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Tree-ring recorded moisture variations over the past millennium in the Hexi Corridor, northwest China

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Abstract Knowledge of the moisture variation is essential for water resources management and policy making, especially for the arid regions, where the water resources can hardly meet the demand of the human being and the ecosystem. Hexi Corridor in northwest China is in a typical arid area with little precipitation and high evaporation. A lot of tree-ring studies were conducted in this area; however, no long-term and large-scale moisture history research had been conducted in this region until now, due to the lack of long-time tree-ring records in eastern and western Qilian Mountains. Here, we synthesized the moisture evolution of nearly one millennium (AD 1161–2006) in this region by using four published moisture-sensitive tree-ring records, including two recently published millennium reconstructions in eastern and western Hexi Corridor. The comparisons of tree-ring records from the eastern, central and western part of Qilian Mountains show that all the reconstructions are statistically similar to each other. The principal component analysis was applied to extract the common signal recorded by these series. The first principal component (PC1), which expressed 61.1% of the total variance, was used as an indicator of regional moisture variations. The PC1 suggests that the Hexi Corridor has alternated between contrasting climatic conditions, with dry periods at AD1161–1216, 1260–1349, 1409–1417, 1443–1510, 1617–1737, 1759–1838 and 1929–1948, wet periods at AD1217–1259, 1350–1408, 1418–1442, 1511–1616, 1738–1758, 1839–1928 and 1949–2006. The droughts and pluvial periods identified in the Hexi Corridor are generally consistent with those in nearby regions recorded by tree-ring and other proxies. We also find that droughts periods in the Hexi Corridor trend to coincide with the solar minimum, highlighting the importance of solar variability on forcing regional moisture variability.

Keywords Tree-ring · Moisture variation · Hexi Corridor

Introduction

Water is possibly the most precious natural resource, especially for arid to semiarid regions, where the quantity and quality of water are often essential to local socioeconomic development as well as ecosystem health and sustainability (Gleick 2010). The Hexi Corridor, a crucial segment of the Silk Road and one of the key regions during the great development of Western China, is dominated by a semiarid to arid climate and very vulnerable to climate changes. This region contains a string of fertile oases; however, persistently increasing water demand with population growth and economic development has caused overuse of water resources and environmental degradation in these areas (Chen and Hao 2005). Thus, knowledge about the water resource variation for these oases is essential for making responsible policies that can balance

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the socioeconomic development and environmental sustainability. These oases are fed by continental rivers originating from the Qilian Mountains. Therefore, fluctuations in climate and, most of all, changes in hydroclimate in the source region are of special significance, since they play an important role in maintaining surface streamflow formed in the mountains. Documenting and better understanding how climate has varied in the Qilian Mountains will enhance our ability to adapt to possible future climate change. However, the climate data recorded by weather stations are scarce in the mountainous area and generally limited in length and thus may not faithfully represent the full range of spatial and regional climate variation. To better understand the course of climatic variability in the pre-instrument period, a wide variety of archives, both natural (ice and sediment cores, tree-rings, corals for example) and documentary, can be used (e.g., Gates et al. 2008; Yang et al. 2014; Zhang et al. 2008). Information obtained from these paleoclimate proxy data is valuable. Among them, the annually resolved tree-ring data play a unique value in understanding the climate history of the last millennium.

The tree-ring studies in the Hexi Corridor are mostly in the Qilian Mountains. Qilian Mountains is one of the regions where tree-ring research in China started. In the recent two decades, tree-ring-based studies in this region have been greatly successful. In the eastern Qilian Mountains, several reconstructions have been conducted; for example, Gao et al. (2015) reconstructed the temperature variation, Chen et al. (2011, 2016), Gou et al. (2001) and Hou et al. (2011) reconstructed the precipitation variation, Deng et al. (2013) and Gou et al. (2015a) reconstructed drought variation. Among them, Gou et al. (2015a)'s drought reconstruction has extended to more than 1000 years. The middle part of the Qilian Mountains is one of the most researched regions in the tree-ring domain in China, and many long-term tree-ring chronologies have been developed in this region. Using tree-ring data, several studies have reconstructed the variation of streamflow for the Heihe River (e.g., Liu et al. 2010; Qin et al. 2010; Yang et al. 2011b), and temperature (e.g., Liu et al. 2005; Zhang et al. 2014) and precipitation (e.g., Sun and Liu 2012; Zhang et al. 2011) variation. Beside the tree-ring width, the carbon and oxygen isotopes have also been applied in the dendroclimate studies in this area (e.g., Liu et al. 2005). In the western Qilian Mountains, Tian et al. (2007), Liang et al. (2009), Liu et al. (2009a), Yang et al. (2011a) and Gou et al. (2015b) have reconstructed the drought and precipitation variation. Outside the Qilian Mountains, several studies have also been conducted in the Hexi Corridor. For example, Liu et al. (2010) reconstructed the groundwater level at the lower reach of the Heihe River. However, all these dendroclimate studies are site or region

