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Simulated and reconstructed winter temperature in the eastern China during the last millennium

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Abstract **The reconstructed temperature anomalies in the eastern China were compared with the output from a 1000-year model simulation in an attempt to evaluate the model's regional simulation skills and to understand the causes of climate change in China over the last millennium. The reconstructed data are the winter half-year temperature anomalies in the central region of eastern China (25°—40°N, east of 105°E) for the last 1000 years with a 30-year resolution. The model used is the global atmosphere-ocean coupled climate model, ECHO-G, which was driven by time-varying external forcings including solar radiation, volcanic eruptions, and greenhouse gas concentrations (CO_2 and CH_4) for the same period. The correlation coefficient between the simulated and reconstructed time series is 0.37, which is statistically significant at a confidence level of 97.5%. The Medieval Warm Period (MWP) during 1000—1300 A.D., the Little Ice Age (LIA) during 1300—1850 A.D. and the modern warming period after 1900 A.D. are all recognizable from both the simulated and reconstructed temperatures. The anomalies associated with the LIA and the modern warming simulated by the model are in good consistency with the reconstructed counterpart. In particular during the Maunder sun-spot minimum (1670—1710 A.D.), both the simulated and reconstructed temperature anomalies reach their minima without any phase difference. But in the earlier MWP, significant discrepancies exist between the simulation and the reconstruction, which might reflect the degrading quality of the reconstruction data. The range of the simulated anomalies (1.62 K) is comparable with that of reconstructed (2.0 K). Diagnosis of the model results indicates that, during the last millennium, variations in solar radiation and volcanic activity are the main controlling factors on regional temperature change, while in the recent 100 years, the change of the concentration of greenhouse gases plays most important role in explaining the rapid temperature rising.**

Keywords: **last millennium climate, paleoclimate simulation, reconstruction, eastern China.**

Since the 1990s, under the auspicious impetus of two international research programs, the "Past Global Changes" (PAGES) and the "Climate Variability and Predictability" (CLIVAR), massive research work has been carried out on climate and environment changes over the past 2000 years[1−3]. But majority of the studies has been centered on obtaining various kinds of climatic proxy data (such as historical documents, tree rings, ice cores, lake cores) and focused on the reconstruction of climatic sequences[4−15]. The investigation of the controlling factors and dynamical mechanisms of the climate changes on different timescales in the past 2000 years have been limited[16−18].

Historical climate simulation through long time integration is undergoing a rapid development phase. The numerical model simulation plays a vital role in understanding the causes and physical mechanisms of climate change on centennial time scale. Because the long-term integration requires fast super computers, so far this kind of work has only been performed in a few developed countries such as USA, Germany, Belgium[19−21]. Due to the limitations of computing power, this kind of simulation remains underdeveloped in China.

Here the temperature over the last millennium simulated by the global climate model ECHO-G[22] is used to compare with the reconstructed temperature anomalies in the eastern China. The purposes are to test the skill of the model in simulating regional climate of China, to find discrepancies and possible deficiencies in the historical climate reconstruction, and to understand the causes and mechanisms of the past climate changes in China. Hopefully, the present study will promote climate research in China and help improving our comprehensive understanding of the historical climate change, enhancing the forecast reliability for predicting the tendency of future climate change, and meeting the needs of sustainable economical development.

1 The model and numerical experiment

The climate model ECHO-G consists of the spectral atmospheric model ECHAM4 and the global ocean circulation model HOPE-G, both were implemented and developed at the Max-Planck-Institute of Meteorology (MPI) in Hamburg[22]. ECHAM4 is a fourth generation of atmospheric general circulation model, which is based on primitive equations with a mixed p-σ coordinate system. The horizontal resolution of the model is T30, or approximately 3.75°×3.75°, and the vertical resolution is 19 levels with five upper levels being located above 200hPa. The horizontal resolution of the ocean model HOPE-G is about 2.8°×2.8° with a grid refinement in the tropical regions, where the meridional grid point separation reaches 0.5°. The ocean model has 20 vertical levels. The model

ECHO-G has been used in a number of simulations for the present and past climates[23,24].

