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An Integrated Analysis of Dry-Wet Variability in Western China for the Last 4–5 Centuries

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ABSTRACT

The dry-wet variability in western China and its spatiotemporal structure during the last 4–5 centuries was examined using 24 climate proxies from sediments, ice cores, historical documents, and tree rings. Spatial patterns and temporal evolutions of dryness and wetness were not only extracted from the proxy data using rotated empirical orthogonal function (REOF) analysis for the last 4 centuries, but also for instrumental data in the last 40 years. The leading five REOF modes indicate that 5 dry-wet variation centers exist in western China. Moreover, long-term variability in dryness and wetness is seen on long (centennial) to short (inter-decadal) timescales. An out-of-phase relationship for the inter-decadal variation was observed between the Hetao-upper Yangtze River region and north Xinjiang, indicating influences on dry-wet variations of the East Asian summer monsoon and the westerly winds over the two regions, respectively. A particularly long dry spell was found in the central Tibetan Plateau in the 19th century. A predominance of wet decades in the last 4 centuries was found in the arid and Hetao regions. Three regional dry-wet series with annual resolution in north Xinjiang, the upper Yellow River valley, and the Hetao area were constructed for analyses of the last 500 years. Dry-wet oscillations with periodicities of 16, 50, and 150 years in north Xinjiang, 50 years in the upper Yellow River valley, and 70–80 years in the Hetao region were identified by wavelet analysis. In general, these periods correspond to large-scale oscillations found in the climate system, are mainly related to ocean-atmosphere interaction.

Key words: dry-wet variability, natural proxy, historical documents, western China

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1. Introduction

In recent years, a number of temperature reconstructions, on regional to global scales and ranging from several centuries to millennia, have been produced (e.g., IPCC, 2001, 2007; NARCC, 2007). Precipitation and dry-wet series, however, are in general of much less extent, usually within the last two centuries, due to limitations in observations and proxy records. Nevertheless, long-term dry-wet variability is of great concern for the public and governments because prolonged drought can cause severe famine and have negative impact on regional ecosystems, particularly over inland areas (Qian et al., 2007).

Western China is located in the interior of the Euro-Asian continent and includes the Tibetan Plateau, and the arid-semiarid and Xinjiang regions. Compared to eastern China, this area has less population and fewer historical documents. Our knowledge of climate variability over western China is still limited, largely due to the scarcity of instrumental records, in both the temporal and spatial perspectives: meteorological stations are sparse, and the majority were established in the late 1950s. A spatial analysis of precipitation in the last 50 years showed that increasing wetness has been found for the Tibetan Plateau and the Xinjiang region, while a dry trend has been noted in the semiarid region over western China (NARCC, 2007; Qian and Qin, 2008). Naturally, such short and sparse climate data limits our ability to examine current climate regimes in a long-term perspective, including identification of long-term trends or periodic-

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ities.

On the other hand, a wealth of climate information is recorded in historical documents spanning over several centuries or even thousands of years in eastern China. Historical climate proxies can also, to lesser extent, be found in the semiarid region of western China, while natural proxies, such as tree rings, ice cores, and lake sediments, can be found throughout this region. Useful information to assess past climate variability in China from historical documents include descriptions of severe drought, floods, severe cold, heavy snow storms, and unusually warm winters (Zhang, 1988). Natural proxies with high resolution are invaluable for extending the limited instrumental records back in time. Tree rings are of particular value since they provide exactly dated, annually resolved information about past climate conditions (Fritts, 1976; Cook and Kairiukstis, 1990).

Since the 1980s, large efforts have been made to reconstruct climate in western China using natural climate proxies, such as in the southeast Tibetan Plateau (Wu et al., 1988), the upper Yellow River valley (Li et al., 1996), and the Xinjiang region (Li et al., 1997). These reconstructions are useful to assess local climate variability. Regional integrated climate analysis based on tree-ring data began in the 1990s. Xu (1997) documented climate change in the arid and semiarid regions in western China during the last 500 years, excluding the Tibetan Plateau and Xinjiang. The first integrated analysis covering the north part of western China was documented by Wang et al. (2002), who used 13 series from natural proxies and 4 series from documents to reconstruct precipitation for the last 4 centuries with decadal resolution. Wang et al. (2004) documented dry-wet variations in the arid and semiarid regions, also for the last 4 centuries, by averaging 14 proxy series with decadal resolution. Consequently, to better understand regional wet-dry variability, it is of great necessity to integrate all available dry-wet series for the whole of western China.

In recent years, updated and reconstructed proxy series from many sites in western China have been published, dealing with local climate variability. This dataset of more and longer records covering western China is highly useful for an integrated analysis. In this paper, multiple proxies from natural measurements and document archives covering western China for up to 500 years are integrated to form three regional long-term climate series. Data and methods are described in section 2. Regional dry-wet variations with decadal resolution for the last four-centuries are extracted in section 3, and three regional dry-wet series with annual resolution for the last 500 years in western China are presented in section 4. Finally, discussion and conclusion are given in section 5.

