Dear editor,

Thank you very much for your letter concerning the manuscript entitled "Decreasing Indian summer monsoon in northern Indian sub-continent during the last 180 years: evidence from five tree cellulose oxygen isotope chronologies. We found the reviewers' comments helpful, and have made corrections accordingly in revised manuscript. Our responses below, which follow each comment.

Best wishes,

Masaki Sano on behalf of all authors

1: Referee #1

The authors attempted to reconstruct long-term Indian monsoon rainfall or intensity variations based on tree-ring oxygen isotope chronologies produced from northern part of the Indian subcontinent. They developed two new isotope chronologies spanning the past two centuries or more. Combined with existing tree-ring oxygen isotope records, they produced a so-called regional composite chronology which is regarded as an indicator of the Indian summer monsoon intensity. Further, the authors explored variation characteristics of the regional composite and potential driving mechanism by the way of statistical comparison. One main conclusion is that the intensity of the Indian summer monsoon exhibits a decreasing trend since the early nineteenth century. However, this conclusion is difficult to assess, and it might be subject to large uncertainties since they did not show the comparison of all available five tree-ring oxygen records. Furthermore, observed all Indian rainfall record does not show a decreasing trend according to much longer observational data. It needs much more evidence to validate. At any rate, given that the high-resolution proxy records are still sparse in this region, their effort is expected to add new contribution to the knowledge of regional climate variability. In general the methodology used here is simple and routine in dendrochronological study. This work is worthy of publication in the Climate of the Past. However, there are some questions should be clarified or explained before it is ready to go.

Specific comments:

1) The main conclusion in this manuscript is that the Indian summer monsoon strength decreased during the last 180 years. To confirm the robustness of this conclusion, much more evidence and discussion are needed to compliment using all available proxy records together with some statistical approach. Furthermore, it is necessary to show a comparison of five isotope chronologies from all five sites. In so soing, one can see how different they are on low-frequency variations, particularly for the time span from 1820 AD till at present. Another concern is why the authors do not use any ring width chronologies into discussion since a large number of chronologies have been published in the study region. It is no problem for ring width to retain century scale climatic signals due to long-lived species used in producing the chronologies.

Answer: In previous manuscript, we compared five isotope chronologies from all five sites in Figure 4a. Based on your helpful suggestion, we added the comparisons among five oxygen isotope chronologies from all sites in new Figure 4. Please see the new

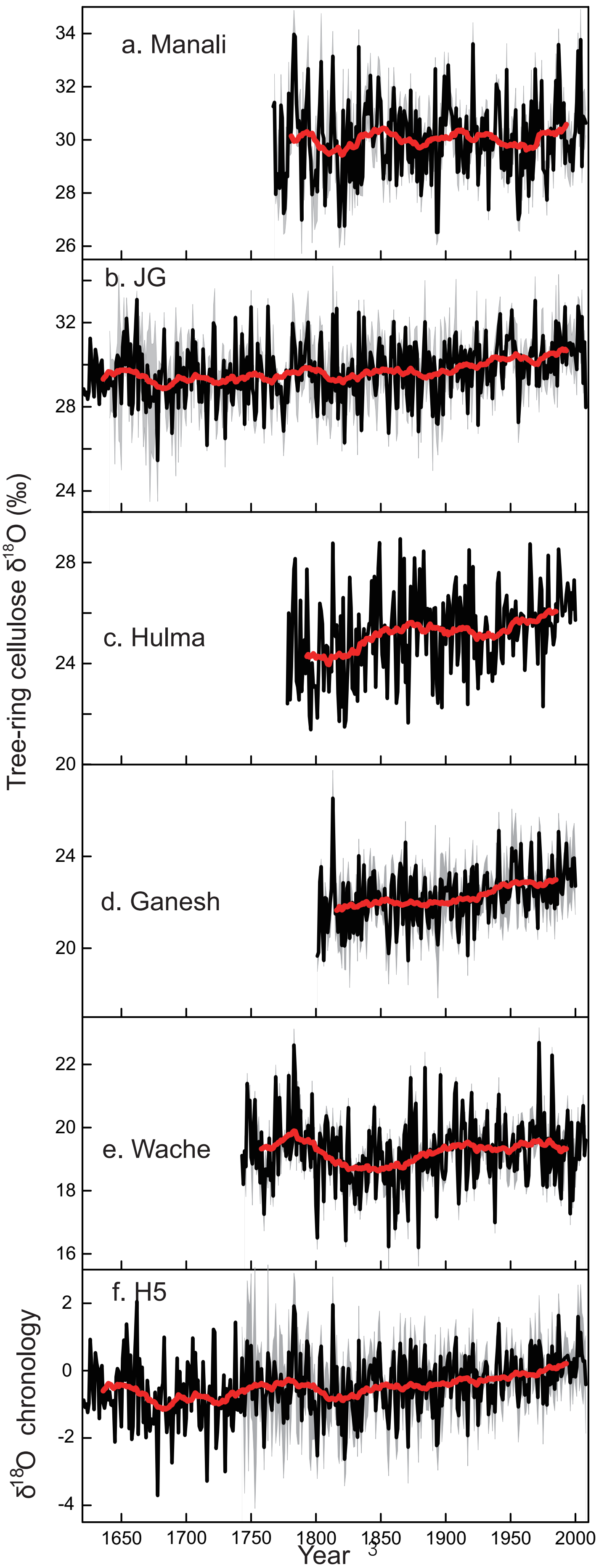
Figure 4 in revised manuscript or the following Figure (red line: 31-year running average; black line: mean value oxygen isotopes from all trees; gray shadows: the 95% (±1.96σ) confidence limits to show the uncertainty of each chronology and regional tree ring oxygen isotope chronology, respectively (except for tree ring oxygen isotope chronology in Hulma, western Nepal, because the tree ring oxygen isotopes chronology was produced by pooling method, and therefore the uncertainty of this chronology was not able to show.).

Yes, there are many ring width chronologies in the study area. There are two reasons that we do not use these ring width chronologies for reconstructing Indian summer monsoon history. 1) Most of ring width chronologies in the study area mainly reflected the climate in spring rather than summer. For example, Cook et al., (2003, International Journal of climatology) reconstructed Kathmandu Temperature based on ring width chronologies. Although Yadav et al., (2014, Quaternary International) reconstructed Februarye-May precipitation using tree-ring width data of Himalayan cedar. Trees throughout the region do not show any direct responses to summer monsoon rainfall (June–September). 2) Teak from Kerala, Southern India reveals that low growth years (narrow rings) are significantly associated with deficient Indian rainfall (DIR). However, normal or above normal rainfall is not consistently reflected as higher tree growth, possibly due to a moisture threshold being reached, above which trees can no longer respond (Borgaonkar et al., 2010, Paleo3). Because the higher tree growth cannot record the signal of strong rainfall, ring width chronology of teak in Southern India was not used for Indian summer monsoon reconstruction.

Borgaonkar H, Sikder A, Ram S, et al. El Nino and related monsoon drought signals in 523-year-long ring width records of teak (Tectona grandis LF) trees from south India. Palaeogeography Palaeoclimatology Palaeoecology, 2010, 285(1):74-84.

Cook E R, Krusic P J, Jones P D. Dendroclimatic signals in long tree-ring chronologies from the Himalayas of Nepal. International Journal of Climatology, 2003, 23(7):707-732.

Yadav R R, Misra K G, Kotlia B S, et al. Premonsoon precipitation variability in Kumaon Himalaya, India over a perspective of ~300 years. Quaternary International, 2014, 325:213-219.



a. Manali
b. JG
c. Hulma
d. Ganesh
e. Wache
f. H5
Tree-ring cellulose δ18O (‰)
δ18O chronology
Year
34
32
30
28
26
24
20
22
18
16
2
0
-2
-4
1650
1700
1750
1800
1850
1900
1950
2000

Figure Caption: 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% (±1.96σ) confidence limits)

2) The overall length of the record is approximately 300 yr or so, so it is impossible to locate a cycle of 350 yr in the composite record.

Answer: Thanks for your helpful comments. We checked the codes that were used to calculate the Power Spectra based on the multi-taper method in previous manuscript. The confidence level in low frequency have some problems. We recalculate power spectra based on the multi-taper method using the Software "kSpectra Toolkit"(v3.4). The results show 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 (~133 years). Please see new Figure 7 in revised manuscript or the following Figure.

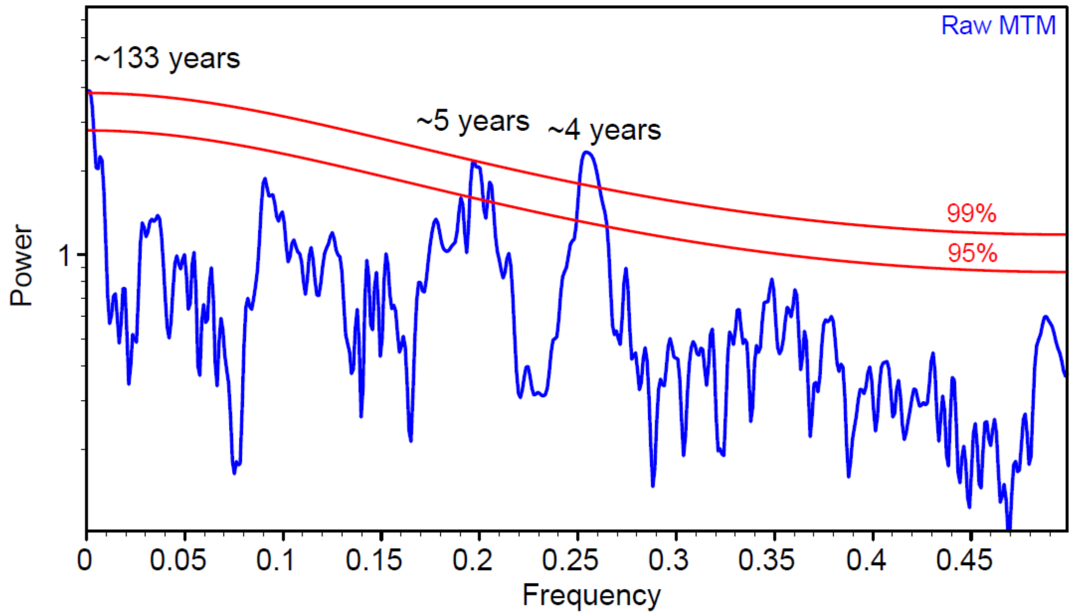


Figure Caption: Figure 7: Multi-taper power spectra for the H5 regional tree ring $\delta^{18}O$ record.

3) ENSO has the strongest power in wave length or cycles 2-7 yr, so 31-yr moving correlations are not suitable in this case.

Answer: Maybe our explanation on 31-year moving correlation is not so clear. ENSO-Monsoon teleconnection is known to be a nonstationary process. We need to evaluate how the relationships between ENSO and monsoon changed in the past. Because ENSO has the strongest power in wave length or cycles 2-7 yr, 31-year or 21-year window moving correlations between ENSO and precipitation were used to evaluate the stability of relationship between ENSO and climate. The 31-year and 21-year window can cover the main cycles (2-7 years) of ENSO. For example, Camberlin et al., (2004, Climate Dynamics) used 31-year moving correlations between NINO3 SST and seasonal rainfall anomalies over a few regions to see ENSO/rainfall teleconnections. 21-year moving window correlation analysis between ENSO and climate was used to investigate the relationship between ENSO and East Asian winter monsoon/precipitation and flood pulse in the Mekong River Basin (Kim et al., 2016; Räsänen and Kummu, 2013)

Camberlin P, Chauvin F, Douville H, et al. Simulated ENSO-tropical rainfall teleconnections in present-day and under enhanced greenhouse gases conditions. Climate Dynamics, 2004, 23(6):641-657.
Kim J W, An S I, Jun S Y, et al. ENSO and East Asian winter monsoon relationship modulation associated with the anomalous northwest Pacific anticyclone. Climate Dynamics, 2016:1-23.
Räsänen T A, Kummu M. Spatiotemporal influences of ENSO on precipitation and flood pulse in the Mekong River Basin. Journal of Hydrology, 2013, 476(1):154-168.

4) Shi et al. (2015) temperature reconstruction represents a 10-year moving average rather than a yearly time resolution. It is suggested that the authors also use other summer season temperature reconstructions (see Cook et al., 2013, CD; Wang et al., 2015, JC). In so doing, it can be regarded as a sensitivity experiment.

Answer: Thanks for your suggestions. We added two summer temperature reconstructions (Cook et al., 2013 and Wang et al., 2015) to calculate the land-sea thermal contrasts (New Figure 10 in revised manuscript). Three land-see temperature anomaly time series (Land temperature: Cook et al., 2013; Shi et al., 2015; Wang et al., 2015; Sea temperature: Tierney et al., 2015) showed similar lower frequency variations. A decreasing trend of land-sea temperature anomaly during the last 180 or 200 years were shown by three land-see temperature anomaly time series. In addition, our regional tree ring $\delta^{18}O$ chronology showed an increasing trend (reduced intensity of Indian summer monsoon) since 1820 CE.

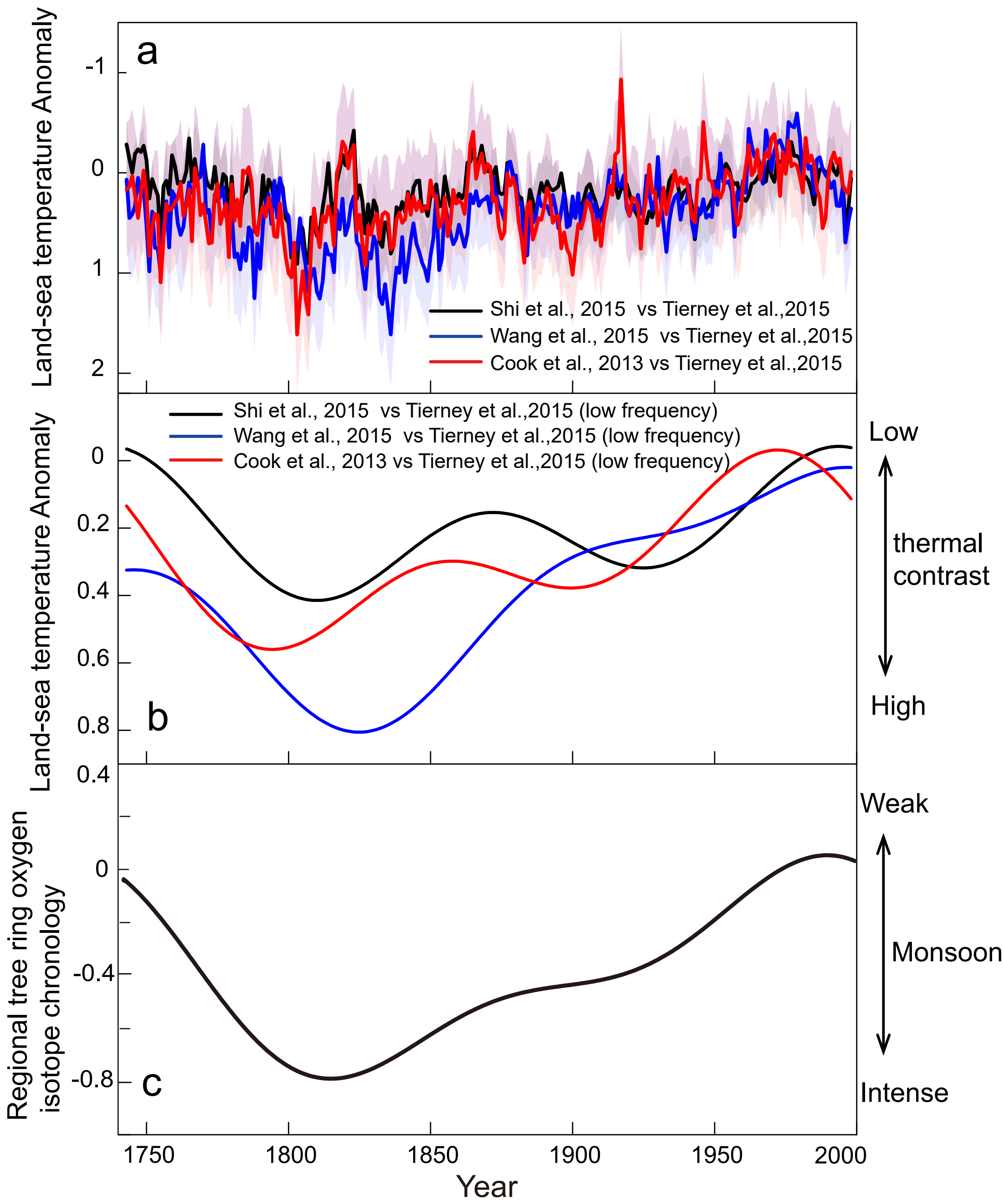


Figure Caption: Figure 10. a: Land-sea Temperature Anomaly based on three summer temperature reconstruction for the Tibetan Plateau and one Indian Ocean SST reconstruction; b and c: centennial variations of land-sea thermal contrasts and the H5 regional tree ring $\delta^{18}O$ chronology.

