MS No.: cp-2016-132

"Decreasing Indian summer monsoon in northern Indian sub-continent during the last 180 years: evidence from five tree cellulose oxygen isotope chronologies"

Dear Dr. Evans,

Thank you for your letter regarding the above-mentioned manuscript. We would like to thank the reviewers for their constructive comments, and we have made corrections accordingly (see details below). Each comment (*italic*) from the editor or the reviewers is followed by our responses.

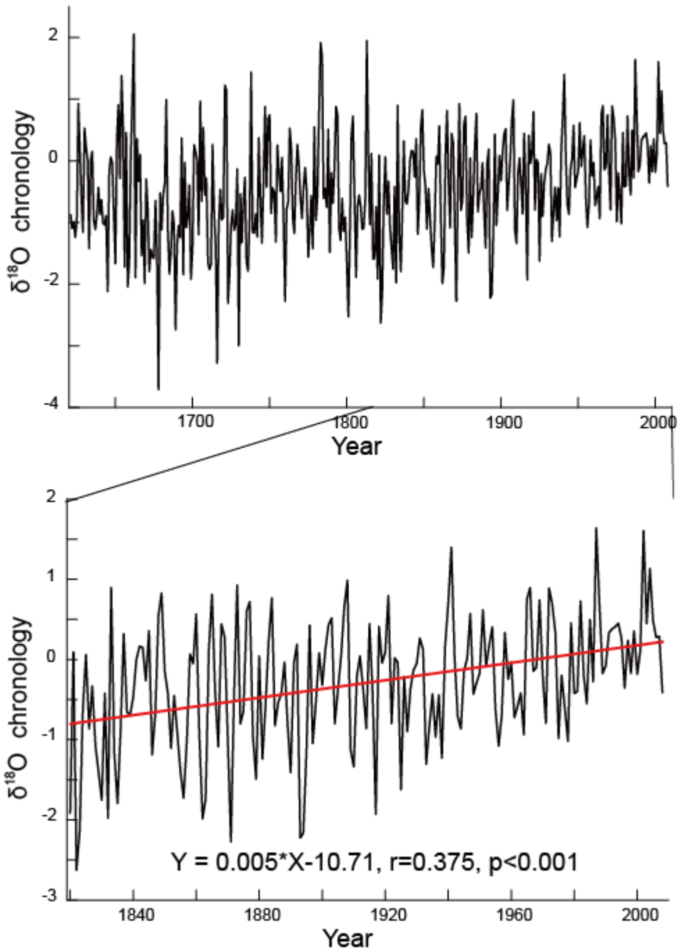
Best regards,

Masaki Sano on behalf of all authors

Comments from editor:

Although three reviewers have recommended acceptance and minor revisions (please do address their suggested revisions), a fourth reviewer has suggested major revisions (document:cp-2016-132-referee-report-3.pdf). I have reviewed these suggestions carefully, and I believe that making these revisions will result in a stronger and more important contribution. In particular, they ask you to consider: (2) justification for the stacked record, given Fig 6; (1abc) strength of conclusions relative to propagated error, especially for the low frequency interpretations (cited figures); and (3) giving greater weight and refocusing the paper's discussion and conclusions around the most-substantiated "ENSO" timescales and patterns evident in the results, making the discussion of the low-frequency variability more speculative, given the uncertainties in the results (cited figures). Therefore I am asking you to revise the paper once more in light of the specific requests from this reviewer.

Answer: We have modified the manuscript based on your suggestions. In summary, 1) Regional tree ring oxygen isotope chronology based on five records showed relatively higher correlations with All Indian rainfall and Indian summer monsoon index, as compared to correlations seen with other chronologies derived from 3 or 4 local chronologies. 2) We have added the uncertainty for the low frequency variability. 3) We have described that Indian Ocean SST may partly modulate the Indian summer monsoon-ENSO relationship. The following figure showed that the increasing trend of tree ring $\delta^{18}O$ from 1820 to 2000 is significant, whereas we have soften the conclusions that the land-sea temperature contrast may be a driving force of the increasing trend in the regional tree-ring record.



In response to comments from the data stewardship team on the Data Availiability Section, we have confirmed that the Hulma, Wache, and Manali d18O datasets are available from the NOAA/NCEI repository at the URLs noted in the paper. Please confirm that the JG and Ganesh d18O chronologies and the composite regional d18O chronology developed in the present manuscript are also available via the NOAA/NCEI repository: per Climate of the Past and PAGES2k Special Issue policies, these revisions are required prior to acceptance of the manuscript. Currently we see only "shell" urls for the JG and Ganesh datasets, and in your prior response, you have not indicated a url for the composite o18 chronology reported in the present manuscript. For these latter three datasets, please forward a copy of the data that *were delivered to NOAA/NCEI. If these data have not yet been delivered to NOAA/NCEI, please cc: me on your email which delivers those data. The goal is to get eyes on the data and to make sure that they are on their way or already at the repository before the paper is officially published.*

Answer: As we sent an email with ccing the editor, the data (five local tree-ring oxygen isotope records and one composite tree-ring oxygen isotope chronology) have been sent to a data manager of *the NOAA/NCEI repository*. The data will be immediately opened once this manuscript is accepted.

Comments from review 1

This sentence 'Monsoon precipitation in northwestern India showed a significant decreasing trend during the period of 1866-2006 (Bhutiyani et al., 2010)' should be deleted due to the same setence appears in the below section.

Answer: We have deleted the sentences based on your suggestions.

Comments from review 2

1-In figure 4 caption, when adding the uncertainty (95% confidence interval), precise that for the regional scale, it was not derived from all chronologies (except for Hulma chronology).

We have described the methodology to calculate the 95% confidence intervals in the manuscript. As you noted, the intervals cannot be provided for the Humla chronology because of single isotope data in a single year, which is also mentioned in the revised ms.

2-in Section 3.4. paragraph 5: "Although reconstructed All India monsoon rainfall does not show a significant decreasing trend during the period of 1813-2005 (Sontakke et al., 2008), the data from only four stations extend back to 1826 CE and four longest stations locate in central or southern India". This sentence needs some editing, below is a suggestion:

"Although reconstructed All India monsoon rainfall does not show a significant decreasing trend during the period of 1813-2005 (Sontakke et al., 2008), only four stations have data extending back to 1826 CE, and are located in central or south India."

This will apply if the four longest records (extending back to 1826) are the 4 stations located in central or south India.

Answer: We have modified the sentence based on your suggestions. Please see Page 12, lines 13-15.

3-in Section 3.5. paragraph 5: When authors state" Model results", what model they are referring to? it is not clear whether it is the "theoretical 18O fractionation model" or "the regression/correlation model when comparing their data with speleothem 18O". I suggest to the authors to clarify this in the text.

Answer: We have deleted Section 3.5 including the paragraph, in response to comments from reviewer #3.

4- In general when using tree ring, it should be hyphenated (tree-ring) when used as an adjective. Example: tree-ring record, tree-ring data, tree-ring 18O. Please correct it in manuscript accordingly.

Answer: We have modified the whole manuscript according to your suggestion.

Comments from review 3

The revised manuscript by Chenxi Xu et al. has been improved relative to the initial submission. However, the manuscript still contains conclusions not supported by the analyses. In general, we suggest the authors focus on presenting only the analyses that persuasively demonstrate their proposed mechanisms of variability. If this cannot be done, we suggest they soften the conclusions that cannot be robustly substantiated. The following review contains three major concerns should be addressed before publication, as well as a short list of smaller issues. Based on the work required to make the suggested changes, we recommend an additional round of major revisions. Major Concerns (1) The authors' treatment of uncertainty has improved from the initial version (e.g., the inclusion of 95% CIs and the age measurement uncertainties in Fig. 11), but the majority of the conclusions in this paper rest upon signals that have not been demonstrated to be more than noise. Specific examples are below: a. What is the uncertainty on the difference presented in Figure 10b? These records seem to have been generated by subtracting one proxy from another without propagating the error. Therefore, it's impossible to determine if there's any trend in these data, or if one *reconstruction is different from another. The authors need to demonstrate this conclusively in order to validate their mechanism. b. We find the relationship in Figure 11 difficult to interpret due to substantial uncertainties in the age model of the stalagmite oxygen record. Time errors in the speleothem record are presented, and are on the same order as the timescale of the signal of interest (10-30 year uncertainty is ~10% of the length of the record, and on the same order of magnitude as the timescale of interest of the analysis). Thus, we expect the analysis comparing multidecadal signals in the tree ring stack to those in the speleothem record to be very sensitive to the uncertainty in the speleothem record timescales. For this analysis to be convincing, the authors need to address the relationship between signal and error. c. Could the authors explain in more detail why error estimates are not available for the Hulma record? It is not clear why they are not available simply because these records were generated by a pooling method.*

Answer: We have added the uncertainty to the long-term variations in the regional tree ring chronology and the land-ocean thermal contrast. Please see Figure 10 and related part in the modified manuscript.

Because uncertainty of the temperature reconstructions for the Indian Ocean (Tierney et al., 2015) and the Tibetan Plateau (Cook et al., 2013; Shi et al., 2015; Wang et al., 2015) was provided as RMSE in the previous studies, the uncertainty range for the land-ocean contrast was estimated as the sum of RMSE of land temperature and Indian Ocean SST for each year. Using a low-pass filter, we extracted the low-frequency signals together with uncertainties (>100 years) for the tree-ring oxygen isotope chronology and the land-ocean contrast.

There is firm evidence of a weakening land-ocean thermal gradient over South Asia, which has been reported using long-term observations and model experiments by Roxy et al (2015). Specifically, rapid warming in the Indian Ocean and relatively subdued warming over the Indian subcontinent both contribute to the weakening land-sea gradient, and thereby reduce amounts of precipitation over parts of South Asia (Roxy et al., 2015). Based on the reviewer's suggestion, we dully noted in the ms that "while the long-term trends are overall consistent between our regional tree-ring chronology and the land-ocean thermal contrasts, possible propagation of uncertainty for the long-term land-sea gradient data should be kept in mind for interpretation."

Based on the reviewer's comment, we entirely deleted the Section 3.5 based on the stalagmite data, because of large uncertainty of age control.