2. Data and analysis methods

In this paper, three types of data sets were used to analyze dry-wet variations in western China. The first dataset is an annual precipitation record based on daily precipitation data from 726 stations from China for 1950–2000 derived from the Chinese National Meteorological Center. This daily dataset has been subjected to quality control (Feng et al., 2004). Here, only annual precipitation datasets from 117 stations in western China are used in the analysis.

The second dataset is based on various documentary records, mainly from diaries. In the summer monsoon region of eastern China, natural proxies are scarce, but a lot of historical records do exist. The Drought-Flood Atlas (Chinese Academy of Meteorology Science, 1981) contains the most well-known documentary information, through the dry-wet (drought-flood) index. The dry-wet index is expressed by five grades: anomalous wet (or flood) (grade 1), wet (grade 2), normal (grade 3), dry (grade 4), and anomalous dry (or drought) (grade 5). It is derived from more than 100 sites in eastern China. These dry-wet grades have been used to understand the long-term dry-wet variations in eastern China (Hu and Feng, 2001; Qian et al., 2003b). However, six of these sites are located in western China and are used in this paper, indicated in Fig. 1. In addition, two historical records are located in the Hexi Corridor (west Gansu Province) and Tangnaihai (Xu, 1997). Thus, eight documentary series are used in western China.

The third type of data comes from natural proxies, including sediment, ice core, and tree-ring records, with lengths spanning from 200 to more than 1000

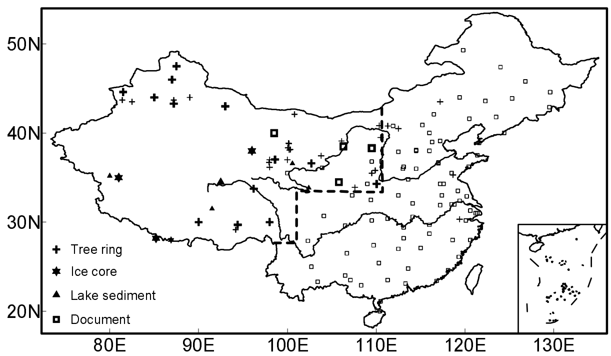


Fig. 1. Maps showing the sites of the original 132 proxies, including 5 sediment records, 4 ice-core records, 83 documentary records, and 40 tree-ring records. The larger ones of the symbols denote the 21 series used in the REOF analysis. The dashed line divides western and eastern China

Table 1. Selected dry-wet proxies in western China and sites in Fig. 1.

No.	Site	Lon (°E)	Lat (°N)	Type	Indicator	Time period	Resolution	Reference
1	Guliya	81	35	Ice core	Precipitation	1470–1990	Decade	Yao et al. (1994)
2	Dasuopu	85	25	Ice core	Precipitation	1600–1990	Decade	Yao et al. (2000)
3	Dunde	96	38	Ice core	Precipitation	1600–1980	Decade	Yao et al. (1991)
4	Goulucuo	92.5	34.6	Sediment	Dryness/wetness	900–1990	Decade	Li et al. (2004)
5	South Tibet	90	30	Tree ring	Precipitation	1620–1970	Decade	Wu (1992)
6	Linzhi	94.4	29.7	Tree ring	Precipitation	1650–1990	Annual	Liu et al. (2003)
7	Hengduan Mt	98	30	Tree ring	Precipitation	1590–1980	Decade	Wu (1992)
8	South Qinghai	96.2	33.8	Tree ring	Precipitation	1550–1990	Annual	Qin et al. (2003)
9	North Qinghai	98.6	37	Tree ring	Dryness/wetness	1170–1980	Decade	Wang and Zhou (2000)
10	East Qilian	102.7	36.6	Tree ring	Precipitation	1730–1996	Annual	Gou et al. (2001)
11	Altai Mt	87.5	47.5	Tree ring	Precipitation	1730–1970	Decade	Li et al. (1989)
12	North Xinjiang	87	46	Tree ring	Precipitation	1470–2002	Annual	Yuan and Han (1991)
13	West Xinjiang	81.5	44.6	Tree ring	Precipitation	1610–2000	Decade	Pan et al. (2005)
14	Mid-west Xinjiang	83	44	Tree ring	Precipitation	1630–2002	Annual	Yu et al. (2005)
15	Middle Xinjiang	87.2	43.3	Tree ring	Precipitation	1650–2001	Decade	Yuan et al. (2001)
16	East Xinjiang	93	43	Tree ring	Precipitation	1470–1970	Decade	Wang et al. (2004)
17	Huashan Mt	110.1	34.3	Tree ring	Precipitation	1600–1996	Annual	Hughes et al. (1994)
18	Hexi	98.5	40.0	document	Drought/flood	1700–1970	Decade	Xu (1997)
19	Tianshui	105.6	34.5	document	Drought/flood	1470–2005	Annual	Li et al. (2005)
20	Yinchuan	106.3	38.5	document	Drought/flood	1470–2005	Annual	Li et al. (2005)
21	Yulin	109.8	38.3	document	Drought/flood	1470–2005	Annual	Li et al. (2005)

years in China. These proxies have been published as indicators of precipitation, dryness/wetness, or drought/flood, with annual to decadal resolution, and with the longest reconstruction going back to 1170 AD. In Fig. 1, all natural proxy series, including 33 tree-ring records, 3 ice-core records, and 5 lake sediment records, all collected from western China are shown.