Two 1000-year integrations with the ECHO-G model have been carried out at MPI. One was a control simulation, in which the external forcings were kept constant values of the present climate. This experiment can simulate annual, interannual and decadal climate oscillations that are determined by the internal dynamics of the coupled climate system, but cannot simulate the climate change caused by external forcings, such as the Medieval Warm Period and the Little Ice Age[25]. Another experiment was externally forced simulation, in which the model ECHO-G was driven by three external forcing factors: solar variability, greenhouse gas concentrations in the atmosphere (including CO_2 and CH_4) and an estimation of radiative effects of stratospheric volcanic aerosols[16], for the period of 1000 to 1990 A.D.[26,27]. The time sequences of these forcing factors are shown in Fig. 1. Further details of the simulations can be found in von Storch et al.[28]. The result from the forced simulation is used for comparison with the reconstructed sequences in this paper.

2 Reconstructed data

Abundant historical, documentary records on phonological events of cold/warm and dry/wet climate are available in China. Numerous studies have been done by Chinese scientists on reconstructing the historical climate change using these documentary records. In recent years, Ge et al.[29] conferred with and developed Zhu's method[30] of deducing climate change for the past 5000 years using phonological records in China. They reconstructed winter half-year (October to April) temperature anomalies for the past 2000 years in the central region of eastern China (25°–40°N, east of 105°E) at 10–30 years' resolutions. In this paper, we used their reconstructed temperature anomalies since 1000 A.D. at a 30-year resolution.

3 Comparison of the simulated and reconstructed data

3.1 Validation of the model skill using instrumental observations

The simulated temperature anomalies from the externally forced simulation with ECHO-G are first compared with 120-year observed data[7] in eastern China (25°—40°N, east of 105°E) in order to test the model's performance. Fig. 2 compares the model simulated and the observed variations of the winter-half year temperature anomalies in the eastern China since 1870. The anomalies are calculated with reference to the 1951—1980 mean temperature. It can be seen that the increasing trends of temperature fluctuations in the eastern China are evident and consistent for both model output and observations. There is a statistically significant correlation between them at 99.5% confidence level, although the simulated mean temperature is about 0.15 K lower than the observed one. The uncertainty with Jones' observed data is of the same order, suggesting that the modeling result and Jones' data may be considerably consistent with each other.

3.2 Comparison of the simulated and reconstructed temperatures in the eastern China

To be compatible in temporal resolution, we first compiled the winter-half year temperature anomalies in the eastern China (25°—40°N, 105°—123.75°E, 20 grid points) from the externally forced simulation, and then calculated 30-year mean temperature anomalies. Finally,

