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# MILLENNIUM-LONG TREE-RING CHRONOLOGY REVEALS MEGADROUGHTS ON THE SOUTHEASTERN TIBETAN PLATEAU

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## ABSTRACT

Millennium-aged trees are rare in natural forests. Here we present an 1184-year-long tree-ring width chronology from living juniper trees in the Biru area on the southeastern Tibetan Plateau. Growth-climate response analysis shows that the Biru chronology is significantly and positively correlated with late-spring (May-June) Standardized Precipitation Evaporation Index (SPEI) ($r = 0.67$, $n = 53$, $p < 0.01$). The tree-ring chronology explains 44.5% of the total variance of SPEI during the period AD 1957–2010. Reconstruction of May-June SPEI shows that there was a two-century-long megadrought during the late 13th to late 15th Centuries, and a seven-decade-long megadrought during AD 1630s to 1690s. Comparisons with other moisture records in the region suggest that the two-century megadrought identified in our reconstruction might be a widespread phenomenon most likely reflecting a stage of reduced Southwest Asian Summer Monsoon. Our results provide new evidence on the megadrought events on the Tibetan Plateau for the last millennium.

*Keywords:* Juniper trees, Biru County, late Spring, paleoclimate, SPEI.

## INTRODUCTION

Climatic droughts have a great influence on natural ecosystems and human society (Zhang and Liang 2010; Buntgen *et al.* 2011). On the Tibetan Plateau (TP), which has an area about 250 million km$^2$ and an average elevation above 4000 m, droughts affects water supply not only to the plateau but also to downstream regions for which the source of the water is located on the TP (Cao *et al.* 2006; Gou *et al.* 2007; Zhang *et al.* 2007; Qin *et al.* 2010). A seesaw pattern of summer precipitation variations between the southern and northern parts of the eastern TP was found by analyzing instrumental meteorological data during the period AD 1961–1990 (Liu and Yin 2001). A recent study based on 79 meteorological stations on the TP implies that dry regions would experience more serious warming than wet regions in the future (Duan *et al.* 2015). To evaluate the effects of droughts on TP water supply, knowledge of long-term drought characteristics is required. To do so, paleoclimatologists have paid great attention to identifying historical droughts (Zhang *et al.* 2003; Zhu *et al.* 2008; Liu *et al.* 2011; Kang *et al.* 2013; Fang *et al.* 2014; Yang *et al.* 2014a). Grießinger *et al.* (2011) found a long-lasting megadrought around the 13th–14th Centuries by studying $\delta^{18}O$ in tree rings in Linzhou of central Tibet. The megadrought in the 13th Century was also reported in a study of an ice core from the Dasuopu glacier of southwestern Tibet (Thompson *et al.* 2000). Despite increasing studies of paleoclimate on the TP, the spatiotemporal characteristics of this megadrought remain unclear mainly because of insufficient data with high temporal resolution and spanning the last millennium.

Previous dendrochronological studies on the TP provided high-resolution and millennium-long records of climate variability. These records are mainly confined to the northeastern (Zhang *et al.* 2003; Sheppard *et al.* 2004; Liu *et al.* 2006; Shao *et al.* 2010; Yang *et al.* 2014b) and central (Grießinger *et al.* 2011; He *et al.* 2013) TP. These chronologies showed historical moisture variability in their study areas. Large spatial-scale study

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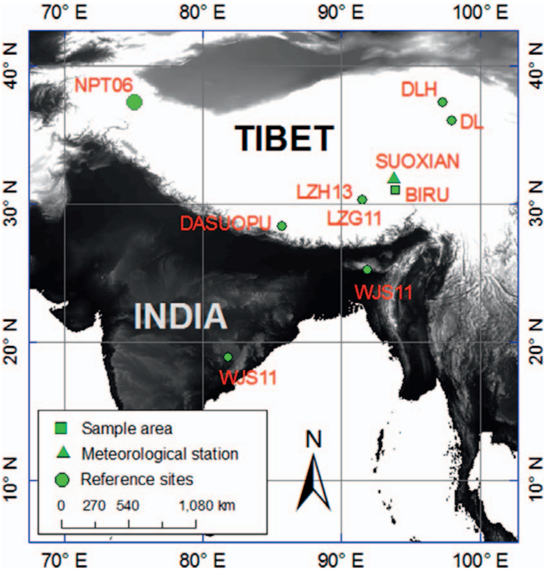