Of the 49 climate proxy series in western China, only 21 were selected for this analysis according to the following criteria. Firstly, series lengths should start before the 1730s and end after the 1970s. Secondly, the proxy series must denote spring-summer or annual dry-wet condition, since the variability in spring-summer dry-wet conditions is consistent with that of the annual. For example, the tree-ring series from east Qilian (No. 10 in Table 1) indicates spring (March–April) precipitation and the tree-ring series from middle-west Xinjiang (No. 14 in Table 1) represents the summer (July–August) precipitation. Both these tree-ring proxies agree well with observational departures of annual precipitation based on the climatology of recent decades. Thirdly, the spatial distribution of proxy sites should be uniform. For example, the sediment record of Goulucuo Lake (No. 4 in Table 1) was used because of the shortage of proxies in its surrounding area. This record might be less precisely dated than the tree ring or document records, but shows good consistency with the other proxies, such as the Dunde ice core and nearby tree-rings data, at decadal to centennial scales (Li et al., 2004). On the other hand, there are 8 proxy series from the Qilian Mountain region, but only 1 tree-ring series, 1 ice core, and 1 document record were selected after considering the series length and spatial-temporal resolutions. In the Hetao area, 15 proxies exist, but only 5 proxies were used in the analysis after considering their distribution. Finally, a uniform proxy data network was established using 21 proxies (Fig. 1 and Table 1).

To achieve consistency of the proxy series, some pretreatments were necessary. The time range of analysis was set to the last 4 centuries, from the 1600s to 1990s. Due to the different time resolution of the proxies (see Table 1), the common proxy data resolution was set at the decadal timescale. All proxy series were standardized, i.e., the mean values and standard deviations were calculated for the period 1780 to 1970, so that the resulting indices were dimensionless with a common variance. Missing values may occur in the proxy series, in early as well as in recent parts of the records. To fill in missing values at one particular site during early parts of the record, an interpolation approach considering the distance-weighted mean and the regression based on its surrounding site series was applied for a backward extension. Those proxy series ending before the 1970s were extended by observational precipitation data according to the methods of the original references.

Empirical orthogonal function (EOF) analysis was used to isolate the potential physical mechanisms associated with climate variability, such as for the recent 50 year observed precipitation record and the past 4 centuries of dry-wet series in the north part of western China from Wang et al. (2002). The leading EOF modes have large variances and are orthogonal with all other EOF modes. Dommenget and Latif (2002) indicated that caution should be taken when trying to interpret statistically derived EOF modes, as well as their significance. This means that in some cases, misleading physical modes other than the leading mode may be produced when applying such methods (Qian et al., 2003a). In order to seek modes which have properties such as a real physical basis and regional consistency, a rotated EOF (hereafter REOF) approach (Richman, 1986) is to be preferred, and it has previously been used in climate analysis (e.g., Vuille and Keimig, 2004). The time series of each REOF mode has high correlation with observational average series which are located in the central part of the REOF domain without correlation with the nearby REOF time series (Qian et al., 2004). In the following sections, REOF is used to analyze the instrumental precipitation records and the dry-wet proxies in western China, and to identify possible changes in the spatial patterns.

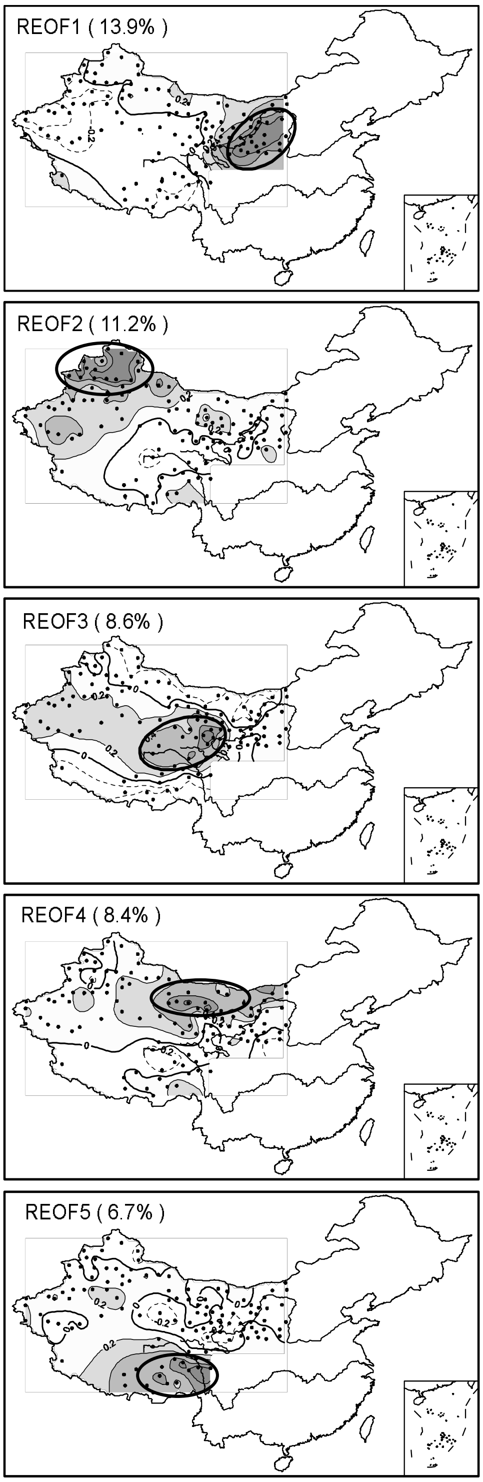
The wavelet analysis technique provides localized time and frequency information without requiring a time series to be stationary. It transforms a one-dimensional time series into a two dimensional function of time and frequency or timescale (Jiang et al., 1997). The wavelet transform method can be used to extract inter-decadal or centennial signals from the original series (Torrence and Compo, 1998). Furthermore, this technique can remove noise at all frequencies and isolate single events that have broad power spectra.

