# Responses to the Editor

*Initial comments in red italics*, **responses in plain text**

*I would like to thank you for your careful revisions. However, I think there are some additional revisions necessary. First of all, I would strongly recommend to find a native speaker to proofread your manuscript. There are many examples of linguistic defficiencies and grammatical inconsistencies. Furthermore, I would suggest strongly to include a map showing all the cave sites used for this study.*

**1）Dr. Nick Belshaw, a native speaker, from Earth Science Department, Oxford University, helped with the manuscript proofreading. And all corrections are shown in the marked-up manuscript version. The deleted words are shown as blue-colored texts with a line in the middle, while the inserted words are shown as red-colored texts.**

**2) A map with all the cave sites used for this study has been included in the revised manuscript shown as Fig. 1.**

# Quantification of southwest China rainfall during the 8.2 ka BP event with response to North Atlantic cooling

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**Abstract.** The 8.2 ka BP event could provide important information for predicting abrupt climate change in the future. Although published records show that the East Asian monsoon area responded to the 8.2 ka BP event, there is no high resolution quantitative reconstructed climate record in this area. In this study, a reconstructed 10-yr moving average annual rainfall record in southwest China during the 8.2 ka BP event is presented by comparing two high-resolution stalagmite $\delta^{18}O$ records from Dongge cave and Heshang cave. This decade-scale rainfall reconstruction is based on a central-scale model and is confirmed by inter-annual monitoring records, which show~~s~~ a significant positive correlation between the regional mean annual rainfall ~~amount~~ and the drip water annual average $\delta^{18}O$ difference from two caves along the same monsoon moisture transport pathway from May 2011 to April 2014. Similar trends between the reconstructed rainfall and the stalagmite Mg/Ca record, another proxy of rainfall, during the 8.2 ka BP period further increase the confidence of the quantization of the rainfall record. The reconstructed record shows that the mean annual rainfall in southwest China during the central 8.2 ka BP event is less than that of present (1950 ~ 1990) by ~200 mm, and decreased by ~350 mm in ~70 years experiencing an extreme drying period lasting for ~50 years. ~~Further analysis on~~ Comparison of the reconstructed rainfall record in southwest China ~~and~~ with Greenland ice core $\delta^{18}O$ ~~with~~ and $\delta^{15}N$ records, suggests that the reduced rainfall ~~decrease~~ in southwest China during the 8.2 ka BP period was coupled with Greenland cooling with a possible response rate of 110±30 mm/℃.

## 1 Introduction

As evidence in support of global warming becomes stronger, it is apparent that the anticipated rise in sea levels may be higher than expected (Rahmstorf, 2007) and the frequency and amplitude of abrupt climate change (Martrat et al., 2004; Pall et al., 2007) may also be greater. As climate events are likely to be problematic for both ecosystems (Walther et al., 2002) and human society (Khasnis and Nettleman, 2005), any aid in prediction is crucial.

Studies of past climate events could hopefully provide useful information for exploring trigger mechanisms (Cheng, et al., 2009; Liu et al, 2013). The 8.2 ka BP event is noted to be the most pronounced abrupt climate event occurring during the whole Holocene (Alley and Ágústsdóttir, 2005). The highest magnitude variation across the low to high latitudes makes a viable target for numerical modelings (Daley et al, 2011; Morrill et al., 2011) and may offer an insight into the sensitivity of climate response in different areas (Condron and Winsor, 2011; LeGrand and Schmidt, 2008). This event was firstly identified in Greenland ice cores (Alley et al., 1997), showing a duration of 160-yr (Thomas et al, 2007) with a temperature drop of 3.3±1.1℃ in central Greenland (Kobashi et al, 2007), and is known globally (Dixit et al., 2014; Morrill et al., 2013; Ljung et al., 2008; Ellwood and Gose, 2006). However, as most records associated with this event mainly derived from North Atlantic and Europe (Daley et al., 2011; Szeroczyńska and Zawisza, 2011; Snowball et al., 2010; Hede et al., 2010; Domínguez-Villar et al., 2009; Prasad et al., 2009), the question remains as to how much it influenced the East Asian monsoon area (EAMA).

Although some proxies from lake sediments (Yu et al., 2006; Hong et al., 2009; Zheng et al., 2009;Mischke and Zhang, 2010), stalagmites (Wu et al, 2012; Cheng et al., 2009; Hu et al., 2008a; Wang et al., 2005; Dykoski et al., 2005) and marine sediments (Zheng et al., 2010; Ge et al., 2010) do record the 8.2 ka BP event in EAMA, only Hu et al. (2008a) attempted a quantitative reconstruction of rainfall by using stalagmite $\Delta\delta^{18}O$ records which indicated a decrease in precipitation during the event in southwest China, an area influenced by East Asian monsoon. However, the resolution of this precipitation record is approximately 100-yr and needs to be improved.

Based on the method presented by Hu et al. (2008a), this study reconstructs a 10-yr averaged annual rainfall record in southwest China during the 8.2 ka BP event by comparing sub-annual (Liu et al., 2013) and 3.5-yr resolution stalagmite $\delta^{18}O$ (Cheng et al., 2009) records from the same moisture transport pathway. This study further addresses the sensitivity of the climate of southwest China to North Atlantic cooling during the 8.2 ka BP event, providing quantitative data for simulating this global event in climate system models.

# 2 Methods

## 2.1 Rainfall reconstruction

It has been previously discussed (Hu, et al., 2008a) that, in a monsoon area, regional rainfall histories could be reconstructed by using coeval stalagmite $\delta^{18}O$ comparisons between two close sites located along the same atmospheric moisture transport pathway, as the difference allows the removal of secondary controls, such as moisture transport and temperature on $\delta^{18}O$. Working with this premise, two published high resolution stalagmite $\delta^{18}O$ sequences during the 8.2 ka BP event from Heshang cave, central China (Liu et al., 2013) and Dongge cave, southwest China (Cheng et al., 2009), located directly upstream in the atmospheric pathway(Fig.1), were investigated.

### 2.1.1 Stalagmite $\Delta\delta^{18}O$ sequence establishment

There is only one high-resolution $\delta^{18}O$ record ~~produced by~~ from stalagmite HS4 ~~from~~ in Heshang cave (30°27~~0~~′N, 110°25′E)(Fig. 1), central China, covering~~ed~~ the 8.2 ka BP period (Liu et al., 2013), with an average resolution of ~0.3-yr. However, there are two published stalagmite $\delta^{18}O$ records (stalagmite DA and D4) from Dongge cave (25°17′N, 108°5′E)(Fig.1), southwest China (Wang et al., 2005; Dykoski et al., 2005). Since Cheng et al.(2009) re-dated both DA and D4 from Dongge cave across during the 8.2 ka BP period to obtain produce a better controlled chronology, both DA and D4 giving $\delta^{18}O$ records with an average resolution of ~3.5-yr and ~2-yr (Cheng et al., 2009) respectively. These records are then compared with HS4 using the approach outlined in Hu et al. (2008a).