(2) We are not yet convinced that these 5 tree ring records should be stacked. Presumably we'd want to stack these records to reduce local noise associated with a coherent regional signal. For the following two reasons, we are not convinced that the 5 sites experience a coherent regional climatic signal. First, the authors' response to our initial review indicated that low correlation between two sites was expected because they are far apart – this would seem to undercut the argument for placing them into the same stack, as the climatic drivers operating on these two sites are likely to be different. Second, Fig. 6 shows that only 3 of the 5 tree ring sites fall in the region where the H5 d18O variation has a significant correlation with precipitation amount variation suggesting that there's not a coherent, single regional signal across this region. We are concerned that by stacking these 5 sites (as opposed to possibly the three or four most westerly sites), the authors may be averaging signals from two separate hydroclimatic regions. We strongly suggest that the motivation for stacking be clarified and strengthened.

Answer: We built up three regional tree ring oxygen isotopes chronologies based on all five records (H5), four records (except Wache in Bhutan, the eastern site, H4) and three records (except Wache in Bhutan and Ganesh in Nepal, H3). The correlation analysis between three regional tree ring oxygen isotopes chronologies (H5, H4, H3) with All Indian rainfall (AIR), Indian monsoon index (IMI) and Intensity of monsoon circulation (Webster and Yang Monsoon Index (WYM) was employed to check which chronology can capture more regional signal. The results were shown in the following table. In general, the correlation coefficients between H5 and regional climate index (AIR, IMI, WYM) are higher than those between H4, H3 and regional climate index in most cases, although the correlation coefficient between H3 and IMI is higher than the correlation coefficient between H4, H5 and IMI. Therefore, regional oxygen isotope chronology based five tree ring records can capture more monsoon-related climate signal, which is the reason that 5 tree ring records were stacked.

r	Five tree ring oxygen isotopes records (H5) vs AIR	Four tree ring oxygen isotopes records (H4, excluding Wache in Bhutan) vs AIR	Three tree ring oxygen isotopes records (H3, excluding Wache in

			Bhutan and Ganesh in Nepal) vs AIR
Correlation coefficient with All Indian Rainfall (AIR)	-0.498 (1871-2008)	-0.476 (1871-2008)	-0.456 (1871-2008)
Correlation coefficient with Indian monsoon index (IMI, Wang et al., 2001)	-0.454 (1948-2008)	-0.438 (1948-2008)	-0.465 (1948-2008)
Correlation coefficient with intensity of the monsoon circulation (WYM, (Webster and Yang, 1992)	-0.424 (1948-2008)	-0.365 (1948-2008)	-0.318 (1948-2008)

(3) The spectral analysis method description and presentation has been substantially improved. The revised power spectrum exhibits a clear, significant signal at periods of ~4 and ~5 years. However, we are not convinced of that the centennial-scale peak, which is reported as corresponding to a ~133-year cycle, is a signal of a centennial-scale cycle as opposed to a secular trend. Part of our concern derives from the mismatch between the timescale of the cycle and the location of the signal peak in Fig. 7. The peak of the ~133-year cycle should be between 0.01 and 0.005 cycles/year. Instead the peak of the signal occurs at a value below 0.005 cycles/year. Because we cannot be confident that centennial scale variability is preserved in H5, the discussion of centennial variability as a preservation of the ISM signal is poorly substantiated. Therefore, we recommend that the authors refocus their paper to interpreting their record with respect to ENSO primarily. We feel this suggestions is robust for the following reasons: a. There is significant, robust spectral power at ~4 and ~5 years, which is consistent with ENSO timescales. b. Spatial patterns shown of the correlation

between SST and d18O looks like ENSO variability, with the strongest impact in the eastern and central tropical Pacific (Fig. 8).

Answer: The results from kSpectra showed that the frequencies of 0.0075188 (~133 years), 0.1992188 (~5 years), 0.2548828 (~4 years) are significant at the confidence of 99% for the H5 tree ring oxygen isotopes during the period of 1743-2008, which is shown in Figure 7. Low frequency signal is obvious from the Figure 7. Because we focused on the long-term changes of ISM, low-pass filter (100 years) was used to extract low frequency signal of ISM. We have added a part describing the ISM-ENSO relationship based on your suggestions.

Minor Comments

(1) Links for Ganesh, JG, and Manali datasets to the NOAA Paleoclimatology Archive do not work. Please update so we can replicate analysis.

Answer: We have already submitted the data to NOAA. The data will be fully opened once the manuscript is accepted.

(2) Organization could still use improvement. For example, many methods are described in the results and discussion section. We need these in the methods section so they can be fully evaluated. For example: a. Pooled method (there must be a way to assess certainty!) b. Bandpass filter for decadal and multidecadal trends

Answer: We have modified organization of the methods, and have added some descriptions in accordance with reviewer's suggestions.

(3) Figure 10: add legend for different colored shaded area.

Answer: We have added legend for colored shaded area in Figure 10.

(4) Figure 7: label y axis "Log power" and x axis with units (cycle/year)

Answer: We have revised the Figure 7 according the reviewers' suggestions.

This comment was prepared following a SPATIAL laboratory group discussion. Rich Fiorella, Annie Putman, and Chao Ma compiled this short comment with additional input from Gabe Bowen, Zhongyin Cai, and Yusuf Jameel.

Comments from review 4

accepted as is

Decreasing Indian summer monsoon in northern Indian sub-continent during the last 180 years: evidence from five tree cellulose oxygen isotope chronologies

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Abstract. We have constructed a regional tree-ring cellulose oxygen isotope ($\delta^{18}O$) record for the northern Indian sub-continent based on two new records from northern India and central Nepal and three published records from northwestern India, western Nepal and Bhutan. The record spans the common interval from 1743-2008 CE. Correlation analysis reveals that the record is significantly and negatively correlated with the three regional climatic indices: All India Rainfall (r = -0.5, p <0.001, n =138), Indian monsoon index (r = -0.45, p <0.001, n =51) and the intensity of monsoonal circulation (r = -0.42, p <0.001, n =51). The close relationship between tree-ring cellulose $\delta^{18}O$ and the Indian summer monsoon (ISM) can be explained by oxygen isotope fractionation mechanisms. Our results indicate that the regional tree-ring cellulose $\delta^{18}O$ record is suitable for reconstructing high-resolution changes in the ISM. The record exhibits significant inter-annual and long-term variations. Inter-annual changes are closely related to the El Niño-Southern Oscillation (ENSO), which indicates that the ISM was affected by ENSO in the past. However, the ISM-ENSO relationship was not consistent over time, and it may be partly modulated by Indian Ocean sea surface temperature (SST). Long-term changes in the regional tree-ring $\delta^{18}O$ record indicate a possible trend of weakened ISM intensity since 1820. Decreasing ISM activity is also observed in various high-resolution ISM records from southwest China and Southeast Asia, and may be the result of reduced land-ocean thermal contrasts since 1820 CE.

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1 Introduction

The Indian summer monsoon (ISM) delivers a large amount of summer precipitation to the Indian continent, and thus has a major influence on economic activity and society in this densely-populated region (Webster et al., 1998). Current research on the ISM is mainly concerned with the study of inter-annual and inter-decadal variations, using meteorological data and climate models. El Niño-Southern Oscillation (ENSO) has great influences on ISM at inter-annual time scales, and El Niño events (Warm phase of ENSO) usually produced ISM failure (Kumar et al., 1999; Kumar et al., 2006; Webster et al., 1998). North Atlantic Sea surface temperature (SST) affected ISM by modulating tropospheric temperature over Eurasia (Goswami et al., 2006; Kripalani et al., 2007). Climate model experiments indicate that there is a significant increase in mean ISM precipitation of 8% under the doubling atmospheric carbon dioxide concentration scenario (Kripalani et al., 2007) and human-influenced aerosol emissions mainly resulted in observed precipitation decrease during the second half of the 20th century (Bollasina and Ramaswamy, 2011). A good understanding of mechanisms driving ISM change on different time scales could help to predict possible changes of ISM in the future. However, the observed meteorological records are too short to assess long-term changes in ISM. Therefore, long-term proxy records of ISM are needed.

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The abundance of *Globigerina bulloides* in marine sediment cores from the Arabian Sea indicated a trend of increasing ISM strength during the last 400 years (Anderson et al., 2002). However, oxygen isotopes in tree rings and ice cores from the Tibetan Plateau revealed a weakening trend ISM since 1840 or 1860 (Duan et al., 2004; Grießinger et al., 2016; Liu et al., 2014; Wernicke et al., 2015). In addition, a stalagmite oxygen isotope record from northern India indicated that the ISM experienced a 70-year pattern of variation over the last 200 years, with no clear trend (Sinha et al., 2015). Since there are spatial differences in the patterns of climate change in monsoonal areas (Sinha et al., 2011), geological records with a wide

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Available tree-ring records are widely distributed in the Indian monsoon region (Yadav et al., 2011). The climate of the southern Himalaya is dominated by changes in the Indian summer monsoon, and therefore the region is well suited to the study of Indian monsoon variations. The oxygen isotopic composition ($\delta^{18}O$) of tree rings is mainly controlled by the $\delta^{18}O$ of precipitation and by relative humidity (Ramesh et al., 1985; Roden et al., 2000), and both are affected by the Indian summer monsoon (Vuille et al., 2005). Compared with tree-ring width data, tree-ring $\delta^{18}O$ records are more suited to retrieving low-frequency climate signals, and therefore they have the ability to record the Indian summer monsoon (Gagen et al., 2011; Sano et al., 2012; Sano et al., 2013). In addition, tree-ring $\delta^{18}O$ is considered as a promising proxy for next phase of Past Global Changes (PAGES) 2k network not only for hydroclimate reconstruction in Asia but also for data-model comparison to understand the mechanisms of climate variability at decadal to centennial timescales.

