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Preliminary Evaluation of a Revised Zhang–McFarlane Convection Scheme Using the NCAR CCM3 GCM①

Guang J. Zhang

Center for Atmospheric Sciences, Scripps Institution of Oceanography, La Jolla, California 92093–0221, *USA*

Guo Mingming (郭明明)

University of Science and Technology of China, Hefei 230026

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ABSTRACT

This study investigates the interaction between convection, clouds, and the large–scale circulation. By examining the sensitivity of the large–scale fields to a modification of the convective parameterization scheme in the NCAR CCM3, we show that the convective parameterization has a strong impact on the temporal characteristics of the large–scale circulation and clouds. When Convective Available Potential Energy (CAPE) in the atmosphere is used to close the convective parameterization, the simulated convection is continuous, and lacks the observed intermittence. When the CAPE change due to the large–scale forcing in the free troposphere is used, the simulated temporal behavior of convection is in much better agreement with the observations. We attribute this improvement to the enhanced coupling between convection and the large–scale forcing in the convective parameterization.

Key words: Convective parameterization, CCM3 GCM

1. Introduction

The parameterization of atmospheric convection is one of the most challenging issues in global climate modeling. Since convection interacts strongly with clouds and the large–scale circulation, its representation in GCMs has a tremendous impact on the simulation of the global climate and its variations. For example, in the National Center for Atmospheric Research (NCAR) Community Climate Model Version 2 (CCM2), excessive surface latent heat flux in the tropics was simulated when the Hack convection scheme (Hack 1994) was used. On the other hand, the use of the Zhang and McFarlane (1995) convection scheme in CCM3 largely eliminated this surface flux bias (Zhang et al. 1998). However, the simulated temporal variability, which was rather realistic in CCM2 (Slingo et al. 1996), was degenerated in CCM3. Recent diagnostic studies using CCM3 output suggest that the lack of temporal variations on intraseasonal timescales, such as that of the Madden Julian Oscillation (MJO), in CCM3 may be related to the failure to simulate the episodic nature of convection. Since CCM3 is used extensively by the climate research community, and it also serves as the atmospheric component of the NCAR Climate Systems Model, it is important that the identified deficiencies be addressed promptly. Toward this objective, we examine the sensitivity of CCM3 simulations to a modification of the Zhang and McFarlane convective

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parameterization scheme (hereafter referred to as the ZM scheme). Section 2 briefly describes the modification to the ZM scheme. In Section 3, we present the results from single column model simulation as well as from CCM3 GCM for the TOGA COARE period. Section 4 is the conclusion of this study.

2. Modification to convection scheme

The Zhang and McFarlane convection scheme uses the large–scale convective available potential energy (CAPE) as the closure condition to predict convection

$$M_{\mathrm{b}} = \frac{E_{\mathrm{CAP}}}{F\tau} \tag{1}$$

where E_{CAP} is CAPE; τ is the time during which CAPE is consumed by convection (set to 2 hours in CCM3); F is the proportionality factor computed from the large–scale thermodynamic profiles and the cloud model; M_{b} is the updraft mass flux at the cloud base. This closure over–emphasizes the thermodynamic properties of the surface air in triggering convection, since the temperature and moisture of the surface air dominate the contribution to CAPE (Emanuel, 1994). In a recent study, Xie and Zhang (2000) showed that the timing of convection is closely tied to the large–scale advective forcing. Consequently, they introduced a triggering function in the Zhang and McFarlane convection scheme. To adequately account for the role of the large–scale forcing in convection, we modify the closure of the ZM scheme by assuming that convection occurs only when there is a net generation of CAPE due to large–scale processes in the free troposphere. Furthermore, the amount of convection is determined by this CAPE generation. Thus, in the revised ZM scheme Eq. (1) is replaced by

$$M_{\mathrm{b}} = \frac{1}{F}\max\left\{\left(\frac{\partial E_{\mathrm{CAP}}}{\partial t}\right)_{\mathrm{non-cu}}, 0\right\} \tag{2}$$

where the subscript non–cu denotes processes other than convection in the free troposphere (above convective cloud base). These processes include large–scale horizontal and vertical advection, radiative heating / cooling, large–scale cloud condensation / evaporation, etc. This modification allows the incorporation of the large–scale forcing to drive convection in the parameterization. To some extend, this closure is similar to the Arakawa–Schubert (1974) scheme in that convection is determined by the large–scale forcing. However, there is an important difference as well. In the Arakawa–Schubert scheme, the large–scale forcing includes that from the boundary layer, which often dominates the CAPE generation.

