ID: ER64557-1031505-0014094
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Title: Validation of Model Simulations of Anvil Cirrus Properties During TWP-ICE
Program Manager: Ashley D. Williamson, Division SC-23.1

DOE Award # DEFG0208ER64557 University of Utah Award # 55800338

Final Report (15 May 2008 – 14 May 2011 with 2 extensions, ending 14 May 2013)

This 3-year grant, with two extensions, resulted in a successful 5-year effort, led by Ph.D. student Adam Varble, to compare cloud resolving model (CRM) simulations with the excellent database obtained during the TWP-ICE field campaign. The objective, largely achieved, is to undertake these comparisons comprehensively and quantitatively, informing the community in ways that goes beyond pointing out errors in the models, but points out ways to improve both cloud dynamics and microphysics parameterizations in future modeling efforts. Under DOE support, Adam Varble, with considerable assistance from Dr. Ann Fridlind and others, entrained scientists who ran some 10 different CRMs and 4 different limited area models (LAMs) using a variety of microphysics parameterizations, to ensure that the conclusions of the study will have considerable generality. This work was reported in 8 different ARM/ASR Science Team meetings, 5 national/international conferences, and 4 articles in peer-reviewed literature with 2 more based on Adam's Ph.D. dissertation to be submitted by July 2013.

The first paper resulting from this major effort (Varble et al. 2011) demonstrated that most of the 9 CRMs consistently overestimated convective area and rainfall while underestimating stratiform rainfall. ALL simulations failed to reproduce observed radar reflectivity distributions above the melting level in convective regions and throughout the troposphere in stratiform regions. For simulations overestimating convective reflectivity aloft, graupel is the main cause for 1-moment schemes and snow for 2-moment schemes. Rather than blame excessive ice water content in the simulations, Varble et al. (2011) finds major problems on errors in the gamma size distribution parameters, pointing to needed corrections to commonly observed size intercept or shape parameter in the gamma distributions.

In Varble (2013), the results from CRMs (Varble et al. 2011; Fridlind et al. 2012; Mrowiec et al. 2012) and LAMs (Zhu et al. 2012) are combined and extended in a comprehensive analysis of differences between simulations and observed data, concentrating on the major mesoscale convective system passing close to Darwin Australia on 23 January 2006. Perhaps *the most important single result is that 10 separate CRMs and 4 separate LAMs show similar structural biases with respect to observations: excessive convective radar reflectivity and insufficient stratiform rainfall.* There is, however, considerable variability in these biases that is heavily modulated by bulk microphysics scheme assumptions, several of which could be made more realistic without major increases in computational expense.

A second important result of Varble (2013) is that it is unlikely that poor representation of ice microphysics is the primary culprit in the excessive radar reflectivity aloft in convective regions. Rather, it is strongly suspected (but difficult to prove) that deep convective updrafts in the simulations are too strong relative to dual-Doppler retrievals, probably resulting in excessive rain water content and subsequent excessive freezing of this rain, resulting in excessive release of latent heat of fusion in the updrafts, and subsequent excessive graupel production. These overly-vigorous convective updrafts seem to be characteristic of CRMs and LAMs and it may not be a simple matter to diagnose and correct the problem, in part because direct observations of convective updrafts in mid-troposphere are rarely obtained, due to aircraft safety and other difficulties.

In Figure 1, the excessive convective vigor shown by all CRMs (symbols) compared with dual-Doppler retrievals and Darwin C-POL radar reflectivity profiles (solid black lines) is shown. Similar figures (not shown) demonstrate that all LAMs also overestimate convective vigor.