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PAGES launched 2k network that produced regional and global temperature and precipitation syntheses based on multi-proxy and multi-record to obtain a better understanding of regional and global climate change. The ISM affected the large area of Indian continent, and a local record may not be fully representative of changes in the ISM. Therefore, we produced regional syntheses based on five tree-ring $\delta^{18}O$ records from the ISM region. Two new records from northern India and central Nepal were obtained in this study, and were combined with three previously published records from northwestern India, western Nepal and Bhutan (Sano et al., 2012; Sano et al., 2013; Sano et al., 2017). The data were integrated in order to produce a regional tree-ring $\delta^{18}O$ record which was used to reconstruct the history of the ISM during the last several hundred years, and to investigate its possible driving mechanisms on various time scales.

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2 Materials and methods

2.1 Sampling sites

Five tree-ring cellulose $\delta^{18}O$ records were used to construct a regional climate signal for the southern Himalaya (Figure 1). Three records (Manali, in northwestern India; Humla, in western Nepal; and Wache, in Bhutan) were published previously (Sano et al., 2012; Sano et al., 2013; Sano et al., 2017). Two tree-ring cellulose $\delta^{18}O$ chronologies were constructed in this study. Core samples for *Cedrus deodara* near Jageshwar (29°38'N, 79°51'E, 3849 m a.s.l., JG) and *Abies spectabilis* near Ganesh (28°10'N, 85°11'E, 3550 m a.s.l.) were collected in 2009 and 2001, respectively. Information about each sampling site is shown in Table 1. In general, two core samples for each tree were collected at breast height using a 5-mm diameter increment corer. The cores were air dried at room temperature for 2-3 days and the surfaces were then smoothed with sand paper to render the ring boundaries clearly visible. The ring widths of the samples were measured at a resolution of 0.01mm using a binocular microscope with a linear stage interfaced with a computer (Velmex™, Acu-Rite). Cross dating was performed in the laboratory by matching variations in ring width from all cores to determine the calendar year of each ring. Quality control was conducted using the COFECHA computer program (Holmes, 1983).

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2.2 Cellulose extraction, isotope measurement and chronology development

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Four trees near Ganesh and three trees near Jageshwar, all with relatively wide rings, were selected for oxygen isotope analysis (Figures 2 & 3). The modified plate method (Xu et al., 2011; Xu et al., 2013b, Kagawa et al., 2015), based on the chemical treatment procedure of the Jayme-Wise method (Green, 1963; Loader et al., 1997), was used to extract α-cellulose. The plate method of extracting α-cellulose directly from the wood plate rather than from individual rings can reduce the α-cellulose extraction time (Xu et al., 2011). In addition, the modified plate method can reduce the amount of sample material lost during cellulose extraction, enabling sufficient material to be obtained to enable narrow rings to be measured by isotope ratio mass spectrometer (Xu et al., 2013b). There is no statistically significant difference between tree-ring $\delta^{18}O$ values obtained by the

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plate and conventional methods (Kagawa et al., 2015; Xu et al., 2013b). For the samples from the Humla site, every annual ring of five individual trees was split with a scalpel, and then the shavings were pooled for each year and subjected to cellulose extraction for each year (Sano et al., 2012).

Cellulose samples (sample weight, 120-260 μg) were wrapped in silver foil, and tree-ring cellulose oxygen isotope ratios ($^{18}O/^{16}O$) were measured using an isotope ratio mass spectrometer (Delta V Advantage, Thermo Scientific) interfaced with a pyrolysis-type high-temperature conversion elemental analyzer (TC/EA, Thermo Scientific) at the Research Institute for Humanity and Nature, Japan. Cellulose $\delta^{18}O$ values were calculated by comparison with Merck cellulose (laboratory working standard), which was inserted after every eight tree samples during the measurements. Oxygen isotope results are presented using the δ notation as the per mil (‰) deviation from Vienna Standard Mean Ocean Water (VSMOW): $\delta^{18}O = [(R_{sample}/R_{standard}) - 1] \times 1000$, where R_{sample} and $R_{standard}$ are the $^{18}O/^{16}O$ ratios of the sample and standard, respectively. The analytical uncertainty for repeated measurements of Merck cellulose was approximately ±0.15‰.

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The local chronology was produced by averaging all the individual series for a given site. The 95% confidence intervals (±1.96σ) for each year of the local chronology were calculated using annual $\delta^{18}O$ values of individual trees. It should be noted that the confidence intervals for the tree-ring chronology from Hulma, western Nepal cannot be calculated because the chronology was produced by pooling method, and therefore only single $\delta^{18}O$ value was measured for a year.

A regional tree-ring $\delta^{18}O$ chronology was produced using the two tree-ring $\delta^{18}O$ records from the JG and Ganesh sites and the three published tree-ring $\delta^{18}O$ records from the Manali, Humla and Wache sites. Specifically, every $\delta^{18}O$ chronology from the five sites was individually normalized over the period 1951-2000 CE, and then the resulting series were averaged to produce a regional Himalayan $\delta^{18}O$ record (H5 $\delta^{18}O$ record) for the entire period (Figure 4f). The 95% confidence intervals for the regional chronology were computed using annual $\delta^{18}O$ values of the five local chronologies. Only one chronology (JG) out of the five local chronologies spans an interval prior to 1742 CE, and therefore we mainly focus on the common interval 1743-2008 CE in this study.

2.3 Climate analyses and Statistical Analysis

In the northern Indian subcontinent, the monsoon season is from June to September. The summer monsoon season supplies 78% and 83% of the annual precipitation for Kathmandu and New Delhi, respectively. The Indian monsoon index (IMI) (Wang et al., 2001, http://apdrc.soest.hawaii.edu/projects/monsoon/definition.html), the intensity of monsoon circulation (Webster and Yang, 1992) and All India Rainfall (AIR, obtained from the Indian Institute of Tropical Meteorology, Pune, India, Mooley et al., 2016) were selected as proxies for the Indian summer monsoon in order to investigate the relationship between tree-ring cellulose $\delta^{18}O$ variations and the monsoon. In addition, we used the Royal Netherlands Meteorological Institute Climate Explorer (http://www.knmi.nl/) to determine spatial correlations between tree-ring cellulose $\delta^{18}O$, precipitation (GPCC V7, Schneider et al., 2015) and sea surface temperature (SST) values obtained from the National Climatic Data Center ERSST v4 data set (Huang et al., 2015). Two reconstructed ENSO indices (Emile-geay et al., 2013; McGregor et al., 2010) based on paleoclimate records (tree-ring, coral, sediment and ice core) were used to evaluate the ISM-ENSO relationship in the past. Temperature reconstructions for the Indian Ocean (Tierney et al., 2015) and the Tibetan Plateau (Cook et al., 2013; Shi et al., 2015; Wang et al., 2015), spanning the last 400 years, were used to obtain a record of the history of land-ocean thermal contrast. The land-ocean thermal contrast is equal to the land temperature minus the ocean temperature. Because uncertainty of the temperature reconstruction was provided as RMSE (Root Mean Square Error) in the previous studies, the uncertainty range for the land-ocean contrast was estimated as the sum of RMSE of land temperature and Indian Ocean SST for each year. The low-frequency signals together with uncertainties (>100 years) for the tree-ring oxygen isotope chronology and the land-ocean

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contrast were extracted by using a low-pass filter. The software "kSpectra Toolkit" was employed to calculate power spectrum of the regional tree-ring oxygen isotope chronology.

3 Results and discussion

3.1 Tree-ring δ[18]O variations in the southern Himalaya and a regional tree-ring δ[18]O record

The oxygen isotopes of four individuals of *Abies spectabilis* in Ganesh (GE, central Nepal) and three individuals of *Cedrus deodara* in Jageshwar (JG, northern India) were measured for the interval from 1801-2000 CE and 1621-2008 CE, respectively. Individual tree-ring $\delta^{18}O$ time series from four cores from central Nepal are shown in Figure 2a. The mean values (standard deviations) of the $\delta^{18}O$ time series from 224c, 233b, 235b, and 226a are 23.09‰ (1.22‰), 22.66‰ (1.27‰), 21.87‰ (1.12‰), and 22.94‰ (1.42‰), respectively, from 1901-2000 CE. The inter-tree differences in $\delta^{18}O$ values are small. The $\delta^{18}O$ values of the four cores exhibit peaks in 1813. The mean inter-series correlations (Rbar) among the cores range from 0.56-0.78 (Figure 2c), based on a 50-year window over the interval from 1801-2000 CE.

Three tree-ring $\delta^{18}O$ time series from northern India (JG) are shown in Figure 3a. The mean values (standard deviations) of the $\delta^{18}O$ time series from 101c, 102c, and 103a are 30.11‰ (1.49‰), 29.7‰ (1.62‰) and 29.47‰ (1.53‰), respectively, over the interval from 1694-2008 CE. Three tree-ring $\delta^{18}O$ time series in JG exhibit a consistent pattern of variations. The mean inter-series correlations (Rbar) among the cores range from 0.61-0.78 (Figure 3c), based on a 50-year window over the interval from 1621-2008 CE.

In northern Indian sub-continent, three long-term tree-ring $\delta^{18}O$ chronologies from northwestern India, western Nepal and Bhutan have been built up in previous studies (Sano et al., 2012; Sano et al., 2013; Sano et al., 2017, Figure 4). Two tree-ring $\delta^{18}O$ chronologies in this study and three tree-ring $\delta^{18}O$ chronologies in previous studies originate in monsoonal area (Figure

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1). Three tree-ring δ¹⁸O chronologies in northwestern India, western Nepal and Bhutan were controlled by monsoon season rainfall or PDSI (Sano et al., 2012; Sano et al., 2013; Sano et al., 2017, Table 1), and the two new tree-ring δ¹⁸O records obtained in the present study (JG and Ganesh) are negatively correlated with June-September PDSI in northern India (Table 1). In addition, the five tree-ring δ¹⁸O records for the Himalayan region are significantly correlated with one another at inter-annual time scale during the common period, and in most cases 31-year running averages of five tree-ring δ¹⁸O chronologies show significant correlations at multi-decadal time scale (Table 2). These results indicate that five tree-ring δ¹⁸O records reflect a common controlling factor that may be related to regional climate. Figure 4f represents the regional tree-ring δ¹⁸O chronology produced using the five local tree-ring chronologies. Because only one local chronology (JG) spans an interval prior to 1742 CE, we focus only on the interval from 1743-2008 CE in the following analysis.