3. Model simulations

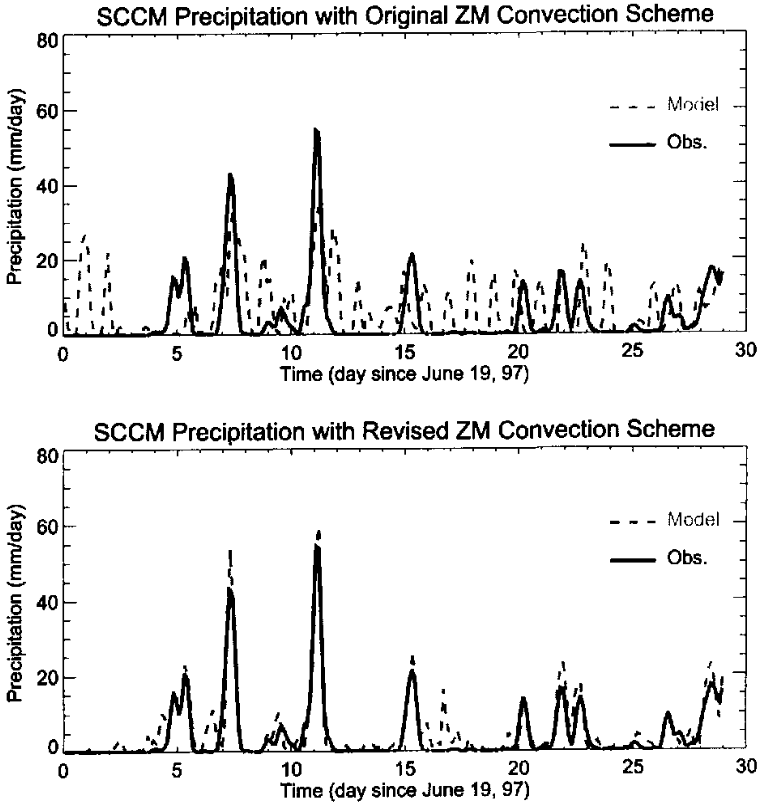
3.1 *Experiment design*

Four simulations are performed, two of which are in single column model (SCM) configuration. In these two simulations, the original and the revised convection scheme as described in Section 2 are tested using the single column model version of the CCM3. The other two simulations are with the full CCM3 GCM using the original and revised scheme. The SCM simulations use the observations in the South Great Plains from the Atmospheric Radiation Measurement (ARM) program for the period of June 19 to July 18, 1997 to drive the model. Ghan et al. (2000) provided the details on how to use the observations to drive single column models. The full CCM3 GCM simulations are carried out for the TOGA COARE period.

The model starts from Sept. 1, 1992 using a previous CCM3 simulation as the initial condition, and ends on Feb. 28, 1993. The observed sea surface temperatures are used as the boundary condition.

3.2 *Results*

We will first present the single column model results to illustrate the sensitivity of the simulated precipitation and temperature field to changes in the closure of the convective parameterization. Since single column model simulations do not allow for feedback of convection to the large–scale forcing, we will mainly focus on the full GCM simulations in this section. Figure 1 shows the time series of the simulated precipitation, together with the observations. When the original ZM scheme is used, the simulated precipitation occurs too often, almost daily, compared to the observations. When the modified convection scheme is used, both the magnitude and the timing of the observed precipitation events are well simulated. Figure 2 shows the time–height plot of the temperature differences between the SCM simulations and the observations for the simulation period. When the standard ZM scheme is


SCCM Precipitation with Original ZM Convection Scheme

SCCM Precipitation with Revised ZM Convection Scheme

Fig. 1. Time series of the simulated and observed precipitation from the NCAR CCM3 single column model for the period of June 19 to July 18 1997 at the Southern Great Plains site of the Atmospheric Radiation Measurement program. The top panel uses the standard CCM3 convection scheme, and the bottom panel uses the revised closure.

