FINAL REPORT
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Project Title: Study of Multi-Scale Cloud Processes Over the Tropical Western Pacific Using Cloud-Resolving Models Constrained by Satellite Data

1. Introduction

The work under this proposal can be categorized into several major themes, (i) simulation of convection in the Tropical Western Pacific, (ii) evaluation and improvement of mesoscale models to handle tropical convection, (iii) addition of CAM climate-model physics into WRF mesoscale model as options, (iv) utilizing cloud observations to improve microphysics parameterizations. This report will summarize the progress made in each of these categories with outlines of publications where appropriate.

2. Theme I: Simulation of Convection in the TWP

In the first years of the proposal, a major effort was made to provide a reanalysis of the period December 2007-January 2008 using advanced data assimilation methods. The period is a year after TWP-ICE but was chosen because of the new GPS data that added an important source for water vapor observations over the oceans. The ensemble Kalman Filter method used a 36-member ensemble at 36 km grid-spacing for the TWP region using data from radiosondes and aircraft, satellite cloud motion winds, AIRS temperature and water vapor, GPS RO refractivity, and land and ocean surface pressure observations in a two-hour assimilation cycle. Satellite data offers a constraint in an otherwise data-sparse region, so the hope was that the reanalysis would be able to represent an MJO event in December 2007. The benefit of such a reanalysis to the ARM program would then be for driving cloud-resolving and single-column models with a four-dimensional dynamically self-consistent dataset. In the course of this work several model deficiencies were identified. In terms of the data assimilation, a large cold bias at the top of the model prevented a good reanalysis and this was addressed in separate work under this project by Cavallo et al. (2011) [see later]. Even resolving this, there were problems in producing the signature propagating signal of the MJO with the physics tested, even though the RRTMG radiation combined with WSM6 microphysics was able to produce realistic OLR values. This failure of the model to produce an MJO precluded our ability to provide a reanalysis product for ARM, but led to more scientific research on the WRF physics associated with tropical convection, particularly the cumulus parameterization and planetary boundary layer representations.

Work by Marcela Ulate (U. Miami graduate student work to be published later) that I collaborated with under this proposal showed extreme sensitivity of the large-scale heating and vertical motion profile with a resultant varying water cycle to the combination of PBL scheme and cumulus scheme using a wide range of WRF's options in three-month simulations (**Figure 1**). However, even with the wide range of water-cycle strengths obtainable by varying the schemes at 50 km, none were able to produce the MJO propagation in the Indian Ocean October 2009 MJO event that was studied.

