Understanding and Improving CRM and GCM Simulations of Cloud Systems with ARM Observations

Final Report

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Abstract

The works supported by this ASR project lay the solid foundation for improving the parameterization of convection and clouds in the NCAR CCSM and the climate simulations. We have made a significant use of CRM simulations and ARM observations to produce thermodynamically and dynamically consistent multi-year cloud and radiative properties; improve the GCM simulations of convection, clouds and radiative heating rate and fluxes using the ARM observations and CRM simulations; and understand the seasonal and annual variation of cloud systems and their impacts on climate mean state and variability. We conducted multi-year simulations over the ARM SGP site using the CRM with multi-year ARM forcing data. The statistics of cloud and radiative properties from the long-term CRM simulations were compared and validated with the ARM measurements and value added products (VAP). We evaluated the multi-year climate simulations produced by the GCM with the modified convection scheme. We used multi-year ARM observations and CRM simulations to validate and further improve the trigger condition and revised closure assumption in NCAR GCM simulations that demonstrate the improvement of climate mean state and variability. We combined the improved convection scheme with the mosaic treatment of subgrid cloud distributions in the radiation scheme of the GCM. The mosaic treatment of cloud distributions has been implemented in the GCM with the original convection scheme and enables the use of more realistic cloud amounts as well as cloud water contents in producing net radiative fluxes closer to observations. A physics-based latent heat (LH) retrieval algorithm was developed by parameterizing the physical linkages of observed hydrometeor profiles of cloud and precipitation to the major processes related to the phase change of atmospheric water.

1. Background

The fundamental goal of the ASR program is ``to improve the treatment of radiation and clouds in the models used to predict future climate, particularly the general circulation models (GCMs)''. In this project, we propose to build on previous works by using the CRM and GCM simulations that integrate ARM measurements to improve the simulations of cloud systems and understand their impacts on climate mean state and variability. Specifically, we propose to:

[1] Conduct multi-year simulations over the ARM SGP site using the CRM with multi-year ARM forcing data. The statistics of cloud and radiative properties from the long-term CRM simulations will be compared and validated with the ARM measurements and value added products (VAP) such as the multi-filter rotating shadowband radiometer (MFRSR) cloud optical depths, the liquid water paths retrieved from the ground-based microwave radiometer, the continuous baseline microphysical retrieval (MICROBASE) cloud liquid and ice water properties, the broadband heating rate profiles (BBHRP), and the SGP-Clouds-Radiation product including cloud properties, radiative fluxes and radiative heating rates. The CRM simulation will be further improved by addressing the specific questions through the sensitivity experiments and diagnostic analysis. We will perform the multi-year CRM simulations over the TWP site when the continuous forcing data is available.

[2] Evaluate the multi-year climate simulations produced by the GCM with the modified convection scheme. We will use multi-year ARM observations and CRM simulations to validate and further improve the trigger condition and revised closure assumption in a 100-year coupled NCAR GCM simulation that demonstrates the improvement of climate mean state and variability. The cloud-related properties from the GCM simulations such as precipitation frequency and diurnal cycle, cloud liquid and ice water, radiative heating rate, TOA and surface shortwave and longwave fluxes, surface latent and sensible heat fluxes, and surface precipitation will be compared with ARM surface measurements and CRM simulations over the SGP and TWP sites.

[3] Combine the improved convection scheme with the mosaic treatment of subgrid cloud distributions in the radiation scheme of the GCM. The mosaic treatment of cloud distributions has been implemented in the GCM with the original convection scheme and enables the use of more realistic cloud amounts as well as cloud water contents in producing net radiative fluxes closer to observations. We will conduct multi-year uncoupled GCM simulations to examine how the combination of improved convection scheme and treatment of cloud distributions in the radiation scheme affects the simulations of climate variability.

2. Accomplishments from this ASR Project

The following is a list of the peer-reviewed journal articles that documented the outcomes of our previous project:

Wu, X., and L. Deng, 2013: Comparison of moist static energy and budget between the GCM-simulated Madden-Julian Oscillation and observations over the Indian Ocean and western Pacific. *J. Climate*, **26**, 4981-4993.

Min, Q., R. Li, X. Wu, and Y. Fu, 2013: Retrieving latent heating vertical structure from cloud and precipitation profiles. Part I: warm rain process. *J. Quant. Spectrosc. Radiat. Transfer,* http://dx.doi.org/10.1016/j.jqsrt.2012.11.030.

Li, R., Min, Q., X. Wu, and Y. Fu, 2013: Retrieving Latent Heating Vertical Structure from Cloud and Precipitation Profiles. Part II: Deep Convective and Stratiform Rains. *J. Quant. Spectrosc. Radiat. Transfer,* http://dx.doi.org/10.1016/j.jqsrt.2012.11.029.

