Test of an Improved Convection Scheme in the National Centers for Atmospheric Research Community Climate System Model (CCSM3)

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Introduction

One of the major scientific objectives of the Atmospheric Radiation Measurement (ARM) Program is to use observations to improve convection and cloud parameterizations in global climate models for use in climate and climate change predictions. In our previous ARM-funded research, we developed an improved convection scheme using ARM data and demonstrated its ability to improve climate simulation in the National Center for Atmospheric Research (NCAR) Community Climate Model (CCM3) (Zhang and Mu 2005). This study continues our effort to develop a better convection parameterization by evaluating its performance in a coupled model, the NCAR Community Climate System Model (CCSM3). Preliminary results based on two 10-year-long model integrations suggest that the improved convection scheme is able to reduce significantly the double intertropical convergence zone (ITCZ) precipitation and tropical sea surface temperature (SST) biases, both of which are major biases in many coupled models (Zhang and Wang 2006). In addition, same as in Community Atmosphere Model (CAM3), the intraseasonal variability in the CCSM3 are simulated much more realistically now.

Model and Experiment Setup

The NCAR CCSM3 consists of five components: the atmospheric model, land surface model, sea ice model, ocean model, and a coupler that links the component models together. The atmospheric model is the CAM3, which is at T42 horizontal resolution with 26 levels in the vertical. The land surface model is the Community Land Model, with the same horizontal resolution. The sea ice model is the Community Sea-Ice Model (CSIM) and the ocean model is the Parallel Ocean Program. Both CSIM and Parallel Ocean Program use a 1° horizontal resolution. For details of the model, see Collins et al. (2006). Two simulations were conducted, starting from the observed SST and Sea Surface Salinity of Levitus et al. (1998) for January. The model is integrated for 10 years. In the control simulation, the standard CCSM configuration is used. In the experimental run, the Zhang-McFarlane convection scheme was revised following the implementation of Zhang and Mu (2005). The setup of the model is identical otherwise.

Results

The effect of the modifications to the Zhang-McFarlane convection scheme on the precipitation simulation in CCSM3 is demonstrated in Figure 1, which shows the 10-year mean precipitation distribution for the northern summer months June-July-August (JJA) from the control run, the experiment run, and the Xie-Arkin (1996) observations, respectively. The precipitation distribution in the control run is very similar to that in the long-term mean of the standard CCSM3 (Collins et al. 2006). In the equatorial Pacific, two ITCZ precipitation bands straddle the equator, and an overly dry tongue on the equator that extends from the eastern into the western Pacific. Both of these features are in gross disagreement with the observations, which show a single ITCZ north of the equator and an SPCZ south of the equator east of Papua New Guinea and north of New Zealand. In comparison, the experiment run shows a precipitation pattern in good agreement with the observations. In addition, the locations of the South Asian monsoon precipitation centers are better simulated than in control. However, the ITCZ south of the equator in the Indian Ocean is not well simulated in the experiment run.

The double ITCZ in the standard CCSM3 is accompanied by biases in SST. Collins et al. (2006) show that on the equator in the central and eastern Pacific, the cold bias is as large as 1 K on the annual average in SST. This cold bias is believed to be the primary cause of the dry tongue in precipitation on the equator. At the same time, south of the equator there is a warm SST bias of similar magnitude, which is associated with the heavy double ITCZ precipitation there. Since convection and SST are highly interactive in a coupled model, changes in convection parameterization should have an impact on SST simulation as well. Figure 2 shows the SST difference between the experiment and the control run for JJA. Between 5ºS and 5ºN east of the dateline, there is a significant warming, up to 1.5 K, in the climatological equatorial cold tongue region. To the southwest of this region, between 10ºS and 5ºS, 160ºE and 120ºW, there is a cooling of up to 1.5 K. These changes are of about the right magnitude to remove both the cold bias on the equator and the warm bias in the southern ITCZ region in the standard CCSM3.