3. Spatial pattern and temporal variation

The long-term signals ranging from inter-decadal to centennial timescales can be derived from and compared among various series by using the wavelet analysis technique. However, this simple approach cannot identify a dry-wet regime that persists under long-term climate change. Since the REOF method is an efficient tool to analyze the spatial pattern and temporal evolution of climate variability, the REOF method was used to integrate and compare both observed precipitation and dry-wet proxies in western China in this study. The leading 5 modes and their time series from the REOF analysis of the precipitation data from 117 stations are shown in Fig. 2. The first mode is centered over the Hetao area with an explained variance of 13.9%. In this area, a drying trend can be noted in the corresponding time series. The second mode, with explained variance of 11.2%, indicates a moistening trend over north Xinjiang. Inter-decadal variation without a strong dry-wet trend is observed in the upper Yellow River valley (REOF3, 8.6% of variance explained). A wet trend is also noted in the arid area crossing between eastern Xinjiang and western Inner Mongolia (REOF4, 8.4% of variance explained). The fifth mode is centered over the southeastern Tibetan Plateau and shows a wet trend (REOF5, 6.7% of variance explained). Of the five leading modes, indication of a drying trend was only observed over the Hetao area, suggesting an increase in wetness over most of western China during the last 40 years.

In a similar REOF analysis of dry-wet variability in eastern China, the centers of the three leading modes were observed in the lower Yellow River valley, the lower Yangtze River valley, and in South China, but the center of the leading mode was not stationary over the last 5 centuries (Qian et al., 2003b). The same phenomenon was also evident (Fig. 3) when the results of the REOF analysis of decadally resolved dry-wet proxies was compared to that of the annual precipitation data in western China. When the proxies are analyzed, the leading mode is centered over the arid area with an explained variance of 14.9%. The second mode with an explained variance of 12.5% is located over the central plateau. The third mode, where 11.3% of the variance is explained, is centered over north Xinjiang. The fourth mode is located over the Hetao area (9.6% of the variance explained), and the fifth mode is centered over the upper Yellow River with 9.2% of the variance explained. Consequently, the areas of action centers of the leading five modes in western China are comparable between the two datasets, although they differ in order.

Long-term trends and centennial-scale oscillations can be identified from the decadally resolved series of the five leading REOF modes for the last 4 centuries in western China. In the arid area (REOF1) and north Xinjiang (REOF3), the last two decades are indicated as wet, a feature also noted by Shi et al. (2003) and analyzed in detail by Qian and Qin (2008). Wet trends are also seen in the REOF time series of observed precipitation in the same two areas shown in Fig. 2 for the last 20 years, and even the last 40 years. During the last 50 years, a drying trend is observed in the Hetao area (REOF4) and also found from the REOF series of the same regional precipitation during the period. In the upper Yellow River-Yangtze River basin, the driest decade during the last 50 years, 1990s (as indicated in REOF5), was also recorded in the REOF time series of precipitation observation. In the arid area, the REOF1 time series suggest that 5 consecutive decades with severely dry conditions occurred in the first half of the 17th century, while two long-term wet phases occurred from the late 18th century to the mid-19th century, and from the late 19th century to the early 20th century. A second dry period is observed from the 1930s to the 1970s major dry decade of the 1710s.