It may be observed that Fig. 2 shows the $\delta^{18}O$ records from HS4 (Fig.21a) (Liu et al., 2013), DA (Fig. 21b) and D4 (Fig. 21c) (Cheng et al., 2009) show where similar structural patterns are observed with matching major peaks and troughs. Typical cCorresponding peaks or troughs are then marked as shown by dashed lines in Fig. 21 and the chronology of DA, D4 and HS4 are so matched to reduce the chronologicaly uncertainty. It should be noted that the wiggle matching is within the analytical uncertainty of the U-Th chronology. As the measurement resolutions of HS4, DA and D4 are different, all the sequences were first processed to create records of equivalent annual resolution and allowing the resultant time sequences, then to be used to construct a 10-yr moving average sequence. Two new $\delta^{18}O$ difference ($\Delta\delta^{18}O$) sequences between HS4 and adjusted DA records (Fig. 21d) and between HS4 and adjusted D4 records (Fig. 21e) were thus established.

Though there is a systematic offset between Fig. 21d and Fig. 21e, generally the variations and trends of the two sequences are similar, suggesting either of the two $\Delta\delta^{18}O$ sequences could be used for the following reconstruction. Since the $\delta^{18}O$ record from Dongge cave adopted in Hu et al.(2008a) is from DA, in this study also uses data from DA $\Delta\delta^{18}O$ from (Fig. 21d) is used for further rainfall reconstruction.

### 2.1.2 Uncertainties of $\Delta\delta^{18}O$

Since tThe use of $\Delta\delta^{18}O$ sequence is intending to reconstruct the regional rainfall quantitatively, it is necessary to assess requires some understanding of the uncertainties of within the measurement records and calculations. The first need to be taken into consideration is the chronology uncertainty. As tThe U/Th dating maximum uncertainty of stalagmite DA during the 8.2 ka BP period is 94 ~90-yr (Cheng et al., 2009) and,while the average difference between the adjusted and original DA data set to match HS4 is ~40-yr;. This adjustment is within the dating uncertainty, but to test the robustness of the approach, is tested by shifting the whole DA $\delta^{18}O$ data set is shifted by 50-yr young and 50-yr in both older and younger directions respectively and the resultant data sets are compared. These three $\Delta\delta^{18}O$ sequences are shown in Fig. 32a along with unchanged DA chronology (in black), shifting DA 50-yr younger (in blue) and 50-yr older (in red). Fig. 32a demontrates suggests that though the time shifted chronology data sets do show increased variability the uncertainty of the $\Delta\delta^{18}O$ with a maximum error of 0.76‰, the general variation trends are similar, suggesting indicating that this difference method is sufficiently accurate robust for this study.

~~Besides~~ In addition to the chronology uncertainty, other factors may affect the ~~uncertainty~~ accuracy of $\Delta\delta^{18}O$. ~~Firstly, it is from the~~ $\delta^{18}O$ analytical uncertainties ~~from~~ of the HS4 and DA datasets~~, which~~ are 0.08‰ (Liu et al. 2013) and 0.15‰ (Cheng, et al., 2009) respectively. ~~Secondly, it is from~~ Additionally the standard deviation of the 10-yr average, ~~and~~ especially the largest standard deviation of $\Delta\delta^{18}O$ between DA and HS4 is 0.62‰. ~~Also, there is~~ And an estimated uncertainty of 0.35‰ from the model established by Hu et al. (2008a) should be noted. Taking all of these factors into consideration, the final uncertainty of the $\Delta\delta^{18}O$ sequence during the 8.2 ka BP period ~~could be~~ is estimated to be ~0.53‰.

### 2.1.3 Rainfall reconstruction

Based on the $\Delta\delta^{18}O$ sequence shown in Fig. 3~~2~~b, the ~~quantitative~~ rainfall ~~reconstruction~~ during the 8.2 ka BP period ~~could be built by~~ is reconstructed using the previous model presented by Hu et al. (2008a)~~, as the established model covering the 8.2 ka BP period. The~~ via the relation between $\Delta\delta^{18}O$ and rainfall (Rainfall=189.08×$\Delta\delta^{18}O$ +1217.4) (Hu et al., 2008a) ~~is therefore considered suitable for this study~~. ~~And t~~The uncertainties from $\Delta\delta^{18}O$ ~~would~~ give an ~~uncertainty~~ error of ~100 mm/yr for the reconstructed rainfall record.

~~The idea of r~~Reconstructi on~~ng~~ of regional rainfall ~~between two caves by comparing~~ using two spatially separated cave records ~~along~~ on the same moisture transport pathway ~~is to presume single~~ requires stalagmite $\delta^{18}O$ values from monsoon areas ~~at least contain~~ to faithfully preserve rainfall information. ~~For Chinese s~~Stalagmite $\delta^{18}O$ values~~, they~~ are ~~indeed~~ influenced by different types of precipitation, ~~and as well as moisture~~ along with the source and ~~its~~ pathways of moisture, plus local condensation and evaporation processes (Dayem et al., 2010). A~~nd a~~ recent millennial scale climate simulation(Liu et al., 2014) ~~also~~ suggests that Chinese stalagmite $\delta^{18}O$ records ~~could be used~~ might be useful as ~~an~~ indicators of intensity of the East Asian summer monsoon in terms of the continental scale Asian monsoon rainfall response in the upstream regions~~ (Liu et al., 2014)~~. As both Dongge and Heshang $\delta^{18}O$ records respond to~~ the~~ upstream rainfall~~ respectively~~, the difference of the two records ~~should be related~~ is expected to directly reflect the ~~regional~~ rainfall between Dongge and Heshang~~ cave~~.

~~Since o~~On decadal scale, ~~the~~ relationships between $\Delta\delta^{18}O$ and rainfall ~~records was confirmed~~ have previously been discussed (Hu et al., 2008a), and we here ~~we further access~~ attempt to utilize this ~~method~~ approach on an inter-annual time scale. ~~Compared with local precipitation $\delta^{18}O$ ($\delta^{18}O_p$), an outside cave signal, monitoring~~ A direct test of the validity of using moisture transport pathways would use cave drip water $\delta^{18}O$ ($\delta^{18}O_d$) signals from both DA and HS4 sites which should reflect speleothem $\delta^{18}O$ variations~~ more~~ directly. ~~Though~~ Unfortunately there is no published monitored~~ing~~ data from Dongge~~,~~. However there ~~are~~ is some ~~latest~~ recently published ~~cave monitoring~~ $\delta^{18}O_d$ data from a cave named Liangfeng (26°16'N, 108°03'E)(Fig. 1) ~~between~~ from May 2011 ~~and~~ to April 2014 with local precipitation $\delta^{18}O$($\delta^{18}O_p$) data (Duan et al., 2016) ~~from a cave named Liangfeng (26°16'N, 108°03'E),~~. Liangfeng is close to Dongge(25°17′N, 108°5′E)(Fig.1) and may therefore~~, which might~~ be an alternative data source to assess the validity of the rainfall reconstruction method.