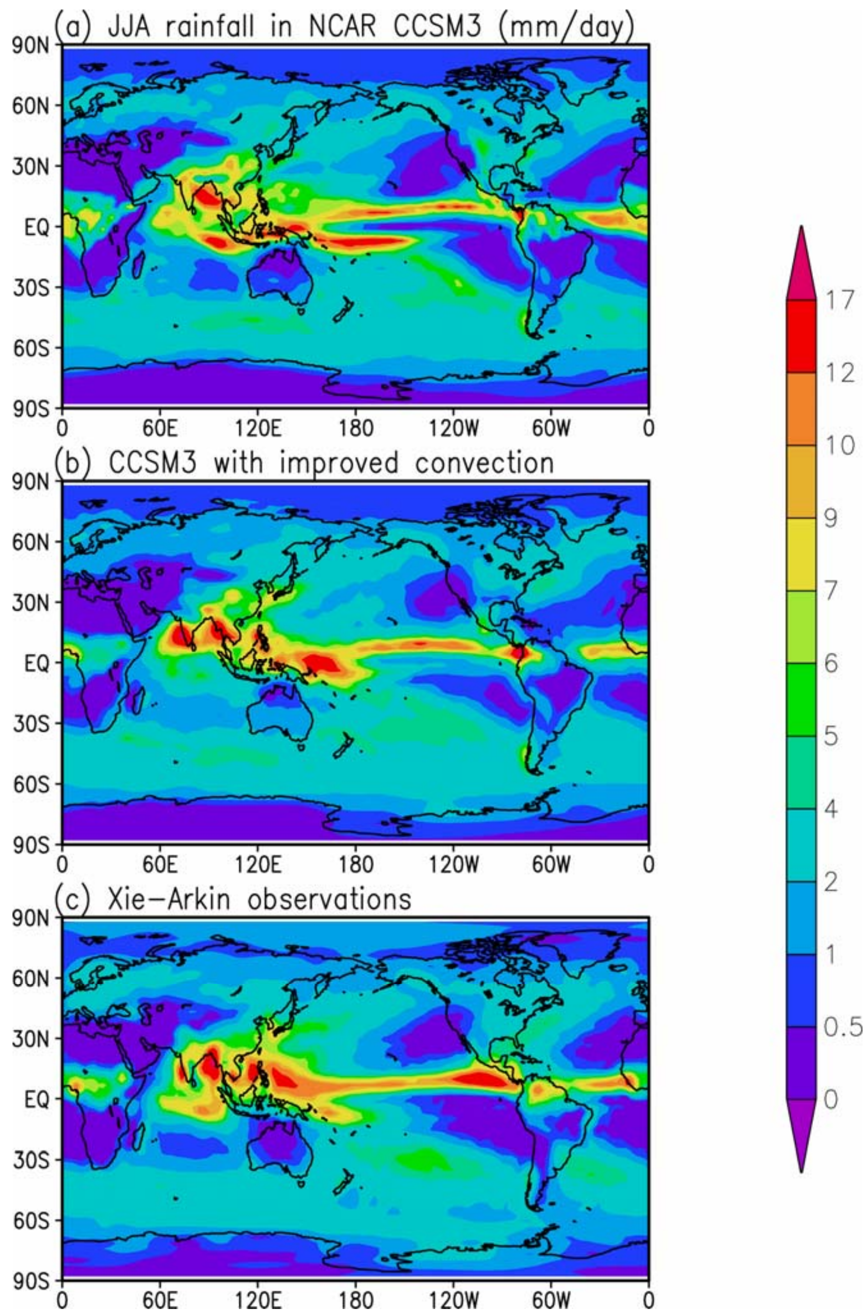

Figure 1. Global distribution of precipitation for JJA for (a) standard CCSM3, (b) CCSM3 with improved convection parameterization, and (c) Xie-Arkin observations. The model results are for a 10-year average.