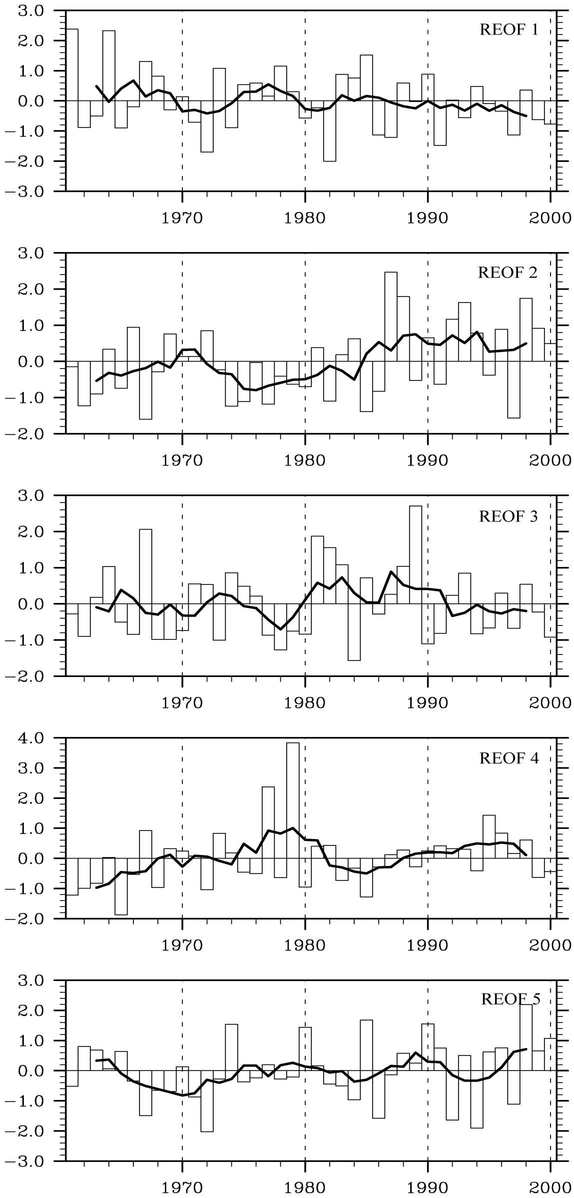


Fig. 2. The leading five REOF modes of annual precipitation (left panel) during 1961–2000 in western China and their corresponding time series (right panel). The black spots denote observational stations. Centers of REOF modes are indicated by shaded ovals (left panel), and the black line in the right panel denotes the 5-point running average of the time series. In the right panel, positive and negative values indicate the above and below normal precipitations, respectively.

with an exception of the wet 1950s. In the central plateau (REOF2), a long-term severe dry period from the 1780s to the 1890s is found in between two long-term wet periods. Significant inter-decadal dry-wet variability is evident in north Xinjiang, e.g., the very wet decade of the 1610s and the An out-of-phase relationship in the inter-decadal variation is clearly observed in the Hetao-upper Yangtze River region and the north Xinjiang region. This pattern may be influenced by the different effects of the East Asian summer monsoon flow and the westerly flow, respectively, as indicated in recent analyses of precipitation (Qian and Qin, 2008) and circulation (Qian et al., 2007) for the last 50 years. A similar phase relationship has also been observed, in a study of the Holocene moisture evolution, between arid central Asia and the Asian monsoon region (Chen et al., 2008).

4. Regional 500-year dry-wet series

Using a multiple-proxy approach, western China dry-wet variability for the last 400 years was inferred (section 3). Due to the lack of proxies with lengths of 500 years in western China, particularly over the southern plateau, REOF analysis could not been used to study the last 5 centuries. Data was used from three "cluster" areas: north Xinjiang, the upper Yellow River basin, and the Hetao area as shown in Fig. 4. In north Xinjiang, three tree-ring records of different lengths, 1470–2002 (No. 12 in Table 1); 1630–2002

