Addressing Major Earth Science Challenges in Cloud and Precipitation Process Modeling

Key Authors: Gail Skofronick Jackson, Gerald Mace, Arlindo da Silva, Sue van den Heever, Simone Tanelli + team members listed in the Table of Contributors.

Executive Summary

Water is necessary for all life on Earth. Thus it is vital for all civilization to know where, when and how clouds form, whether they precipitate or not, and how those patterns may change in a future climate. Central to this required knowledge are better predictions of atmospheric water at all scales. This necessitates a *paradigm shift away from our current practices that largely observe states to future observing strategies that can deliver information on both states and the processes that govern model physics and prediction skill.* The new insights afforded by these process-oriented measurements can inform the next generation of cloud and precipitation models for weather forecasting and climate change.

Our **Earth Science Objective** is to *considerably improve the accuracy of cloud-precipitation processes in Earth system models at scales from microphysical to regional to global.* Currently in 2016, Cloud Resolving Models (CRMs, i.e., any numerical model that explicitly resolves convective motions and/or microphysics) are at a roadblock and cannot improve without observational constraints to assess the fidelity of existing microphysical schemes and processes (e.g., Hagos et al., 2014, Bassill 2014, Stephens and Ellis, 2008), or to point in the direction of new ground breaking formulations. The **geophysical variables** we aim to measure include *cloud and precipitation particle vertical velocities and microphysical properties*, particularly of ice particles. These are key for improving climate and weather forecasting models currently and in the coming decades when these models will be able to explicitly resolve microphysical processes at convective updraft scales (e.g., Hagos et al., 2014, Popkin, 2014).

The ***importance*** of these observations comes in their ability to inform and constrain models so as to better understand and predict the Earth's Water and Energy cycles for our everyday lives and long-term future. The ***utility*** of the proposed measurements brings much needed constraints to allow for improvements in our ability to assess the availability of fresh water from precipitation and to examine the occurrence and characteristics of extreme-weather. The ***quality*** of the measurements to address these shortcomings is high. Indeed we contend that without these measurements models cannot measurably improve. In terms of ***affordability***, the specifications for our geophysical measurements remain flexible and we are committed to finding the most cost effective approach to meet our baseline science objectives.

This Cloud and Precipitation input to the 2017-2027 Earth Science Decadal Survey Request for Information (RFI#2) is drawn from nearly 3 years of team discussions and several workshops from what we are calling the Cloud and Precipitation Process Measurements (CAPPM) group (URL http://pmm.nasa.gov/CAPPM). The traceability from science requirements to measurements has benefitted from the activities funded by the Aerosol, Cloud, Ecosystem (ACE) study, a mission recommended by the 2007 Decadal Survey. This CAPPM RFI is complementary to Aerosol-Cloud RFI inputs. Our key geophysical measurements of cloud and precipitation processes needed for models are cross cutting for the following Decadal Survey theme panels: I. Global Hydrological Cycles and Water Resources, II. Weather and Air Quality: Minutes to Subseasonal, and IV. Climate Variability and Change: Seasonal to Centennial. Precipitation and clouds are inherently linked to these three theme panels.

Introduction

The 21st century poses extreme challenges for the sustainable management of the Earth's water resources at all levels from the local to the global scale. The international climate community through the World Climate Research Programme (WCRP) has identified the issues underlying water availability, climate extremes and cloud influences on climate as three of the grand challenges facing both our understanding of and our ability to adapt to climate change (http://wcrp-climate.org/grand-challenges). Three basic questions posed under these challenges are: how will the availability of fresh water change in the coming decades, what is the predictability of changes in frequency and intensity of extremes at seasonal to decadal time scales, and how does convection shape cloud feedbacks? Central to these questions are better predictions of water at the local scales at which it has the most profound societal impact. This requires a paradigm shift away from our current practices that largely observe the *state* of precipitation and hope that a better measurement will lead to improved model predictions, to future observing strategies that can deliver information on both *states* and the *processes* that deliver improvements to model physics and prediction skill. Processes here refer to the various physical mechanisms within clouds that act to produce precipitation. In a changing climate it becomes essential to understand at both the local and global scale the underlying cloud processes (via measurable proxies) that result in precipitation such that these can be incorporated into the next generation of climate and numerical weather prediction (NWP) models. In the next decade as the resolution of these climate models increase to explicitly represent cloud and convective processes, it is equally imperative to plan for timely observations that can constrain and define these processes to produce more accurate predictions of the water cycle at both the weather and climate timescales.