5) It is strange why the best spatial correlations between the regional tree ring _18O record with May-September SST during 1871-2008 CE (Fig. 8) center around the central tropical ocean rather than in the eastern tropical ocean due to a close association between the ENSO and the Indian monsoon.

Answer: Historical rainfall record and atmospheric general circulation model experiments showed that El Nino events with the warmest sea surface temperature (SST) anomalies in the central equatorial Pacific are more effective in weakening the Indian monsoon severely than events with the warmest SSTs in the eastern equatorial Pacific (Kumar et al., 2006, Science).
Kumar K K, Rajagopalan B, Hoerling M, et al. Unraveling the mystery of Indian monsoon failure during El Nino. Science, 2006, 314(5796):115-119.

6) Fig. 10 is not helpful due to poor agreement between the two curves.

Answer: We have added uncertainty of age for stalagmite samples and more discussion on the similarities and dissimilarities between regional tree ring oxygen isotope chronology and stalagmite oxygen isotope time series in northern India. Please see the revised Figure 11 and Section 3.5 in the revised manuscript.

Thank you very much for your helpful suggestions.

2: Anonymous Referee #2

Received and published: 22 March 2017
In their work, combining a new tree-ring isotope record with the existing records, Chenxi et al have constructed a regional tree ring cellulose oxygen isotope record for the northern Indian Subcontinent. The authors further show correlation between the tree-ring isotopic record and various indices of the monsoonal strength. After establishing this coherence, the authors further use the tree-ring isotope record for understanding long term variation in monsoonal precipitation. Overall the manuscript is written well and arguments are coherently presented. I recommend publishing the manuscript with minor revision.

Following points should be considered while revising the manuscript.
(1) Section 3.3 is too long to read. Consider subdividing into smaller sections.

Answer: Thanks for your helpful suggestions. The previous Section 3.3 was divided into three parts. New Section 3.3 (Interannual variability of the ISM inferred from the regional tree ring δ^{18}O record), Section 3.4 (Centennial variability of the ISM inferred from the regional tree ring δ^{18}O record) and Section 3.5 (Comparison of regional tree ring δ^{18}O record with speleothem δ^{18}O record in northern India).

(2) Page 9 first paragraph: epikarst dynamics could be more responsible for the incoherence of the two records. Some discussion is required.

Answer: Thanks for your helpful suggestions. We added the related discussion on epikarst dynamics. Please see the following paragraph.

3.5 Comparison of regional tree ring δ^{18}O record with speleothem δ^{18}O record in northern India
The H5 regional tree 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 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, 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 ring δ^{18}O and speleothem δ^{18}O should share similar changes (Managave, 2014) if both of them inherit a common source water δ^{18}O signal, as shown by Ramesh, et al (2013). The following reasons may cause incoherence between regional tree ring δ^{18}O and speleothem δ^{18}O. Other controlling factors differentially affect tree ring δ^{18}O and speleothem δ^{18}O values. Relative humidity has an important impact on tree ring δ^{18}O in regions where the variation of relative humidity during the growing season exceeds 1% (Managave, 2014), while 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. In addition, limited three ^{230}Th dates points (3 control points) and relative large age uncertainty (9-31 years) of speleothems $\delta^{18}O$ time series during the common period of 1743-2000 may result in the incoherence between tree ring and speleothems $\delta^{18}O$. Long-term process-based study on tree ring $\delta^{18}O$ and speleothem $\delta^{18}O$ variations in future study are needed for a better understanding for climatic implication of two proxies.

(3) It would be helpful for the reader if authors describe the nature of long-term variations in modern instrumental rainfall data. Analysis by Sontakke et al Holocene 2008 and Bhutiyani et al IJC 2010 could be helpful. In fact, the latter article also points out to a significant decreasing trend since 1866 in the monsoonal rainfall.

Answer: Thanks for your helpful suggestions. We have added the description of nature of long-term variations in modern instrumental rainfall data based on the Sontakke et al., (2008) and Bhutiyani et al., (2010) in the Introduction and Section 3.4 (Page 10: line 14-15; Page 11, line 4-5).

(4) The way regional isotope record is constructed (average of averages of d18O records of different sites) underestimates the uncorrelated variability. Quantification regarding this should be added to Table 2.

Answer: Thanks for your helpful suggestions. We have added the uncertainty in regional tree ring oxygen isotope chronology in Figure 4f to evaluate the inter-site variability. In addition, we checked the uncorrelated variability by comparison between regional tree ring oxygen isotope chronology and PC1 of five tree ring oxygen isotope chronologies in northern Indian sub-continent. The regional tree ring oxygen isotope chronology is highly correlated with PC1 of five tree ring oxygen chronologies ($r=0.998$, $n=200$, $p<0.001$), which indicates that regional tree ring oxygen isotope chronology reflect the main common signal of five tree ring oxygen isotope chronologies.

Thank you very much for your helpful suggestions.

3: Referee #3

In their work, Xu et al. develop two new tree-rings isotopic chronologies of $\delta^{18}O$ from Northern India, and, combined with three other $\delta^{18}O$ chronologies, propose a multi-decadal regional reconstruction of the Indian summer monsoon. The regional record is further investigated using correlation and spectral analyses to document: 1) the drivers of Indian summer monsoon variability, and 2) the long-term trends of Indian summer monsoon intensity.
The new Data and this regional reconstruction are valuable to document a key hydroclimate component of the region, which lacks high resolution and long-term proxy records.
The methodology used in this paper as well as the results are robust. The data analyses, however, would benefit from further in depth exploration of each chronology signal. The discussion needs more regional scope but this can be improved if more data analyses are carried.

General Comments
- The authors present only correlations between the five $\delta^{18}O$ chronologies. How are the correlations for high and low frequency between the 5 chronologies?

Answer: Thanks for your helpful suggestions. We have added the correlation coefficient between the five $\delta^{18}O$ chronologies at multi-decadal time scale into Table 2 and the related sentences "the five tree ring $\delta^{18}O$ records for the Himalaya region are significantly correlated each other at inter-annual time scale during the common period, and in most cases 31-year running averages of five tree ring $\delta^{18}O$ chronologies show significant correlations at multi-decadal time scale (Table 2)" in the manuscript. In general, the correlation coefficient among $\delta^{18}O$ chronologies decreased when the distances between two near $\delta^{18}O$ chronologies increased. In addition, the regional tree ring oxygen isotope chronology is highly correlated with PC1 of five tree ring oxygen chronologies (r=0.998, n=200, p<0.001), which indicates that regional tree ring oxygen isotope chronology reflect the main common signal of five tree ring oxygen isotope chronologies.

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<0.0

- Climate correlations for each chronology $\delta^{18}O$ are summarized in the text however a figure of correlation between each chronology and the main climate factor (precipitation and/or PDSI) should be presented to assess the climate signal in each chronology before creating the composite regional signal.

Answer: Thanks for your helpful suggestion. We have added the correlation between tree ring $\delta^{18}O$ in five sites and regional June-September PDSI/Precipitation in Table 1. Because the correlations between tree ring $\delta^{18}O$ in Manali, Hulma and Wache and monsoon season (JJAS) precipitation/PDSI were already showed and mechanisms that JJAS precipitation/PDSI affect tree ring $\delta^{18}O$ in Manali, Hulma and Wache were already explained in previous study. (Sano et al., 2011, 2013, in press), we added climatic response of each tree ring $\delta^{18}O$ chronology in Table 1.

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

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., In press	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

- The composite signal (average of 5 centered $\delta^{18}O$ chronologies) should be presented with a standard deviation or an uncertainty term in order to see if the uncertainty changed over time. This will be important to discuss the relationship between the composite regional signal and its relation with Indian summer monsoon indices for the last ~200 years.

Answer: Thanks for your helpful suggestion. We have added the 95% (±1.96σ) confidence to evaluate the uncertainty not only for the regional chronology and but also for each tree ring $\delta^{18}O$ chronology (except for chronology in Hulma, because the tree ring oxygen isotopes chronology was produced by pooling method, and therefore the uncertainty of this chronology was not able to show). Please see Figure 4 in revised manuscript or the following figure. gray shadows show the 95% (±1.96σ) confidence for each chronology.

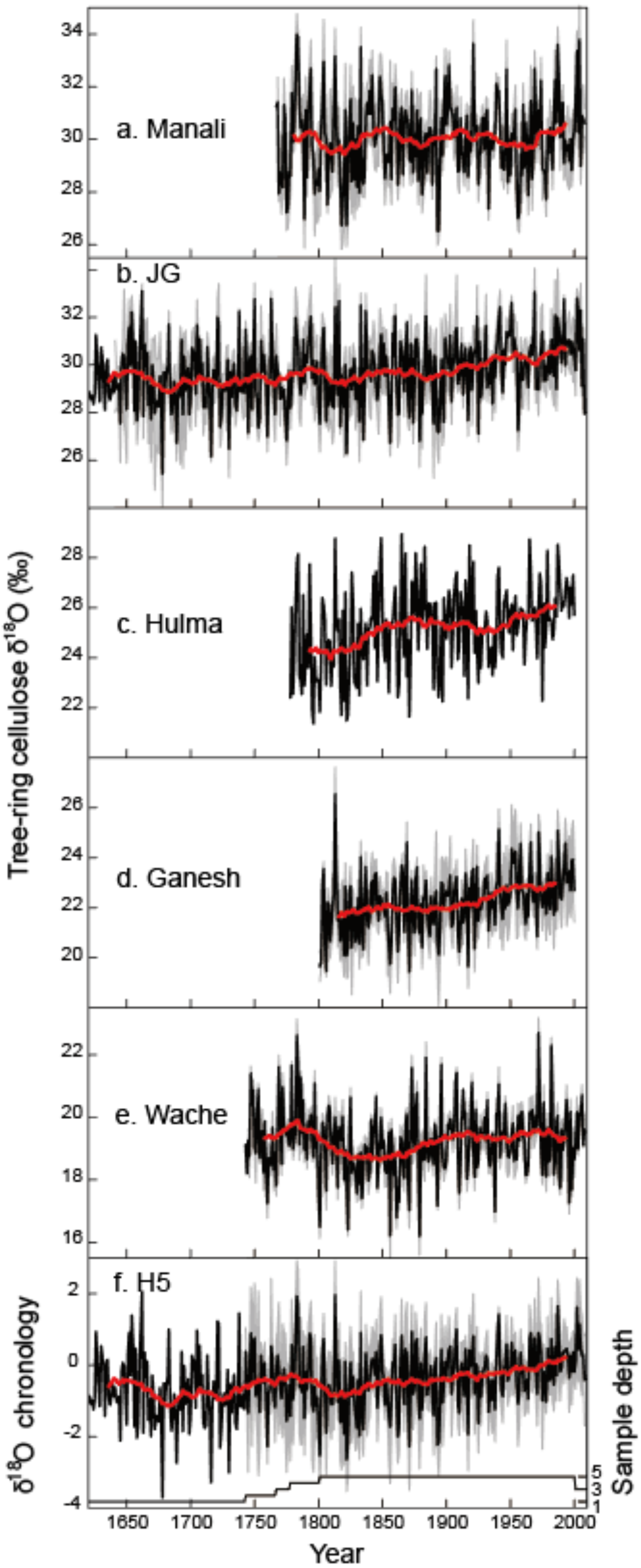


Figure Caption: New Figure 4: Tree ring oxygen isotopes chronology from five sites (a-e) and regional tree ring oxygen isotope chronology (f). (black line: mean value for all samples; red line: 31-year running average; gray line: uncertainty for each chronology)

- The $\delta^{18}O$ signal is often described from a theoretical perspective. Could the authors provide more evidence of the $\delta^{18}O$ signal in these particular chronologies? Comparison with RH or source water isotopes? Or using process based evaluation by means of $\delta^{18}O$ forward modelling (Eg. Evans 2007).

Answer: Source water $\delta^{18}O$ and relative humidity are two main controlling factors for tree ring cellulose $\delta^{18}O$. Comparison between tree ring $\delta^{18}O$ and source water $\delta^{18}O$/relative humidity and using tree ring $\delta^{18}O$ forward modelling would be helpful to understand source water $\delta^{18}O$ and relative humidity influences' on tree ring $\delta^{18}O$. However, long-term continuous precipitation $\delta^{18}O$ records are scarce in the study area. A better model parameterization for each species in each site depends on many observed parameters that are not available in five sites. The good things are that previous studies already showed the relationship between precipitation $\delta^{18}O$/relative humidity and tree ring $\delta^{18}O$ in study area. For example, Sano et al. (2011) indicated that tree ring $\delta^{18}O$ in Hulma showed negative correlations with June-September relative humidity and positive correlations with June-September precipitation $\delta^{18}O$ in New Delhi. Sano et al., in press revealed that tree ring $\delta^{18}O$ in Manali showed the negative correlations with June-September relative humidity. In some sites, relative humidity record is not available. PDSI was employed to evaluate the relationship between tree ring $\delta^{18}O$ and moisture condition. Tree ring $\delta^{18}O$ in JG, Ganesh and Wache showed negative correlations with regional PDSI. Such negative correlations between tree ring $\delta^{18}O$ and summer PDSI or relative humidity have also been found in other areas of monsoonal Asia, such as northern Laos (Xu et al., 2013a), northern Vietnam (Sano et al., 2012), southeast Tibet Plateau (Grießinger et al., 2011; 2016, Liu et al., 2013, Wernicke et al., 2015), southeast China (Xu et al., 2013b, Xu et al., 2016) and Japan (Sakashita et al., 2015; Yamaguchi et al., 2010).

