General characteristics of temperature variation in China during the last two millennia

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[1] Three alternate China-wide temperature composites covering the last 2000 years were established by combining multiple paleoclimate proxy records obtained from ice cores, tree rings, lake sediments and historical documents. Five periods of temperature variation can be identified: a warm stage in AD 0–240, a cold interval between AD 240 and 800, a return to warm conditions from AD 800–1400, including the Medieval Warm Period between AD 800–1100, the cool Little Ice Age period between 1400–1920, and the present warm stage since 1920. Regional temperature variation is found during AD 800–1100, when warm conditions occurred in Eastern China and in the northeastern Tibetan Plateau and in AD 1150–1380, when the southern Tibetan Plateau experienced a warm interval. In contrast, evidence for cool conditions during the LIA is more consistent among the proxy records. The temperature reconstructions for China and the Northern Hemisphere show good agreement over the past millennium. *INDEX TERMS:* 3344 Meteorology and Atmospheric Dynamics: Paleoclimatology; 9320 Information Related to Geographic Region: Asia

1. Introduction

[2] Evidence of regional paleoclimatic reconstructions have shown that the timing and intensity of the two pronounced climatic fluctuations of the "Medieval Warm Period" (MWP) and the "Little Ice Age" (LIA) differed geographically [*Frenzel*, 1975; *Solomina*, 1999; *Hughes and Diaz*, 1994; *Jones and Bradley*, 1992]. Several reconstructions of temperature variation in the Northern Hemisphere (NH) published recently in the past three years suggest that the NH warmth during the Middle Ages was less than or at most comparable to the mid-20th-century warm period and that average temperature was higher than during the LIA of the last 600 years [*Mann et al.*, 1999, *Crowley and Lowery*, 2000, *Jones et al.*, 1998, *Briffa*, 2000]. However, what are the so-called MWP and LIA in China? Although several climate reconstructions extending from 1000 to 2000 years have been developed in parts of China (Figure 1), little has been accomplished so far in terms of comprehensive analysis of all sorts of proxy data. In this study, we have derived three composite temperature series composed of up to 9 individual temperature reconstructions from different proxy records to gain a better understanding of the overall and regional features of temperature changes in China during the last two millennia.

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2. Data and Method

[3] Locations of the proxy records used in this paper are shown in Figure 1. Four of the series are related to the Tibetan Plateau (TP) (Guliya ice core, Dunde ice core, Dulan tree-ring record in the northeastern TP and a composite tree-ring record from the southern TP) and 5 series were obtained from Eastern China and Japan. A close correlation between the annual averages of ice core $\delta^{18}O$ and mean annual air temperatures from the nearby Mangnai meteorological station indicates that $\delta^{18}O$ in the Guliya ice core [*Shi et al.*, 1999] is a reasonable proxy for the near surface air temperature [*Lin et al.*, 1995]. The $\delta^{18}O$ values also correlate (r = 0.2 to 0.4) with annual temperature observations from the Xinjiang region in China for the period from 1951 to 1996 [*Wang et al.*, 1998]. Likewise, ice-core $\delta^{18}O$ records of Dunde are regarded to represent temperature changes in northwestern China (mainly in the Inner Mongolia region), since they correlate closely (r = 0.2 to 0.37) to the temperature observations of that region for the period from 1951 to 1996 [*Lin et al.*, 1995; *Wang et al.*, 1998]. We used the $\delta^{18}O$ values measured from core 3 because their sample number (7045) more than doubles the sample number (3280) in core 1 [*Thompson et al.*, 1993]. In the northern Tibetan plateau, tree-ring indices from Dulan are significantly correlated ($r = 0.69$, $p < 0.01$) to autumn temperatures [*Yang et al.*, 2000]. Averaging 12 temperature-sensitive tree-ring series from various parts of Tibet ($r = 0.52$ to 0.79, $p < 0.01$), *Wu and Lin* [1981] established a reconstruction of yearly average temperatures anomalies. However, there is a data gap from the 7th to 11th century in this series (Figure 2). The reconstruction of winter temperature from Eastern China are based on 5 proxy observations of changes in distribution of temperature sensitive biota and other climate indices, such as dates of flowering of shrubs, freezing of rivers, or displacements of the boundary of the farming zone [*Zhang*, 1996]. This record represents a noticeable improvement over the temperature reconstructions of *Zhu* [1973] and *Wang and Wang* [1989]. The original historical data of the reconstruction cover most of Eastern China, including North China and Jianghuai region to the east of Lanzhou and Chengdu City. By analyzing tree-ring data from Japan, *Kitagawa and Matsumoto* [1995] suggest that the variation of $\delta^{13}C$ in wood cellulose mainly reflects changes of temperature. In Jinchuan in North Eastern China, variations of $\delta^{18}O$ in peat cellulose can be considered as a proxy of temperature change, since the peat plants are predominantly fed by meteoric water and $\delta^{18}O$ values in precipitation are closely associated with the mean annual temperature [*Hong et al.*, 2000]. The total organic carbon content (TOC) and the C/N ratio records from Great Ghost Lake and Jiaming Lake in Taiwan are reliable paleotemperature proxies, in that during the warm/wet period the lake sediments contain a higher TOC and C/N ratios and vice versa [*Lou and Chen*, 1997;