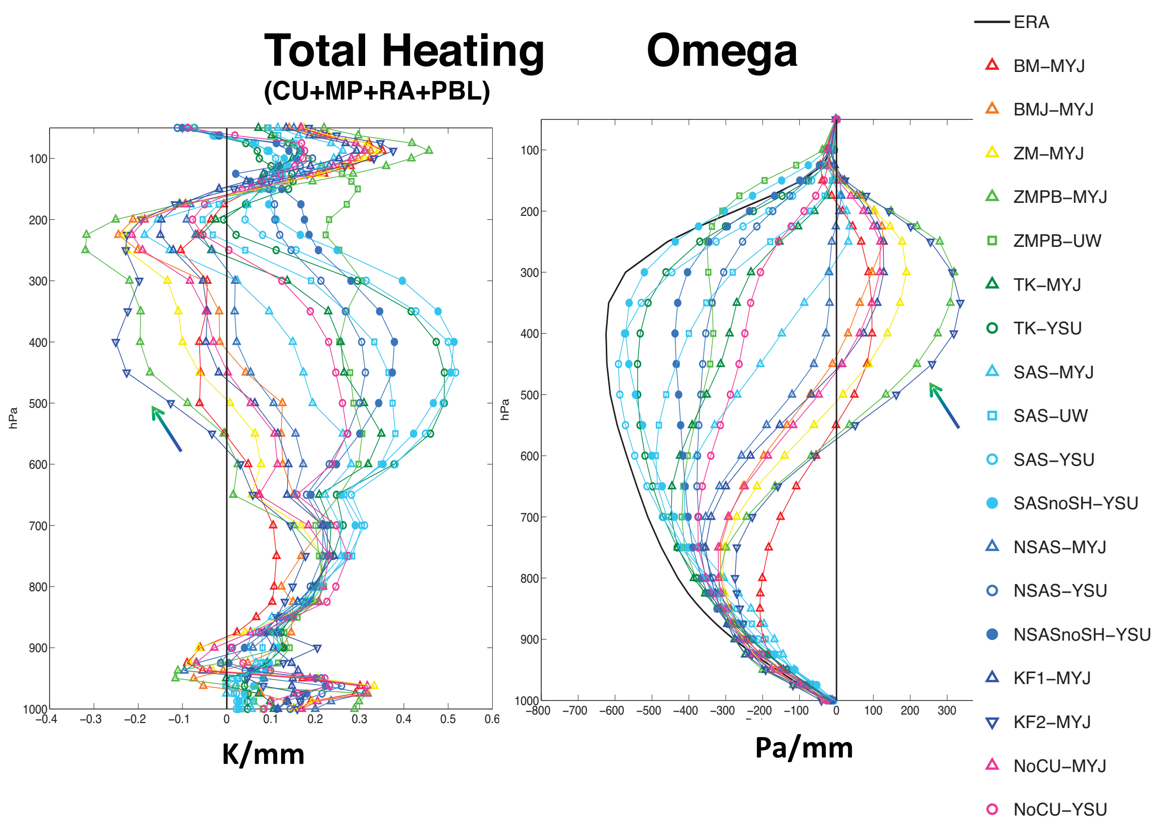


Figure 1: Heating and vertical motion (negative upwards) profiles for various cumulus and PBL options. [Ulate, U. Miami, unpublished graduate work]

Other work by Ulate demonstrated that even weakly nudging the moisture at longer wavelengths helped to produce an MJO, giving an indication that the physics was missing a large-scale mid-level moistening process, such as the previously hypothesized pre-conditioning by shallow-mid-level convection. While WRF has several shallow convection schemes, and continuing development in this area, this has not yet proved to be a solution to the MJO problem of the model.

Collaborative work with Pacific Northwest National Laboratory (PNNL) has also addressed the simulation of tropical convection. Early in the funded period, I collaborated on the paper by Wang et al. (2009) using a 4-km WRF model with various physics combinations for TWP-ICE simulations. The paper focused on evaluating the cloud and radiative properties against observations and found that WSM6 was the best for this case. The study also found that short three-day simulations were significantly better than longer simulations, showing the importance of properly constraining the larger scales to obtain better results. This is consistent with the Ulate work above that showed that in the tropics, the model physics can modify the large-scale circulation, so it is clear that constraints are needed until an appropriate set of physics is found that minimizes this large-scale error, which is critically dependent on the convective heating profile.

Another collaborative effort with PNNL was Hagos et al. (2011), which also used moisture nudging to enable WRF to produce two MJOs in winter 2007-8. The paper, similar to the conclusions mentioned above, showed that low-level moistening was required for the MJO to be simulated. There was also a study of the energetics of the MJO using the model results summarized in **Figure 2.**