Grießinger J, Bräuning A, Helle G, Thomas A, Schleser G (2011) Late Holocene Asian summer monsoon variability reflected by $\delta^{18}O$ in tree-rings from Tibetan junipers. Geophysical Research Letters 38 (3):L03701

Grießinger J, Bräuning A, Helle G,Hochreuther P, Schleser G (2016) Late Holocene relative humidity history on the southeastern Tibetan plateau inferred from a tree-ring $\delta^{18}O$ record: Recent decrease and conditions during the last 1500 years. Quaternary International, In press

Liu X, Zeng X, Leavitt SW, Wang W, An W, Xu G, Sun W, Yu W, Qin D, Ren J (2013) A 400-year tree-ring $\delta^{18}O$ chronology for the southeastern Tibetan Plateau: Implications for inferring variations of the regional hydroclimate. Global & Planetary Change 104:23-33

Sakashita W, Yokoyama Y, Miyahara H, (2015) Relationship between early summer precipitation in Japan and the El Niño-Southern and Pacific Decadal

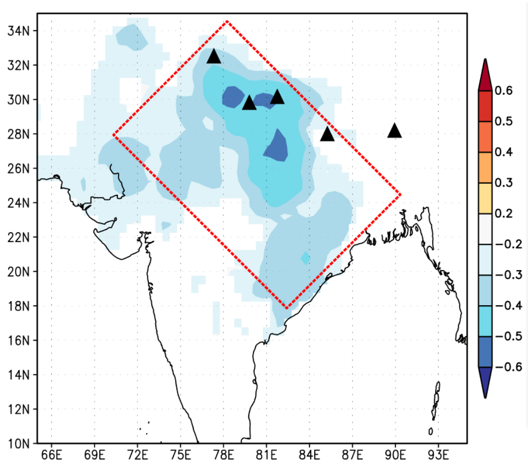
Oscillations over the past 400 years. Quaternary International, 397(4):300-306.
Sano M, Xu C, Nakatsuka T (2012). A 300-year Vietnam hydroclimate and ENSO variability record reconstructed from tree ring δ^{18}O. Journal of Geophysical Research Atmospheres, 117(D12):12115.
Wernicke J, Grießinger J, Hochreuther P, Bräuning A (2015) Variability of summer humidity during the past 800 years on the eastern Tibetan Plateau inferred from δ^{18}O of tree-ring cellulose. Climate of the Past11:327-337
Xu C, Sano M, Nakatsuka T(2013a). A 400-year record of hydroclimate variability and local ENSO history in northern Southeast Asia inferred from tree-ring δ^{18}O. Palaeogeography Palaeoclimatology Palaeoecology, 386:588-598.
Xu C, Zheng H, Nakatsuka T, Sano M (2013b) Oxygen isotope signatures preserved in tree ring cellulose as a proxy for April–September precipitation in Fujian, the subtropical region of southeast China. Journal of Geophysical Research: Atmospheres 118 (23):12,805-812,815
Xu C., J. Ge, T. Nakatsuka, L. Yi, H. Zheng, and M. Sano (2016), Potential utility of tree ring δ18O series for reconstructing precipitation records from the lower reaches of the Yangtze River, southeast China, J. Geophys. Res. Atmos., 121, doi:10.1002/2015JD023610.
Yamaguchi Y T, Hughen K A. (2010) Synchronized Northern Hemisphere climate change and solar magnetic cycles during the Maunder Minimum. Proceedings of the National Academy of Sciences of the United States of America, 107(48):20697-20702.

- Analyses of observations would enhance the strength of the tree rings data: trends of rainfall for the region, as well as the various indices discussed in the paper. Additionally, δ^{18}O tree-rings and rainfall amount over the observations period should be plotted to strengthen the interpretation of the amount effect described in the results-discussion sections. This can be done for each site or at regional scale.

Answer: Thanks for your suggestion. We have added the description of nature of long-term variations in modern instrumental rainfall data based on the Sontakke et al., 2008 and Bhutiyani et al., 2010 in section 3.4 (*Centennial variability of the ISM inferred from the regional tree ring δ^{18}O record*). Please see the Section 3.4.

Sontakke, N. A., Singh, N., and Singh, H. N.: Instrumental period rainfall series of the Indian region (AD1813-2005): revised reconstruction, update and analysis, Holocene, 18(7), 1055-1066, 2008.
Bhutiyani, M. R., Kale, V. S., and Pawar, N J: Climate change and the precipitation variations in the northwestern Himalaya: 1866-2006, International Journal of Climatology, 30(4), 535-548, 2010.

On the amount effect, we employed the amount effect to explain that how ISM affect tree ring δ^{18}O. At regional scales, regional tree ring δ^{18}O show significant negative correlations with June-September precipitation in northern India. The following figure supports the amount effect to some extent.



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.

- In Page 9 paragraph 1 (~ line 5): Is the RH threshold 1%?

Answer: Yes, we refer to the results from Managave (2014). Maybe our explaination on relative humidity's influence on the correlation between two proxies is not so clear. We have revised this part. "Relative humidity has an important impact on tree ring $\delta^{18}O$ (Roden et al., 2000). Lower relative humidity result in enhanced evaporative enrichment of leaf water and then higher tree 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 results show that relative humidity's influences on the correlation between tree 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)."

Managave, S. R.: Model evaluation of the coherence of a common source water oxygen isotopic signal recorded by tree-ring cellulose and speleothem calcite, Geochemistry Geophysics Geosystems, 15, 905–922, 2014.

- In Page 9 paragraph 1 (~ line 5): further discussion is required when assessing how the source $\delta^{18}O$ is integrated differently between tree-rings and speleothem proxies.

Answer: Thanks for your helpful suggestion. We have revised this part. Please see the revised part. "Based on the oxygen isotope fractionation theory, tree 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 ring $\delta^{18}O$ and speleothem $\delta^{18}O$. Other controlling factors differentially affect tree ring $\delta^{18}O$ and speleothem $\delta^{18}O$ values. Relative humidity has an important impact on tree ring $\delta^{18}O$ (Roden et al., 2000). Lower relative humidity result in enhanced evaporative enrichment of leaf water and then higher tree 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 results show that relative humidity's influences on the correlation between tree 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 ring and speleothem. In addition, limited three ^{230}Th dates points (3 control points) and relative large age uncertainty (9-31 years) of speleothems $\delta^{18}O$ time series during the common period of 1743-2000 may result in the incoherence between tree ring and speleothems $\delta^{18}O$. Long-term process-based study on tree ring $\delta^{18}O$ and speleothem $\delta^{18}O$ variations in future study are needed for a better understanding for climatic implication of two proxies."

- Page 10 from line 10 to 25: the text needs substantial editing, there are lot of repetitions and the discussion is not clear. Often the authors start describing the implication of their record and its comparison with regional records without an in-depth discussion.

Answer: Thanks for your helpful suggestion. We have described the implication of our records and comparison with other records in the study in previous paragraphs. In this paragraph, we try to explain the reason that caused the weakened ISM. We revised this paragraph. Please see the revised part. "The land-sea thermal contrast which is also an important influencing factor for ISM (Roxy et al., 2015), is evaluated by atmospheric temperature gradient between the Tibetan Plateau and the tropical Indian Ocean (Fu and Fletcher, 1985; Sun et al., 2010). The history of land-sea thermal contrasts is reconstructed based on temperature differences between the Tibetan Plateau and the Indian Ocean (Figure 10a), and centennial variations of land-sea thermal contrasts are shown in Figure 10b. Three reconstructed land-sea thermal contrasts showed a decreasing trend since 1800 CE and 1820 CE (Figure 10b), and the H5 record exhibits a similar pattern of changes on a centennial scale (Figure 10c). The decreasing land-sea thermal contrast since 1800 and 1820 CE has resulted in a weaker ISM, and the increasing trend of the H5 record since 1820 CE also indicates a reduced ISM intensity. In addition, 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."

- Page 9 starting line ~20. The discussion here is interesting, however, needs some clarification and editing.

Answer: Thanks for your helpful suggestion. We have revised this paragraph according to your suggestion. Please see the revised part. "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 northwest India, influenced by the Arabian Sea branch of the ISM, exhibits a drying trend since 1950 CE (Sano et al., submitted), 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), the data from only four stations extend back to 1826 CE and four longest stations locate in central or southern India. Monsoon season drying trend in northern India revealed by H5 regional tree ring $\delta^{18}O$ record may indicate that inland areas appear to be particularly sensitive to the weakening of monsoon circulation."

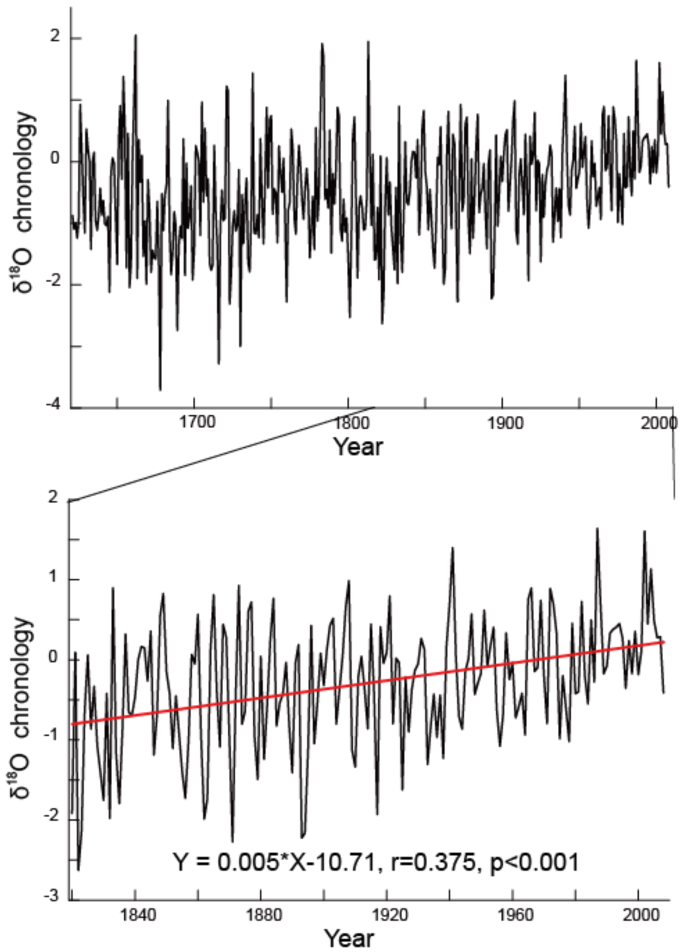
For the clarification: 1) the authors report a decreasing δ18O trend from 1743-1820. How many chronologies are included in this part of the record? According to Table 1 and Figure 4, only 2 chronologies extend back to 1743. Authors should use caution when making regional trend interpretations

Answer: Thanks for your helpful suggestion. We have added the sample depth in Figure. Please see the revised Figure 4 in manuscript. There are three tree ring $\delta^{18}O$ chronologies since 1767 CE. The main conclusion is based on the result since 1800 CE. There are five tree ring $\delta^{18}O$ chronologies since 1800 CE.

2) an increasing δ18O trend from 1820 to 2000 is observed in the δ18O tree-rings interpreted as an increase in the Indian monsoon intensity, also observed from other

regional proxies. Is this trend also observed when considering the chronologies individually? What are the statistics for this trend?

Answer: an increasing tree ring $\delta^{18}O$ trend from 1820 to 2000 is interpreted as a decrease in the Indian monsoon intensity. Such increasing trend of tree ring $\delta^{18}O$ from 1820 to 2000 is also found in JG, Hulma, Ganesh and Wache in Figure 4. The increased trend of regional tree ring $\delta^{18}O$ chronology during the period of 1820-2008 was tested using linear regression. Please see the following figure and Figure in Page 11 in this file.



- Page 10, line 20. The discussion of factors (for instance aerosols) other than the decreasing land-ocean thermal contrast and their role in the decreasing Indian Monsoon intensity needs to be more detailed. What is the land-ocean thermal contrast resolution, interannual? Decadal? From Figure 11 the proxy records for ocean and land temperature do not seem to have the same temporal resolution.

Answer: Thanks for your suggestion. We have added the sentences on how the aerosols affect Indian summer monsoon. Please see the following paragraph. "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)."

For the land-ocean thermal contrast, temperature reconstruction in Tibet Plateau (Shi et al., 2015) represents a 10-year moving average and the resolution of SST reconstruction is annual in previous manuscript. In revised manuscript, we have added two annual-resolution summer temperature reconstruction in Tibetan Plateau (Cook et al., 2013; Wang et al., 2015) to evaluate the land-ocean thermal contrast history. Please see the following figure or Figure 10 in manuscript.

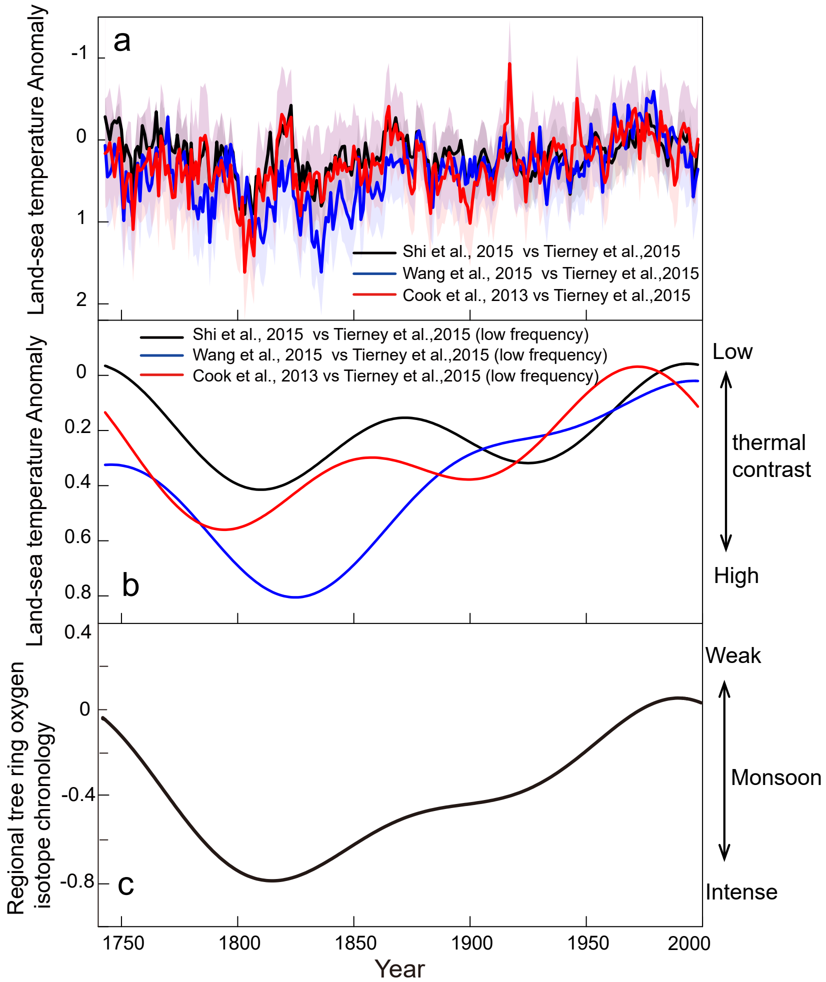


Figure Caption: Figure 10. a: Land-sea Temperature Anomaly based on three summer temperature reconstruction for the Tibetan Plateau and one Indian Ocean SST reconstruction; b and c: centennial variations of land-sea thermal contrasts and the H5 regional tree ring $\delta^{18}O$ chronology.

- when assessing the ENSO-and H5 regional $\delta^{18}O$ correlations, a 31-year window is too large (ENSO is 2-7 years). It would be helpful to investigate ENSO- and Tree-rings $\delta^{18}O$ correlation for individual chronologies to test whether the decorrelation is observed for all chronologies which reflect sites under slightly different precipitation regime and Indian summer monsoon influence (based on Fig 1).

Answer: ENSO-Monsoon teleconnection is known to be a nonstationary process. We need to evaluate how the relationships between ENSO and monsoon changed in the past. Because ENSO has the strongest power in wave length or cycles 2-7 yr, 31-year or 21-year window moving correlations between ENSO and precipitation were used to evaluate the stability of relationship between ENSO and climate. The 31-year and 21-year window can cover the main cycles (2-7 years) of ENSO. For example, Camberlin et al., (2004, Climate Dynamics) used 31-year moving correlations between NINO3 SST and seasonal rainfall anomalies over a few regions to see ENSO/rainfall teleconnections. 21-year moving window correlation analysis between ENSO and climate was used to investigate the relationship between ENSO and East Asian winter monsoon/precipitation and flood pulse in the Mekong River Basin (Kim et al., 2016; Räsänen and Kummu, 2013)

Thanks for your helpful suggestion on the relationship between individual tree ring $\delta^{18}O$ chronology and ENSO. We did not add the related part in previous manuscript based on two reasons. 1) this manuscript mainly focused on the variations of ISM at regional scale rather than local scale. 2) Due to the complexity of ENSO-monsoon relationship, more tree ring $\delta^{18}O$ chronologies from Asian monsoon area (for example, Laos, Myanmar, Thailand, Vietnam, China and Japan) are needed. Now we are working on ENSO-Asian summer monsoon relationship based on lots of tree ring chronologies from Asian monsoon area.