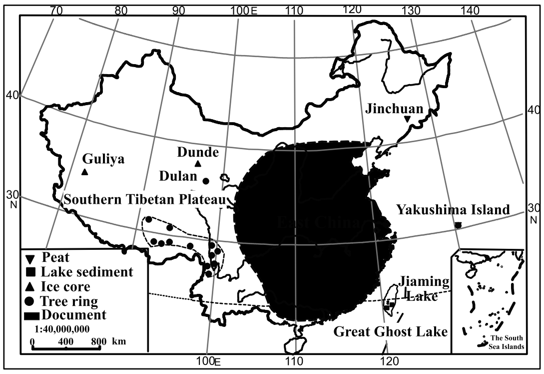

Figure 1. Sketch map showing locations of 9 proxy climate records. The circle around groups of tree-ring sites indicates that data from these sites were merged to calculate regional temperature averages of the southern Tibetan Plateau.

Lou et al., 1997]. The peat and lake chronologies used in this paper were based on AMS (accelerator mass spectrometry) radiocarbon dating in combination with sedimentation rates derived from sampling distances ranging from 0.5 cm to 2 cm. Timescales of the Guliya and Dunde ice cores were established by counting visible dust layers and extrapolating the age of deeper ice layers by a flow-model approach. The dates of glacier advances were determined by means of conventional ^{14}C dating. In this article, all of the ^{14}C dates are converted to calendar years. Although a quantitative relationship between the proxy records of the Jinchuan peat, the Japan tree-ring series and the Taiwanese sediment records with modern climate data are not given in the original works, the qualitative connectivity with temperature as the dominant controlling factor has undoubtedly been verified.

[4] The records chosen are not homogeneous in terms of the type of natural archive, time resolution and their correlation with temperature. Three of the records (Great Ghost Lake, Jiaming Lake and Jinchuan) have bidecadal-scale resolution and one (Dunde) have a sampling resolution of 50 years. In a sense, these heterogeneities and the use of multiple records can be considered favorably as a sensitivity test to the robustness of the paleotemperature reconstruction. In this study, we have used a uniform decadal time resolution for the proxy data. In the case of proxy records with a coarser resolution (Great Ghost Lake, Jiaming Lake and Jinchuan and Dunde), decadal resolution was obtained by linear interpolation between existing data points.

[5] There are two ways to reconstruct regional paleo-temperature series under the constraint of lacking sufficient data. One way is to compute the average of all available proxy series in a study area. According to *Jones et al.* [1999] and *Crowley and Lowery* [2000], the general characteristics of large-scale climatic change can also be reproduced by analyzing a relatively small and heterogeneous data set. Taking this into account, we reconstructed historical temperature change in China on the basis of the 9 proxy records mentioned above. Another approach to reconstructing regional temperature series is based on merging proxy records of several subregions by a specific area weight [*Wang and Gong*, 2000]. Before averaging, each series has been standardized to homogenize the original variability of all series. The standardized records do not provide numerical values of temperature variation but indicate the relative amplitude of temperature change as shown in Figure 2.