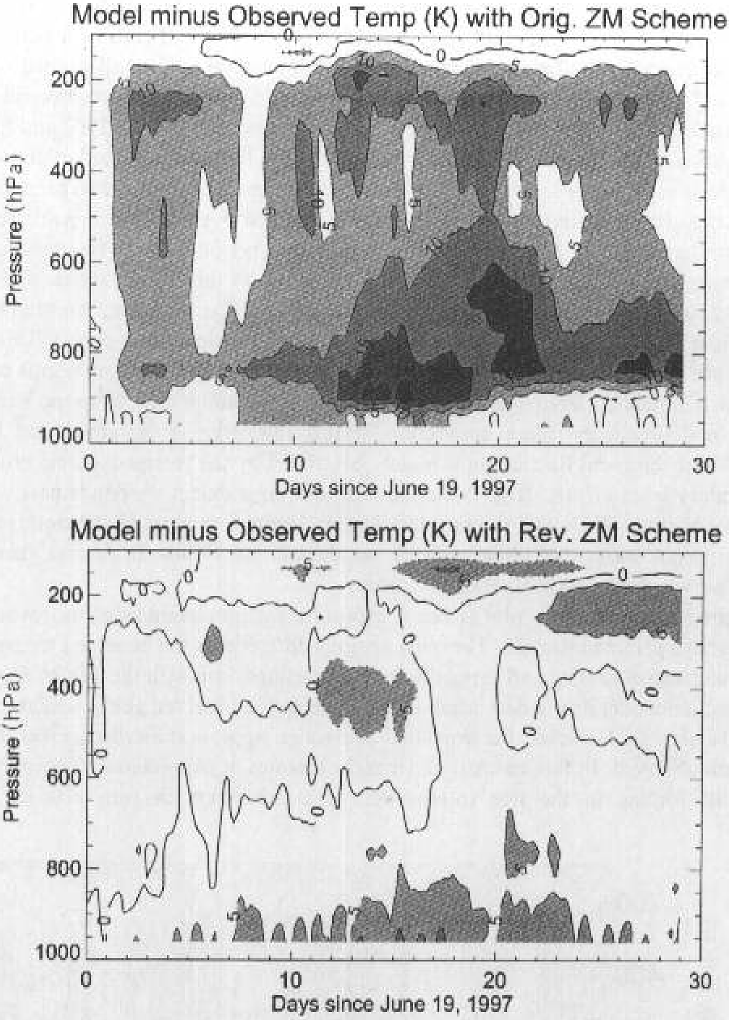


Fig. 2. Biases of the simulated temperature fields. The top panel uses the standard CCM3 convection scheme, and the bottom panel uses the revised closure. Contour intervals are 5 K, with magnitude larger than ± 5 K shaded with increasing darkness.

used, there are large warm biases in the simulated temperature field, often more than 10 K in the lower and upper troposphere. The differences are seldom within 5 K. On the other hand, when the revised closure for the ZM scheme is used, the simulated temperature bias is reduced dramatically, to within 5 K most of the time, except in the boundary layer and above 200 hPa where it is slightly larger than ± 5 K. This clearly demonstrates that use of an appropriate closure in the convective parameterization can significantly improve the model simulation of the large–scale fields.

To understand the interaction of convection with the large–scale fields, we need to invoke the full GCM simulations. Here we use the TOGA COARE period to demonstrate the sensitivity of the temporal variability of the CCM3 simulation to the modification of the convection scheme. The COARE IOP started from Nov. 1, 1992 and ended on Feb. 28, 1993, lasting 120 days. Figure 3 shows the time–height cross section of the diagnosed convective heating① Q_1 using the sounding data over the TOGA COARE IFA to show the episodic characteristics of convection. There is strong convective heating in Dec. 1992 and Feb. 1993, corresponding to the active phases of the two MJOs. There is also a period of active convection in late Jan. 1993. Figure 4 shows the time–height cross section of the large–scale vertical velocity, convective heating, and cloud fraction averaged over the warm pool, defined by (10°S, 10°N) and (140°E, 170°E) for the TOGA COARE period with the standard full CCM3 GCM configuration. One of the most serious weaknesses of the CCM3, the lack of temporal variability, is clearly seen in the convective heating field. For instance, convective heating greater than 3 K / day appears continuously throughout the simulation period. This has little resemblance to the observed convective heating. Associated with the continuous convective heating, the simulated large–scale vertical velocity also exhibits little temporal variation on intraseasonal timescales. Since convection in this simulation is parameterized based on CAPE, whose temporal fluctuation is mainly controlled by the thermodynamic properties of the boundary layer air, the large–scale motion, to a large extent, responds passively to the convective heating. The cloud fraction distribution shows that most of the clouds are in the upper troposphere above 400 hPa, with few middle and low clouds. In general, there is more cloud cover when the upward motion is stronger.