Figure 1. Locations of the Biru sampling area, the Suoxian meteorological station, and other reference sites for comparison in discussion: DLH (Zhang and Qiu 2007); DL (Zhang *et al.* 2003); NPT06 (Treydte *et al.* 2006); LZH13 (He *et al.* 2013); LZG11 (Grießinger *et al.* 2011); DASUOPU (Thompson *et al.* 2000); WJS11 (Sinha *et al.* 2011).

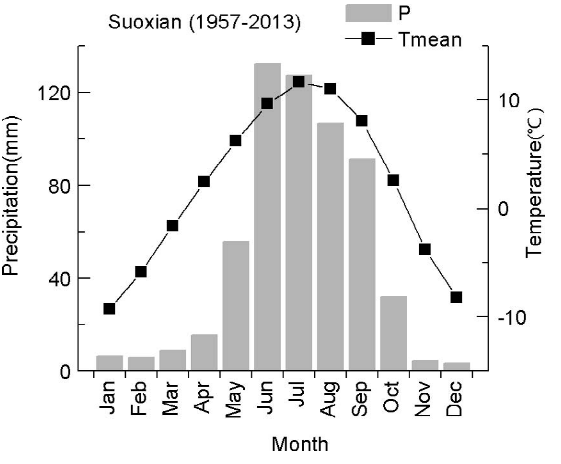


Figure 2. Mean monthly temperature and precipitation for the Suoxian meteorological station from AD 1957 to 2013.

of juniper tree rings indicated moisture differences between the north and south TP over the past five and a half centuries (Zhang *et al.* 2015). Development of a new millennium-long tree-ring chronology in the southern TP is of importance for better understanding the spatiotemporal characteristics of megadroughts during the last millennium. However, such a long chronology is not easily available because of the limitation of tree longevity and decay of dead trees in natural forests.

The objectives of this study were (1) to develop a millennium-long ring-width chronology of juniper trees from the Biru area of the southern TP, (2) to reconstruct the history of moisture change, and (3) to discuss the spatiotemporal characteristics of the megadroughts revealed in the moisture reconstruction.

## MATERIALS AND METHODS

### Study Area and Climate

Our sampling sites are located in Biru county, Naqu prefecture of Tibet (Figure 1). The area of Biru is 11,000 $km^2$, and the human population is 60,000. Tibetan juniper (*Juniperus tibetica* Kom.) is one of the dominant tree species in the alpine forests. The regional climate is dominated by South Asian Monsoon in summer and the Westerlies in winter (Webster *et al.* 1998; Thompson *et al.* 2000). Climate data from the Suoxian meteorological station (31°53′N, 93°47′E, 4020 m a.s.l.) show that monthly mean temperature ranges from −9.3°C in January to 11.6°C in July during AD 1957–2013. Most rainfall occurs in June–September (457.1 mm), accounting for 77.6% of the total annual precipitation (588.9 mm) (Figure 2).

Standardized Precipitation Evapotranspiration Index (SPEI), a measure of moisture condition by calculating the difference between precipitation and potential evapotranspiration, is obtained from a globally gridded dataset at a resolution 0.5° longitude × 0.5° latitude (http://sac.csic.es/spei/database.html) (Vicente-Serrano *et al.* 2010). We extracted the SPEI data (in a time-scale of one month) in the grid (central coordinate: N31.25°, E94.25°) covering our sampling sites from the database v1.0 that ends in year 2006. We calculated the SPEI for the years 2007–2010 following the methods in SPEI v1.0 using meteorological data from the Suoxian station that is about 80 km northwest of the sampling sites. The analysis of the relationship between tree growth and SPEI is based on their common period 1957–2010.

