Final Report to the U.S. Department of Energy for studies of

Further Development and Applications of A Multi-scale Modeling Framework

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Principal Investigator: David A. Randall

Co-Principal Investigator: Marat Khairoutdinov

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A. Introduction

The Colorado State University (CSU) Multi-scale Modeling Framework (MMF) is a new type of general circulation model (GCM) that replaces the conventional parameterizations of convection, clouds and boundary layer with a cloud-resolving model (CRM) embedded into each grid column. The MMF that we have been working with is a "super-parameterized" version of the Community Atmosphere Model (CAM). As reported in the publications listed below, we have done extensive work with the model. We have explored the MMF's performance in several studies, including an AMIP run and a CAPT test, and we have applied the MMF to an analysis of climate sensitivity.

B. Tests of the CRM

We have conducted several studies using the MMF's cloud-resolving model in a stand-alone mode, outside the GCM. Some of this work has been done in collaboration with the University of Washington group (Bretherton et al., 2005; Khairoutdinov and Randall, 2006)).

As an example, we analyzed results from a high-resolution three-dimensional simulation of shallow-to-deep convection transition based on idealization of observations made during the Large-Scale Biosphere–Atmosphere (LBA) experiment in Amazonia, Brazil, during the Tropical Rainfall Measuring Mission (TRMM)-LBA

mission on 23 February. The doubly periodic grid has 1536 x 1536 x 256 grid cells with horizontal grid spacing of 100 m, thus covering an area of 154 x 154 km^2. The vertical resolution varies from 50 m in the boundary layer to 100 m in the free troposphere and gradually coarsens to 250 m near the domain top at 25.4 km. The length of the simulation is 6 h, starting from an early morning sounding corresponding to 0730 local time. Convection is forced by prescribed surface latent and sensible heat fluxes and prescribed horizontally uniform radiative heating

Despite a considerable amount of convective available potential energy (CAPE) in the range of 1600– 2400 J kg^{-1}, and despite virtually no convective inhibition (CIN) in the mean sounding throughout the simulation, the cumulus convection starts as shallow, gradually developing into congestus, and becomes deep only toward the end of simulation. Analysis shows that the reason is that the shallow clouds generated by the boundary layer turbulence are too small to penetrate deep into the troposphere, as they are quickly diluted by mixing with the environment. Precipitation and the associated cold pools are needed to generate thermals big enough to support the growth of deep clouds. This positive feedback involving precipitation is supported by a sensitivity experiment in which the cold pools are effectively eliminated by artificially switching off the evaporation of precipitation; in the experiment, the convection remains shallow through- out the entire simulation, with a few congestus but no deep clouds.

The probability distribution function (PDF) of cloud size during the shallow, congestus, and deep phases was analyzed using a new method. During each of the three phases, the shallow clouds dominate the mode of the PDFs at about 1-km diameter. During the deep phase, the PDFs show cloud bases as wide as 4 km. Analysis of the joint PDFs of cloud size and in-cloud variables demonstrates that, as expected, the bigger clouds are far less diluted above their bases than their smaller counterparts. Also, thermodynamic prop- erties at cloud bases are found to be nearly identical for all cloud sizes, with the moist static energy exceeding the mean value by as much as 4 kJ kg^{-1}. The width of the moist static energy distribution in the boundary layer is mostly due to variability of water vapor; therefore, clouds appear to grow from the air with the highest water vapor content available.

No undiluted cloudy parcels were found near the level of neutral buoyancy. It appears that a simple entraining-plume model explains the entrainment rates rather well. The least diluted plumes in the simulation correspond to an entrainment parameter of about 0.1 km^{-1}.

C. AMIP Run

The MMF has been used to perform a 19-year long AMIP style simulation using the 1985-2004 sea surface temperature (SST) and sea ice distributions as prescribed boundary conditions. This is a major milestone, made possible by DOE supercomputer power. An analysis of the results has been submitted for publication. In the analysis of the results, particular focus has been given to the simulation of the interannual and subseasonal variability.

The annual mean climatology is generally well simulated. Prominent biases include excessive precipitation associated with the Indian and Asian Monsoon seasons, precipitation deficits west of the Maritime Continent and over Amazonia, shortwave cloud effect biases west of the subtropical continents due to insufficient stratocumulus clouds, and longwave cloud effect biases due to overestimation of high cloud amounts especially in the Tropics. The geographical pattern of the seasonal cycle of precipitation is well reproduced, although the seasonal variance is considerably overestimated mostly because of the excessive monsoon precipitation mentioned above. The MMF does a good job of reproducing the interannual variability in terms of spatial structure and magnitude of major anomalies associated with the the El Niño / Southern Oscillation (ENSO).

