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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 the same moisture transport pathway. Trends between the reconstructed rainfall sequence and stalagmite Mg/Ca record, another proxy of rainfall, are compared. 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 ~50 years. Further analysis suggests that the rainfall decrease in southwest China coupled with the Greenland cooling, the correlation between the annual rainfall and the Greenland ice core $\delta^{18}O$, an indicator of temperature, during the 8.2 ka BP event is significantly higher than today, and may provide insights into abrupt climate prediction under warming conditions.

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 (Chen, 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 Holocene period(Alley and Ágústsdóttir, 2005). Of significance is the observation that the climate at the time was experiencing a warming period similar to that of today (Alley and Ágústsdóttir, 2005). The highest magnitude variation across the low to high latitudes makes a viable target for numerical modeling (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

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160 yr (Thomas et al, 2007) with a temperature drop of 3.3±1.1 °C 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, K. and Zawisza E, 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 the 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 same method from 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 2.5-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 by comparing with present day climate, providing quantitative data for simulating this global event in climate system models.

2 Methods

It has been previously discussed (Hu, et al., 2008) that, in a monsoon area, local 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 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 around 8.2 ka BP from central China (Liu et al., 2013) and southwest China (Cheng et al., 2009) were investigated. The central China $\delta^{18}O$ data with an average resolution of ~0.3-yr are from stalagmite HS4, Heshang Cave (30°270′N, 110°25′E), Hubei (Liu, et al., 2013) and the southwest China $\delta^{18}O$ data with an average resolution of ~2.5-yr are from stalagmite DA, Dongge Cave (25°17′N, 108°5′E), Guizhou (Cheng et al., 2009). Both of the stalagmites were well-dated by the U-Th technique and record the 8.2 ka BP event with a similar variation trend.

The patterns of the two stalagmite $\delta^{18}O$ sequences during 8.2 ka BP event were compared using the approach outlined in Hu et al. (2008a). Dongge Cave is located 600 km southwest of Heshang Cave which is directly upstream in the atmospheric pathway. There are two published stalagmite $\delta^{18}O$ records from Dongge (stalagmite

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DA and D4) (Cheng et al., 2009; Wang et al., 2005; Dykoski et al., 2005). Cheng et al.(2009) re-dated the two stalagmites, to obtain a better controlled chronology and the δ^{18}O records we use are from Cheng et al.(2009). Though there are some differences in detail, both record climate change information and their general patterns demonstrated by the two δ^{18}O sequences are similar, as shown in Fig. 1b and 1c. (Cheng, et al., 2008).

It may be observed that the δ^{18}O records from HS4 (Fig.1a) and DA (Fig. 1b) show similar patterns with matching peaks and troughs. Typical corresponding peaks or troughs are marked as shown by dashed lines in Fig. 1 and the chronology of DA and HS4 are so matched to reduce chronology uncertainty. As the resolutions of HS4 and DA are different, both sequences were first processed to create records of equivalent annual resolution and the resultant time sequences then used to construct a 10-yr moving average. A new δ^{18}O difference ($\Delta\delta^{18}$O) sequence was thus established between the matched HS4 and DA records (Fig.1d).

The rainfall calculation methods used in this study are those derived in the previous work by Hu et al. (2008a), as the established model covering the 8.2 ka BP period. The relation between $\Delta\,\delta^{18}$O and rainfall (Rainfall=189.08$\times\Delta\delta^{18}$O+1217.4) (Hu et al., 2008a) is therefore considered suitable for this study.

In addition to $\Delta\,\delta^{18}$O, the Mg/Ca ratio, another important rainfall proxy, is considered in this paper. The Mg/Ca data set is taken from Liu et al. (2013) measured by 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 δ^{18}O.

