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Climate of the Past Discussions

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

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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We synthesized high-resolution precisely-dated stalagmite records and historical document records from north central China to reconstruct a decadal resolution precipitation record during the last 1800 yr (190–1980 AD). Several notable wet intervals were identified: 190s–290s, 560s–850s, 920s–1000s, 1090s–1130s, 1880s–1910s. The most remarkable dry epoch was inferred in 1330s–1860s, and the driest period was in the first half of the 17th century. Other decade droughts were found in the 300s–310s, 340s, 460s, 880s, 1030s, 1070s, 1210s and 1920s. The precipitation variability shows significant positive correlation with the temperature variability, suggesting a warm-humid or cool-dry pattern in north central China over the past 1800 yr. The abnormal warm-dry climate observed in the late 20th century in this region may suggest that the dominant forcing of climate variability changed from natural to anthropogenic. Solar activity may be the dominant natural force that drove the same-phase variations of the temperature and precipitation in north central China on centennial- to decadal-scale.

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 the East Asia (An, 2000). The EAM exhibits not only significant tectonic-, orbital- and millennial-scale variability (e.g., An, 2000; Wang et al., 2008), 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 interesting.

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 culturalstatus, 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 full 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 also discussed.

2 Data and method

To synthesize a decadal resolution precipitation record for north central China over the past two millennia, the datasets were required as: (1) the length of the dataset is

CPD
7, 1029–1048, 2011

longer than or near to 2000 yr, (2) the resolution of the dataset is or less than a decade, (3) the dataset should have an accurate chronology. Hence, four proxy records of precipitation were selected: (1) Stalagmite δ^{18}O record with a resolution of 2–5 yr from Wanxiang cave in Gansu province (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 δ^{18}O record with a resolution of 2–7 yr from Huangye cave in Gansu province (138–2002 AD, Tan et al., 2011). (3) Decadal resolution drought/flood (D/F) index record of Longxi inferred from historical documents (1–2000 AD, Tan et al., 2008; 2010). (4) Decadal resolution D/F index record of the Haihe River Basin inferred from historical documents (50 BC–1980 AD, Yan et al., 1993) (Fig. 2).

An increased D/F index was defined to represent enhanced precipitation in the Haihe River Basin (Yan et al., 1993), but was defined to represent decreased precipitation in the Longxi area (Tan et al., 2008, 2010). In addition, the stalagmite δ^{18}O from Wanxiang (Zhang et al., 2008) and Huangye cave (Tan et al., 2011) are negatively correlated with the local precipitation. So, we do Principal Component Analysis to the negative of the Longxi, Wanxiang and Huangye datasets, as well as the original Haihe dataset.

3 Results and discussion

Three components were extracted, and they explained 41.5%, 25.0% and 19.7% of the total variance, respectively. The matrixes of the first component are positive values (Table 1), indicating that the first component reflects the common variability in the four series. Therefore, we defined it as precipitation index (PI) to represent synthesized precipitation record for north central China, with increased index represent increased precipitation.

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

Figure 2e shows the synthesized precipitation record of north central China during the last 1800 yr (190–1980 AD). The precipitation record 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. 3). The comparisons indicate that the synthesized record can reflect the precipitation variations in north central China very well.

The average value of the synthesized PI series is zero, and the standard deviation σ is one. We defined PI < mean-0.5σ and PI > mean+0.5σ as dry and wet climate, respectively. Hence, several notable wet intervals were identified: 190s–290s, 560s–850s, 920s–1000s, 1090s–1130s, 1880s–1910s. At the same time, the most remarkable dry epoch was inferred in the 1330s–1860s. In addition, there are some decadal-scale droughts in the 300s–310s, 340s, 460s, 880s, 1030s, 1070s, 1210s and 1920s. The driest period during the last 1800 yr was found in the first half of the 17th century.

As north central China is a semi-humid/semi-arid area, long-lasting drought with great intensity may cause severe disasters to the society. For example, the super-droughts (PI < mean-2σ) happened in the 1350s and the 1610s–1640s may have had important effects on the collapse of the Yuan (1206–1368 AD) and Ming Dynasty (1368–1644 AD) (Zhang et al., 2008; Tan et al., 2011). Furthermore, droughts occurred against the background of wet climate may also have great impacts on the society, although their intensities may be much weaker than that occurred against the background of dry climate. For instance, the drought happened in the 1920s 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

CPD
7, 1029–1048, 2011

the droughts in the 1330s–1860s. Similarly, the droughts happened in the 300s–310s and the 880s also had caused a great loss to the society in north central China, and may be an important factor for the collapse of the West Jin (265–310 AD) and Tang (618–907 AD) Dynasty (Tan et al., 2011).