Importance of Cloud and Precipitation Observations

The microphysical processes acting within clouds are fundamentally linked to the cloud-scale dynamics such as updraft speed and entrainment (e.g., Fig. 1). Observationally establishing relationships between microphysical processes and cloud-scale dynamics is what we refer to as process-level understanding. Our objective is to translate process-level understanding to improved climate models. Only when relationships between environmental conditions and the resulting microphysics are established and finally replicated in Earth system models will we have reduced the fundamental uncertainty in process level understanding. With additional effort this process level understanding can then finally be translated into improved climate prediction. Because of the tight connection between cloud-scale vertical velocities and the resulting ice hydrometeors, the concept proposed here is to simultaneously infer *vertical velocities* and the accompanying *hydrometeor microphysical characteristics* with sufficient accuracy to inform model developers as to what microphysical processes (and even, perhaps, what process rates) are dominant in a given dynamical scenario or within dynamical regimes as well as assist in identifying realistic microphysical parameterizations as a function of environmental conditions or dynamical regimes. This information on microphysical processes is needed globally so that the full continuum of microphysical processes can be characterized as a function of large-scale dynamical regimes. Such information will allow for development and validation of robust GCM parameterizations.

Incorrectly representing dynamical and microphysical processes in models of all scales, and the feedbacks between them, has significant implications for predicting (1) precipitation rates and efficiency, convective-stratiform partitioning; (2) the horizontal and vertical distribution of clouds including the properties of radiatively active anvil cirrus clouds; (3) the partitioning between the liquid water and ice phase; and (4) the location and amount of latent energy release associated with phase changes. All of these factors impact the climate directly through the amount and character of the precipitation produced, cloud-radiation interactions, and the depth and intensity of the precipitating cloud systems produced, and hence the detrainment of water vapor and condensed mass to the free troposphere. For example, vertical velocity is explicitly simulated and directly linked to microphysical process parameterizations in cloud-resolving models, whereas the necessarily large grid spacing in global climate models means that sub-grid scale vertical velocity and the links to the microphysics are much more highly parameterized. Weather forecast models may either utilize convective parameterizations or explicitly represent cloud-scale vertical velocity depending on their grid resolution, a problem that gets exacerbated in the so-called *grey-zone* (resolutions in the range 1-10km) where *some* cloud systems are resolved. Precipitation processes in clouds fundamentally couple vertical velocities to hydrometeor production. Thus, by understanding those processes we enhance predictions of precipitation and thereby ultimately improve predictions of cloud-radiative forcing, the two fundamental cloud processes impacting climate change, by observationally enhancing our representation of both microphysical and dynamical processes. We anticipate that new knowledge will emerge regarding cloud-precipitation-dynamics interactions via global analysis of the covariance of retrieved properties as a function of large-scale forcing within various dynamical regimes. Ensuring that climate system models replicate these relationships will be a fundamental application of the CAPPM objective.

Utility for Improved Cloud and Precipitation Process Modeling

Vertical velocity and microphysical processes are more explicitly represented and more directly linked in Cloud Resolving Models (CRMs) than in Global Climate Models (GCMs). By virtue of this, it is imperative to enhance our understanding and hence the representation of the interaction between dynamical and microphysical processes if we are to improve our forecasts of precipitation and cloud properties, and the subsequent upscale feedbacks to climate. Furthermore, the rapid development and increasing use of global CRMs means that an understanding of such processes is rapidly becoming critical for accurate climate prediction. Improving our observations of dynamical and microphysical cloud processes, as would be the focus of this proposed work, would contribute to improving the following CRM topics through process evaluation or model constraints (see also Table 1):