Camberlin P, Chauvin F, Douville H, et al. Simulated ENSO-tropical rainfall teleconnections in present-day and under enhanced greenhouse gases conditions. Climate Dynamics, 2004, 23(6):641-657.
Kim J W, An S I, Jun S Y, et al. ENSO and East Asian winter monsoon relationship modulation associated with the anomalous northwest Pacific anticyclone. Climate Dynamics, 2016:1-23.
Räsänen T A, Kummu M. Spatiotemporal influences of ENSO on precipitation and flood pulse in the Mekong River Basin. Journal of Hydrology, 2013, 476(1):154-168.

Specific comments

- In Results and Discussion, section 3.1. The standard deviation of individual tree-ring cores can be added next to the mean.

Answer: Thanks for your suggestion. We have modified the section 3.1 according to your suggestion. Please see the revised part. "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 1643-2008 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 1641-2008 CE."

- In Table 1 the mean $\delta^{18}O$ for each chronology should have a unit (‰)

Answer: We have modified the Table 1 according to your suggestion. Please see revised Table 1.

- In Fig 1 and Table 2 the chronologies from previous studies have a different name. Bhutan in -Table 2 and Wache in Fig 1.

Answer: We have modified the Table 2 according to your suggestion. Please see the following Table 2.

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*

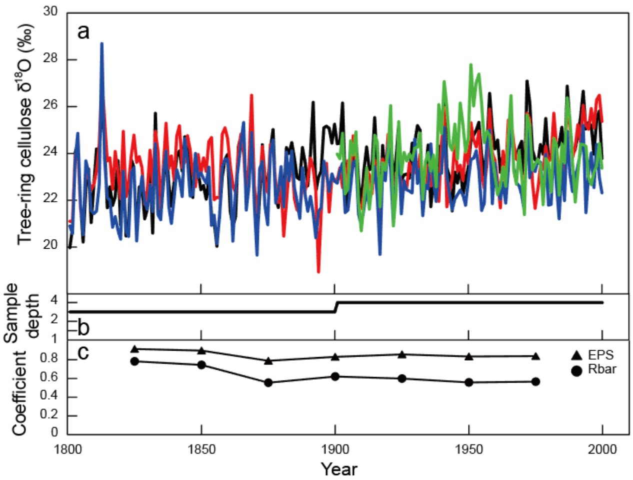
r-multi-decadal	Manali	JG	Hulma	Ganesh
JG	0.36*			

Hulma	0.37*	0.64*		
Ganesh	-0.03	0.94*	0.66*	
Wache	0.11	0.39*	0.38*	0.70*

*$p<0.01$

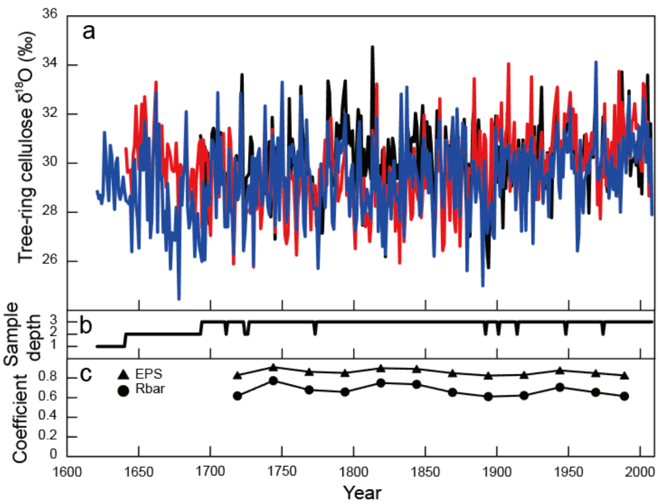
- In Fig 2 the triangle and circle symbols have no legend.

Answer: We have modified the Figure according to your suggestion. Please see the following Figure.



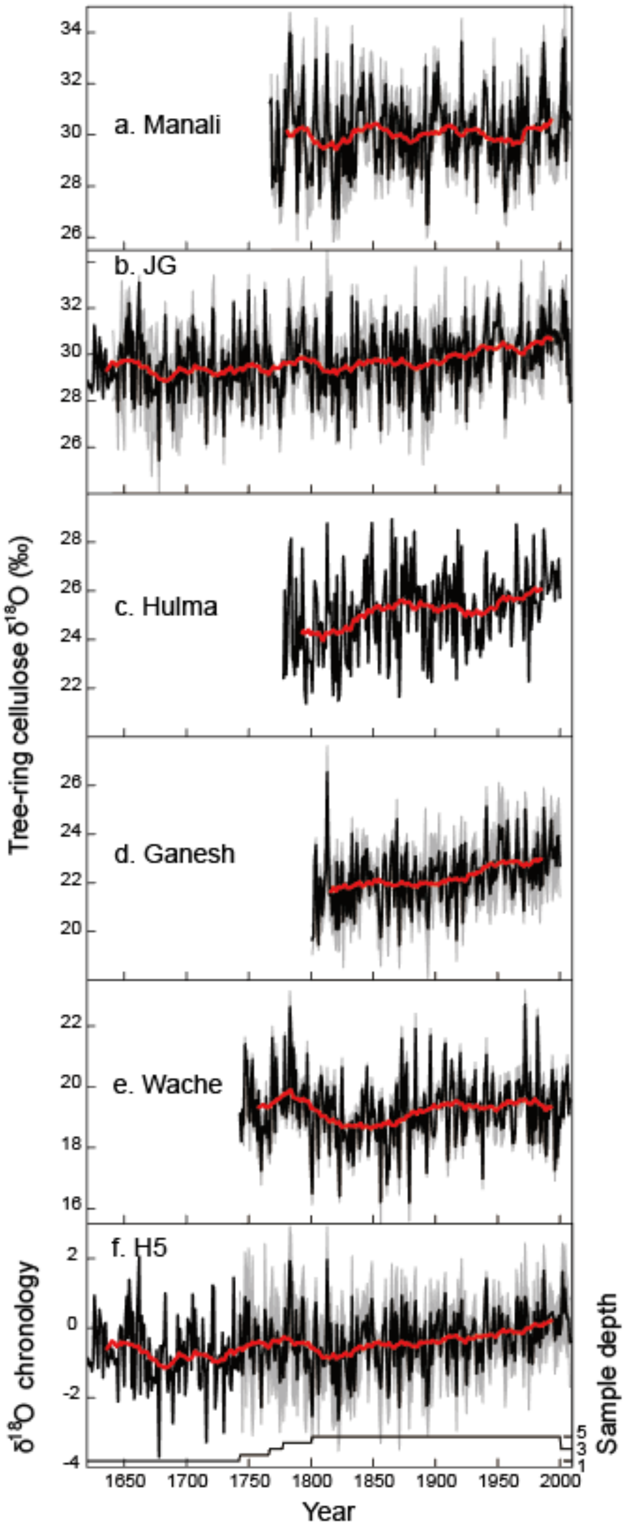
- In Fig 3 the triangle and circle symbols legend is too big. This can be reduced to only the symbols without the line (same should be applied to Fig 2).

Answer: We have modified the Figure according to your suggestion. Please see the following Figure.



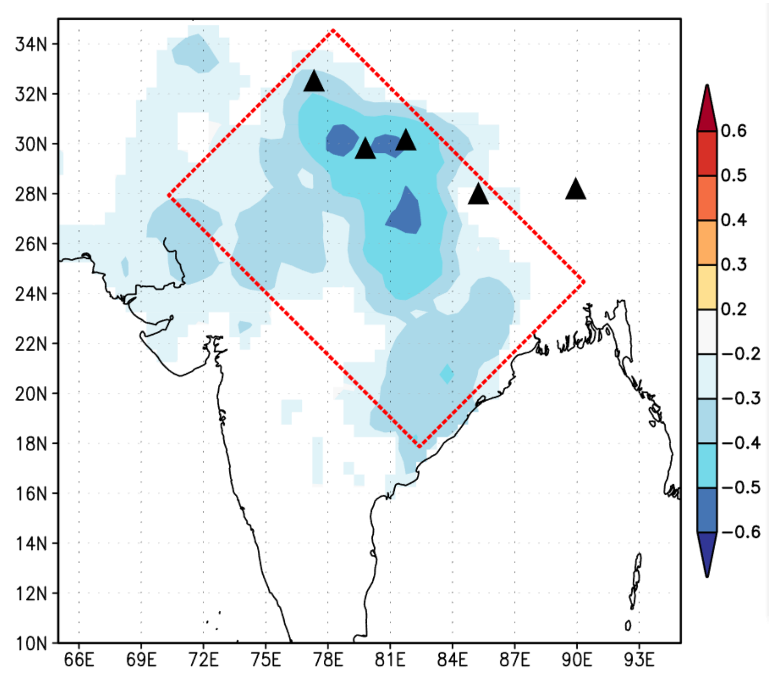
- In Fig 4, the sample depth (number) should be added in a graph below the composite time-series since the number of averaged trees over time is not the same (prior to 1740 and after 2000).

Answer: We have added the sample depth in the Figure according to your suggestion. Please see the following Figure or Figue 4.



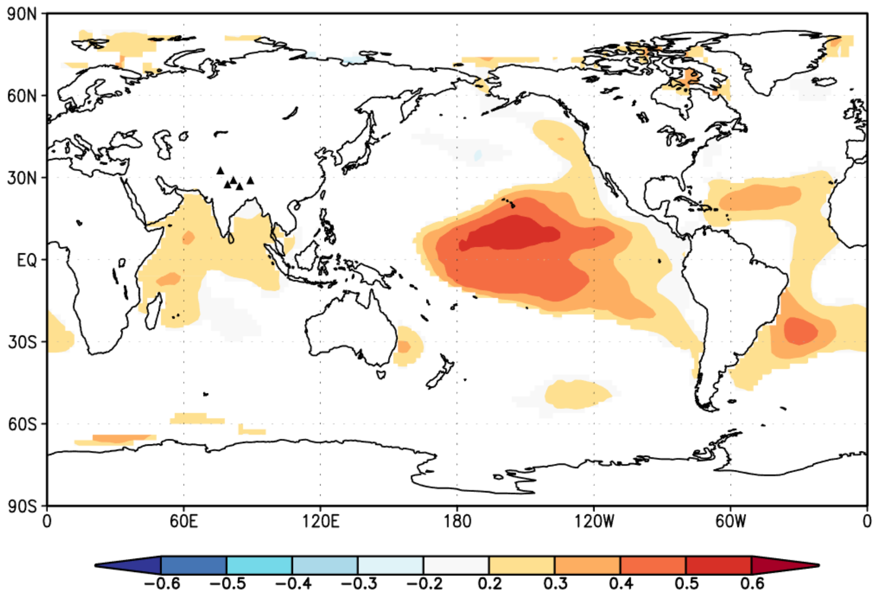
- In Fig 5, add the location of all the sites to help visualize the strength of the field correlations.

Answer: We have modified the Figure according to your suggestion. Please see the following Figure.



- In Fig 8, add the location of the 18O chronologies for spatial reference of the SST correlations.

Answer: We have modified the Figure according to your suggestion. Please see the following Figure.



-Page 8 line 1, a word or punctuation is missing after the parenthesis (eastern-Pacific el Nino).

Answer: We have modified the related part according to your suggestion. Please see the revised part. "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)".

Thank you very much for your helpful suggestions.

4. Short Comments:

This comment was prepared through a group discussion of the SPATIAL laboratory at the University of Utah.

Overview: Xu et al. provide a new stacked record of tree ring cellulose oxygen isotopes from five locations along the southern Himalaya, spanning a time range of 1743-2008 CE. They find significant correlations with regional climate indices of precipitation and Indian monsoon strength over the instrumental record, and from this, infer that their stacked record can be used to reconstruct the strength of the Indian monsoon prior to the industrial record. From this, they draw two potentially exciting conclusions from their analysis: (a) high-frequency ENSO variability (e.g., periods of 2.4-5 years in their figure 7) may be recorded in the stacked tree ring dataset and (b) low-frequency centennial scale variability (e.g., periods of 160-350 years in their figure 7) may reflect long-term variability in monsoon strength, which they support by an analysis of long-term changes in the land-sea temperature contrast derived from proxy records. However, the authors do not provide information on uncertainty and error, and therefore, it is difficult to assess the robustness of their conclusions. Our view is that this data merits publication, but that considerable revisions need to be made to help clarify their analyses and support their conclusions. Therefore, we recommend acceptance pending major revisions described below.

Major comments:

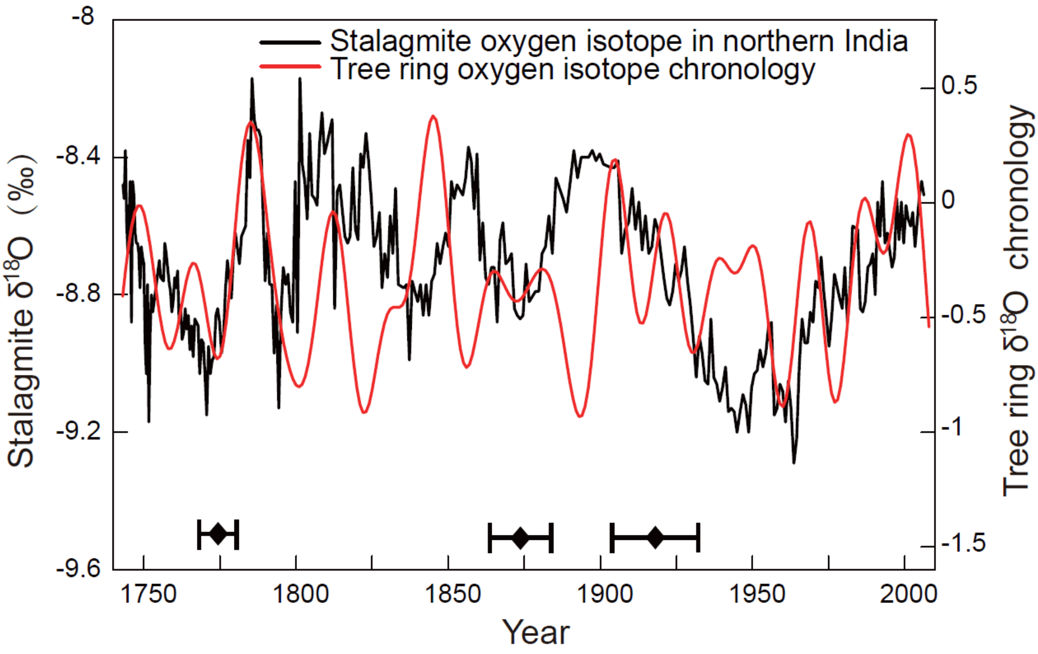
(1) Error and uncertainty are not adequately explored or explained.

We provide several examples of analyses in the paper that would benefit from a more thorough treatment of error and uncertainty propagation: No uncertainty is given on the individual chronologies provided (e.g., the uncertainty from combining individual trees at a location to estimate the average delta18O record at that location), nor is it propagated to the averaged delta18O chronology of the stacked record in figure 4. The authors make several comparisons between their stacked tree ring record and other proxy indicators of ENSO (Fig. 9), stalagmite oxygen isotopes (Fig 10), and Indian Ocean SSTs and Tibetan Plateau temperatures (Fig 11). However, they do not consider either the potential errors in proxy reconstructed values (e.g., the error in reconstructed SSTs), nor potential errors in the age model used to assign a date to those proxy values. As a result, it is difficult to assess how robust the signals they derive from comparisons between proxy records are, and how they compare to the variability. For example, in figure 11, it is not clear that the reconstructed land-sea temperature anomaly is a substantial, robust, or significant deviation from zero if estimates of uncertainty are absent.

Answer: Thanks for your suggestions. We have added the 95% (±1.96σ) confidence limits of different tree ring oxygen isotope time series in Manali, JG, Ganesh and Wache as the uncertainty of inter-tree variability, which are shown in New Figure 4a,b,d,e in revised manuscript by gray shadows. For tree ring oxygen isotopes data in

Hulma, we cannot evaluate the inter-tree oxygen isotope variability, because tree ring oxygen isotope chronology in Hulma was built up by pooling method. The uncertainty of regional tree ring oxygen isotope chronology was evaluated by showing the 95% (±1.96σ) confidence limits (Figure 4f). Please see the revised Figure 4.