3 Results

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

It may be observed in Fig. 2 (upper panel) that during the center event, 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 below -0.50‰ (Fig. 2), we do not expected negative $\Delta\,\delta^{18}$O values. These anomalous results may result from imprecision of carbonate δ^{18}O measurements which are ±0.08‰ for HS4(Liu et al, 2013) and ±0.15‰ for DA(Cheng et al., 2009) , which might lead to apparent negative $\Delta\,\delta^{18}$O values. We argue that the difference in evaporation in the two sites contributes to the negative $\Delta\,\delta^{18}$O. Compared with Dongge Cave, Heshang is a half-open cave and an obvious heat and moisture exchange between the inside and outside

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cave could be observed (Hu et al, 2008b), which means Heshang cave is better ventilated than Dongge Cave and the evaporation effect is more significant when the climate is drier, especially true during the 8.2 ka BP event.

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

Based on the $\Delta\delta^{18}O$ sequence, using the previously determined relation (Rainfall=189.08×$\Delta\delta^{18}O$ +1217.4) published in Hu et al. (2008a), the rainfall record in southwest China during the 8.2 ka BP period could be established as shown in Fig. 2 (upper panel). Since the reconstructed rainfall record from $\Delta\delta^{18}O$ is intending to be quantitative, it is necessary to assess the uncertainties of the record. Firstly, analytical uncertainty in $\delta^{18}O$ from HS4 and DA, which are 0.08‰ (Liu et al. 2013) and 0.15‰ (Cheng, et al., 2009) respectively. Secondly, the standard deviation of the 10-yr average data set, the largest standard deviation of $\Delta\delta^{18}O$ between DA and HS4 is 0.62‰. Also, the model established by Hu et al. (2008a) has an estimated uncertainty of 0.35‰. Taking these factors into consideration, the final uncertainty of the $\Delta\delta^{18}O$ sequence could be estimated to be ~0.42‰, giving an uncertainty of ~80 mm/yr for the calculated rainfall sequence shown in Fig.2. Although the robustness of the reconstructed rainfall record cannot be directly tested, stalagmite Mg/Ca ratio, might provide some useful information.

The stalagmite Mg/Ca ratio is another proxy controlled mostly by local rainfall, though it may show some temperature dependence, increasing slightly with temperature increases, higher Mg/Ca values usually correspond to lower rainfall (Fairchild and Treble, 2009). This 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 of Mg/Ca may give a qualitative indication of rainfall variability and trend. Therefore the variation trend of Mg/Ca ratios could tell us whether the reconstructed rainfall from $\Delta\delta^{18}O$ is reliable or not.

The HS4 Mg/Ca data presented as a 10-yr moving average record during the 8.2 ka BP event is shown in Fig. 2 (lower panel). 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 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

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trends of the two patterns with high (low) Mg/Ca values corresponding to low (high) rainfall, which suggests that the Mg/Ca results roughly support the reconstructed rainfall record.

The reconstructed rainfall record (Fig. 2) shows a highest annual rainfall of approximately 350 mm/yr, which is nearly twice that obtained from the low-resolution (~100yr) 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. 2 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. Prior to the event, the annual rainfall showed an average vaule of ~1300 mm but in the central period of the event, the average yearly rainfall is only ~1200 mm, which appears to be the driest period during the whole Holocene in this area, lasting for ~50 years.

4 Discussion

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 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 intertropical 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 allow comparison with modern data and provide a clue to how North Atlantic cooling affects the EAMA.

Fig. 3 demonstrates three sequences of Greenland ice core $\delta^{18}O$ (Thomas et al., 2007) , a palaeo-temperature indicator (Stuiver, et al., 1995), Greenland ice core $\delta^{15}N$ (Kobashi et al., 2007), 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. The data shown in Fig. 3a 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 10-yr moving average. The $\delta^{15}N$ data in Fig. 3b 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. 3a and Fig. 3b reveal a similar trend of decreasing temperature during the 8.2 ka BP event. The comparison between each data set in Fig. 3 suggests that the decrease in rainfall (Fig. 3c) in southwest China may indeed be in response to Greenland cooling. Further analysis shows a slight positive relationship between Greenland ice core $\delta^{18}O$ and the reconstructed rainfall with a correlation coefficient (R^2) of 0.47 (n=219) perhaps indicating a 1‰ drop in Greenland ice core $\delta^{18}O$ could lead to ~7% decrease in rainfall. Though there is not enough $\delta^{15}N$ data to reveal further correlations it does indicate a drop of 3.3 ± 1 ℃ during the 8.2 ka BP (Kobashi et al., 2007). As the annual rainfall difference from

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before and during the 8.2 ka BP event is ~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/℃.