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

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 very well with the ECHO-G simulated millennial temperature for China (Tan et al., 2009). In addition, Liu et al. (2009) reconstructed a 2485-yr temperature record based on tree ring width from Dulan, northeastern Tibetan Plateau (DL record). The ring-width-based reconstruction is also significantly correlated with the observed temperature (1958–2000 AD) in north central China. Therefore, it can be a temperature record for this region (Liu et al., 2009).

We compared our synthesized precipitation record with the BQ and DL temperature records (Fig. 4). Despite some differences in fluctuation amplitude, the three records show coincident variations on centennial- to decadal-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-yr moving average) in the last 1800 yr. That means the climate pattern was warm-humid or cool-dry in north central China during the last 1800 yr (190–1980 AD). For example, the extreme wet period in the later half of the 10th century corresponded to an abnormal warm period in DL record, and another extreme wet period in the early

CPD
7, 1029–1048, 2011

12th century also corresponded to a warm period in DL and BQ record. In contrast, two remarkable droughts in the late 14th century and the early 17th century corresponded to cold periods in both BQ and DL record. However, the pattern was broken in the late 20th century. Modern meteorological observations show that the precipitation has decreased in north central China after the 1970s, but the temperature has increased (Ma and Fu, 2006). This warm-dry pattern in the late 20th century is distinctly anomalous as compared to earlier times, which was characterized by warm-humid or cool-dry pattern. The anomaly may suggest that the dominant forcing of climate variability in north central China changed from natural to anthropogenic in the late 20th century (Zhang et al., 2008).

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 Asian 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 $I_{\mathrm{APO}} = T'_{60^\circ-120^\circ\,\mathrm{E},15^\circ-50^\circ\,\mathrm{N}} - T'_{180^\circ-120^\circ\,\mathrm{W},15^\circ-50^\circ\,\mathrm{N}}$, 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 Asian and the Pacific. We compared our synthesized precipitation record with the reconstructed I_{APO} record, and found a significant correlation during the last millennium ($R = 0.40$, $P < 0.001$, $N = 99$). On multidecadal- to centennial- scale, there is a one-to-one correspondence between the peaks of the two series (Fig. 5). High precipitation in north central China corresponded to high value of the I_{APO}, and *vice versa*. This result is consistent with the modern meteorological observed result (Zhao et al., 2007). The fact suggests that the precipitation variability in north central China on centennial- to decadal-scale has been controlled by natural factor-the thermal contrast between the Asian and the North Pacific. However, the abnormal warm-dry climate in the late 20th century suggests that human activities such as greenhouse gas emission, aerosols discharge may have affected the temperature changes in the late 20th century, although it's hard to evaluate the degree of influence.

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 compared 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 were observed. During the last millennium, every fluctuations in the solar activity records expressed well in the I_{APO} and the precipitation series (Fig. 5), 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 lagged those of the solar activity. When the I_{APO} and the precipitation lagged for 20–30 yr, the significant correlations are the highest, up to ~0.35 and ~0.40, respectively. Further spectrum analysis suggested that the precipitation variations have significant ~160-yr and ~35-yr periodicities, which correspond to the periodicity of the total solar irradiance (Scafetta and West, 2006) and the Brckner 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 other air-sea coupled system such as El Niño-Southern Oscillation (ENSO) may affect the precipitation variability in north central China, superimposing on the solar's 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), and lead to a noteworthy variation in surface temperature. Because of the differences of heat capacity between land and ocean, the thermal contrast between the Asian 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 moves northwards and stays 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 yr (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. During the last 1800 yr, several notable wet intervals were identified: 190s–290s, 560s–850s, 920s–1000s, 1090s–1130s, 1880s–1910s. The most remarkable dry epoch was inferred in the 1330s–1860s. Other decade droughts were found in the 300s–310s, 340s, 460s, 880s, 1030s, 1070s, 1210s and 1920s. The driest period was observed in the first half of the 17th century.