There are three separate sequences of $\delta^{18}O_d$ from different drip~~ping~~ sites in Liangfeng cave (Zeng et al, 2015). ~~Among~~ From them, LF6 ~~$\delta^{18}O_d$~~ with ~~a~~ the lowest drip rate but highest variation ~~amplitude~~ has been selected, as it ~~may~~ is considered to record climate information more efficiently. The lowest drip rate of LF6 from Liangfeng cave ~~indicates~~ suggests fresh water is being mixed with ~~more~~ delayed transit stored water for this drip~~ping~~ site (Zeng et al, 2015)~~, which~~ and may provide longer term instead of short seasonal information compared with the other two sites. Based on the 3~~ yr~~ years of monthly monitored~~ing~~ data of LF6 and HS4 (Duan et al., 2016), the sequences of annual moving average $\delta^{18}O_d$ of LF6 and HS4 have been ~~established respectively~~ calculated. Generally LF6 $\delta^{18}O_d$ values are higher than those of HS4 ~~$\delta^{18}O_d$~~, which is sensible since Heshang cave is further along the moisture transport pathway(Fig.1). ~~Since~~ LF6 $\delta^{18}O_d$ is considered mixed ~~by~~ fresh and stored water, so its response to the local rainfall ~~may~~ is expected to be delayed. ~~As there is a~~ A calculated positive correlation($R^2$=0.62) between the local annual moving average $\delta^{18}O_p$ and the 2-month delayed annual moving average of LF6 $\delta^{18}O_d$ (monthly $\delta^{18}O_p$ and $\delta^{18}O_d$ data are from Duan et al., 2016)~~, it is presumed~~ strongly suggests that ~~LF6 $\delta^{18}O_d$ may be~~ a delay~~ed by~~ of 2 months should be applied when using LF6 $\delta^{18}O_d$ data. A~~nd the same~~ similar analysis ~~on~~ of $\delta^{18}O_d$ at HS4 site and $\delta^{18}O_p$ outside Heshang cave (Duan et al., ~~2015~~ 2016) reveals a positive correlation($R^2$=0.71) between the local annual moving average $\delta^{18}O_p$ and ~~the~~ a 4-month delayed annual moving average ~~of~~ for HS4 $\delta^{18}O_d$. ~~Further~~ Combined analysis shows a positive correlation ($R^2$=0.72) between the 2-month delayed annual moving average of LF6 $\delta^{18}O_d$ and the 4-month delayed annual moving average of HS4 $\delta^{18}O_d$, ~~indicating the main~~ giving some support to the idea that the controlling factors ~~controlled~~ on both LF6 and HS4 $\delta^{18}O_d$ ~~values should be~~ are similar~~, so it is sensible to use their $\Delta\delta^{18}O_d$ records to discuss the efficiency of the rainfall reconstruction method~~.

After the time adjusted ~~annual moving average~~ $\Delta\delta^{18}O_d$ sequence ~~between 2-month delayed LF6 $\delta^{18}O$ and 4-month delayed HS4 $\delta^{18}O_d$~~ has been built, the correlation between $\Delta\delta^{18}O_d$ and the regional average annual rainfall ~~amount from~~ at six sites between Dongge cave and Heshang cave ~~mentioned~~ detailed in Hu et al. (2008a)(Fig. 1) ~~could~~ may be ~~analyzed~~ compared. The regional average annual rainfall ~~amount~~ is calculated from monthly instrumental records between May 2011 and April 2014 from http://www.wunderground.com/history/. Fig. 4~~3~~ shows that there is a significant positive correlation ($R^2$=0.79) between annual average $\Delta\delta^{18}O_d$ and regional annual rainfall ~~amount. The significant correlation further~~, supporting~~s~~ the idea that the stalagmite $\Delta\delta^{18}O$ between two caves located along the same moisture transport pathway ~~could reveal the~~ can provide information on regional rainfall variation~~, since stalagmite $\delta^{18}O$ derives from the drip water $\delta^{18}O$~~.

## 2.2 Mg/Ca data processing

In addition to $\Delta\delta^{18}O$, the Mg/Ca ratio, another important rainfall proxy, ~~is~~ can be considered~~ in this paper~~. The Mg/Ca data set is taken from Liu et al. (2013) measured ~~by ~~using a JEOL JXA8800R Electron Microprobe at the Department of Material Sciences, Oxford, along the HS4 stalagmite growth axis. The Mg/Ca data were processed to provide annual resolution and a 10-yr moving average constructed in the same way as for $\delta^{18}O$.

## 3 Results

The 10-yr moving average $\Delta\delta^{18}O$ record~~s between~~ from DA and HS4 is shown in Fig. 3~~2~~b. It is reasonable that the DA $\delta^{18}O$ values are generally higher than those of HS4 (Fig. 2~~1~~a and Fig. 2~~1~~b) ~~as ~~since Heshang Cave is located further along the moisture transport pathway(Fig. 1)~~, which produces ~~and is so expected to displayed a systematic $\delta^{18}O$ offset. ~~Compared with an ~~The average $\delta^{18}O$ difference between HS4 and DA is ~~of ~~1.0‰ ~~(Hu, et al, 2008) between HS4 and DA ~~during the whole Holocene (Hu, et al, 2008), while the average $\Delta\delta^{18}O$ value during the 8.2 ka BP event shown in Fig. 3~~2~~b is much lower~~, only with a value of ~~at 0.26‰.

~~It may be observed in Fig. 2b that d~~During the central event, it is notable that some of the $\Delta\ \delta^{18}O$ values are around zero or even negative, indicating much reduced moisture transport during that time. While the lowest value of $\Delta\ \delta^{18}O$ is nearly -0.50‰ (Fig. 3~~2~~b), we do not expected negative $\Delta\ \delta^{18}O$ values. ~~Besides t~~The estimated uncertainty of ~0.53‰ ~~produced by ~~in the $\Delta\ \delta^{18}O$ ~~mentioned ~~detailed in section 2.1.2, along with ~~the ~~difference in evaporation in the two caves is likely to contribute~~s~~ to producing a ~~the ~~negative $\Delta\ \delta^{18}O$~~ as well~~. ~~Actually c~~Cave monitored~~ing~~ data ~~do~~ suggest evaporation may occur during~~ the~~ dripping and ~~exuding ~~enhanced processes in a dry season could result in heavier drip water $\delta^{18}O$ values (Zeng et al., 2015), ~~so evaporation must result in heavier stalagmite $\delta^{18}O$ values during dry period,~~ especially in a well ventilated cave.