## Sample Collection and Chronology Development

We conducted an extensive field investigation to search for old-growth juniper trees in Biru in the summer of 2011. Tree-ring samples were collected from naturally growing juniper forests at three sites, including Longla, Ga and Puqionggou. The longest distance among these sites is 52.5 km from Longla to Puqionggou. The elevation of sample collection ranges from 4230–4440 m a.s.l. The forests have no sign of human disturbances. In the field, we collected increment cores from seemingly old-growth trees as judged by stem size, stripped bark, downward branches and lichen-covered crowns. Mostly, one core per tree was collected at breast height using a 4.5-mm inner-diameter increment borer, but additional cores were extracted from trees if one core was not of good quality (such as broken and/or rotten pieces). A total number of 137 cores from 97 trees were collected.

In the laboratory, all the core samples were air dried, mounted on wood slots, and polished following standard dendrochronological methods (Stokes and Smiley 1968). Tree-ring widths of all samples were measured to the nearest 0.001 mm in precision on a LINTAB station (Rinntech, Heidelberg, Germany). The tree-ring series were crossdated using a variety of techniques, including skeleton plots, visually examining ring features under a microscope, curve matching among series, and statistical aid from computer program COFECHA (Holmes 1983).

A tree-ring chronology was developed from the crossdated samples using program ARSTAN (Cook 1985). Age-related growth trend in each sample was removed by fitting a curve to the original tree-ring series. The curve was either a negative exponential curve or a cubic smoothing spline with a 50% frequency-response cutoff equal to two-thirds of the series length depending on which better fits the original data. We truncated the chronology length to the period within which the expressed population signal (EPS) is greater than 0.85 so as to ensure sufficient common signal in the tree-ring chronology (Wigley *et al.* 1984).

To assess the potential bias caused by detrending methods, we selected the 31 oldest samples and excluded the early period of high growth, leaving the last 700 years for analysis. A conservative chronology was then developed for the 700-year interval using a horizontal line passing the mean of these original series to obtain standardized and averaged tree-ring indices. The rationale for this method is that strip-bark growth of old junipers has minimum age-related growth trend (Esper *et al.* 2002).

## Tree Growth-Climate Relationship and Reconstruction of Past Climate

Pearson correlation coefficients were calculated between tree-ring width chronologies and monthly climatic variables from September of the prior growth year to September of the growth year for the common period of tree rings and climate data in AD 1957–2010. The climatic variables under analysis include mean monthly air temperature ($T_{mean}$), total monthly precipitation (P) and monthly SPEI of the corresponding grids. Following tree physiology, we also examined the relationship between tree-ring growth and seasonal climatic factors.

A linear regression model was used to reconstruct past climate. The climatic variable that significantly correlates with the tree-ring chronology and is also explainable by tree physiology was chosen to be the dependent variable and the tree-ring chronology served as independent variable.

Reliability of the regression model was verified by comparing the reconstructed data with the observed data using the "leave-one-out" cross-validation method (Michaelsen 1987). The statistics for evaluation included sign test (*ST*), product means test (*PMT*), square of Pearson correlation coefficient ($r^2$), reduction of error (*RE*) and the coefficient of efficiency (CE) (Fritts 1976; Briffa *et al.* 1988). ST is a count of the number of times that the signs of the departures from the sample mean agree or disagree without consideration of the magnitude of the departure. *PMT* accounts for both the signs and the magnitudes of the similarities in the two data sets. $r^2$ measures the association between two data sets and takes into account the relative degree of correspondence. RE is a sensitive measure of the reliability, which calculates the shared variance between the actual and estimated series. CE is described as an expression of the true $R^2$ of a

**Table 1.** The statistics of the Biru standard tree-ring chronology on the southeastern Tibetan plateau.

| Site | T/C | Time Span | SD | MSL | MS | AC1 | Rbar | SNR | EPS | PC1 |
|---|---|---|---|---|---|---|---|---|---|---|
| LL | 53/79 | AD874–2010 | 0.159 | 546 | 0.136 | 0.409 | 0.206 | 20.84 | 0.954 | 18.66 |
| GA | 31/39 | AD827–2010 | | | | | | | | |
| PQG | 1/2 | AD952–2010 | | | | | | | | |

Note: T/C, number of trees/cores; SD, standard deviation; MLS, median of segment length; MS, mean sensitivity; AC1 first-order autocorrelation; Rbar, mean correlation between tree-ring series; SNR, signal to noise ratio; EPS, expressed population signal; PC1, variance explained by the 1$^{st}$ principal component.

regression equation when it is applied to new data (Cook *et al.* 1994). The reconstruction was further validated by comparison with other independently derived past climate records.

