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Evaluating and Improving Cloud Processes in the Multi-Scale Modeling Framework

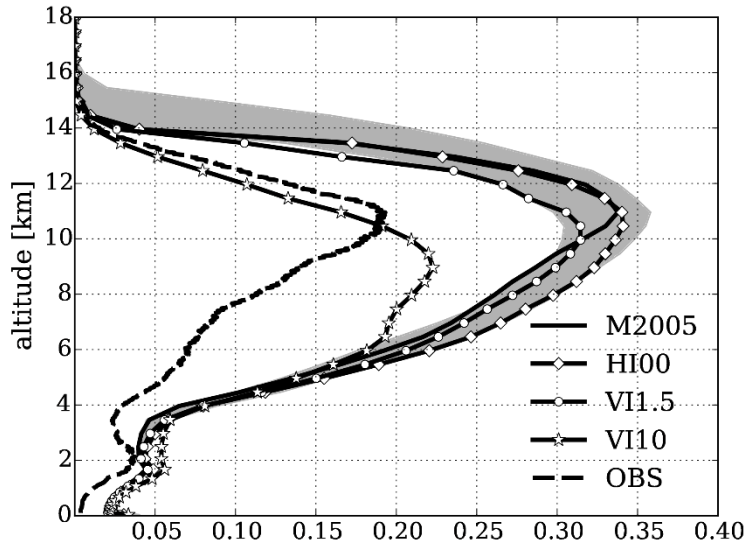
The over-arching goal of this proposal was to explore the use of the Multiscale Modeling Framework (MMF) to explore statistical feedback relationships between coupled cloud-scale and synoptic-scale motions. The broad hypothesis is that cloud parameterizations continue to produce divergent results in climate model simulations because these relationships are currently ill-defined and therefore are not constrained during parameterization development. We further hypothesize that the MMF can be used to define important aspects of these relationships but only if the MMF produces realistic cloud fields with representative properties. It is our immediate goal to address this latter point by providing a specific path for MMF improvement and evaluation.

The research performed under this grant was intended to improve the embedded cloud model in the MMF for convective clouds by using a 2-moment microphysics scheme (Morrison and Pinto 2006) rather than the single moment scheme used in all the MMF runs to date. We evaluated the Morrison microphysics scheme in a series of cloud-resolving model runs for specific cases in both a 2D and 3D framework. We chose to examine the uncertainty in SAM runs in both 2D and 3D caused by perturbations in the initial conditions. We used the forcing from the ARM9707 case study at the SGP site. This forcing data set of summer convection has been used by a number of previous investigators. The domain size was 256 km x 256 km x 30 km for the 3D cases and 256 km x 30 km for the 2D cases. The resolution was 1 km in the horizontal and between 50 m and 250 m in the vertical. Surface sensible and latent heat fluxes were fixed. We ran 6 ensemble members for the 3D case, each with different perturbations to the initial temperature and humidity profiles. We subsequently investigated the influence of the 2-moment microphysics scheme, especially the ice microphysics, on the performance of SAM. The 2-moment scheme has several “tunable” parameters that affect simulations of cloud amount and precipitation. For example, a change in the snow autoconversion threshold affects the partition between ice species and alters the cloud amount through sedimentation of larger particles. This also affects the precipitation rate and cloud lifetime. We carried out simulations in both 3D and 2D to understand how these parameter settings can be used to improve model agreement with observations. We carried out simulations of both mid-latitude continental convection using the ARM SGP summer 1997 IOP case that we used in the current study and convection over tropic oceans using forcing and data from KWAJEX.

In our studies, we found the two-moment microphysical scheme produced cloud occurrence histograms by reflectivity and height compared well with cloud radar and satellite observations, but the reflectivity simulated by the one-moment microphysics is too low by over 20 dB. During convective events, the two-moment microphysics scheme overestimated the amount of high-level cloud and the one-moment microphysics scheme precipitated too readily and underestimated the amount and the height of high-level cloud.

For ARM9707, an extensive layer of high-level ice cloud is found to cycle around the model domain for both microphysical schemes, while little high-level cloud was actually observed. Sensitivity tests using the two-moment microphysics showed that the modeled high-level cloud amount is not sensitive to changes in the ice microphysics. We explored the reason for the persistent high-level cloud with two approaches: running the model in a “forecast” mode and applying thermodynamics nudging. We found that this issue is related to biases in the large-scale forcing and the maintenance of the high-level cloud by the periodic lateral boundary conditions. The combined effects result in significant biases in high-level cloud amount and radiation and a high sensitivity of the cloud amount to the nudging time scale in both convective cases.