~~Compared with ~~Dongge is~~,~~ a cave consisting of branches with twists and turns, ~~the structure of ~~while Heshang is a much simpler cave ~~is much simpler only ~~with a nearly straight main passage, and ~~with ~~a 20 m high entrance (Hu et al., 2008b). ~~So ~~Heshang cave is clearly~~ much~~ more open and better ventilated than Dongge cave~~, and indeed it~~ leading~~s~~ to ~~an obvious ~~greater heat and moisture exchange between the inside and outside cave (Hu et al, 2008b). ~~Therefore on ~~During similar dry conditions, the evaporation effects in Heshang cave are expected to be ~~is much ~~more significant than in Dongge Cave, and the drier the condition ~~it is,~~ the heavier HS4 $\delta^{18}O$ values expected ~~would be~~, leading to lower or even negative $\Delta\delta^{18}O$ values between DA and HS4. ~~That means ~~Thus less rainfall is still related to lower $\Delta\delta^{18}O$ values~~ with the consideration of cave evaporation effect~~. Since the 8.2 ka BP event is the driest period during the whole Holocene (Hu et al., 2008), negative $\Delta\delta^{18}O$ values produced during the centrale event ~~is ~~are possible.

From the 10-year moving average $\Delta\delta^{18}O$ ~~between the~~ obtained from HS4 and DA records(Fig. 3~~2~~b), there is a significant change in value ~~by 1.8‰ ~~from 1.3‰ to -0.5‰ over approximately ~~happened in ~~~~~70 years at the ~~beginning~~ commencement of the event. Compared with the average amplitude of Δ$\delta^{18}$O during the whole Holocene of 1.0‰ (Hu et al., 2008a), ~~during the 8.2 ka BP period, the $\delta^{18}$O value drops greatly and the amplitude is nearly doubled~~ this is a surprisingly large change.

~~Based on~~ From the Δ$\delta^{18}$O record shown in Fig.3~~2~~b, using the previously determined relation (Rainfall=189.08×Δ$\delta^{18}$O +1217.4) ~~published in~~ from Hu et al. (2008a), the rainfall record in southwest China during the 8.2 ka BP period ~~could~~ may be established as shown in Fig.3~~2~~b. ~~Besides the~~ While some support for the reconstruction method can be obtained using recent ~~by~~ monitoring records ~~shown~~ detailed in section 2.1.3, stalagmite Mg/Ca ratios ~~might~~ also provide some useful corroborative information~~ to test the robustness of the reconstructed rainfall record as well~~.

Stalagmite Mg/Ca ratio is a~~nother~~ proxy mainly controlled by local rainfall with higher Mg/Ca values corresponding to lower rainfall (Fairchild and Treble, 2009), though it may show some temperature dependence, increasing slightly with temperature ~~raise~~ increase~~, higher Mg/Ca values usually correspond to lower rainfall (Fairchild and Treble, 2009)~~. ~~This~~ The variation is understood to result from $CO_2$-degassing occurring earlier during water movement in dry seasons as cave water seeps more slowly, thus Ca is lost from karst waters by formation of calcite earlier during transport processes and before waters reach the stalagmite. Such a prior-calcite-precipitation process would be expected to produce higher Mg/Ca ratios (Tremaine and Froelich, 2013; Fairchild and Treble, 2009). Although it is hard to obtain quantitative rainfall data from Mg/Ca ratios, the ~~change~~ variation of Mg/Ca may give a qualitative indication of ~~the~~ rainfall variability and trend. Therefore the variation ~~trend~~ of Mg/Ca ratios could ~~tell~~ indicate whether the reconstructed rainfall from Δ$\delta^{18}$O is reliable or not.

The HS4 Mg/Ca sequence presented as a 10-yr moving average record during the 8.2 ka BP event is shown in Fig. 3~~2~~c. As high Mg/Ca values are considered to indicate low rainfall, the Y axis of Mg/Ca was reversed to make the comparison clearer. Both the Mg/Ca ratios and the reconstructed rainfall data are presented as 10-yr moving average values. Although the two data sets show slight differences, there is a general inverse relationship between the two sequences giving a correlation coefficient ($R^2$) of 0.56 (n=219). And overall similarity could be observed between the trends of the two patterns with high (low) Mg/Ca values corresponding to low (high) rainfall, which suggests that the Mg/Ca results ~~roughly~~ generally support the reconstructed rainfall record~~ as well~~.

The reconstructed rainfall record (Fig.3~~2~~b) shows a maximum decline in annual rainfall of 350 mm/yr, which is nearly twice that obtained from the low-resolution (~100-yr) rainfall record (Hu et al., 2008a) during the same period and the lowest annual rainfall in this study is lower than that from Hu et al. (2008a) by ~100 mm. This is believed to be a result of the record resolution. Fig.3~~2~~b also shows that the period of decreasing rainfall at the beginning of the event lasts for ~70 years, before entering into an extreme dry period. During the central period of the 8.2 ka BP event, the average annual rainfall is only ~1200 mm, which appears to be the driest period during the whole Holocene in this area, lasting for ~50 years. ~~As t~~The rainfall calculation developed in Hu et al. (2008a) was made by averaging annual rainfall records from 6 sites between Heshang and Dongge(Fig. 1) and the averaged annual rainfall between 1950 and 1990 from the 6 sites is ~1380 mm, indicating the average annual rainfall during the central 8.2 ka BP period is less than present by ~200 mm.

## 4 Discussions

It has been reported that the response of the EAMA to North Atlantic cooling during the 8.2 ka BP event results from atmospheric rather than oceanic processes (Liu et al., 2013). It might be assumed that the high northern latitude ice-cover reinforces Northern Hemisphere cooling, increasing the temperature gradient between the high and low latitudes which leads to southward migration of the inter-tropical convergence zone (Chiang and Bitz, 2005; Broccoli et al., 2006). This would result in weakening of the East Asian Monsoon and increased aridity ~~around~~. Assessment of the sensitivity of southwest China climate response to North Atlantic cooling might provide a clue to how North Atlantic cooling affects the EAMA.

Fig. ~~4~~5 demonstrates three sequences of Greenland ice core $\delta^{18}O$ (Thomas et al., 2007)(Fig. ~~4~~5a) , a palaeo-temperature indicator (Stuiver, et al., 1995), Greenland ice core $\delta^{15}N$ (Kobashi et al., 2007)(Fig. ~~4~~5b), a newly developed palaeo-temperature proxy (Buizert et al., 2014) and the reconstructed rainfall record in southwest China during the 8.2 ka BP period(Fig. ~~4~~5c). The data shown in Fig. ~~4~~5a are from Thomas et al. (2007) with a 3-yr resolution. To allow comparison with the reconstructed rainfall records, the $\delta^{18}O$ of the ice core was processed to provide a 10-yr moving average ~~squence~~. The $\delta^{15}N$ data in Fig. ~~4~~5b are from Kobashi et al. (2007) with a 11-yr resolution and were processed similarly.