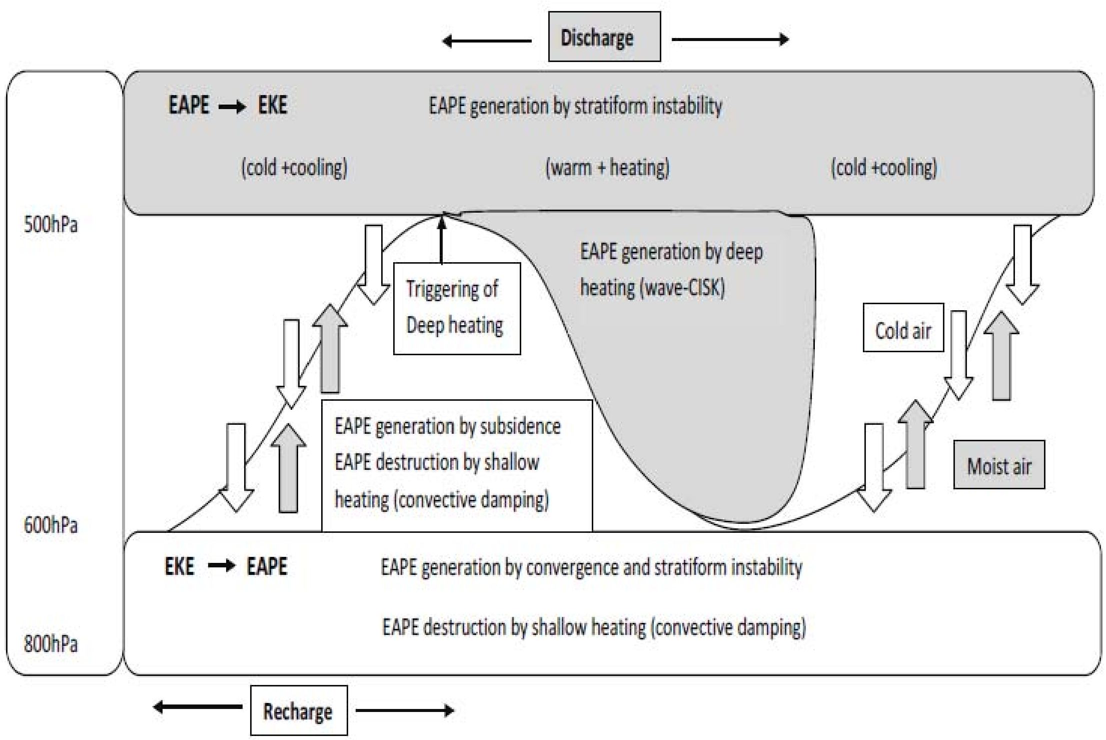


Figure 2: Schematic of MJO energetics (Hagos et al. 2011)

3. Theme II: Evaluation and Improvement of Mesoscale Models for Tropical Convection

In the data assimilation work mentioned above, one of the problems identified was a strong cooling at the top of the model, which hinders adding data by having a large model error for the first guess. This was addressed in work for this project by Cavallo et al. (2011). Mesoscale model tops are usually low compared to those in climate models, being around

50 hPa (22 km) , so when a radiation scheme is used that has been developed for global models, such as RRTMG, it was found that the assumptions made at the model top are critical to obtaining reasonable cooling rates at the top. In this paper, Cavallo et al. (2011) identified a cold bias as a function of model top (**Figure 3** curve labelled Current), which is particularly bad for tops in the lower stratosphere. The corrected assumption at the top involved adding a few more layers for the radiation calculation up to the top of atmosphere with a positive thermal gradient typical of the stratosphere. This warmer layer produced sufficient downwelling radiation at the model top to prevent the cold bias. The old assumption that the stratosphere was isothermal was producing the cold bias. This corrected scheme is now in the standard WRF code for RRTMG radiation as a result of this work. Another remedy would involve putting the model top higher, near 10 hPa, which as seen from Figure 3 would lead to a reduced error.