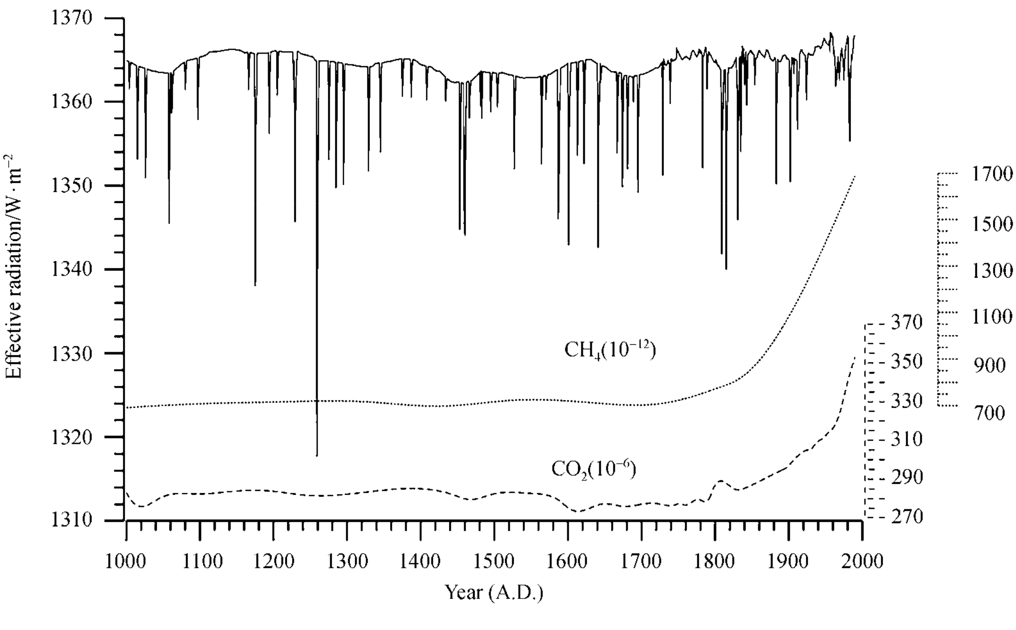

Fig. 1. Time sequence of external forcing factors.

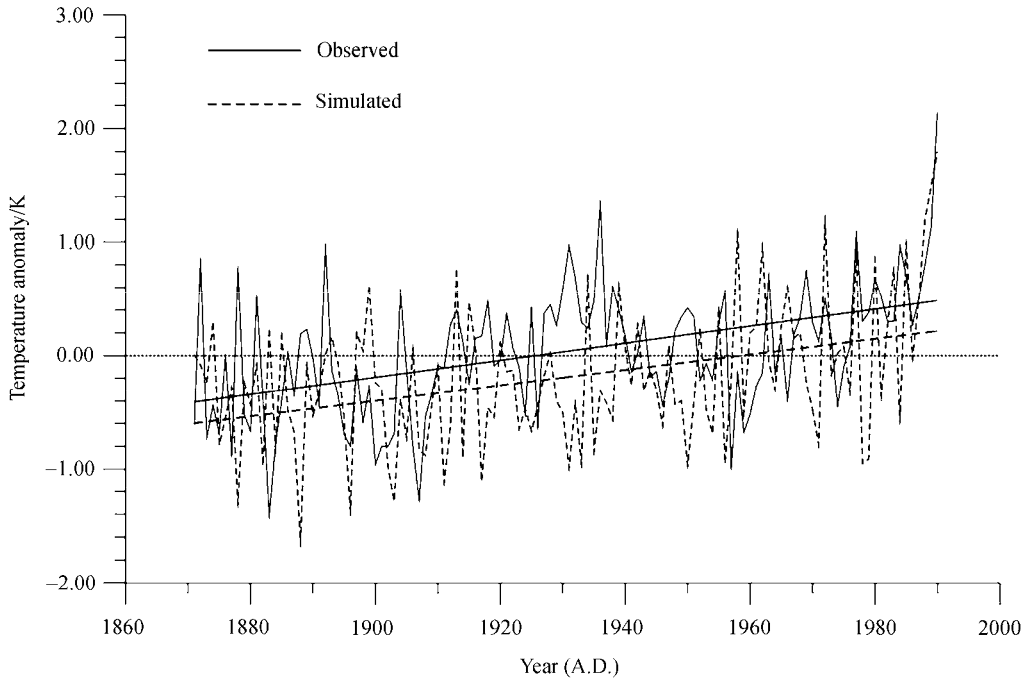

Fig. 2. Comparison of model-simulated and the observed winter half-year temperature anomalies[7] in the eastern China. The dashed line and solid line stand for the simulation and Jones' data respectively, and the dotted line indicates the zero anomaly level.

the simulated results were compared with reconstructed winter-half year temperature anomalies (at a 30-year resolution) of the eastern China. Fig. 3 shows these two time series along with their corresponding polynomial fitting curves.

Fig. 3 indicates that the reconstructed and the simulated results exhibit similar low-frequency variations and long-term trends. The range of the simulated temperature is from –0.70 K to –0.92 K, and that of the reconstructed is –1.1—0.9 K. The amplitude of the simulated temperature anomalies is about 1.62K, a little bit less than that of reconstructed (2.0K). The correlation coefficient of the two time series is 0.37, which is significant at 97.5% confidence level. Overall, both simulation and reconstruction show the Medieval Warm Period from 1000 to 1300, the Little Ice Age from 1300 to 1850, and the recent warming period since 1900. The anomalies from simulation and reconstruction in the Little Ice Age (1300—1850) and warming since 1900 are particularly consistent. Especially, both simulated and reconstructed temperatures reach their minimum values without phase difference during the Maunder sunspots minimum 1670 to 1710. However, for the Medieval Warm Period of 1000—1300, the simulation and reconstruction show some phase differences: The reconstruction displays two peaks with one valley in between, whereas the simulation shows three peaks with two valleys in between.