1. **The manner in which the large ice species are parameterized –** this will shrink inaccuracies in surface precipitation rates, convective-stratiform precipitation and precipitation PDFs (Bryan and Morrison, 2013; Adams-Selin et al 2013; Tao et al 2016).
2. **The connection between vertical velocities and resulting ice hydrometeor species** - properly representing vertical velocity reduces inaccuracies in the nucleation rates, numbers and sizes of cloud droplets and ice crystals and hence the hydrometeor size distributions (Saleeby and Cotton, 2004; Saleeby and van den Heever 2013; Varble et al 2014).
3. **The understanding of the partitioning between liquid and ice particles -** accurately representing cloud microphysical processes reduces significant inaccuracies in the partitioning between the liquid and ice water species, the depth of the mixed phase cloud region, the vertical redistribution and location of ice and liquid water, & upper-level detrainment of water vapor.

As an example, Fig. 2 shows percent change in precipitation frequency for NASA Unified-Weather Research Forecasting (Nu-WRF) microphysical tests from three identical CRM simulations except for changes to the ice parameterizations (van den Heever et al, 2016). As can be seen, rainfall PDFs vary quite significantly. Figure 3 displays some key mean characteristics of the liquid and ice hydrometeor profiles, along with the averaged and maximum vertical velocities within the convective regions. Many of the ice parameterization perturbation tests reveal substantial variability in both vertical motion and hydrometeor mass. If one takes a step back and compares Ice Water Content (IWC) over various models in the Intergovernmental Panel on Climate Change (IPCC) Assessment Report archive, there is a widely varying difference in total IWC (Fig. 4). Constraining ice is shown to be fundamentally important.

Improved understanding of critical cloud-resolved processes, either by means of CRM improvements or by direct insights gained through analysis of the proposed measurements, will also help address shortcomings in climate and cloud-permitting global models (henceforth referred to as GCMs). GCM simulations forecast important changes to cloud systems as global warming progresses. Mid-latitude storms and extratropical cyclones are predicted to shift poleward (Bengstsson et al, 2006) with significant impacts on the water resources of those regions (Frederiksen and Frederiksen, 2007). Storm intensity is also widely expected to increase although our understanding of how intensity will change is rudimentary. The upscale development and organization of large convective complexes MCS, (a critical source of summer water resources over the continental midlatitudes) is difficult to represent in current climate models. The overarching deficiency of GCMs is the inability to simulate long-term precipitation ultimately because GCMs have difficulty representing the vertical distribution (Fig. 4) of ice versus liquid water contents, particle sizes, and microphysical processes linking them. These deficiencies in GCMs will be addressed via improved cloud-resolved processes-level knowledge as shown in Table 1. This knowledge must arise ultimately from comprehensive measurements of cloud-precipitation-dynamical processes from observational systems like that envisioned by CAPPM and described herein.

Quality and Applicability of the Measurements

The science objectives outlined above require an observational strategy consisting of a satellite component that is able to quantify vertical velocities and hydrometeor microphysics. The satellite component envisaged significantly advances upon the capabilities afforded individually by the Tropical Rainfall Measuring Mission (TRMM), CloudSat, Global Precipitation Measurement (GPM), and EarthCare missions, as well as the capabilities afforded jointly through these missions in convoys (e.g., A-Train concept) and/or constellations (e.g., GPM partner constellation concept). While this concept paper does not advocate for a specific spacecraft/instrument solution, the core of the required observing system is envisioned to be a triple-frequency (Ku/Ka/W-band) Doppler radar (Fig. 5) together with a wideband imaging microwave radiometer (Fig. 6). Furthermore the radar can be designed to have radiometric capabilities as demonstrated by CloudSat. The combination of three radar frequencies on a single platform allows complete observation of non-precipitating clouds through heavy precipitation and encompasses the liquid to ice phase processes that link them. While it is beyond the scope of this document to describe retrieval algorithms, we only note here that our retrievals have many degrees of freedom and it is our objective to obtain as many independent pieces of information as is practical in the cloudy/precipitating vertical column. Multi-frequency Doppler radar combined with multi-channel microwave accomplishes this objective. We will build upon this measurement suite to develop innovative algorithms to estimate the geophysical parameters that are necessary. We are well aware that development of such algorithms will be challenging given the high bar we have established to resolve cloud-scale vertical motions and microphysical processes simultaneously. Note that there is heritage in that GPM's dual frequency Ka+Ku band radar is designed to estimate particle size distributions while ground based Doppler radars can provide vertical velocities. If necessary, well-designed (prior or future) field campaigns (e.g., Fig. 7) can provide more detailed cloud observations in regimes where models do not properly reproduce the observed cloud structures. Furthermore, there is flexibility in the observational instrument space in terms of frequencies, specifications, and orbital characteristics (the required geophysical variables could be obtained via a single well-outfitted spacecraft or temporally spaced radars that can infer vertical velocities from the time evolution of cloud systems, while passive sensors provide the broader cloud context).