3.2 Climatic signals in the regional tree-ring δ¹⁸O chronology

We assessed the potential of the H5 δ¹⁸O record as an indicator of past monsoon changes by correlating it with All India Rainfall (AIR), the Indian Monsoon Index (IMI) and the intensity of monsoon circulation. The results revealed a significant negative correlation with AIR (r = -0.5, p <0.001, n =138), IMI (r = -0.45, p <0.001, n =51) and the intensity of the monsoon circulation (r = -0.42, p <0.001, n =51) (Figure 5). In addition, the results of spatial correlation analyses reveal that the H5 δ¹⁸O record is negatively correlated with gridded June-September precipitation in northern India and Nepal (Figure 6). These findings indicate that the H5 δ¹⁸O record is capable of reflecting ISM changes from a statistical perspective.

Tree-ring δ¹⁸O has a close relationship with the ISM based on tree-ring cellulose oxygen isotope fractionation model. Precipitation δ¹⁸O and relative humidity are the two main factors controlling tree-ring δ¹⁸O (Roden et al., 2000), and both are related to ISM changes in the monsoonal area. There is a negative correlation between the ISM and precipitation δ¹⁸O in the monsoonal area (Vuille et al., 2005; Yang et al., 2016). Asian summer monsoon affects the δ¹⁸O of precipitation through the

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amount effect (Cai and Tian, 2016; Lekshmy et al., 2015; Dansgaard, 1964). A stronger summer monsoon usually brings more summer rainfall to the southern Himalaya. The removal of the heavier isotopes during the condensation process results in the oxygen isotopic depletion of the water vapor. The greater the total amount of precipitation, and the stronger the convection, the more the oxygen isotopic composition of the rainwater is affected by depletion (Lekshmy et al., 2014; Vuille et al., 2003), and this signal is reflected in tree-ring $\delta^{18}O$ values. In addition, monsoon-related factors (e.g. upstream rainout process) other than the ''amount effect'' may affect precipitation $\delta^{18}O$ significantly (Vuille et al., 2005). On the other hand, a stronger ISM leads to higher relative humidity, and a lower re-evaporation rate for rainfall or a reduced evaporation of leaf water in trees, resulting in less enriched tree-ring $\delta^{18}O$ values (Risi et al., 2008; Roden et al., 2000).

3.3 Interannual variability of the ISM inferred from the regional tree-ring $\delta^{18}O$ record

The results of spectral analysis using the multi-taper method (Mann and Lees, 1996) indicates that the H5 regional tree-ring $\delta^{18}O$ record contains several high-frequency periodicities (4 and 5 years), as well as lower frequency periodicities at a confidence level greater than 99% (Figure 7). This indicates that interannual and long-term variability of the ISM was dominant characteristic feature during the last several hundred years. The interannual variability (4-5 years) of the H5 record is similar to that of ENSO, suggesting a possible relationship (Mason, 2001). The spatial correlation between the H5 record and SST also reveals a close relationship between the ISM and ENSO (Figure 8). Other high-resolution ISM-related records from monsoonal Asia also exhibit similar inter-annual periodicities (Sun et al., 2016; Xu et al., 2013a; Yadava and Ramesh, 2007). In addition, meteorological data indicates that ENSO has had a significant influence on changes in the ISM change (Kumar et al., 1999; Webster et al., 1998).

However, observational data indicate that the ENSO-ISM relationship is not consistent over time because of the southeastward shift of the descending limb of the Walker circulation and the varying monsoonal impact of the different patterns of El Niño

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(Kumar et al., 1999; Kumar et al., 2006). Thirty-one-year running correlations between the H5 regional tree-ring $\delta^{18}O$ record and two reconstructed ENSO indices (Emile-geay et al., 2013; Figure 9a red line; McGregor et al., 2010, Figure 9a blue line) shared similar variations, indicating that this type of unstable ISM-ENSO relationship occurred during the last 250 years. It should be noted that these two ENSO reconstructions, which shared similar proxies such as tree-ring data from southwest United States and Mexico, were highly correlated with each other. The reason causing the unstable ENSO-ISM relationship may be responsible for the two different patterns of El Niño (developed in eastern-Pacific or central-Pacific) yielding different monsoon impacts (Kumar et al., 2006). In addition, other factors, such as Indian Ocean SST, also influence the ISM-ENSO relationship (Ashok et al., 2001; Abram et al., 2008; Wu and Kirtman, 2004).

Most proxy-based ENSO reconstructions focused on canonical El Niño events (eastern-Pacific El Niño) that are characterized by unusually warm sea surface temperatures (SST) in the eastern equatorial Pacific (Gergis and Fowler, 2009; Li et al., 2011; McGregor et al., 2010); while a different type of El Niño (central-Pacific El Niño) is characterized by warm SSTs in the central Pacific, flanked by cooler SSTs to the west and east. The latter is termed El Niño Modoki or the central-Pacific El Niño (Ashok et al., 2007; Kao and Yu, 2009; Yeh et al., 2009), and it has a different effect on the ISM (Kumar et al., 2006). In order to characterize in detail the relationship between the ISM and the two types of ENSO during the last several hundred years, spatial configuration of the SST anomalies reconstruction based on long-term coral-based records from the tropical eastern and central Pacific are needed. However, such high-resolution, continuous and robust SST reconstructions are scarce. Even in the equatorial Pacific 'centre of action' (COA) of ENSO, the COA SST reconstruction is not considered robust prior to 1850 CE (Wilson et al., 2010). A new eastern Pacific SST record for the last 400 years is not reliable during the interval from 1635-1702 CE and 1840-1885 CE (Tierney et al., 2015). In addition to ENSO's influences, Indian Ocean SST changes also have significant influences on ISM (Ashok et al., 2001), which was evident by spatial correlations between the H5 tree-ring $\delta^{18}O$ chronology and SST (Figure 8). Indian Ocean SST changes that were shown to be strongly related to ENSO changes also

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affect ISM-ENSO relationships (Wu and Kirtman, 2004). Numerical simulations showed that ISM-ENSO relationship reversed when Indian Ocean was decoupled from the atmosphere (Wu and Kirtman, 2004). Thirty-one year running correlations between Indian Ocean SST reconstruction (Tierney et al., 2015) with two ENSO indices reconstruction were used to evaluate the relationship between Indian Ocean SST and ENSO during the last 250 years (Figure 9b), which indicated that Indian Ocean SST showed consistent change with ENSO during most of the period but decoupled with ENSO variability during the period of 1820–1860. The ISM-ENSO relationship was weak or reversed when Indian Ocean SST show negative correlations with ENSO. Besides, observed data and atmospheric general circulation model result revealed that ENSO's influences on ISM was reduced when a strong positive Indian Ocean Dipole (IOD) event simultaneously occurs with El Niño, and ISM-ENSO correlation is low when IOD-ISM correlation is high (Ashok et al., 2001; 2004). The weak ISM-ENSO correlation may be related to enhanced IOD-ISM correlation during the past 250 years (Figure 9a). However, absence of long-term IOD reconstruction impeded the investigation on ISM-ENSO and ISM-IOD relationship in the past. The future availability of longer, annually resolved marine records that provide spatial configuration of SSTs in the tropical Pacific and Indian Ocean will improve our understanding of the relationship between the ISM and the two types of ENSO/Indian Ocean SST.

3.4 Long-term of the ISM inferred from the regional tree-ring $\delta^{18}O$ record

The long-term changes of regional tree-ring $\delta^{18}O$ record exhibits a decreasing trend from 1743 to 1820 CE and an increasing trend since 1820 CE (Figure 10c), which may indicate a weakening trend of the ISM during the interval from 1820-2000 CE. A reduction in the monsoon precipitation/relative humidity of the ISM in the last 200 years is also evident in other areas influenced by the ISM. Maar lake sediments in Myanmar exhibit a decreasing trend of monsoonal rainfall since 1840 CE (Sun et al., 2016); a tree-ring $\delta^{18}O$ record from southeast Asia exhibits a drying trend since 1800 CE (Xu et al., 2013a); a stalagmite $\delta^{18}O$ record from southwest China reveals an overall decreasing trend in monsoon precipitation since 1760 CE (Tan et al., 2016); and in southwest China, tree-ring $\delta^{18}O$ and maar lake records indicate reduced monsoon precipitation/relative

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humidity/cloud cover since 1840 or 1860 CE (Chu et al., 2011; Grießinger et al., 2016; Liu et al., 2014; Wernicke et al., 2015; Xu et al., 2012). Monsoon precipitation in northwestern India shows a significant decreasing trend during the period of 1866-2006 (Bhutiyani et al., 2010).

However, in contrast, marine sediment records from the Western and Southeastern Arabian Sea exhibit an increasing trend of ISM strength over the last four centuries (Anderson et al., 2002; Chauhan et al., 2010). A recent study indicated that the contrasting trends in the ISM during the last several hundred years observed in geological records resulted from the different behavior of the Bay of Bengal branch and Arabian Sea branch of the ISM (Tan et al., 2016), and the Bay of Bengal branch of ISM weakened while intensity of Arabian Sea branch of the ISM increased during the last 200 years. However, the tree-ring $\delta^{18}O$ record in northwestern India, influenced significantly by the Arabian Sea branch of the ISM, exhibits a drying trend since 1950 CE (Sano et al., 2017), which does not support the idea of a strengthening Arabian Sea branch of the ISM (Anderson et al., 2002). Moreover, there are no calibrated radiocarbon dates for the last 300 years for the two records from the Arabian Sea (Anderson et al., 2002a; Chauhan et al., 2010). We suggest that further high-resolution and well-dated ISM records from western India are needed to improve our understanding of the behavior of the ISM. Although reconstructed All India monsoon rainfall does not show a significant decreasing trend during the period of 1813-2005 (Sontakke et al., 2008), only four stations have data extending back to 1826 CE, and are located in central or south India. Monsoon season drying trend in the Himalaya revealed by the H5 regional tree-ring $\delta^{18}O$ record may indicate that inland areas appear to be particularly sensitive to the weakening of monsoon circulation, as indicated by Sano et al. (2013).