The precipitation variability shows significant positive correlation with the temperature variability, suggesting a warm-humid or cool-dry pattern in north central China during the last 1800 yr. However, this pattern was broken by the warm-dry climate in the late 20th century. Comparison shows that the precipitation in north central China during the last millennium was controlled by the thermal contrast between the Asian and the North Pacific, which is consistent with the modern meteorological observation result. The abnormal warm-dry climate in the late 20th century suggests that human

CPD
7, 1029–1048, 2011

activities may have affected the temperature changes in the late 20th century, although it's hard to evaluate the degree of influence. Solar activity may be the dominant natural force that drives the same-phase variations of the temperature and precipitation in north central China on centennial- to decadal-scale.

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CPD
7, 1029–1048, 2011

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.

CPD
7, 1029–1048, 2011

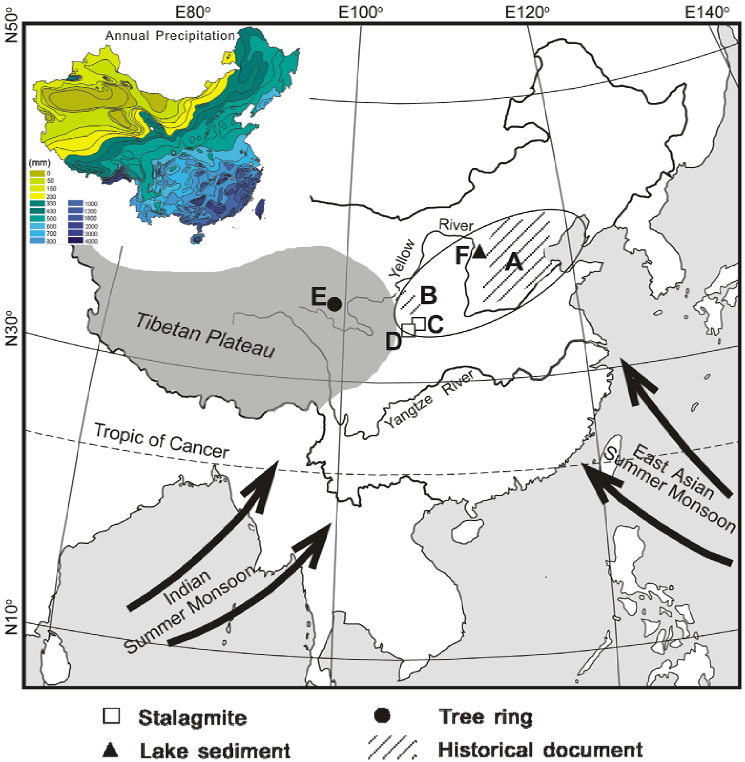

Fig. 1. Map showing the location of north central China and the palaeoclimate sites mentioned in this study. **(A)** Haihe River Basin (Yan et al., 1993), **(B)** Longxi (Tan et al., 2008; 2010), **(C)** Huangye cave (Tan et al., 2011), **(D)** Wanxiang cave (Zhang et al., 2008), **(E)** Dulan (Liu et 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.