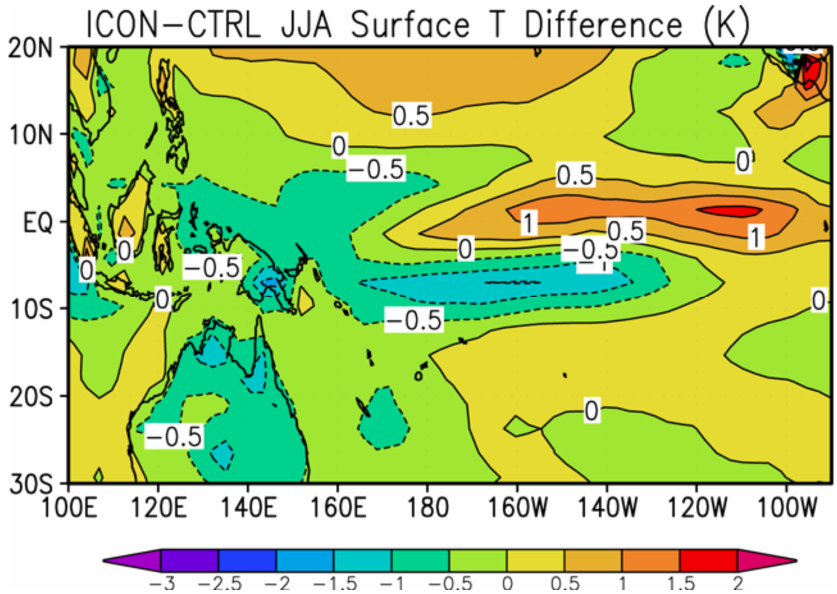

Figure 2. A 10-year average JJA SST difference in the tropical Pacific between the experiment and the control runs.

Not only are the long-term mean fields sensitive to modifications in convection parameterization, the intraseasonal variability in the coupled model also shows great sensitivity as well. As an example, Figure 3 shows the Madden-Julian Oscillation (MJO) variance of the 850 mb zonal wind averaged between 5ºS and 5ºN from the European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis and the model simulations. The variance is obtained through the following procedure: (1) isolate the 20-80 waves in the 850-mb zonal wind by applying a band-pass filter at each model grid point, (2) perform an empirical orthogonal functions (EOF) analysis on the filtered data to obtain the first two principal components, (3) reconstruct the MJO component of the 850-mb zonal wind time series at each grid point using these two principal components and the corresponding EOF modes, and (4) compute the partial variance using this time series. The ECMWF reanalysis shows a peak MJO variance in the western Pacific, with a secondary maximum in the Indian Ocean. The CCSM3 control simulation produces a very weak MJO variance in the western Pacific. In contrast, CCSM3 experiment simulation produces a maximum variance in the western Pacific comparable to that in the reanalysis data, although the location of the maximum is about 30º to the east of that in the reanalysis data. To get a sense of the effect of atmosphere-ocean coupling on the intraseasonal variability, in Figure 3 we also include the 850-mb zonal wind variance from the stand-alone atmospheric model CAM3 simulations. Although the CAM3 control run shows little qualitative difference from the CCSM3 control run in 850 mb wind intraseasonal variance, the CAM3 experiment has a significantly stronger variance than CCSM3 experiment. Previous studies suggest that air-sea interaction helps to enhance the MJO variability. This is not seen in our simulations here. Further investigation is needed to understand the effect of the air-sea interaction on MJO simulations.