The H5 record suggests a decreasing trend of ISM strength, which is supported by most of the other well-dated and high-resolution ISM records in ISM margin areas (Xu et al., 2012, 2013a, Liu et al., 2014, Sun et al., 2016). A previous study has indicated that solar irradiance has a significant influence on the ISM on multi-decadal to centennial timescales, and that reduced

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solar output is correlated with weaker ISM winds (Gupta et al., 2005). However, solar irradiance has increased since 1810-1820 CE (Bard et al., 2000; Lean et al., 1995) and therefore it cannot be the main reason for the weaker ISM since 1820 CE. Atmospheric CO_2 content is another forcing factor for the ISM, with higher atmospheric CO_2 content resulting in a stronger ISM (Kripalani et al., 2007; Meehl and Washington, 1993). Thus, the increased atmospheric CO_2 content during the last 200 years is unlikely to be the reason for the weakened ISM.

Firm evidence of a weakening land-ocean thermal gradient over South Asia has been shown using long-term observations and model experiments by Roxy et al (2015). Rapid warming in the Indian Ocean and relatively subdued warming over the Indian subcontinent both contribute to the weakening land-ocean gradient, and thereby reduce amounts of precipitation over parts of South Asia (Roxy et al., 2015). The history of land-ocean thermal contrasts is reconstructed based on temperature differences between the Tibetan Plateau and the Indian Ocean (Figure 10a), and centennial variations of land-ocean thermal contrasts are shown in Figure 10b. Three reconstructed land-ocean thermal contrasts showed a decreasing trend since the early 19th century (Figure 10b), and the H5 record exhibits a similar pattern of changes on a centennial scale (Figure 10c). The decreasing land-ocean thermal contrast since the early 19th century has potentially resulted in a weaker ISM, which is consistent with the increasing trend of the H5 record since 1820 CE. It should be noted, however, while the long-term trends are overall consistent between our regional tree-ring chronology and the land-ocean thermal contrasts, possible propagation of uncertainty for the long-term land-ocean gradient data should be kept in mind for interpretation. Aerosol emissions may be another reason to cause weakened ISM. Because the aerosol-induced differential cooling of the source and nonsource regions resulted in not only reduced local land-ocean surface thermal contrast but also weaken large-scale meridional atmospheric temperature gradients, both of which caused weakening Indian summer monsoon circulation (Bollasina et al., 2011; Cowan and Cai, 2011). Long-term aerosol emissions record is needed to evaluate aerosol emission's influences on ISM in the past.

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4 Conclusions

We have combined three published tree-ring cellulose $\delta^{18}O$ records (from northwestern India, western Nepal and Bhutan) with two new tree-ring cellulose $\delta^{18}O$ records (from northern India and central Nepal) to produce a regional record (H5) for the northern Indian sub-continent for the interval from 1743-2008 CE. This record is significantly and negatively correlated with All India Rainfall (r = -0.5, p <0.001, n =138), the Indian monsoon index (r = -0.45, p <0.001, n =51) and the intensity of the monsoon circulation (r = -0.42, p <0.001, n =51). Spatial correlation analysis indicates that the H5 record is negatively correlated with June-September precipitation in the northern Indian sub-continent. The Indian summer monsoon (ISM) controls the tree-ring cellulose $\delta^{18}O$ record via its effects on the $\delta^{18}O$ of precipitation and relative humidity. Based on the observed statistical relationships and the physical mechanisms linking variations in tree-ring $\delta^{18}O$ and the ISM, regional tree-ring cellulose $\delta^{18}O$ chronology in the northern Indian sub-continent is a suitable high-resolution proxy for past ISM changes.

Significant correlations between inter-annual changes of tree-ring $\delta^{18}O$ and ENSO indices indicate that the ISM was affected by ENSO. However, the ISM-ENSO relationship was not consistent in the past, and may be affected by different type of ENSO and Indian Ocean SST. A robust, high-resolution and continuous SST spatial reconstruction from the 'centre of action' area of the Pacific and Indian Ocean would shed more light on this relationship. Long-term variations in the H5 record may reveal a trend of weakened ISM intensity since 1820 CE, which is also evident in various high-resolution ISM records from southwest China and Southeast Asia. Reduced land-ocean contrasts since 1820 CE, together with increased anthropogenic aerosol emissions during the last hundred years, may have contributed to the weakened ISM.

Data availability:

The tree-ring cellulose oxygen isotope data in this paper are available from NOAA Paleoclimatology Datasets (https://www.ncdc.noaa.gov/data-access/paleoclimatology-data). The Hulma $\delta^{18}O$ chronology should be available at this link:

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Acknowledgments:

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Table 1. Tree-ring cellulose oxygen isotope data sets used in this study

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No.	Sample ID	Location	Period	Tree species	Mean	Climatic response of tree-ring $\delta^{18}O$	Data source	Data Citations
1	Manali	32˚13′N, 77˚13′E, 2700 masl, India	1768-2008	*Abies pindrow*	29.97‰	Regional JJAS PDSI *r* =-0.67	Sano et al., 2017	Sano et al., 2017c
2	JG	29°38′N, 79°51′E, 3849 masl, India	1641-2008	*Cedrus deodara*	30.39‰	Regional JJAS PDSI *r* =-0.50	This study	Xu et al., 2017a
3	Hulma	29°51′N, 81°56′E, 3850 masl, Nepal	1778–2000	*Abies spectabilis*	25.94‰	Regional JJAS PDSI *r* =-0.73	Sano et al., 2012	Sano et al., 2017a
4	Ganesh	28°10′N, 85°11′E, 3550 masl, Nepal	1801-2000	*Abies spectabilis*	23.01‰	Regional JJAS PDSI *r* =-0.55	This study	Xu et al., 2017b
5	Wache	27°59′N, 90°00′E, 3500 masl, Bhutan	1743-2011	*Larix griffithii*	19.38‰	Regional JJAS PDSI *r* =-0.59	Sano et al., 2013	Sano et al., 2017b

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Table 2: Correlation coefficients between the tree-ring $\delta^{18}O$ records from different sampling locations

R (annual)	Manali	JG	Hulma	Ganesh
JG	0.50*			
Hulma	0.52*	0.51*		
Ganesh	0.47*	0.66*	0.61*	
Wache	0.23*	0.26*	0.37*	0.52*

R (multi-decadal)	Manali	JG	Hulma	Ganesh
JG	0.36*			
Hulma	0.37*	0.64*		
Ganesh	-0.03	0.94*	0.66*	
Wache	0.11	0.39*	0.38*	0.70*

*$p<0.01$

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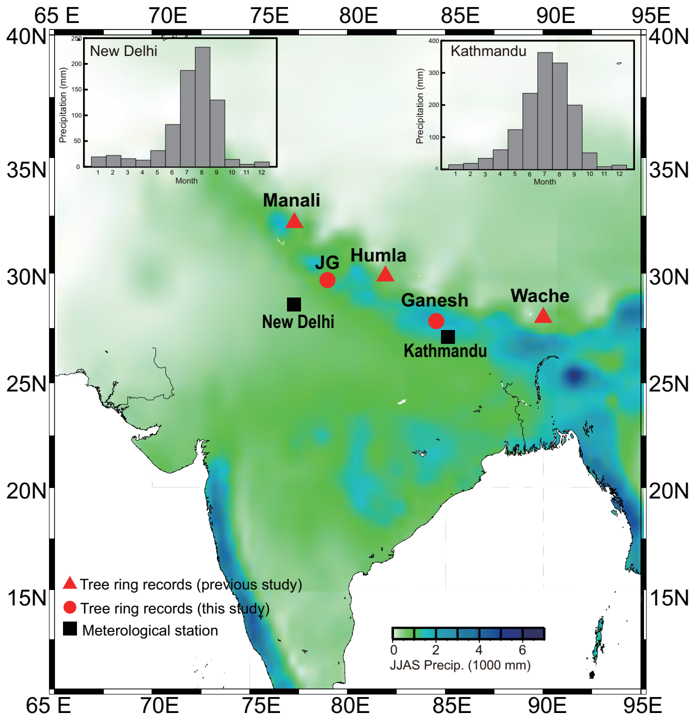

Figure 1. Map of the subcontinent showing tree-ring sites and color coded climatological monsoon precipitation from June to September. Insets show climatology of monthly precipitation at Kathmandu and New Delhi.

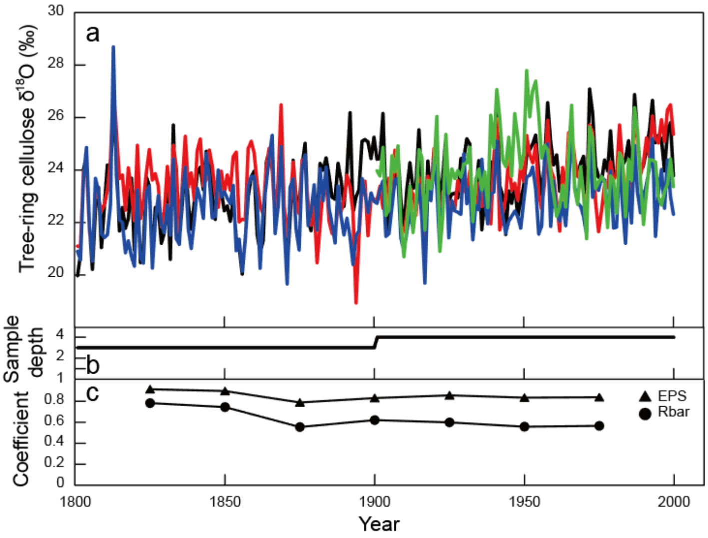

Figure 2. a: Tree-ring $\delta^{18}O$ series of four individual trees: b: sample size, c: running EPS and Rbar statistics used 50-year windows and a 25-year lag for samples near Ganesh, Nepal.

