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Influence of parallel computational uncertainty on simulations of the Coupled General Climate Model

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Abstract

This paper investigates the impact of the parallel computational uncertainty on climate simulations using the Community Climate System Model Version 3 (CCSM3). A series of sensitivity experiments have been conducted and the analyses are focused on the Global and Nino3.4 sea surface temperatures. It is shown that the amplitude of the deviation induced by the parallel computational uncertainty is the same order as that of the climate system change. However, the ensemble mean method can reduce the influence and the ensemble member number of 15 is enough to ignore simulated errors. For climatology, the influence can be ignored when the climatological mean is calculated by using more than 30-yr simulations. It is also found that the parallel computational uncertainty has no effect on the simulated periods of climate variability such as ENSO. Finally, it is suggested that the influence of the parallel computational uncertainty on Coupled General Climate Models (CGCMs) can be a quality standard or a metric for developing CGCMs.

1 Introduction

Coupled General Circulation Models (CGCMs) have been widely used since they serve as a powerful tool for climate research and prediction. However, there are still many problems faced by CGCMs, one of which is uncertainty. The IPCC-AR4's report (Meehl et al., 2007) stated that the correct analysis of model uncertainties is one of the IPCC's duties and goals. Generally, CGCM's uncertainties, which usually result from the nonlinear interaction of the component of the climatic system (Tebaldi et al., 2004; Held et al., 2002), have two types. The first one is due to uncertainty of the physical parameterization (Meehl et al., 2007; Moss and Schneider, 2000; Wittenberg and Anderson, 1998; Dorn et al., 2007), and the other one is from amplification of the computational errors (Cousins and Xue, 2001; Wang et al., 2007; Chen et al., 2008).

Held et al. (2002) concluded that the nonlinear interaction in the coupling system has greater impact on uncertainties than the linear interaction, by analyzing a simple air-sea coupled model. Dorn et al. (2007) used a pan-Arctic coupled regional model to study the effect of different parameterizations such as Arctic clouds and sea-ice albedo on the coupled system. The results showed that uncertain processes or parameter schemes could cause a major uncertainty of the climate simulation. Other related studies, such as the driven-data error (Santer et al., 2003) and how to define and describe uncertainty in the climate research (Patt and Schrag, 2003; Patt and Dessai, 2005), are also performed.

The computational error, such as round-off error, is also a major reason for the uncertainty of CGCMs. With the higher resolutions and increased physical processes in General Circulation Models (GCMs), Message Passing Interface (MPI) is widely used to improve the computational efficiency. MPI is also used to exchange the data among sub-components in the coupled system. Therefore, the analysis of the parallel computational error due to MPI is a key and necessary step to determine the coupled model stability and accuracy. Cousins et al. (2001) developed the parallel version of Princeton Ocean Model (POM) and found that there is a significant difference between the serial and parallel version of POM. Furthermore, they concluded that the error from the data communication process via MPI is the main reason for the difference. Wang et al. (2007) studied the results of the atmospheric model SAMIL simulated with different CPUs and pointed out that the difference is chiefly caused by the round-off error. Chen et al. (2008) introduced the uncertainty of the global mean Sea Surface Temperature (SST) simulated by the Community Climate System Model Version 3 (CCSM3) with different computational platforms or different CPU configuration. Their analysis showed that the simulation results are dependent on the computational environments and the magnitude of uncertainty due to the parallel computational error could be in the same order as that of natural variations in the climate system.

Since a large amount of resource is required to simulate climate variability by using CGCMs and the resource is limited, it is very common to change the CPU configuration during a long-term model run. Therefore, it is important for us to know the usability and applicability of the models' simulation uncertainty caused by the parallel computational

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error. In other words, can the uncertainty by the parallel computational error be ignored when we use CGCMs to simulate climate variations on different timescales? In the present paper, we use the CCSM3 model as an example to explore and investigate the effect of the parallel computational uncertainty on climate simulations. Our focus is on the simulated SST, with the aim to gain a better understanding on how the simulation could be used rationally.

The paper is organized as follows. Section 2 briefly describes the CCSM3 and experimental designs. Section 3 shows the impact of the parallel computational uncertainty on the global and Nino3.4 SSTs. Finally, Sect. 4 gives the conclusion and discussion.