It can be seen from Fig. 3 that after 1500 the phases and amplitudes of the reconstruction and the simulation match better than those in the period prior to 1500 A.D. This may be related to the fact that less amount of data sites were used for climate reconstruction in the earlier period. Of also notable is that the difference between the simulation and reconstruction enlarges in the last 100 years. The simulation shows a faster increasing trend and is higher than reconstructed temperature. The possible cause for this discrepancy may be partially due to the exclusion of the aerosol forcing in the forced experiment. The effects of aerosol have been thought to be a factor that can offset the warming. It is conceivable that the regional cooling effect of aerosols could reduce the warming if they were included in the model, especially in the 20th century.

It is worthy to point out that the simulated temperature anomaly in the 20th century is higher than that of the Medieval Warm Period, while the reconstructed temperature in the 20th century is lower, albeit close to, that of the Medieval Warm Period (Fig. 3). These two different results provide two different interpretations regarding the amplitude of recent global warming. One states that the 20th century warming has exceeded the normal range of the climate change, and it will result in catastrophic impact on human beings if warming continues going up[31]. The other underlines that the current climate change has not yet exceeded the range of natural climate change in the past millennium[29]. The debate of these two standpoints remains, and no conclusion has been yet reached. The final resolution of this problem calls for both the improvement of the fidelity of the climate models in their

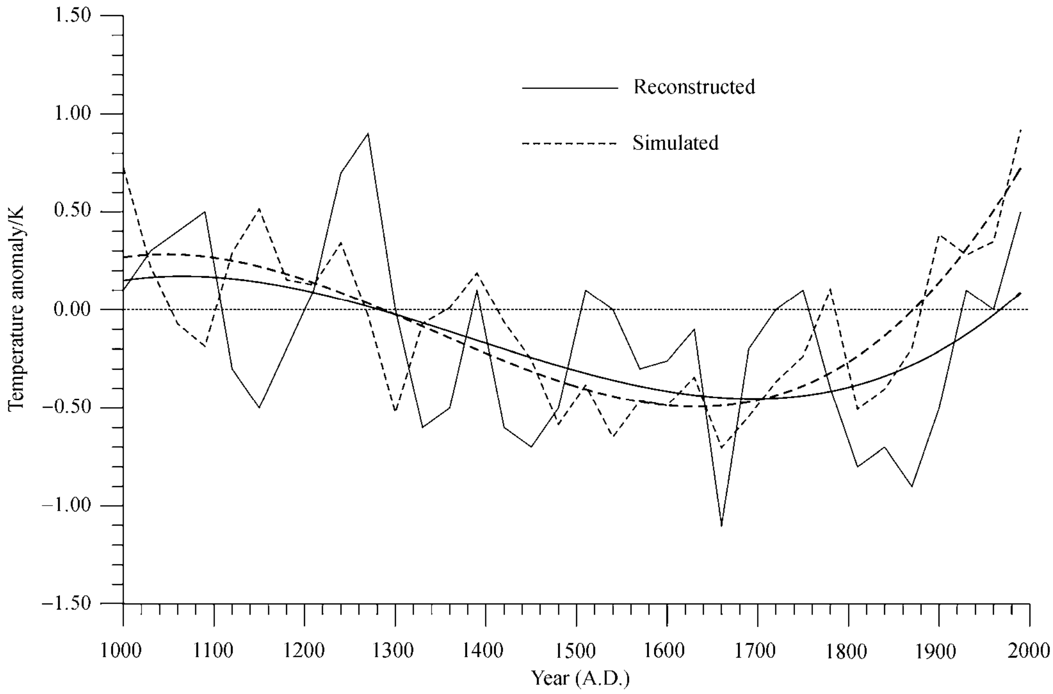

Fig. 3. Comparison of simulated and reconstructed winter half-year temperature anomalies in the eastern China. Detailed explanation is referred to the text.

long-term climate simulation and more profound works on quantitative reconstruction of paleo-climatological data. The latter requires reconstructing historical climate change sequences with higher resolution, precision, and reliability.