When compared with modern records, what is the response of rainfall in southwest China to Greenland cooling?

The rainfall calculation developed in Hu et al. (2008a) was established by averaging yearly rainfall records from 6 cities located between Heshang and Dongge. The averaged yearly rainfall from 1950 ~ 1990 from the 6 sites is 1370 mm, which is higher than the average annual rainfall during central 8.2 ka BP period (Fig. 2) by ~200 mm. However, 40 years of records is perhaps too short to calculate a reasonable correlation between southwest China rainfall and modern Greenland temperature. We presume to approximate by using the longest data (Yichang rainfall) sequence from the 6 sites.

To better assess the relative response between modern and the 8.2 ka BP period, in addition to Greenland temperature records, modern Greenland ice core $\delta^{18}O$ data has also been reviewed, as this proxy has been included from the 8.2 ka BP period. The modern Greenland ice core $\delta^{18}O$ data (a), measured annual temperature (b) and Yichang recorded annual rainfall (c) in Fig. 4 from White et al. (1997), with two sites average $\delta^{18}O$ between 64.17 °N, -51.75 °E and 65.60 °N, -37.63E from KNMI(Koninklijk Nederlands Meteorologisch Instituut) Climate Explorer (http://climexp.knmi.nl/selectstation.cgi?id=someone@ somewhere) and Hubei Province Meteorological Bureau respectively. The data has additionally been processing to produce annual 10-year resolution records to make them comparable with data during the 8.2 ka BP period.

Broadly similar trends are observed in the 3 data Fig. 4 commencing in 1887 with a major peak appearing in all 3 records. Analysis indicates that the correlation coefficient between 10-yr moving Yichang annual rainfall and Greenland ice core $\delta^{18}O$ (R^2=0.16，n=81) is poor compared with that between Yichang rainfall and Greenland temperature (R^2=0.30，n=75), and is also much lower than that between the rainfall in southwest China and the Greenland ice core $\delta^{18}O$ during 8.2 ka BP period (0.47). If the yearly rainfall record from Yichang is replaced by the record from the 6 sites used in Hu et al. (2008a), then the correlation coefficient must be lower. This suggests the response of rainfall in southwest China to North Atlantic cooling during the 8.2 ka BP event was much stronger than that of today.

Further study of existing records shows that the modern 10-yr averaged Yichang rainfall shows an apparent response to Greenland temperature of ~50 mm/℃. In the last 40 years, the yearly rainfall at the 6 sites used in Hu et al. (2008a) is generally higher than that from Yichang by 17%, the response rate of the yearly rainfall from the 6 sites to the Greenland temperature might be around 60 mm/℃. Even though the

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temperature drop from Greenland was predicated by modeled nitrogen isotope ratios (Kobashi et al., 2007), it perhaps gives a possible way to assess the different response between the 8.2 ka BP period and today. As the response rate of 60 mm/℃ is clearly lower than the rate of 110±30 mm/℃ during 8.2 ka BP event, the yearly rainfall decrease in southwest China was stronger than that of today.

5 Conclusions

1. Based on a comparison of two high-resolution stalagmite $\delta^{18}O$ records from two caves along the monsoon moisture pathway in China, a 10-yr moving average quantitative annual rainfall record in southwest China was established for the 8.2 ka BP event. Similar trends between reconstructed rainfall sequence and the stalagmite Mg/Ca ratios, another proxy of rainfall, increase the confidence of the quantization of this record.
2. The reconstructed rainfall record shows that the local annual rainfall decreased sharply during the 8.2 ka BP event by ~350 mm in 70 years and experienced an extreme drying period lasting for around 50 years during the 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 today (1950 ~ 1990) by ~200 mm.
3. The decrease in rainfall in southwest China coupled with Greenland cooling, and the correlation coefficient between the two data sets during the 8.2 ka BP event appears to be at least 3 times higher than that of today, which provides an insight into abrupt climate prediction under warming conditions.