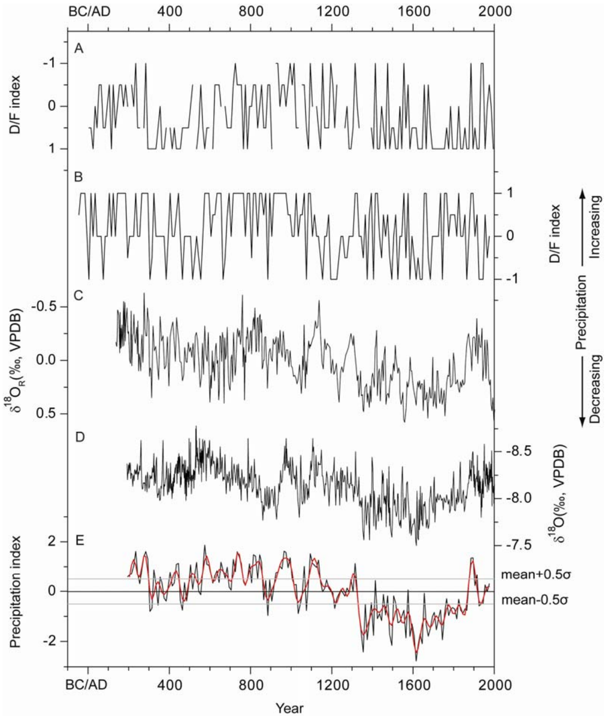

Fig. 2. The selected high-resolution precipitation records and the synthesized precipitation index for north central China during the last 1800 yr. **(A)** Drought/Flood (D/F) index record of the Longxi area, with increased D/F index representing decreased precipitation (Tan et al., 2008, 2010). **(B)** D/F index record for the Haihe River Basin, with increased D/F index representing increased precipitation (Yan et al., 1993). **(C)** Stalagmite δ^{18}O record from Huangye cave, with lighter δ^{18}O represents more precipitation (Tan et al., 2011). **(D)** Stalagmite δ^{18}O record from Wanxiang cave, with lighter δ^{18}O represents more precipitation (Zhang et al., 2008). **(E)** The synthesized precipitation index record for north central China. The red line is the record after 50-yr low pass FFT filter.

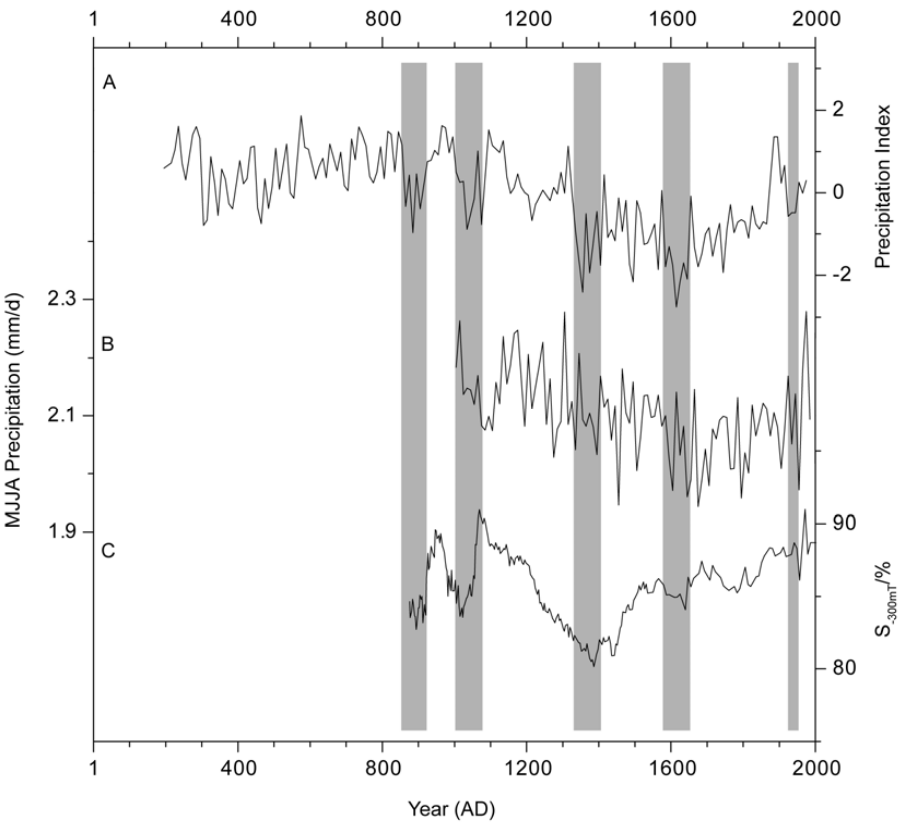

Fig. 3. Comparison of the synthesized precipitation record **(A)** with the coupled ECHO-G simulated precipitation record after 10-yr averaged (**(B)**, Liu et al., 2011) and the precipitation record reconstructed from the lake sediment in Gonghai lake, Shanxi province, north central China (**(C)**, Liu et al., 2011).

