Clim. Past, 7, 685–692, 2011
www.clim-past.net/7/685/2011/
doi:10.5194/cp-7-685-2011

Climate of the Past

Climate patterns in north central China during the last 1800 yr and their possible driving force

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Received: 15 March 2011 – Published in Clim. Past Discuss.: 24 March 2011
Revised: 8 June 2011 – Accepted: 9 June 2011 – Published: 4 July 2011

Abstract. We synthesized high-resolution precisely-dated stalagmite records and historical document records from north central China to reconstruct a decadal resolution precipitation record during the last 1800 years (190–1980 AD). The synthesized precipitation record shows coincident variations and significant positive correlations with the temperature reconstructions on centennial- to multidecadal-scale, suggesting warm-humid/cool-dry was the main climate pattern in north central China over the past 1800 years. Solar activity may be the dominant force that drove the same-phase variations of the temperature and precipitation in north central China.

1 Introduction

The East Asian monsoon (EAM) is an integral part of the global climate system and plays a significant role in the climate variability of East Asia (An, 2000). The EAM exhibits not only significant tectonic-, orbital-, and millennial-scale variability (e.g., An, 2000; Wang et al., 2008; Cai et al., 2010), but also centennial- to decadal-scale variability (Wang, 2006). For example, modern meteorological studies suggested that the East Asian summer monsoon (EASM) had weakened after the 1970s (e.g., Chang et al., 2000; Wang, 2001). Centennial- to decadal-scale abnormal climate usually causes severe disasters and large loss of lives and property, so it has been an area of increasing interests.

North central China (Fig. 1) is strongly affected by the EAM (Gao et al., 1962; Xu et al., 2007). The monsoon precipitation in this region is positively correlated with the intensity of the EASM (e.g., Guo, 1983; Huang and Yan, 1999; Zhang et al., 2003). When the EASM is strong, the monsoon precipitation in this region increases. In contrast, when the EASM is weak, the monsoon precipitation decreases (Guo et al., 2003). This region is also one of the most important cradles of Chinese civilization, and various cultures flourished here during the Neolithic Age (Zhang, 2006 and references therein). Because of the important geographical location and cultural status, a lot of palaeoclimate studies were done here, including loess (e.g., An et al., 1991; Liu and Ding, 1998), lake sediment (e.g., Xiao et al., 2004; Peng et al., 2005), stalagmite (e.g., Tan et al., 2003; Zhang et al., 2008), tree ring (e.g., Hughes et al., 1994; Liu et al., 1996), and historical document (e.g., Yan et al., 1993; Tan et al., 2008). However, centennial- to decadal-scale climate variability in north central China during the last two millennia is far from being fully understood. For instance, it remains unclear what are the precipitation and temperature patterns in north central China, and what is the driving force behind them?

The analysis of rainfall datasets from all the meteorological stations in north central China showed a collective decreasing trend in precipitation during the last several decades (Qian and Lin, 2005). Recently, Tan et al. (2011) compared several high-resolution precipitation records from this area, and suggested synchronous precipitation changes in north central China on centennial to decadal scales during the last two millennia. Here, we synthesize high-resolution precisely-dated geologic and historical palaeoclimate records from north central China to reconstruct a decadal resolution precipitation record during the last two millennia. The precipitation and temperature patterns, as well as the mechanism of climate variability in north central China are discussed.

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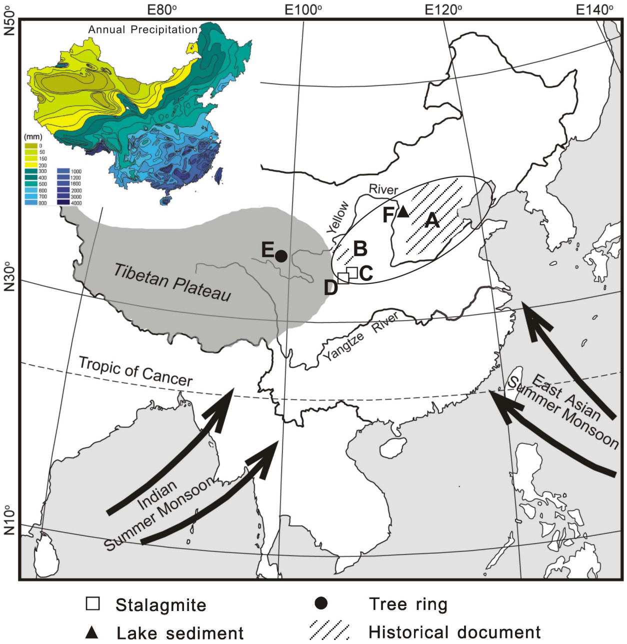