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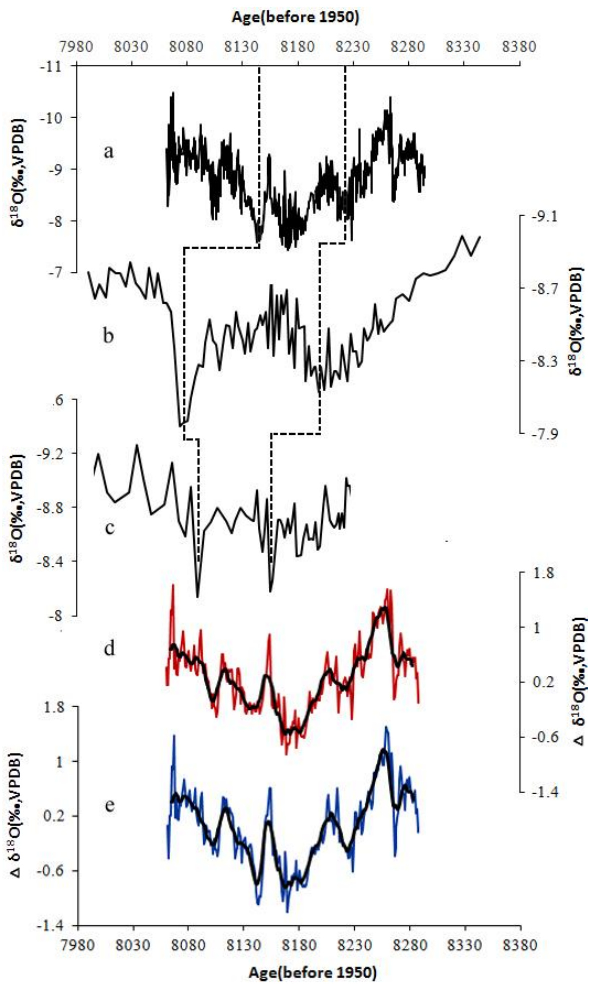

Figure 1. Original $\delta^{18}O$ stalagmite records adopted in this paper with difference $\delta^{18}O$ between stalagmites from Dongge and Heshang. a. HS4 record (Liu et al., 2013); b. DA record (Cheng et al., 2009); c. D4 record (Cheng et al., 2009); d. $\Delta\delta^{18}O$ between DA and HS4 (red) with 10-year moving average(black); e. $\Delta\ \delta^{18}O$ between D4 and HS4 (blue) with 10-year moving average (black). The dashed lines show typical corresponding peaks from each original record.

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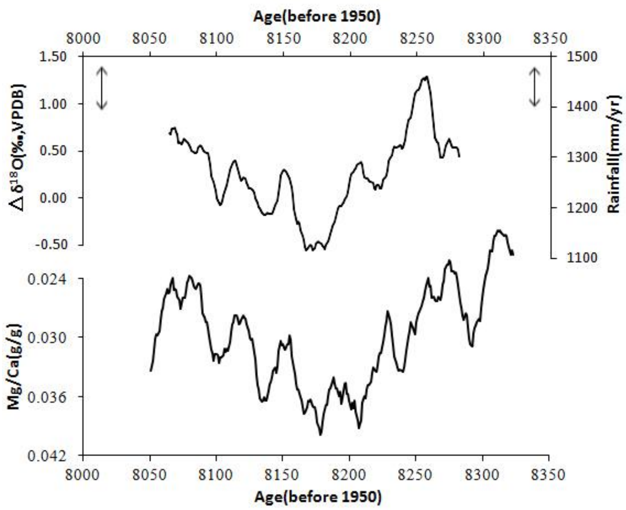

Figure 2. 10-yr moving average of $\Delta\delta^{18}$O between DA and HS4 with reconstructed 10-yr moving average of annual rainfall in southwest China (upper panel) and Mg/Ca ratios of HS4 (lower panel) during the 8.2 ka BP period. The arrows showing the average uncertainties of the $\Delta\delta^{18}$O and rainfall record respectively. The Mg/Ca ratios, another rainfall indictor, with a similar trend to the rainfall sequence increasing the confidence of the quantization of the reconstructed record.

