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Reply to interactive comment on "Variability of summer humidity during the past 800 years on the eastern Tibetan Plateau inferred from δ^{18}O of tree-ring cellulose" by J. Wernicke et al.

[reply] Dear anonymous referee # 1,

Thank you very much for your constructive comments and all the critical questions and suggestions you made on the interactive discussion paper "Variability of summer humidity during the past 800 years on the eastern Tibetan Plateau inferred from δ^{18}O of tree-ring cellulose". We express our gratitude that you recommend our paper to be published and to give us the opportunity to resend a revised manuscript. As suggested, we herewith resubmit our carefully and comprehensively revised manuscript (modified parts are highlighted in blue). We basically rewrote the discussion part and achieved new insights to the control mechanisms of relative humidity at the study site by applying spatial correlation analyses. Furthermore, we omitted the spectral analysis part since a cross-spectral-like time series comparison is somewhat beyond the scope of this paper. Apart from the revised manuscript, each single comment was replied in detailed within this letter. Doing so, we hope that we satisfactorily responded to all critical points. If you have any further requests or questions, do not hesitate to contact us immediately.

Sincerely,

Jakob Wernicke

Anonymous Referee 1

Received and published: 2 September 2014

This paper presents an 800 year d18O cellulose record from eastern Tibet. The record is presented as an RH reconstruction. The data is very strong, there are good statistical constraints on the transfer function and the record comes from a place with limited data. For all these reasons, I support the publication of the data so others can take advantage of this important reconstruction. That said, I found much of the discussion on the climate dynamics and proxy processes to be extremely lacking. There is no extensive discussion of the processes that give rise to the RH control on the proxy. For example, there is a slope of -2.3 permille% RH. What can this slope tell about the processes that transfer a change in RH onto the tree ring cellulose? This needs attention. Further, some of the statistics, namely those devoted to spectral analysis to be superficial.

[reply] The focus of this study is to present a long-term temporally high resolved new climate reconstruction at a place with limited data. That implies in remote areas, like the eastern TP, plant physiological studies might be infrastructural and technical very difficult to conduct. That means to really determine the plant physiological processes that transfer the rH signal into the cellulose must currently remain insufficiently clarified in most of the remote study sites in high mountain ecosystems. We depart from the approach of determining spectral signals of our times series, because we might consider these analyses in a more concrete and comprehensive future study examining exclusively these such issues.

There are a number of weak and confusing discussions about land-surface thermal gradients, ENSO, NAO, solar controls on the monsoon. These discussions are often confusing and occasionally lack logic. Ultimately, a lot of the space that is devoted to large scale climate modes turns out to be unimportant. Therefore, the discussion of climate dynamics can be simplified and focused.

[reply] We explicitly referred to findings of Liu et al. *(2013) and* Sano et al. *(2013), who found strong relations to ENSO, PDO and the Pacific sea surface temperature at locations approximately 500km south of our study site. We followed their work and expected to find similar strong correlations of our $\delta^{18}O$ record with ENSO (Sea surface temperature in region 3.4). Surprisingly, we couldn' t find reliable indications for a Pacific influence. Accordingly, referred to recent findings of* Mölg et al. *(2014), we assume that a strong westerly signal might modulate our record. Thus, we applied the monthly resolved NAO indices in order to find a link to the North Atlantic climate. However, we could not verify any significant and stable relationship with large-scale circulation modes (see discussion paper Figure 7). For that reason we summarized in the discussion paper (*Wernicke et al, 2014*) : "... a superimposing large-scale circulation influence neither from NAO nor Nino 3.4 SST can be confirmed ." Consequently, we assumed that a more regional to local signal controls the reconstructed relative humidity at our study site. Therefore we conducted the heat flux spatial correlation within the discussion paper.*

I suggest starting the discussion start from the simple question of what controls RH on the eastern Tibetan Plateau. RH can be controlled by 1) air mass trajectory, 2) whether air is principally subsiding or rising, 3) local land surface processes such as soil moisture, 4) boundary layer dynamics for example, the stable nighttime boundary layer tends to have 100% RH whereas daytime turbulence and mixing of free tropospheric air tends to lower RH. Once a clear understanding of controls of RH at the proxy site are established than the significance of this in terms of large scale climate can be explored. Ultimately, the observation of a century long decline in RH is fascinating but understanding the processes that actually led to this decline would make this study really breakthrough. I recommend this paper be published but only after a major rewrite of the Discussion is conducted.

[reply] We conducted spatial correlations of the ERA interim data in order to determine the spatial variability of the rH over the TP for several elevation levels. We obtained a very regional pattern, which highlights the strong link of relative humidity at our study site to the relative humidity variability of the entire TP. Additionally, a strong negative relationship of the rH conditions in our study region to the west-central Asia region was found, which may be an indication for a westerly influence in the mid-altitude troposphere.
Furthermore, we examined references providing explanations for the remarkable rH decline since ~1870s (see revised discussion part). Unfortunately none of these studies give a conclusive explanation about the dynamic causes causes for the moisture decline, which has to be considered in a more detailed future study.

Pg 3328 4: "This is the first chrononolgy for eastern Tibet..." 8: "variations...More moist conditions prevailed during the termination..." 10: Simply state that there is no systematic shft in the mean state during the LIA, which is contrary to Indian Summer Monsoon reconstructions. 10: Your record does not show a consistent decline through the 20th century. It appear to flatten off by the 1950's. 19-20: It is never clear what records share the same spectra. Cross spectral analysis is needed. 24: Vuille is a good reference for d18O of monsoon but not a good reference for the socio-economic impacts of the monsoon.

[reply] Pg 3328

- *We applied the suggestions of line 4,8,10 in the revised manuscript.*
- *Indeed, the trend slope between 1950 and 1996 is not significantly different from zero. Thus, the moisture decline is attuned since around the ~1950s, or a little later (~1970s), which coincides with the restrengthening of the thermal gradient between Bay of Bengal-North Indian Ocean and the Equatorial Ocean (see Figure 7).*
- *As mentioned above, we will consider the spectral analysis in a future study.*

Pg 3329 1: Do these references actually discuss changes in humidity or a decline in precipitation. The two are not identical, related-yes, but not identical. 1:..."explained by a reduction in the thermal gradient..." 11: "... increases and can be used to facilitate targeted decision making regarding water and resource management." 12: "dislocation" is the wrong word. Northerly movement... 15: Intraseasonal oscillations such as the madden Julian Oscillation have strong controls on monsoon precip and particularly in generating the complex spatial patterns. 29: ”stronger rainfalls...”

[reply] Pg 3329

- *1: . . . weakening trend of the ASM precipitation amount was reported. . .*
- *We included the comments of line 1, 11 in the text*
- *We implemented the suggestion concerning short-term monsoon variability, such as the MJO, at the beginning of our discussion part. Nevertheless, we want to point to the fact, that the climate signal recorded within the tree-ring cellulose contains annually integrated information, rather than signals on a monthly or daily scale. According to the nature of the MJO as a highly variable phenomena appearing between 30-90 days, these modulations are only hardly detectable within tree-ring cellulose. In principle, tree-ring inferred data provide the opportunity for intra-annual signals. In case of the very narrow tree-rings of our studied trees, an intra-annual analysis was not feasible. Thus, we cannot provide indications for the modulating effect of the MJO to our relative humidity reconstruction.*
- *29: changed into ”strong rainfalls”*

Pg 3330 11: erase ”sensitive” 14: ”Therefore,” 15: ”... unclear to what extent ...”

[reply] Pg 3330
We have indicated this in the revised version.

Pg 3331 6: ”The oldest tree is 804 years old”

[reply] Pg 3331
We have indicated this in the revised version.

Pg 3332 5: ”During periods of the chronology with extremely narrow rings, we used shifted block pooling to obtain sufficient material.” 11: Spectrometer misspelled

[reply] Pg 3332
We have indicated this in the revised version.

Pg 3333 22: fix ”the the”

[reply] Pg 3333
We have indicated this in the revised version.