CPD
7, 1029–1048, 2011

Climate patterns in north central China

L. Tan et al.

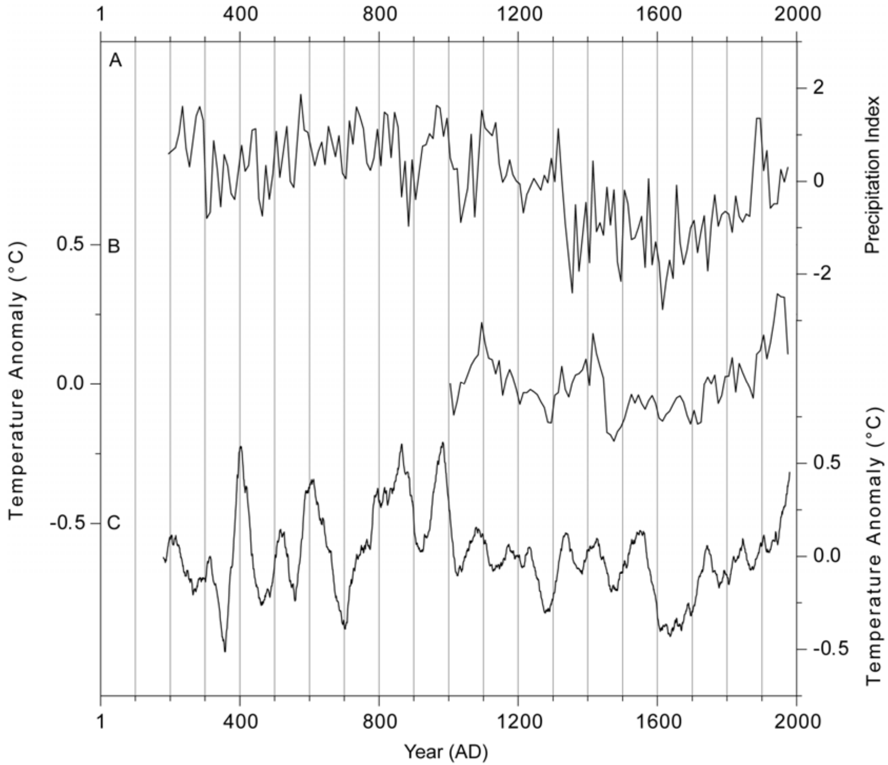

Fig. 4. Comparison of the precipitation and temperature variations in north central China during the last 1800 yr. **(A)** is the synthesized precipitation record. **(B)** is the millennium temperature record by combining stalagmite layer series and tree ring sequence after 10-yr averaged (Tan et al., 2009). **(C)** is the temperature record reconstructed from tree ring in Dulan, eastern Tibetan Plateau after 40-yr moving average (Liu et al., 2009).

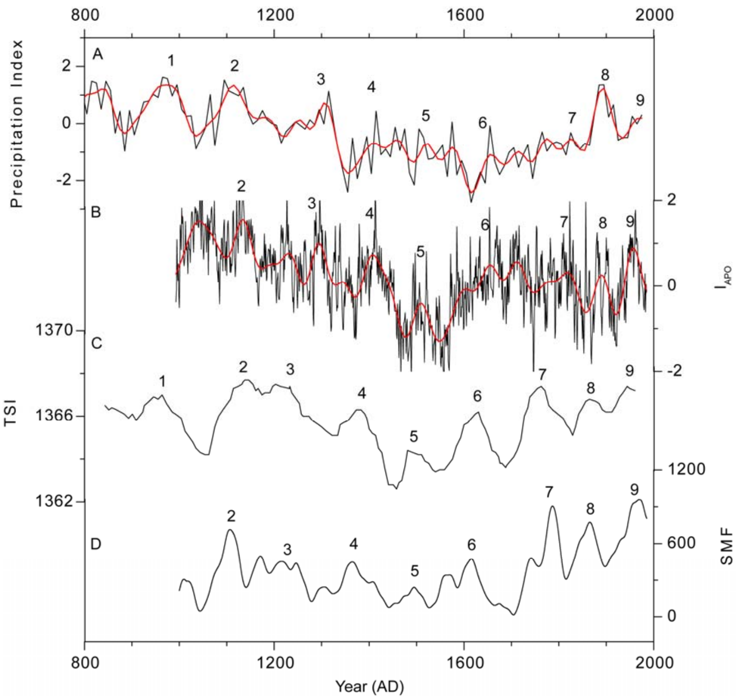

Fig. 5. Comparison of the precipitation variations in north central China, the Aian Pacific Oscillation and the solar activity. **(A)** is the synthesized precipitation index record. **(B)** is the Asian Pacific Oscillation index record (Zhou et al., 2009). **(C)** is the reconstructed total solar irradiance (TSI) record (Bard et al., 2000). **(D)** is the reconstructed solar modulation function (SMF) record (Muscheler et al., 2007). The red lines in **(A)** and **(B)** are records after 50-yr low pass FFT filter.