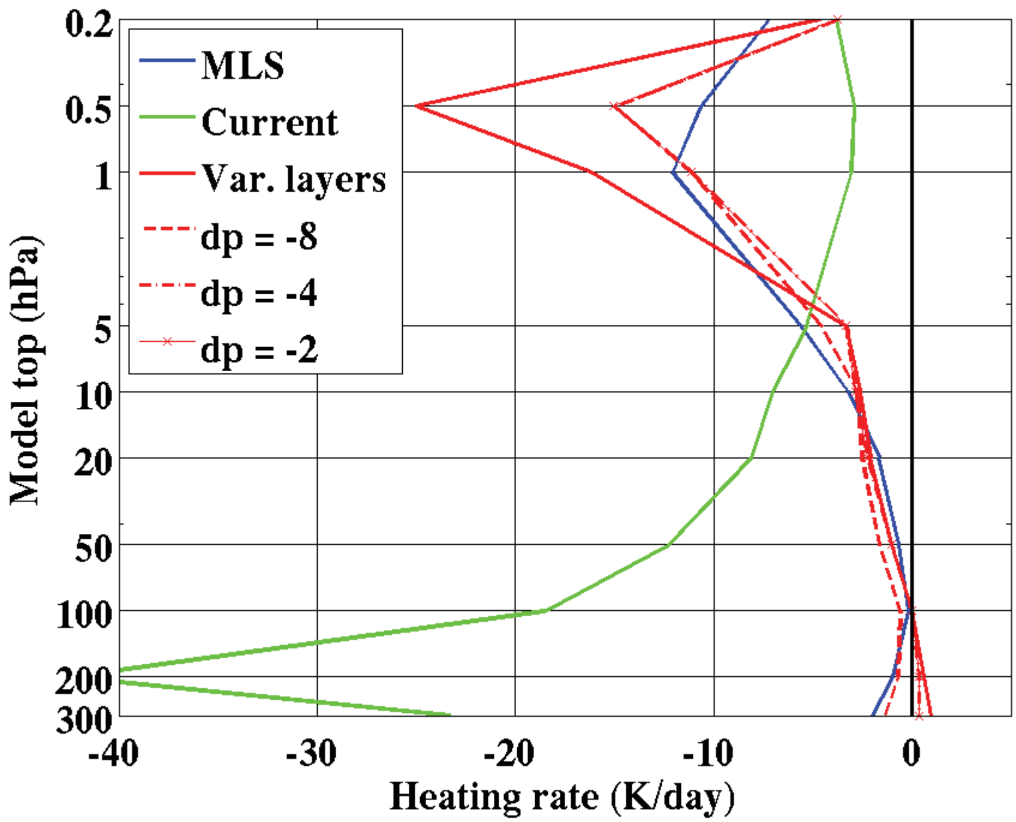


Figure 3: Variation of top-level cooling as model top is changed. Green line is before adding extra layers above; other lines add layers above model top for radiation. [Cavallo et al. 2011]

An important model output for comparison with observations in data-sparse regions is outgoing longwave radiation (OLR) that has a key role in the global energy balance. This is particularly sensitive to the cirrus cloud extent that produces large negative deviations on the OLR field, and therefore also provides a way to verify how well microphysics schemes are producing cirrus clouds. In the course of our work (as described in the Dudhia et al., 2010, ARM Science Team Meeting poster), we found that in some microphysics options (especially the Thompson microphysics developed at NCAR), the OLR effect of cirrus clouds was unrealistically small. The reason for this is that this scheme partitions more of its total ice cloud into the snow category rather than the ice category. The radiation schemes at this time were only using the ice category for an ice cloud effect because they assumed most of the effect came from the assumed smaller particles in that category. However, in the end it was decided that adding the ice and snow together for the purposes of radiation calculations was the best solution, and as seen in **Figure 4,** this brings the Thompson scheme more into line with the other microphysics options while not affecting these other results very noticeably. Since this time, the WRF model has been using the sum of ice and snow for radiation. A more ideal solution is being pursued at NCAR (with Greg Thompson) that would pass particle size information from the microphysics to the radiation (not just the mass contents), because an existing issue is that the radiative schemes in WRF make their own assumptions about particle sizes for ice and snow. This is expected to improve longwave and shortwave cloud-radiative heating profiles by accounting for the vertical size change in stratiform ice clouds with larger snow aggregates near the base having less radiative effect per unit mass.