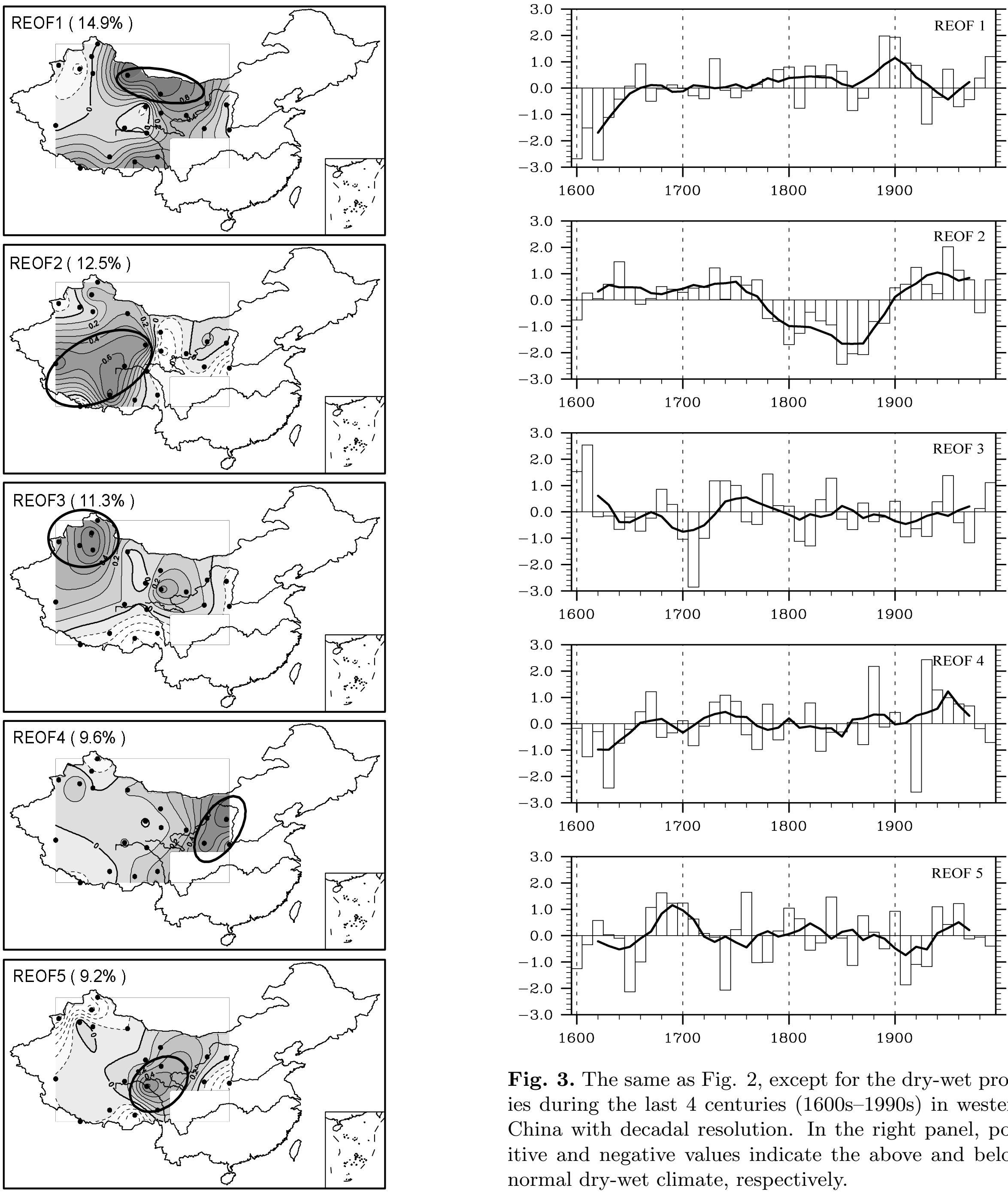


Fig. 3. The same as Fig. 2, except for the dry-wet proxies during the last 4 centuries (1600s–1990s) in western China with decadal resolution. In the right panel, positive and negative values indicate the above and below normal dry-wet climate, respectively.

Table 2. Three proxies with annual resolution in Fig. 1.

No.	Site	Lon	Lat	Type	Indicator	Time period	Resolution	Reference
1	Gimusaer	89°E	44°N	Tree ring	Precipitation	1840–1989 A.D.	Annual	Zhang (1998)
2	Dulan	98°E	36°N	Tree ring	Precipitation	324 B.C.–2000 A.D.	Annual	Zhang et al. (2003)
3	Qilian Mt.	100°E	38°N	Tree ring	Precipitation	1752–2000 A.D.	Annual	Yang et al. (2005)

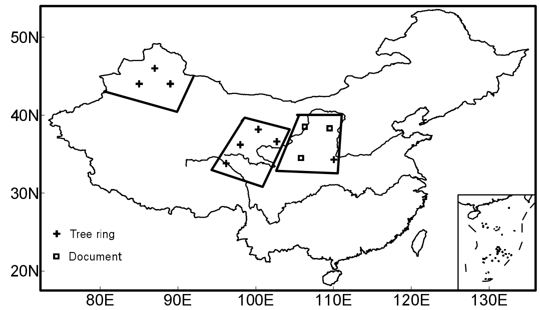


Fig. 4. Three cluster areas of 11 sites with annually resolved proxy records used in the analyses of dry-wet variations for the last 500 years.

