Final Report on Evaluating the Representation and Impact of Convective Processes in the NCAR's Community Climate System Model

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Convection and clouds affect atmospheric temperature, moisture and wind fields through the heat of condensation and evaporation and through redistributions of heat, moisture and momentum. Individual clouds have a spatial scale of less than 10 km, much smaller than the grid size of several hundred kilometers used in climate models. Therefore the effects of clouds must be approximated in terms of variables that the model can resolve. Deriving such formulations for convection and clouds has been a major challenge for the climate modeling community due to the lack of observations of cloud and microphysical properties. The objective of our DOE CCPP project is to evaluate and improve the representation of convection schemes developed by PIs in the NCAR (National Center for Atmospheric Research) Community Climate System Model (CCSM) and study its impact on global climate simulations.

Highlights of Accomplishments

- The project resulted in eleven peer-reviewed publications and numerous scientific presentations that directly address the CCPP's scientific objective of improving climate models.
- We developed a package of improved convection parameterization that includes improved closure, trigger condition for convection, and comprehensive treatment of convective momentum transport.
- We implemented the new convection parameterization package into several versions of the NCAR models (both coupled and uncoupled). This has led to 1) Improved simulation of seasonal migration of ITCZ; 2) Improved shortwave cloud radiative forcing response to El Niño in CAM3; 3) Improved MJO simulation in both uncoupled and coupled model; and 4) Improved simulation of ENSO in coupled model.
- Using the dynamic core of CCM3, we isolated the dynamic effects of convective momentum transport.
- We implemented mosaic treatment of subgrid-scale cloud-radiation interaction in CCM3.

Specific Achievements

1) An improved convection parameterization package

Following the Arakawa-Schubert's concept of quasi-equilibrium assumption between the destabilization of large-scale forcing and the stabilization of convection, the closure assumption of Zhang-McFarlane (ZM) convection scheme has been revised based on the work of Zhang (2002, JGR). While several research groups have tested the revised ZM scheme using the uncoupled CAM and weather forecast models, we have made further improvement to the scheme

in the NCAR models and have investigated the response of coupled CCSM simulations to the revised ZM scheme.

In the revised ZM scheme, the activation of deep convection requires the relative humidity near the surface to exceed 80%. The use of this condition has shown strong impact on the simulation of Madden-Julian Oscillation (MJO) by some GCMs. However, the model-produced MJO propagates too fast compared with observations and the seasonal variation of ITCZ has the peak in late summer and fall while CMAP observations show the peak in early summer. These inconsistencies motivate the further investigation of convection triggering using the cloud-resolving model (CRM) simulations. The quasi-equilibrium closure assumption, to certain degrees, is consistent with the successful CRM simulations of cloud systems forced by the large-scale forcing, but allows the deep convection when the convective available potential energy (CAPE) is increased by the large-scale advection and radiative cooling. The analysis of CRM simulations suggests that deep convection occurs only when the CAPE changes due to the large-scale forcing reach certain threshold (60 J/kg/hour). We replace the relative humidity constraint by the CAPE change constraint for the activation of deep convection in the revised ZM scheme.

The increasing evidence has suggested the important role of convective momentum transport (CMT) in the global climate simulations. We have implemented a CMT parameterization scheme in the NCAR models. The evaluation of the CMT scheme against three-dimensional CRM simulations demonstrates that it can capture the dominant physical processes and is able to reproduce the CRM-simulated momentum transport by convection and clouds. The essential physical processes considered in the CMT scheme include (i) the vertical momentum advection due to subsidence of environmental air compensating cloud mass flux; (ii) the detrainment of excess momentum from clouds; and (iii) the convection-induced pressure gradient force. Comparison between two sets of 20-year (1979-1998) integration using the CCM3 illustrates that the inclusion of CMT in the convection scheme systematically modifies the climate mean state over the equatorial region.

The CCSM, like most GCMs, has to tune cloud fields (e.g., cloud cover and cloud water) in order to match the observed radiation budgets. In CCM3, it calculates the cloud water path integrated from the top of the atmosphere (TOA) to altitude using a diagnostic scale height from column total precipitable water together with the prescribed exponential decay vertical distribution scaling factor, to constrain the model radiation budgets close to observations. This unrealistic setting is necessary to compensate for the CCM3 substantial overestimation of cloud amounts, especially in high levels, as well as the consequence of using the random overlap assumption. In CAM3, cloud liquid and ice condensates are predicted by the bulk microphysics parameterization. A similar problem of inconsistency between cloud properties, however, remains unsolved. As a first step to improve the cloud scheme in CCSM, a vertical scaling factor of cloud water path is derived by a fit to the CRM simulation of ARM and TOGA COARE cloud systems. The new scaling factor results in cloud water concentration that decrease with height much slower than the original CCM3 profile. As such, there is more cloud water (optically thicker) distributed in the upper troposphere with the CRM-derived profile.