Pg 3334 9-11: More information on the met data is needed. Sunshine hours and vapor pressure are not common met products. Is the sunshine hours, photosynthetic active radiation or net radiation? Is vapor pressure obtained with a hygrometer or inferred through the RH sensor? What equation is used to calculate vapor pressure? Vapor Pressure Deficit would be useful to correlate against d18O cellulose, following the work of Ansgar Kahmen. 12: Evapotranspiration is used here but actually it is only transpiration that influences the leaf water fractionation. Unless you are referring to the secondary effects that evaporation had on soil water and consequently on the d18O of the plant source water. 13: "has demonstrated" 14: "temperatures on tree ring growth." 14-16: Why would May temperatures influence d18O of cellulose. I understand that growth is limited by temperature at high altitude sites but why would temperatures have an effect on the isotope ratio? Could this be tied to the temperature controls on RH? Please explain. 16-18: Sunshine has a negative impact on d18O of cellulose, which seems odd to me. Later on in the paper you discuss that less sunshine=more cloudiness=higher relative humidity which would lead to lower d18O cellulose. What is the mechanism by which more sunshine actually decreases d18O of cellulose? Perhaps, more sunshine=more convection=more rainfall=higher humidity=low d18O cellulose. Please elaborate on how sunshine directly influences the isotope ratio in the cellulose. 27: should be "r=-073"

[reply] Pg 3334

- *The meteorological data were provided by our Chinese colleagues. They obtained the data from the "China Meteorological Administration". Sunshine hours were accounted as duration of net radiation greater than 120W/m^2. Unfortunately, the equation how vapor pressure was calculated, was not made available to us on request. We have indicated this in the revised version.*
- *The findings of* Kahmen et al *(2011) about an integrating climate predictor may be applicable in case of a $\delta^{18}O$ response to both, temperature and relative humidity. Our correlation analysis revealed only a weak and non-significant response of 18O to temperature. Therewith Vapor Pressure Difference (VPD) is expected to explain not more of the $\delta^{18}O$ record. Nonetheless, using the Magnus formula, we calculated the Saturation Vapor Pressure and subtracted the vapor pressure in order to obtain the VPD. The mean VPD of July-August significantly correlates with our $\delta^{18}O$ record during the calibration period ($r = 0.68$, $p < 0.01$). This was not unexpected, since VPD was evaluated from rH. However, the expected weaker relationship was achieved and thus less explanatory power of VDP to our record can be confirmed. Additionally, in perspective of climate projections or forecasts, working with "hard" climate elements, such as rH (precipitation, temperature), is more targeting than the reconstruction of integrated climate elements.*
- *12: Thank you, we changed evapotranspiration into transpiration*
- *13,14: The tree growth is limited by temperature and early summer temperatures might alter the snow melting time. Thus, if temperatures in May are reasonable high, the snow melt would be initiated early and might contribute to plant accessible water. Accordingly, tree metabolism and plant water fractionation would start earlier. However, that is only an assumption we are not able to validate with our data and therefore exclude this discussion from the manuscript.*
- *16-18: The sentence of in line 16 was misleading, because we referred "inversely" to the negative correlation of $\delta^{18}O$ with relative humidity. Sunshine hours are of course not inversely correlated to $\delta^{18}O$, but positively correlated to $\delta^{18}O$ (see figure 3). The relationship of high sunshine hours, less cloudiness, decreased relative humidity and therewith an enrichment of heavy isotopes is correct. This positive feedback was validated by findings from the southeastern Tibetan Plateau (*Shi et al., 2012*). We corrected accordingly in the revision.*
- *27: We fixed that in the revised version*

Pg. 3335 1-2: "more robust than for single months" 13: should that be "binomial" 19: The slope between d18O cellulose and RH is -2.3. How does this compare with previous studies such as Roden 2000. Please consider quantitative comparisons of the slope you found with as many previous studies as possible. For modeling proxies, it is useful to understand how global these slopes are or whether they are species and region-specific 23-25: It really seems that the decline in RH begins in 1871 and ends in the 1950s. The low pass filter suggests the trend continues but this appears to be an artifact of edge effects. I would like the slope of d18O calculate for 1950 through the present and see if it is statistically different than 0.

[reply] Pg 3335

- *1,2,13: We fixed those in the revised version*

- *Several studies have documented that the leaf water enrichment with heavy isotopes is related to air moisture and leaf temperature (VPD), but also to the isotopic composition of atmospheric water vapor (*Flanagan et al., 1991*). Thus, under stable moisture conditions the kinetic isotope fractionation mostly depends on the isotopic composition of atmospheric water vapor. Due to mean moisture conditions and water vapor isotope content of air varies among different regions, the relationship between several microenvironments varies respectively. Additionally, the "effective path length" differs among species, which induces different slopes of the regression function (*Kahmen et al, 2009*). Nevertheless, under natural circumstances negative slopes between rH and $\delta^{18}O$ were identified globally (*McCarroll and Loader (2004); **?***). We added the relevant information in the revised manuscript and appreciate these suggestions in order to achieve deeper insights about plant-physiological processes.*

- *We considered your comments and received a slope that apparently flattens at ~1950s, perhaps a little later (~1970s). The slope is very small (m = 0.01) and statistically not significantly different from zero (p = 0.63).* Chung and Ramanathan (2006) *see the reason in uneven warming trends over the northern and equatorial Indian Ocean. We tested their argumentation by adding a gradient calculation in the manuscript (see Figure 7). The graph shows the difference (blue line) between the HadSST2 data for the Pacific Ocean along the equator and Bay of Bengal region. Since ~1950s the temperatures seems to evenly increase, while the gradient becomes larger since ~1970s. Based on the traditional temperature driven gradient approach of strengthening/weakening monsoon moisture conditions, the observed gradient increase since ~1970s implies an attenuation of the distinct moisture decline.*

Pg 3336 4: consider an alternative word to "confuted" 10-13: From the wavelength analysis it appears that the cycles are very intermittent. It would be good to show the global wavelet and also standard FFT to argue that these cycles are statistical and persistent through the record. If these cycles are going to be compared against other records cross-wavelet or cross-spectral analysis is needed. It is not sufficient to say they are commonly forced signals without doing a cross spectral analysis. 26-27: "data sets and the Lhamcoka ....On the contrary, the tree ring width"

[reply] Pg 3336

- *4: We changed "confuted" to "were not corroborated" in the revised manuscript.*

- *10-17: We excluded all frequency analysis of our and other time series, due to these analyses are beyond the scope of this paper of presenting a new rH reconstruction on the eastern TP. However we are aware that these analyses have should be conducted in a comprehensive future study.*

- *26-27: We entirely rewrote the Discussion paragraph.*

Pg 3337 18-22: If the humidity decline is associated with a change in the thermal gradient than show this. Please calculate the thermal gradient using ocean and land temperature datasets such as from Hadley Centre and correlate it to the reconstructed humidity. It is not sufficient to say this, when data is available to test this. 22: "reduction are not sufficiently clear." 24: replaces "discovered" with "found" 26-28: The solar argument for the humidity decline requires significantly more explanation. If solar forcing is heating the land and ocean evenly, than this would not generate a change in the thermal gradient. If solar is heating up the land more than the ocean than this would increase the monsoon and humidity. If solar is heating up the ocean faster than this could theoretically increase the thermal gradient and be a plausible explanation for the change in moisture. There are solar reconstructions and recent observations that could be used to support your argument. In general, this argument needs to be significantly elaborated. Further, I would argue that your record shows flattening off since the 1950's which is consistent with the timing of massive aerosol loading over Asia.

[reply] Pg 3337
18-22: We implemented a new graphic (Figure 7), which displays the SST gradient between the equatorial and northern Pacific

Ocean. The variations are rather small, but seemingly increase since the ~1970s. This uneven temperature contrast might be the reason for the attenuation of the moisture declining trend at our study site.

Pg 3338 5: Why would increasing distance from the Bay of Bengal result in an amplified signal. Please explain the logic here. 13-18: The presence of a North South bipolar in Tibetan Plateau humidity is interesting. Is there a modern analog for anti correlation between the north and south TP? This would help to support the proxy observation. 24: "postulated a dominant influence ..."

Pg 3339: 1-2: Please rewrite this sentence beginning, "However..." 4: It is unclear to me, do you argue that cloudiness directly influences RH or that cloudiness is a proxy for precipitation, which directly influences RH? The argument gets obscure in text. 9: "positively associated with the NAO via its impact on Eurasian snow cover and thus invokes ... " 11: "might induce an el nino..." Is this saying the NAO causes ENSO events? Unclear what is meant by this.