### Climate Variability in the Last Millennium

To identify climatic states and fluctuations in the last millennium, we smoothed the reconstructed climate series using a running average over a 31-yr window. The spatial representation of our reconstructed climate was obtained by calculating the spatial correlations of the reconstructed series and the regional gridded climate data during the period AD 1957–2010 on KNMI Climate Explorer (http://climexp.knmi.nl). We evaluated the characteristics of major climatic events by comparing them with those shown in other reconstructions on the TP and southern Asia.

## RESULTS

### Tree-Ring Crossdating and Chronology Development

Among the 137 increment cores we collected, a total of 120 cores from 85 trees were successfully crossdated (Table 1). Seventeen samples could not be crossdated because of too many broken pieces or missing rings and were not used for further analysis. For those crossdated samples, the percentage of missing-ring occurrence is 0.34%. The four years with the highest frequency of missing rings among trees were 1799, 1653, 1972 and 1806.

The sample depth is 31 for GA, 53 for LL and 1 for PQG. We developed site chronologies for GA and LL separately and found they are significantly correlated ($r$ = 0.31, $p$ < 0.001, $n$ = 1136) for the period AD 874–2010. We then combined the samples in the two sites, plus the only sample from PQG to develop a regional chronology for Biru area. The chronology interval during which the EPS > 0.85 is AD 1080–2010. The minimum sample replication for the early period is 11 trees. The mean segment length is 546 years and the oldest tree is 1184 years of age measured at breast height of the stem (Table 1).

Comparison of the above tree-ring chronology with the chronology developed from the 31 oldest trees (>700 years) using the most conservative detrending method showed that they agreed fairly well at decadal to multi-centurial scales (Figure 3b). This observation confirmed the robustness of the detrending method in developing the standard tree-ring chronology.

### Tree Growth-Climate Relationships

The results of correlation analysis showed that our tree-ring chronology had significant negative correlation with mean temperature in May and June, and positive correlation with total precipitation in May and June (Figure 4). Considering the effect of both temperature and precipitation, we examined the relationships between tree rings and SPEI, and the results showed the highest correlation coefficient in May and June ($r = 0.67$, $n = 53$, $p$ < 0.01). This correlation still existed when the low-frequency growth trend in tree rings was removed by calculating the first-order differences of the tree-ring chronology ($r = 0.65$, $n = 52$, $p < 0.01$). Recent research demonstrated that the initiation of xylogenesis for juniper on the TP occurs in late spring and early summer (*i.e.* May and June), and moisture availability in this season can be a critical trigger in the onset of xylem increment (Ren *et al.* 2015).