2) *Improved ITCZ simulation*

The tropical precipitation belt known as ITCZ undergoes a north-south migration following the season (Fig. 1, CMAP observations). However, in the NCAR CCM3 (as well as its successors), ITCZ remains in the northern hemisphere year around (Fig. 1, upper right). By using a revised closure for convection parameterization developed by one of the PIs, we are able to simulate realistically the migration of the ITCZ (Fig. 1, lower right). Addition of convective momentum transport (CMT) in convection parameterization further improves its magnitude and timing of maximum (Fig. 1, upper left). Analysis of the mechanism of interactions among convective heating, CMT and the large-scale circulation indicates that the coupling of CMT with convective heating results in a secondary meridional circulation that slows down the equatorward flow at higher latitudes near the surface, and weakens the equatorial convergence and convection. The reduced convective heating around the Equator produces an improved meridional distribution of precipitation within the upward branch of the Hadley circulation.

Fig. 1. Ten-year mean annual cycle of zonal averaged precipitation rates from Xie and Arkin (1998) observations (CMAP, bottom left), CCM3 run with the improved convection scheme (NCCM, top left), NCCM run without CMT (NOCMT, bottom right), and standard CCM3 run (CCM3, top right).

3) *Shortwave cloud forcing response to El Niño*

Observations from Earth Radiation Budget Experiment show strong negative shortwave cloud radiative forcing (SWCF) in the central and eastern equatorial Pacific during El Niño.

However, documentation of the NCAR models shows that this SWCF response is severely underestimated by the standard CAM3 simulation at T42 resolution. We carried out two 22-yr simulations using the CAM3 with the improved and original convection scheme, respectively. The cloud shortwave response to El Niño is much improved in the CAM3 simulation with the improved convection scheme (Fig.2). It is found that positive cloud liquid water path (LWP) anomalies are mainly responsible for the improved SWCF response to El Niño. Negative LWP anomalies, largely due to reduced shallow convection and much faster decrease of low clouds during El Niño in the standard CAM3, weaken the SWCF response.

Fig.2. SWCF anomalies from (a) ERBE/CERES observations, (b) standard CAM3 and (c) CAM3 with the revised closure. The anomalies are obtained by subtracting the mean SWCF at each longitude over the period of February 1985-April 1989 for ERBE and January 1980-December 2001 for CAM3.

4) *Improved MJO simulation*

Use of the revised convection closure assumption significantly improved the simulation of MJO in CAM3, which is illustrated through longitude-phase hovmöller plots of several composite fields averaged over 10°S-10°N (Fig.3). Phases 1, 5 and 9 correspond to the beginning, mature phase and the end of the MJO cycle, respectively. The observed eastward propagation and magnitude of the MJO signals in 850 mb zonal wind, precipitation and OLR are reproduced by the new CAM3 simulation although the phase speed is still too fast. On the other hand, the MJO signal in the control run is very weak everywhere although there is a hint of eastward propagation. The analysis of the energetics of intraseasonal variability indicates that

perturbation kinetic energy (PKE) and its sources and sinks through conversion from potential energy and mean flow and generation from wave energy flux are strong in the modified CAM3 simulation and too weak in the standard CAM3 when compared with the reanalysis. The interaction between convection and large-scale circulation plays an important role in the maintenance of intraseasonal variability and MJO through PKE conversion from potential energy generated by convective heating.

Fig.3. Phase-longitude plots of 850 mb zonal wind, precipitation and outgoing longwave radiation for a composite MJO cycle from (a) NCEP reanalysis/CMAP observations, (b) CAM3 with the revised closure, and (c) standard CAM3.

5) *ENSO simulation in coupled model*

The El Niño-Southern Oscillation (ENSO) simulation remains a challenge for the fully coupled atmosphere-ocean GCM despite great progress made in observing the genesis and evolution of the phenomenon and modeling ENSO with intermediate coupled models. Part of the difficulties arises from the great uncertainty in the treatment of convection, clouds, and cloud-radiation interaction in GCMs. Cloud systems affect large-scale circulation and wave disturbances through the release of latent heat; the redistribution of heat, moisture and momentum; the reflection, absorption and emission of radiation; and the precipitation. The large-scale forcing influences and modulates the development and organization of convection and clouds. The coupling of convective processes with the large-scale dynamics is crucial for modeling the global distribution of precipitation and the MJO. Activities of MJO in the coupled model may play an important role in the simulation of ENSO. However, how these two phenomena with widely different timescales (intraseasonal and interannual) interact with each

other is still unknown, partly due to the lack of skill of fully coupled GCMs in simulating both MJO and ENSO.