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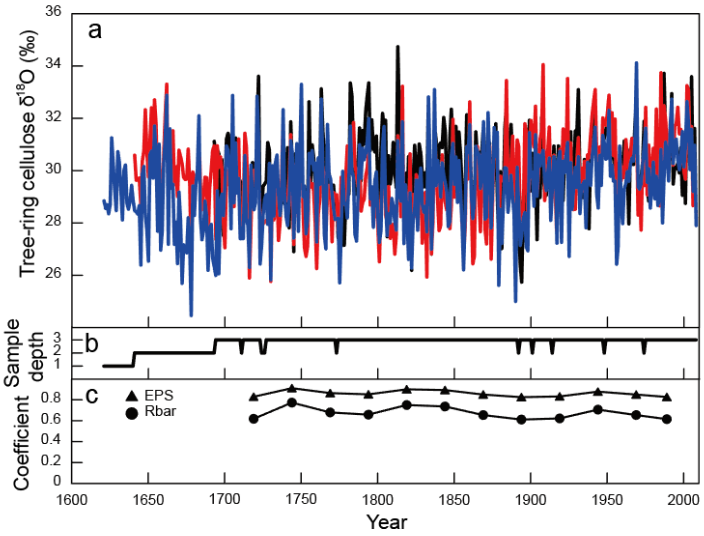

Figure 3. a: Tree-ring $\delta^{18}O$ series for three individual trees: b: sample size, c: running EPS and Rbar statistics using 50-year windows and a 25-year lag for samples near Jageshwar, India.

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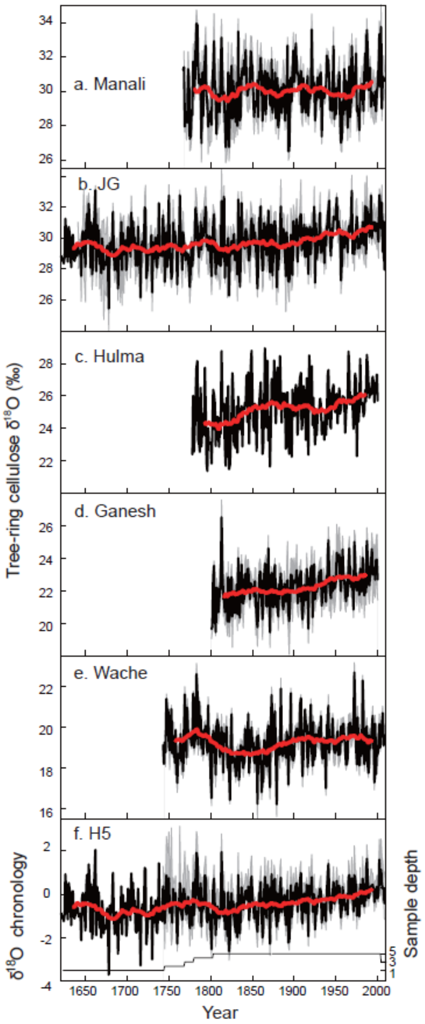
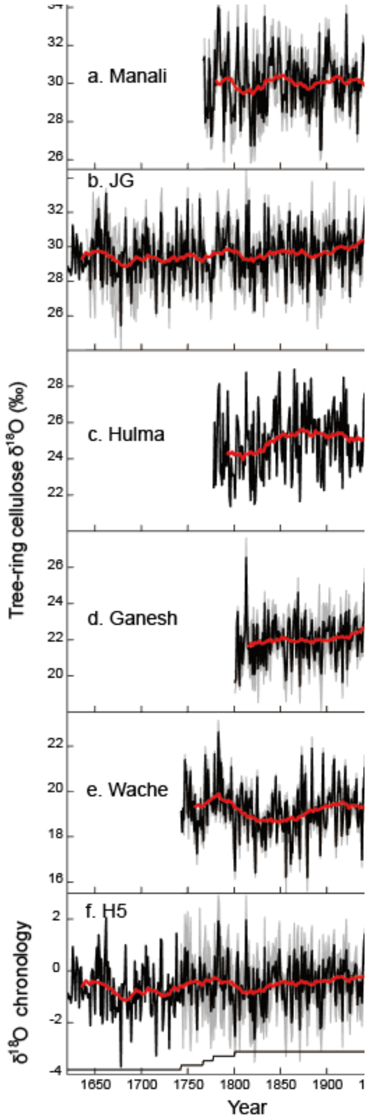
削除: Age profile


a. Manali
b. JG
c. Hulma
d. Ganesh
e. Wache
f. H5
Tree-ring cellulose δ18O (‰)
δ18O chronology
Sample depth
Year
1650
1700
1750
1800
1850
1900
1950
2000

30

Figure 4: Tree-ring oxygen isotope chronologies from five sites (a-e) and the regional tree-ring oxygen isotope chronology (f). (black line: mean values for all samples; red line: 31-year running average for the chronology; gray shadows: the 95% confidence intervals for the local and regional chronologies.)



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削除: Tree ring…ree-ring oxygen isotope chronologies from five sites (a-e) and the regional tree ring

削除: inter-tree and inter-site variations for tree-ring oxygen isotopes.

削除: the 95% (±1.96σ) confidence limits

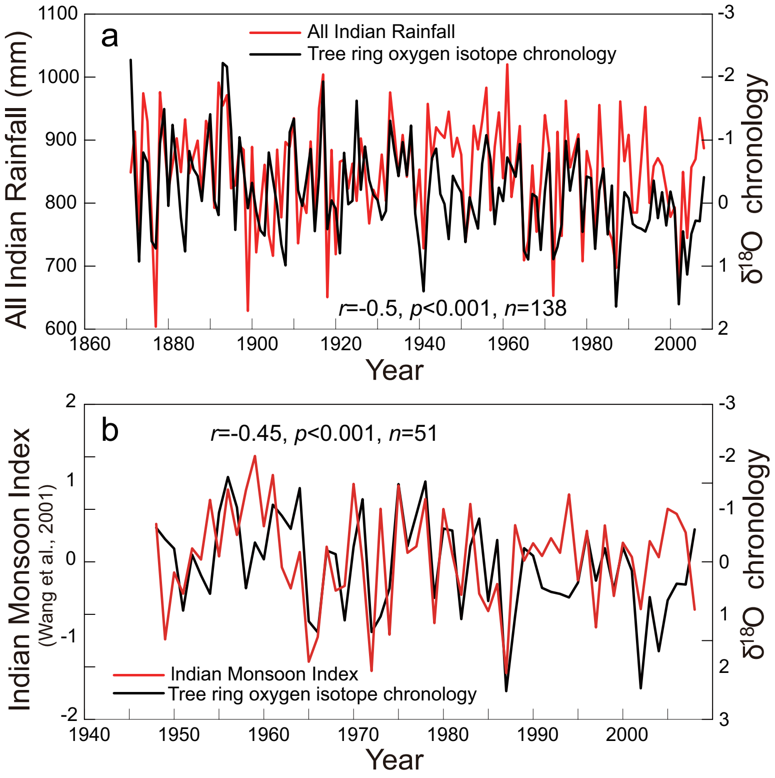

Figure 5. Comparison of the H5 regional tree-ring $\delta^{18}O$ chronology with the All India Rainfall (a) and Indian Monsoon Index (b).

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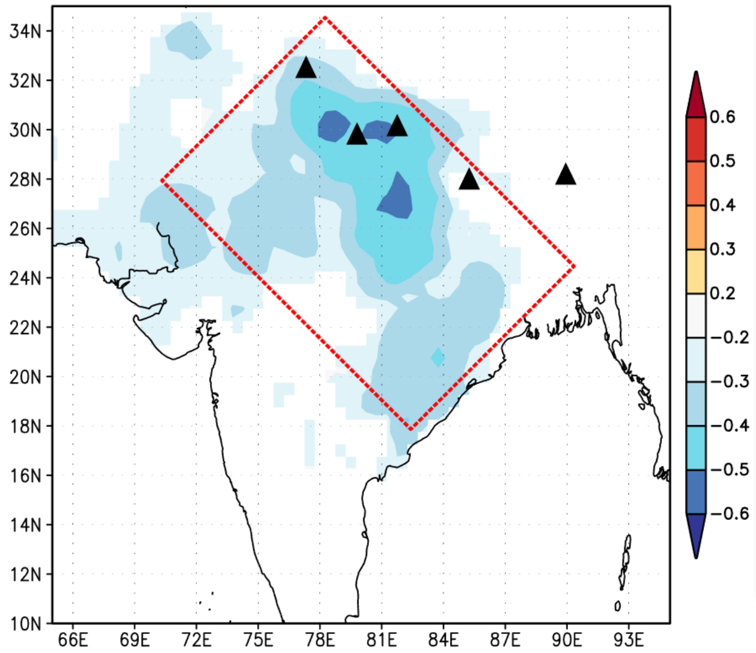

Figure 6. Spatial correlations between the H5 regional tree-ring $\delta^{18}O$ record with June-September precipitation from GPCC V7 over interval from 1901-2008 CE. Only correlations significant at the 95% level are shown.

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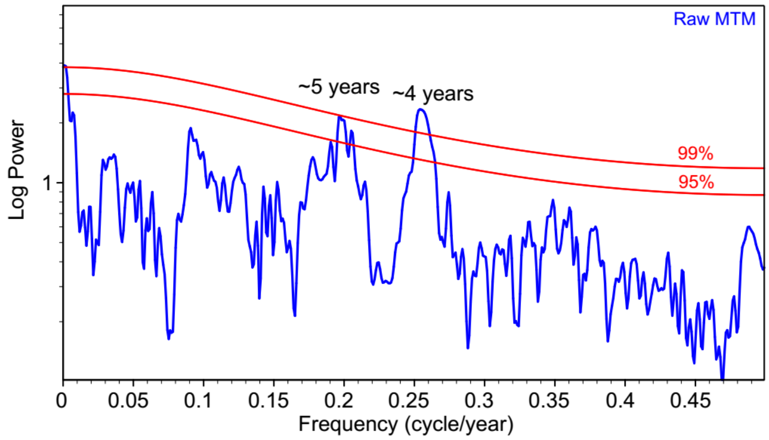
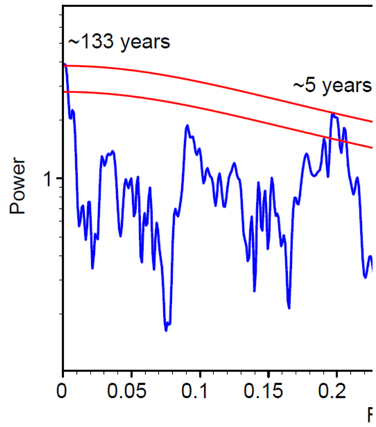


Figure 7. Multi-taper power spectra for the H5 regional tree-ring $\delta^{18}O$ record.