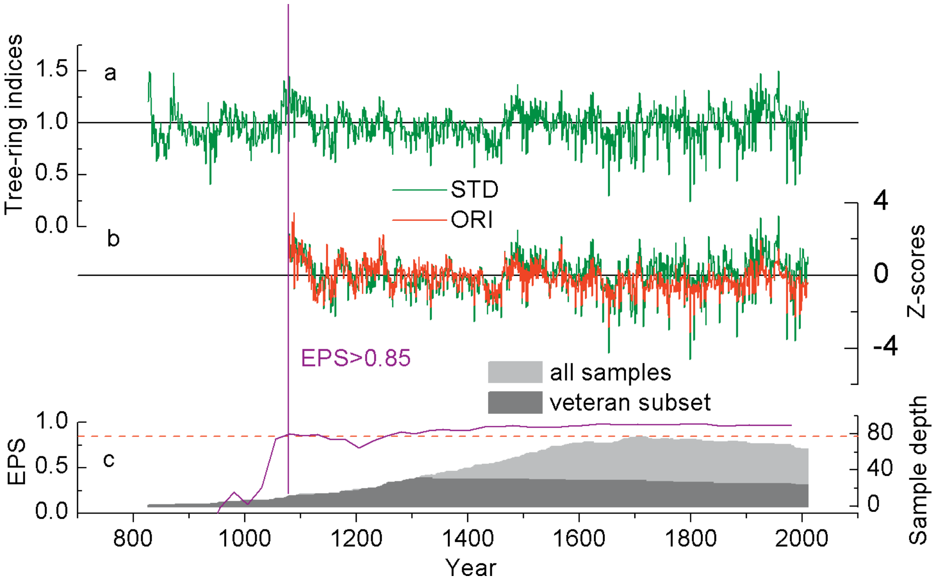


**Figure 3.** (a) The standard chronology, (b) normalized standard chronology (green) and original chronology (red), and (c) the EPS (purple line) and sample depth for all samples (light gray area) and for the original subset (exceeding 700 years, gray area). The dashed line represents EPS = 0.85.

## Reconstruction of May–June SPEI for the Last Millennium

According to the characteristics of the tree growth-climate response, we developed a simple linear transfer function (Y = 2.91X − 2.89), where the independent variable is tree-ring chronology and the dependent variable is May–June SPEI. The reconstruction represents 44.5% of the variance in actual May–June SPEI during the period AD 1957–2010 (Table 2). Validation metrics using the "leave-one-out" cross-validation method (Michaelsen 1987) showed that the values of ST (37 + /17−), PMT (2.96), $r^2$ (0.41), RE (0.41) and CE (0.41) confirmed the reliability of the transfer function (Table 2). To further assess our reconstruction reliability, we compared the reconstructed and the actual May–June SPEI for the period 1957–2010 (Figure 5a). The result shows that they matched each other fairly well, especially in extreme dry years, such as 1972, 1979, 1987 and 1995. Thus, we reconstructed May–June SPEI back to AD 1080 using the transfer function and the Biru tree-ring chronology.

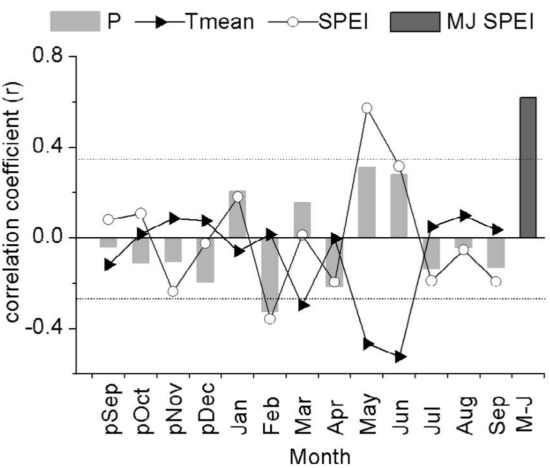


**Figure 4.** Correlation coefficients between the standard tree-ring chronology and monthly variables (monthly mean temperature, monthly total precipitation and SPEI) from previous September (pSep) to current September (Sep) over the period AD 1957–2010. MJ SPEI represents May–June averaged SPEI. The horizontal dotted lines denote significance levels at $p < 0.01$.

The reconstruction of May–June SPEI showed variability at annual to centennial scale (Figure 5b). The 31-year running average window of this reconstruction highlights multidecadal to centennial changes in SPEI. It is easily discernible that a two-century megadrought occurred during the AD 1260s to 1460s and a seven-decade

**Table 2.** Statistics of calibration and leave-one-out verification for the regression model of May–June SPEI reconstruction.

| Calibration | | | | | Leave-One-Out Verification | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Period | r | $R^2$ | $R^2_{adj}$ | F | Sign Test | PMT | $r^2$ | RE | CE |
| 1957–2010 | 0.67** | 44.5% | 43.4% | 41.6 | 37+/17−* | 2.96** | 0.41 | 0.41 | 0.41 |

Note: r, correlation coefficient; $R^2$ and $R^2_{adj}$, coefficient of determination and adjusted coefficient of determination; F, F statistic for regression model; PMT, product mean test; RE, the reduction of error; CE, the coefficient of efficiency. * Significance at $p < 0.05$. **Significance at $p < 0.01$.

megadrought occurred during the AD 1630s to 1690s. Persistent moist conditions occurred during AD 1080s–1120s, 1470s–1570s and 1900s–1960s. Fluctuation in moisture conditions at a decadal scale appeared in the other time periods.