Pg 3340 1-3: Many previous studies have noted a recent reduction in ENSO's influence on the monsoon. See the pioneering work by Kumar on this. 4: Should that read "cannot be confirmed"? There are a number of issues with this section 1) A lot of time is spent laboring through ENSO and NAO influences and then at the end you just reject that idea and invoke a local control argument. Why not just remove all this NAO-ENSO discussion ... it is confusing, takes up a lot of space and is ultimately irrelevant. 2) The statistical significance of the running correlations is not really properly treated. The df is low for running correlations. 6-15: I found the discussion on the correlation with sensible heat to be rather confusing and missing some key discussion points. It is true, that the correlations are very strong but the argument that sensible heat flux is a "direct expression of vertical air motion" is incorrect. Within the ERA Interim model there are directly modeled "vertical velocity" and "convective precipitation rate" terms, which are actually direct indicators of convection as opposed to sensible heat, which is a combined term sensitive to surface temperature, soil moisture etc.... Furthermore, the argument that sensible heat is an indicator of evapotranspiration is also odd. Latent heat flux is the better indicator of moisture fluxes. It is also important to discuss that ERA Interim is a model not an observation. I would like to see correlations with latent heat flux, soil moisture, skin temperature, vertical velocity etc...all the component that control sensible heat flux to get a sense of the actual process that leads to these strong correlations. Further, I think it is worth discussing that the spatial correlations with sensible heat appear to be focused along a latitudinal band. I wonder if this is an indicator of westerly controls or on interannual variation in the northern extent of the ASM.

[reply] Pg 3338-3340
We appreciate your suggestion of rewriting the discussion discussion part entirely after intense discussions with other colleagues. Thereafter we focused the discussion on what controls rH at our study site (new spatial correlations displayed in Figure 5), took large-scale modulations into account, discussed the different behavior of other proxies from the TP (hopefully accomplishing), and summarized dynamic reasons for the rH variability on the eastern TP. Thus, we hope that all confusing and inflated argumentations were removed. However, we believe that according to the results of Liu *et al. (2013) and* Sano *et al. (2013) (already mentioned previously) the association of our $\delta^{18}O$ record to common and frequently used large-scale circulation indices (ENSO,NAO,El Nino/La Nina Events) was targeting, even though we were not able to verify a large-scale effect with these methods.*

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Reply to interactive comment on "Variability of summer humidity during the past 800 years on the eastern Tibetan Plateau inferred from δ^{18}O of tree-ring cellulose" by J. Wernicke et al.

[reply] Dear anonymous referee # 2,

Thank you very much for your additional comments and your feedback on the comments of anonymous referee 1. Moreover, we like to thank you for your general support of publishing our δ^{18}O tree-ring cellulose based relative humidity reconstruction. On December 16th we already submitted a revised version of our manuscript (see supplement of Author Comment C2098), according to the concerns raised by referee 1. Therewith we might have already discussed most of the critical aspects of your review. We appreciate to reply on your comments and questions in detail within this letter. Attached to this reply letter you will find a revised version of the manuscript with additional information highlighted in cyan. Furthermore a detailed graph about the single segment lengths is attached to the reply letter (see Figure 1). Doing so, we hope that we satisfactorily responded to all critical points. If you have any further requests or questions, do not hesitate to contact us immediately.

With kind regards,

Jakob Wernicke

Anonymous Referee 2

Received and published: 19 December 2014

Dear editor and authors of the manuscript "Variability of summer humidity during the past 800 years on the eastern Tibetan Plateau inferred from 18O of tree-ring cellulose", I fully agree with referee 1 on the importance of the reconstruction, the strong data and also all general and specific comments which were raised. I therefore have only very few additional comments and I do recommend publication of the manuscript after these minor revisions. Even though the study focusses on d18O as a climate proxy, it would be interesting to read more about the ring-width data. It is mentioned in the text (line 125) that tree-ring growth is limited by temperature and spring precipitation, but as I understand it, this conclusion is derived from trees different from the ones used in the present study? In any case, I think a brief description and discussion about the climate sensitivity of ring-width data would be helpful. Please also provide information about the segment length of the five trees (it is hard to see that in figure 2) and whether the youngest part of each tree has been omitted (juvenile effect).

[reply] Our chronology comprises of samples collected from the Lhamcoka E site in 1996, identical with the ring-width data published by Bräuning (2006, p.373). These samples are neither affected by human chopping activities nor by LIA glacier advances. The trees from site E are the only ones of the entire Lhamcoka site (A-E), who show a significant positive correlation with precipitation during spring. Thus, Bräuning (2006) summarized: "...dry and cold winters..." reduce the annual growth of Juniper at that site. Therefore, temperature and spring precipitation are the limiting factors for tree-ring growth exactly for the trees we used within our stable oxygen isotope analysis. We will implement a short discussion of the tree-ring width data in the revised manuscript.

- *Segment length will be added to the revised version. The cores have a mean length of 633 years with the single segment lengths of 801, 697, 668, 528, and 469 years (see supplementary figure 1).*

- *We sustained the youngest parts of our chronology in order to achieve a maximum age. That is of course only feasible, if we can exclude the so called "juvenile" affect which would result in a systematic decline of oxygen isotope values during the approximately first 100 years after germination (Esper et al. (2010); Treydte et al. (2006)). We aligned our stable isotope data to the cambial age of the trees (see Figure 1) and found no declining trends within the first decades or century that might be attributed to a so called "juvenile effect". Hence, we used the entire segment length for our reconstruction.*

Line 140: Is it possible to quantify the amount (ratio) of snow? According to figure 1, temperatures are below zero during December and January. I'm not sure if the numbers in the climate diagram are readable in the printed version (too small?). It is known from a number of studies that snow can have a large effect on the isotope ratio in tree rings since the highly depleted melt water gets incorporated in the tree, with some temporal offset (depending on soil properties).

[reply] We re-sized the climate diagram of Figure 1 to ensure clear readability of all numbers in the printed version. We are furthermore aware that snow derived melt water might contribute to the source water in high altitude ecosystems (Treydte et al., 2006). That of course affects the source water $\delta^{18}O$ composition and might, perhaps with some delay, influence the $\delta^{18}O$ values in tree-ring cellulose. This is especially the case in climate regions, where winter precipitation contributes to a major part to the annual precipitation amount (e.g. regions dominated by the Westelies). Nevertheless, the eastern TP derives the vast majority of its annual precipitation during the summer monsoon season, while the winter precipitation contribution is minor due to the prevailance of dry continental air mass and a strong westerly influence (Wang and Ding (2006); Webster et al. (1998)). Therewith, snow accumulation mostly occurs during the summer monsoon season, leading also to the so called "summer accumulation type glaciers" in that region (Mölg et al., 2012). Additionally, solid precipitation at the study site only occurs during the months with temperatures below the freezing point. According to the adiabatic temperature lapse rate, respective conditions may occur during October to April (see climate diagram). However, these winter months contribute only by 13% to the total precipitation of the entire year. Thus, the influence of solid precipitation is likely to have only a minor influence on the $\delta^{18}O$ values of the source water and stable oxygen isotope ratios of the tree-ring cellulose.

Line 156: Can you specify whether one core or two cores per tree were used?

[reply] Two cores per tree were sampled in order to enhance the chance to detect missing rings. From the two cores the longest sample was selected.

Line 167: Please provide the reproducibility for d18O mass spectrometer analysis.

[reply] The standard deviation for the repeated analysis of an internal standard (IAEA 601 cellulose standard) was better than 0.25‰. We added this information in the revised manuscript.