4 Mechanism analysis

By comparing the real forced experiment (driven by time-dependent external forcing factors such as effective solar radiation, CO_2 and CH_4 concentrations) and the control experiment (forced by the constant solar radiation, CO_2 and CH_4 concentrations in 1990), we found that the control experiment, although reproduces climate fluctuations around a mean state, cannot reproduce the climate changes on the centennial time scale, such as the Medieval Warm Period and the Little Ice Age (figure not shown). So, it is concluded that the solar radiation, volcanic activity, and increase of greenhouse gases by human activities are the main forcing factors for the centennial climate changes in the past 1000 years.

In order to identify the contribution of solar activity, volcanic activity, and greenhouse gas concentration changes to the Chinese climate changes in the past 1000 years, we applied empirical fitting to the simulated 10-year average temperature anomalies in the eastern China from 1951 to 1980 under two scenarios: In the first scenario, only changes in the effective solar radiation are considered (i.e., the coupled system is affected by solar activity and volcanic activity); while in the second one, changes in both effective solar radiation and greenhouse gases are considered.

The fitting equation for the first scenario is

$$\Delta T = 0.17 + 0.13\Delta S, \quad (1)$$

where ΔT is the 10-year average temperature anomaly (K, with reference to 1951–1980 mean) in the eastern China, and ΔS is the 10-year average solar radiation anomaly from its averaged value for the period of 1951—1980 (1365.75 W/m^2).

The fitting equation for the changes of both effective solar radiation and greenhouse gases is

$$\Delta T = 0.73 + 0.10\Delta S + 5.28\ln\left(\frac{C}{C_0}\right) + 0.04\left(\sqrt{H} - \sqrt{H_0}\right), \quad (2)$$

where ΔT and ΔS are the same as eq. (1), C is the 10-year mean CO_2 concentration of the atmosphere (10^{-6}), C_0 is the 1951—1980 mean CO_2 concentration (322.65×10^{-6}), H is 10-year mean CH_4 concentration of the atmosphere (10^{-12}), and H_0 is the 1951—1980 mean CH_4 concentration (1510.85×10^{-12})[32].

The correlation coefficient is 0.53 between the fitted curve (1) and the simulated temperature anomaly series, while that is 0.66 between the fitted curve (2) and the simulated temperature anomaly series, both with the confidence level of 99.9%. The two fitted curves derived from the above equations and the simulated curve are shown in

Fig. 4 .

From Fig. 4, it can be found that the effective irradiance (combined solar and volcanic effects) determined the main trend of temperature change in the last 1000 years (fitting (1), the dashed line). From 1000 to 1900, the curve concurs with that of the simulated temperature. However, in the last 100 years since 1900, it differs from the simulation, and the warming trend is not significant, only oscillating around an equilibrium state. Only when the greenhouse gases (CO_2 and CH_4) are included, the increase of temperature in the 20th century is well matched (fitting (2), the dotted line). The fitted curve (2) matches with fitted curve (1) quite well in the time period from 1000 to 1900. But in the last 100 years, curve (2) is much more consistent with the simulated temperature, showing a significant warming trend in the 20th century. This means that the increase of greenhouse gases contributes to global and regional warming more significantly in the last 100 years. Therefore, in the millennium time scale, the solar radiation and volcanic activity are the main forcing factors for global and regional temperature changes, but in the last century, greenhouse gases may play a more important role than effective solar forcing in the warming process.