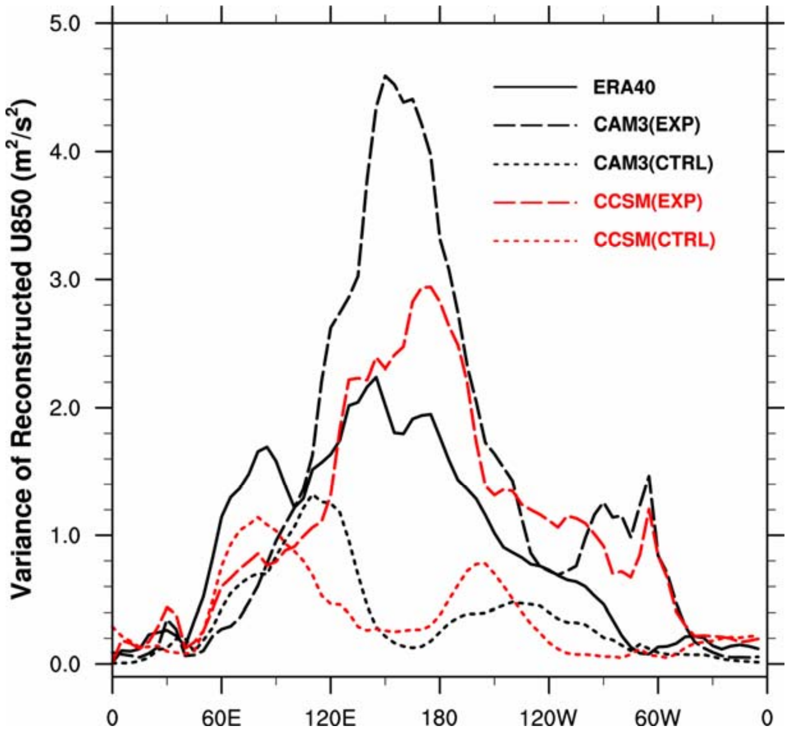

Figure 3. Variance of 850 mb zonal wind from ECMWF reanalysis and NCAR model simulations. CAM3 is the stand-alone atmospheric model, CCSM3 is the fully coupled model.

The time series of the principal components of the two leading EOFs PC1 and PC2 are used in the following way to construct an MJO index:

$$I_{mjo}(t) = PC_1(t) + PC_2(t+\tau),$$

where t is time in pentads, τ is the lag time when the maximum correlation between PC1 and PC2 is reached. Linear regressions of the 850 mb zonal wind and precipitation against the MJO index at different time lags are calculated. Figure 4 presents the hovmöller plots of the precipitation and 850 mb zonal wind based on this regression averaged from 10ºS to 10ºN from the observations and model simulations. The observed precipitation data are from Xie and Arkin (1996) and the ECMWF precipitation is the output from the reanalysis model. The wind field in Figures 4a and 4b are both from the ECMWF reanalysis. The observations and the reanalysis show clear eastward propagation of the MJO from the Indian Ocean to the western Pacific in precipitation, and further east into the eastern Pacific in wind field. In CCSM3 control run, the MJO signal is very weak, particularly in the precipitation field. The CCSM3 experiment simulation has a much better simulation of the MJO intensity and propagation. The same is true qualitatively in the CAM3 simulations. In comparison with the observations, the eastward propagation of MJO in both CCSM3 and CAM3 experiments are somewhat too fast. We are currently investigating ways to improve this aspect of the model simulations.