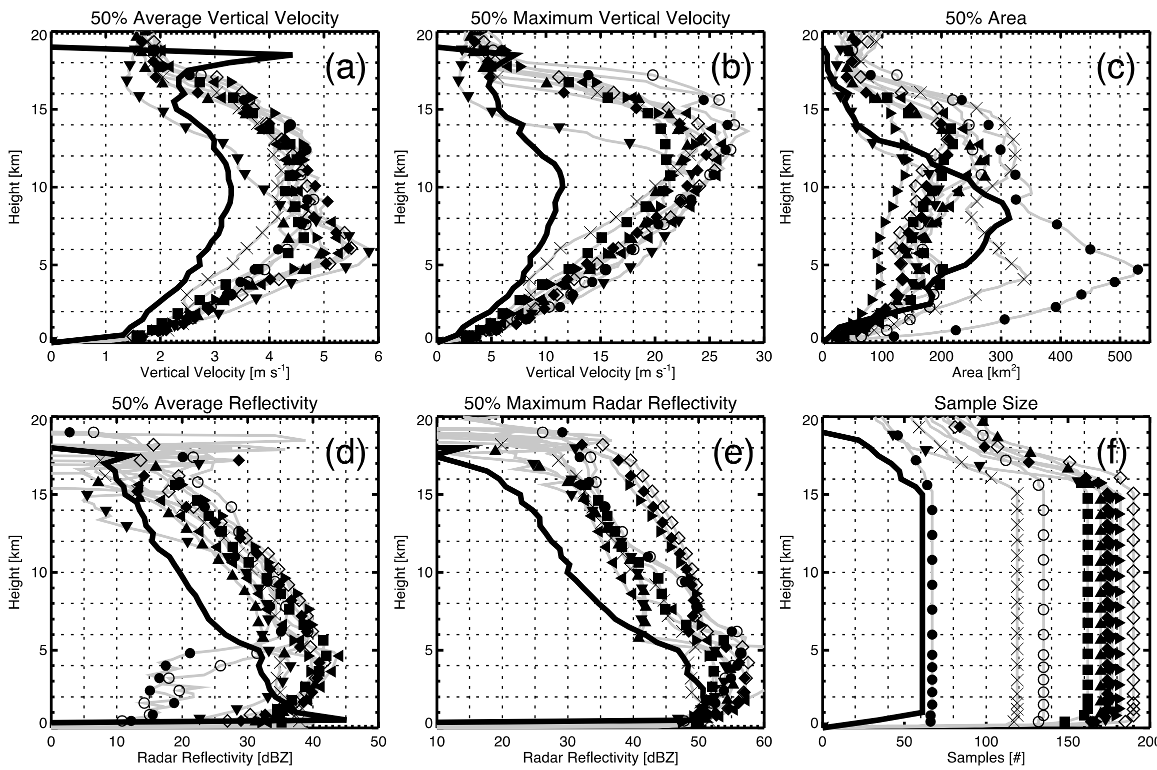

Figure 1. The median profiles of several variables are shown for three-dimensionally defined convective updrafts beginning below 1 km and ending above 15 km in both CRMs and dual-Doppler retrievals for the period of 1310Z to 1750Z on January 23. Average vertical velocity is shown in (a), maximum vertical velocity in (b), average radar reflectivity in (c), maximum radar reflectivity in (d), area in (e), and sample size in (f). From Varble (2013).

Such large vertical velocities are well in excess of the fall speeds of raindrops, and would be expected to loft raindrops through the freezing level, resulting in extraordinarily large mixing ratios of graupel, as demonstrated in Figure 2. There is no clear path to compare simulated in-cloud mixing ratios of hydrometeors with actual data, because aircraft did not penetrate these strong convective clouds during TWP-ICE, but they are larger than almost any observations ever reported over tropical oceans or coastal regions, so one needs to be cautious in drawing such conclusions, while being skeptical that actual mixing ratios reach such values in this case.