based, and no long-term research for the whole Hexi Corridor has been conducted yet.

To explore the drought variability of the Hexi Corridor during the last millennium and its possible forcing mechanism, in this study, we collected four moisture-sensitive tree-ring records from the eastern to western Qilian Mountains and used their PC1 to represent the regional drought variation for the Hexi Corridor. Possible influence of solar activity on regional drought variation is also discussed.

Materials and methods

Study area

The Hexi Corridor lies in the northwest of the Gansu Province and to the west of the Yellow River in China (Fig. 1). It is a narrow natural land passage, bound by the South Mountains (including Qilian Mountains and Aerjin Mountains) from the South and the North Mountains (including Longshou Mountains, Heli Mountains and Mazong Mountains) from the north, stretching some 1000 km from Wushaolin Mountain to the Yumen Pass. The Badain Jaran Desert and the Tengger Desert lie to its northeast. The study area has an arid continental climate. According to the data obtained from the Climatic Research Unit (CRU) of the University of East Anglia (CRU TS v. 3.22; Harris et al. 2014; available at http://www.cru.uea.ac.uk/cru/data/hrg/), average annual temperature of Hexi Corridor ranges from −12.2 to 10.0 °C, and annual precipitation ranges from 15 to 375 mm (Fig. 2). The temperature has a tendency of decreasing from the northeast to the southwest, corresponding to the increase in elevation. The annual precipitation also shows an obvious spatial pattern, and it should be related to the distance to the ocean. The Hexi Corridor includes three river systems, namely the Shiyang, the Heihe and the Shule Rivers from southeast to northwest, all of them originating from the Qilian Mountains. The water resources of all three rivers are over-utilized, according to internationally recognized alarm line (Chen and Hao 2005).

Tree-ring data

To represent the moisture variation of the Hexi Corridor in the past millennium, we collected four drought, streamflow and precipitation reconstructions from the eastern to the western Qilian Mountains (Gou et al. 2015a, b; Qin et al. 2010; Zhang et al. 2011) (Fig. 1). Among them, the millennium standardized precipitation–evapotranspiration index (SPEI) reconstruction in the eastern Qilian Mountains was based on two tree-ring chronologies sampled in the Langya valley (LYG) (Gou et al. 2015a); the millennium Heihe River streamflow reconstruction was made