[6] In this study, we established three different composite temperature records for China (Figure 3). The first, called "H-res", was derived by averaging only the high-resolution proxy records. Considering the relatively large age uncertainties of the lake-sediment and peat records (±50 years), these records were not included in this composite. The second composite, named "Complete", was derived directly by averaging all 9 proxy records shown in Figure 1. The "Weighted" composite reconstruction was formed by combining area weighted regional proxy records. *Wang and Gong* [2000] used this method to establish an annual mean temperature series of China for the period 1880 to 1998. They divided the Chinese territory into ten regions according to inter-correlations among gridded $1° \times 1°$ latitude $\times$ longitude mean temperature records. According to *Wang and Gong* [2000], the area weights of Eastern China, Dunde ice core, Guliya ice core, southern TP tree-rings and Jinchuan peat are 0.329, 0.198, 0.149, 0.182 and 0.131, respectively. The data of Great Ghost Lake and Jiaming Lake in Taiwan were considered with an area weight of 0.011.

3. Results and Discussion

[7] The three composite paleotemperature records show good agreement with one another, particularly in the prominent peaks and troughs (Figure 3). Correlation coefficients for the period AD 1 to 1960 are 0.76 for the comparison of "H-res" with "Weighted", 0.79 for the comparison of "Complete" with "Weighted", and 0.83 for the comparison of "H-res" with "Complete" ($p < 0.01$). The high degree of similarity of the three types of reconstruction suggests that the final conclusions are not altered by chronology uncertainties in the case of the inclusion of the coarser resolution lake and peat series. As shown in Figure 3, all three curves display obvious warming during AD 0–240, AD 800–1100, around AD 1400 and in the 20th century and the cool LIA between the 15th and 19th century.

[8] General characteristics of temperature change in China during the last two millennia are most clearly expressed by the "Weighted" reconstruction (Figure 3). According to the "Weighted" reconstruction curve, temperatures in China were above average in AD 0–240 with two peaks around AD 50 and in AD 100–240. The peak at about AD 200 represents the warmest stage of the last two millennia, temperature was even higher than during the 20th century. The area that experienced warm conditions extended from Eastern to North Western China, the northern boundary of the farming zone even extended to the northern limit of the present farming-grazing zone. Following this period, temperatures decreased below average until AD 600. All proxy records display apparent cooling during this period with the exception of Jinchuan peat (Figure 2). The period between AD 600–1400 is characterized by decadal to centennial variability around the mean and notable warm peaks around AD 1000, 1250, 1400. The prominent warming period between AD 800 and 1100 (which is also indicated in the "H-res" and "Complete" reconstructions) in China evidently corresponds to the MWP (AD 800–1300) [*Hughes and Diaz*, 1994]. Of the 9 regional Chinese records, only δ^{18}O in the Guliya ice core shows evidence of cooling between AD 800 and 1100. This finding is corroborated by the evidence of glacier advances in the Himalaya and Karakorum between ~AD 800 and 1100 [*Röthlisberger and Geyh*, 1985]. However, a 1400 year tree-ring chronology from the Karakorum in Pakistan shows that the warmest conditions there occurred between AD 800 and 1100 [*Esper et al.*, 2002], which is consistent with contemporaneous warming in Eastern China but different from the δ^{18}O record of the Guliya ice core. This discrepancy can partly be explained by the different climatic conditions in Guliya and Pakistan. Although there is a lack of tree-ring data between AD 800–1000 in the southern TP, a well-replicated juniper ring width series from Qamdo in Eastern Tibet indicates that a cooler interval occurred between 800 and 1150 and that warmer conditions prevailed between 1150 and 1380 [*Braeuning*, 1999]. Further evidence from stable carbon isotope analysis confirms a warming period around AD 1204 to 1360 [*Helle et al.*, 2002]. Additional evidence is that the