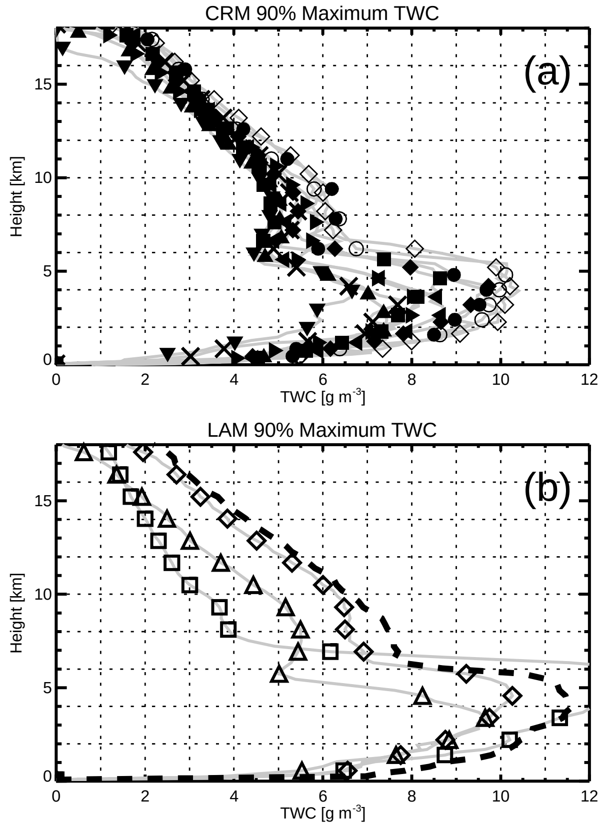

Figure 2. The 90th percentile of maximum total hydrometeor water contents in deep convective updrafts within (a) CRM simulations and (b) LAM simulations. Deep updrafts are defined as continuous greater than 1 m/s between 1-15 km. After Varble (2013).

Summary: *The following concluding paragraphs are mostly directly quoted from Varble (2013), soon to appear in Varble et al. (2013a,b), with some paraphrasing,* because in many ways these conclusions represent the culmination of the 5 years of research supported by this grant.

Specific CRM and LAM simulation biases found in this research and published in Varble et al. [2011], namely a high bias in convective area and radar reflectivity aloft as well as a low bias in stratiform rainfall, are not entirely surprising. Such results had been found in previous literature. Differences between simulations are more correlated with hydrometeor size distribution assumptions than differences in hydrometeor water contents. Unlike many past studies, 2-moment schemes did not outperform 1-moment schemes for the 23 January 2006 TWP-ICE case despite the clear advantage of 2-moment schemes in representing sedimentation of different sized hydrometeors and effects of phase changes on hydrometeor size distributions. One likely reason for the difference with past studies is that the humid maritime environment of this case differs from most mid-latitude continental cases, which limits major issues in 1-moment schemes, such as excessive evaporation. Another issue in increasingly complex microphysics schemes is the lack of high quality observations to constrain the schemes. While more complex schemes should be more realistic in theory, they also have more freedom to be wrong, which is one of the reasons arbitrary thresholds are often put in place.

Results from detailed comparison with observational retrievals show, however, that causes for simulation biases are likely much more complicated than simply improving ice microphysics schemes as has been emphasized in some previous literature; rather, they depend on achieving the correct interplay between model forcing, resolution, and physics complexity to yield proper interactions between dynamics and microphysics that produce appropriate convective mode. Mode not only encompasses instantaneous structural properties, but also involves convective life cycle. Both are important in determining system precipitation coverage and the proportioning of convective to stratiform precipitation, which in the case of mesoscale systems alters the large-scale environment.

This conclusion is founded upon comparison of many different CRM and LAM simulations with observational retrievals of convective vertical velocity and raindrop size distributions. Without significant sample sizes of in situ convective properties, it is difficult to prove that simulated convective updrafts are stronger, but a significant amount of indirect evidence has been shown to support this conclusion including comparisons with a dual-Doppler retrieval and comparison of convective vertical velocity and condensate values with relevant published literature. This does not appear to be due to unresolved large eddies based on results of a 102 m quarter domain DHARMA-2M simulation. Therefore, it appears to be linked to some mixture of model forcing biases and interactions between dynamics and microphysics that are able to shift convective feedbacks and mode from those that occurred in reality. Interactions between convective dynamics and microphysics are sensitive to the microphysics and sub-grid scale turbulence parameterizations, both of which could be factors in the difference between simulations and observations.

The intensity of simulated convection and model forcing are likely linked to the under-prediction of ice water content just above the melting level in simulations with appropriately large areas of stratiform precipitation, which limits higher simulated stratiform rain rates. For the LAM simulations that do have some higher stratiform rain rates, stratiform ice water content is higher but stratiform area is far too low. This is partially due to dry biases in the ECMWF forcing, but also due to the convection, which dominates vertical mass flux in the upper troposphere, detrains near the tropopause, and does not efficiently transfer condensate and buoyancy to stratiform regions. These convective issues are present in CRM simulations as well, but the dry bias is not present in those simulations. Instead, the domain size with periodic lateral boundary conditions prevents an adequately large and well-developed stratiform region from forming.

A unique aspect of this research was the comparison of CRMs and LAMs, which has not been thoroughly done to date, at least for the topics considered in this research. While some differences were apparent, such as the location and timing of convection and the amount of stratiform area, these differences make sense in the context of the different model forcings and boundary conditions. Many other model biases relative to observations that relate to microphysics and convective dynamics were present in both model setups, an important finding because such biases could have possibly been attributed to idealized model forcing without such a comparison.

