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Plausible effect of climate model bias on abrupt climate change simulations in Atlantic sector

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ABSTRACT

Although considerable progress towards reducing tropical climate biases in the tropical Pacific has been made in many current-generation of climate models over the past decades, reducing large biases and maintaining good agreement with the observations in the tropical Atlantic is still a major challenge and this deficiency may seriously degrade the credibility of the models in their simulation and projection of future climate change in the Atlantic sector. In this paper, we show that the bias in the eastern equatorial Atlantic has a major effect on sea-surface temperature (SST) response to a rapid change in the Atlantic Meridional Overturning Circulation (AMOC). By comparing identical water hosing experiments conducted with two different coupled general circulation models, we dissect oceanic mechanisms underlying the difference in models' SST response. The results show that the different SST response is plausibly attributed to systematic differences in the simulated tropical Atlantic ocean circulation. Therefore, in order to accurately simulate past abrupt climate changes and project future changes, the bias in climate models must be reduced.

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1. Introduction

The notorious tropical bias problem in climate simulations of global coupled general circulation models (CGCMs) (e.g., Mechoso et al., 1995; Latif et al., 2001; Davey et al., 2002; Meehl et al., 2005) manifests itself particularly strongly in the tropical Atlantic. While progress towards reducing tropical climate biases has been made in the tropical Pacific over the past decades (e.g., Deser et al., 2006), little or no progress has been made in the tropical Atlantic (Breugem et al., 2006; Richter and Xie, 2008; Wahl et al., 2009). The climate bias problem is still so severe that one of the most basic features of the equatorial Atlantic Ocean – the eastward shoaling thermocline – cannot be reproduced by most of the Intergovernmental Panel on Climate Change (IPCC) assessment report (AR4) models (Richter and Xie, 2008). This deficiency seriously degrades the credibility of the models in their simulation and projection of future climate change in the Atlantic sector.

Reducing biases in the Atlantic sector has particularly important implications for climate change studies, because the Atlantic Ocean has a special place in Earth's climate system. It is the only ocean where deep water forms in northern high latitudes and feeds into a large-scale circulation system known as the AMOC. Past climate change records indicate that abrupt climate transitions are associated with pronounced changes in the AMOC, and a future abrupt climate change is within the realm of possibility (Broecker, 1997). If it occurs, its impact on climate patterns in the Atlantic sector, as well as on the rest of the planet will be enormous. The latest IPCC report projects a 25% reduction in the AMOC strength by the end of 21st century. What are the ramifications of a weakened AMOC to regional scale climate change in the Atlantic sector? The severe bias problem in current global climate models seriously hampers our ability to address this issue. In this study, we exemplify this problem through an inter-model comparison study of tropical Atlantic response to an abrupt change in AMOC using the Geophysical Fluid Dynamics Laboratory (GFDL) Coupled Climate Model (CM2.1) and the National Center for Atmospheric Research (NCAR) Community Climate System Model (CCSM3).

The focus of the study is on oceanic processes. One important feature of the tropical Atlantic ocean circulation system is the appearance of a cold tongue of SST in the Gulf of Guinea during the boreal summer. The SST decreases from above 28 °C in May to below 23 °C in August. This Atlantic cold tongue is maintained by strong stratification of the upper-ocean and strong equatorial upwelling. Changes in either one of these processes can result in anomalous SSTs in the Gulf of Guinea, which can have a profound impact on regional climate phenomena, such as the African

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monsoon (e.g., Vizy and Cook, 2002). Chang et al. (2008) recently investigated how the cold tongue processes are affected by a substantial weakening in the AMOC. They identified an ocean pathway change mechanism on how the weakened AMOC can cause a warming in the upper equatorial ocean. The mechanism involves interactions between the AMOC and the wind-driven subtropical cell (STC) in the northern tropical Atlantic along the western boundary. A key to this mechanism is the existence of a sharp subsurface temperature gradient along the boundary between the subtropical and tropical gyres (Wen et al., 2010). North of the boundary, the salinity maximum water (SMW) subducted in the subtropical north Atlantic is much warmer than the fresher tropical gyre water to the south. The two water masses remain separate and distinct in the upper ocean (Kirchner et al., 2009), because the equatorward pathway of the north Atlantic subtropical cell is blocked by the potential vorticity barrier in the ocean interior and by the strong northward AMOC return flow along the western boundary under the present climate condition (Fratantoni et al., 2000; Hazeleger, and Drijfhout, 2006; Jochum and Malanotte-Rizzoli, 2001). The maximum subsurface temperature gradient forms around 200 m, extending all the way to the western boundary and intersecting with the western boundary near 10°N. Chang et al. (2008) showed, based on an ensemble of GFDL CM2.1 water-hosing runs, that a substantially weakened AMOC can cause the equatorward pathway of the subtropical cell to open, allowing the warm SMW of the subtropical gyre to enter the equatorial zone along the western boundary. In this study, we further examine this mechanism by comparing the GFDL CM2.1 simulations to an identical ensemble of water-hosing runs using the NCAR CCSM3. We will demonstrate the efficiency of the oceanic pathway change mechanism depends on the severity and different pattern of the bias problem in the model, which in turn affects the model's ability to simulate tropical Atlantic response to AMOC changes.