Fig. 1 Map of the study area showing the location of the four moisture reconstructions (*red dots*). LYG, HH, HYG and WFQ denote moisture-related reconstructions at Langya valley (Gou et al. 2015a), Heihe River (Qin et al. 2010), Haiya valley (Zhang et al. 2011) and Qifeng conservation station (Gou et al. 2015b), respectively
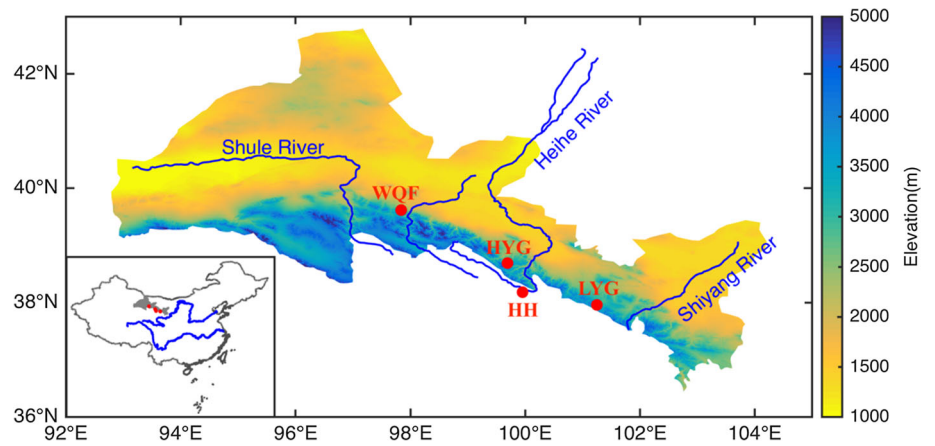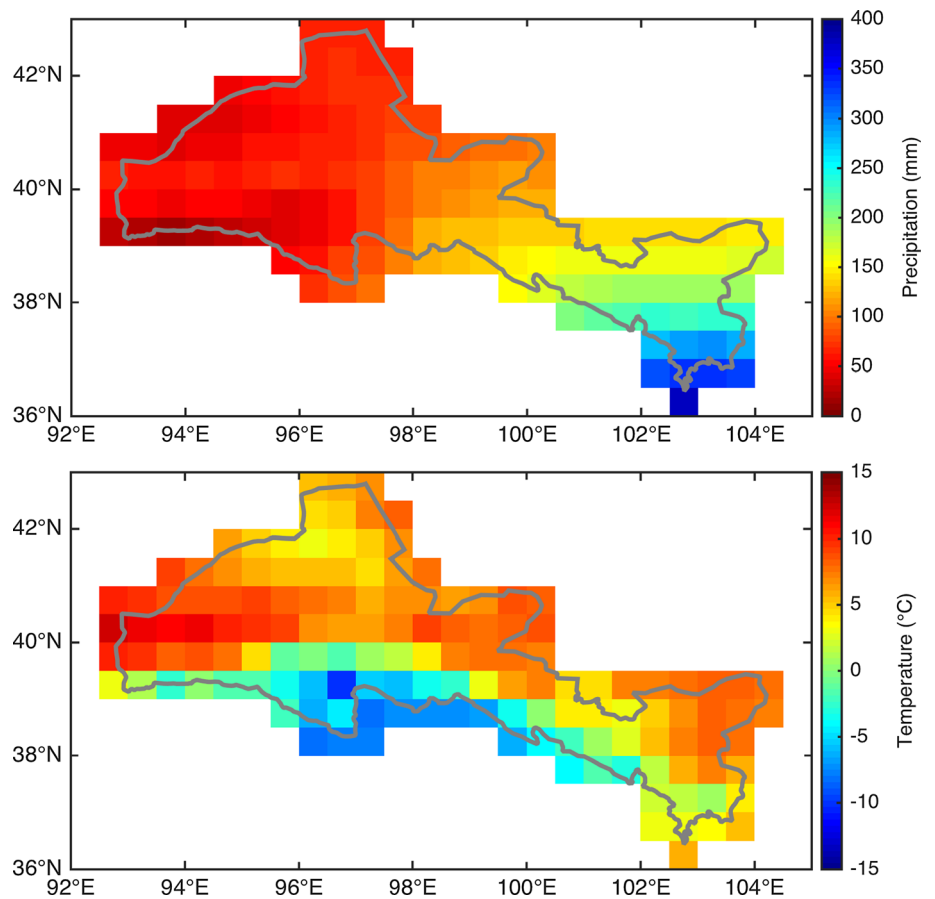
Fig. 2 Annual total precipitation (*upper*) and mean temperature (*lower*) of the Hexi Corridor

available by using three tree-ring chronologies in the middle Qilian Mountains (HH) (Qin et al. 2010); the precipitation in the middle Qilian Mountains over the past 1232 years was reconstructed by using the tree-ring data originating from Haiya valley (HYG) (Zhang et al. 2011); and the 850-year reconstruction of May–July self-calibrating Palmer drought severity index (scPDSI) in the western Qilian Mountains was based on two nearly millennia long ring-width chronologies sampled in Qifeng conservation station (WFQ) (Gou et al. 2015b). All the reconstructions are based on Qilian juniper (*Juniperus przewalskii* Kom.) tree-ring width chronologies. During the development of each chronology, all or most of the tree-ring records were detrended by using the conservative curves, such as the negative exponential function or linear regression function. All the tree-ring indices were calculated as ratios between the raw measurements and fitted values, except the chronologies used in the Heihe River streamflow reconstruction, which were calculated by using the residuals between them. Detrended tree-ring indices

were averaged to generate chronologies based on robust mean methodology (Cook and Kairiukstis 1990).