For the uncertainty of age model for stalagmite oxygen isotope time series, we have added the dating results and uncertainty of stalagmite oxygen isotope data in northern India in new Figure 11. During the common period (1743-2000) between regional tree ring oxygen isotope chronology and stalagmite oxygen isotope data, there are three dating point with uncertainty in range of 9~31 years.



New Figure 11. Comparison between multi-decadal regional tree 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.

To check robustness of the low-frequency land-sea temperature anomaly, three different temperature reconstruction (Cook et al., 2013; Shi et al., 2015; Wang et al., 2015) in Tibetan Plateau and one Indian Ocean SST reconstruction was used. Three land-see temperature anomaly time series showed similar lower frequency variations. A decreasing trend of land-sea temperature anomaly during the last 200 years were shown by three land-see temperature anomaly time series. In addition, we added the ± 1 RMSE (root mean square error) as uncertainties of each temperature reconstruction in Tibetan Plateau and Indian Ocean. The uncertainty of land-see temperature anomaly was calculating by adding RMSE from land and sea temperature reconstruction, which was shown by shadows in New Figure 10 in the revised manuscript.

(2) The rationale for why the authors think that their stacked record reflects regional changes in the monsoon is absent – the signals from each location appear coherent, but it is not shown that they are actually coherent. There's a wide range in correlation coefficients between sites in Table 2, where the lowest correlation coefficients suggest that sampling at Manali only explains _5% of the variance observed at Bhutan. Thus, while we find the possibility that these sites record a regional-scale signal to be exciting, the rationale for combining all of these datasets for a regional interpretation should be explained in more detail. Additionally, the authors hint that the relationship between sites may not be stationary (pg 5, L18-21), as they note decadal-scale changes are often not observed coherently through their stacked record. The analysis would benefit from exploring potential reasons for why this might be the case - are there other potential explanations than variations in the ISM?

Answer: The rationale for combing five tree ring oxygen isotope chronologies in monsoon area is that: tree ring oxygen isotopes in five sites show significant correlations with summer precipitation/PDSI, and summer climate in five sampling areas are controlled by Indian summer monsoon, so combining five oxygen isotope chronologies should be helpful to obtain monsoon-related information. The significant correlations between regional tree ring oxygen isotope chronology and all Indian monsoon/Indian summer monsoon Index/grid summer precipitation indicated that regional tree ring oxygen isotope chronology can reflect Indian summer monsoon changes. Given long distances (around 1400 km) between Manali and Buthan, correlation coefficient ($r=0.23$, $p<0.001$) is not bad. In addition, the regional tree ring oxygen isotope chronology is highly correlated with PC1 of five tree ring oxygen chronologies ($r=0.998$, $n=200$, $p<0.001$), which indicates that regional tree ring oxygen isotope chronology reflect the main common signal of five tree ring oxygen isotope chronologies. On the decadal-scale changes between different tree ring oxygen isotope chronologies, we discussed on it in another paper (Sano et al., in press). In addition, this is not the main topic of this paper.

We added the paragraph on the rationale for combing five tree ring oxygen isotope chronologies in monsoon area. Please see the following paragraph.

3.1 Tree ring $\delta^{18}O$ variations in the southern Himalaya and a regional tree ring $\delta^{18}O$ 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 1643-2008 CE, respectively. Individual tree ring $\delta^{18}O$ time series from four cores from central Nepal are shown in Figure 2a. The mean values of the $\delta^{18}O$ time series from 224c, 233b, 235b, and 226a are 23.09‰, 22.66‰, 21.87‰, and 22.94‰, respectively, from 1901-2000 CE; the standard deviations are 1.22‰, 1.27‰, 1.12‰, and 1.42‰, respectively. 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 of the $\delta^{18}O$ time series from 101c, 102c, and 103a are 30.11‰, 29.7‰ and 29.47‰, respectively, over the interval from 1694-2008 CE; the standard deviations are 1.49‰, 1.62‰ and 1.53‰, respectively. 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 1641-2008 CE.

In northern Indian sub-continent, three long-term tree ring $\delta^{18}O$ chronologies from northwest India, eastern Nepal and Bhutan have been built up in previous studies (Sano et al., 2011; Sano et al., 2013; Sano et al., submitted, Figure 4). Two tree ring $\delta^{18}O$ chronologies in this study and three tree ring $\delta^{18}O$ chronologies in previous studies located in monsoonal area (Figure 1). Three tree ring $\delta^{18}O$ chronologies in northwest India, eastern Nepal and Bhutan were controlled by monsoon season rainfall or PDSI (Sano et al., 2011; Sano et al., 2013; Sano et al., submitted), and the two new tree ring $\delta^{18}O$ records obtained in the present study (JG and Ganesh) are negatively correlated with June-September PDSI in northern India. In addition, the five tree ring $\delta^{18}O$ records for the Himalaya region are significantly correlated each other during the common period (Table 2). These results indicate that five tree ring $\delta^{18}O$ records reflect a common controlling factor that may be related to regional climate. Therefore, we combined two tree ring $\delta^{18}O$ records in this study with three previously published tree ring $\delta^{18}O$ chronologies to construct a regional tree ring $\delta^{18}O$ record. The five $\delta^{18}O$ records were individually normalized over the interval from 1801-2000 CE, and then averaged to produce a regional Himalayan $\delta^{18}O$ record (H5 $\delta^{18}O$ record) for the entire interval (Figure 4f). Only one chronology (JG) spans an interval prior to 1742 CE, and therefore we focus on the interval from 1743-2008 CE in this study.

(3) The authors draw conclusions that may not be supported by their time series analysis methods. A section describing the spectral analysis methods, software, etc. that were used should be added to the methods section so that their results could be replicated by other researchers. Additionally, it is not clear how the authors determined the significance levels plotted in Figure 7 – this should be explained. A few additional comments/questions regarding the time series analysis are provided below: The conclusion that their record captures centennial-scale variability requires more justification considering their record is only 350 years long. They claim significant spectral power at 160 and 350 year intervals (Fig 7) – though the 350 year peak is the secular trend in their 350 year dataset, and the 160 year cycle may also not be significant-more details about how significance levels are

determined should be provided. It was not clear why a 31-year moving correlation was used in figure 9 – could you expand on this choice?

Answer: Thank you for helpful suggestion. We have added the related sentence in Section 2.3 Meteorological data and climate analyses. We checked the codes that were used to calculate the Power Spectra based on the multi-taper method in previous manuscript. The calculation of the confidence level in low frequency have some problems. We recalculated power spectra based on the multi-taper method using the Software “kSpectra Toolkit”(v3.4). The results show that H5 regional tree ring $\delta^{18}O$ record contains several high-frequency periodicities (4 and 5 years), as well as lower frequency periodicities (~133 years) (New Figure 7).

Maybe our explanation on 31-year moving correlation is not so clear. ENSO-Monsoon teleconnection is a nonstationary process. We need to evaluate the relationship between ENSO and monsoon. Because ENSO has the strongest power in wave length or cycles 2-7 yr, 31-year or 21-year window moving correlation between ENSO and precipitation were used to evaluate the stability of relationship between ENSO and climate. 31-year and 21-year window can cover the main cycles (2-7 years) of ENSO. For example, Camberlin et al., (2004, Climate Dynamics) used 31-year moving correlations between NINO3 SST and seasonal rainfall anomalies over a few regions to see ENSO/rainfall teleconnections. 21-year moving window correlation analysis between ENSO and climate was used to investigate the relationship between ENSO and East Asian winter monsoon/ precipitation and flood pulse in the Mekong River Basin (Kim et al., 2016; Räsänen and Kummu, 2013)

Camberlin P, Chauvin F, Douville H, et al. Simulated ENSO-tropical rainfall teleconnections in present-day and under enhanced greenhouse gases conditions. Climate Dynamics, 2004, 23(6):641-657.
Kim J W, An S I, Jun S Y, et al. ENSO and East Asian winter monsoon relationship modulation associated with the anomalous northwest Pacific anticyclone. Climate Dynamics, 2016:1-23.
Räsänen T A, Kummu M. Spatiotemporal influences of ENSO on precipitation and flood pulse in the Mekong River Basin. Journal of Hydrology, 2013, 476(1):154-168.

(4) Writing is imprecise and organization needs improvement. We have provided a few of the more pressing examples to help guide revisions:

- The methods section requires substantial additions. First, the time series analysis methods used need to be described in an additional subsection, and in enough detail that other researchers could recreate the analysis. Second, many of the paragraphs in the results start with a description of how an analysis was done - these should be moved to the methods section.

Answer: Thank you for helpful suggestions. We have revised this part according to your suggestions. Please see the revised part (Section 2.3) in revised manuscript.

- The introduction brings up several relevant factors about the ISM without relating them directly to this study. This section would be more impactful if it were better focused on what is known about how these factors influence the ISM rather than just providing a list. This addition would help clarify how your results improve our understanding of the ISM.

Answer: Thank you for helpful suggestions. We have revised this part according to your suggestions. Please see the revised Introduction.

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 centennial changes in ISM. Therefore, long-term proxy records of ISM are needed.

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). Monsoon precipitation in northwestern India showed a significant decreasing trend during the period of 1866-2006 (Bhutiyani et al., 2010). 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 distribution are needed. In addition, the climate proxies used should be closely related to the ISM and the records need to be well-replicated and accurately dated.

Available tree ring records are widely distributed in the Indian monsoon region (Yadav et al., 2011). The climate of the southern Himalayas is dominated by changes in the Indian summer monsoon, and is 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., 2011; 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.

PAGES launched 2k network that produced regional and global temperature and precipitation syntheses based on multi-proxy and multi-record to get a better understanding of regional and global climate change. 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 several 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 northwest India, western Nepal and Bhutan (Sano et al., 2011; Sano et al., 2013; Sano et al., submitted). 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 few hundred years, and to investigate its possible driving mechanisms on various time scales.

- The discussion section analyzing why there may be a weakening monsoonal circulation over last few hundred years requires a more in-depth analysis. The presented tree ring records cannot answer this question, and the question diverges from the main focus of the paper. The land-sea contrast mechanism described is potentially interesting, but the authors need to be more descriptive about: (a) how well do we know there has been a change in the land-sea temperature contrast? (b) are there other potential explanations, given the long list of factors influencing the ISM the authors list in the introduction?

Answer: We have discussed possible reasons to result in the weakening Indian summer monsoon. Sun activity and atmospheric CO2 content were not the reasons caused reduced the ISM. Decreased land-sea temperature contrast may be the main reason, based on the fact that low-frequency variations in our regional tree-ring chronology are well correlated with those in the land-sea contrast data. In addition, aerosol emissions may be another reason to cause weakened ISM. Please see the revised part.

3.4 Centennial variability of the ISM inferred from the regional tree ring $\delta^{18}O$ record
There are also significant centennial-scale variations in the H5 record (Figure 7), which were extracted using a 100-year low-pass filter (Figure 10c, red line). The record exhibits a decreasing trend from 1743 to 1820 CE and an increasing trend since 1820 CE, which indicates 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 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 northwest India, influenced by the Arabian Sea branch of the ISM, exhibits a drying trend since 1950 CE (Sano et al., In press), 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), the data from only four stations extend back to 1826 CE and four longest stations locate in central or southern India. Monsoon season drying trend in northern India revealed by H5 regional tree ring $\delta^{18}O$ record may indicate that inland areas appear to be particularly sensitive to the weakening of monsoon circulation.

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. A previous study has indicated that solar irradiance has a significant influence on the ISM on multi-decadal to centennial timescales, and that reduced 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.

The land-sea thermal contrast which is also an important influencing factor for ISM (Roxy et al., 2015), is evaluated by atmospheric temperature gradient between the Tibetan Plateau and the tropical Indian Ocean (Fu and Fletcher, 1985; Sun et al., 2010). The history of land-sea thermal contrasts is reconstructed based on temperature differences between the Tibetan Plateau and the Indian Ocean (Figure 10a), and centennial variations of land-sea thermal contrasts are shown in Figure 10b. Three reconstructed land-sea thermal contrasts showed a decreasing trend since 1800 CE and 1820 CE (Figure 10b), and the H5 record exhibits a similar pattern of changes on a centennial scale (Figure 10c). The decreasing land-sea thermal contrast since 1800 and 1820 CE has resulted in a weaker ISM, and the increasing trend of the H5 record since 1820 CE also indicates a reduced ISM intensity. In addition, 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.

Following the SPATIAL laboratory group discussion, Rich Fiorella compiled this short comment based on input from Gabe Bowen, Rose Smith, Annie Putman, Crystal Tulley-Cordova, Chao Ma, Zhongyin Cai, Yusuf Jameel, Brenden Fischer-Femal, and Sagarika Banerjee.

Thank you very much for helpful suggestions from SPATIAL lab.

5: Comments from PAGES 2k team:

The PAGES Data Stewardship Integrative Activity seeks to advance best practices for sharing data generated and assembled as part of all PAGES-related activities. As part of this activity, a team of reviewers has been constituted for the "Climate of the Past 2000 years" Special Issue. The data team is reviewing the data handling within each of the CP-Discussion papers in relation to the CP data policy and current best practices. The team has identified essential and recommended additions for each paper, with the goal of achieving a high and consistent level of data stewardship across the 2k Special Issue. We recognize that an additional effort will likely be required to meet the high level of data stewardship envisaged, and we appreciate dedication and contribution of the authors. This includes the use of Data Citations (see example in supplement). We ask authors to respond to our comments as part of the regular open interactive discussion. If you have any questions about PAGES Data Stewardship principles, please contact any of us directly.
Best wishes for the success of your paper,
2k Special Issue Data Review Team (Darrell Kaufman, Nerilie Abram, Belen Martrat, Raphael Neukom, Scott St. George) and ex-officio team members (Marie-France Loutre, Lucien von Gunten)

Thanks for your suggestions.

Essential additions for this paper:
(1) Add a "data availability" section that describes where the data can be accessed, including a Data Citation for the new data generated in this study (see below).
Answer: We have added the "Data availability section before "acknowledgments".
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). Hulma $\delta^{18}O$ chronology should be available at this link: https://www.ncdc.noaa.gov/paleo-search/study/22547 (Sano et al., 2017a), which was described by Sano et al. (2012).; Wache $\delta^{18}O$ chronology should be available at this link: https://www.ncdc.noaa.gov/paleo-search/study/22548 (Sano et al., 2017b), which was described by Sano et al. (2013); Manali $\delta^{18}O$ chronology should be available at this link: https://www.ncdc.noaa.gov/paleo-search/study/22549 (Sano et al., 2017c), which was described by Sano et al. (in press); JG $\delta^{18}O$ chronology should be available at this link: https://www.ncdc.noaa.gov/paleo-search/study/22550 (Xu et al., 2017a); Ganesh $\delta^{18}O$ chronology should be available at this link: https://www.ncdc.noaa.gov/paleo-search/study/22551 (Xu et al., 2017b).

(2) Add Data Citations for each of the five datasets listed in Table 1, including both the previously published data, and the new data from this study. Note that the publication citation for record #3 is incorrect; a journal issue was assigned in 2012

(not 2011; doi:10.1177/0959683611430338).

Answer: Thanks for your suggestions. We have modified the Table 1 according to the suggestions.

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

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., in press	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

(3) Add a note to explain that the spelling of the site name used in the previous paper is “Julma” rather than “Hulma” as it appears in the current paper.

Answer: In previous paper (Sano et al., 2012), Hulma is the name for sampling site, while Julma is the name of meteorological station.

(4) For those data not already in a public repository, submit essential metadata along with the time series shown in Figs 2a, 3a, and 4a, plus the averaged time series (H5) in Fig 4b, and its smoothed versions (Fig 10 (red) and Fig 11b (red)).

Answer: We have added the unpublished data into NOAA Paleoclimatology Datasets.

Recommended additions:

(1) Add Data Citations for each time series used to compare with the 18O tree-ring time series, including: Fig 5a (Indian rainfall); Fig 5b (Indian Monsoon); Fig 9 (ENSO

from McGregor and Wilson); Fig 10 (Stalagmite 18O); Fig 11 (Tibetan temperature and Indian Ocean SST)

Answer: We have added the data citations for these records. Please see the following part.