Fig. 1. Map showing the location of north central China and the palaeoclimate sites mentioned in this study. **(A)** Haihe River Basin (Yan et al., 1993), **(B)** Longxi (Tan et al., 2008, 2010), **(C)** Huangye cave (Tan et al., 2011), **(D)** Wanxiang cave (Zhang et al., 2008), **(E)** Dulan (Liu et al., 2009), **(F)** Gonghai Lake (Liu et al., 2011). The elliptic area generally indicates north central China. The small insert image in the top left corner shows the annual precipitation of China.

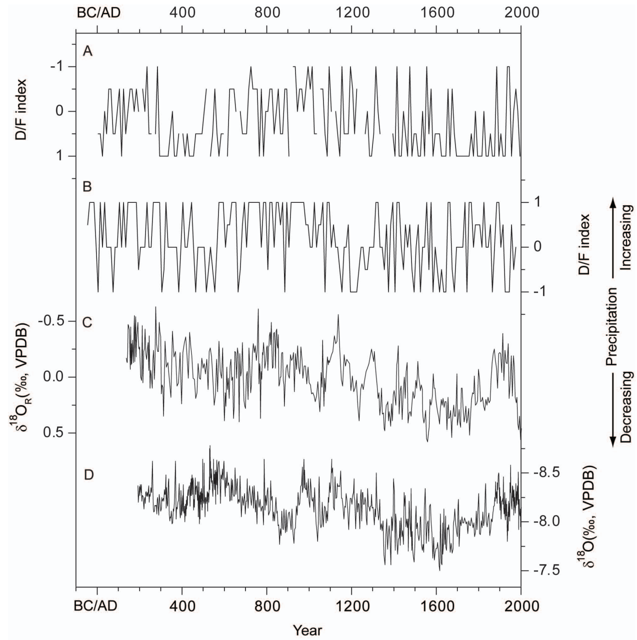

Fig. 2. The selected high-resolution precipitation records and the synthesized precipitation index for north central China during the last 1800 years. **(A)** Drought/Flood (D/F) index record of the Longxi area, with increased D/F index representing decreased precipitation (Tan et al., 2008, 2010). **(B)** D/F index record for the Haihe River Basin, with increased D/F index representing increased precipitation (Yan et al., 1993). **(C)** Stalagmite $\delta^{18}O$ record from Huangye cave, with lighter $\delta^{18}O$ represents more precipitation (Tan et al., 2011). **(D)** Stalagmite $\delta^{18}O$ record from Wanxiang cave, with lighter $\delta^{18}O$ represents more precipitation (Zhang et al., 2008).

2 Data and method

To synthesize a decadal resolution precipitation record for north central China over the past two millennia, the datasets have to meet these requirements: (1) the length of the dataset is longer than or near to 2000 years, (2) the resolution of the dataset is or less than a decade, and (3) the dataset should have an accurate chronology. Hence, four proxy records of precipitation were selected: (1) stalagmite $\delta^{18}O$ record with a resolution of 2–5 years from Wanxiang cave in Gansu province (WX record, 192–2003 AD; Zhang et al., 2008; Data are available from ftp://ftp.ncdc.noaa.gov/pub/data/paleo/speleothem/china/wanxiang2008.txt); (2) stalagmite $\delta^{18}O$ record with a resolution of 2–7 years from Huangye cave in Gansu province (HY record, 1380–2002 AD; Tan et al., 2011); (3) decadal resolution drought/flood (D/F) index record of Longxi inferred from historical documents (LX record, 1–2000 AD; Tan et al., 2008, 2010); and (4) decadal resolution D/F index record of the Haihe River Basin inferred from historical documents (HH record, 50 BC–1980 AD, Yan et al., 1993) (Fig. 2).