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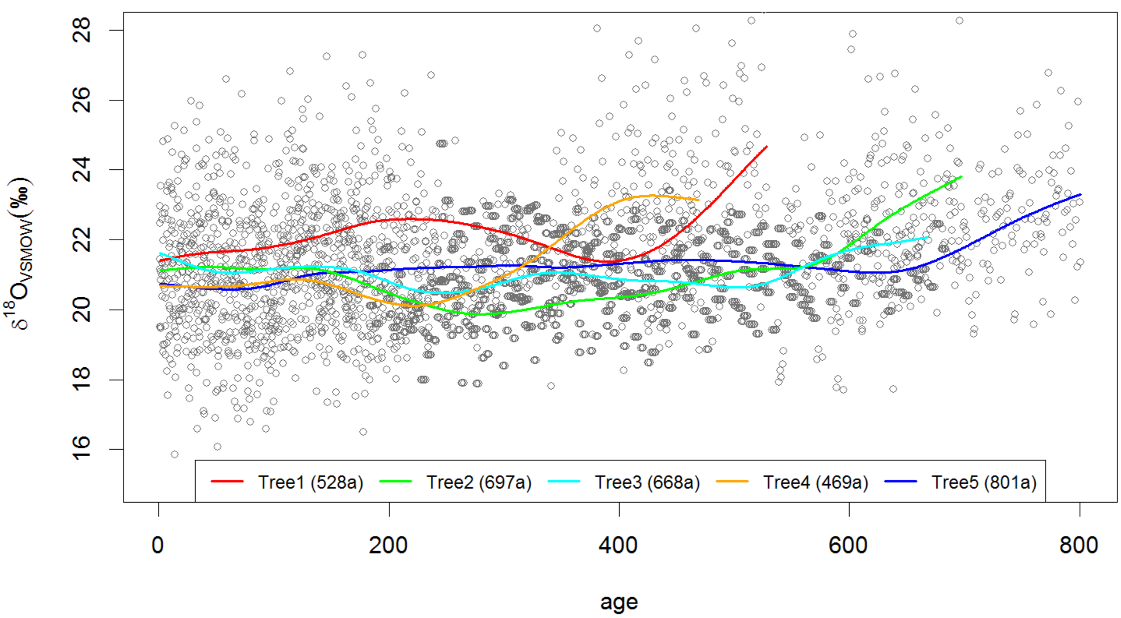

Fig. 1. δ^{18}O variation (gray dots) after trees germination in order to detect a potential juvenile effect. Colored lines represent a 200 years smoothed splines of each individual tree with respective ages of the trees (see legend).

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Variability of summer humidity during the past 800 years on the eastern Tibetan Plateau inferred from δ^{18}O of tree-ring cellulose

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Abstract.

We present an 800 years long δ^{18}O chronology from the eastern part of the Tibetan Plateau (TP). The chronology dates back to 1193 AD and was sampled in 1996 AD from living *Juniperus tibetica* trees. This first long-term tree-ring based δ^{18}O chronology for eastern Tibet provides a reliable archive for hydroclimatic reconstructions. Highly significant correlations were obtained with hydroclimatic variables (relative humidity, vapour pressure and precipitation) during the summer season. We applied a linear transfer model to reconstruct summer season relative humidity variations over the past 800 years. More moist conditions prevailed during the termination of the Medieval Warm Period while, a systematic shift during the Little Ice Age is not detectable. A distinct trend towards more dry conditions is apparent since the 1870s. The moisture decline weakens around the 1950s but still shows a negative trend. The mid-19th century humidity decrease is in good accordance with several multiproxy hydroclimate reconstructions for south Tibet. However, the pronounced summer relative humidity decline is stronger on the central and eastern TP. Furthermore, the relative humidity at our study site is significantly linked to the relative humidity at large parts of the TP. Therewith we deduce that the reconstructed relative humidity is mostly controlled by local and mesoscale climatic drivers, although significant connections to the higher troposphere of west-central Asia were observed.

1 Introduction

The variation in strength, timing and duration of the Asian summer monsoon (ASM) system affects life and economy of many millions of people living in south and east Asia (Immerzeel et al. (2010); Zhang et al. (2008)). In remote areas, such as the Tibetan Plateau (TP), reliable climate records are short and scattered. Nevertheless, a recent weakening trend of the ASM precipitation amount was reported in several studies (Bollasina et al. (2011); Sano et al. (2011); Zhou et al. (2008b)). The decline in air humidity was explained by a reduction in the thermal gradient between the surface temperatures of the Indian Ocean and the TP due to Global Warming (Sun et al., 2010). Contemporaneously, different locations and climate archives reveal a strengthened monsoonal precipitation (Anderson et al. (2002); Kumar et al. (1999); Zhang et al. (2008)). This discrepancy may be explained by the high variability of the monsoon circulation itself, but also due to a limited number of available palaeoclimate studies and resulting climate modeling uncertainties. Thus, for a better understanding of the circulation system as a whole, but also for the verification of climate change scenarios, a keen demand for reliable climate reconstructions exists for the TP. With increasing numbers of palaeoclimatic records, forecast and climate projection precision increases and can be helpful to facilitate targeted decision making regarding water and resource management.

The northward movement of the Intertropical Convergence Zone (ITCZ) on the Northern Hemisphere in boreal summer is amplified over the Asian continent by the thermal contrast between the Indian Ocean and the TP (Webster et al., 1998). Convective rainfalls during the summer monsoon season between June and September are strongly altered by the complex topography of the Himalayas and western Chinese mountain systems (e.g. Böhner (2006); Maussion et al. (2014); Thomas and Herzfeld (2004)). Extreme climatic events that may have devastating effects, but also long-term trends of ASM intensity are therefore in the focus of numerous climate reconstruction efforts (e.g. Cook et al. (2010); Xu et al. (2006b); Yang et al. (2003)). Most of these studies use tree-ring width as a proxy for palaeoclimate reconstructions. Nonetheless, several studies demonstrated that δ^{18}O of wood cellulose is a strong indicator of hydroclimatic conditions (McCarroll and Loader (2004); Roden et al.

(2000); Saurer et al. (1997) ; Sternberg (2009)). Even if tree stands might have been influenced by external disturbances (e.g. competition, insect attacks or geomorphological processes) they still reflect variations of the local hydroclimate accurately (Sano et al., 2013). Recently published tree-ring δ^{18}O chronologies from the TP show a common strong response to regional moisture changes. Grießinger et al. (2011) successfully reconstructed August precipitation over the past 800 years. They demonstrated reduced precipitation during the Medieval Warm Period (MWP), stronger rainfalls during the Little Ice Age (LIA), decreasing precipitation rates since the 1810s , and slightly wetter conditions after 1990s. In addition, shorter δ^{18}O chronologies from the central Himalayas showed consistent negative correlations to summer precipitation (Sano et al. (2010); Sano et al. (2011); Sano et al. (2013)). The detected recent reduction of monsoonal precipitation has been interpreted as a reaction to increased sea surface temperatures over the tropical Pacific and Indian Ocean (Zhou et al., 2008a). Strong responses to regional cloud cover changes were found for tree-ring δ^{18}O chronologies from the south-eastern TP (Liu et al. (2013); Liu et al. (2014); Shi et al. (2012)). The local moisture reduction since the middle of the 19th century is less pronounced than for south-west Tibet and was associated with complex El Niño-Southern oscillation teleconnections (Liu et al., 2012). Existing tree-ring δ^{18}O chronologies on the north-eastern part of the TP respond to local precipitation and relative humidity (Wang et al. (2013); Liu et al. (2008)). Except for a relatively short summer moisture sensitive time series (An et al., 2014), no long-term δ^{18}O chronologies and reliable reconstruction have been conducted for the eastern TP so far. It still remains unclear to what extent the MWP, LIA, and the modern humidity decrease are reflected in tree-ring δ^{18}O on the eastern TP, where the influence of the ASM, the Indian Summer monsoon and the westerlies overlap.

We present a new, well replicated 800 years long δ^{18}O chronology, representing a unique archive for studying the past hydroclimate in eastern Tibet. We applied response and transfer functions and obtained a reliable reconstruction of summer relative humidity (July+August). We compared the long-term trend of our chronology to other moisture sensitive proxy archives from several sites over the TP and discuss climatic control mechanisms on the relative humidity.