The subseasonal variability of tropical climate associated with the Madden-Julian Oscillation (MJO) and equatorially trapped waves are particular strengths of the simulation. The wavenumber-frequency power spectra of the simulated outgoing longwave radiation (OLR), precipitation rate and zonal wind at 200 and 850-mb for time scales in the range 2 to 96 days compare very well to the spectra derived from observations, and show a robust MJO, Kelvin waves and Rossby waves with phase speeds similar to those observed. The geographical patterns of the MJO and Kelvin-wave filtered OLR variance for summer and winter seasons are well simulated; however, the variances tend to be overestimated by as much as 50%. The observed seasonal and interannual variations of the strength of the MJO are also well reproduced.

The physical realism of the simulated marine stratocumulus clouds is demonstrated by an analysis of the composite diurnal cycle of cloud water content, longwave (IR) cooling, vertical velocity variance, rainfall, and sub-cloud vertical velocity skewness. The relationships between vertical velocity-variance, IR cooling, and negative skewness all suggest that, despite the coarse numerical grid of the CRM, the simulated stratucumulus clouds behaves in a manner consistent with our understanding of the stratocumulus dynamics. In the stratocumulus-to-cumulus transition zone, the diurnal cycle of the inversion layer as simulated by the MMF also bears a remarkable resemblance to in situ observations. It is demonstrated that in spite of the coarse spacing of the CRM grid used in the current version of MMF, the bulk of vertical transport of water in the MMF is carried out by the circulations explicitly represented on CRM grid rather than by the CRM's sub-grid scale parameterization.

D. Madden-Julian Oscillation

We have completed an observational study of the MJO (Benedict and Randall, 2007), and are comparing the results with our simulations of the MJO, in order to better understand the physical mechanisms that produce the MJO, and the reasons for our model's success in simulating it. We have examined various dynamical and thermodynamical processes that characterize the Madden–Julian oscillation (MJO). Episodes of deep convection related to the MJO based on rainfall data from the Tropical Rainfall Measuring Mission (TRMM) satellite and the Global Precipitation Climatology Project (GPCP) are identified. Although broad convective envelopes are located utilizing spectrally filtered precipitation, analyses of the features within the envelopes are carried out using unfiltered rainfall and 40-yr ECMWF Re-Analysis (ERA-40) fields. The events are composited and categorized based on geographic location and relative intensity.

The composited fields illustrate that, prior to the onset of deep convection, shallow cumulus and cumulus congestus clouds are actively involved in vertical convective transport of heat and moisture. Drying, first accomplished immediately following deep convection in the lower troposphere, is associated with an enhanced horizontal (westerly) advective component and may be related to mesoscale processes. Drying related to deep-layer subsidence is delayed until one to two weeks following intense rainfall. The importance of gradual lower-tropospheric heating and moistening and the vertical transport of energy and moisture are shown in a comparison of vigorous and weak MJO events. Additionally, a comparison of the composite fields to proposed wave instability theories suggests that certain theories are effective in explaining specific phases of the disturbance, but no single theory can yet explain all aspects of the MJO. Our resultsshow that The discharge–recharge and frictional moisture convergence mechanisms are most relevant for explaining many of the observed features of MJO evolution.

E. Hydrologic cycle

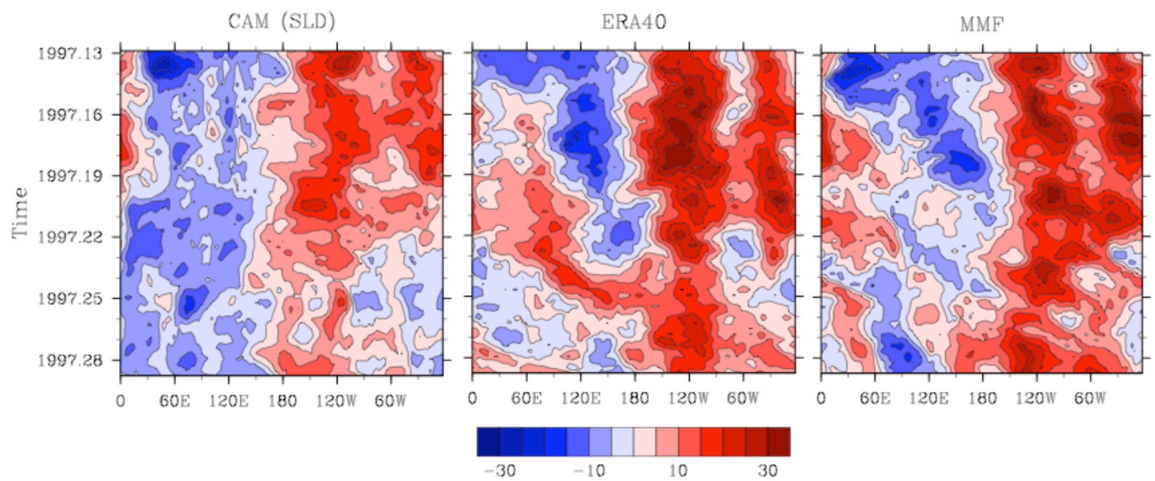
We have completed an analysis of the simulated hydrologic cycle over the Oklahoma ARM site and the Amazon (DeMott et al., 2007). We compared the precipitation variability produced by the standard CAM, and the MMF. Probability distribution functions (PDFs) of daily mean rainfall in three geographic locations [the Amazon Basin and western Pacific in December–February (DJF) and the North American Great Plains in June–August (JJA)] indicate that the CAM produces too much light–moderate rainfall (10 - 20 mm day-1), and not enough heavy rainfall, compared to observations. The MMF underestimates rain contributions from the lightest rainfall rates but correctly simulates more intense rainfall events. These differences are not always apparent in seasonal mean rainfall totals.