Climate data

Because all these tree-ring chronologies are sensitive to moisture variation, only the standardized precipitation evapotranspiration index (SPEI; Vicente-Serrano et al. 2010), a multi-scalar drought index, was used in this study. The SPEI measures the dryness (or wetness) based on both precipitation and evapotranspiration, and its timescale is defined so that an n-month scale considers the accumulated climatic water balance (difference between precipitation and evapotranspiration) of the current month and n-1 previous months. For example, to obtain the 6-month SPEI, the climatic water balances from five months before to the current month were considered. The SPEI has been widely used as a drought index in the past several years (e.g., Vicente-Serrano et al. 2013; Hernandez and Uddameri 2014; Gou et al. 2015a). The SPEI data used in this study were obtained from the SPEIbase version 2.3 (Beguería et al. 2010; available at http://sac.csic.es/spei/database.html), which has a spatial resolution of $0.5° \times 0.5°$ in longitude and latitude and covers the period 1901–2013. To explore the impact of drought on regional trees' growth, the SPEI at 1-, 3-, 6-, 9- and 12-month scale were used in this study.

Methods

The visual comparison and correlation analysis were employed to test whether similar information had been recorded by these tree-ring chronologies. To extract the common signals in the four moisture reconstructions, we applied the principal components analysis (PCA) and used the first principal component (PC1) to represent regional moisture variation. To explore the season and timescale of drought signals embedded in the PC1, the correlation coefficients between the PC1 and SPEI of different timescales at different month and season from April to August are computed. The PC1 is considered to denote the one that having both the largest number of positively correlated SPEI grids in Hexi Corridor and the largest mean of those significant correlations. A low-pass filter with a cutoff frequency of 0.02 cycles/year was used to highlight regional moisture variability at low frequency (Mann 2008).

Results and discussion

Figure 3 shows the four moisture-related reconstructions in the Hexi Corridor, while Table 1 presents the correlation coefficients among them. The reconstructions show some
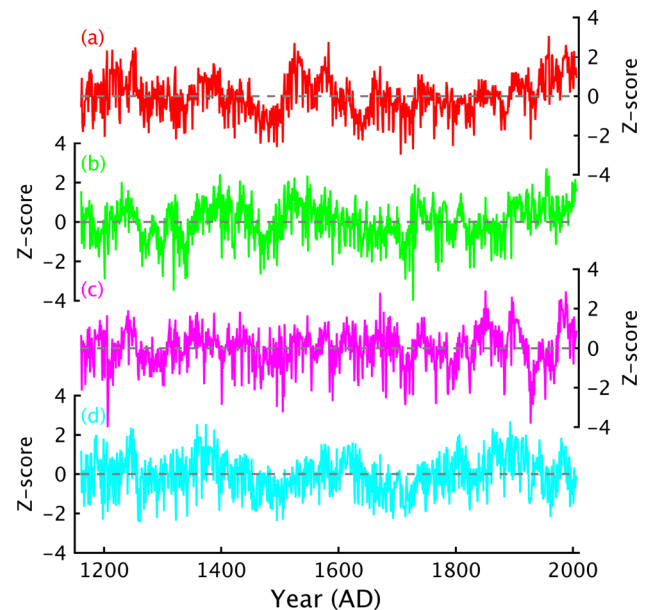

Fig. 3 Comparison between the four moisture reconstructions in the Hexi Corridor. **a** LYG (Gou et al. 2015a); **b** HH (Qin et al. 2010); **c** HYG (Zhang et al. 2011); **d** WFQ (Gou et al. 2015b). All series are standardized to their common period (AD 1161–2006)

Table 1 Correlation coefficients between four moisture reconstructions in Hexi Corridor during their common period (AD 1161–2006)