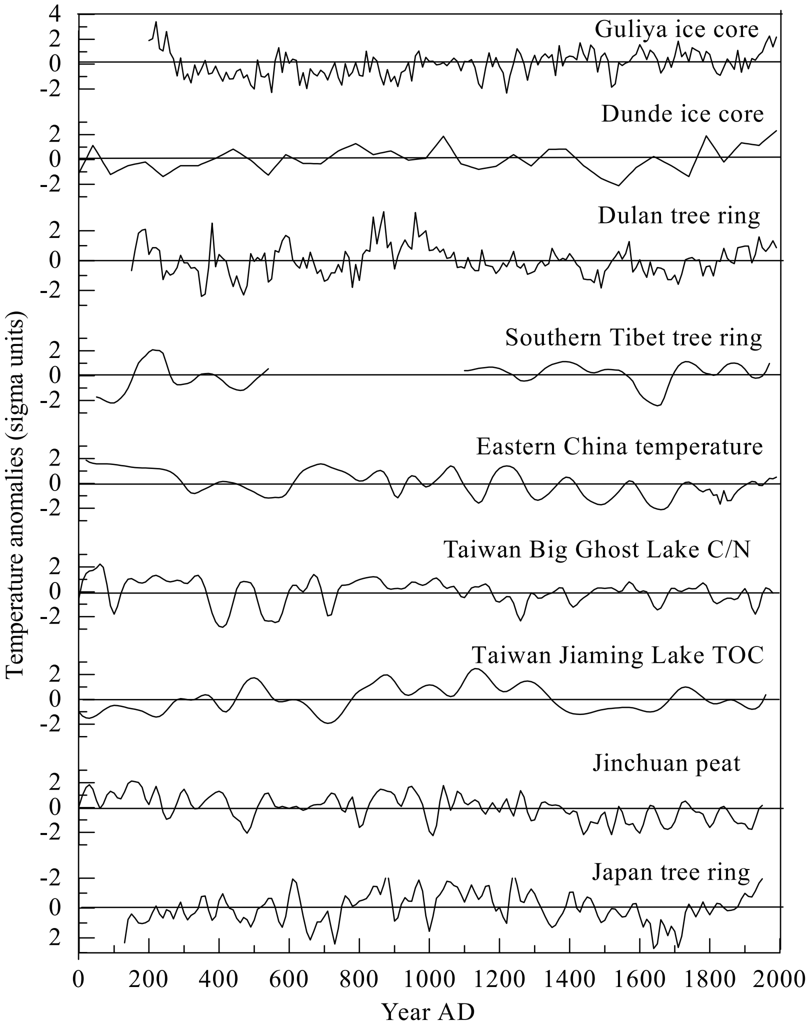

Figure 2. Standardized 2000-year regional temperature series for China and its vicinity.

Hailuogou glacier in South Eastern Tibet advanced markedly between AD 1010 ± 85 and 1170 ± 90 [*Zheng*, 1994]. In contrast, indications for warmer conditions around AD 800–1100 are recorded in a pollen record from Maili near Jinchuan. It testifies a lush growth for almost all the taxa between AD 950 and 1290, which might indicate general summer warming in Eurasia [*Ren*, 1998]. For the period of 1100–1320, only 4 records indicate cooling, mainly in western China, whereas Eastern China experienced one warm interval around the 13th century [*Zhang*, 1994, 1996]. During 1320–1400, all records were characterized by warming except for Jiaming Lake. After AD 1400, China entered into the cold stage of the so-called LIA period until 1920, with the coldest events in AD 1500 and 1700. This cold spell is documented in each proxy record except in the Guliya ice core. After the LIA, the modern warming stage commenced.