2 Material and methods

2.1 Study site - Lhamcoka

Lhamcoka is located on the eastern TP (see Figure 2 green pentagon). During a field campaign in 1996, 16 living *Juniperus tibetica* trees were cored twice in order to enhance the chance of detecting missing rings. The samples were collected from a steep, south-east exposed slope at an elevation of 4350m asl (31°49'N/99°06'E). The oldest tree is 801 years old, resulting in an overall chronology time span of 1193-1996 AD. The average single core length is 633 years with single segment lengths of 801a, 697a, 668a, 528a, and 469a, respectively. The chronology is not biased by an age trend as it was supposed for different high altitude mountain ecosystems (Esper et al. (2010); Treydte et al. (2006). We applied a spline based trend analysis and revealed non systematic trends during the first 100 years after germination (graph not shown here). Therefore a "juvenile" effect is not likely to affect our chronology, justifying the retention of the oldest parts of each single core. Juniper forms the upper timberline in the region due to its cold temperature tolerance (Bräuning, 2001). The species' annual tree-ring growth is limited by temperature and spring precipitation (February-April) (see Lhamcoka E site description in Bräuning (2006)). Therefore the early wood formation is negatively affected by the spring conditions, leading to growth reduction of the annual growth rings. Due to the steep slope angle of more than 30° and well drained substrate properties at the study site, ground water influence can be excluded. Therefore we assume the trees δ^{18}O source water properties are mainly controlled by the oxygen isotope configuration of summer precipitation, although it is known that snow derived melt water input affects the source water properties of trees (Treydte et al., 2006). According to dry and cold winter monsoon conditions (see climate diagram in Figure 2), a high and persistent snow cover at our study site is not likely. Hence, 13% of potential solid precipitation falling during October and April will probably not strongly influence the source water properties at our study site.

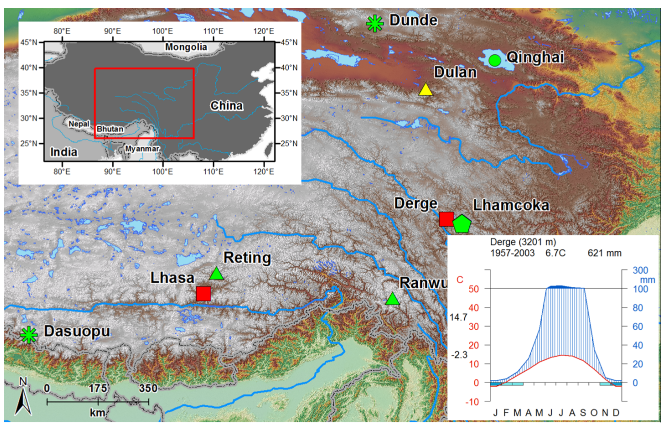

Fig. 1. Location of the study site Lhamcoka (green pentagon) and other proxy archives mentioned in the text. Green triangles: tree-ring δ^{18}O chronologies; Yellow triangle: tree-ring width chronology; Green flake: ice cores; Green circle: Lake sediments. Red rectangles indicate climate stations.

Lhamcoka is influenced by the Indian Summer Monsoon system with typical maxima of temperature and precipitation during the summer months (see climate diagram in Figure

2). The nearby climate station Derge (3201m absl, 50km distance to sampling site) records 78% (541mm) of its annual precipitation between June and September which is in accordance to common monsoonal climate properties (Böhner, 2006). The Derge climate record (data provided by China Meteorological Administration) revealed increasing temperatures of about 0.6°C during the period 1956-1996, whereas the amount and interannual variability of precipitation remains constant within these 41 years.

Five trees were chosen for isotope analysis, to adequately capture inter-tree variability of δ^{18}O (Leavitt, 2010). The trees were selected according to (i) old age of the cores to maximize the length of the derived reconstruction, (ii) avoidance of growth asymmetries due to slope processes, (iii) sufficient amounts of material (samples with wider rings were favoured), and (iv) a high inter-correlation among the tree-ring width series of the respective cores.

2.2 Sample preparation

We used the tree-ring width master chronology of Bräuning (2006) in order to date each annual ring precisely. The dated tree-rings were cut with a razor blade under a microscope. δ^{18}O values were measured from each tree individually in annual resolution. During periods of the chronology with extremely narrow rings, we used shifted block pooling to obtain sufficient material (Böttger and Friedrich, 2009). Pooling was applied between the years 1864-1707 (see chronology parts with missing EPS in Figure 3). To obtain pure α-cellulose, we followed the chemical treatment presented in Wieloch et al. (2011). The α-cellulose was homogenised with an ultrasonic unit and the freeze dried material was loaded into silver capsules (Laumer et al., 2009). The ratio of ^{18}O/^{16}O was determined in a continuous flow mass spectrometer (Delta V Advantage; Thermo Fisher Scientific Inc.). The standard deviation for the repeated measurement of an internal standard was better than 0.25‰.

2.3 Statistical analyses

We used standard dendrochronology techniques of chronology building, model building and verification for the purpose of a reliable climate reconstruction (Cook and Kairiukstis, 1990). All analysis were conducted with the open source statistical software R (http://cran.r-project.org/). The stable isotope chronology was calculated within the "dplR" package developed by Bunn (2008) and the dendroclimatological correlation and response analyses were conducted by the "bootRes" package (Zang and Biondi, 2012). The pooling method we executed required a running mean calculation. Thus, the presented chronology has a quasi annual resolution, smoothed with a five years running mean filter. To evaluate the isotope chronology reliability the Expressed Population Signal (EPS, introduced by Wigley et al. (1984)) and the Gleichläufigkeit (GLK) were computed. The EPS expresses the variance fraction of a chronology in comparison with a theoretically infinite tree population, whereas the GLK specifies the proportion of agreements/disagreements of interannual growth tendencies among the trees of the study site. The EPS is interrupted within our δ^{18}O chronology at parts were we applied shifted block pooling.

3 Results

3.1 Chronology characteristics

The Lhamcoka δ^{18}O chronology is defined by a mean of 21.27‰ and global minima/maxima of 18.24‰/ 24.83‰, respectively. The values are similar to results from nearby studies (An et al. (2014); Liu et al. (2012); Liu et al. (2013)). Moreover, the trees within the chronology are characterized by a common signal that is expressed in an EPS of 0.88 and a highly significant GLK of 0.57 ($p < 0.01$). Thus, we consider a common forcing among all trees and therefore a reliable mean δ^{18}O chronology. The chronology can be sub-divided into two parts (see Figure 3). The younger section (1868-1996) shows a pronounced trend of about 2‰ towards heavy isotope ratios. Within this segment the year with the most heavy ratio was detected in 1943 (24.8‰). Before the late 1870s the isotope δ^{18}O values oscillate around the chronology mean. A phase of considerable low δ^{18}O values is obvious from 1200 to 1300. Within this section the lightest isotope ratio was detected in 1272 (18.2‰). The signal strength (EPS) occasionally drops below the commonly accepted threshold of 0.85 during several periods. One reason might be the imprecise cutting of very narrow rings (ring width <0.2 mm). A mix of several rings produces a signal that cannot be related with certainty to a specific year, a problem well known when using very old trees (Berkelhammer and Stott (2012); Xu et al. (2013)). Nevertheless we have confidence in the Lhamcoka chronology due to an EPS above the threshold during the period 1300-1700 AD.

3.2 Climatic response of tree-ring stable oxygen isotopes

We conducted linear correlation analyses between the δ^{18}O values and monthly climate data as well as calculated seasonal means of climate elements. The available climate record of station Derge covers 41 years (1956-1996 AD) and correlations were calculated for temperature (mean), precipitation, relative humidity, sunshine hours (duration of global radiation >120W/m²), and vapour pressure (see Figure 4).

Summer moisture conditions explain most of the variance of the δ^{18}O chronology during the calibration period (1956-1996 AD). The stable oxygen isotopes are highly significantly ($p<0.01$) correlated with precipitation, relative humidity, sunshine hours and vapour pressure during July and

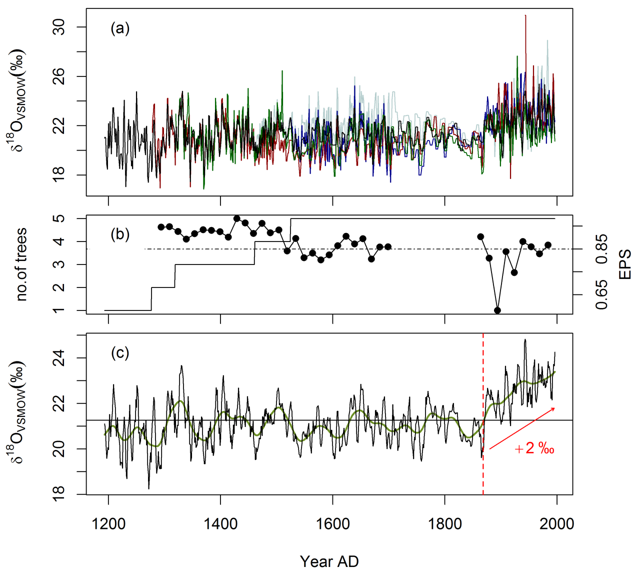

Fig. 2. Lhamcoka tree-ring δ^{18}O isotope chronology. (a) Individual δ^{18}O time series of five individuals. The coarse resolution between 1867 and 1707 results from shifted block pooling. (b) Running EPS (calculated for 25 year intervals, lagged by 10 years) and number of trees used for the reconstruction (solid line). Dashed line represents the theoretical EPS threshold of 0.85. (c) Tree-ring δ^{18}O chronology spanning the period 1193-1996 (AD). Green solid line represents a 50-year smoothing spline. Red dashed line marks the turning point towards heavier isotope ratios after ~1870.