We calculated the spatial correlations of our reconstructed and the actual May–June SPEI in Biru with the regional gridded SPEI dataset on KNMI Climate Explorer over their common period AD 1957–2010 (Figure 6a, b). The results showed that our reconstruction represents SPEI conditions approximately over the region 31°N–33°N and 92°E–95°E, with the highest correlation close to the sampling sites.

## DISCUSSION

To evaluate the spatiotemporal characteristics of the megadroughts that we discovered in the Biru chronology, we compared them with those also shown in other proxy records in the Southwest Asian Monsoon-influenced regions (Figure 7). Grießinger *et al.* (2011) reconstructed August precipitation from tree-ring $\delta^{18}O$ of Tibetan junipers in the Reting temple area, about 250 km to the southwest of Biru County, and found a megadrought in AD 1200s–1450s. Treydte *et al.* (2006) studied tree-ring $\delta^{18}O$ of Karakorum junipers in the high mountains of northern Pakistan and reported a long-lasting low annual precipitation period in AD

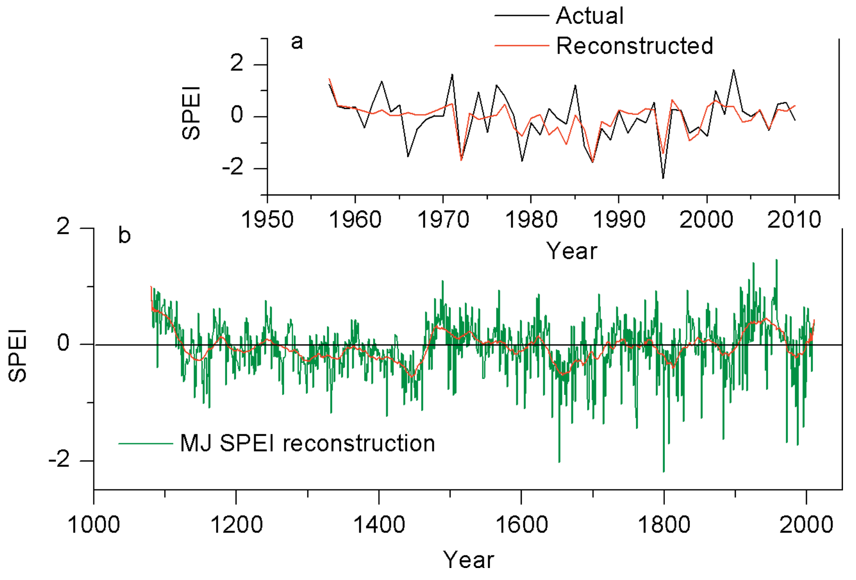


**Figure 5.** (a) The comparison of actual and reconstructed May–June SPEI in their common period AD 1957–2010. (b) The reconstruction of May–June SPEI for the period AD 1080–2010 in Biru, Tibet. The reconstruction is smoothed with a running average over a 31-year window.