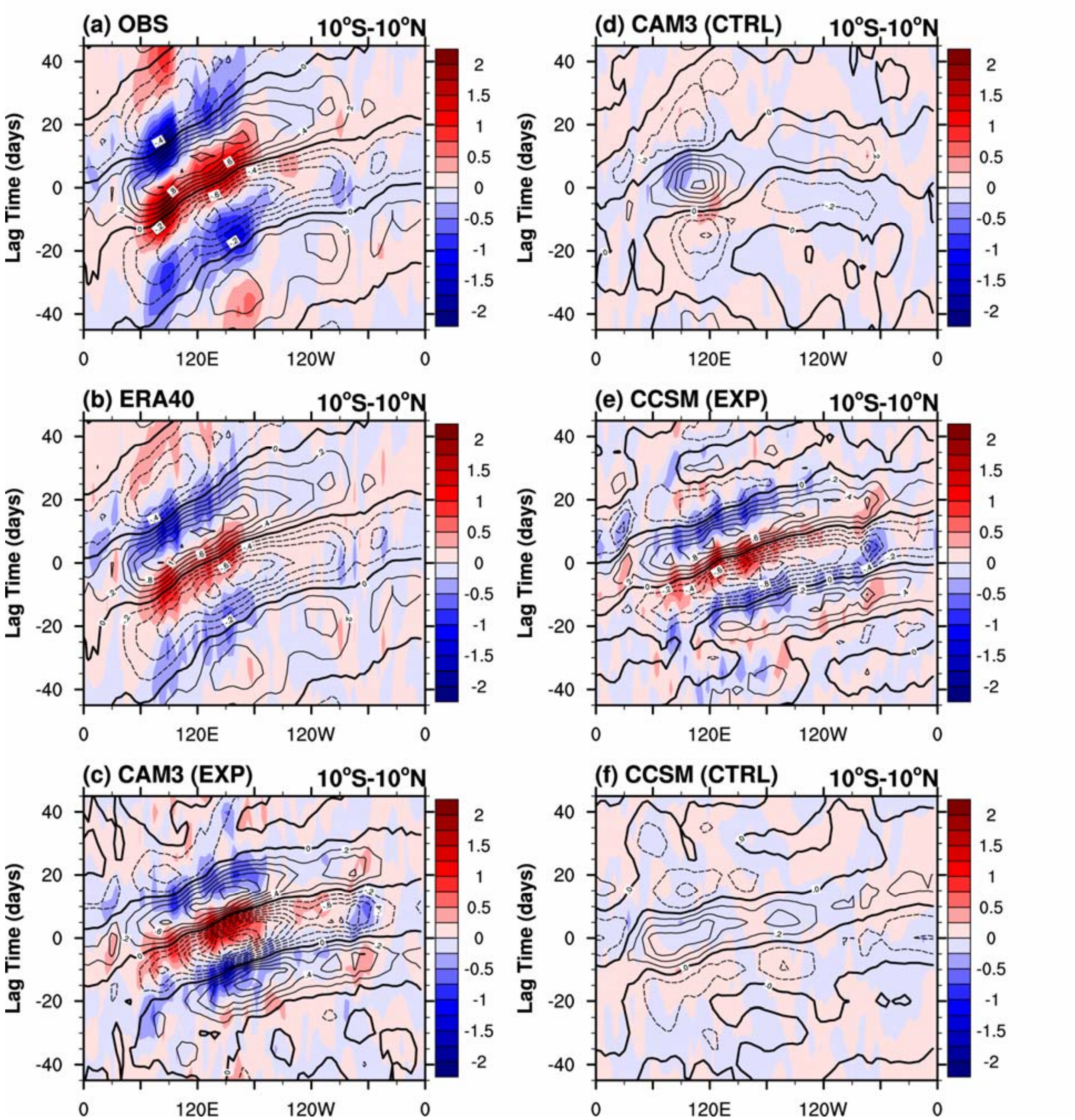

Figure 4. Time-lagged linear regression between MJO index and 850 mb zonal wind and precipitation from (a) observations, (b) ECMWF reanalysis, (c-f) experiment and control for CAM3 and CCSM3, contours are for U850 and color shadings are for precipitation. The MJO index constructed from the first two PCs of EOF is used to regress with other fields.

Conclusions

The NCAR CCSM3 simulations are performed to evaluate the modified Zhang-McFarlane convection scheme. It shows that significant improvement is made in the simulation of the Pacific ITCZ and SST. The spurious ITCZ south of the equation in the central and eastern equatorial Pacific in the control CCSM3 simulation is greatly mitigated. Accompanying this change, the eastern Pacific cold tongue SST is warmed up by over 1 K, and the southern ITCZ region SST is reduced by a similar magnitude. The SST changes in both regions help to reduce the simulated SST biases in the current CCSM3 model.

Intraseasonal variability and MJO are also simulated well in the coupled model with the use of a modified convection parameterization. These results together demonstrate the robustness of improvements from the modified convection scheme in both coupled and uncoupled NCAR GCM. Work is in progress to diagnose the mechanisms responsible for the changes and improvements in the model simulations.

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