ID	LYG	HH	HYG	WQF
LYG	1			
HH	0.620	1		
HYG	0.514	0.473	1	
WQF	0.388	0.328	0.547	1

All correlations are significant at the 0.01 level

degree of consistency over their common period, as correlation coefficients among the four reconstructions are all significant and positive (Table 1). However, obvious differences also exist, especially at the low frequency. For example, during the last two centuries, there was a dramatic increasing trend in the tree-ring series labeled with LYG and HH, which was not recorded by HYG and WFQ. This indicates that a single local reconstruction cannot represent regional moisture variation, highlighting the importance of using records from different regions to denote it. Therefore, the PC1 of the four reconstructions (Fig. 4), which explained 61.1% of the total variance, is used to represent the moisture variation in the Hexi Corridor.

The summary of the correlation result between PC1 and SPEI in Hexi Corridor is shown in Fig. 5. The PC1 is well correlated (with more than half of the grids statistically significant) with June SPEI in Hexi Corridor, for all timescales except the 12-month. For May, the PC1 is only well correlated with the short timescale (1- and 3-month) SPEI.
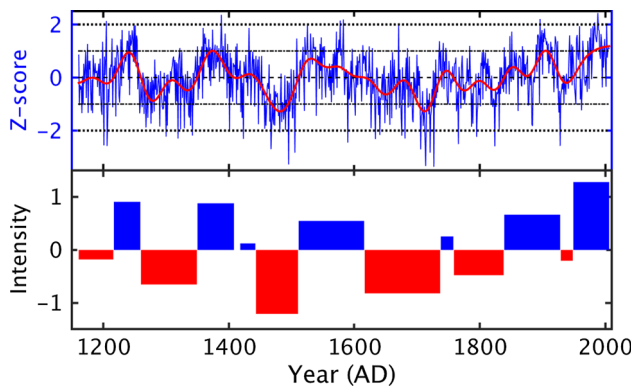
Fig. 4 Standardized PC1 and the 50-year low-pass filtered curve (*upper*), and the intensity, duration and magnitude of the droughts and pluvial identified in the smoothed series (*lower*). The *dashed line* is the long-term average, the years out of the range of *dash-dot lines* are dry or wet years, and that out of the range of *dotted lines* are extreme dry or wet years. The duration of drought (pluvial) is the number of consecutive years when smoothed series lower (higher) than long-term mean. The magnitude is the accumulated negative (positive) anomalies belonging to the same drought (pluvial) event. The intensity is the mean deviation over the duration (magnitude/duration)

The July SPEI at 1-month scale is not significantly correlated with the PC1, while July SPEI at 3- and 6-month scale are also well correlated the PC1, which may be because the longer timescales have taken the water balance of the prior months into consideration. For seasonalized SPEI, the May–June SPEI at 1-month scale show the best results: The correlation coefficients with the PC1 were significant ($p < 0.05$) and positive for all grid points in Hexi Corridor, and the mean value of significant correlation coefficients is also the highest (0.42), indicating that the PC1 can generally represent the regional drought variation at this season and timescale. The spatial pattern of correlation between the PC1 and May to June SPEI at 1-month scale is shown in Fig. 6. The highest correlation coefficients are located in middle-east part of the Hexi Corridor, and relative low ones in the northwestern and the eastern parts, where there is no tree distribution or the age of trees is relative young. Therefore, further studies with additional proxy data from these regions should improve this result.

The PC1 is centered to have a mean of 0 and scaled to have standard deviation of 1 over the full period. Figure 4 shows the unfiltered and 50-year low-pass filtered PC1 from AD 1161–2006. The wet (>1) and dry (<-1) years occur almost equally, accounting for 16.6 and 15.5% of the entire time span. Extreme wet years with a value higher than 2 occurred in AD 1205, 1249, 1388, 1525, 1577, 1583, 1896, 1983, 1988 and 2002, while extremely dry (<-2) was identified at 25 years, much more than the extremely wet years. The smoothed series suggest that the Hexi Corridor had alternated between contrasting climatic conditions, with dry periods occurring at AD 1161–1216, 1260–1349, 1409–1417, 1443–1510, 1617–1737, 1759–1838 and 1929–1948, and wet periods at AD 1217–1259, 1350–1408, 1418–1442, 1511–1616, 1738–1758, 1839–1928, and 1949–2006. And the peaks and troughs have a good consistency with the moisture-sensitive tree-ring series in the source region of Yellow River (Gou et al. 2010) and Qaidam Basin (Zhang et al. 2003) (Fig. 7).