We implemented the revised Zhang and McFarlane convection scheme in the NCAR Community Climate System Model version CSM 1.4. A 100-year simulation (NCSM) is conducted and compared with the standard CSM simulation and observations. It is found that the simulations of both interannual ENSO and intraseasonal MJO variability are much improved and is closer to observations. The frequent occurrence of El Nino with excessive amplitude simulated in CSM is greatly reduced to the level closer to the observations in NCSM (Fig.4). Furthermore, while the CSM fails to simulate the seasonal cycle of the ENSO variability, the NCSM correctly produces the minimum variability during May-July and the maximum during November-January as in observations although the variability during winter (December-February) is weaker than the observations. The power of intraseasonal MJO in NCSM is also much enhanced from CSM and

Fig.4. Monthly time series of Niño-3.4 SST anomaly and wavelet power spectrum analysis (left) and monthly averaged variances (right) from observations of the Hadley Centre Sea Ice and SST dataset (HadISST, 1950-1999), CSM1.4 at resolution T31 with the modified convection scheme

(NCSM, years 50-99), and standard CSM1.4 at T31 (CSM, years 50-99). Standard deviations (std) and skewness of each time series are included in the plots. The seasonal variation of SST anomaly time series is shown in the right panel.

closer to observations (Fig.5). Both NCSM and observed spectra show a peak of power at wavenumber 1 and eastward period of 64 days. The observed power spectrum also has a secondary peak at 40 days, while NCSM has a peak at 32 days. It is encouraging that the coupled GCM with the modified convection scheme is able to improve the simulation of both ENSO and MJO phenomena with very different timescales.

Fig.5. Wavenumber–frequency spectra of 200-hPa velocity potential averaged between 10°N and 10°S for ERA (ECMWF Re-Analysis)-40 reanalysis (years 1989-1998), NCSM (years 80-89) and CSM (years 80-89). The contour starts from $0.25 \times 10^{11} \text{ m}^4 \text{ s}^{-2}$ with the interval of $0.25 \times 10^{11} \text{ m}^4 \text{ s}^{-2}$. Positive (negative) frequency and period represent the eastward (westward) propagation.

A 20-100-day band-pass filter is applied to remove the annual cycle and lower frequencies in the pentad time series. The averaged spectrum is derived from individual spectra that are 64 pentads in length overlapping each other by 10 pentads.

With the improved climate variability in the coupled model NCSM, we are able to simulate an El Niño that behaves very much like a 97/98 El Niño-type event, as shown in Fig.6. It has been ten years after the strongest 1997/98 El Niño event that affected the global and regional climate and weather patterns. The origin and development of the event has been well documented in the literature and received by the public and government. The successful simulation of this El Niño event provides a unique data together with available observations to understand the physical mechanisms responsible for the El Niño events.

Figure 6. Temporal-spatial evolution of pentad 850-hPa zonal wind anomalies (ms^{-1} , middle) and SST anomalies ($^{\circ}\text{C}$, right) averaged between 2°N and 2°S and time series of pentad MJO index (left) for observations (NCEP, July 1996-July 1998, top), and NCSM (July year 89-July year 91, bottom). Anomalies are with respect to the mean over the two-year period. To get the MJO index, a band-passed 20-100-day band-pass filter is applied to 850-hPa streamfunction field (50°N to 50°S). A space-time extended empirical orthogonal function (EEOF) analysis is then used to get the dominant modes. Each mode of EEOF has a set of substructures that represent the

time lags at -10 day, -5 day, 0 day, +5 day, +10 day. With the first two dominant EEOF modes, the MJO index is obtained as the square root of the sum of the squares of the two principle components (EEOF-1 and EEOF-2).