The stalagmite $\delta^{18}O$ from Wanxiang (Zhang et al., 2008) and Huangye cave (Tan et al., 2011) are negatively correlated with the local precipitation. The yearly D/F index is based mainly on time of occurrence, affected area, and degree of drought or flood conditions in spring, summer, or autumn (Zhang, 1983). It can reflect local precipitation changes too (e.g., Gong et al., 1983; Zhang, 1996; Tan et al., 2008 and references therein). An increased D/F index was defined to represent enhanced precipitation in the HH record (Yan et al., 1993), but was defined to represent decreased precipitation in the LX record (Tan et al., 2008, 2010). For coherence, we use the negative of the LX, WX, and HY records (LX_n, WX_n, HY_n), as well as the original HH record for further study.

Principal components analysis (PCA) was then applied to the standardized LX_n, WX_n, HY_n, and HH records in 10-year time-steps to synthesize a decadal resolution precipitation record for north central China. PCA aims to reduce the complexity of multivariate data into a few interpretable directions of variability (principal components) that represent synthetic variables that explain cumulative, but independent, proportions of variance within the raw data (ter Braak and Prentice, 1988). It is commonly used for characterizing and tracking the spatial and temporal variability of physical fields (Raick et al., 2006), such as regional and global climate changes (e.g., Jones et al., 1998; Mann et al., 1998,

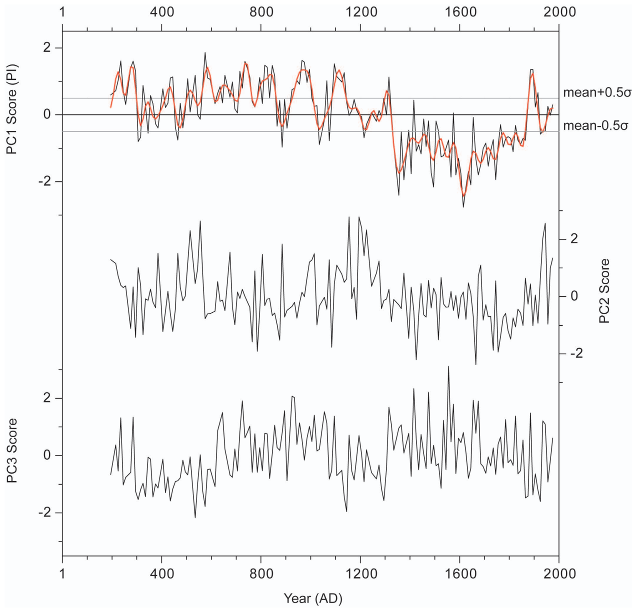

Fig. 3. Principal Component Analysis results. PC1 was defined as precipitation index (PI) to represent synthesized precipitation record for north central China. The red line is the record after 50-year low pass FFT filter.

1999; Kaplan and Wolfe, 2006; Meyers and Pagani, 2006). Here, PCA is computed with SPSS 15.0.

3 Results and discussion

Three principal components were extracted, and they explained 41.5 %, 25.0 %, and 19.7 % of the total variance, respectively (Fig. 3). The matrixes of the first principal component (PC1) are positive values (Table 1), indicating that the PC1 reflects the common variability in the four series. The other principal components are more likely to capture variance due to uncertainties of individual reconstructions and/or local climate change. Therefore, we assume the leading mode (PC1) of the four series represents regional climate change, and define it as synthesized precipitation index (PI) for north central China, with increased index representing increased precipitation.

Generally speaking, historical climate records have accurate dates (Gong et al., 1983), so we just test the influence of chronological uncertainties in the stalagmite records on the synthesized result. Taking into account the drilling thickness, the dating errors, and the uncertainty in the slope of the linear fit in the age model, the average age error of the WX record is about ±8 yr, and is about ±26 yr for the HY record. We run the PCA for different chronologies within ±8 yr error (from original age − 8 yr to original age + 8 yr) to the WX record, and for different chronologies within ±26 yr error (from original age − 26 yr to original age + 26 yr) to the

Table 1. Component matrix[a].