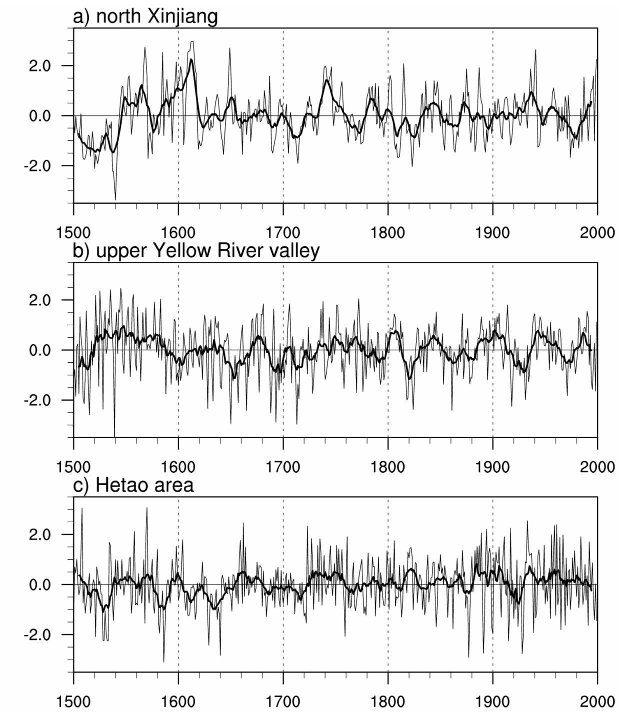


Fig. 5. Integrated regional dry-wet series averaged from those sites in the three typical areas (Fig. 4) of (a) north Xinjiang, (b) the upper Yellow River valley, and (c) the Hetao area. The heavy black lines indicate the 11-point running average.

(No. 14 in Table 1); and 1840–1989 (No. 1 in Table 2), were averaged to form an annually resolved series. In the upper Yellow River basin, four tree-ring records spanning 1550–1990 (No. 8 in Table 1), 1730–1996 (No. 10 in Table 1), 324 B.C.–2000 A.D (No. 2 in Table 2), and 1752–2000 (No. 3 in Table 2) were combined. In the Hetao area, three historical document series and one tree ring series of different lengths, 1470–2005 (No. 19 in Table 1), 1470–2005 (No. 20 in Table 1), 1470–2005 (No. 21 in Table 1), and 1600–1996 (No. 17 in Table 1) were averaged.

The resulting three regionally averaged series with annual resolution (Fig. 5) were used to detect if regular oscillations between dry-wet periods exist. From the wavelet power spectrum (Fig. 6), noticeable centennial and inter-decadal variability in the dry-wet signals in each of the three areas is observed. In north Xinjiang, three periods stand out: periods of about 16, 50, and 150 years are evident, where the 16- and 150-year oscillations are highly significant (0.01 level). Two peaks in the power spectrum at 50 and 150 years were observed in the upper Yellow River basin, but only the 50-year oscillation reached the 0.01 significance level. In the Hetao area, a periodicity of 70–80 years was found, although not statistically significant. However, this oscillation with a periodicity of about 70–80 years has previously been revealed in studies of long-term historical records in eastern China (Hu and Feng, 2001; Zhu and Wang, 2001).

5. Conclusions and discussion

This study documented the dry-wet fluctuations in western China for the last 500 years using multiple proxy records, and dry-wet variations on various timescales were analyzed by wavelet analysis. The analysis results, highlighted as follows, can help to increase our understanding of the observed climate variability in China in a longer temporal context.

5.1 *Five independent modes*

Five independent modes of dry-wet variability were derived from REOF analyses of instrumental precipitation and proxies in western China: the arid area, the central plateau, north Xinjiang, the Hetao area, and the upper Yellow River-Yangtze River. Although the leading modes differ between observed and proxy data in their order, there is a general agreement of the location of the action centers, suggesting that the proxy data are useful dry-wet indicators back through time.