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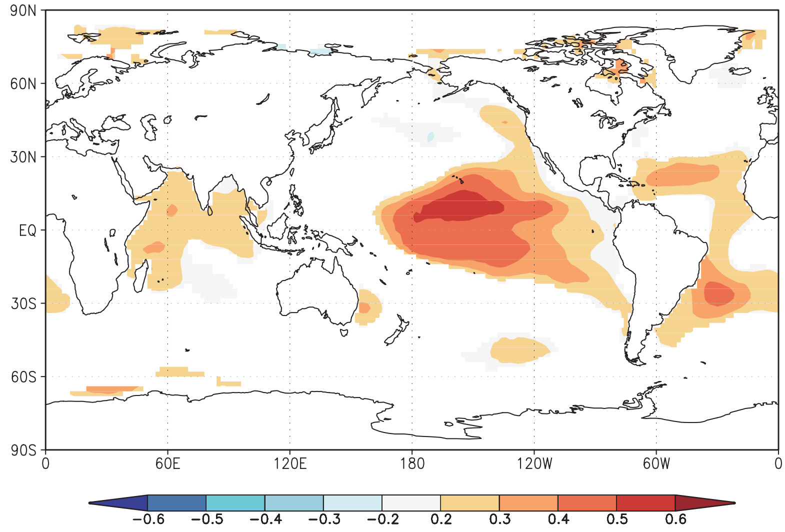

Figure 8. Spatial correlations between the H5 regional tree-ring $\delta^{18}O$ record with May-September SST over the interval from 1871-2008 CE. Only correlations significant at the 95% level are shown.

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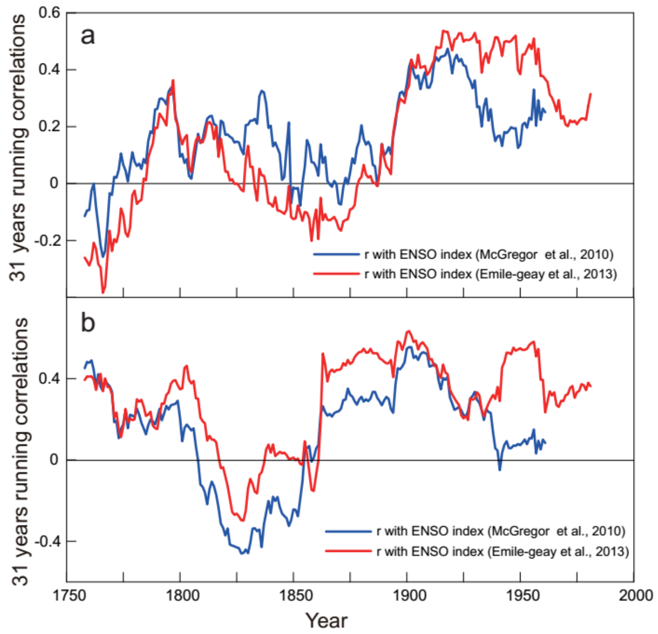

Figure 9. Thirty-one-year running correlations between two ENSO reconstruction and the H5 regional tree-ring $\delta^{18}O$ record (a), and Indian Ocean SST reconstruction (b).

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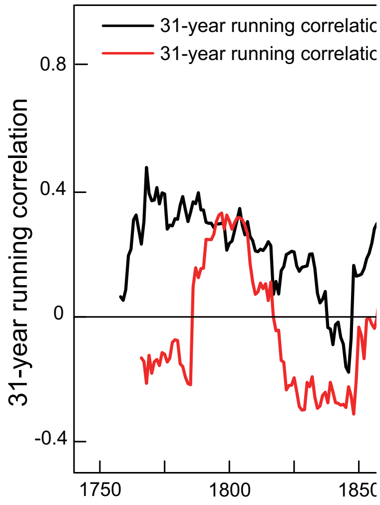

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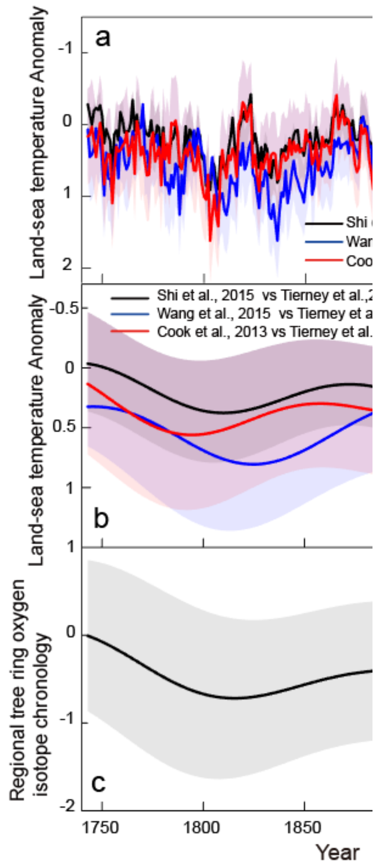
削除: and twofour reconstructed ENSO-related indices.



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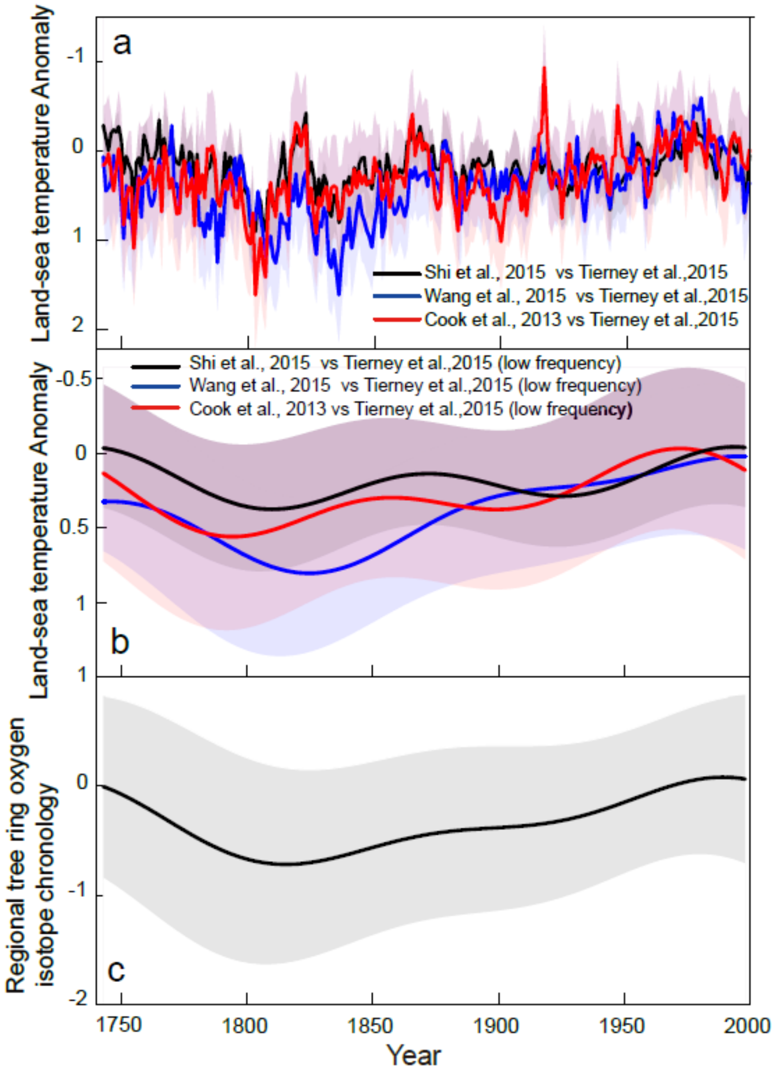

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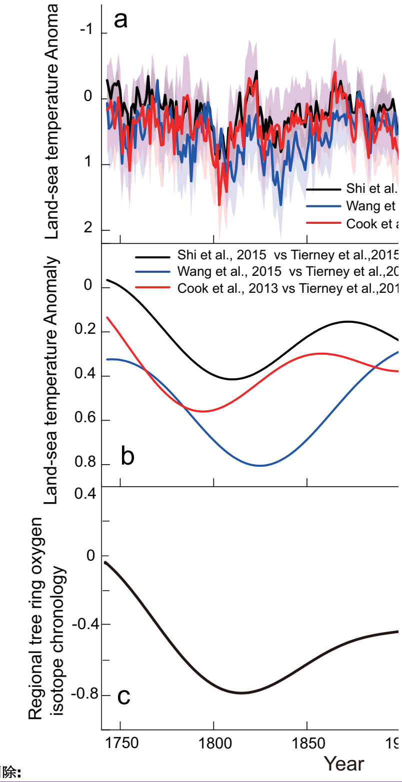
Figure 10. a: Land-ocean temperature anomaly based on three summer temperature reconstruction for the Tibetan Plateau and one Indian Ocean SST reconstruction; b and c: low frequency variations of land-sea thermal contrasts and the H5 regional tree-ring δ[18]O chronology. Shades with different colours indicate uncertainty for each time series.



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削除: sea…tT…mperature aA

書式変更: 1
行の文字数を指定時に右のインデント幅を自動調整する,
日本語と英字の間隔を自動調整する,
日本語と数字の間隔を自動調整する, タブ: 65.21 字(なし)

削除: centennial

削除: n

削除: tree ring…ree-ring δ[18]O chronology.

削除: .

書式変更: フォント:(日) 宋体, (言語 1) 中国語 (中国)

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Explain what data and how to calculate the land-sea thermal contrast.

The 95% (±1.96σ) confidence limits for each chronology and the regional chronology were calculated to show the uncertainty of each chronology and the regional chronology, respectively (except for the tree-ring chronology from Hulma, western Nepal, because the chronology was produced by pooling method, and therefore the uncertainty of this chronology was not able to show).