	Component		
	1	2	3
Huangye	0.775	−0.325	0.017
Wanxiang	0.729	−0.388	0.295
Longxi	0.398	0.782	0.476
Haihe	0.608	0.367	−0.688

Extraction Method: Principal Component Analysis. [a]3 components extracted.

HY record, respectively. The derived PC1 results show significant positive correlations ($R > 0.84$, $P < 0.001$) with the original one, indicating that the chronological uncertainties of the stalagmite series have no significant influences on the synthesized precipitation record.

3.1 Precipitation variations in north central China during the last 1800 years

The synthesized precipitation record (190–1980 AD) shows significant correlation ($R = 0.24$, $P < 0.05$, $N = 98$) with the coupled ECHO-G simulated millennial monsoon precipitation for north China (100–120° E, 36–50° N) (Liu et al., 2011). And it also shows broad similarities with a millennial precipitation record, which was reconstructed from environmental magnetism of the lacustrine sediments from Gonghai lake, Shanxi province, north central China (Liu et al., 2011) (Fig. 4). The comparisons indicate that the synthesized record can well reflect the precipitation variations in north central China.

The average value of the synthesized PI series is zero, and the standard deviation σ is one. We defined PI < mean − 0.5 σ and PI > mean + 0.5 σ as dry and wet climate, respectively. Hence, several notable wet intervals were identified in the periods 190–300, 560–860, 920–1010, 1090–1140, and 1880–1920. At the same time, the most remarkable dry epoch was inferred in the period 1330–1870. In addition, there are some decadal-scale droughts in decade 300–310 and decades around 340, 460, 880, 1030, 1070, 1210, and 1920. The driest period during the last 1800 years was found in the first half of the 17th century.

As north central China is a semi-humid/semi-arid area, long-lasting droughts with great intensity may cause severe disasters to the society. For example, the superdroughts (PI < mean − 2σ) that happened in the 1350 decade and the period 1610–1650 may have had severe effects on the collapse of the Yuan (1206–1368 AD) and Ming Dynasties (1368–1644 AD) (Zhang et al., 2008; Tan et al., 2011). Furthermore, droughts that occur against the background of wet climate may also have great impacts on the society, although their intensities may be much weaker than those that occur against the background of dry climate. For instance, the

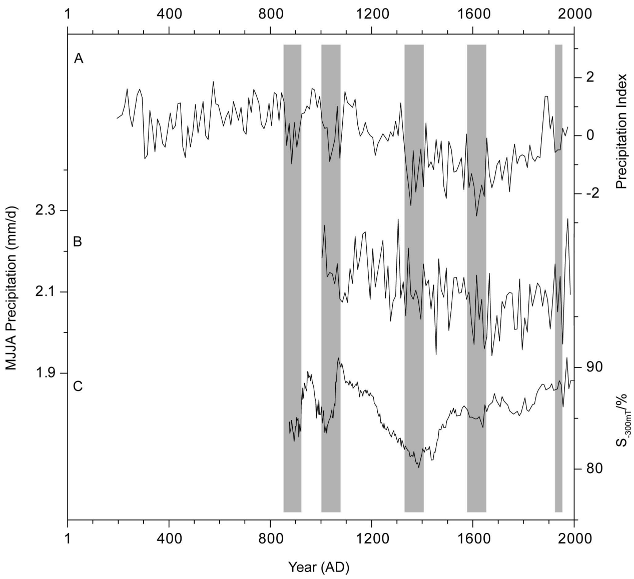

Fig. 4. Comparison of the synthesized precipitation record **(A)** with the coupled ECHO-G simulated precipitation record after 10-year averaged **(B)**– Liu et al., 2011 – and the precipitation record reconstructed from the lake sediment in Gonghai lake, Shanxi province, north central China **(C)**, Liu et al., 2011.