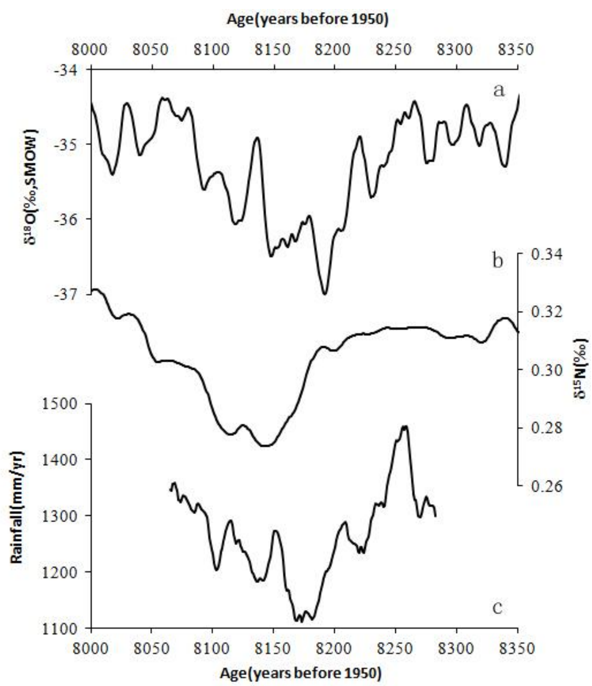

Figure 3. Records from Greenland ice core δ^{18}O (Thomas et al., 2007) (a), Greenland ice core

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$\delta^{15}N$ (Kobashi et al., 2007) (b) and the reconstructed annual rainfall from this study(c) during the 8.2 ka BP event. Three sequences showing a similar pattern indicate the decrease in rainfall in southwest China occurs in response to the Greenland cooling.

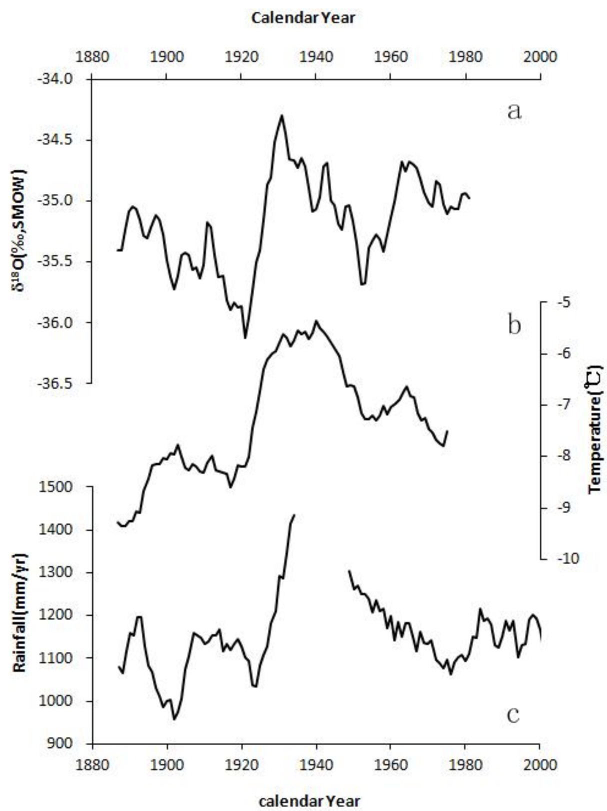

Figure 4. Modern 10-yr moving average $\delta^{18}O$ record of Greenland ice cores (a) (White et al., 1997) and Greenland annual temperature (b) (http://climexp.knmi.nl/selectstation.cgi?id= someone@somewhere) with Yichang yearly rainfall (c) (Hubei Province Meteorological Bureau). The Yichang rainfall data are missing from 1938 to 1950 because of the wars. Similar trends from the 3 sequences could be observed since 1887 and a peak appears in all these 3 records.