Despite the differences in CRM and LAM forcing biases and the apparent difference in convective strength, these simulations do show that there are specific microphysics assumptions that could be improved without much of an increase in computing time. These microphysics scheme alterations are not simply changes to tunable parameters to achieve agreement in one variable, but changes that should produce improvement and be more realistic. As pointed elsewhere, implementation of potential improvements in GCM convective parameterizations often lead to worse simulations because the parameterizations have become so full of unphysical tunable parameters that are set to hide errors. The same can be said of some model physics variables such as hydrometeor conversion thresholds and collection efficiencies used in cloud-resolving simulations. The following are changes in hydrometeor properties based on intercomparison of many simulations with observations guided by past observational results that could improve bulk microphysics schemes with some that have been preliminarily tested, as will be discussed more fully in Varble et al. (2013a,b):

1. Inclusion of a fast falling dense precipitating ice species (i.e., hail), or a variable dense precipitating ice density such as that in Milbrandt and Morrison [2013] with a fall speed relationship that covers a larger range of fall speeds than is currently done in most schemes. This would better represent the faster fall speeds of frozen raindrops, which are very common, and alter the amount of dense ice in the upper troposphere. Setting the graupel μ parameter to greater than 0 may prevent excessively large graupel from occurring and improve radar reflectivity comparisons, but it is unclear whether this is more realistic.
2. A rain μ parameter greater than 0, such as 2.5 used in the UKMO model, or a diagnostic μ-λ relationship based on observations such as that in Cao et al. [2008]. This may improve excessive size sorting issues in 2-moment rain schemes and produce more realistic fall speeds. It would also likely affect evaporation rates, but the impacts of such effects are unknown at this time.
3. Inclusion of a more aggressive raindrop breakup parameterization to prevent very large diameters from occurring in convective rain. Such parameterizations have major impacts on mesoscale convective systems in mid-latitude continental situations (e.g., Morrison et al. [2012]) through alteration of evaporation rates, but have not been thoroughly tested in the deep tropics.
4. Implementation of a non-spherical snow mass-diameter relationship that allows density to decrease with size, as used in the MESONH or Thompson schemes, where mass is proportional to $D^{1.9}$ and D^2, respectively. Such relationships are based on observations in Locatelli and Hobbs [1974] and Field et al. [2005]. It is important that this is used in schemes that diagnostically vary the size intercept or predict number concentration to avoid low biased radar reflectivities in regions of snow aggregation.

Papers and other products delivered

Peer-reviewed publications:

Varble, A., A. M. Fridlind, E. J. Zipser, A. S. Ackerman, J.-P. Chaboureau, J. Fan, A. Hill, S. A. McFarlane, J.-P. Pinty, and B. Shipway (2011), Evaluation of cloud-resolving model intercomparison simulations using TWP-ICE observations: Precipitation and cloud structure. *J. Geophys. Res.*, **116,** D12206, doi:10.1029/2010JD015180.

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

Zhu, P., J. Dudhia, P. R. Field, K. Wapler, A. Fridlind, A. Varble, M. Chen, J. Petch, Z. Zhu, and E. Zipser (2012), A limited area model (LAM) intercomparison study of a TWP-ICE active monsoon mesoscale convective event. *J. Geophys. Res.*, **117**, D11208, doi:10.1029/2011JD016447..

Mrowiec, A.A., C.Rio, A.M.Fridlind, A.S.Ackerman, A.D.Del Genio, O.M.Pauluis, A.C.Varble, and J.Fan (2012): Analysis of cloud-resolving simulations of a tropical mesoscale convective system observed during TWP-ICE: Vertical fluxes an draft properties in convective and stratiform regions. *J. Geophys. Res*., **117**, D19, DOI: 10.1029/2012JD017759

Varble, A.C., 2013: Using TWP-ICE observations to evaluate and improve high resolition simulations of tropical convective precipitation systems. *Ph.D. Dissertation*, University of Utah, Salt Lake City, UT 84112-0110, 190 pp.

Varble, A., E. J. Zipser, A. M. Fridlind, P. Zhu, A. S. Ackerman, J.-P. Chaboureau, S. Collis, J. Fan, A. Hill, and B. Shipway, 2013a: Evaluation of cloud-resolving and limited area model intercomparison simulations using TWP-ICE observations. Part 1: Convective dynamics and microphysics. *J. Geophys. Res.*, to be submitted.