Affordability of Proposed Observations

Radar technology specifically relevant to spaceborne cloud and precipitation radars has advanced significantly in the last decade through advancements in component technologies motivated by other application sectors: miniaturization, efficiency and maximum RF peak power of solid state power amplifiers, especially at Ka- and W-band; digital processing capacity and miniaturization; innovative machining and packaging techniques. All of the above have been at the focus of NASA-sponsored instrument development projects funded mainly by NASA's Earth Science Technology Office (ESTO), but also by JPL and GSFC institutional funding, as well as other Programs such as ACE pre-formulation studies and internationally at the Japanese Exploration and Space Agency (JAXA). The most significant evolution with respect to the first decade of this millennium is that now both Ka-band (Hand et al. 2013) and W-band (Sadowy et al. 2016) channels with electronic scanning, sufficient sensitivity and Doppler accuracy of 20 cm/sec are feasible: key technologies have either been demonstrated (Durden et. al 2016) or are on track to reach TRL 5 by 2017. Furthermore unprecedented miniaturization (with direct impact on affordability) of spaceborne precipitation radars should be demonstrated in space under the ESTO InVEST Program by the RainCube TechDemo mission (Peral et al. 2015, launch readiness August 2017). This assessment also leverages on the full mission design studies performed at JPL and GSFC for the ACE mission concept and the associated lessons learned (see e.g., Tanelli et al. 2010).

Radiometer technology is mature. TMI, AMSR-E, AMSR-2, TMI, GMI and the ESA Ice Cloud Imager have all paved the way for stable radiometer observations. Indeed, if needed, there is a second copy of GMI parts in storage that could be assembled at a reasonable cost. There is flexibility in the channel selection, although key would be V & H polarized channels at 19, 37, 89, 166 GHz and several channels surrounding the 183 V water vapor lines. Lower/Higher channels are more sensitive to other cloud and precipitation parameters as shown in Fig. 6. Radiometers are critical for providing vertically integrated constraints on retrievals - especially liquid water, supercooled water, ice particle size, etc.

To provide a first assessment of affordability, Table 2 provides a high level comparative chart of NASA missions that involve radars and radiometers in terms of Size, Weight and Power. International partnerships are also likely as these measurements would be of value beyond the United States. The CAPPM team is committed to finding a cost-effective implementation that meets measurement needs.

Summary

One of the key NASA objectives, consistent with US Climate research goals, is to reduce the uncertainty in future climate projections. Today, much of the uncertainty can be attributed to cloud/climate feedbacks, and in particular, the role of convective clouds in driving the global circulation through the release of latent heat, and in the radiative feedbacks through the detrainment of water vapor and condensate that alter the incoming solar and outgoing planetary and infra-red radiation. Examples such as in Tao *et al*. (2016) clearly illustrate the sensitivity of current climate simulations to the details of the microphysical assumptions used in the cloud scale models. Zhao *et al*., (2016) shows very distinct [0.48 – 0.82] equilibrium climate sensitivity in the sensitivity in the next-generation GFDL global climate models when the formulation of convective precipitation is changed. Our **science and application target** is the improvement of cloud and precipitation processes in Earth system models through focused global spaceborne measurements of cloud and precipitation *vertical velocities and hydrometeor microphysical characteristics.* These relate directly to microphysical processes that form the key linchpin of uncertainty in Earth system predictive capacities.