[9] A comparison of two temperature reconstructions for China and standardized decadal averages for the total Northern Hemisphere (NH) over the last millennium is shown in Figure 4. The reconstruction by *Mann et al.* [1999] was accomplished by regressing an empirical orthogonal function of the 20th-century's mean annual temperatures against various proxy indices and includes a varying number of records per unit of time. *Crowley and Lowery* [2000] used a more heterogeneous data set, but the number of records is nearly constant in time. The reconstruction by *Jones et al.* [1998] was derived from 10 temperature-sensitive

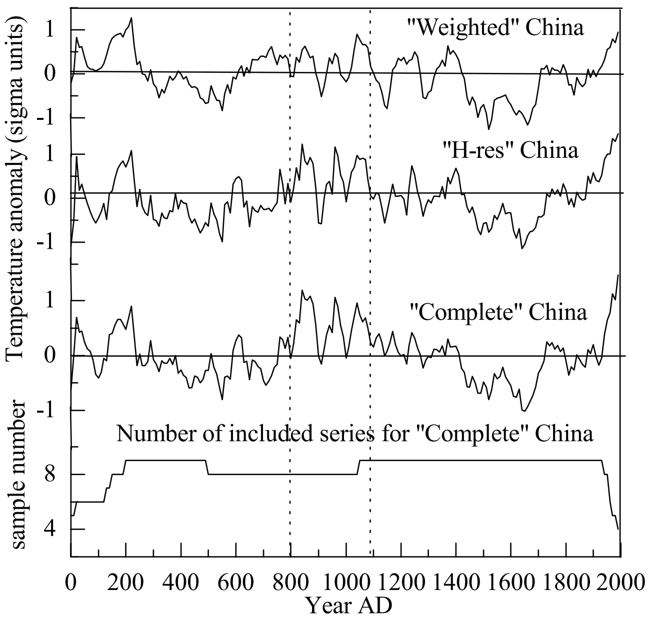

Figure 3. Comparison of several temperature reconstructions for whole China.

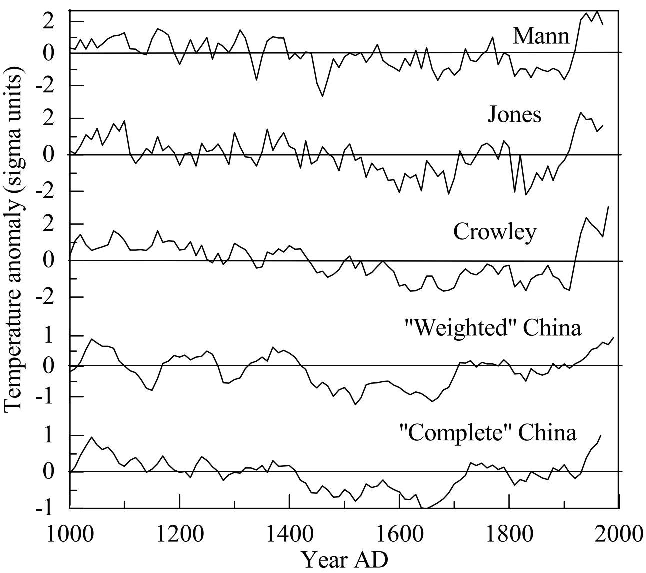

Figure 4. Comparison of several temperature reconstructions for China and the Northern Hemisphere [*Mann et al.*, 1999; *Jones et al.*, 1998; *Crowley and Lowery*, 2000] during the last millennium.

tree-ring series and explains 70% of the variance of the NH summer temperatures on a decadal scale during the period of 1901–1991. There is a significant correlation between the "Complete" and NH temperature reconstructions of *Jones et al.* [1998], *Mann et al.* [1999] and *Crowley and Lowery* [2000], with correlation coefficients of 0.45, 0.47 and 0.45, respectively (all significant at the 99% level). The correlation coefficients between the "Weighted" China temperature reconstruction and the above NH temperature series are 0.56, 0.45 and 0.56, respectively. Cross-correlations show that there is no phase shift in temperature change between China and the NH, indicating that temperature change in China was in phase with that of the NH during the last millennium. All the curves display the warming periods between 1000 and 1400 and during the 18th and 20th centuries. Another prominent corresponding feature is the post-1400 cooling, which marks the onset of the LIA in China and the NH. These coincidences suggest a close connection of temperature changes in China and the whole NH.

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