Analysis of 3–6-hourly rainfall and sounding data in the same locations reveals that the CAM produces moderately intense rainfall as soon as the boundary layer energizes. Precipitation is also concurrent with tropospheric relative humidity and lifted parcel buoyancy increases. In contrast, the MMF and observations are characterized by a lag of several hours between boundary layer energy buildup and precipitation, and a gradual increase in the depth of low-level relative humidity maximum prior to rainfall.

The environmental entrainment rate selection in the CAM cumulus parameterization influences CAM precipitation timing and intensity, and may contribute to the midlevel dry bias in that model. The resulting low-intensity rainfall in the CAM leads to rainfall–canopy vegetation interactions that are different from those simulated by the MMF. We present evidence suggesting that this interaction may artificially inflate North American Great Plains summertime rainfall totals in the CAM.

F. Tests of the MMF using CAPT

We have recently tested the super-CAM by using the CAPT approach with a focus on forecasting of the Madden-Julian Oscillation. Such tests determine how well a model can perform in deterministic weather prediction. The errors in model parameterizations are often apparent in such forecasting tests, and are sometimes easier to diagnose than in longer climate simulations. Some results are shown in the figure below. The super-CAM is able to maintain the



Forecasts of the 200 mb zonal wind along the Equator. Time increases down, and the horizontal axis is longitude, starting from the Greenwich Meridian. The ERA40 analysis is shown in the center, while the forecast with the standard CAM is on the left, and the forecast with the super-CAM is on the right.

observed structure of the MJO for a week or more, while the standard CAM cannot. Further studies are ongoing.

G. Climate sensitivity tests

One of the important applications that we have made of the MMF is an idealized "Cess-type" experiment on the-sensitivity of clouds to-SST perturbations. In such experiments, the simulated climate obtained by using prescribed climatological SSTs is compared to the climate obtained by perturbing the SSTs. In original Cess-type experiments, the SST are uniformly perturbed by 2 K. The main idea is to derive the implied cloud feedback to such SST perturbations. The problem is that different GCMs produce different cloud feedback not only in magnitude but also sign even when driven by identical SST perturbations. Since the CSU MMF does not parameterize convection but explicitly represents it, it would be interesting to compare its feedbacks to conventional GCMs. We have done one such experiment using the CSU MMF (Wyatt et al., 2006). This work was performed in collaboration with Chris Bretheron, Matt Wyatt, and colleagues at the University of Washington. First we ran a control simulation for three years using climatological SSTs. Then the SSTs were perturbed uniformly by +2 K. Sea ice was not interactive and was prescribed based on its climatology. The perturbed case was also run for 3 years. It appears that three-year period in this fixed-SST runs is quite sufficient to give us a high noise-to-signal ratio. Preliminary results show that the +2K climate exhibits much ‘wetter’ mean climate, with global amount of water vapor increasing by as much as 18%, mostly the in tropics. The cloud feedback is negative, -1.7 W m^{-2}, with most of the contribution coming from the solar feedback, -2.0 W m^{-2}, and the longwave feedback being positive and much smaller, +0.3 W m^{-2}. The main contribution to the negative cloud feedback appears to come from regions with stratocumulus and trade cumulus cloud regimes.

H. Geodesic MMF

We are currently testing a second super-parameterized GCM, based on the geodesic dynamical core developed under DOE’s SciDAC program. We are currently analyzing results from a 500-day simulation performed with this new model.

I. Concluding remarks

Our ARM-sponsored research project produced a wealth of scientific results, reported in numerous publications. It also supported several graduate students as they completed their training.

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Persons supported	Roles in the project
Michelle Beckman	Administrative Assistant
Mark Branson	Research Associate
Cindy Carrick	Office Manager
Ming Xuan Chen	Research Associate
Thomas Cram	Research Associate
Donald Dazlich	Research Associate
Charlotte DeMott	Research Scientist
Mostafa El Kady	System Administrator
Grant Firl	Graduate Student
Joon-Hee Jung	Research Scientist
Marat Khairoutdinov	Co-Principal Investigator
Celal Konor	Research Scientist
David Randall	Principal Investigator
Kelley Wittmeyer	System Administrator
Takanobu Yamaguchi	Graduate Student