Figure 5 shows the same plot as Fig. 4, except for the simulation using the revised closure for convective parameterization. The most obvious difference is the increased temporal variability in convective heating and vertical velocity. In comparison with the TOGA COARE observations, the model does a decent job in reproducing the observed episodic character of the convective activity. However, the simulated convection appears somewhat earlier (by several days) than observed. In this simulation, since the amount of convection is determined by the large–scale forcing in the free troposphere, and convection in turn acts to drive the

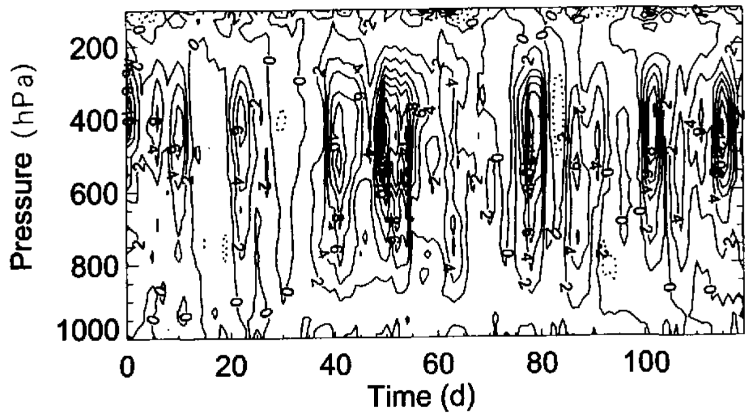


Fig. 3. Time–Height cross section of the observed convective heating over the COARE IFA for the 120–day COARE IOP.

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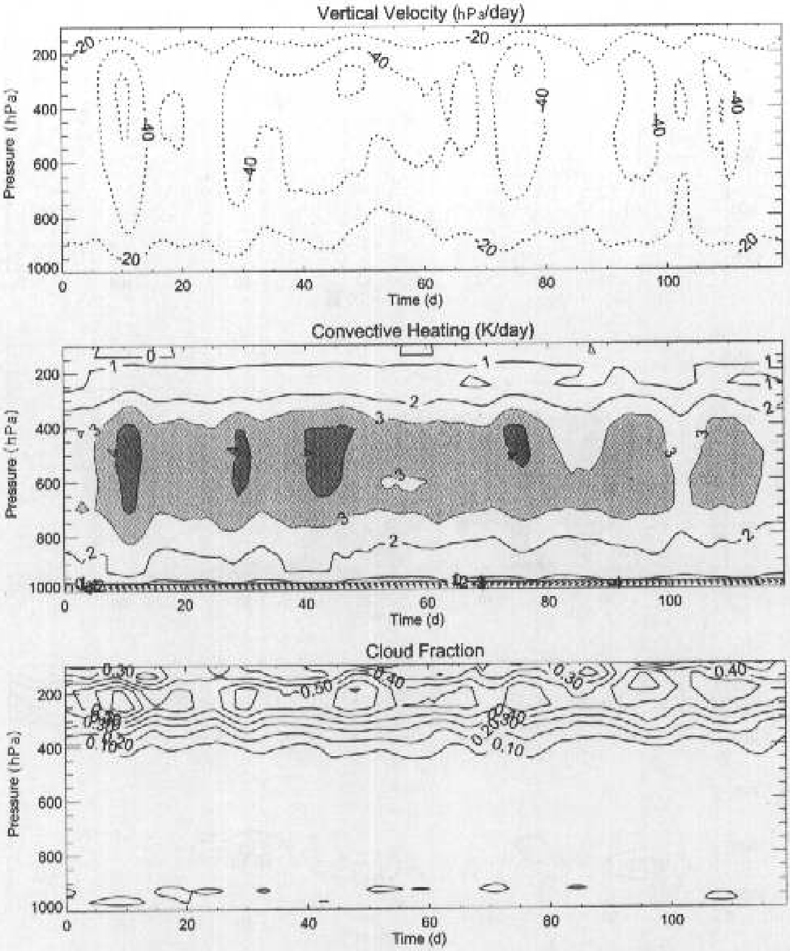
①The convective heating data is provided by Prof. R.H. Johnson of Colorado State University.