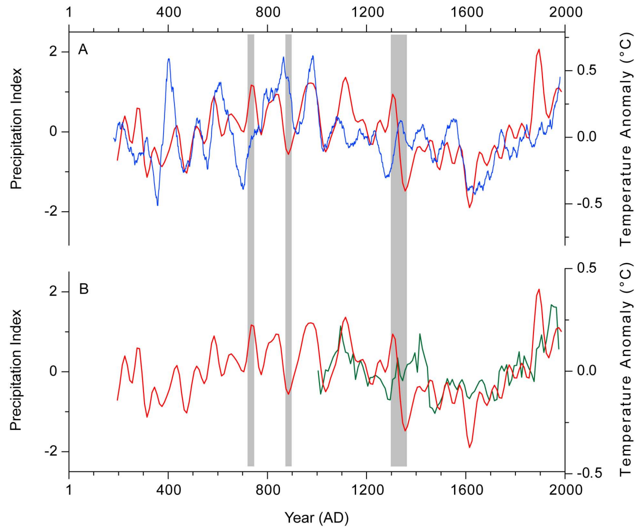

Fig. 5. Comparison of the precipitation and temperature variations in north central China during the last 1800 years. The blue line in panel **(A)** represents the temperature record reconstructed from tree ring in Dulan, eastern Tibetan Plateau after 40-year moving average (Liu et al., 2009). The green line in panel **(B)** represents the millennium temperature record by combining stalagmite layer series and tree ring sequence after 10-year averaged (Tan et al., 2009). The red lines in both panels represent the detrended precipitation record after 50-year low pass FFT filter. The gray vertical bars depict periods characterized by discrepancies between the precipitation record and temperature reconstructions, as discussed in the text.

drought happened in the 1920 decade is one of the biggest disasters in modern China. A variety of historical documents recorded the catastrophic effect of the drought on the socioeconomic conditions in north China (Liang et al., 2006 and references therein), yet the intensity of this drought was much weaker than most of the droughts in the period 1330–1860. Similarly, the droughts that happened in the 300–310 and the 880 decades caused great losses to the society in north central China, and may make drought an important factor for the collapse of the West Jin (265–310 AD) and Tang (618–907 AD) Dynasties, respective (Tan et al., 2011).

3.2 Precipitation and temperature patterns in north central China in the last 1800 years

Understanding the precipitation and temperature patterns in a natural state in the last two millennia is not only crucial to predict future precipitation changes against the background of global warming, but also important to distinguish the impact of human activities and natural factors on recent climate changes. Tan et al. (2009) combined stalagmite layer series (Tan et al., 2003) and tree ring sequence (Liu et al., 2007) to reconstruct a millennium temperature record (BQ record) for north China. The reconstruction correlates well with the ECHO-G simulated millennial temperature for China (Tan et al., 2009). In addition, Liu et al. (2009) reconstructed a 2485-year temperature record based on tree ring width from Dulan, northeastern Tibetan Plateau (DL record). When they compared the Dulan (DL) tree ring series with the observed temperature records in thirteen stations over north central China during 1958–2000 AD, they found significant positive correlations. As temperature may show consistent variability over a large region, they suggested the DL record can also represent temperature changes in north central China (Liu et al., 2009). Broad similarities between the DL record and BQ record during the last 1000 years further support this explanation (Fig. 5).

Here we compare our synthesized precipitation record with the BQ and DL temperature records. Because the tree ring series have been detrended (Liu et al., 2009), we remove the linear trend in our precipitation record using a linear regression model for a better comparison. As shown in Fig. 5, the three records show coincident variations on centennial- to multidecadal-scale. Both the detrended precipitation record and the DL temperature record follow a "W" pattern during the last 1800 years. In the most recent millennium, the precipitation generally declines from the "Medieval Warm Period" to the "Little Ice Age". It decreases to a minimum at the coldest time in the 17th century (Liu et al., 2009), and then increases, accompanied by warming. The comparison suggests warm-humid/cool-dry climate pattern in north central China during the last 1800 years (190–1980 AD) on centennial-scale. Significant correlations are also observed among the three records. The correlation between the precipitation record and the BQ record in the last millennium (1000–1980 AD) is 0.41 ($P < 0.001$, $N = 98$), and is 0.31 ($P < 0.001$, $N = 179$) between the precipitation record and the DL record (11-year moving average) in the last 1800 years.

