Global mean temperature changes during the last millennium*

WANG Shaowu[1]**, XIE Zhihui[1], CAI Jingning[1], ZHU Jinhong[1] and GONG Daoyi[2]

(1. Department of Atmospheric Science, School of Physics, Peking University, Beijing 100871, China; 2. Key Laboratory of Environmental Change and Natural Disaster, Beijing Normal University, Beijing 100875, China)

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Abstract A synthetic study is made on the global or hemispheric mean temperature series for the last millennium worked out by Mann et al., Jones et al., Crowley and Lowery, and Briffa. The global mean temperature series reconstructed by using proxy data at 30 sites by Wang et al. and simulations from AD 1000 to 2000 by energy balance model are described and compared with the series of others. Wang's series gives greater variability and shows the highest correlation coefficient (0.83) with the simulation results. Uncertainties in the reconstructions and simulations are discussed. The errors in reconstructing a global mean temperature series according to 30 sites as used in the research are estimated. Wang's series indicate that temperature average for the 11th century is higher than the mean of the last millennium. It infers that the Medieval Warm Period predominated to some extent over the globe. However, the 20th century is no doubt the warmest century during the last millennium.

Keywords: last millennium, temperature changes, Medieval Warm Period, Little Ice Age, modern climate warming.

Recently, four global or hemispheric mean temperature series were reconstructed to assess if the climate warming of the 20th century was unusual, and if the Medieval Warm Period (MWP) and the Little Ice Age (LIA) were of global or hemispheric scale. Both these events are usually attributed to natural variability, for anthropogenic impact was still negligible. The modern warming in the 20th century can be, at least partially, attributed to the natural factors such as solar activity or volcanism, if the amplitude and the coverage of temperature changes during the MWP or LIA was greater or comparable to that of the modern warming. *The Climate Change* 2001[1] cited the studies and reported that (1) the increase in temperature in the 20th century (the increase is 0.6 ± 0.2℃ in the century) is likely to have been the largest of any century during the past 1000 years. (2) It is also likely that, in the Northern Hemisphere, the 1990s was the warmest decade. (3) 1998 was the warmest year. These are the most important evaluation to the modern climate warming. These conclusions are obtained mainly on the basis of temperature series for the last millennium. Thus a study on the information provided by the series and on the uncertainties contained in it is critical.

1 Reconstruction of temperature series for the last millennium

Instrumental observations of temperature on global extent began in AD1861[1]. Therefore, examination of climate change for longer time interval has to go on the basis of proxy data. Mann et al.[2] reconstructed successfully the Northern Hemispheric temperature series for the last 600 years, then the series extended to 1000 years long[3] (denoted as M later). Mann et al. emphasized the important contribution of key regions in simulating principal component (PC) of global temperature variability. However, Jones et al.[4] suggested using all 17 proxy data series to get a mathematical mean temperature for the globe (J). Crowley and Lowery[5] indicated the inhomogeneity of M and J, for the number of sites used in reconstruction significantly varied throughout the last millennium. They adopted 15 series, each of them extended to AD 1000, to form the global mean (C). Briffa[6] provided a new series based on tree-ring data at higher latitudes of the Northern Hemisphere (B). The numbers of sites in which proxy data are available in reconstruction of global or hemispheric mean temperature series are given in Table 1. The numbers in the parentheses show the sites where proxy data are available at least since AD1100.

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** To whom correspondence should be addressed. E-mail: swwang@pku.edu.cn

Table 1. Numbers of sites used in reconstruction of temperature series for the last millennium

No.	Northern Hemisphere	Southern Hemisphere	Globe	Authors
M	8(8)	4(4)	12(12)	Mann et al. (1999)[3]
J	10(4)	7(3)	17(7)	Jones et al. (1998)[4]
C	15(15)		15(15)	Crowley et al. (2000)[5]
B	7(3)		7(3)	Briffa (2000)[6]
W	20(20)	10(10)	30(30)	Wang et al. (1996)[9]

Great inhomogeneity was found not only in M, but also in J and B. For example, 31 tree-ring data, 6 ice core data, 7 coral data, and 8 documentary data sites were used in reconstruction of temperature series for the last 600 years. The total number of data sites used was greater than 70, but only about one third of them extended to AD and 1400. The coral data began in AD1750. Before AD 1400 12 data sites were applied, it in several times reduced to that since AD1400. Therefore, the numbers of data sites, and then the coverage of data varied greatly with time, which will stain the scientific significance of reconstruction.