Fridlind, A.M., A.S. Ackerman, J.-P. Chaboureau, J. Fan, W.W. Grabowski, A. Hill, T. Jones, M.M. Khaiyer, G. Liu, P. Minnis, H. Morrison, L. Nguyen, S. Park, J. C. Petch, J.-P. Pinty, C. Schumacher, B. Shipway, A. Varble, X. Wu, S. Xie, and M.H. Zhang, 2012: A comparison of TWP-ICE observational data with cloud-resolving model results. *J. Geophys. Res.,* **117**, D05204, doi:10.1029/2011JD016595.

Deng, L., and X. Wu, 2011: Physical mechanisms for the maintenance of GCM-simulated Madden-Julian Oscillation over the Indian Ocean and Pacific. *J. Climate*, **24**, 2469–2482.

Chen, H., T. Zhou, R. B. Neale, X. Wu, and G.J. Zhang, 2010: Performance of the new NCAR CAM3.5 model in East Asian Summer Monsoon simulations: Sensitivity to modifications of the convection scheme. *J. Climate,* **23**, 3657-3675.

Park, S., and X. Wu, 2010: Effects of surface albedo on cloud and radiation processes in cloud-resolving model simulations. *J. Atmos. Sci*., **67**, 1474-1491.

Deng, L., and X. Wu, 2010: Effects of convective processes on GCM simulations of the Madden-Julian Oscillation. *J. Climate*, **23**, 352–377.

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, and Q. Min, 2008: Seasonal variation of cloud systems over ARM SGP. *J. Atmos. Sci*., **65**, 2107-2129.

2.1 Multi-year CRM-simulated cloud properties and validation against ARM observations

Increased observational analyses provide a unique opportunity to perform years-long cloud-resolving model (CRM) simulations and generate long-term cloud properties that are very much in demand for improving the representation of clouds in general circulation models (GCMs). A year 2000 CRM simulation is presented here using the variationally constrained mesoscale analysis and surface measurements. The year-long (3 January–31 December 2000) CRM surface precipitation is highly correlated with the Atmospheric Radiation Measurement (ARM) observations with a correlation coefficient of 0.97. The large-scale forcing is the dominant factor responsible for producing the precipitation in summer, spring, and fall, but the surface heat fluxes play a more important role during winter when the forcing is weak. The CRM-simulated year-long cloud liquid water path and cloud (liquid and ice) optical depth are also in good agreement (correlation coefficients of 0.73 and 0.64, respectively) with the ARM retrievals over the Southern Great Plains (SGP). The simulated cloud systems have 50% more ice water than liquid water in the annual mean. The vertical distributions of ice and liquid water have a single peak during spring (March–May) and summer (June–August), but a second peak occurs near the surface during winter (December–February) and fall (September–November). The impacts of seasonally varied cloud water are very much reflected in the cloud radiative forcing at the top-of-atmosphere (TOA) and the surface, as well as in the vertical profiles of radiative heating rates. The cloudy-sky total (shortwave and longwave) radiative heating profile shows a dipole pattern (cooling above and warming below) during spring and summer, while a second peak of cloud radiative cooling appears near the surface during winter and fall.

The relationship among the surface albedo, cloud properties, and radiative fluxes is investigated for the first time using a year-long cloud-resolving model (CRM) simulation with the prescribed evolving surface albedo. Surface albedo plays an essential role in computing the energy budget at the surface and the top of the atmosphere (TOA). Most albedo-related studies have focused on snow-albedo feedback and its impacts on climate sensitivity in general circulation model (GCM) simulations. Analyzing observed daily broad band surface albedo over the ARM SGP for two years (1998 and 1999), ARM scientists reported that there is obvious horizontal inhomogeneity of surface albedo among the six observational ground stations, and surface albedo over bare soil is significantly affected by precipitation but vegetated surfaces are not strongly affected. They also found that on an overcast day surface albedo tends to decrease. In this study, a year-long simulation is performed over the ARM SGP site during the year 2000 using the Iowa State University (ISU) CRM with the prescribed evolving surface albedo from the ARM observational estimates. In comparison with the run using a fixed surface albedo, the CRM with the observed surface albedo represents the shortwave radiative budget closer to the observations in the winter. The greater surface albedo induces weaker instability in the low troposphere so that the amount of low clouds decreases during the winter. This reduces the shortwave and longwave cloud radiative forcing at the surface. The analysis of the CRM simulations with the evolving surface albedo reveals that there is a critical value (0.35) of the surface albedo. For albedos greater than the critical value, the upward shortwave flux at TOA is positively proportional to the surface albedos when optically thin clouds exist, and is not much affected by reflection on the cloud top. If optically thick clouds occur and the surface albedo is greater than the critical value, the upward shortwave flux at the TOA is significantly influenced by the reflection of cloud top, but not much affected by the surface albedo. In addition, for albedos larger than the critical value, the downward shortwave flux at the surface is primarily influenced by the surface albedo and the reflection from the cloud base if optically thick clouds occur. However, the downward shortwave flux at the surface is not significantly affected by the surface albedo when optically thin clouds exist because the reflection on the cloud base is weak. When surface albedos are less than the critical value, those relationships among surface albedo, shortwave flux, and cloud properties are not obvious.