2 Model description and experimental designs

The CCSM3 (Collins et al., 2006a), which was released to the public by the National Center for Atmospheric Research (NCAR) in June 2004, is one of the state-of-art climate models for simulating the earth's climate. It consists of four dynamical geophysical models (i.e., atmosphere, ocean, land and sea ice) linked by a central coupler. The coupler exchanges fluxes and state information among the above four components by MPI technique. The atmosphere, ocean, land and ice components of CCSM3 are the NCAR Community Atmospheric Model (CAM3), the Parallel Ocean Program (POP1.4.3), the NCAR Community Land Model Version 3 (CLM3), and the NCAR Community Sea Ice Model Version 5 (CSIM5), respectively. More technical details about CCSM3, CAM3, POP, CLM3, and CSIM5 can be found in Vertenstein et al. (2004), Collins et al. (2004), Smith and Gent (2004), Dickinson et al. (2006) and Briegleb et al. (2004).

In this study, the CCSM3 configuration is referred to as "-compset B -res T31_gx3v5" (Vertenstein et al., 2004). This means the horizontal resolutions are the T31 spectral truncation for both CAM3 (Collins et al., 2006b) and CLM (Dickinson et al., 2006) and a nominal 3-degree for CSIM (Briegleb et al., 2004) and POP (Simith et al., 2002). The machine used in our study is the HP Superdome Workstation (Table 1).

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As we know, the multi-year climatological mean and ensemble mean are common methods used in the climate research. We thus design two groups of experiments (Table 2) for studying these two methods. According to the CCSM3 manual (Vertenstein et al., 2004) and previous research (Chen et al., 2008), the simulated results depend on the CPU numbers of each component except the land model component. Therefore, we would like to design various experiment cases by changing the CPU numbers used in each component. Considering both the representative of the parallel computational error and the computational resource, we design 16 cases in which the model is run for 100 yr of the multi-year climatological mean (Experiment 1; Table 2), and 54 cases in which the model is run for 10 yr of the ensemble mean (Experiment 2; Table 2). All of the model outputs are the monthly average. These experiments represent any combinations of different CPU number with each component and have prominent representativeness for the analysis of the parallel computational uncertainty.

3 Analyses and results

SST is an important parameter to measure the coupled model simulations since it is in the interface of the ocean and atmosphere and plays a key role in the ocean and atmosphere interaction for shaping climate variability. In this paper, we analyze the influence of the parallel computational uncertainty on the simulated SST. We choose the global average SST (Global-SST) for representing the global simulation, and Nino3.4 SST (Nino-SST) for manifesting variability in the equatorial Central/Eastern Pacific where the ocean-atmosphere interaction is one of the strongest regions in the climate system.

From the model-simulated perspective, there is no exactly true value in the climate simulation. In order to clearly describe and compare the experiment results, we define

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a standard value and a deviation as:

$$\overline{X} = \frac{1}{N}\sum_{i=1}^{N} X_i$$

$$D_i = X_i - \overline{X}, \quad i = 1, 2, \cdots, N$$

where $\overline{X}$ is the standard value, D_i is the deviation between simulation and the standard value. X_i is the case's simulations in two experiments, and N is the number of cases in two experiments (which is 16 and 54 in Experiments 1 and 2, respectively).

3.1 Results with the monthly time series

The time series of a variable is often used to reflect climate variations in climate research. Here we first diagnose the impact of the parallel computational error on the monthly time series. The deviations of the Global-SST and Nino-SST for 16 cases in Experiment 1 are shown in Figs. 1 and 2, respectively. The deviation of the Global-SST is $\pm 0.2\,^{\circ}$C, while the deviation of the Nino-SST can reach to $\pm 2.0\,^{\circ}$C. The differences among 16 cases are caused by the parallel computational uncertainty. The amplitude of the deviation induced by the parallel computational uncertainty is in the same order as that of the climate system change. Furthermore, a comparison of each sub-figure shows that the deviation is not the same with each other. We also check the model runs from Experiment 2 showing a consistent result (not shown). Therefore, the uncertainty due to the parallel computational error has a major impact on the monthly time series. The influence cannot be ignored if the computing platform or the CPU distribution scheme used by CGCMs is changed. A determination of the reliability of the simulated time series is needed, especially for a climate jump phenomenon.