Wang, B., Wu, R., and Lau, K., Indian monsoon index, http://apdrc.soest.hawaii.edu/projects/monsoon/definition.html, 2001

Mooley, D., Parthasarathy, B., Kumar, K., Sontakke, N., Munot, A., and Kothawale, D. Indian Institute of Tropical Meteorology Homogeneous Indian Monthly Rainfall Data Sets (1871-2014), http://www.tropmet.res.in/static_page.php?page_id=53, 2016

McGregor, S., Timmermann, A., and Timm, O.: A unified proxy for ENSO and PDO variability since 1650, World Data Center for Paleoclimatology, https://www.ncdc.noaa.gov/paleo-search/study/8732, 2010

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.

Sinha, A., Kathayat, G., Cheng, H., Breitenbach, S. F. M., Berkelhammer, M., Mudelsee, M., Biswas, J., and Edwards, R. L.: Trends and oscillations in the Indian summer monsoon rainfall over the last two millennia, Supplementary Data 2, Nat Commun, 6, 2015.

Tierney, J., Abram, N., Anchukaitis, K., Evans, M., Cyril, G., Halimeda, K., and Saenger, C., PAGES Ocean2K 400 Year Coral Data and Tropical SST Reconstructions, World Data Center for Paleoclimatology, https://www.ncdc.noaa.gov/paleo-search/study/17955, 2015.

Shi, F., Ge, Q., Bao, Y., Li, J., Yang, F., Ljungqvist, F. C., Solomina, O., Nakatsuka, T., Wang, N., and Zhao, S.: Asian 1,100 Year Multiproxy Gridded Summer Temperature Reconstructions, World Data Center for Paleoclimatology, http://ncdc.noaa.gov/paleo/study/18635, 2015.

Cook, E., Krusic, P., Anchukaitis. K., Buckley, M., Nakatsuka, T., Sano, M., and PAGES Asia2k Members: Asia 1200 Year Gridded Summer Temperature Reconstructions, World Data Center for Paleoclimatology, https://www.ncdc.noaa.gov/paleo-search/study/19523, 2013.

Wang, J., Yang, B., and Ljungqvist, F.: Eastern Tibetan Plateau 1000 Year Summer Temperature Reconstruction, World Data Center for Paleoclimatology, https://www.ncdc.noaa.gov/paleo-search/study/20590, 2015.

(2) Submit for archival: (a) the correlation time series in Fig 9 and (b) the land-sea thermal contrast time series in Fig 11b (black).

Answer: The data are easily got based on raw data of five tree ring cellulose oxygen isotopes chronologies and data in public repository. After we contribute tree ring oxygen isotope data to a public repository, other researchers can use the data based on their own interests.

6 Comments from editor:

Comments to the Author:
I am grateful to the authors for their patience during editorial consideration, and for their responses. The paper is recommended for major revisions. Please address all reviewer concerns directly, including input from the 2K data stewardship team and input from the public review ("short comments"). This may include, but is not limited to, the changes you proposed in your author responses. The revised manuscript is subject to approval by the reviewers and the editor before a final decision on publication is made.
In particular, please give careful attention to the description, incorporation and consideration of uncertainties when reporting the results and in the discussion of correlation, spectral and other analyses of data.
In addition, your response to input from the PAGES2K Data Stewardship Team is judged to be insufficient. Please be sure that the following changes are made in the revised manuscript:

- Data-review comment #1 asked the authors to add a "Data availability" section (as does CP instructions to authors). Please create a "Data availability" section, rather than adding a statement to "Acknowledgments".

Answer: We added the "Data availability section before "acknowledgments". Please see this part in the revised manuscript.

- Data-review comment #2 asked authors to add data citations to Table 1. Please do so, rather than adding a missing publication citation.

Answer: We have added the data citations into Table 1.

- Data-review comment #4 asked authors to submit the data that are used in the paper to a public archive. Your response was that the data will be submitted "after the manuscript was published", but the data need to be submitted before the manuscript is published. Note that data may be archived with NOAA prior to acceptance of the paper, but only made fully visible to the public once the paper is published.

Answer: We have added these five tree ring oxygen isotope chronologies into NOAA Paleoclimatology Datasets

Thank you very much for helpful suggestions.

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

Chenxi Xu[1], Masaki Sano[2,3], A. P. Dimri[4], Rengaswamy Ramesh[5,6], Takeshi Nakatsuka[2], Feng Shi[1], Zhengtang Guo[1,7,8]

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6. School of Earth and Planetary Sciences, National Institute of Science Education and Research, Odisha 752050, India
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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 north India and central Nepal and three published records from Northwest 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 centennial 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. Centennial changes in the regional tree ring $\delta^{18}O$ record indicate a 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.

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 centennial changes in ISM. Therefore, long-term proxy records of ISM are needed.

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). Monsoon precipitation in northwestern India showed a significant decreasing trend during the period of 1866-2006 (Bhutiyani et al., 2010). 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 distribution are needed. In addition, the climate proxies should be closely related to the ISM and the records need to be well-replicated and accurately dated.

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2 **Materials and methods**

2.1 Sampling sites

Five tree ring cellulose $\delta^{18}O$ records were selected to construct a regional climate signal for the southern Himalaya (Figure 1). Three records (Manali, in northwest India; Humla, in west Nepal; and Wache, in Bhutan) were published previously (Sano et al., 2012; Sano et al., 2013; Sano et al., In press). 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).

2.2 Cellulose extraction and isotope measurements

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 plate and conventional methods (Kagawa et al., 2015; Xu et al., 2013b).

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‰.

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) and sea-surface temperature (SST) values obtained from the National Climatic Data Center v4 data set. 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 software "kSpectra Toolkit" was employed to calculate power spectrum of the regional tree ring oxygen isotope chronology. 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).

3 Results and discussion

3.1 Tree ring $\delta^{18}O$ variations in the southern Himalaya and a regional tree ring $\delta^{18}O$ 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 1643-2008 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 1641-2008 CE.

In northern Indian sub-continent, three long-term tree ring $\delta^{18}O$ chronologies from northwest India, eastern Nepal and Bhutan have been built up in previous studies (Sano et al., 2012; Sano et al., 2013; Sano et al., In press, 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 1). Three tree ring $\delta^{18}O$ chronologies in northwest India, eastern Nepal and Bhutan were controlled by monsoon season rainfall or PDSI (Sano et al., 2012; Sano et al., 2013; Sano et al., In press, Table 1), and the two new tree ring $\delta^{18}O$ 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 $\delta^{18}O$ records for the Himalaya 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 $\delta^{18}O$ chronologies show significant correlations at multi-decadal time scale (Table 2). These results indicate that five tree ring $\delta^{18}O$ records reflect a common controlling factor that may be related to regional climate. Therefore, we combined two tree ring $\delta^{18}O$ records in this study with three previously published tree ring $\delta^{18}O$ chronologies to construct a regional tree ring $\delta^{18}O$ record. The five $\delta^{18}O$ records were individually normalized over the interval from 1801-2000 CE, and then averaged to produce a regional Himalayan $\delta^{18}O$ record (H5 $\delta^{18}O$ record) for the entire interval (Figure 4f). Only one chronology (JG) spans an interval prior to 1742 CE, and therefore we focus on the interval from 1743-2008 CE in this study.

3.2 Climatic signals in the regional tree ring $\delta^{18}O$ chronology

We assessed the potential of the H5 $\delta^{18}O$ 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

$\delta^{18}O$ record is negatively correlated with gridded June-September precipitation in northwest and northern India and Nepal (Figure 6). These findings indicate that the H5 $\delta^{18}O$ record is capable of reflecting ISM changes from a statistical perspective.

Tree ring $\delta^{18}O$ has a close relationship with the ISM based on tree ring cellulose oxygen isotope fractionation model. Precipitation $\delta^{18}O$ and relative humidity are the two main factors controlling tree ring $\delta^{18}O$ (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 $\delta^{18}O$ in the monsoonal area (Vuille et al., 2005; Yang et al., 2016). Asian summer monsoon affects the $\delta^{18}O$ of precipitation through the 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 (~133 years) at a confidence level greater than 99% (Figure 7). This indicates that interannual and centennial 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 since 1870 CE (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 (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 (McGregor et al., 2010; Wilson et al., 2006) reveal that this type of unstable ISM-ENSO relationship occurred during the last 250 years (Figure 9). The reason may be that the two different patterns of El Niño (eastern-Pacific and central-Pacific) yield different monsoon impacts (Kumar et al., 2006). In addition, other factors, such as the Indian Ocean Dipole, also influence the ISM (Ashok et al., 2001; Abram et al., 2008).

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 Nino (central-Pacific El Nino) 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, 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). The future availability of longer, annually resolved marine records that provide independent estimates of SSTs in the tropical Pacific will improve our understanding of the relationship between the ISM and the two types of ENSO.

3.4 Centennial variability of the ISM inferred from the regional tree ring $\delta^{18}O$ record

There are also significant centennial-scale variations in the H5 record (Figure 7), which were extracted using a 100-year low-pass filter (Figure 10c, red line). The record exhibits a decreasing trend from 1743 to 1820 CE and an increasing trend since 1820 CE, which indicates 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 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 northwest India, influenced by the Arabian Sea branch of the ISM, exhibits a drying trend since 1950 CE (Sano et al., In press), 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), the data from only four stations extend back to 1826 CE and four longest stations locate in central or southern India. Monsoon season drying trend in northern India revealed by H5 regional tree ring $\delta^{18}O$ record may indicate that inland areas appear to be particularly sensitive to the weakening of monsoon circulation.

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. A previous study has indicated that solar irradiance has a significant influence on the ISM on multi-decadal to centennial timescales, and that reduced 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.

The land-sea thermal contrast which is also an important influencing factor for ISM (Roxy et al., 2015), is evaluated by atmospheric temperature gradient between the Tibetan Plateau and the tropical Indian Ocean (Fu and Fletcher, 1985; Sun et al., 2010). The history of land-sea thermal contrasts is reconstructed based on temperature differences between the Tibetan Plateau and the Indian Ocean (Figure 10a), and centennial variations of land-sea thermal contrasts are shown in Figure 10b.

Three reconstructed land-sea thermal contrasts showed a decreasing trend since 1800 CE and 1820 CE (Figure 10b), and the H5 record exhibits a similar pattern of changes on a centennial scale (Figure 10c). The decreasing land-sea thermal contrast since 1800 and 1820 CE has resulted in a weaker ISM, and the increasing trend of the H5 record since 1820 CE also indicates a reduced ISM intensity. In addition, 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.

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

The H5 regional tree ring $\delta^{18}O$ record does not exhibit significant decadal to multi-decadal periodicities (Figure 7), while the main spectral component of high-resolution speleothem $\delta^{18}O$ 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 ring $\delta^{18}O$ 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, while the H5 record are out-of-phase with speleothem $\delta^{18}O$ records during several intervals (Figure 11).

Based on the oxygen isotope fractionation theory, tree 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 ring $\delta^{18}O$ and speleothem $\delta^{18}O$. Other controlling factors differentially affect tree ring $\delta^{18}O$ and speleothem $\delta^{18}O$ values. Relative humidity has an important impact on tree ring $\delta^{18}O$ (Roden et al., 2000). Lower relative humidity result in enhanced evaporative enrichment of leaf water and then higher tree 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 results show that relative humidity's influences on the correlation between tree 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 ring and speleothem. In addition, limited three ^{230}Th dates points (3 control points) and relative large age uncertainty (9-31 years) of speleothems $\delta^{18}O$ time series during the common period of 1743-2000 may result in the incoherence between tree ring and speleothems $\delta^{18}O$. Long-term process-based study on tree ring $\delta^{18}O$ and speleothem $\delta^{18}O$ variations in future study are needed for a better understanding for climatic implication of two proxies.

4 Conclusions

We have combined three published tree ring cellulose $\delta^{18}O$ records (from Northwest 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.

Inter-annual and centennial variations are evident in the regional tree ring $\delta^{18}O$ chronology. Significant correlations between inter-annual changes and the El Niño-Southern Oscillation (ENSO) indicate that the ISM was affected by ENSO; however, this relationship was not consistent in the past. A robust, high-resolution and continuous ENSO reconstruction from the 'centre of action' area of the Pacific would shed more light on this relationship. Centennial-scale variations in the H5 record 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). Hulma $\delta^{18}O$ chronology should be available at this link: https://www.ncdc.noaa.gov/paleo/study/22547 (Sano et al., 2017a), which was described by Sano et al. (2012).; Wache $\delta^{18}O$ chronology should be available at this link: https://www.ncdc.noaa.gov/paleo/study/22548 (Sano et al., 2017b), which was described by Sano et al. (2013); Manali $\delta^{18}O$ chronology should be available at this link: https://www.ncdc.noaa.gov/paleo/study/22549 (Sano et al., 2017c), which was described by Sano et al. (in press); JG $\delta^{18}O$ chronology should be available at this link: https://www.ncdc.noaa.gov/paleo/study/22550 (Xu et al., 2017a); Ganesh $\delta^{18}O$ chronology should be available at this link: https://www.ncdc.noaa.gov/paleo/study/22551 (Xu et al., 2017b).

Acknowledgments:

This work was jointly funded by the Ministry of Science and Technology of the People's Republic of China (Grant No. 2016YFA0600502), the Chinese Academy of Sciences (CAS) Pioneer Hundred Talents Program, the National Natural Science Foundation of China (Grant No. 41672179, 41630529 and 41430531), an environmental research grant from the Sumitomo Foundation, Japan, a research grant from the Research Institute of Humanity and Nature, Kyoto, Japan, and grant in-aid from the Japan Society for the Promotion of Science Fellows (23242047 and 23-10262). Indian Space Research Organization's Geosphere Biosphere Programme supported RR and APD. This study was conducted in the framework of the Past Global Changes (PAGES) Asia2k programme. We deeply appreciate the helpful comments from three anonymous reviewers, the editor and the group members of SPATIAL laboratory at the University of Utah to improve the manuscript.

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

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., In press	Sano et a 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 a 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 a 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 a 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 a 2017b

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*

*$p<0.01$

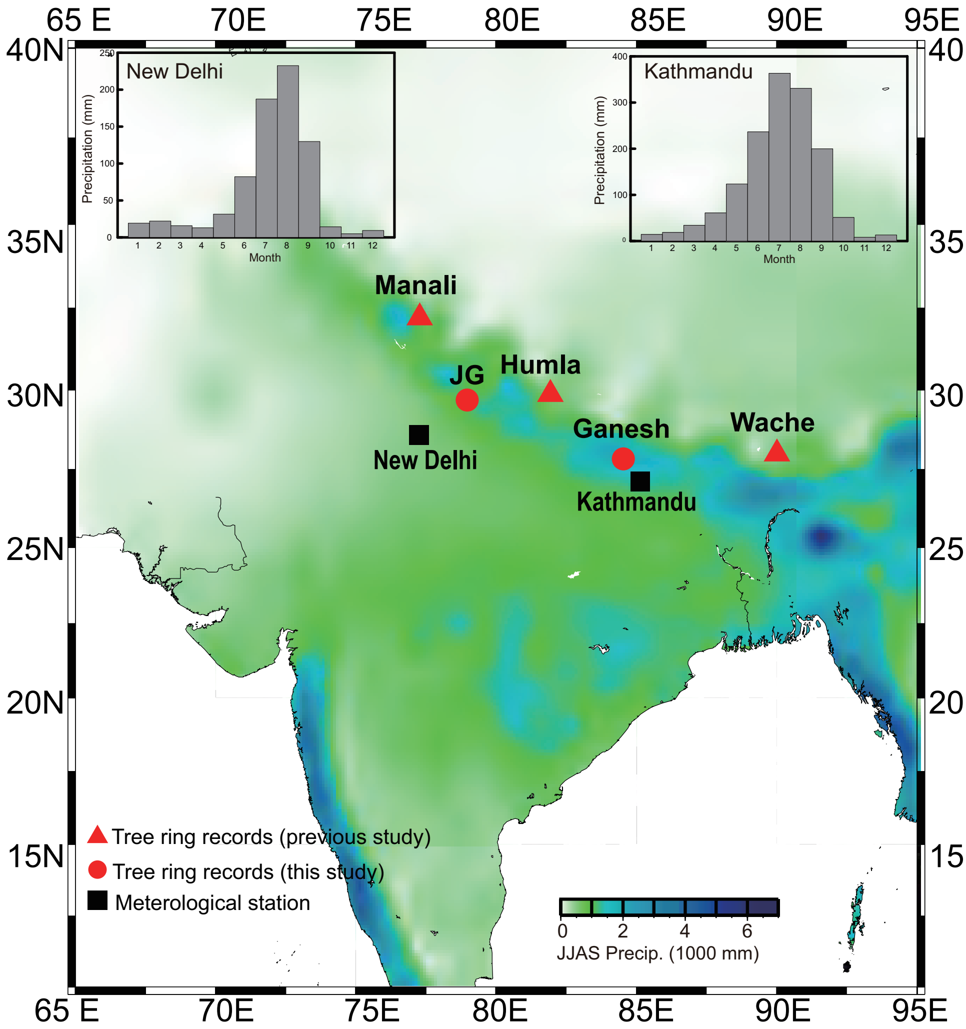

Figure 1. Map of the subcontinent showing tree-ring sites and color coded climatological monsoon precipitation from June to September. Insets show climatology of monthly precipitation at Kathmandu and New Delhi.