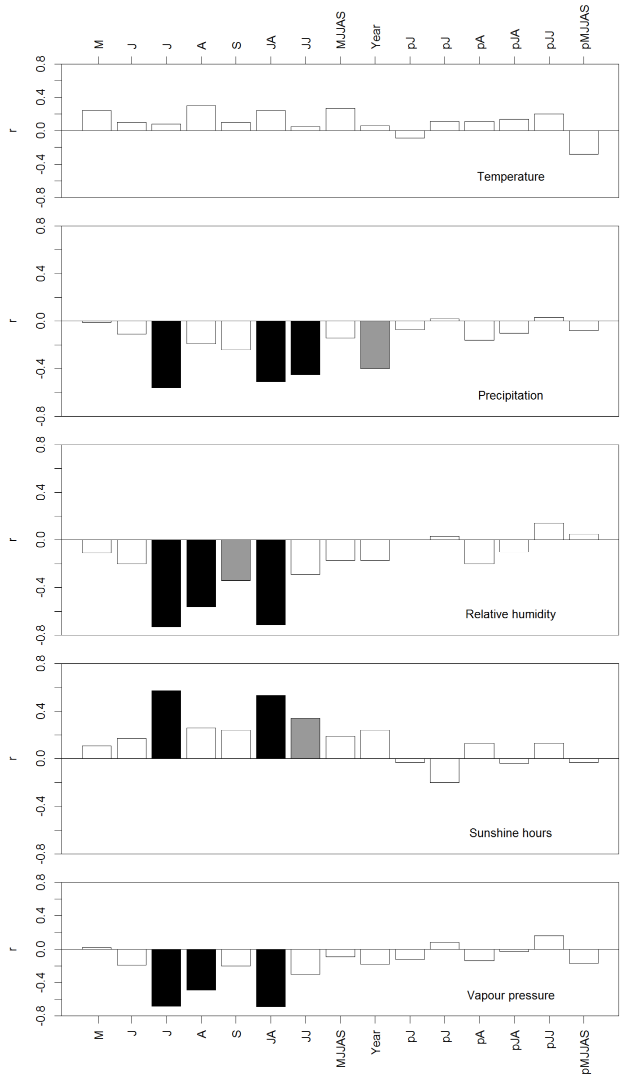

Fig. 3. Response of tree-ring δ^{18}O to monthly/seasonal temperature, precipitation, relative humidity, sunshine hours and vapour pressure over the period 1956-1996 AD. Gray and black bars indicate correlations significant at p<0.05 and p<0.01, respectively; p indicates months/seasons of the previous year.

August. Highest (negative) correlations were obtained with relative humidity during July (r= -0.73) and July/August (r= -0.71). Thus, if relative humidity is high, transpiration is lowered and the depletion of light δ^{16}O due to leaf water fractionation is reduced. Additionally, weak and non-significant relationships were found with the mean temperature in all months/seasons. Thus, concepts of integrated temperature-moisture indexes, e.g. the vapour pressure difference (VPD: Kahmen et al. (2011)), are unlikely to explain more of the variance in our data. However, we calculated the VPD as the difference between water vapour saturation pressure (E) and vapour pressure (e) and correlated the VPD time series against the δ^{18}O during the calibration period. Therewith we obtained significant but slightly weaker relationships with VPD (r = 0.68, p <0.01), since relative humidity and VPD are both influenced by temperature. Moreover, sunshine hours are positively related to the δ^{18}O variation. This association of high sunshine hours, less cloudiness, decreased relative humidity and thus increased δ^{18}O values was corroborated by findings for southeast Tibet (Shi et al., 2012). Very weak correlations were found with climate conditions during the previous year. Therefore, plant physiological carry over effects as well as stagnating soil water can be regarded as inferior factors for tree-ring δ^{18}O variations. The explained variance of linear regressions between stable oxygen isotopes and relative humidity accounts for 53%. Hence, the δ^{18}O value mainly depends on relative humidity, which is in accordance to findings of Roden and Ehleringer (2000). Although highest correlations were obtained with single months (July: r = -0.73 (p<0.01)), the reconstruction was established for the summer season (mean relative humidity of July and August). In terms of using wood cellulose of a single year, the humidity reconstruction of the major growing season is more robust than for single months.

3.3 Reconstruction of relative humidity

We employed a linear model for the reconstruction of relative humidity over the past 800 years. The linear relationship was achieved for the δ^{18}O values and instrumental records of relative humidity at climate station Derge between 1956-1996 AD. The model was validated according to standard methods presented in Cook and Kairiukstis (1990) and Cook et al. (1994). We applied the leave-one-out validation procedure due to the short time period of available climate data. The model statistics are summarized in Table 1.

Table 1. Verification statistics according to the linear transfer model of δ^{18}O and relative humidity within the calibration period 1956-1996 AD.

Sign-test (ST)	0.73 ($p<0.1$)
Product-moment correlation (PMC)	0.67 ($p<0.01$)
Product means test (PMT)	3.3 ($p<0.01$)
Reduction of Error (RE)	0.45
Coefficient of efficiency (CE)	0.45

The validation tests indicated that (1) the number of agreements between the reconstructed climate series and the meteorological record is according to the sign orientation significantly different from a pure chance driven binomial test (ST); (2) the cross-correlation between the reconstruction and the measurement is highly significant (PMC, PMT) and (3) the reconstruction is reliable due to a positive RE and CE, indicating the reconstruction is better than the calibration period mean (Cook et al., 1994). Thus, our linear model is suitable for climate reconstruction purposes. The model related to the reconstruction of summer relative humidity is described as: $\mathrm{rh}_{JA} = -2.3 * \delta^{18}O + 125.3$ (rh_{JA}, expressed in %). A negative relationship between tree-ring stable oxygen isotopes and relative humidity was documented properly in several studies around the globe and among different species (Anderson et al. (1998); Burk and Stuiver (1981); Ramesh et al. (1986); Tsuji et al. (2006)). However, due to varying environmental settings (e.g. climate, soil) and different biological leaf properties (Kahmen et al., 2009), the slopes of the regression function differ significantly among study sites and species. Hence, δ^{18}O inferred model parameters from a neighboring summer relative humidity reconstruction (June-August) using Abies trees differ from our regression model (An et al., 2014). Our reconstruction reveals several phases of high and low summer humidity (see Figure 5). Negative deviations from the mean value (72.4%; sd = 4.9%) occurred during 1300-1345, 1475-1525, 1630-1670 and 1866-1996 (periods are emphasized with dashed vertical lines in Figure 5). The most pronounced relative humidity depression started in the late 1870s (dashed red line in Figure 5) and lasts until the ~1950s. The period is characterized by the driest summer in 1943 (rh = 68.4%). The remarkable moisture reduction since the end of the LIA has been validated for the southern and south-eastern part of the TP (Liu et al. (2014); Xu et al. (2012); Zhao and Moore (2006)). After the ~1950s a clear trend towards even drier conditions is attenuated (trend slope = 0.01, p = 0.63). This finding is in accordance with results from the central and southeastern TP (Grießinger et al. (2011); Liu et al. (2013); Shi et al. (2012)) and might be caused by uneven warming trends of the northern and equatorial Indian Ocean sea surface temperatures (Chung and Ramanathan, 2006). More humid periods were detected during 1193-1300, 1345-1390, 1455-1475 and 1740-1750, with the highest relative humidity in 1272 (rh = 83.5%), respectively. Thus, the MWP is characterized by the highest humidity values within the past 800 years. Similar conditions were observed for Inner Asia and the northern TP (Pederson et al. (2014); Yang et al. (2013)) but were not corroborated for the central TP (Grießinger et al., 2011). The moderate oscillation of our humidity reconstruction during the LIA contrasts results of increasing and decreasing moisture trends at different parts of the TP (Grießinger et al. (2011); Shao et al. (2005); Yao et al. (2008)). We identified extreme inter-annual humidity variations by calculating the third standard deviation of the first differences. Years with humidity variations above 10% were detected in 1960/1961, 1946/1947, 1941/1942, 1706/1707, 1253/1254, 1238/1239, 1233/1234, 1230/1231 and 1225/1226.