The recent wetness of the instrumental period (1951–2006) was unprecedented in the entire record, and it happened within a prominent pluvial period (1949–2006) that has the largest magnitude and strongest intensity. Also, three extremely wet years occurred in this period, and no extremely dry year happened; even though extremely dry years were much more frequent in the full period. This pluvial may have extended
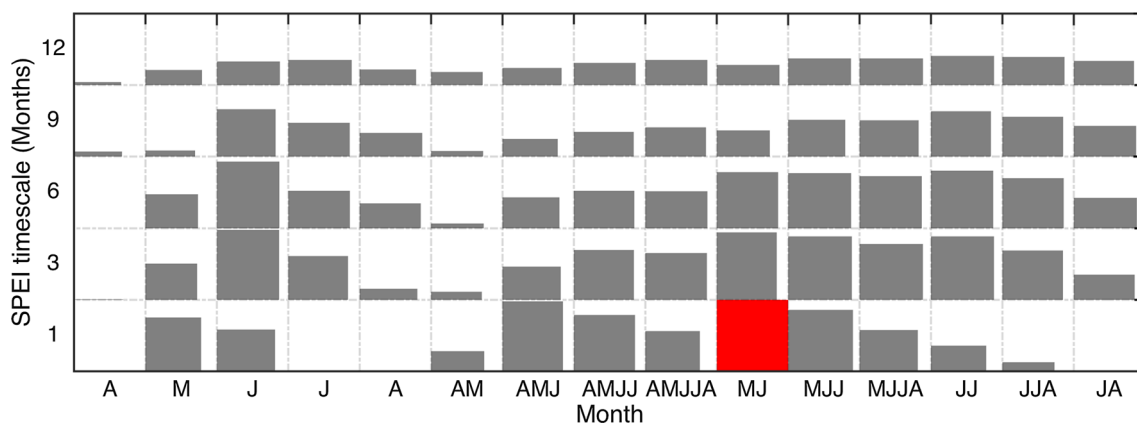

Fig. 5 Summary of the correlation results between PC1 and gridded climate variables (monthly SPEI from April to August and their seasonalized combination) in Hexi Corridor. Each row (column) is the result for each timescale (climate variable). The height of *shaded area* is the proportion of climate variable grid points that having significant positive correlation with the PC1, while the width is the ratio of the mean significant correlation coefficients and the largest mean. The square highlighted with *red* indicates that the PC1 significantly and positively correlated with May–June (MJ) SPEI at 1-month scale for all the grid points, and the mean value of these significant correlation coefficients is also the largest (0.42)
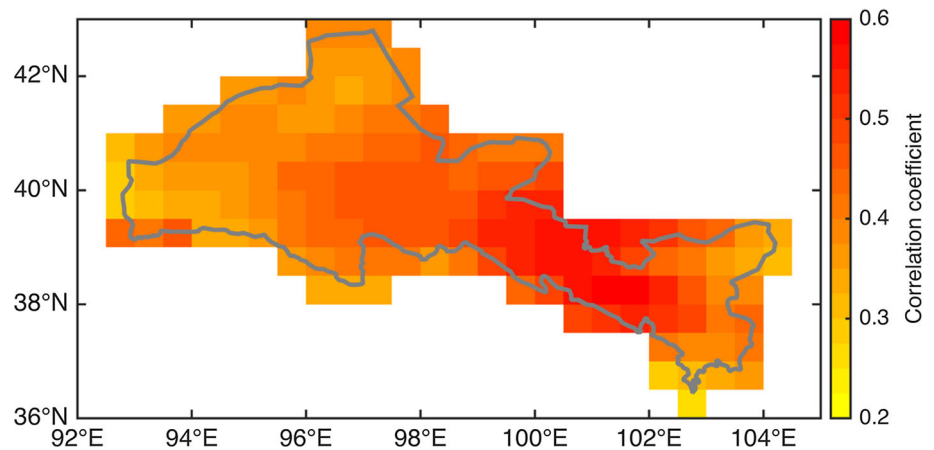
beyond this period and this region. Previous tree-ring-based three millenniums long precipitation reconstruction for the northeastern Tibet Plateau found that the last several decades were the wettest period in the entire reconstruction (Yang et al. 2014). In northern Pakistan, the twentieth century was also found to be the wettest over the past millennium as suggested by oxygen isotope record from tree-rings (Treydte et al. 2006). The unprecedented wetting at this period maybe the result of enhanced hydrological cycle coincident with warming (Treydte et al. 2006; Yang et al. 2014).