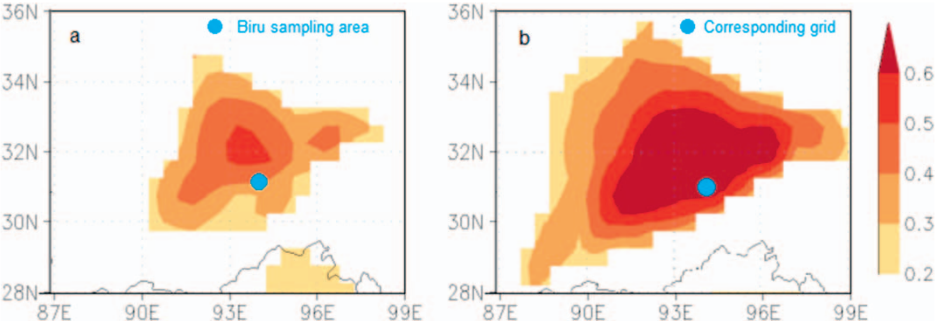


**Figure 6.** Spatial-field correlations of (a) the reconstructed and (b) the actual May–June SPEI in Biru with gridded May–June SPEI in the period 1957–2010. The analysis was performed using KNMI Climate Explorer (http://climexp.knmi.nl).

1220s–1490s. Thompson *et al.* (2000) studied ice cores in the Dasuopu glacier on the south central rim of the Himalayas and found a condition of low precipitation during AD 1300s–1390s when there was an increase in dust concentrations in ice cores. Sinha *et al.* (2011) reconstructed June to September precipitation from stalagmite $\delta^{18}O$ data in two caves of central and northeastern India and indicated a persistent drought period during AD 1280s–1450s. The correspondence of these megadroughts among independent reconstructions suggests that the megadrought during the late 13th to late 15th Centuries, although not identical in duration among study areas, may be widespread in

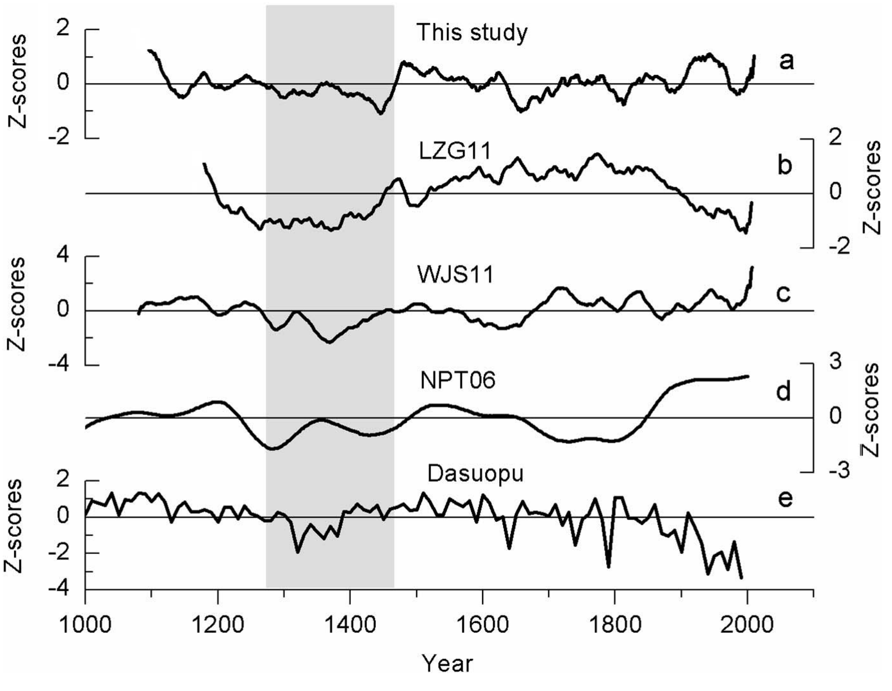


**Figure 7.** (a) The 31-yr running mean of May–June SPEI reconstruction in Biru, (b) summer precipitation as inferred from tree-ring $\delta^{18}O$ series in Reting by Grießinger *et al.* (2011), (c) June–September precipitation as inferred from stalagmite $\delta^{18}O$ series in central and northeastern India by Sinha *et al.* (2011), (d) annual precipitation as inferred from tree-ring $\delta^{18}O$ for northern Pakistan by Treydte *et al.* (2006), and (e) decadal dust concentrations in Dasuopu ice core by Thompson *et al.* (2000). The shaded area denotes the two-century megadrought as identified in this study. Each series was transformed into Z scores so that the mean value is 0 and the standard deviation is 1.

space and also the longest dry period in the last millennium.