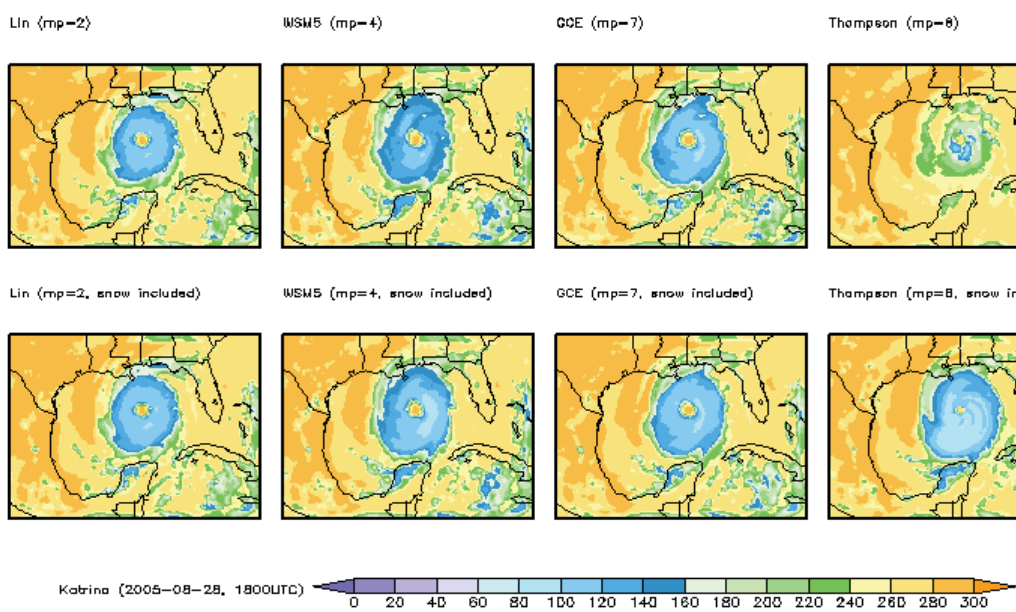
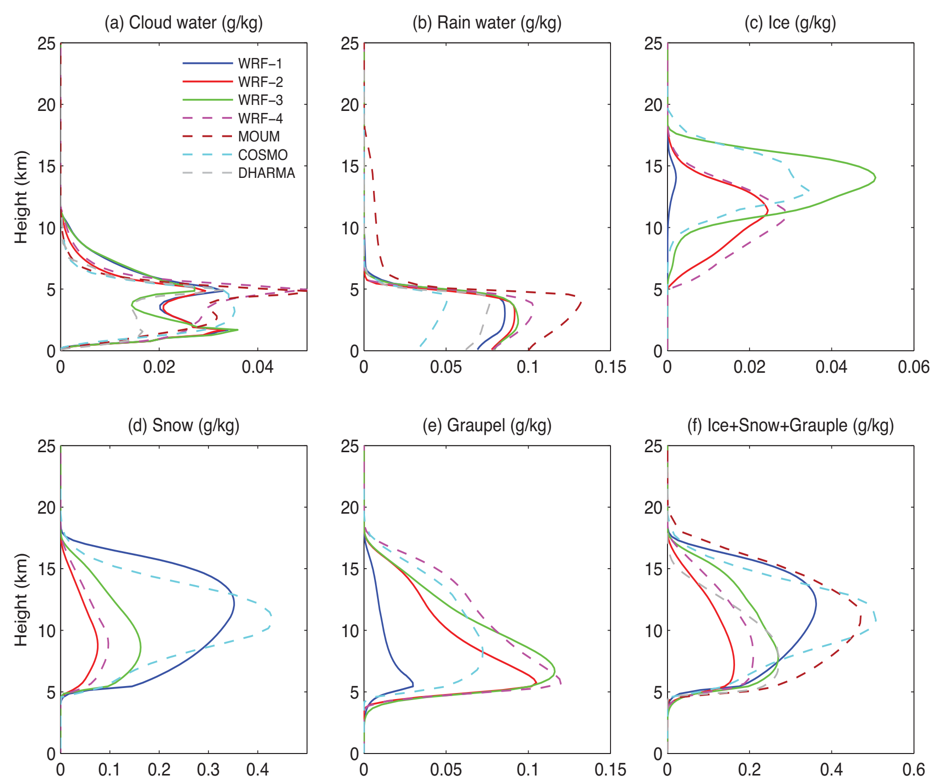