Vertical Velocity (hPa/day)

Convective Heating (K/day)

Cloud Fraction

Fig. 4. Time–height plots of large–scale vertical velocity (top), convective heating (middle) and cloud fraction (bottom) averaged over the warm pool region for the TOGA COARE period (Nov. 1 1992 to Feb. 28 1993), as simulated from the standard CCM3. The contour units are hPa / day for vertical velocity, K / day for convective heating.

large–scale forcing, there is an enhanced coupling between the two processes. The major difference in the simulated cloud cover distribution is the increased amount of low level clouds in this simulation. Note that low clouds appear during convectively inactive periods when the high–level cloud amount is relatively low. In the absence of convective cooling and drying in the boundary layer, the surface heat and moisture fluxes act to heat and moisten the boundary layer, conducive to the formation of the low–level clouds.

4. Summary and discussions

In this study, we showed that modification of the closure condition of the convective

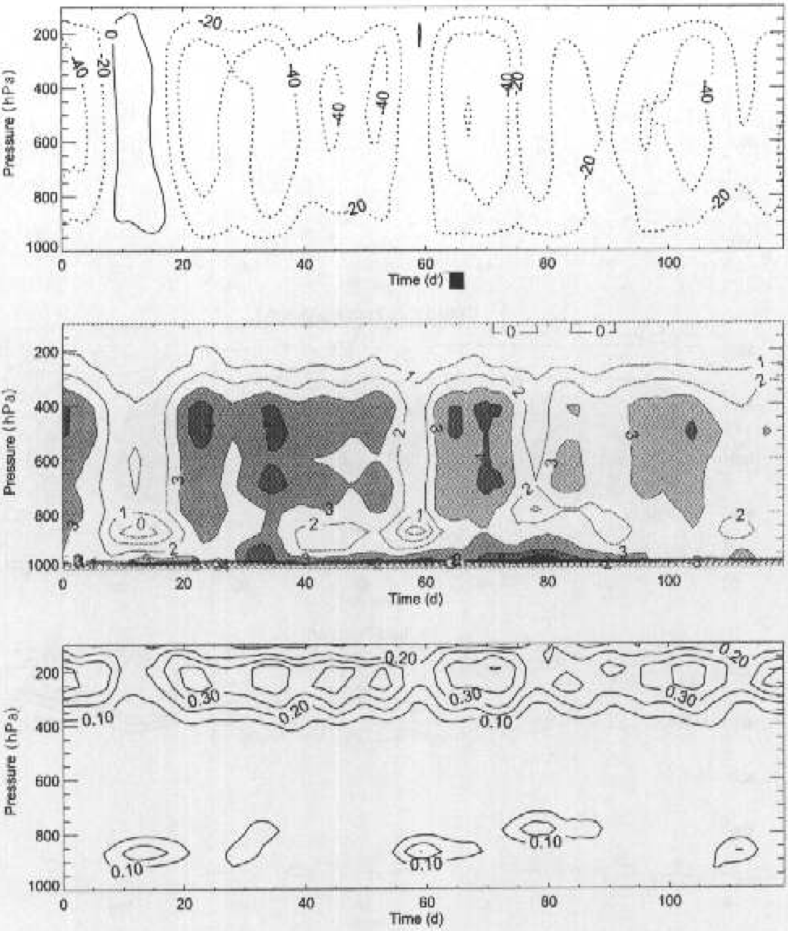


Fig. 5. Same as Fig. 4 except for the simulation using the revised closure condition.

parameterization has a significant impact on the temporal characteristics of the interaction between convection, clouds and the large-scale circulation. When CAPE is used to close the parameterization, convection tends to occur too often because the tropical atmosphere is climatologically neutral to slightly unstable (Xu and Emanuel, 1989). When CAPE generation by the large-scale forcing is used to predict convective activity, the simulated convection shows the observed episodic character. We attribute this improvement to the enhanced coupling between convection and the large-scale forcing in the parameterization.

Many climatically important tropical systems are a result of the interaction of convection and the large-scale circulation. One example is the Madden Julian Oscillation. During the disturbed phase of the MJO, convection and the large-scale upward motion mutually enhance each other as the disturbance propagates eastward. With the revised closure that represents the impact of the large-scale forcing on convection more faithfully, we expect that the simulated MJO characteristics will be improved compared to the standard CCM3 simulation.

In a recent study, Maloney and Hartmann (2001) demonstrated that when a relaxed Arakawa–Schubert scheme is used in CCM3, the simulated intraseasonal variability is indeed improved. Further investigation is currently in progress.

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