All of 15 proxy data series used by Crowley and Lowery extended to AD1000. However, time resolutions vary from one to another, the number of sites with annual, decadal and 50-year resolution was 7, 5 and 3, respectively. It shows that the inhomogeneity in time resolution has prevented reconstruction of annual temperature series for the last millennium. Situations are nearly the same for M, J, and B as for C.

Difference in data sources also contributed to the inhomogeneity and uncertainty in temperature reconstruction. It has been discussed in detail by Jones[7,8]. The only thing that needs to mention is that close correlation of tree-ring width was found to the summer half-year temperatures (April to September), not only for the same year, but also for one or two years before. Therefore, it is proper to concentrate the study in the low frequency variability of global mean temperatures.

2 Low frequency variability of global mean temperatures

Wang et al.[9,10] have reconstructed a global mean temperature series based on proxy data (denoted as W later). 30 data sites used in reconstruction are shown in Fig. 1. Data sources are outlined in Tables 1 and 2, line of W. All the series were updated to 1975 according to temperature observations[11]. Each of 30 temperature series was smoothed with 50-year running mean. Then figures at AD 1000, 1025, 1050, ···, 1975 were abstracted and the normal was found by averaging 40 figures. Finally anomalies were calculated by subtracting the normal from each figure of the series. Fig. 2 gives temperature anomalies at 30 sites. Positive anomalies are shaded.

Table 2. Data sources of temperature reconstruction

Data sources	M	J	C	B	W
Tree-ring	9(9)	8(6)	8(8)	7(3)	8(8)
Ice core	3(3)	4(1)	3(3)		8(8)
Documentary		2(0)	2(2)		7(7)
Pollen			1(1)		2(2)
Coral		3(0)			
Borehole					3(3)
Glacier					2(2)
Sea ice			1(1)		

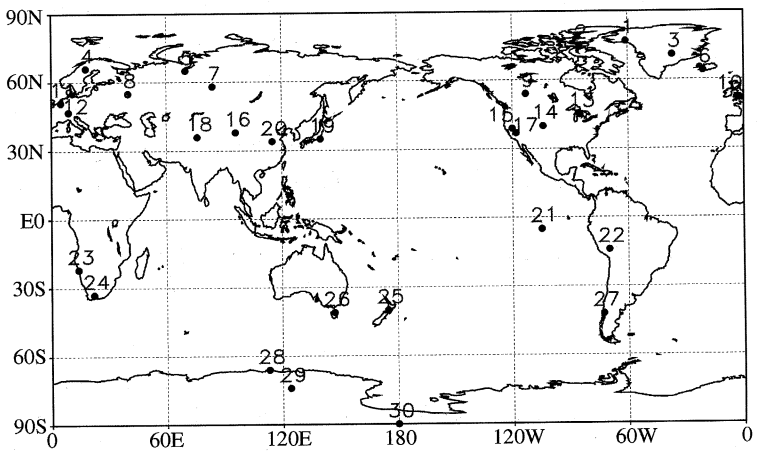

Fig. 1. Geographical locations of 30 series used in W.