The ensemble mean is a common method to eliminate the uncertainty in the forecast. The question is whether the ensemble mean can reduce the parallel computational uncertainty in climate simulations. The maximum and minimum deviations change as

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a function of the member numbers of the ensemble mean is shown in Fig. 3. For both the Global-SST and Nino-SST, the deviations decrease as the numbers increase. It is noticed that when the member numbers of the ensemble mean is less than 15, the deviations decrease rapidly and therefore the change of the deviation is very steep. The maximum deviation of the Global-SST is decreased from 0.1 to 0.03, while the minimum changes from −0.14 to −0.03. For the Nino-SST, the maximum deviation is decreased from 1.2 to 0.4, whereas the minimum changes from −1.4 to −0.4. In contrast, when the average number is larger than 15, the deviations decrease slowly and their changes are almost a constant. This indicates that the increase of the ensemble mean number has a small effect if the number is already larger than 15. Thus, we can conclude that the ensemble mean can reduce the parallel computational uncertainty and more average number is better, but the ensemble mean number of 15 is enough for the sake of saving computation time.

3.2 Impact on simulated periods

The simulated period of a climate signal is very important since it can help us understand climate variability and improve climate prediction. A natural question is: does the parallel computational uncertainty affect the simulated climatic periods? The power spectrums of the Global-SST and Nino-SST for 16 case of Experiment 1 are shown in Fig. 4. For the Global-SST, all of 16 power spectrums are almost identical (Fig. 4a), with two peaks at the annual and semi-annual timescales (with 99 % confidence interval). All of 16 power spectrums for the Nino-SST peak around the 2.5-yr timescale (Fig. 4b). These indicate that all of the experiment cases are able to simulate the periods of climate signals and that the parallel computational uncertainty does not affect simulated periods.

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3.3 Results with the climatological mean

The climatological mean or climatology is also common to use for representing the seasonal cycle. In this sub-section, we investigate the influence of the parallel computational uncertainty on climatology. Figure 5 shows the changes of the annual mean Global-SST and Nino-SST deviation as a function of the number of the average years. The x-axis is the number of average years, so the number of 100 represents the climatological mean used 100-yr data. As seen in Fig. 5, the deviation is very large with a small number of average years. The amplitudes of the Global-SST and Nino-SST deviations are 0.12 °C (varying from −0.4 to 0.08) and 1.0 °C (from −0.5 to 0.5), respectively. With increasing the number of average years, the ranges of the annual mean Global-SST and Nino-SST deviation decrease and concentrate in small ranges that are only 0.04 °C and 0.1 °C. When the climatological mean is averaged by using more than 30-yr data, these small ranges of the deviations can be ignored (which can be regarded as the truncation error). Thus, the impact of the parallel computational error on the climatological mean can be ignored if we use more than 30 yr data for the average.

4 Discussion and conclusion

We design the parallel computational uncertainly experiments by using different CPU configuration based on the state-of-art climate model of CCSM3. The results show that the influence of the parallel computational uncertainly on model simulations cannot be ignored if the computing platform or the CPU distribution scheme used by CGCMs is changed. However, the ensemble mean method is able to reduce the impact of the parallel computational uncertainty and the member number of the ensemble mean is 15 is enough to ignore simulated error. The random perturbation experiments also show the similar results (Z. Y. Song, personal communication, 2011). The parallel computational uncertainly can affect the climatology results, but it can be ignored if we use more than 30 yr to average the climatological mean. The power spectrum analyses show that the parallel computational uncertainty does not largely affect the period of climate signal. Finally, it is suggested that the influence of the parallel computational uncertainty on the CGCMs can be a quality standard or a metric for developing CGCMs. And, the present paper mainly focuses on SST and other variables such as precipitation and radiative flux need to be analyzed in the future.

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Table 1. Computer configuration.

HP Superdome Workstation	
Hardware	128-core 1.66GHz Itanium2 IA64 CPU
OS	HP-UX B.11.23
Fortran Compiler	HP F90 V3.0
C Compiler	HP c/aC++ A.06.15
MPI	HP-MPI A.06.15 for HP-UX

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Table 2. Experiments descriptions.