As low Greenland ice $\delta^{18}O$ and $\delta^{15}N$ values indicate local cooling (Thomas et al., 2007; Kobashi et al., 2007), both Fig. ~~4~~5a and Fig. ~~4~~5b reveal similar trends of decreasing temperature during the 8.2 ka BP event. The comparison between each data set in Fig.~~4~~5 suggests that the decrease in rainfall in southwest China may indeed be in response to Greenland cooling. Further analysis shows a ~~slight positive~~ weak correlation between Greenland ice core $\delta^{18}O$ and the reconstructed rainfall with a correlation coefficient ($R^2$) of 0.47 (n=219) indicating a 1‰ drop in Greenland ice core $\delta^{18}O$ could lead to ~7% decrease in rainfall in southwest China. Though there is not enough $\delta^{15}N$ data to reveal further correlations, it does indicate a drop of 3.3±1℃ when the 8.2 ka BP event occurred(Kobashi et al., 2007). As the reconstructed annual rainfall record reveals a maximum decrease of 350 mm, the magnitude of rainfall response of southwest China to Greenland cooling during 8.2 ka BP period could be assessed as 110±30 mm/℃.

## 5 Conclusions

1. Based on a comparison of two high-resolution stalagmite $\delta^{18}O$ records from Dongge cave and Heshang cave along the monsoon moisture transport pathway in China, a 10-yr moving average quantitative annual rainfall record in southwest China is established during the 8.2 ka BP event.
2. Significant positive correlation between recent monitored drip water annual average $\delta^{18}O$ differences from two caves along the monsoon moisture transport pathway and the regional average annual rainfall from May 2011 to April 2014 provides~~ a monitoring ~~support for the reconstruction. ~~And s~~Similar trends between the reconstructed rainfall ~~sequence ~~and~~ the~~ stalagmite Mg/Ca ratios, another proxy of rainfall, ~~further ~~increase the confidence of the quantization of the rainfall record.
3. The reconstructed rainfall record shows that the annual rainfall in southwest China decreased sharply by ~350 mm in ~70 years when the 8.2 ka BP event occurred and experienced an extreme drying period lasting for ~50 years during the central event. Compared with the modern instrumental records, the averaged annual rainfall in southwest China during the 8.2 ka BP event is less than that of present (1950 ~ 1990) by ~200 mm.
4. ~~The correlation analysis~~ A comparison between ~~the ~~reconstructed rainfall in southwest China and Greenland ice core $\delta^{18}O$, an indicator of temperature, suggests that the rainfall decrease in southwest China during the 8.2 ka BP period coupled with Greenland cooling. A~~nd a ~~possible response rate of 110±30 mm/℃ could be presumed by the temperature drop derived from Greenland ice core $\delta^{15}N$ and rainfall decrease from the reconstructed record.

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## References

Alley, R. B. and Ágústsdóttir, A. M.: The 8k event: cause and consequences of a major Holocene abrupt climate change, Quaternary Sci. Rev., 24, 1123–1149, 2005.

Alley, R. B., Mayewski, P. A., Sowers, T., Stuiver, M., Taylor, K. C., and Clark, P. U.: Holocene climatic instability: Aprominent, widespread event 8200 yr ago, Geology, 25, 483–486, 1997.

Broccoli, A. J., Dahl, K. A., and Stouffer, R. J.: Response of the ITCZ to Northern Hemisphere cooling, Geophys. Res. Lett., 33, L01702, 2006.

Buizert, C., Gkinis, V., Severinghaus, J. P., He, F., Lecavalier, B. S., Kindler, P., Leuenberger, M., Carlson, A. E., Vinther, B., Masson-Delmotte, V., White, J. W. C., Liu, Z., Otto-Bliesner, B., and Brook, E. J.: Greenland temperature response to climate forcing during the last deglaciation, Science, 345, 1177–1180, 2014.

Cheng, H., Fleitmann, D., Edwards, R. L., Wang, X., Cruz, F. W., Auler, A. S., Mangini, A., Wang, Y., Kong, X., Burns, S. J., and Matter, A.: Timing and structure of the 8.2 kyr B.P. event inferred from $\delta^{18}O$ records of stalagmites from China, Oman, and Brazil, Geology, 37, 1007–1010, 2009.

Chiang, J. C. H. and Bitz, C. M.: Influence of high latitude ice cover on the marine Intertropical Convergence Zone, Clim. Dynam., 25, 477–496, 2005.

Condron, A. and Winsor, P.: A subtropical fate awaited freshwater discharged from glacial Lake Agassiz, Geophys. Res. Lett., 38, L03705, 2011.

Daley, T. J., Thomas, E. R., Holmes, J. A., Street-Perrottd, F. A., Chapmane, M. R., Tindallf, J. C., Valdesf, P. J., Loaderd, N. J., Marshallg, J. D., Wolffb, E. W., Hopleyh, P. J., Atkinsonc, T., Barberi, K. E., Fisherg, E. H., Robertsond, I., Hughesi, P. D. M., and Robertsa, C. N.: The 8200 yr BP cold event in stable isotope records from the North Atlantic region, Global Planet. Change, 79, 288–302, 2011.

Dayem, K. E., Molnar, P., Battisti, D. S., and Roe, G. H.: Lessons learned from oxygen isotopes in modern precipitation applied to interpretation of speleothem records of paleoclimate from eastern Asia, Earth Planet. Sc. Lett., 295, 219–230, 2010.

Ding, Y., Li, C., and Liu, Y.: Overview of the South China Sea Monsoon experiment. Adv. Atmos. Sci., 21, 343–360, 2004.

Dixit, Y., Hodell, D. A., Sinhab, R., and Petrie, C. A.: Abrupt weakening of the Indian summer monsoon at 8.2 kyr B.P., Earth Planet. Sc. Lett., 391, 16–23, 2014.

Dom ńguez-Villar, D., Fairchild, I. J. Baker, A., Wang, X., Edwards, R. L., and Cheng, H.: Oxygen isotope precipitation anomaly in the North Atlantic region during the 8.2 ka event, Geology, 37, 1095–1098, 2009.

Duan, W., Ruan, J., Luo, W., Li, T., Tian, L., Zeng, G, Zhang, D., Bai, Y., Li, J., Tao, T., Zhang, P., Baker, A., and Tan, M.: The transfer of seasonal isotopic variability between precipitation and drip water at eight caves in the monsoon regions of China, Geochim. Cosmochim. Acta, 183: 250–266, 2016.

Dykoski, C. A., Edwards, R. L., Cheng, H., Yuan, D, Cai, Y., Zhang, M., Lin, Y., Qing, J., An, Z., and Revenaugh, J.: A high-resolution, absolute dated Holocene and deglacial Asian monsoon record from Dongge Cave, China, Earth Planet. Sc. Lett., 233, 71–86, 2005.