In addition to addressing core questions related to climate projections, high quality precipitation measurements address a set of specific questions related to extreme events. Models suggest that increased amounts of water vapor in a future climate would lead to increased extremes in the precipitation distribution (Berg & Hall, 2015). Such changes, while perhaps also evident from the surface, require globally complete analyses in order to assess if the changes are physical, or merely reflect changes in the spatial patterns that are also likely as the circulation patterns change. Changes in the extremes, and its tremendous impact on human lives [Ruin et al., 2014; Cheng, et al., 2016] also illustrate the central role that precipitation plays in our climate observing system. Just as it is not sufficient to study precipitation in absence of clouds, it is equally valid that an understanding of important hydrologic variables such soil moisture or inland water storage cannot be understood without knowledge of precipitation as an input variable.

A final value argument for the above measurement concept is the clear opportunity for NASA to extend the time record continuity of high quality near-global precipitation estimates. With TRMM and GPM, NASA and JAXA have a 19-year time record of surface precipitation and 3-dimensional precipitation profiles as derived from spaceborne radiometers and radars. Assuming GPM outlasts its design lifetime by 10 years (TRMM outlasted its design life by 14 years), NASA will extend this record to 30 years. Given the tremendous value of this data, and the increased value as the record becomes longer, not continuing this measurement will represent a significant loss to mankind though an imperfect record of precipitation patterns. Vertically resolved cloud (precipitation) structures became available in 2006 (1997; 2014) with the W-Band (Ku-Band; Ku and Ka-band) radar on CloudSat (TRMM; GPM) and assuming that CloudSat lasts until the launch of EarthCare, global space agencies will create a substantial record of cloud structures as well. This valuable climate marker would also be extended through this proposed measurement concept. Importantly, the CAPPM concept brings together the clouds and precipitation into a logical combination and adds the critical aspect of cloud scale dynamics. So, not only will CAPPM extend the measurements but also CAPPM will add critical new dimensions to our understanding. The CAPPM geophysical observations are essential to improve accuracy in Earth system models for predicting near term weather forecasts and climate change over seasons and centuries.

Table 1: Measurement basis and concepts for addressing science topics proposed for essential cloud and precipitation measurements and their impact on cloud modeling:

Topic #1	**Improve the manner in which the large ice species are parameterized**
Measurement Basis	Parameterizations of snow, graupel and hail in all current schemes are based upon parcel supersaturation and assumed shape of particle size distributions. Vertical velocities are a reliable proxy for supersaturation. Snow is formed when vertical velocities are near 1 m/s while graupel is formed when velocities reach 3-4m/s. Hail is formed when velocities are of the same order of magnitude but supercooled liquid is readily available.
Measurement Concept	Measure particle vertical velocities ideally with 20 cm/sec accuracy or better in cloud and stratiform precipitation, and 50 cm/s inside deep convection, using Doppler at one or more channels. Measure radar reflectivity of ice particles with a sensitivity of approximately -30 dBZ in cloud and -10 dBZ in precipitation. Use the mean particle diameter estimated from multi-frequency reflectivity observations to estimate the terminal fall speed and estimate density and habit. All measurements are expected to be acquired at a vertical resolution of at least 250 m to resolve the vertical structure, and a horizontal resolution of 1 km in cloud and light precipitation. A horizontal resolution of 2 km is preferred to resolve convection; and 4 km to resolve stratiform precipitation. All measurements are to be acquired over a swath sufficient to cover the convective scale (i.e., a few tens of km). Higher frequency microwave radiometer channels can be used to estimate the presence of supercooled water above the freezing level and to identify scattering from large ice species.
Modeling Impact	More sophisticated ice microphysical parameterizations within the MMF produce a better vertical distribution of cloud ice in the upper troposphere down to the melting level, as well as more accurate cloud ice amounts in the tropics and mid-latitudes (Tao et al 2016) Representing mid to upper level ice amounts correctly has significant impacts on cloud-radiative forcing and hence climate implications. Correctly predicting the strengths of updrafts and downdrafts is critical since all CRMs typically over-predict these drafts and the snow/graupel production *(Varble et al 2014; Fan et al 2015).* Misrepresentation of precipitation rates bias model depictions of the tails of the precipitation distribution and hence the ability to simulate extreme events including flooding and long-term droughts. GCMs to produce too much snow over the Arctic and Antarctic for example Arctic: CloudSat: 208 (σ=18) mm/yr; CESM = 242 ±15 mm/yr (Palerme et al 2014), Antarctic: CloudSat = 172 mm y^{-1}; ERA-interim = 167 mm y^{-1}; CMIP5 Mean/Max = 215/285 mm y^{-1} (L'Ecuyer et al 2015). This has important implications for ice sheet mass balance and, therefore, the rate of global sea level rise.
Topic #2	**Improve the connection between vertical velocities and resulting ice hydrometeor species**
Measurement Basis	Need measurements of air vertical velocities (50 cm/sec or better) together with ice hydrometeor species as a function of the large scale environment. Many studies have shown that the pre-storm environment is sufficiently well characterized by reanalyses

