extend well before the commencement of the Industrial Revolution and the mass injection of greenhouse gases into the atmosphere. Thus, this study offers a potential perspective to investigate how annual precipitation in a mid-latitude region (China) responded to ENSO prior to the anthropogenic warming, and could provide a reference for studies on teleconnections of precipitation under the present and future warming (e.g., Cai et al. 2015; Yeh et al 2018).

There has been ample evidence that there exist multi-decadal oscillations of the global ocean–atmosphere system (e.g., Mann et al. 1995; Schlesinger and Ramankutty 1994). Such oscillations in the amount of annual precipitation have profound implications on the historical evolution and development of society in China (Fan 2015). In particular, the economic level was found to be significantly correlated with the amount of precipitation on time scales longer than 20 years in dynastic China (Wei et al. 2015). It seems therefore imperative to further investigate the varying characteristics of annual precipitation on multiple time scales, in connection with large-scale oscillations in the coupled ocean–atmosphere system.

Some aspects of precipitation in China have been found to be related to some other climate indices, such as the Pacific Decadal Oscillation (PDO) and the Atlantic Multidecadal Oscillation (AMO). These indices are speculated to cast their influence on precipitation either directly, or indirectly by modulating the ENSO-monsoon relationship (Turner and Wang 2017). It is a very interesting problem to investigate the relationships among precipitation in China, ENSO, PDO, and AMO in a historical context, but this task requires statistical tools for multivariate time series analysis, which is beyond the scope of this manuscript.

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### Table 2

Summary of intervals of significant coherence between ENSO and FDI series for the different regions of China (see Fig. 1 for geographical division)

| Region | Intervals of significant coherence | Bands of significant coherence | Phase difference* |
|--------|----------------------------------|------------------------------|-------------------|
| NN     | 1700–1820                        | 10- to 30-yr                 | 0°–90°            |
| NC     | 1630–1670                        | 5- to 8-yr                   | 30°–60°           |
| NC     | 1690–1730                        | 14- to 18-yr                 | 45°–90°           |
| NC     | 1730–1800                        | 18- to 24-yr                 | 45°–90°           |
| YR     | 1790–1880                        | 30- to 50-yr                 | Approx. 180°      |
| SC     | 1760–1820                        | 12- to 30-yr                 | 120°–150°         |
| SC     | 1830–1960                        | 30- to 40-yr                 | 120°–150°         |
| SW     | 1845–1880                        | 10- to 14-yr                 | 80°–90°           |
| SW     | 1880–1970                        | 16- to 30-yr                 | 80°–100°          |
| NW     | 1775–1820                        | 2- to 8-yr                   | Approx. 240°      |

*Phase difference is calculated by subtracting the phase angle of the FDI series from the phase angle of the ENSO series.
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Author contribution DW and WJ conceived and designed the study. DW and WJ collected the data. DW and SD performed the analyses. WJ contributed to the interpretation of the data and results, and substantively revised the manuscript. All authors discussed and contributed to the manuscript revision. All authors read and approved the final manuscript.

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Data availability The historical FDI atlas is freely available on the web site of China Meteorological Data Service Centre (http://data.cma.cn/). The ENSO proxy series is freely available on the web site of the National Centers for Environmental Information (NCEI) of the National Oceanic and Atmospheric Administration (NOAA) (https://www.ncei.noaa.gov/).

Code availability The code for continuous wavelet transform can be freely downloaded from https://github.com/chris-torrence/wavelets, and the code for cross wavelet transform and wavelet coherence analyses can be freely downloaded from http://grinsted.github.io/wavelet-coherence/.

Declarations

Conflict of interest The authors declare no competing interests.

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