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3.5 Comparison of regional tree ringtree-ring $\delta^{18}O$ record with speleothem $\delta^{18}O$ record in northern India

The H5 regional tree ringtree-ring δ^{18}O record does not exhibit significant decadal to multi-decadal periodicities (Figure 7), while the main spectral component of high-resolution speleothem δ^{18}O records (a proxy of ISM rainfall in northern and central India) consists of multi-decadal periodicities (~15, 20, 30, 60 and 70 years) (Sinha et al., 2011; Sinha et al., 2015). This inconsistency may be the result of the different types of proxy record used together with micro-environmental differences between the sampling sites. Although decadal to multi-decadal variability of the H5 tree ringtree-ring δ^{18}O record is not strongly developed, the record does contain decadal to multi-decadal changes. Decadal to multi-decadal variability was extracted using bandpass filters (15-80 years) (Figure 11, red line). From the perspective of decadal to multi-decadal changes, the H5 record shares similarities with the speleothem record in the period of 1743-1800 and 1960-2000, while the H5 record are out-of-phase with speleothem δ^{18}O records during several intervals (Figure 11).

Based on the oxygen isotope fractionation theory, tree ringtree-ring $\delta^{18}O$ and speleothem $\delta^{18}O$ should share similar changes (Managave, 2014) if both of them inherit a common source water $\delta^{18}O$ signal, as shown by Ramesh et al. (2013). The following reasons may cause incoherence between regional tree ringtree-ring $\delta^{18}O$ and speleothem $\delta^{18}O$. Other controlling factors differentially affect tree ringtree-ring $\delta^{18}O$ and speleothem $\delta^{18}O$ values. Relative humidity has an important impact on tree ringtree-ring $\delta^{18}O$ (Roden et al., 2000). Lower relative humidity result in enhanced evaporative enrichment of leaf water and then higher tree ringtree-ring cellulose $\delta^{18}O$, while the relative humidity may not affect speleothem $\delta^{18}O$ when relative humidity does not correlate with precipitation $\delta^{18}O$ (Managave, 2014). Model resultsBased on tree-ring and speleothems oxygen isotopes fractionation model, the correlation between simulated tree-ring and speleothem $\delta^{18}O$ decreased rapidlyshow that relative humidity's influences on the correlation between tree ringtree-ring $\delta^{18}O$ and speleothem $\delta^{18}O$ is more pronounced in the regions where the variation of relative humidity during the growing season exceeds 1% (Managave, 2014). In contrast, the cave epikarst dynamics affect speleothems $\delta^{18}O$ significantly (Lachniet, 2009). The infiltrating water from different rainfall events may be stored and mixed in the epikarst. Lag times of $\delta^{18}O$ values in drip waters relative to rainfall are several years or decades in some locations (Lachniet, 2009), and a slow transit time smoothed climate signal. These processes may result in different source water for tree ringtree-ring and speleothem. In addition, limited three ^{230}Th dates points (3 control points) and relative large age uncertainty (9-31 years) of speleothems δ^{18}O time series during the common period of 1743-2000 and uncertainty of H5 regional tree-ring δ^{18}O chronology may result in the incoherence between tree ringtree-ring and speleothems δ^{18}O. Long-term process-based study on tree ringtree-ring δ^{18}O and speleothem δ^{18}O variations in same sampling site in future study are needed for a better understanding for climatic implication of two proxies.

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Wilson, R., Tudhope, A., Brohan, P., Briffa, K., Osborn, T., and Tett, S.: Two-hundred-fifty years of reconstructed and modeled tropical temperatures, Journal of Geophysical Research, 111, C10007, 2006.

Wilson, R., Tudhope, A., Brohan, P., Briffa, K., Osborn, T., and Tett, S.: Coral-based Tropical Sea Surface Temperature Reconstruction, World Data Center for Paleoclimatology, https://www.ncdc.noaa.gov/paleo-search/study/6359, 2006.

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Tree ring

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Tree ring

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sea

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tree ring

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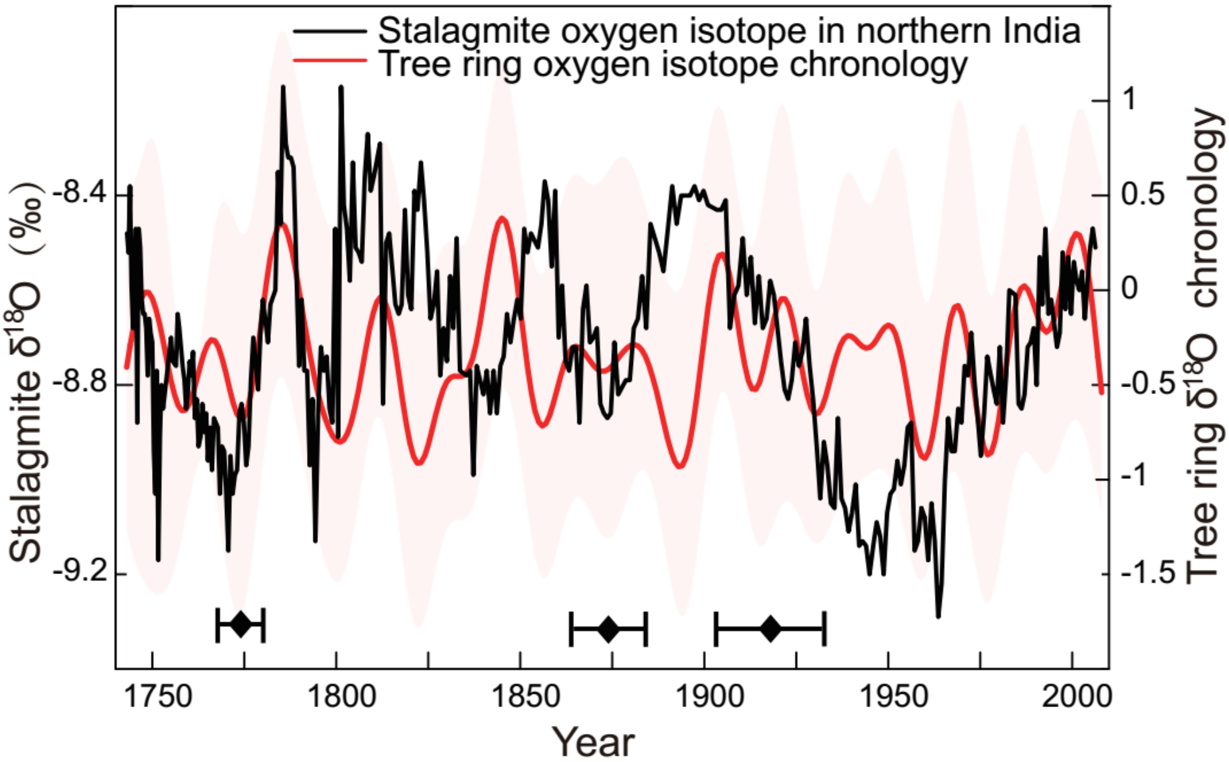
Stalagmite oxygen isotope in northern India
Tree ring oxygen isotope chronology
Stalagmite δ18O (‰)
Tree ring δ18O chronology
-8.4
-8.8
-9.2
1
0.5
0
-0.5
-1
-1.5
1750
1800
1850
1900
1950
2000
Year

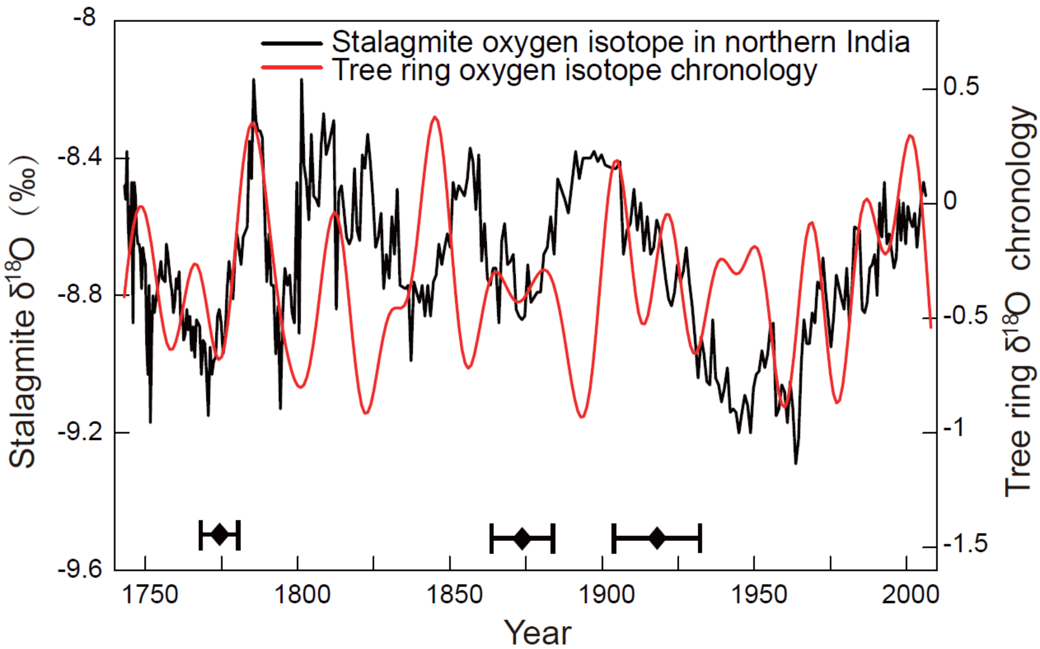
Stalagmite oxygen isotope in northern India
Tree ring oxygen isotope chronology
Stalagmite δ18O (‰)
Tree ring δ18O chronology
-8
-8.4
-8.8
-9.2
-9.6
0.5
0
-0.5
-1
-1.5
1750
1800
1850
1900
1950
2000
Year

Figure 11. Comparison between multi-decadal regional tree ringtree-ring $\delta^{18}O$ variations (red line) with stalagmite $\delta^{18}O$ changes (black line) in northern India. Rhombus with error indicates the ^{230}Th dates with uncertainty in stalagmite $\delta^{18}O$ chronology. Shades indicate uncertainty for regional tree-ring $\delta^{18}O$ chronology.