	such as ERA-I and MERRA.
Measurement Concept	Measure vertical velocities with ~20 cm/sec accuracy using Doppler radar. Measure radar reflectivity of ice particles at multiple frequencies. Use the mean particle diameter estimated from multi-frequency reflectivity observations, to estimate the terminal fall speed and estimate density and habit. Deduct the estimated terminal fall speed from the directly observed Doppler velocity to estimate vertical air velocity at the 50 cm/sec accuracy. Use microwave radiometer to estimate the presence of supercooled water above the freezing level. All measurements are to be acquired at a vertical resolution of ~ 250 m to resolve the vertical structure, and a horizontal resolution of 1 km in cloud and light precipitation. A horizontal resolution of 2 km is instead needed to resolve convection, and 4 km to resolve stratiform precipitation. Aircraft observations can assist in difficult regimes. All measurements are to be acquired over a swath sufficient to cover the convective scale (i.e., a few tens of km). Use a microwave radiometer to estimate the presence of supercooled water above the freezing level, and high frequency (>89 GHz) to detect scattering from ice particles aloft.
Modeling Impact	Properly representing vertical velocity reduces inaccuracies in the nucleation rates, numbers and sizes of cloud droplets and ice crystals and hence the hydrometeor size distributions (Saleeby and Cotton, 2004; Saleeby and van den Heever 2013; Varble et al 2014). All of these factors impact the DSDs and CSDs (crystal size distributions), which in turn influence cloud-radiative forcing, cloud lifetime and precipitation rates. DSDs and CSDs play a significant role in evaporation and melting rates and hence in the generation of downdrafts, large-scale subsidence, and entrainment / detrainment; they also impact cold pool development and hence subsequent convective initiation (*van den Heever and Cotton*, 2004, 2007; *Dawson et. al*, 2010; *Storer et. al*, 2010). A recent model TWP-ICE intercomparison project of 30 different regional and cloud-resolving models demonstrated that while liquid water is relatively well represented in those models that resolve convection (and hence vertical velocity), there is significant spread amongst those models that parameterize convection (Petch et al 2013). Large discrepancies were found in representing ice processes, suggesting that even those models that are able to represent the dynamical processes of convective clouds relatively well have great difficulties in accurately capturing the ice phase characteristics. More sophisticated ice microphysical parameterizations within the MMF produce a better vertical distribution of cloud ice in the upper troposphere down to the melting level, as well as more accurate cloud ice amounts in the tropics and mid-latitudes (Tao et al 2016) Representing mid to upper level ice amounts correctly has significant impacts on cloud-radiative forcing and hence climate implications. The inability to directly link storm dynamical and microphysical processes in models influences the representation of microphysical processes such as aerosol activation (Saleeby and Cotton, 2004; Saleeby and van den Heever 2013), droplet number concentrations, size distributions and autoconversion (Saleeby et. al., 2015), and convective invigoration through latent heating (van den Heever and Cotton, 2004; Sheffield et al., 2015) all of which have implications for cloud radiative forcing, surface precipitation and vertical heating.