Lack of observations of long-term (multi-year) cloud properties and radiative heating rates under different climate regimes is partly responsible for the slow progress in representing convection, cloud and radiative processes in general circulation models (GCMs). The Atmospheric Radiation Measurement (ARM) observational analysis at the Southern Great Plains site provides a unique opportunity to performing long-term cloud-resolving model (CRM) simulations and generating long-term cloud and radiation properties that are very much in demand for evaluating and improving the representation of convection and clouds in GCMs. In this study, statistical comparison is made between the year-long CRM simulation and several value added products from ARM such as the continuous baseline microphysical retrieval (MICROBASE) cloud liquid and ice water properties, the column physical characterization product (CPC), and the multifilter rotating shadowband radiometer (MFRSR) cloud optical depths. The CRM-produced cloud liquid and ice water paths for overcast and non-precipitating clouds agree with observations in terms of monthly and diurnal cloud occurrence frequency. The simulations show that the most frequent cloud type is low level cloud that usually occurs in November and December. For non-precipitating and overcast clouds, both the CRM and observations show that major cloud types such as low, thick middle and thin high clouds usually occur in winter, spring and summer, respectively. The CRM is able to represent major cloud types such as thick mid-level and stratiform clouds as shown in the observations. However, the occurrence frequency of high level clouds in the CRM is much smaller compare to the observations. The CRM-produced cloud liquid water path (LWP) has a maximum monthly mean value of 94.6 g m^{-2} in October and the minimum is 13.7 g m^{-2} in April. The maximum of cloud ice water path (IWP) is 122.7 g m^{-2} in June and the minimum of 15.4 g m^{-2} in September. The low level clouds are usually constituted with medium values of LWP and small values of IWP, and thick mid-level clouds with medium values of LWP and IWP. The vertical distribution of liquid and ice water content simulated by the CRM is generally consistent with that from the observational estimate. Both the CRM and observations show that the height of ice water content peak decreases as the IWP increases. The observed cloud radiative heating rates for each cloud type are properly represented by the CRM. However, the CRM-produced clouds tend to have greater longwave cooling in the upper troposphere because of weak cloud top cooling from the high level clouds in the observations and greater cloud top cooling from the thick mid clouds in the CRM. Low level clouds have the strongest net cooling effect, while thick mid-level clouds have strong net heating through the atmosphere.

2.2 Improved climate simulation and validation against CRMs and ARM observations

Weak temporal variability in tropical climates such as the Madden-Julian Oscillation (MJO) is one of major deficiencies in general circulation models (GCMs). The uncertainties in the representation of convection and cloud processes are responsible for these deficiencies. With the improvement made to the convection scheme, the Iowa State University (ISU) GCM, which is based on a version of the NCAR Community Climate Model, is able to simulate many features of MJO as revealed by observations. In this study, four 10-year (1979-88) ISUGCM simulations with observed sea surface temperatures are analyzed and compared to examine effects of the revised convection closure, convection trigger condition and convective momentum transport (CMT) on the MJO simulations. The modifications made in the convection scheme improve the simulations of amplitude, spatial distribution, eastward propagation, and horizontal and vertical structures, especially for the coherent feature of eastward propagating convection and the precursor sign of convective center. The revised convection closure plays a key role in the improvement of eastward propagation of MJO. The convection trigger helps produce less frequent but more vigorous moist convection and enhance the amplitude of the MJO signal. The inclusion of CMT results in more coherent structure for the MJO deep convective center and its corresponding atmospheric variances.