The drought in the latter half of the fifteenth century had the strongest intensity. Droughts at this time had also been
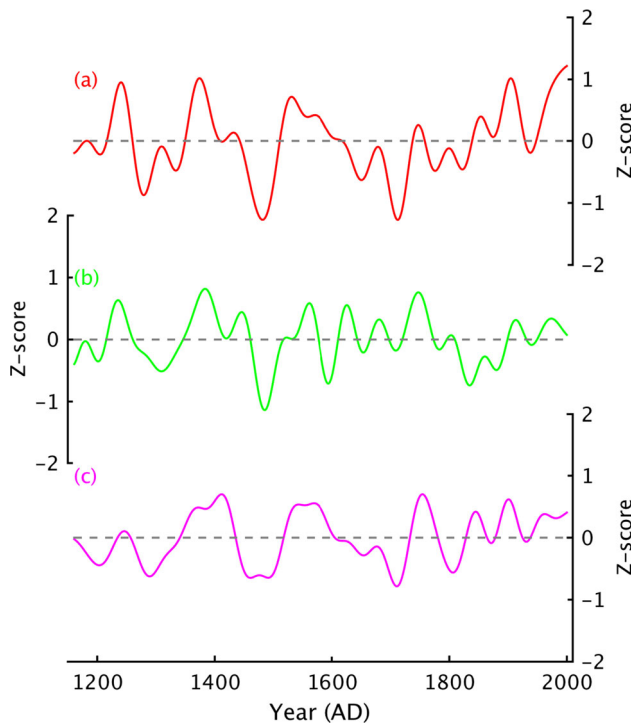

Fig. 7 Comparison between PC1 and moisture-related reconstructions in the source region of Yellow River (Gou et al. 2010) and the Qaidam Basin (Zhang et al. 2003). All the series are smoothed using a 50-year low-pass filter

recorded by tree-ring and many other proxies in many other studies in Hexi Corridor and adjacent areas. Studies from the Badain Jaran Desert (Gates et al. 2008), the Qinghai Lake (Zhang et al. 2004), Kusai Lake (Liu et al. 2009b), the source of the Yellow river (Gou et al. 2010), the Qaidam Basin (Zhang et al. 2003; Sheppard et al. 2004; Shao et al. 2005; Liu et al. 2006; Yang et al. 2014) all supported the existence of a severe drought during this time. A drought in the middle to late fifteenth century has also occurred in the north-central Europe and the southeastern United States (Cook et al. 2015).

The drought from the early seventeenth to early eighteenth century had the largest magnitude (Fig. 4). The drought in the early eighteenth century (1701–1737) is very severe; this 37-year long period included 17 dry years, with 5 extreme dry years. This drought was also reported in the Qaidam Basin (Zhang et al. 2003; Sheppard et al. 2004; Shao et al. 2005; Wang et al. 2013), and many sites in Mongolia (Davi et al. 2006, 2013; Pederson et al. 2013), as recorded by tree-ring width and oxygen isotope.

The study area is located in the margin of the monsoon-affected area; therefore, monsoon strength may influence regional climate. At the long-term scale, solar variability may play an important role in modulating the Asian monsoon (e.g., Wang et al. 2005). So here we compared the PC1 with a millennium solar activity reconstruction, which is inferred from ^{10}Be and ^{14}C records (Muscheler et al. 2007). In the Hexi Corridor, the association of drought during solar minima and wetness during maxima indicates a possible influence of solar activity on regional moisture variability (Fig. 8). The possible influence of solar variability on climate change has also been reported in studies nearby (Zhang et al. 2008; Gou et al. 2014).