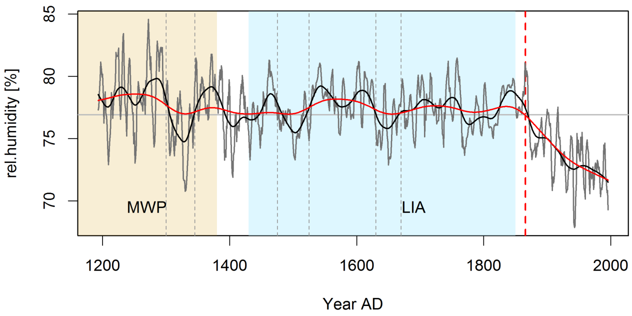

Fig. 4. Summer (July+August) relative humidity reconstruction 1193-1996 AD for the eastern TP. Solid black and red lines represent 50-year and 150-year smoothing splines, respectively. Red dashed line emphasises the turning point towards drier conditions (~1870s). The horizontal gray line illustrates mean relative summer humidity (rh = 72.4%). Vertical dashed lines are marking relatively dry periods. The Medieval Warm Period (MWP) and Little Ice Age (LIA) are emphasized in yellow and blue.

4 Discussion

Lhamcoka is located at the assumed boundary zone of air masses from the Indian Ocean, South, the North Pacific and Central Asia (Araguás-Araguás et al., 1998). Thus, our study site is likely influenced by the monsoon circulation (Indian and Southeast Asian monsoon) as well as by the westerlies (Morrill et al., 2003). Especially the long term spatio-temporal modulation of the monsoon circulation systems has been intensively studied (e.g. Kumar et al. (1999); Wang et al. (2012); Webster et al. (1998)) and may significantly control the moisture availability at our study site. The pre-condition for the formation of the monsoon is the land-sea surface temperature gradient between the Asian land mass and the surrounding oceans (Kumar et al., 1999). However, the monsoon circulation system shows variations at interannual and intraseasonal timescales (Webster et al., 1998). In particular, the ENSO impact on the monsoon circulation has been studied extensively (e.g. Cherchi and Navarra (2013); Kumar et al. (2006); Park and Chiang (2010)). We tested the influence of ENSO on our humidity reconstruction and achieved no significant relationships, implying an ENSO decoupled climate variability at our proxy site (see interactive discussion of this paper Wernicke et al. (2014)). On an intraseasonal timescale the Madden-Julian-Oscillation (MJO) modulates the monsoonal precipitation (Madden and Julian, 1994), where the 30-90 days zonal propagation of cloud clusters causes breaks and strengthening of the monsoonal precipitation (Zhang, 2005). More recently, the monsoon circulation system has been affected by greenhouse gas and aerosol emissions (Hu et al. (2000); Lau et al. (2006)). Both induce a positive anomaly of monsoonal precipitation due to the strengthening of the thermal gradient in the upper troposphere.

However, in this study we primarily focus on the controls of relative humidity at our study site, rather than targeting large-scale atmospheric circulation influences immediately. Therefore we conducted correlation analysis of the July-August relative humidity at the grid cell of our study site with the July-August relative humidity in the area of 0°-45°N/40°-120°E (ERA Interim data: http://apps.ecmwf.int/datasets/data). Beforehand, we examined the accordance of our summer relative reconstruction and the ERA interim data (mean relative humidity July-August). The significant relationship (r = 0.77, p <0.01) suggests that the ERA interim data are likely to represent our relative humidity reconstruction. As shown in figure 6 (A), significant correlations at the 500hPa pressure level are found with almost the entire TP. This suggests a regional signal, reflecting the strong connection of moisture variability at our study site with moisture variability over the whole TP. However, significant negative relationships were found with the southwest and southeast Asian regions. These correlations are even more evident on the 300hPa level (Figure 6 (B)) and show a remarkable spatial pattern. Interestingly, the negative correlation in southwest Asia contains the region where Ding and Wang (2005) defined an index for the westerly wave activity (west central Asia: 60°-70°E /35°-40°N). The significance of this finding is corroborated by strong correlations of the mean summer relative humidity in 200hPa of the west central Asian region and our proxy record (r = -0.58, p <0.05). Several studies highlight the general influence of the ASM as the major driver for Tibetan moisture variability (Araguás-Araguás et al. (1998); Hren et al. (2009); Tian et al. (2007)). However, the results of Ding and Wang (2005), Saeed et al. (2011) or Mölg et al. (2014) and our findings indicate that the mid-latitude westerlies influence should be be taken into consideration in future studies.

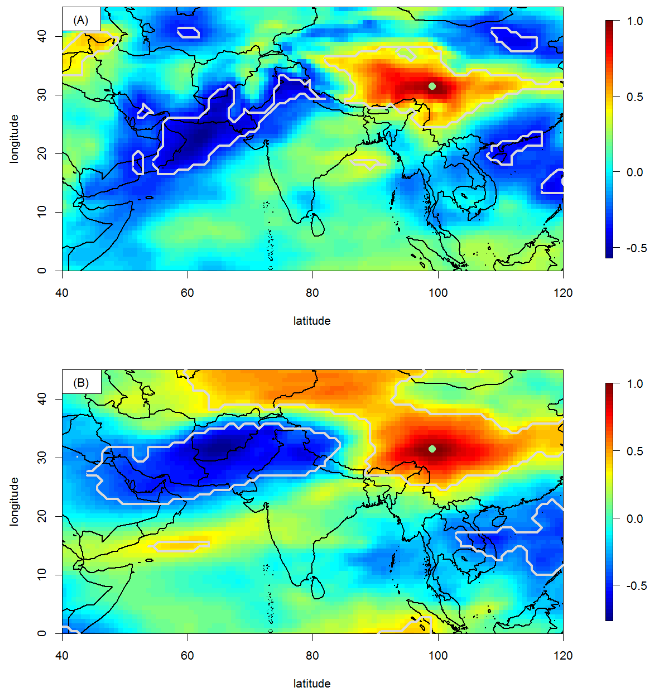

Fig. 5. Spatial correlation of July-August relative humidity (ERA interim data, 1979-2013) at the (A) 500hPa and (B) 300 hPa pressure level. Color code represents the Pearson correlation coefficient. White lines delineate the 95% significance level. Proxy location is shown by the light green dot.

For an analysis of the regional representativeness of our data set, we compared the Lhamcoka δ^{18}O chronology with six moisture sensitive proxies from the TP (see Figure 8 and locations in Figure 2), including normalized tree-ring (TR) δ^{18}O records (Ranwu TR: Liu et al. (2013); Reting TR: Grießinger et al. (2011)), tree-ring width data (Dulan TR: Sheppard et al. (2004)), accumulation records (Dasuopu and Dunde ice cores: Thompson et al. (2000) and lake sediments (Qinghai Sediment: Xu et al. (2006a)). We found significant positive correlations between our time series and the Ranwu (r = 0.55, p <0.01), Reting (r = 0.23, p <0.01), Dunde (r = 0.16, p <0.01) and Qinghai (r = 0.22, p <0.1) data sets. Only the tree-ring width series of Dulan is negatively correlated to the δ^{18}O values of Lhamcoka (r = -0.16, p <0.01). The snow accumulation rate of Dasuopu ice core has no relationship to our δ^{18}O chronology (r = -0.04, p = 0.3). In case of weak correlations ($|r| < 0.2$) and due to the degrees of freedom (DF >100), significance levels alone might be misleading and indicate only a statistical and not a causal relationship. However, strong relationships between the tree-ring δ^{18}O chronologies of Lhamcoka and Ranwu, and partly Reting, are reasonable, since moisture reconstructions from these sites rely on the same proxy (δ^{18}O of tree-ring cellulose) and the trees grew under similar climate conditions. Relationships to the more northern located sites (Dunde, Dulan, Qinghai) are difficult to verify, according to a clearly detectable westerly influence at these sites. We adapted the color scheme of figure 5 and highlighted the MWP (yellow polygon), LIA (blue polygon), and the remarkable humidity decline since the late 1870s (dashed red line) in figure 8. The MWP is characterized by more humid conditions on the eastern TP (Lhamcoka), a drier phase on the central plateau (Reting) and moderate humidity conditions on the northern plateau (Dulan). During the LIA a remarkable moisture increase occurred at the central and southern plateau (Reting, Dasuopu). Although humidity was high according to these archives, the ASM was weak during that time (Anderson et al. (2002); Gupta et al. (2003)).