The remainder of this paper is organized as follows: Section 2 gives a brief description of the two models and the experiments analyzed in this study. In Section 3, we examine the systematic bias of each model in the tropical Atlantic section by comparing model control simulations to observations and an ocean data assimilation product. In Section 4, tropical Atlantic response to AMOC changes are intercompared between the two models with an emphasis on the oceanic pathway change mechanism and effect of the model bias. Major conclusions and their implications are summarized and discussed in Section 5.

2. Model description and numerical experiments

2.1. Model description

The GFDL CM2.1 is a fully coupled ocean–atmosphere global general circulation model. The model has been used to conduct a suite of climate change simulations for the 2007 IPCC assessment report, and is able to simulate the main features of the observed 20th century climate change. The output of these simulations is freely available at http://nomads.gfdl.noaa.gov. The ocean model employs an explicit free surface and a true freshwater flux exchange between the ocean and atmosphere. It has 50 vertical levels (22 levels of 10-m thickness each in the top 220 m), and 1° zonal resolution. The meridional resolution is 1° outside the tropics and refined to 1/3° at the equator. The atmosphere model has 24 vertical levels, with a horizontal resolution of 2° in latitude and 2.5° in longitude. The model has produced a stable realistic multicentury control integration without flux adjustments (Delworth et al., 2006; Zhang and Delworth, 2005).

The NCAR CCSM3 is also a fully coupled model of the physical climate system, comprised of the Community Atmosphere Model (CAM), the Community Land Model (CLM), the Community Sea Ice Model (CSIM) and the Parallel Ocean Program (POP). We use the intermediate resolution configuration of the model referred to as T42 $\times$ 1 which consists of a CAM using spectral truncation of T42 (grid spacing of 2.8°) coupled to a POP and a CSIM on a grid with approximately 1° horizontal resolution. More detailed information about CCSM3 can be found at the CCSM website: http://www.ccsm.ucar.edu/models. The performance of the CCSM in simulating present and past climate can be found in the special issue of the *Journal of Climate (vol. 19, no. 11)*.

2.2. Numerical experiments

We will analyze two sets of model experiments for each of these models. The first is a long control simulation. The GFDL CM2.1 control simulation uses the 1860 values of aerosol and trace gas concentrations, insolation, and distribution of land cover types. The integration was carried out for 1000 years without the use of flux adjustment. The control simulation produces a stable climate that resembles the observed current climate in many respects. For a detailed description and discussion of the GFDL CM2.1 control simulation, the readers are referred to Delworth et al. (2006). The NCAR CCSM3 control simulation is similar in many respects to the GFDL CM2.1 simulation, including the values of aerosol and trace gas concentrations, insolation, and distribution of land cover types used in the GFDL simulation. The model was integrated for more than 600 years. Detailed description and discussion of the NCAR CCSM3 control simulation can be found in Collins et al. (2006). We used the last 100 years of the simulations from each model for the analysis of model bias and for comparison with the water hosing experiments.

The water hosing experiments carried by both models are identical in freshwater forcing strength and location. Each model experiment contains an ensemble of five 60-year runs, each of which has slightly different atmospheric and oceanic initial conditions. The freshwater forcing is set at 0.6 Sv (1 Sv $\equiv$ $10^6\ m^3\ s^{-1}$) and is uniformly distributed over northern North Atlantic (55°–75°N, 63°W–4°E) for the entire 60-year duration of the experiment. The GFDL CM2.1 water hosing experiment was conducted by Zhang and Delworth (2005), whereas the NCAR CCSM3 water hosing experiment was carried out by the authors of this paper. The large amplitude of the freshwater forcing was chosen to clearly illustrate the response of the climate system to an abrupt change in the AMOC. The rationale of using an ensemble approach is to reduce the effect of internal atmospheric and oceanic variability on the forced response. In the following discussion, all the analyses of the water hosing experiments, unless noted otherwise, are based on ensemble-average of five individual members. The model bias analysis is based on comparison between annual mean values of model control simulations and of the simple ocean data assimilation (SODA) product (Carton and Giese, 2008).

3. Model bias in tropical Atlantic sector

As in other fully coupled climate models, the GFDL CM2.1 and NCAR CCSM3 show strong biases in the tropical Atlantic. Fig. 1a shows the annual mean SODA SST and observed surface wind stresses used in the SODA reanalysis. The observed precipitation used for the Common Ocean-ice Reference Experiments (CORE) (http://data1.gfdl.noaa.gov/nomads/forms/mom4/CORE.html) is shown in Fig. 1B. The simulated fields and the model biases defined as simulations minus SODA/CORE are shown in Fig. 1C, E