Solar activity is an important external forcing on climate variation, affecting surface temperature and evaporation and then the local moisture budget (Gray et al. 2010). Considering the high specific heat of water, the oceans are expected to respond to the changes in solar irradiance more

Fig. 8 Comparison between PC1 and a solar irradiance reconstruction (Muscheler et al. 2007). The PC1 is smoothed using a 100-year low-pass filter
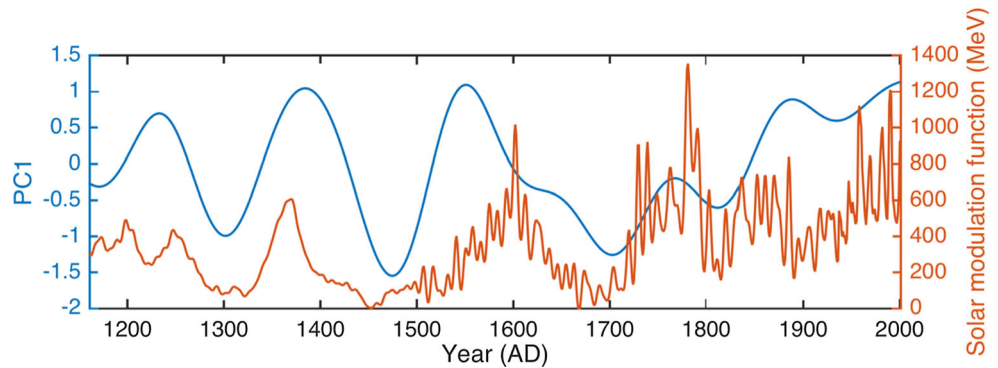
slowly than continents. The land-sea thermal contrast would be greater during a period of high net radioactive forcing than a period of low net radioactive forcing. The Asian summer monsoon systems are controlled mainly by thermal forcing (Wu et al. 2012); therefore, higher land-sea thermal contrast will increase the monsoon strength. Rising temperatures will also dramatically increase the air moisture holding capacity as the specific humidity would increase roughly exponentially with temperature (Allen and Ingram 2002). Hence, during the period of high net radioactive forcing, intensified Asian monsoons would bring more moist air to this region, resulting in more precipitation. In addition, because of the large percentage difference in continents and oceans between the two Hemispheres, the Northern Hemisphere will heat up more quickly than the Southern Hemisphere. The asymmetry in warming between the two Hemispheres will shift the position of the thermal equator (Broecker and Putnam 2013), which is sometimes referred to as the intertropical convergence zone (ITCZ). So the ITCZ is expected to move north (south) when the North Hemisphere is warm (cool). During the Little Ice Age, the ITCZ had shifted about 500 km south than its present position (Sachs et al. 2009). The north–south shift of the ITCZ will result in corresponding hydroclimatic changes in many regions, and monsoonal Asia is expected to become wetter when the ITCZ moves north (Broecker and Putnam 2013). The coinciding moisture and solar activity at centennial to multi-centennial scale maybe introduced by some or all of the proposed mechanisms. Additional paleoclimate records and climate modeling studies are needed to further confirm the relationships between moisture variation and solar actively at centennial to multi-centennial scale and improve our understanding of their physical mechanisms.

Conclusions

Principal component analysis was used to identify the common signals of the four moisture-sensitive tree-ring width chronologies from the Hexi Corridor, and the PC1

was found to be an indicator of regional drought variation. Wet spells are from AD 1217–1259, 1350–1408, 1418–1442, 1511–1616, 1738–1758, 1839–1928 and 1949–2006. The dry periods are from AD 1161–1216, 1260–1349, 1409–1417, 1443–1510, 1617–1737, 1759–1838 and 1929–1948. The droughts and pluvial periods identified in the PC1 are consistent with other studies nearby. Series comparison also suggests that solar variation may be an important driving force of the moisture variations in the Hexi Corridor, at centennial and longer timescale. Several mechanisms may have involved for this relationship; however, more investigation is needed to test and understand the associations and physical mechanisms.

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