On multidecadal-scale, it seems warm-humid/cool-dry was also the main climate pattern in north central China most of the time during the last 1800 years. For example, the extreme wet period in the later half of the 10th century corresponds to an abnormal warm period in DL record, and another extreme wet period in the early 12th century also corresponds to a warm period in DL and BQ record. In contrast, two remarkable droughts in the early 11th century and the early 17th century correspond to cold periods in both BQ and DL record. Nevertheless, some differences between precipitation and temperature variations are also observed, such as in ~730 AD, ~890 AD and ~1350 AD (Fig. 5). These may be ascribed to two factors. On one hand, the discrepancies may be caused by the uncertainties of the precipitation and temperature reconstructions. As shown in Fig. 5, there are also some differences between the two temperature records (BQ and DL) besides their broad similarities. On the other hand, they may suggest warm-dry and cool-wet climate patterns also existed in north central China during historical times. Modern meteorological observations show a warm-dry trend in north central China after the 1970s (Ma and Fu, 2006). If the warm-dry pattern never existed during historical times, the anomaly may indicate that human activities have affected the climate changes in the late 20th century. More high-resolution, absolute-dated precipitation and temperature reconstructions from this region may help to resolve this question.

3.3 Possible driving forces of the climate changes in north central China

Precipitation variability in north central China is controlled by the EASM (Gao et al., 1962; Xu et al., 2007), and the EASM has a close relationship with the thermal contrast between the Asia and the North Pacific (Zhao et al., 2007; Zhou et al., 2009). Zhao et al. (2007) defined the arithmetic difference between the Asian and Pacific T' as an index of the Asian Pacific Oscillation (I_{APO}), that is:

$$I_{\mathrm{APO}} = T'_{60°-120°\mathrm{E},\ 15°-50°\mathrm{N}} - T'_{180°-120°\mathrm{W},\ 15°-50°\mathrm{N}},$$

in which T' is the vertically averaged (500 to 200 mb) eddy temperature. Recently, Zhou et al. (2009) reconstructed a millennium I_{APO} series by using proxy temperature records of the Asia and the Pacific. We compare our synthesized precipitation record with the reconstructed I_{APO} record, and find a significant positive correlation during the last millennium ($R = 0.40$, $P < 0.001$, $N = 99$). On centennial- to decadal-scale, there is good correspondence between the peaks of the two series (Fig. 6). High precipitation in north central China corresponds to high value of the I_{APO}, and vice versa. This result is consistent with the modern meteorological observation (Zhao et al., 2007). The fact suggests that the precipitation variability in north central China on centennial- to decadal-scale is controlled by natural factor – the thermal contrast between the Asia and the North Pacific.

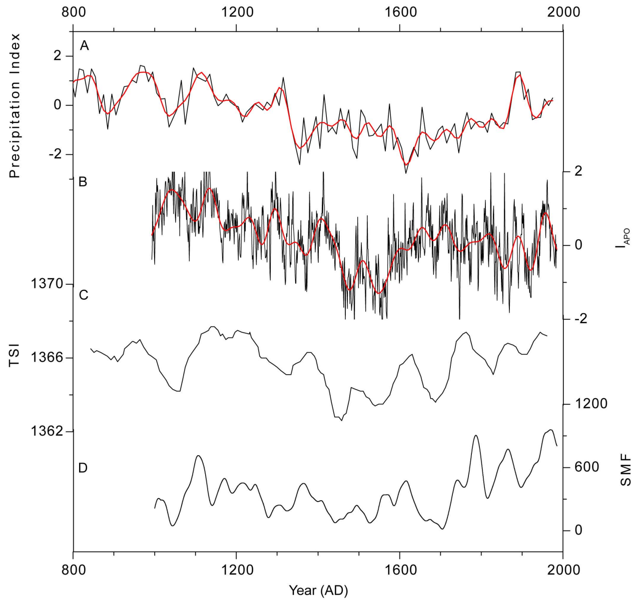

Fig. 6. Comparison of the precipitation variations in north central China, the Asian Pacific Oscillation, and the solar activity. Panel **(A)** is the synthesized precipitation index record. Panel **(B)** is the Asian Pacific Oscillation index record (Zhou et al., 2009). Panel **(C)** is the reconstructed total solar irradiance (TSI) record (Bard et al., 2000). Panel **(D)** is the reconstructed solar modulation function (SMF) record (Muscheler et al., 2007). The red lines in panels **(A)** and **(B)** are records after 50-year low pass FFT filter.