Component	Experiment 1 (16 cases) CPU Numbers		Simulation length (years)	Experiment 2 (54 cases) CPU Numbers			Simulation length (years)
Land Surface	2		100	2			10
Atmosphere	2	4	100	2	4		10
Sea Ice	2	4	100	2	4	6	10
Ocean	4	8	100	4	8	12	10
Coupler	2	4	100	2	4	6	10

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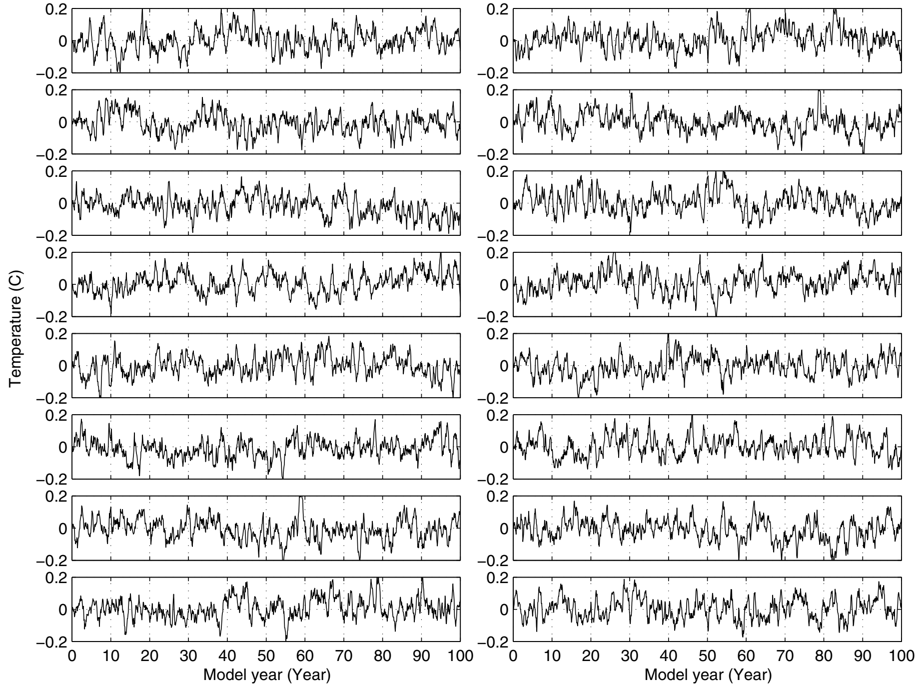

Fig. 1. Deviations of the Global-SST for 16 cases in Experiment 1.

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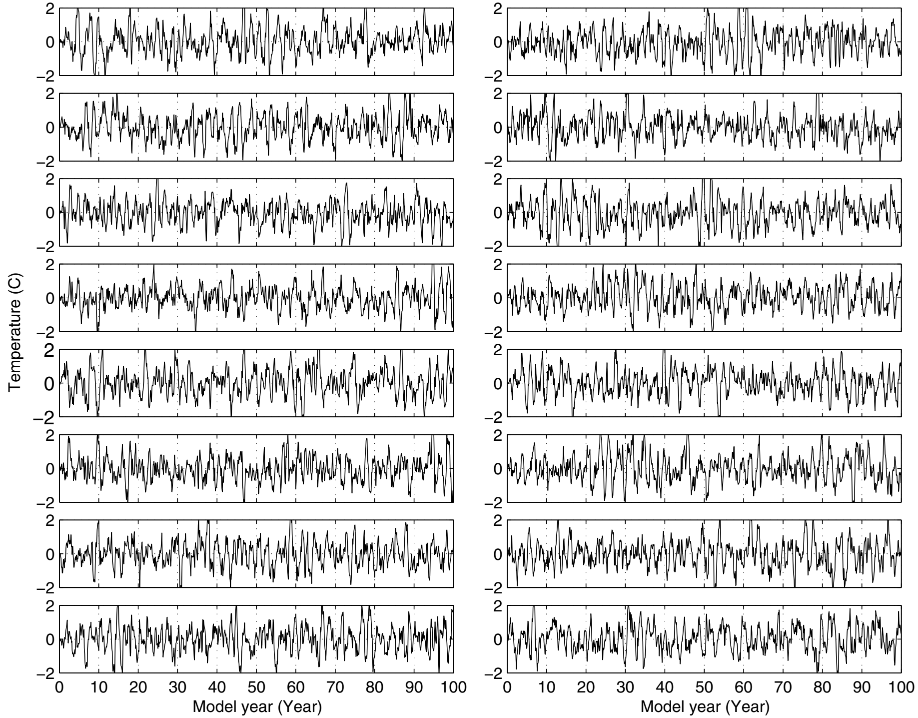

Fig. 2. Deviations of the Nino-SST for 16 cases in Experiment 1.