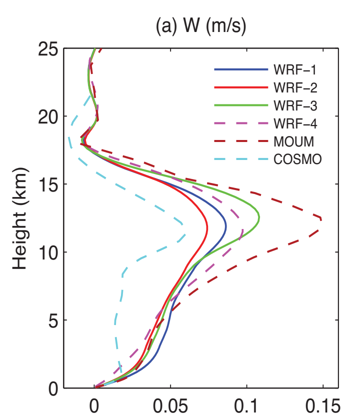
Figure 4: Outgoing longwave radiation for various microphysics options (left to right: Lin, WSM5, Goddard, Thompson). Second row is adding snow to ice effects.

A collaborative effort for the Zhu et al. (2012) publication was on a limited-area model comparison study at high resolution for two TWP-ICE cases. The simulations carried out at NCAR for this intercomparison nested down to a 1 km grid-size so that the convection was largely resolved and the microphysics was responsible for the cloud properties. **Figure 5** shows a sample of the intercomparison output presenting the mean microphysical profiles over the active period (WRF-4 was the NCAR contribution using the WSM6 microphysics). Again here, WRF-1 using the Thompson scheme shows much larger snow amounts and less ice amounts than other microphysical options, as mentioned previously. The vertical velocity profiles also vary. Even though all the WRF runs used the same lateral boundary conditions they have different magnitudes of vertical motion, diabatic heating and precipitation, showing the variability due to physics. High stratiform ice clouds were the most variable among the LAMs but generally agreed with observations from ARSCL more than DHARMA. Another conclusion of this study emphasized the value of LAMs over more idealized cloud-resolving models (CRMs) in systems where the dynamical organization is from a cyclonic circulation and also where the land-sea contrast played a role in the development. More idealized CRMs driven by a specified uniform large-scale uplift cannot represent these features.

Figure 5: (below) Mean profiles of microphysics species in the TWP-ICE intercomparison runs.



(right) Mean vertical motion. [Zhu et al. 2012].



4. Theme III: Addition of CESM Model Physics as WRF Options

At NCAR, we have a lead role in the support and development of the WRF model, developing new options and components for WRF releases each year. The user community is large (several thousand), international and diverse in their applications, and there is a significant regional climate subset in this group. While WRF has many physics options in the categories of cumulus parameterization, shallow convection, land surface, planetary boundary layer, radiation and microphysics, few of these were developed with climate applications in mind. It has been a major effort in the last few years, in collaboration with PNNL, to bring the current set of CESM climate model physics in as WRF options. This will allow for testing climate physics against other options, and also allows for using it in regional simulations and real-weather case studies at various resolutions. Another component of this effort is making the chemistry component in the climate model available to WRF-Chem. This was one of the main goals in our ARM proposal, and this has been completed within the timeline proposed with the final component, the microphysics, being added in the next official WRF release, Version 3.5 due in April 2013, at which time the user community will have access to all the CAM physics in WRF. With the broader WRF community having access to CAM physics, there is now a possibility of more feedback on problems and improvements that may be valuable in further physics development for climate models. A summary of the CESM physics additions to WRF and the code contributors is as follows:

- RRTMG longwave and shortwave radiation added in 2009 (WRF V3.1 from AER, Inc.)
- Zhang-McFarlane deep convection (2011, V3.3 from PNNL)
- UW Park-Bretherton shallow convection (2011, V3.3 from PNNL)
- UW Bretherton-Park PBL (2011, V3.3 from PNNL)
- Morrison-Gettelman microphysics (2013, V3.5 from PNNL)
- Community Land Model, CLM4 (2013, V3.5 from Utah State University and UC Berkeley)

The plan is to keep these physics options up to date with the physics of the CESM climate modelling system. Along with this we are improving the ozone and aerosol climatology in V3.5 that are also of value in climate-type runs. Further work is looking at ocean coupling with WRF, which is currently not a supported feature, but has been done by various WRF user groups independently.