The Sun is the energy source of the Earth, and numerous studies show that solar activity is the main force driving regional climate changes in the Holocene (e.g., Perry and Hsu, 2000; Bond et al., 2001; Hodell et al., 2001; Fleitmann et al., 2003; Wang et al., 2005; Haltia-Hovi et al., 2007; Xu et al., 2008). Tan et al. (2009) also found a close relationship between the temperature variations in north China and the solar activities in the last millennium. When we compare our synthesized precipitation record and the I_{APO} record (Zhou et al., 2009) with the solar activity records (Bard et al., 2000; Muscheler et al., 2007), strong similarities are observed. During the last millennium, every fluctuation in the solar activity records expressed well in the I_{APO} and the precipitation series (Fig. 6), with strengthened (weakened) solar activity corresponding to increased (decreased) I_{APO} and precipitation in north central China. But the variations of the I_{APO} and the precipitation lag those of the solar activity. When the I_{APO} and the precipitation lag for 20–30 years, the significant correlations are the highest, up to ~0.35 and ~0.40, respectively. Further spectrum analysis suggests that the precipitation variations have significant ~160-year

(142–178-year) and ∼35-year periodicities. The ∼160-year periodicity corresponds to the periodicity of the total solar irradiance (Scafetta and West, 2006), and is similar to the ∼148 yr periodicity found in the spectral results of atmospheric ^{14}C residual data (Stuiver and Braziunas, 1993). The ∼35-year periodicity corresponds to the Brückner periodicity of the solar activity (Raspopov et al., 2000). The discrepancies such as the fluctuation amplitude between the precipitation record and the solar activity records may be ascribed to two factors. For one thing, they may be caused by the uncertainties of the reconstructions. For the other, the discrepancies indicate that another air-sea coupled system such as El Niño-Southern Oscillation (ENSO) may affect the precipitation variability in north central China, superimposing on the solar dominant control.

The mechanism of the climate variability in north central China on centennial- to decadal-scale is probably as follows: The strengthening of the solar activity can be remarkably amplified by the changes of ultraviolet radiation and clouds (Shindell et al., 1999; van Geel et al., 1999; Tinsley, 2000), leading to a noteworthy variation in surface temperature. Because of the differences of heat capacity between land and ocean, the thermal contrast between the Asia and the North Pacific increases. As a result, the lower-troposphere low-pressure system over eastern Asia strengthens, and the western Pacific subtropical high strengthens with its location shifting northwards (Zhao et al., 2007; Zhou et al., 2009). In consequence, the EASM strengthens (Cheng et al., 1991), with its rain belt moving northwards and staying longer in the north, bringing more rainfall to north central China. In contrast, when the solar activity is weak, the temperature will decrease and the EASM will weaken. The weakened EASM will cause the rain belt reaching more southward than normal and retreating rapidly, resulting in a decrease of rainfall in north central China.

4 Conclusions

We synthesized high-resolution absolute-dated stalagmite records and historical document records from north central China to reconstruct a decadal resolution precipitation record during the last 1800 years (190–1980 AD). The synthesized record is in agreement with the simulated precipitation record and another precipitation record reconstructed from lacustrine sediments in north central China, indicating that it can well reflect the precipitation variations in this region.

The synthesized precipitation shows coincident variations and significant positive correlation with the temperature variations on centennial- to multidecadal-scale, suggesting warm-humid/cool-dry was the main climate pattern in north central China over the past 1800 years. Comparison shows that the precipitation in north central China during the last millennium was controlled by the thermal contrast between the Asia and the North Pacific, which is consistent with the modern meteorological observation result. Solar activity may be the dominant force that drives the same-phase variations of the temperature and precipitation in north central China.

Acknowledgements. We thank Y. Liu and M. Tan for providing the reconstructed temperature data. We also wish to thank J. Liu for providing the coupled ECHO-G simulated precipitation data for north China. We would like to thank A. Mangini and the other two anonymous referees for their constructive comments. Thanks are also given to Z. Lai and J. Chen for their suggestive discussions. This work was supported by the National Science Foundation of China (grant 41001061); National Basic Research Program of China (grant 2010CB833405); CAS Strategic Priority Research Program (grant XDA05080502); CAS West Doctoral Foundation.

Edited by: J. Guiot

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