6) *Dynamic effects of CMT*

The effect of CMT in a full GCM is intertwined with other model physics effects. To isolate the dynamical effects of the CMT on global circulation, we performed an idealized GCM experiment using the CCM3 dynamic core. Here, an experimental setup is designed in which all physical parameterizations except the deep convection scheme are replaced with the idealized forcing. The CMT scheme is incorporated into the convection scheme to calculate the CMT forcing, while convective temperature and moisture tendencies are replaced with Newtonian cooling to remove its physical feedback. Excluding the response of complex physical processes, the idealized CCM3 contains a complete dynamical core and the CMT forcing. Two sets of five-year simulations using the idealized CCM3 with (IDCMT) and without (IDCTL) convective momentum transport are presented in Fig.7. The zonal wind difference between the IDCMT and the IDCTL run is large. The tropical easterlies become stronger and broader above 700 mb when CMT is included and westerly occurs below 700 mb between 10°S and 10°N. The meridional wind difference shows that the equatorward and poleward branches of the Hadley circulation are strengthened when the CMT is included. The meridional wind and vertical velocity together clearly show that the inclusion of CMT leads to an increase in intensity of the Hadley circulation.

Fig.7. Zonal average of the difference of (a) zonal wind (m s^{-1}), (b) meridional wind (m s^{-1}), (c) vertical velocity (mb day^{-1}), and (d) temperature (K) between the IDCMT and IDCTL runs.

The CCM3 with idealized physics captures the fundamental response of large-scale circulation to the CMT forcing, indicating that the dynamical process makes a significant contribution to the total response of circulation to the CMT forcing in the full GCMs. For the temperature field, there is cooling near the equator and warming in the subtropics in troposphere when the CMT is taken into account. The temperature change is generally consistent with the adiabatic heating/cooling associated with the vertical velocity change. Further analysis finds that the modification of the Hadley circulation is an indirect response of meridional wind to the zonal CMT forcing through the Coriolis effect, which is required to maintain near-geostrophic balance.

7) *Effect of subgrid cloud-radiation interaction on climate simulations*

Most GCMs have to tune the cloud fields such as cloud liquid/ice water paths and cloud fractions in order to match the observed radiation budgets at the TOA and the surface. For the CCM3, which calculates the cloud liquid water using a diagnostic liquid water scale height from total precipitable water, this tuning procedure is accomplished with very unrealistic representation in both cloud amount and cloud water path to constrain the model radiation budgets close to observations. The reference water concentration is set to an unrealistically low value and the vertical distribution is prescribed as an exponential decay function of the scaled altitude. The setting compensates for the large overestimation of total cloud amount due to the random overlap assumption, which is physically inconsistent.

Improved mosaic treatment of subgrid cloud-radiation interactions was implemented into the CCM3. The 5-year (1979-1983) AMIP simulations prescribed with the observed SST showed encouraging results. In particular, the mosaic treatment produces smaller radiation-effective clouds than the random overlap assumption. This facilitates removal of the necessity to use unrealistic cloud amount and cloud water contents in order to maintain the global radiation budget closer to satellite observations in the standard CCM3 simulation. Sensitivity experiments with modified cloud parameterizations showed that the mosaic approach enables the use of more realistic cloud amounts *as well as* cloud water contents (Fig.8) in producing net radiative fluxes closer to observations (Fig.9). This leads to a significantly different radiative heating rate; consequently, not only the representation of cloud-radiation interaction is more physically consistent and accurate, but also mean climate variables, such as the temperature field, are better simulated over the tropical upper troposphere and overall are closer to reanalysis and observational data (Fig.10). The global annual mean precipitation rates from the mosaic and the standard CCM3 simulations are 2.97 and 3.10 mm day^{-1} , as compared to 2.69 mm day^{-1} in observations.

Fig. 8. Left: 5-year (79-83) averages of high-level cloud fraction (percent) from CCM3 (GCM, top), mosaic run (MOS, middle), and ISCCP (bottom). Right: 5-year averages of total cloud liquid water path (g m^{-2}) from CCM3 (GCM, top), mosaic run (MOS, middle), and SSM/I (bottom).

Fig. 9. 5-year global averages of radiative fluxes (Wm^{-2}) from observations (OBS), CCM3 (GCM) and mosaic run (MOS).

Fig.10. 5-year zonal average of the difference of radiative heating rate (Kday^{-1}) between mosaic run (MOS) and GCM (left), the differences of temperature (K) between GCM and NCEP (middle) and between MOS and GCM (right).