5. Theme IV: Cloud Observations and Microphysics Improvement

The final key theme of this project's work was to utilize the vast resource of ARM microphysical observations along with other field programs to improve our understanding of cloud processes with the aim of representing them better in climate and weather prediction models. Some funding from this proposal went to university collaboration with Dr. Gerald Mace at the University of Utah to enable him to provide ground-based cloud retrieval products at the ARM sites. This complemented the expertise of Dr. Andrew Heymsfield and his group at NCAR that was also supported by this proposal to process aircraft microphysical data with the aim of improving especially ice particle property characterizations. Heymsfield's work focused on developing better ice sedimentation velocities and this resulted in a publication (Heymsfield et al., 2013). Ice particle fall speeds are known to be important for climate models because they determine the lifetime and extent of ice clouds that have a significant impact on the outgoing longwave radiation and surface solar radiation, so this paper represents progress in an area where there has been significant uncertainty due to the wide variation of ice clouds globally. In their work, they have used ten aircraft field programs and separated the convective-produced and in-situ or stratiform-produced ice clouds.

Figure 6, on the next page, illustrates some of the terminal velocity-diameter relations designed to fit the ice-particle properties, and they also focused on a more sophisticated pressure correction for terminal fall speeds than in any previous work based on particle shape and size representations that fitted the observed habits at various temperatures.

A preliminary form of this parameterization was presented at the 2010 ARM Cloud Working Group meeting where initial tests in a model were also presented. The parameterization of the particle-size distribution was in terms of a gamma function with temperature-dependent coefficients, not a function ice mass content. With the size distribution and a fall-speed diameter relation that takes into account the variation of particle cross-sectional area with temperature, it was possible to derive a mass-weighted fall speed that only depended on temperature, not mass content, a unique and simple feature of this scheme. There was also presented observational evidence to support this surprising idea about the fall-speed dependencies. Note also that the ice particles considered here span the range from single crystals to aggregates, and these could be represented in a unified (ice and snow) particle type in the model. This type of simplification is potential of interest in climate models where microphysical schemes can remain simple and still be justified by studies such as this in representing the main size and sedimentation properties.