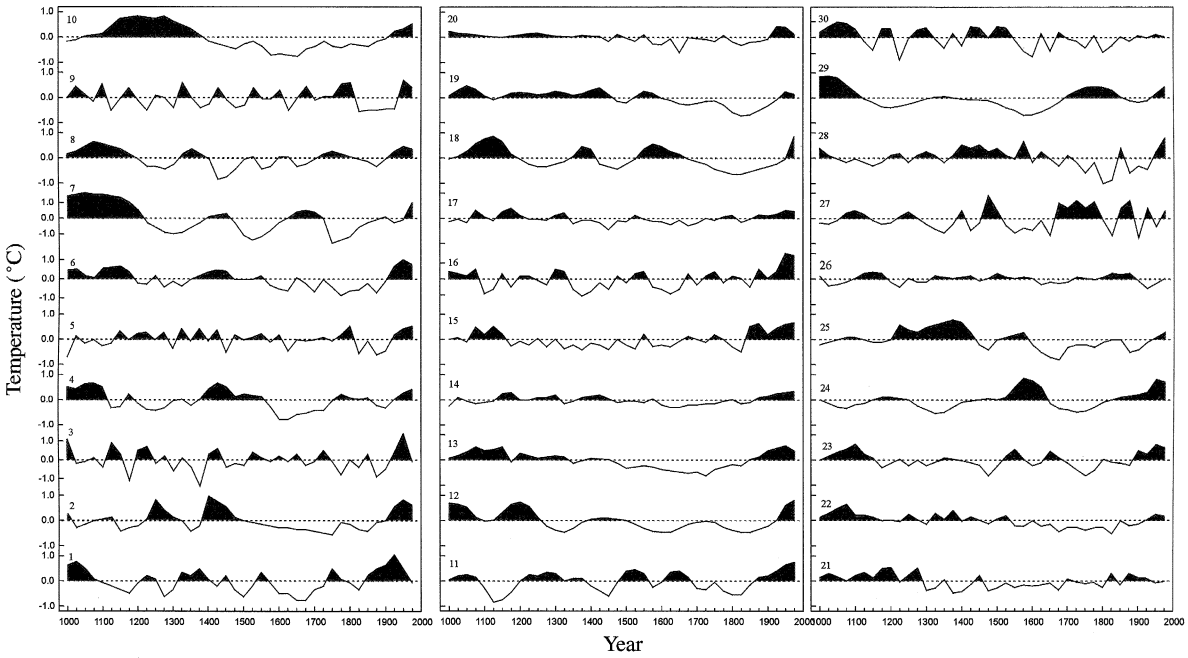

Fig. 2. 30 series of temperature changes, sites are shown in Fig. 1.

Simulation of global mean temperature changes for the period of AD1000 to 1999 was carried out by using zero-dimension energy balance model[12], in which upwelling and diffusion in the oceans were considered. Changes in solar activity, volcanism and CO_2 were used as a forcing factor to simulate the variations of solar irradiance, atmospheric transparency and greenhouse effect. Finally impact of atmospheric sulphur and ENSO events on temperature changes was also considered (Table 3). Simulation of global mean temperature changes from AD 1880 to 1995 shows close correlation to temperature observations (0.88). Simulation for the last millennium (denoted as S) was compared with the reconstructions (Fig. 3).

Table 3. Forcing factors used in simulation

Factors	Data sources	Authors
Solar activity	Tree-ring ^{14}C	Stuiver et al.[13]
Volcanism (NH)	Ice core acidity	Porter[14]
Volcanism (NH)	Ice core particles	Mosley-Thompson et al.[15]
CO_2	Ice core	Houghton et al.[16]
ENSO	Ice core	Diaz et al.[17]

3 Discussions

The same procedure used in processing series W was applied to normalize the series M, J, C and B, for making a direct comparison between the different series of global or hemispheric mean temperature for the last millennium (Fig. 3). Cross-correlation coefficients (C. C.) between the series are given in Table 4.

Table 4. Cross-correlation coefficients between the temperature series for the last millennium

No.	M	J	C	B	W	S
M	×	0.77	0.79	0.60	0.73	0.65
J		×	0.81	0.69	0.74	0.56
C			×	0.66	0.85	0.76
B				×	0.84	0.59
W					×	0.83
S						×
σ	0.10	0.11	0.16	0.17	0.18	0.13

From Fig. 3 and Table 4 one can conclude that:

(1) There are significantly high C. C. between the series. Average C. C. of any one with other four series is greater than 0.70. The maximum is found between W and other four series, which reaches 0.79. High C. C. between the series shows great similarity in the low frequency variations of temperature, no matter what method or data sources are applied. The highest C. C. with W infers better representativeness of it.