List of published and submitted journal articles resulting from this project:

- Wu, X., and X. Liang, 2005: Effect of subgrid cloud-radiation interaction on climate simulations, *Geophys. Res. Lett.*, **32**, L24806, doi:10.1029/2005GL024432.
- Wu, X., and S. Guimond, 2006: Two- and three-dimensional cloud-resolving model simulations of the mesoscale enhancement of surface heat fluxes by precipitating deep convection. *J. Climate*, **19**, 139-149.
- Wu, X., L. Deng, X. Song, and G. J. Zhang, 2006: Coupling of convective momentum transport with convective heating and moistening in global climate simulations. *J. Atmos. Sci.*, **64**, 1334-1349.
- Song, X., X. Wu, G. J. Zhang, and R. W. Arritt, 2008: Dynamic effects of convective momentum transports on global climate simulations. *J. Climate*, **21**, 180-194.
- Wu, X., and X.-Z. Liang, and S. Park, 2007: Cloud-resolving model simulations over the ARM SGP. *Mon. Wea. Rev.*, 2841-2853.
- Wu, X., L. Deng, X. Song, G. Vettoretti, W. R. Peltier, and G. J. Zhang, 2007: 1997/98 El Niño-type event simulated by the coupled global climate model. *Geophys. Res. Lett.*, **34**, L16823, doi:10.1029/2007GL030637.
- Li, G., and G. J. Zhang, 2008: Understanding biases in shortwave cloud radiative forcing in the National Center for Atmospheric Research Community Atmosphere Model (CAM3) during El Nino, *J. Geophys. Res.*, **113**, D02103, doi:10.1029/2007JD008963.
- Mu, M., and J. G. Zhang, 2008: Energetics of the Madden Julian Oscillation in the NCAR CAM3: A composite view. *J. Geophys. Res.*, **113**, D05108, doi:10.1029/2007JD008700.
- Wu, X., and X. Li, 2008: A review of cloud-resolving model studies of convective processes. *Advances in Atmospheric Sciences*, **25**, 202-212.
- Wu, X., S. Park, Q. Min, 2008: Seasonal variation of cloud systems over ARM SGP. *J. Atmos. Sci.*, **65**, 2107-2129.
- Song, X., X. Wu, G.J. Zhang, and R. Arritt, 2008: Understanding the effects of convective momentum transport on climate simulations: The role of convective heating. *J. Climate.*, **21**, 5034-5047, doi: 10.1175/2008JCLI2187.1

Conference proceedings:

- Wu, X., and G. J. Zhang, 2004: Evaluating the representation and impact of convective Processes in the NCAR's Community Climate System Model, CCPP Science Team Meeting, October 18-20, 2004, Settle, Washington.
- Wu, X., 2005: Analysis of subgrid cloud-radiation interaction and its effect on climate simulations using CRMs, observations and GCMs (Invited talk). The Fourth Gordon Research Conference on Radiation and Climate, Colby College, Maine, July 28, 2005.
- Zhang, G.J., and M. Mu, 2005: Effects of convection parameterization closure on the simulation of tropical climate in the NCAR CCM3 GCM. 16th Conference on Climate Variability and Change, 85th AMS Annual Meeting, San Diego, CA, 9-13 Jan. 2005.
- Wu, X., G. J. Zhang, R. Arritt, X. Song, and L. Deng 2006: Improvement to convective processes in CCSM and its impacts on climate simulation. Part I: Physics and climate variability. CCPP Science Team Meeting, April 24-26, 2006, Cambridge, Massachusetts.
- Zhang, G. J., X. Wu, and M. Mu, 2006: Improvement to convective processes in CCSM and its impacts on climate simulations, Part II: Coupled model simulations. CCPP Science Team Meeting, April 24-26, 2006, Cambridge, Massachusetts.

- Wu, X., 2006: Further improvement to the convection scheme in CCSM. The CCSM Atmosphere Model Working Group Meeting, March 20-22, 2006, NCAR, Boulder, Colorado.
- Zhang, G. J., 2006: An Update on Testing Modifications in CAM3 Convection Parameterization: Results from Coupled Model Simulations. The CCSM Atmosphere Model Working Group Meeting, March 20-22, 2006, NCAR, Boulder, Colorado.
- Wu, X., 2006: Representation of subgrid cloud-radiation interaction and its impact on global climate simulations. The CCSM Atmosphere Model Working Group Meeting, March 20-22, 2006, NCAR, Boulder, Colorado.
- Zhang, G. J., 2006: Simulation of Madden-Julian Oscillation in NCAR Global Climate Models (Invited talk). AGU Joint Assembly, Baltimore, MD, May 23-26, 2006.
- Wu, X., 2006: Toward improving the GCM representation of convection, clouds and radiation for global climate simulations. AGU Joint Assembly, Baltimore, MD, May 23-26, 2006.
- Zhang, G. J., Dissecting Tropical Biases in the NCAR CAM3 and CCSM3. Third WGNE Workshop on Systematic Errors in Climate and NWP Models, San Francisco, CA, Feb. 12-16, 2007.