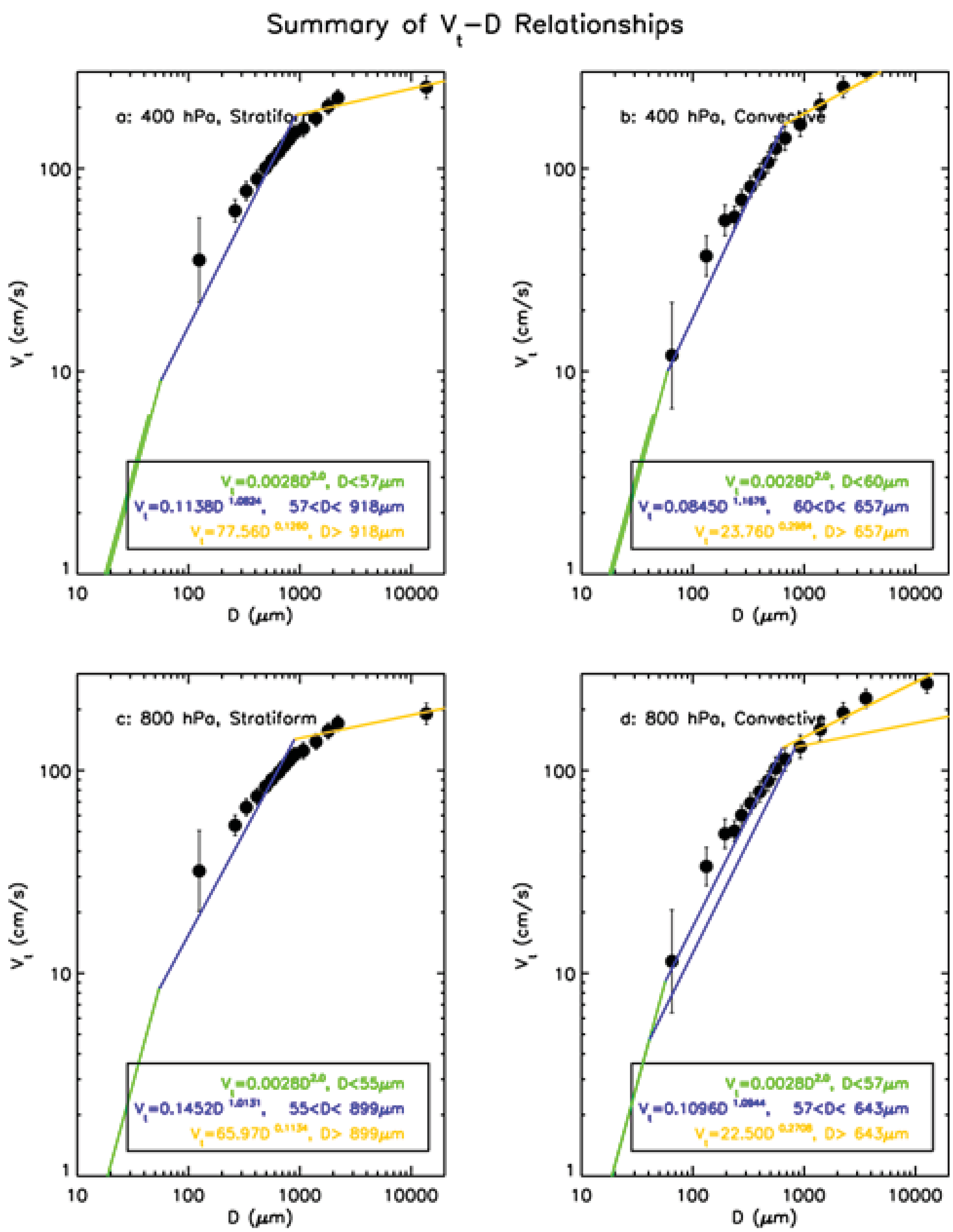


Figure 6: Terminal velocity versus diameter for stratiform (left) and convective (right) showing fitted curves to derived sizes. [Heymsfield et al. 2013].

Work will continue past this project to collaborate with Dr. Heymsfield to bring his newer ideas on functional forms for the size distributions and particle fall speeds into microphysical packages we are developing at NCAR or in collaboration with scientists outside. There are also ongoing efforts to better match the particle sizes with those in radiative schemes as mentioned above, so this work will also tie into that effort by getting observed particle sizes into microphysical schemes, thereby allowing the radiation to interact with realistic ice particle sizes.

6. Concluding Remarks

This DOE project has pushed forward on several fronts. While the initial intention of providing an analysis dataset for the TWP region was thwarted by the MJO problem, research has progressed in terms of understanding what is required in low-resolution models to produce these and this work is continuing in a follow-on project related to the DYNAMO field program (PI: Chidong Zhang, U. Miami). The project also resulted in several improvements to the radiation scheme in the WRF model to better represent both clear-sky and cloudy condition radiative heating profiles. The last section described advances that can potentially improve ice microphysical properties in future parameterizations. From the perspective of broader impacts, this work in a successful partnership with PNNL, has provided the WRF atmospheric modelling community with the complete suite of climate physics of the current CESM version that now enables the large WRF community to work with climate physics to evaluate it against other physics, or at other grid sizes, in various regions, which may lead to an acceleration in the development of climate physics packages, and certainly allows for more testbeds.

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