5 Conclusions

We have shown that the temperatures reconstructed and simulated by the ECHO-G model bear close similarity in their low-frequency (centennial) variation and trends. With a 30-year resolution, the correlation coefficient between the reconstruction and simulation is 0.37 in the last millennium. Both simulation and reconstruction show the overall Medieval Warm Period from 1000 to 1300, the Little Ice Age from 1300 to 1850, and the warming period since 1900. The range of the simulated temperature is from −0.70—0.92 K, and that of reconstructed is −1.1—0.9 K. The amplitude of simulated temperature anomaly is about 1.62 K, a little bit less than that of the reconstructed one (2.0 K). Of note is the very good agreement between the reconstruction and the simulation in the periods of the Little Ice Age (1300—1850) and the recent warming period since 1900, in particular during the Maunder Minimum from 1670 to 1710. However, for the earlier epoch during the Medieval Warm Period from 1000 to 1300, the simulation and reconstruction show considerable discrepancies. This overall performance is particularly encouraging considering that this is a regional check of a global climate model.

Driven by time-dependent effective irradiance, CO_2 concentration, and CH_4 concentration, the model ECHO-G can replicate the main features of climate changes in the eastern China in the past 1000 years. It means that the solar activity, volcanic activity, and greenhouse gases are the key controlling factors for historical climate changes during this period. On the millennium time scale, the solar radiation and volcanic activity are the main forcing factors for global and regional temperature changes. In the last century, greenhouse gases play a more important role in explaining the unusual warming. However, the simulation does not faithfully reproduce all climate fluctuations in

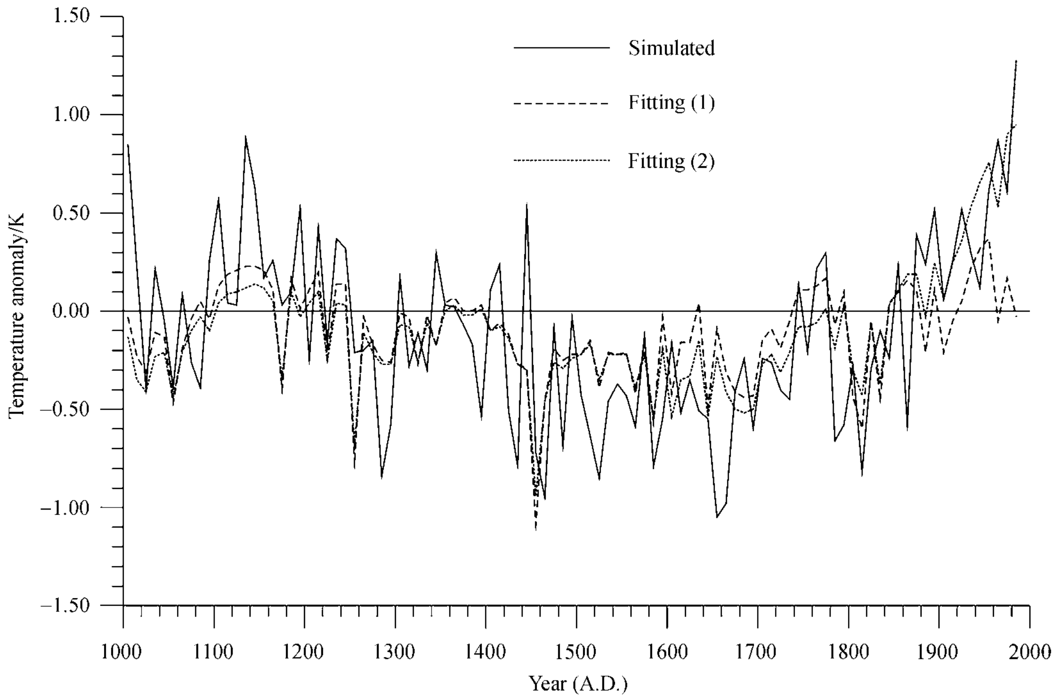

Fig. 4. Time series of simulated temperature anomaly and the two empirical fitting scenarios over the eastern China.

multi-decadal time scale. That may suggest either other factors, such as changes of aerosols and land surface processes, might play a role or the internal variability of the coupled climate system may limit the capability of the model's simulation.

The time resolution of reconstructed data used here is coarse (about 30 years). The uncertainties of the data also increase backwards in time. Therefore, we have to improve our reconstruction of historical climate, and develop more efficient proxies. Higher time resolution, more accurate and reliable historical climate series of China need to be reconstructed to understand the mechanisms of historical climate changes.

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