Ellwood, B. B. and Gose, W. A.: Heinrich H1 and 8200 yr B.P. climate events recorded in Hall's Cave, Texas, Geology, 34, 753–756, 2006.

Fairchild, I. J. and Treble, P. C.: Trace elements in speleothems as recorders of environmental change, Quaternary Sci. Rev., 28, 449–468, 2009.

Ge, Q., Chu, F. Y., Xue, Z., Liu, J. P., Du, Y., and Fang, Y.: Paleoenvironmental records from the northern South China Sea since the Last Glacial Maximum, Acta Oceanol. Sin., 29, 46–62, 2010.

Hede, M. U., Rasmussen, P., Noe-Nygaard, N., Clarke, A. L., Vinebrooke, R. D., and Olsen, J.: Multiproxy evidence for terrestrial and aquatic ecosystem responses during the 8.2 ka cold event as recorded at Højby Sø, Denmark, Quaternary Res., 73, 485–496, 2010.

Hong, Y. T., Hong, B., Lin, Q. H., Shibatab, Y., Zhua, Y. X., Lengc, X. T., and Wanga, Y.: Synchronous climate anomalies in the western North Pacific and North Atlantic regions during the last 14,000 years, Quaternary Sci. Rev., 28, 840–849, 2009.

Hu, C., Henderson, G. M., Huang, J., Xie, S., Sun, Y., and Johnson K. R.: Quantification of Holocene Asian monsoon rainfall from spatially separated cave records, Earth Planet. Sc. Lett., 266, 221–232, 2008a.

Hu, C., Henderson, G. M., Huang, J., Chen, Z., and Johnson, K. R.: Report of a three-year monitoring programme at Heshang Cave, Central China, Int. J. Speleol., 37 : 143–151, 2008b.

Khasnis, A. A. and Nettleman, M. D.: Global warming and infectious disease, Arch. Med. Res., 36, 689–696, 2005.

Kobashi, T., Severinghaus, J. P., Brook, E. J., Barnola, J. M., and Grachev, A. M.: Precise timing and characterization of abrupt climate change 8200 years ago from air trapped in polar ice, Quaternary Sci. Rev., 26, 1212–1222, 2007.

LeGrande A. N. and Schmidt G. A.: Ensemble, water isotope–enabled, coupled general circulation modeling insights into the 8.2 ka event, Paleoceanography, 23, PA3207, 2008.

Liu, Y., Henderson, G. M., Hu, C., Mason, A. J. Charnley, N., Johnson, K. R., and Xie, S.: Links between the East Asian monsoon and North Atlantic climate during the 8,200 year event, Nat. Geosci., 6, 117–120, 2013.

Liu, Z., Wen, X., Brady, E.C., Otto-Bliesner, B., Yu, G. , Lu, H., Cheng, H., Wang, Y., Zheng, W., Ding, Y., Edwards, R.L., Cheng, J., Liu, W., and Yang, H.: Chinese cave records and the East Asia Summer Monsoon, Quaternary Sci. Rev., 83, 115-128, 2014.

Ljung, K., Björck, S., Renssen, H., and Hammarlund, D.: South Atlantic island record reveals a South Atlantic response to the 8.2 kyr event, Clim. Past, 4, 35–45, 2008.

Martrat, B., Grimalt, J. O., Lopez-Martine, C., Cacho, I., Sierro, F. J., Flores, J. A., Zahn, R., Canals, M., Curtis, J. H., and Hodell, D. A.: Abrupt temperature changes in the western Mediterranean over the past 250,000 years, Science, 306, 1762–1765, 2004.

Mischke, S. and Zhang, C. J.: Holocene cold events on the Tibetan Plateau, Global Planet. Change, 72, 155–163, 2010.

Morrill C., Anderson, D. M., Bauer, B. A., Buckner, R., Gille, E. P., Gross, W. S., Hartman, M., and Shah, A.: Proxy benchmarks for intercomparison of 8.2 ka simulations, Clim. Past, 9, 423–432, 2013.

Morrill, C., Wagner, A. J., Otto-Bliesner, B. L., and Rosenbloom, N.: Evidence for significant climate impacts in monsoonal Asia at 8.2 ka from multiple proxies and model simulations, J. Earth Environ., 2, 426–441, 2011.

Pall, P., Allen, M. R., and Stone, D. A.: Testing the Clausius–Clapeyron constraint on changes in extreme precipitation under $CO_2$ warming, Clim. Dynam, 28, 351–363, 2007.

Prasad, S., Witt, A., Kienel, U., Dulski, P., Bauer, E., and Yancheva, G.: The 8.2 ka event: Evidence for seasonal differences and the rate of climate change in western Europe, Global Planet. Change, 67, 218–226, 2009.

Rahmstorf, S.: A semi-empirical approach to projecting future sea-level rise, Science, 315, 368–370, 2007.

Snowball, I., Muscheler, R., Zillén, L., Sandgren, P., Stanton, T., and Ljung, K.: Radiocarbon wiggle matching of Swedish lake varves reveals asynchronous climate changes around the 8.2 kyr cold even, Boreas, 39, 720–733, 2010.

Stuiver, M., Grootes, P. M., and Brazunias, T. F.: The GISP2 $\delta^{18}O$ record of the past 16,500 years and the role of the Sun, ocean and volcanoes, Quaternary Res., 44, 341–354, 1995.

Szeroczyńska, K. and Zawisza, E.: Records of the 8200 cal BP cold event reflected in the composition of subfossil Cladocera in the sediments of three lakes in Poland, Quatern. Int., 233, 185–193, 2011.

Thomas, E. R., Wolff, E. W., Mulvaney, R., Steffensen, J. P., Johnsen, S. J., Arrowsmith, C., White, J. W.C., Vaughn, B., and Popp, T.: The 8.2 ka event from Greenland ice cores, Quaternary Sci. Rev., 26, 70–81, 2007.

Tremaine, D. M. and Froelich, P.N.: Speleothem trace element signatures: A hydrologic geochemical study of modern cave dripwaters and farmed calcite, Geochim. Cosmochim. Acta, 121, 522–545, 2013.

Walther, G. R., Post, E., Convey, P., Menzel, A., Parmesan, C., Beebee, T. J. C., Fromentin, J. M., Hoegh-Guldberg, O., and Bairlein, F.: Ecological responses to recent climate change, Nature, 416, 389 –395, 2002.

Wang, Y., Cheng, H., Edwards, R. L., He, Y., Kong, X., An, Z., Wu, J., Kelly, M. J., Dykoski, C. A., and Li, X.: The Holocene Asian Monsoon: links to solar changes and North Atlantic climate, Science, 308, 854–857, 2005.

Wu, J., Wang, Y., Cheng, H., Kong, X., and Liu, D.: Stable isotope and trace element investigation of two contemporaneous annually-laminated stalagmites from northeastern China surrounding the “8.2 ka event”, Clim. Past, 8, 1497–1507, 2012.