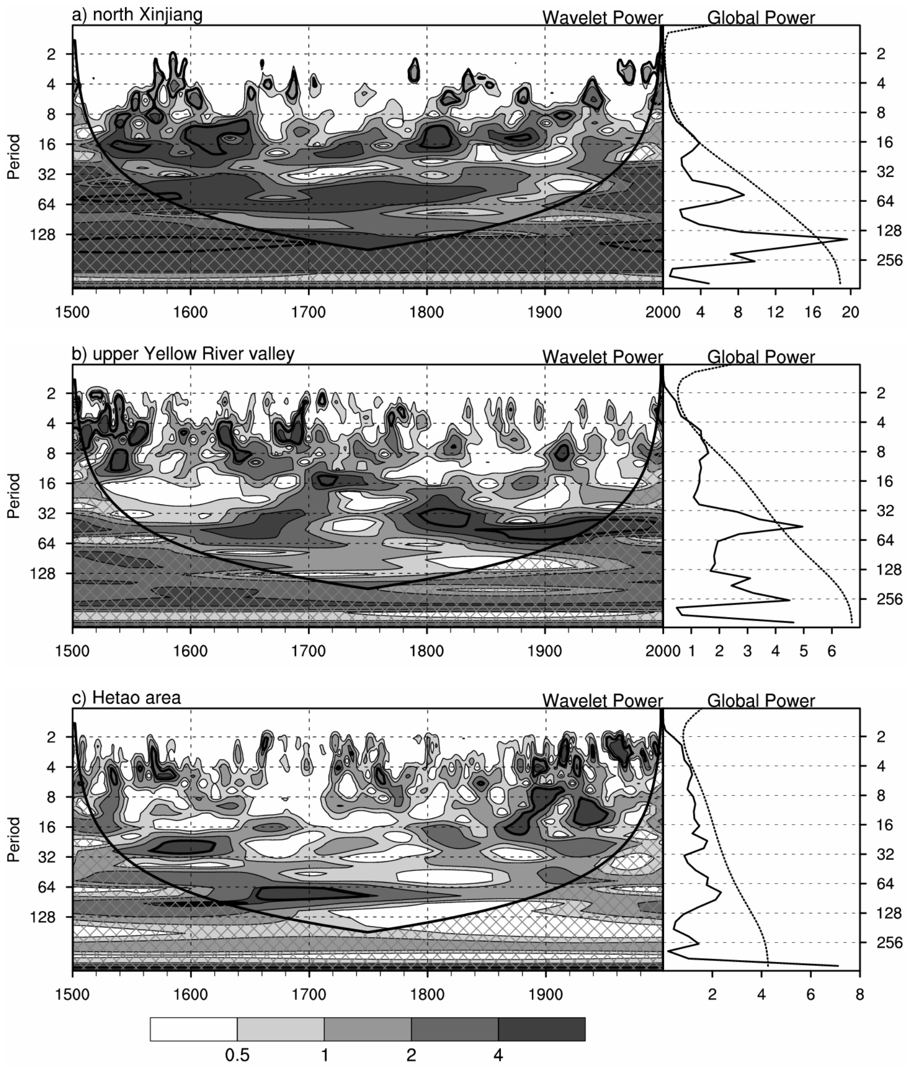


Fig. 6. The wavelet power spectrum of annual composite series for (a) north Xinjiang, (b) the upper Yellow River valley, and (c) the Hetao area, corresponding to the series in Fig. 5. In the left panel, the left axis is the Fourier period (yr), and the bottom axis is time (yr). The shaded contours are at normalized variances of 0.5, 1, 2, and 4. The thick line encloses regions of greater than 95% confidence for a red-noise process with a lag-1 coefficient of 0.72. Cross-hatched regions on either end indicate the "cone of influence", where edge effects become important. In the right panel, the thick line is the global wavelet power spectrum and the dashed line shows its significance level at 0.01.

Long-term dry spells were found in the central plateau in the 19th century. A predominance of wet decades in the last 4 centuries is indicated in the arid area and the Hetao area. Inter-decadal oscillations were obvious in the upper Yellow River-Yangtze River valley and north Xinjiang. An out-of-phase relationship for the inter-decadal variation was observed in the Hetao-upper Yangtze River region and North Xinjiang, indicating the different effects of the East Asian summer monsoon flow and the westerly flow, respectively (Qian et al., 2007).

5.2 *Interdecadal oscillations*

The annually resolved dry-wet proxies for the last 500 years were categorized into 3 groups centered on north Xinjiang, the upper Yellow River basin, and the Hetao area. Dry-wet oscillations with timescales of 16, 50, and 150 years were found in north Xinjiang, while a 50-year oscillation was observed in the upper Yellow River basin, including the area of the Qilian Mountains. A 70–80-year oscillation was identified in the arid-semiarid region (Hetao area). The quasi-16-year periodicity found in north Xinjiang may be linked to the 18.6-year soli-lunar tide, which has been related to precipitation variability over the Northern Hemisphere (e.g., Mitra et al., 1991; Currie and O'Brien, 1992; Linderholm, 2001). In particular, Currie (1995) found the cycle with a period of 18.6 years in Chinese dryness-wetness indices. A 50-year periodicity in drought-flood characteristics in China has previously been found by Lin et al. (1996), and an oscillation in the climate system of 40–50 years has been related to the irregular oscillations of the thermohaline circulation in the North Atlantic (Greatbatch and Zhang, 1995). Moreover, the 70–80 year cycle in the Hetao region corresponds to the oscillation in the global climate system of around 60–80 years, interpreted as an internal oscillation in the atmosphere-ocean system (e.g., Schlesinger and Ramankutty, 1994).

5.3 *Dry-wet decades*

During the twentieth century, a dry climate in the 1920s occurred in the arid-Hetao areas and the upper Yellow River basin (Deng, 1937; Qian et al., 2007), while wet condition prevailed from north Xinjiang to the central and southeast plateau. During the 1940s and the 1950s, a wet climate was observed in many places in western China except for the southeast plateau. The dry climate reappeared in the 1960s and 1970s in the regions of north Xinjiang, the upper Yellow River, and the southeast plateau. These dry or wet decades can be found from the individual series used in this paper. The last transition from dry to wet conditions in Xinjiang was in 1980s (Shi et al., 2003).

Although the climate proxies were evaluated and some interesting results were integrated, attention should be paid to some uncertainties. For example, the secular centennial variability of dryness-wetness on the plateau may possibly be due to the ice core and lake sediment data with resolution lower than that of tree ring records. Also, the relative difference in lengths of the tree-ring data series, in addition to decreasing numbers of trees back in time in each series, likely has an effect on the variability and uncertainty of these records. The uneven spatial distribution of proxies also affects the true representation of dry-wet variability in western China. Proxy records with long temporal coverage and high resolution are still scarce in these regions. By using natural proxies in western China and document records in eastern China, an integrated analysis of dry-wet variability for the whole country should be attempted, to achieve more comprehensive insight at a larger scale.

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