(2) C. C. with S varies between 0.56 and 0.83, all of them are significant at 99.9% of confidence level. It proves the successfulness of the simulation on the one hand, and validity of the reconstruction on the other. The maximum C. C. between W and S (0.83) indicates that series W provides maybe, more real information of temperature changes than

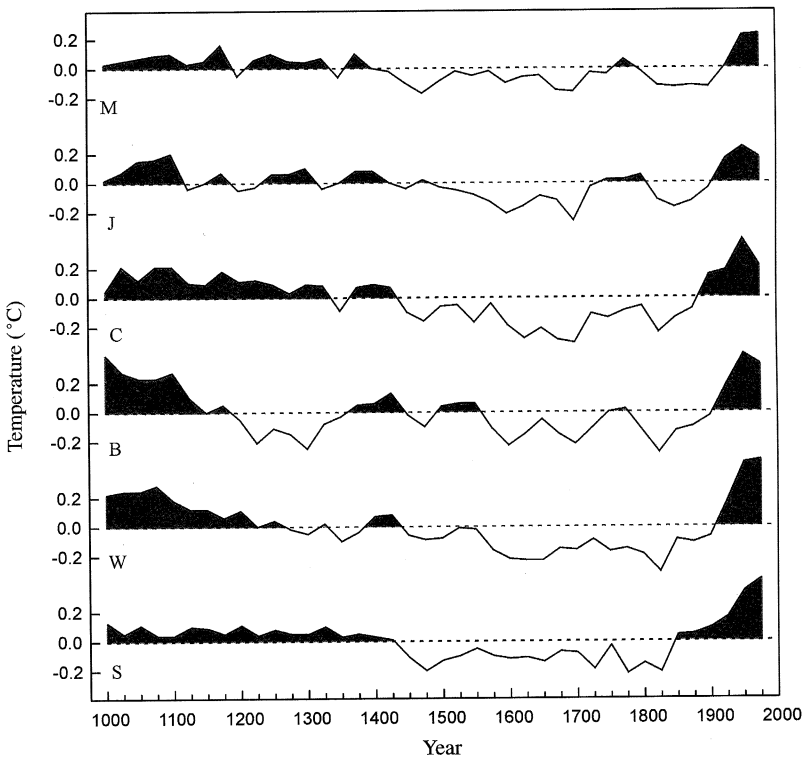

Fig. 3. Global mean temperature changes for the last millennium. M, Mann et al.[3]; J, Jones et al.[4]; C, Crowley et al.[5]; B, Briffa[6]; W, Wang et al.[9]; S, Simulation[11].

the other series, and of course uncertainties exist in all of the series.

(3) Mean square root of temperatures (σ) is shown in the last line of Table 4. It varies from 0.10 (M) to 0.18 (W) for the five reconstructions. The low value of σ in series M may relate, at least partially, to the procedure applied in [3]. σ value of S is also lower than that of C, B and W. It means that the list of forcing factors is not complete. For example, feedback of sea ice and ice cover over continent, and impact of changing in the thermohaline circulation was not considered in the simulations. Of course, errors also exist in the variations of forcing factor, which was estimated according to proxy data.

(4) LIA was clearly manifested in all of the series, three cold periods are evident: in the second-half of 15th, in the 17th and the 19th century. MWP is not significant as LIA, but mean temperature of the 11th and the 12th is usually higher than the average of the last millennium, or even comparable with that of the 20th century in series C, B and W.

(5) All of the series end in 1975, the low frequency temperature change from 1975 to 2000 may reach 0.45℃ according to temperature observations. Then, mean temperature anomaly of the 20th century may increase to 0.50℃, if it was calculated according to temperatures at 1925, 1950, 1975 and 2000. Mean temperature anomaly is only 0.25℃ when temperature at 1900, 1925, 1950, and 1975 is averaged. Therefore, the warming in the 20th century is unique during the last millennium, if the significant warming in the last quarter of the century is taken into consideration.

(6) Geographical coverage of all the series J, M, C, B and W is not complete. Uncertainty can be estimated by using General Circulation Model (GCM) simulation. A 100-year (AD 1900～1999) simulation was carried out with CCM3.6, observed sea surface temperature (SST) was used as forcing factor. The simulation provided temperatures in a complete grid point series. Then, temperatures at 30 sites shown in Fig. 1 are abstracted; global mean temperature is calculated by directly averaging at 30 sites (denoted as T). "Real" global mean temperature is found by using all the grid points with area weighting (denoted as T_0). Correlation coefficient between T and T_0 is 0.89. It indicates that reconstruction of global mean temperature with that in 30 sites provides no bad result. However, the difference between T and T_0

gives 0.14℃ of σ, and it is comparable to that listed in the last line of Table 4. Therefore, both the reconstruction and simulation of global mean temperature changes during the last millennium should be considered as preliminary in essence.

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