The kinetic energy budget is conducted to analyze the physical processes responsible for the improved Madden–Julian oscillation (MJO) simulated by the Iowa State University general circulation models (ISUGCMs). The modified deep convection scheme that includes the revised convection closure, convection trigger condition, and convective momentum transport (CMT) enhances the equatorial (10S–10N) MJOrelated perturbation kinetic energy (PKE) in the upper troposphere and leads to a more robust and coherent eastward-propagating MJO signal. In the MJO source region, the Indian Ocean (45–120E), the uppertropospheric MJO PKE is maintained by the vertical convergence of wave energy flux and the barotropic conversion through the horizontal shear of mean flow. In the convectively active region, the western Pacific (120E–180), the upper-tropospheric MJO PKE is supported by the convergence of horizontal and vertical wave energy fluxes. Over the central-eastern Pacific (180–120W), where convection is suppressed, the upper-tropospheric MJO PKE is mainly due to the horizontal convergence of wave energy flux. The deep convection trigger condition produces stronger convective heating that enhances the perturbation available potential energy (PAPE) production and the upward wave energy fluxes and leads to the increased MJOPKE over the Indian Ocean and western Pacific. The trigger condition also enhances the MJO PKE over the central-eastern Pacific through the increased convergence of meridional wave energy flux from the subtropical latitudes of both hemispheres. The revised convection closure affects the response of mean zonal wind shear to the convective heating over the Indian Ocean and leads to the enhanced upper-tropospheric MJO PKE through the barotropic conversion. The stronger eastward wave energy flux due to the increase of convective heating over the Indian Ocean and western Pacific by the revised closure is favorable to the eastward propagation of MJO and the convergence of horizontal wave energy flux over the central-eastern Pacific. The convection-induced momentum tendency tends to decelerate the upper-tropospheric wind, which results in a negative work to the PKE budget in the upper troposphere. However, the convection momentum tendency accelerates the westerly wind below 800 hPa over the western Pacific, which is partially responsible for the improved MJO simulation.

The moist static energy (MSE) anomalies and MSE budget associated with the Madden–Julian oscillation (MJO) simulated in the Iowa State University General Circulation Model (ISUGCM) over the Indian and Pacific Oceans are compared with observations. Different phase relationships between MJO 850-hPa zonal wind, precipitation, and surface latent heat flux are simulated over the Indian Ocean and western Pacific, which are greatly influenced by the convection closure, trigger conditions, and convective momentum transport (CMT). The moist static energy builds up from the lower troposphere 15–20 days before the peak of MJO precipitation, and reaches the maximum in the middle troposphere (500–600 hPa) near the peak of MJO precipitation. The gradual lower-tropospheric heating and moistening and the upward transport of moist static energy are important aspects of MJO events, which are documented in observational studies but poorly simulated in most GCMs. The trigger conditions for deep convection, obtained from the year-long cloud-resolving model (CRM) simulations, contribute to the striking difference between ISUGCM simulations with the original and modified convection schemes and play the major role in the improved MJO simulation in ISUGCM. Additionally, the budget analysis with the ISUGCM simulations shows the increase in MJO MSE is in phase with the horizontal advection of MSE over the western Pacific, while out of phase with the horizontal advection of MSE over the Indian Ocean. However, the NCEP analysis shows that the tendency of MJO MSE is in phase with the horizontal advection of MSE over both oceans.

Improved mosaic treatment of subgrid cloud-radiation interactions was implemented into the CCM3. The initial 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 in producing net radiative fluxes closer to observations. 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. 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. The CCM3 study was our first attempt to explore the impact of subgrid cloud-radiation interactions on climate simulations. We made adjustments to the diagnostic scheme of cloud cover and the prescribed scale factor of cloud water content to obtain global mean values close to the observed ISCCP (International Satellite Cloud Climatology Project) cloud amounts and SSM/I (Special Sensor Microwave/Imager) liquid water paths. The main purpose of this experiment was to demonstrate that the mosaic treatment enables the incorporation of cloud amounts and water paths that are consistent with observations while maintaining the global radiation budget close to observations. As such, questions were raised regarding the feedback processes that may explain the resulting large climate responses when the mosaic approach is compared with the standard CCM3. Further analysis and sensitivity experiments are required to understand the physical processes involved in the climate responses to the improved radiation scheme.

2.3 Retrieving Latent Heating Vertical Structure from Cloud and Precipitation Profiles

A physics-based latent heat (LH) retrieval algorithm is developed by parameterizing the physical linkages of observed hydrometeor profiles of cloud and precipitation to the major processes related to the phase change of atmospheric water. Specifically, rains are segregated into three rain types: warm rains, convective rains, and stratiform rains, based on their dynamical and thermodynamical characteristics. As the first of series, only warm rain LH algorithm is presented and evaluated here. The major microphysical processes of condensation and evaporation for warm rains are parameterized through traditional rain growth theory, with an aid of Cloud Resolving Model (CRM) simulations. The evaluation or self-consistency test indicates that the physics-based retrievals capture the fundamental LH processes associated with warm rain life cycle. There is no significant systematic bias in terms of convection strength, illustrated by the month-long CRM simulation as the mesoscale convective systems (MCSs) experience from initial, mature, to decay stages. The overall monthly mean LH comparison showed that the total LH, as well as condensation heating and evaporation cooling components, agree with the CRM simulation, a maximum difference of 0.17 ^{o}C/h.

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