Thus, the findings for Reting and Dasuopu revealed moisture conditions during cold phases and even drier circumstances during warm periods which might be contrary to findings of Meehl (1994) and Zhang and Qiu (2007)). The sudden moisture decrease since the late 1870s affects the eastern (Lhamcoka), southern (Dasuopu), and central (Reting) parts of the TP. Reasons for the sudden moisture decline were discussed in detail by Xu et al. (2012). They address the moisture decrease to the reduction in the thermal gradient induced by uneven land-ocean temperature rise, caused by aerosol and greenhouse gas loads. In fact, under rising north hemispheric air temperatures (Shi et al., 2013) the air moisture load over sea is increased but due to solar dimming effects of black aerosols, the northeastward moisture transport is hampered (Sun et al., 2010). In addition, Zhao and Moore (2006) attributed the moisture decline to the “weakening of the easterly trade wind system along the equatorial Pacific since the middle of 19th century”. Moreover, decreasing varve thicknesses imply a weakening Asian summer monsoon in the past 160 years (Chu et al., 2011). The latter analysis revealed a link to warm phases of ENSO and an anomalous regional Hadley circulation. However, their explanation approach remains incomplete due to dynamic issues associated with rising temperatures and a weakening South Asian summer monsoon. Therewith a terminal explanation is not given yet and should be discussed in future studies.

In comparison to tree-ring sites located further south (e.g. Liu et al. (2013); Sano et al. (2013); Shi et al. (2012)), the distinct humidity decline is more pronounced on the central and eastern TP. Sano et al. (2013) concluded from that observation a weakening of the monsoon since the last 100-200 years due to uneven SST variation (equatorial vs. northern Indian Ocean regions). To test this hypothesis, we calculated the averaged SST anomalies of the equatorial and northern Indian

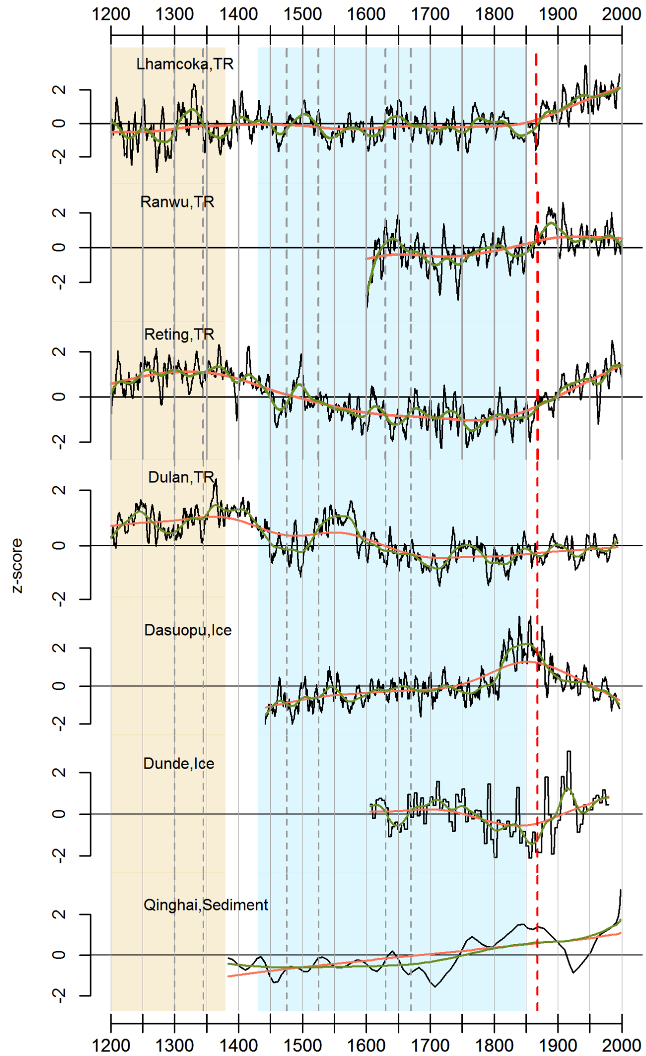

Fig. 6. Multiproxy comparison of tree-ring data (TR), ice core and lake sediment data. TR: Lhamcoka: this study; Ranwu: Liu et al. (2013) ; Reting: Grießinger et al. (2011) ; Dulan: Sheppard et al. (2004). Ice: Dasuopu and Dunde: Thompson et al. (2000). Sediment: Qinghai: Xu et al. (2006a). Locations of the several proxies are shown in Fig. 1. Z-scores were derived from raw proxy data and not from reconstructions. High positive z-scores indicating dry conditions for TR and sediment records, whereas high z-scores of ice accumulations represent humid conditions, respectively.

Ocean (52.5°-112.5°E /2.5°N-2.5°S; 52.5°-112.5°E /22.5°-27.5°N). As shown in figure 8, a slight SST increase in both regions since ~1950s is obvious. Besides, the gradient constantly decreases, but restrengthens since ~1970s. This finding contrasts with a generally weakening monsoon circulation since the past 100-200 years deduced from a thermal gradient reduction. Therefore, the various moisture variations of the southern and central/eastern TP during the last 100-200 years might be evoked by varying local air mass characteristics.

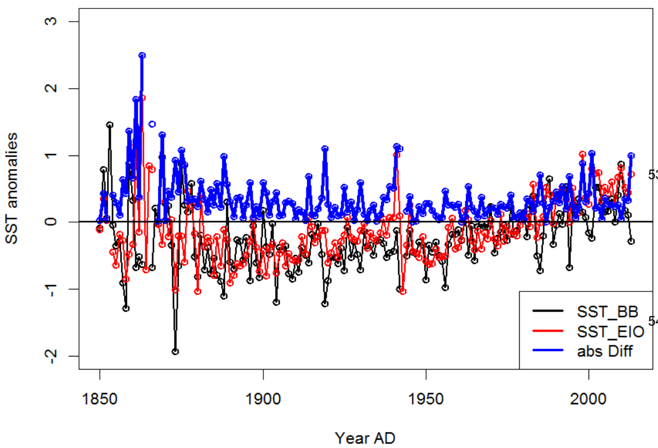

Fig. 7. Sea surface temperature anomalies in different regions of the Indian Ocean: Bay of Bengal-North Indian ocean (SST BB: 52.5°-112.5°E/22.5°-27.5°N) and equatorial Indian Ocean (SST EIO: 52.5°-112.5°E/2.5°N-2.5°S) (Rayner et al., 2006). Difference between the two time series is marked with a blue line.

5 Conclusions

We demonstrated that our 800 years long δ^{18}O chronology is suitable for a reliable reconstruction of summer relative humidity. Long-term air humidity variations revealed more humid conditions during the termination of the MWP, relatively stable humidity during the LIA and a sudden decrease in summer humidity since the 1870s. After the ~1950s the trend towards more heavy oxygen isotope ratios is mitigated due to the restrengthening of the ISM. These findings are in accordance with other reconstructions of moisture conditions for the central and eastern TP. Spatial correlations indicate a significant relationship of summer relative humidity at our study site and major parts of the TP. Additionally, a negative correlation within the higher atmosphere over the west central Asia region imply a westerly influence. Furthermore, the thermal contrast between the equatorial and northern Indian Ocean, which is assumed to control moisture supply during the ISM, is slightly stable over time. Thus, to comprehensively indicate reasons for the distinct ~1870s moisture decline more detailed climate dynamic studies and highly-resolved spatio-temporal hydroclimate reconstructions are needed.

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