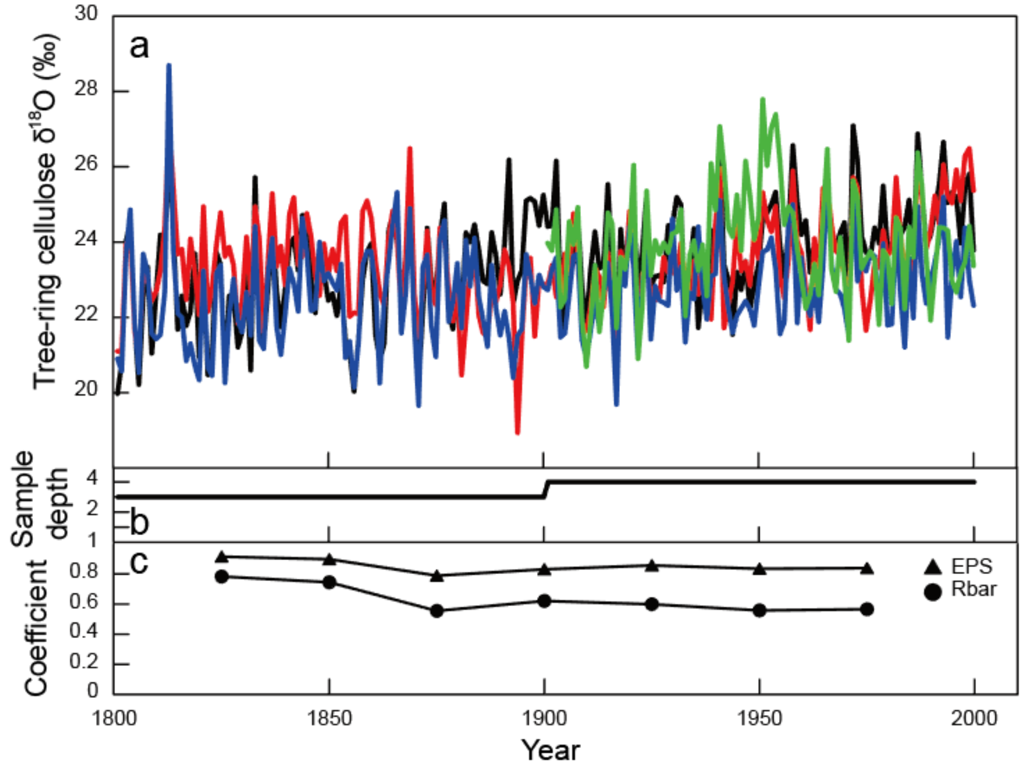

Figure 2. a: Tree ring $\delta^{18}O$ series of four individual trees: b: age profile, c: running EPS and Rbar statistics used 50-year windows and a 25-year lag for samples near Ganesh, Nepal.

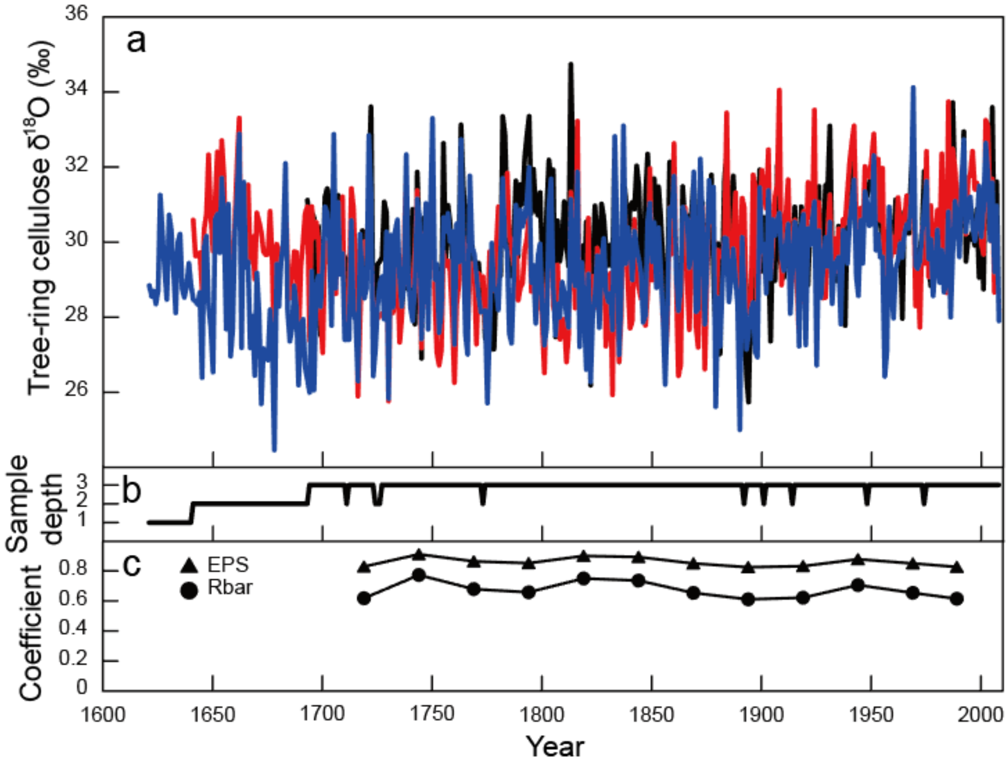

Figure 3. a: Tree ring $\delta^{18}O$ series for three individual trees: b: Age profile, c: running EPS and Rbar statistics using 50-year windows and a 25-year lag for samples near Jageshwar, India.

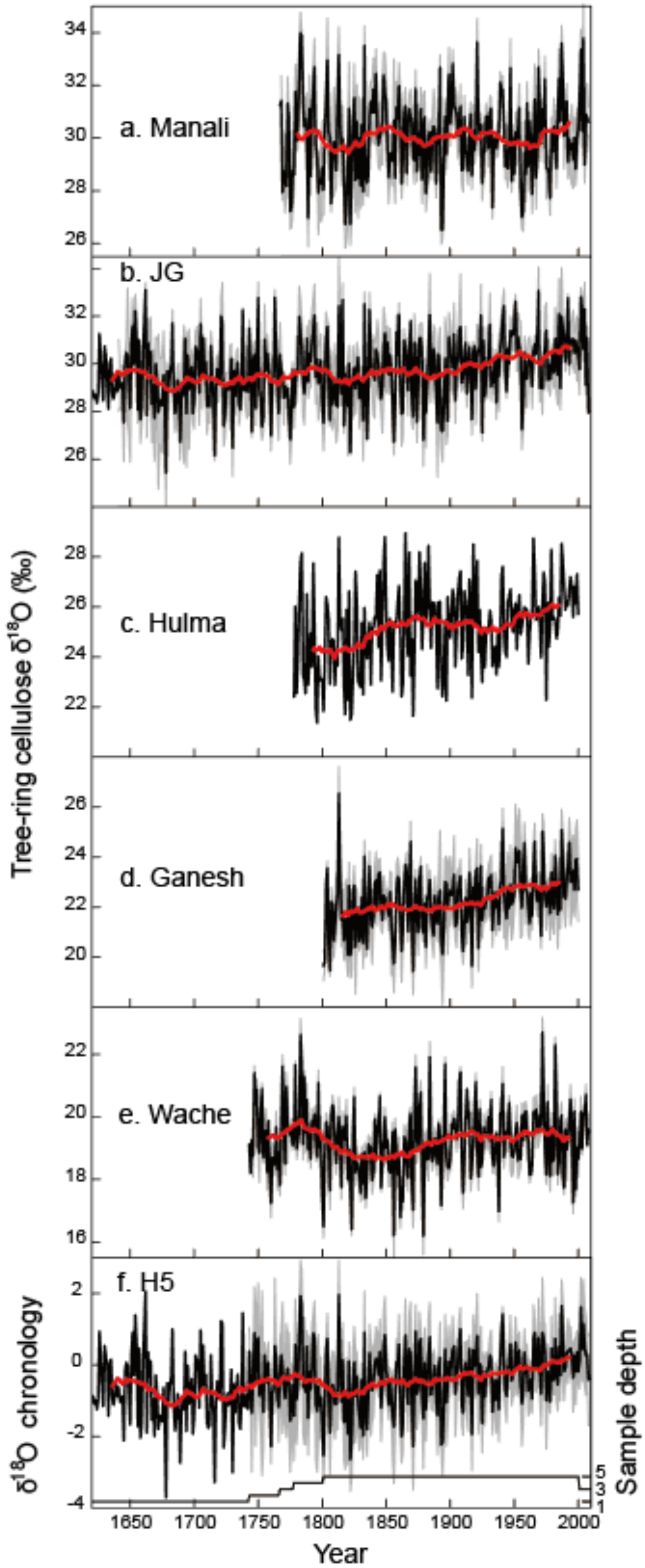
a. Manali
b. JG
c. Hulma
d. Ganesh
e. Wache
f. H5
Tree-ring cellulose δ18O (‰)
δ18O chronology
Sample depth
Year
1650
1700
1750
1800
1850
1900
1950
2000

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% (±1.96σ) confidence limits)

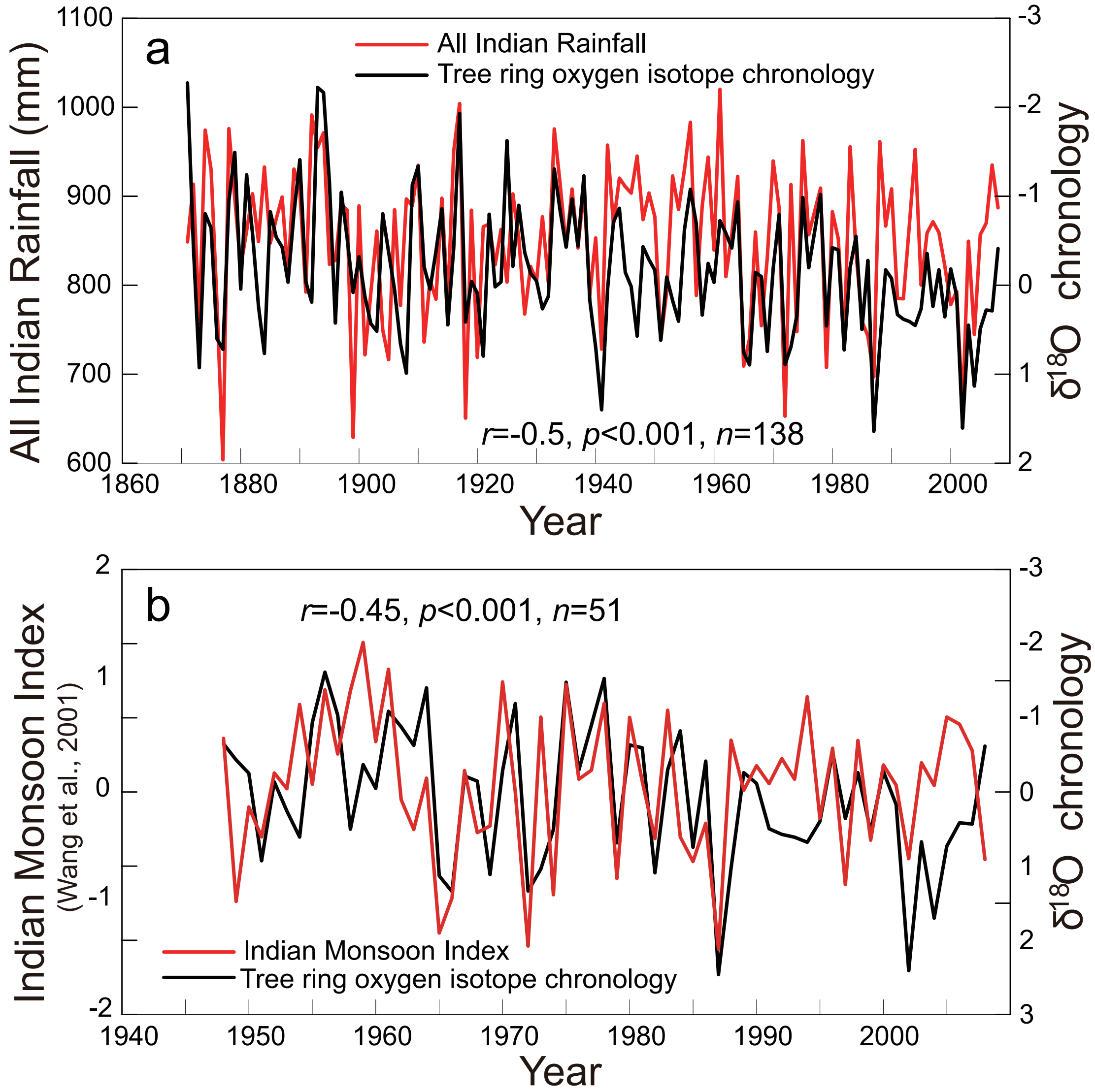

Figure 5. Comparison of the H5 regional tree ring $\delta^{18}O$ chronology with the All India Rainfall (a) and Indian Monsoon Index (b).