Yu, X., Zhou, W., Franzen, L. G., Feng, X., Peng, C., and Jull, A. J. T.: High-resolution peat records for Holocene monsoon history in the eastern Tibetan Plateau, Sci. China Earth Sci., 49, 615–621, 2006.

Zeng, G., Luo, W., Wang, S., and Du, X.: Hydrogeochemical and climatic interpretations of isotopic signals from precipitation to drip waters in Liangfeng Cave, Guizhou Province, China, Environ. Earth Sci.,74, 1509-1519, 2015.

Zheng, Y., Zhou, W., Xie, S., and Yu, X.: A comparative study of n-alkane biomarker and pollen records: an example from southern China, Chinese Sci. Bull., 54, 1065–1072, 2009.

Zheng, Y., Kissel, C., Zheng, H., Lajb, C., and Waang, K.: Sedimentation on the inner shelf of the East China Sea: Magnetic properties, diagenesis and paleoclimate implications, Mar. Geol., 268, 34–42, 2010.

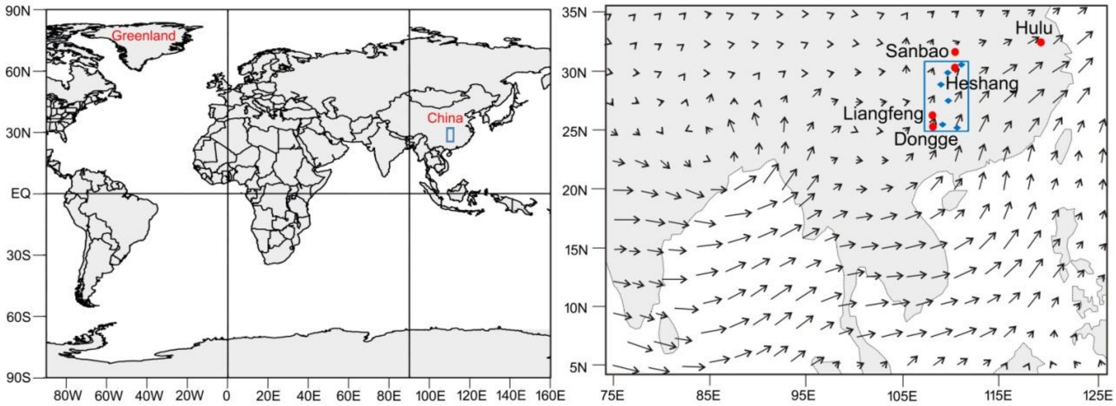


Figure 1. Location maps. The left map shows the location of Greenland and southwest China(blue box). The right map shows the location of Heshang cave and other Chinese caves(red points), with main feature of the summer monsoon marked. Smaller arrows reflect moisture transport and direction averaged over the whole atmosphere (Ding et al., 2004). The blue box indicates the specific region for which comparison of Heshang and Dongge allows rainfall reconstruction, and the blue diamond patterns show the location of six modern rainfall stations detailed in Hu et al.(2008) .

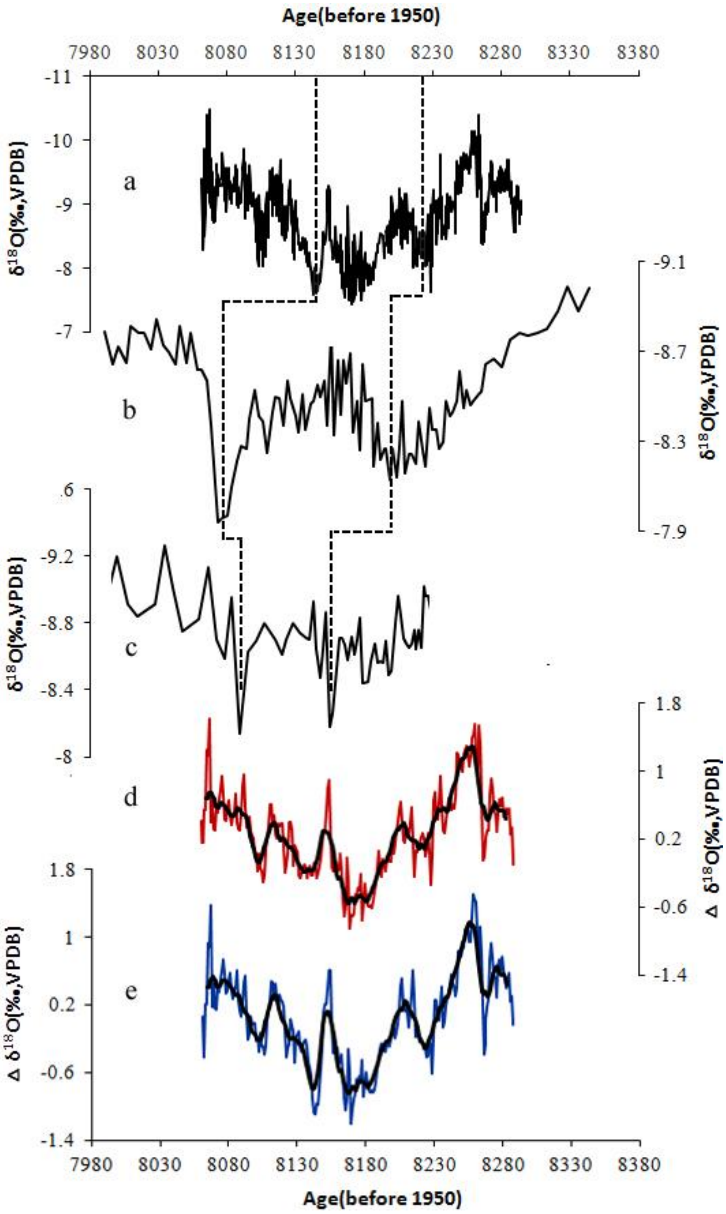


Figure 21. Original $\delta^{18}O$ stalagmite records adopted in this paper displayed with $\Delta\delta^{18}O$ sequences between stalagmites from Dongge and Heshang. a. HS4 $\delta^{18}O$ record from Heshang cave(Liu et al., 2013); b. DA $\delta^{18}O$ record from Dongge cave(Cheng et al., 2009); c. D4 $\delta^{18}O$ record from Dongge cave (Cheng et al., 2009); d. $\Delta\delta^{18}O$ between DA and HS4 (red) with a 10-year moving average(black); e. $\Delta\ \delta^{18}O$ between D4 and HS4 (blue) with a 10-year moving average (black). The dashed lines show matched typical corresponding peaks from each original record.