Varble, A., E. J. Zipser, A. M. Fridlind, P. Zhu, A. S. Ackerman, J.-P. Chaboureau, J. Fan, A. Hill, B. Shipway, and C. R. Williams, 2013b: Evaluation of cloud-resolving and limited area model intercomparison simulations using TWP-ICE observations. Part 2: Rain microphysics. *J. Geophys. Res.*, to be submitted.

Conference Presentations:

1. “Hot towers and mesoscale convective systems in the vicinity of Darwin, Australia,” poster, 3rd NASA/JAXA TRMM Conference, Las Vegas, NV, Feb. 4-8, 2008.

2. “Toward a comprehensive model validation database of convective precipitation systems near Darwin, Australia,” talk, AGU Fall Meeting, San Francisco, CA, Dec. 15-19, 2008.

3. “Climatological context for TWP-ICE convective precipitation features,” poster, ARM Science Team Meeting, Louisville, KY, Mar. 30 – Apr. 3, 2009.

4. “Some difference between TWP-ICE data from the CPOL radar and the CRM: Should we point fingers at convective intensity, microphysics, or both?” talk, ARM Science Team Meeting, Louisville, KY, Mar. 30 – Apr. 3, 2009.

5. “Using radar data to evaluate CRM simulations of TWP-ICE monsoonal convection,” talk,

ARM Cloud Properties/Radiative Properties Working Group Meeting, Boulder, CO, Sep. 15-18, 2009.

6. “A comparison framework to evaluate TWP-ICE cloud-resolving simulations with observations,” poster, ASR Science Team Meeting, North Bethesda, MD, Mar. 15-19, 2010.

7. “Evaluation of model radar reflectivities using the CPOL radar,” talk, ASR Science Team Meeting, North Bethesda, MD, Mar. 15-19, 2010.

8. “Evaluating cloud-resolving model updrafts with dual-Doppler radar retrievals,” talk, ASR Science Team Meeting, North Bethesda, MD, Mar. 15-19, 2010.

9. “Using TWP-ICE observations with model intercomparison to improve simulations of tropical oceanic convection,” poster, 13th AMS Conference on Cloud Physics, Portland, OR, June 28 – July 2, 2010.

10. “Evaluation of cloud-resolving model intercomparison simulations using TWP-ICE radar and satellite data,” talk, ASR Fall Working Groups Meeting, Boulder, CO, Oct. 11-15, 2010.

11. “Investigating simulated convective and stratiform structures of monsoonal convection using TWP-ICE observations,” poster, ASR Science Team Meeting, San Antonio, TX, Mar. 28 – Apr. 1, 2011.

12. “Strategies for using observational datasets that may lead to more realistic simulations of convective-to-stratiform transition regions,” talk, ASR Fall Working Groups Meeting, Annapolis, MD, Sep. 12-15, 2011.

13. “A brief description of MC3E cases suitable for running and evaluating LAM simulations,” talk, ASR Fall Working Groups Meeting, Annapolis, MD, Sep. 12-25, 2011.

14. “Toward constraining simulated stratiform (+convective) precipitation properties with observations,” talk, AGU Fall meeting, San Francisco, CA, Dec. 5-9, 2011.

15. “Targeted bulk microphysics improvements through cloud-resolving and limited area model intercomparison and observations,” poster, ASR Science Team Meeting, Arlington, VA, Mar.12-16, 2012.

16. “The challenge of adequately representing deep convective dynamics, bulk microphysics, and their interaction in CRM and LAM simulations,” talk, ASR Science Team Meeting, Arlington, VA, Mar. 12-16, 2012.

17. “Improving bulk microphysics schemes in deep convective systems using observations,” poster, 16th International Conference on Clouds and Precipitation, Leipzig, Germany, July 30-Aug. 3, 2012.

18. Varble, A.C., 2012: Targeted bulk microphysics scheme improvements through high

resolution model intercomparison with observations. Poster, 1st Pan-GASS Meeting, Boulder, CO, Sep. 10-14, 2012.

19. Varble, A.C., 2013: Using TWP-ICE and MC3E observations to expose dynamical and microphysical causes of CRM and LAM simulated deep convection biases. Poster and Plenary Talk, ASR Science Team Meeting, Potomac, MD, Mar. 18-21, 2013.