Although LZG11 showed dry conditions in the 13th and 14th Centuries as recorded in the Biru reconstruction, the two curves exhibited different variations in this period. The LZG11 showed an increasing trend from the trough in the second half of 14th Century, but the Biru record had a clear declining trend in the same period. These differences are possibly caused by different target seasons from the proxies, and/or spatial variation in moisture conditions related to influence of mountainous topography. The megadroughts we found in this study therefore indicate long droughts in the Biru area and droughts of different length over the TP.

For the megadrought during AD 1630s–1690s in our Biru chronology, no similar water deficits were found in the previous four drought reconstructions (Figure 7). However, a 50-year dry period in AD 1630s–1680s was observed in an annual (previous July to current June) precipitation reconstruction from junipers for Linzhou, about 250 km southwest of Biru in the south-central TP (He *et al.* 2013). Additional evidence for this megadrought comes from Wang *et al.* (2008) who reconstructed May–June Palmer Drought Severity Index (PDSI) and found that the 17th Century was the longest dry period for past five centuries in the central of TP. These results suggest that the seven-decade megadrought in AD 1630s–1690s was not as widespread as the megadrought in the late 13th to late 15th Century.

A distinct drying trend was found since the 1870s from tree-ring $\delta^{18}O$-based hydroclimatic reconstruction for the past 800 years on the eastern TP (Wernicke *et al.* 2015). This trend was also shown in several other proxy reconstructions, including tree rings (Grießinger *et al.* 2011; Liu *et al.* 2013), ice core (Thompson *et al.* 2000) and lake sediment (Xu *et al.* 2006). However, records from Biru, LZG11 and WJS11 did not show such a clear trend in this interval. These three reconstructions showed a very similar trend in the last century, *i.e.* dry condition before the AD 1970s and wet condition in the last 40 years. The difference of trend in moisture variation indicated the importance of mountainous topography in regulating spatial variation of moisture conditions over the TP.

Our millennium-long chronology not only showed megadrought events in history, but also provided information about single-year events. For example, missing rings occurred mostly in years 1653, 1799, 1806 and 1972, indicating extreme conditions for tree growth in these years. The observed May–June SPEI in 1972 is $-1.68$, suggesting that the trees with missing rings are quite sensitive to the dry conditions. The occurrence of missing rings in years 1653, 1799 and 1806 suggested extreme conditions, most likely drought, in these years.

It was reported that May–June moisture variability has different characteristics between the north and south TP during the past five and a half centuries (Zhang *et al.* 2015). Our study in Biru provided a new millennium-length tree-ring chronology that is sensitive to May–June moisture variation for the southern TP, thus creating an opportunity to examine the south-north moisture differences prior to five-and-a-half centuries before present. We compared our Biru chronology with millennial juniper tree-ring chronologies on the northeastern TP (Zhang *et al.* 2003; Zhang and Qiu 2007). We found that the northeastern TP did not have a two-century-long megadrought in the late 13th to late 15th Centuries, suggesting that the megadrought observed in Biru area most likely reflects a stage of reduced South Asian monsoon.

## CONCLUSIONS

A moisture difference between the north and south TP was detected over the past five-and-a-half centuries (Zhang *et al.* 2015). Located in the southern TP, our Biru chronology extends the regional moisture record in south TP five centuries further back in time. Our chronology disclosed a two-century megadrought during the late 13th to late 15th Centuries and a seven-decade megadrought during AD 1630s to 1690s. These megadroughts indicate the vulnerability of TP to moisture deficits that cannot be discernible from the limited length of observed records. Our findings add new evidence of megadrought occurrence on the TP in the last millennium and provide data for further studying how the megadroughts could have been developed and persisted so long. Particularly, comparisons between our reconstruction and other millennium-long records of moisture variations showed that the two-century megadrought was spatially extensive, suggesting a stage of weakened Southwest Asian monsoon. Knowledge of the historical megadroughts will help understand the likelihood of their recurrence and manage water resources on the TP.

## ACKNOWLEDGMENTS

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