Because the large-scale forcings are strongly constrained by design (Zhang and Lin, 2001) to conserve column integrated heat and water, the precipitation records are very well reproduced by both microphysical schemes in both the ARM9707 case and the KWAJEX case. The cloud statistics and radiation on the other hand are not so well reproduced. Analysis of the simulations of ARM9707 convective events shows that the single moment scheme underestimates the cloud occurrence and the double-moment scheme overestimates the cloud occurrence. Both of them have persistent high-level cloud cover during the dry periods in between convective events when the cloud radar observes little cloud. The cloud radar reflectivity simulated by the double moment scheme agrees well with observations for high-level clouds while the single moment scheme simulated reflectivity is much weaker than observations, by over 20 dB. At lower altitude, the differences between the double-moment scheme simulated radar reflectivity are larger, likely because the complicated processes involving snow and graupel are not well represented. Sensitivity tests on both the cloud ice fall speed and the ice nucleation schemes in the double-moment scheme suggest that moderate and realistic changes in microphysics cannot produce distinguishable reduction in the simulated cloud occurrence (Figure below). The relatively weak impacts of cloud microphysics on simulated cloud amount is consistent with some recent studies (e. g., Wang et al., 2011; Muhlbauer et al., 2014).



Comparison of simulated and observed cloud occurrence profiles for the entire ARM9707 simulation. The solid line is the double-moment control run (M2005) and the shaded area indicates the spread among the 2D ensemble members of that same model. The other three solid lines represent runs with modified microphysical fall speed parameterizations. The dashed line denotes the ARM MMCR observations. It is quite clear that none on the modified schemes are able to simulate the observations, even when quite extreme changes are made (HI00 model).

Using two different approaches, running SAM in a “forecast” mode and apply thermodynamics nudging, we found that the large-scale forcing fields for ARM9707 during the dry periods in between convection may have a moist bias. The influence of this moist bias on simulated cloud statistics and radiation is further amplified by the periodic lateral boundary conditions. The periodic lateral boundary conditions can effectively maintain the residual high-level cloud layer, which is confirmed by the high sensitivity of the simulated cloud occurrence to the water vapor nudging time scale. By construction, if the large-scale forcing fields are perfect, the periodic lateral boundary conditions are consistent with the design of the large-scale forcing fields. However, in cases where hydrometeor advection of the ice phase cloud cannot be neglected, the large-scale forcing fields can be biased. In addition, even small biases in column integrated water vapor mixing ratio can be related to the large variability of the relative humidity at high levels. Taking all these factors into account, in the absence of nudging, the periodic lateral boundary condition may introduce large biases in simulated cloud amount and radiation even if the biases in the large-scale forcing fields are small. The simulated cloud occurrence in both the ARM9707 and KWAJEX cases are highly sensitive to the nudging time scale. The influence of thermodynamical nudging on cloud amount, especially high-level clouds, is also reported in recent studies of cloud resolving simulations of TWP-ICE (Varble et al., 2011; Fridlind et al., 2012). However, because the simulated cloud occurrence is highly sensitive to the nudging time scale,

the choice of the nudging time scales has to be made carefully. The comparison between CRM simulations and radar observations also requires careful examination to ensure the agreements with observations are not the result of potential “tuning” with a fortuitous pair of nudging time scales for temperature and water vapor.

When a cloud resolving model (CRM) is coupled with the host global climate model (GCM) in the MMF, the cloud statistics simulated by the CRMs can feedback to the host GCM and interact with the large-scale dynamics. The impact of the periodic lateral boundary conditions globally is likely quite different from the case studies in the stand-alone mode discussed in this study. Nevertheless, we expect that the periodic lateral boundary conditions are still likely to overestimate high-level cloud amount in the MMF, given the tendency of the periodic lateral boundary conditions to maintain moist biases and the induced high sensitivity of the simulated cloud amount to moist biases in the large-scale forcing fields. The investigation of the interaction between the CRM and its host GCM on both grid scales may hold the key to fully understand the influence of the periodic lateral boundary conditions in the fully coupled MMF. The idea of communication between CRM and GCM at the CRM level between different GCM grid boxes in the MMF, or the quasi-3D MMF, has been around since the early stages of the MMF’s development. A comparison study using a quasi-3D MMF and a conventional MMF may provide an opportunity to directly evaluate the impact of the periodic lateral boundary conditions, such as the effect of the overestimation of high-level clouds on the longwave cloud forcing and feedback and the lower climate sensitivity of MMF compared to the conventional GCMs.

Additional discussion of our results is available in the Ph. D. Thesis of Z. Liu and a manuscript in preparation (Liu et al. 2015).

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