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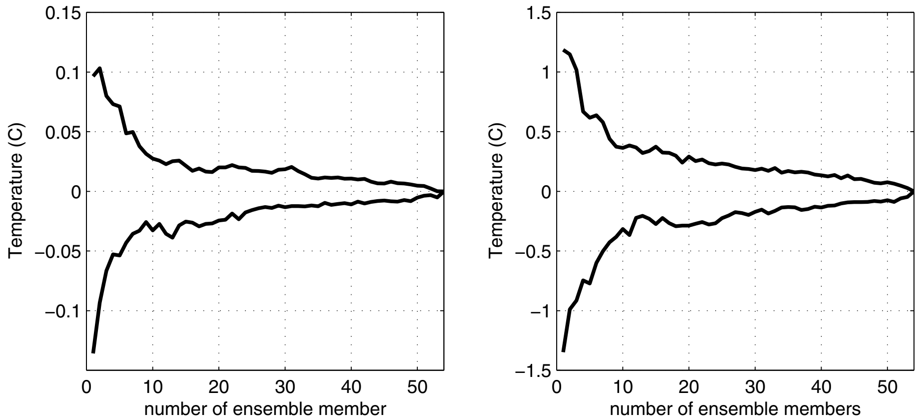

Fig. 3. The evolution of maximum and minimum Global-SST (left) and Nino-SST (right) deviation with the number of ensemble members.

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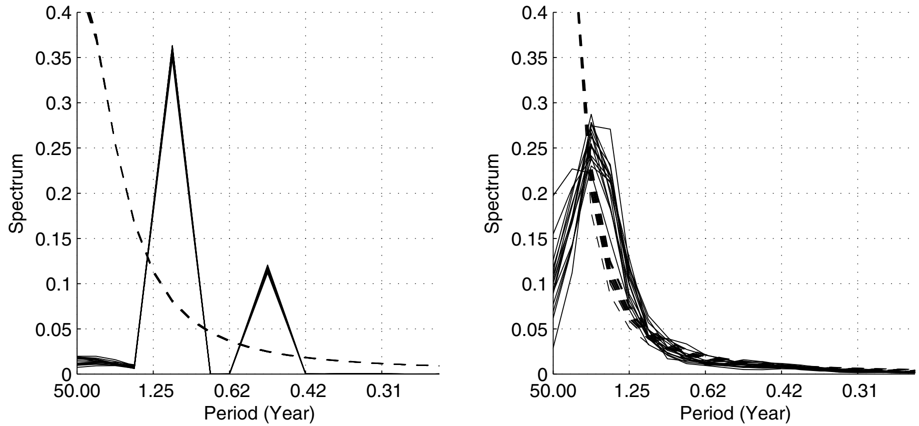

Fig. 4. The power spectrums of Global-SST (left) and Nino-SST (right) for 16 cases in Experiment 1.

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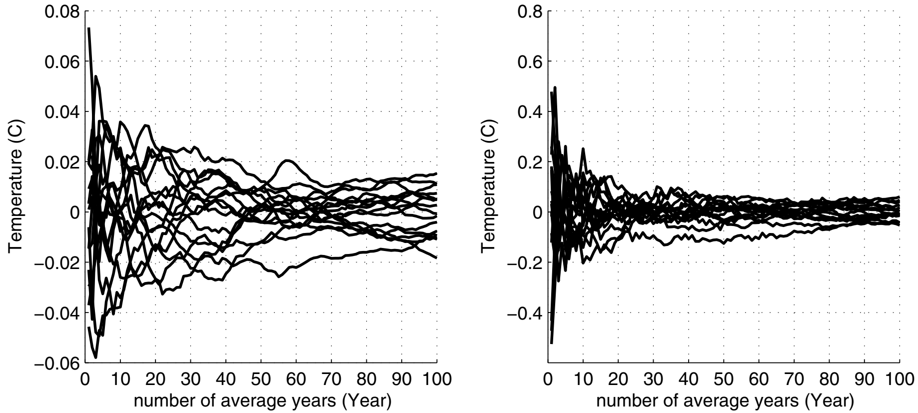

Fig. 5. The evolution of maximum and minimum Global-SST (left) and Nino-SST (right) deviation with the number of average years in climatology.

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