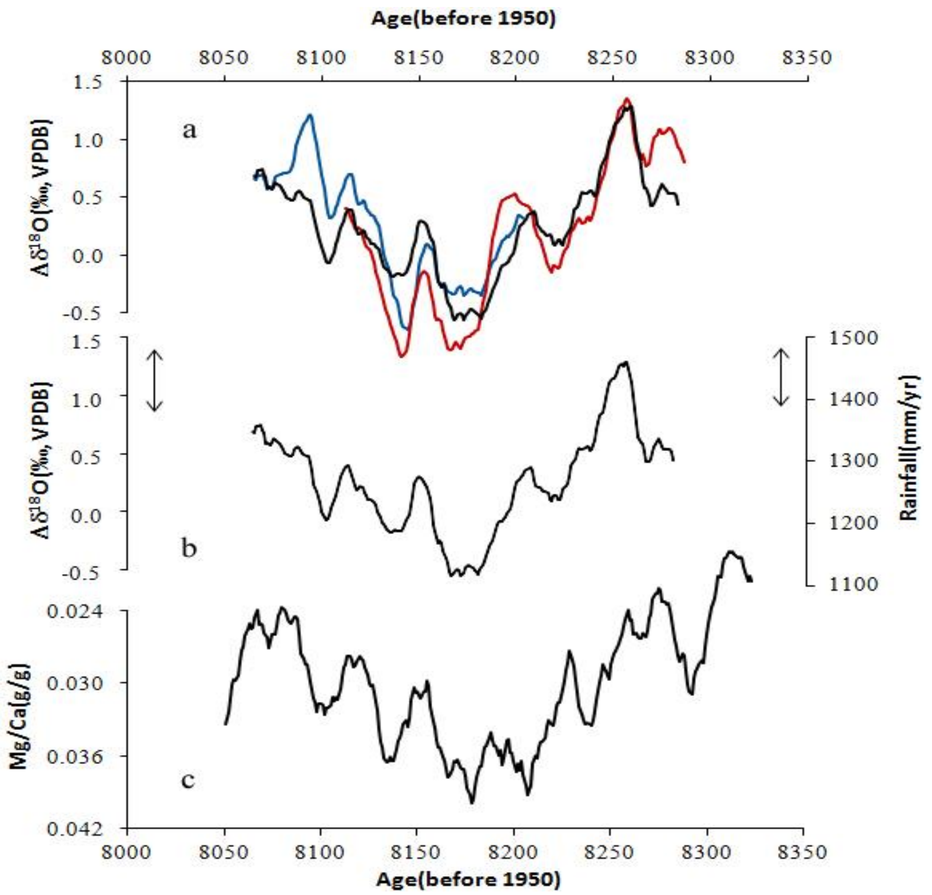


Figure 3~~2~~. 10-yr moving average records during the 8.2 ka BP period. a~~)~~. Δ $\delta^{18}O$ records between HS4 and DA with unchanged chronology (black), shifting DA 50-yr younger (blue) and 50-yr older (red); b~~)~~. Δ $\delta^{18}O$ record between HS4 and DA and reconstructed annual rainfall in southwest China with error bars indicated; c~~)~~. Mg/Ca ratios of HS4 shown on inverted scales, which reveals a similar trend to the rainfall sequence, increasing the confidence of the quantization of the reconstructed record.

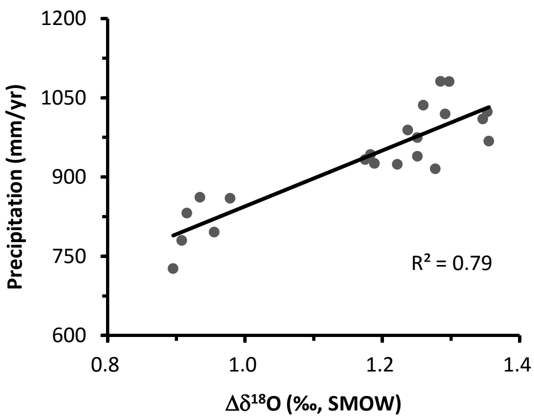


Figure 4~~3~~. Correlation analysis between mean annual ~~moving average~~ precipitation and drip water $\delta^{18}O$ difference~~ of~~ from 2-month delayed LF6 and 4-month delayed HS4 from May 2011 to April 2014. The $\Delta\delta^{18}O$ data are calculated from monthly monitored~~ing~~ data from Liangfeng cave and Heshang cave (Duan et al., 2016). The annual precipitation data are the average from six sites between Dongge cave and Heshang cave ~~mentioned~~ detailed in Hu et al.

(2008a) and the original monthly rainfall data are from http://www.wunderground.com/ history/. The correlation factor of 0.79 indicates a significant positive correlation between ~~annual~~ regional annual rainfall and annual $\Delta\delta^{18}O$.

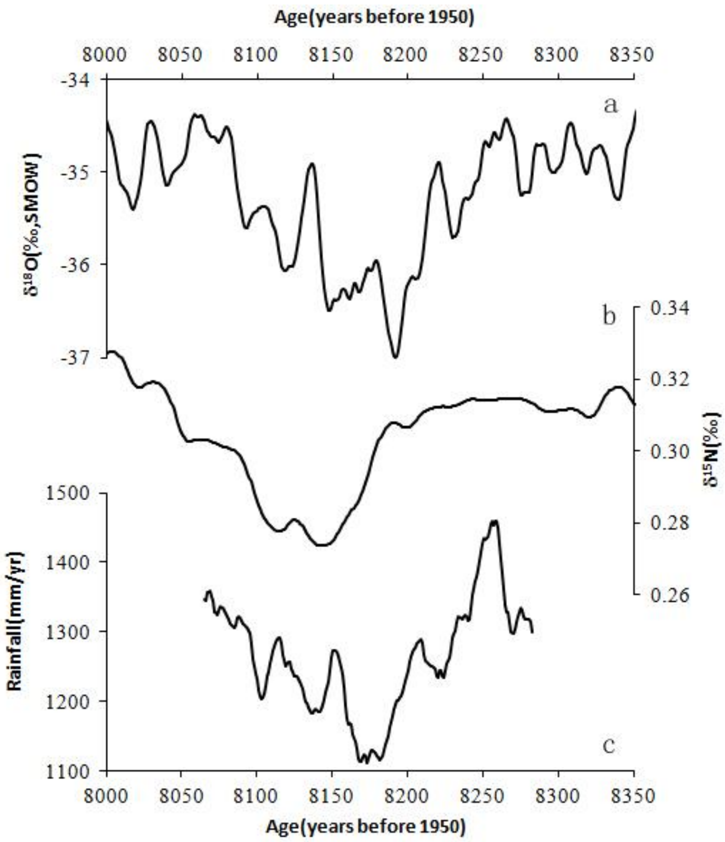


Figure 54. Records from Greenland ice core $\delta^{18}O$ (Thomas et al., 2007) (a), Greenland ice core $\delta^{15}N$ (Kobashi et al., 2007) (b) and the reconstructed annual rainfall from this study(c) during the 8.2 ka BP event. Three sequences show a similar pattern indicating the decrease in rainfall in southwest China was coupled with Greenland cooling during the 8.2 ka BP event.