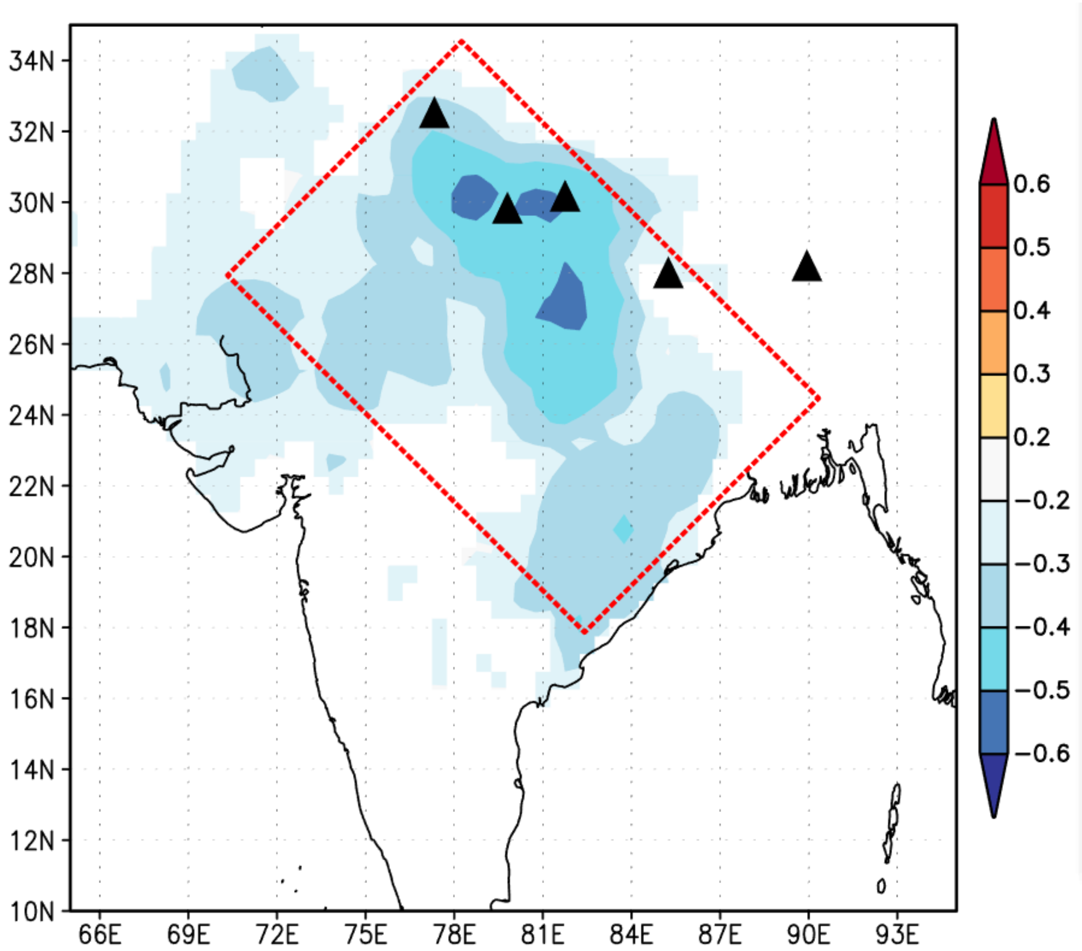

Figure 6. Spatial correlations between the H5 regional tree ring $\delta^{18}O$ record with June-September precipitation from GPCC V7 over interval from 1901-2008 CE. Only correlations significant at the 95% level are shown.

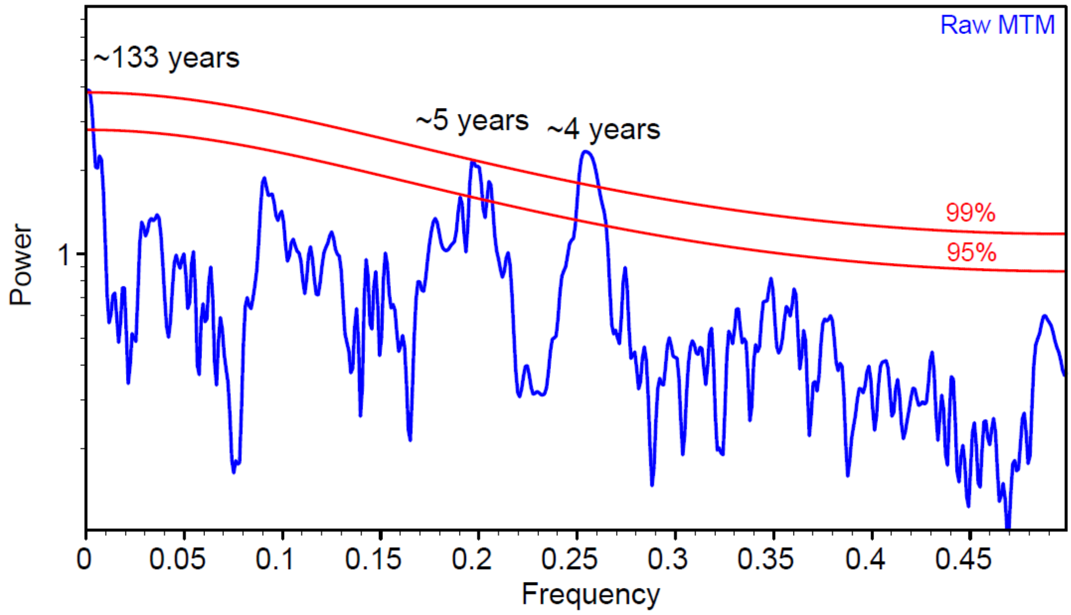

Figure 7. Multi-taper power spectra for the H5 regional tree ring $\delta^{18}O$ record.

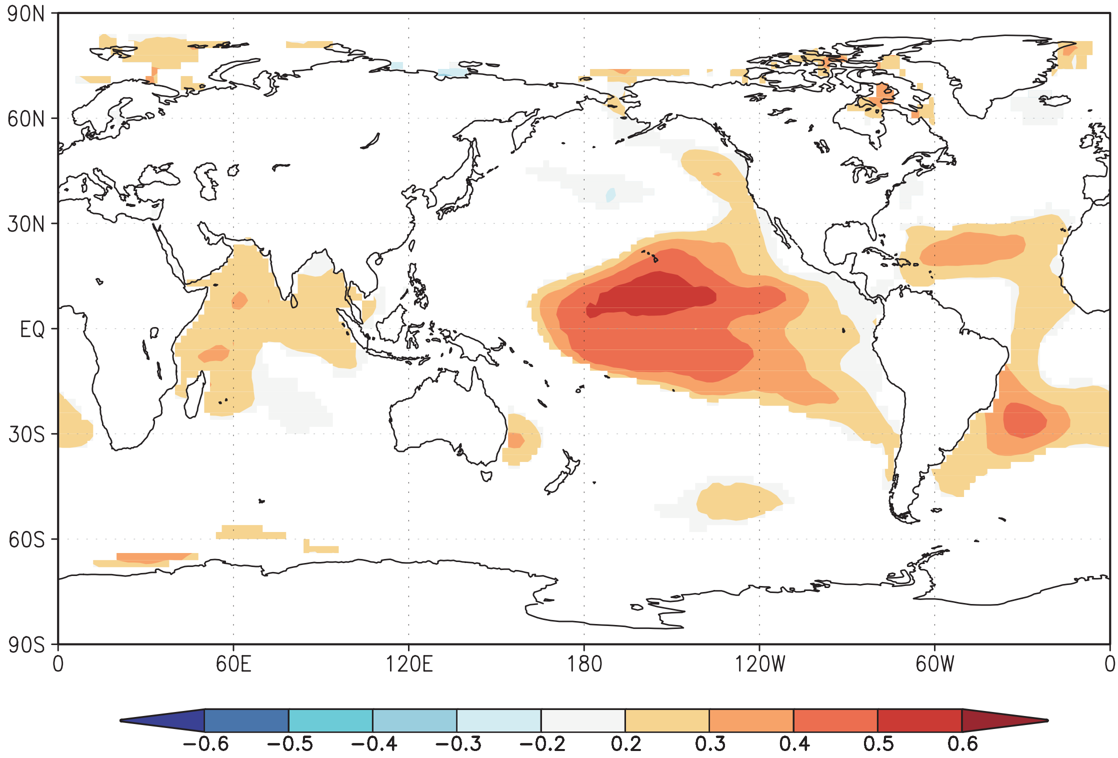

Figure 8. Spatial correlations between the H5 regional tree ring $\delta^{18}O$ record with May-September SST over the interval from 1871-2008 CE. Only correlations significant at the 95% level are shown.

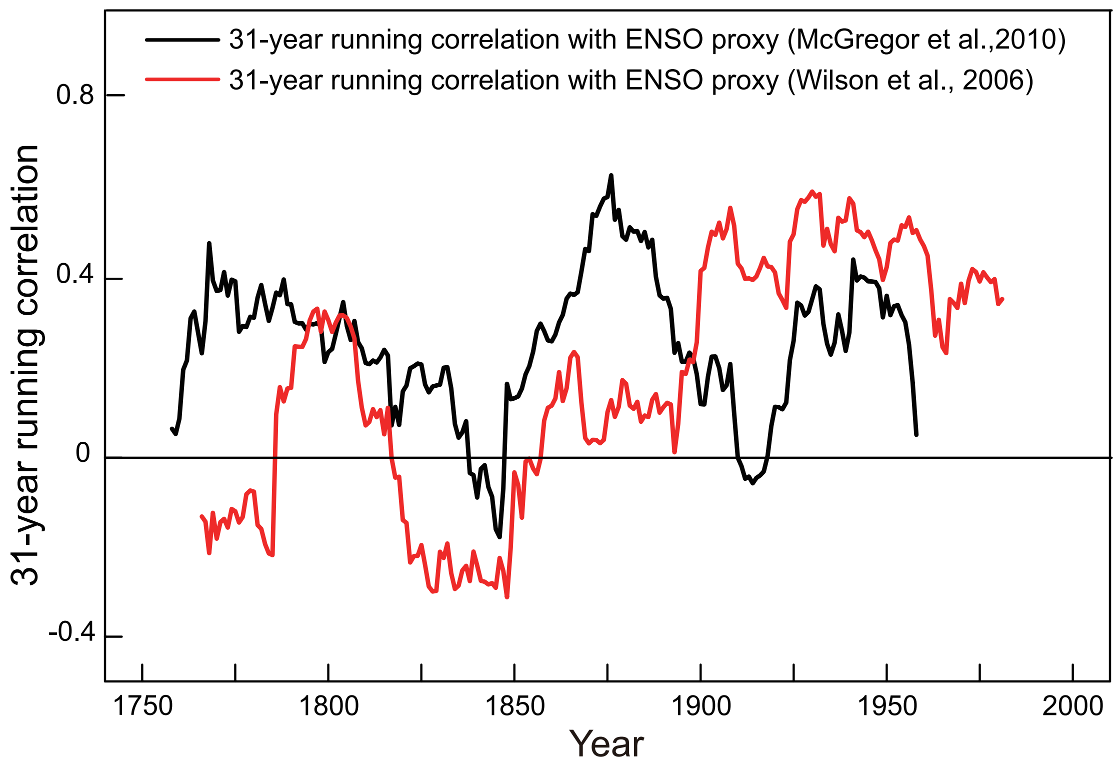

Figure 9. 31-year running correlation between the H5 regional tree ring $\delta^{18}O$ record and two reconstructed ENSO indices.

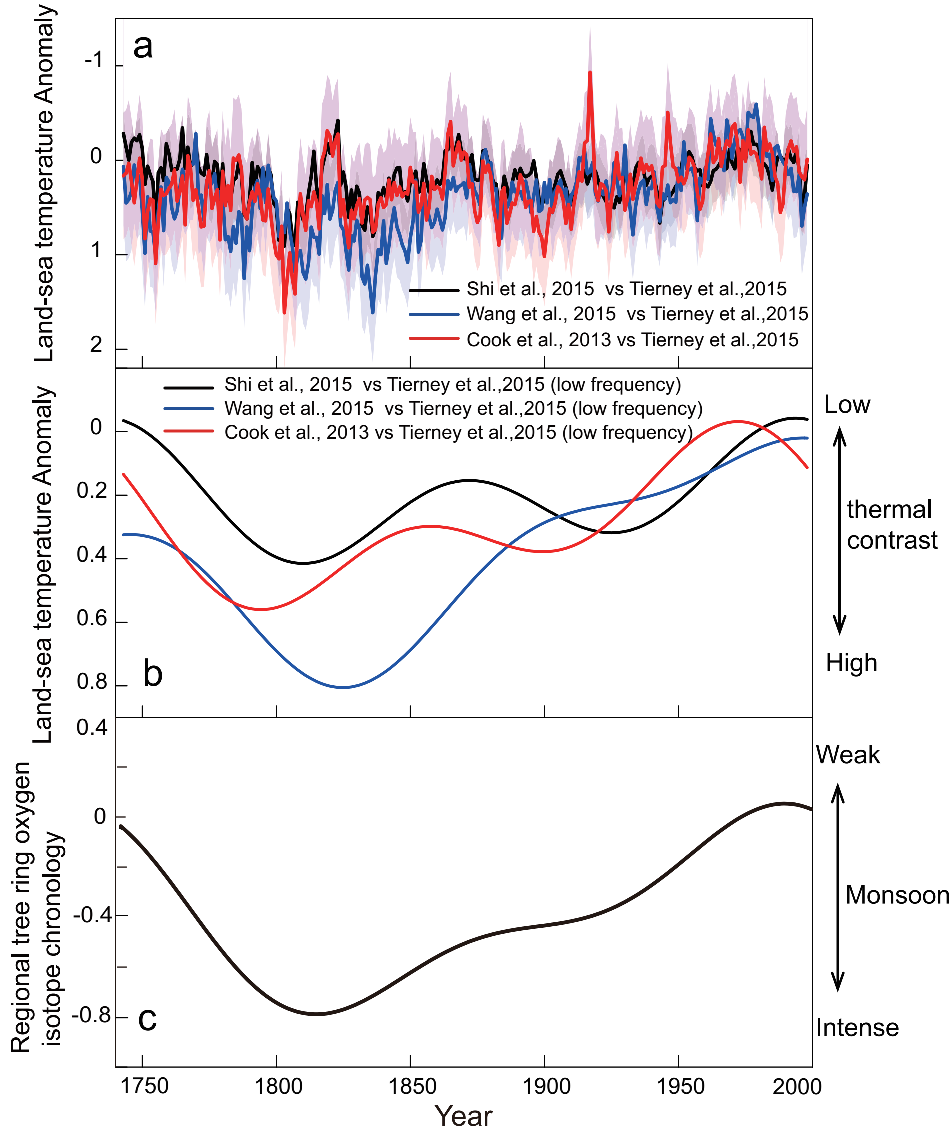

Figure 10. a: Land-sea Temperature Anomaly based on three summer temperature reconstruction for the Tibetan Plateau and one Indian Ocean SST reconstruction; b and c: centennial variations of land-sea thermal contrasts and the H5 regional tree ring $\delta^{18}O$ chronology.

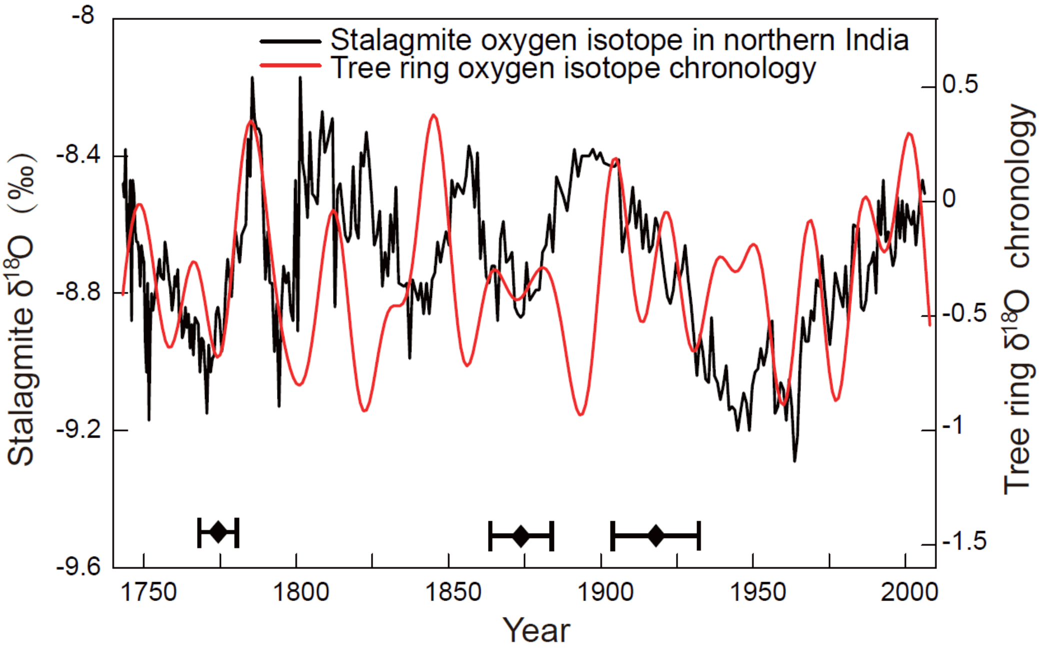

Figure 11. Comparison between multi-decadal regional tree ring $\delta^{18}O$ variations (red line) with stalagmite $\delta^{18}O$ changes (black line) in northern India. Rhombus with error indicates the ^{230}Th dates with uncertainty in stalagmite $\delta^{18}O$ chronology.