	There are no global estimates of cloud venting. Cloud venting / convective mass flux is the process of transporting heat, moisture, momentum, trace gases and aerosols from the lower troposphere into the middle and upper troposphere. Venting varies as a function of storm type and updraft strength. Model results suggest venting of entire boundary layer (BL) about 90 times per year due to convective storms but there are no global estimates of venting.
Topic #3	**Improve the understanding of the partitioning between water and ice particles**
Measurement Basis	Liquid and ice particles have significantly different backscatter and attenuation characteristics at different frequencies. Multifrequency active and passive observations can distinguish between these hydrometeor types. Wideband passive observations are sensitive to heavy rain (<= 37 GHz), moderate and light rain (37-166 GHz) and ice scattering (>=89 GHz)
Measurement Concept	It is important to cover all reflectivity ranges with at least two distinct radar frequencies coupled to a multi-channel microwave radiometer in order to separate liquid from frozen hydrometeors. A three frequency radar (Ku, Ka and W) has been used to distinguish hydrometeor phase based upon backscatter while a coincident GMI-like radiometer footprint should provide the necessary attenuation measurements, precipitation rates, and precipitation climate continuity records. All radar measurements should be acquired at a vertical resolution of at least 250 m to resolve the vertical structure, and a horizontal resolution of 1 km in cloud and light precipitation. A horizontal resolution of 2 km is instead necessary to resolve shallow convection and the ice phase portion of deep convection, and 4 km to resolve deep convective and stratiform rain. All measurements are to be acquired over a swath sufficient to cover the convective scale (i.e., a few tens of km). For this purpose designing radiometric capability in the radar instrument electronics is beneficial because of its intrinsic collocation and identical horizontal resolution to the radar reflectivity profiles.
Modeling Impact	Accurately representing cloud microphysical processes reduces significant inaccuracies in the partitioning between the liquid and ice water species, the depth of the mixed phase cloud region, the vertical redistribution and location of ice and liquid water, and upper-level detrainment of water vapor. The inability to directly link storm dynamical and microphysical processes in models influences the representation of microphysical processes such as aerosol activation (Saleeby and Cotton, 2004; Saleeby and van den Heever 2013), droplet number concentrations, size distributions and autoconversion, and convective invigoration through latent heating (van den Heever and Cotton, 2004) all of which have implications for cloud radiative forcing, surface precipitation and vertical heating. Model transports are too widespread and too weak (Parazoo et al., 2011) thereby influencing the vertical distributions of water vapor, and thus the water vapor feedbacks, cloud structures, precipitation, heating, momentum transport (Lane and Moncrieff, 2010), aerosols (and thus all types of aerosol indirect effects) (van den Heever et al., 2006; 2011) and trace gas distributions and their related greenhouse effects.

Table 2: Recent LEO missions by NASA (and partnering agencies) that include a radar (and in some cases a radiometer), and their Size, Weight and Power (SWaP). All numbers are approximated for the purpose of preliminary comparative assessment of cost. The last line represents a baseline convoy. The closest proxy to evaluate affordability is the GPM core platform (which however had 2 radars + 1 radiometer, instead of 1 radar + 1 rdiometer), but also SWOT is a valuble point of comparison (with one frequency only but larger mass, power, antenna size and significantly more stringent phase requirements due to its interferometric nature). (*) co-manifested on a DPAF with CALIPSO, (**) will be launched with many other 6U through a standard CubeSat dispenser (TBD), (***) GPM core is part of a constellation of several platforms, here only the core is captured, (#) includes the radar and radiometer, (##) includes the L-band and S-band Synthetic Aperture Radars, (###) 3 different antennas for the Ku radar, Ka radar and GMI.

Mission	Payload Mass [Kg]	Payload Power [W]	Antenna Size [m]	# of platf.	Launch Vehicle	Obit Type	Mission Duration
CloudSat	250	300	2	1 (*)	Delta II	LEO	22 mo
RainCube Tech Demo	7	35	0.5	1 (**)	TBD (CSLI)	LEO	6 mo
GPM Core (#)	950	950	2 (Ku), 1 (Ka) , 1.5 (GMI) (###)	1 (***)	H-IIA	LEO	3 yr
SMAP (#)	300	450	6	1	Delta II	LEO	3 yr
NISAR (##)	1300	4300	12	1	PSLV	LEO	> 3 yr
SWOT (#)	700	1350	10 (baseline)	1	TBD	LEO	3 yr
Baseline (#)	650	1150	5	1	Atlas V (500) or H-IIA equiv.	LEO	3 yr

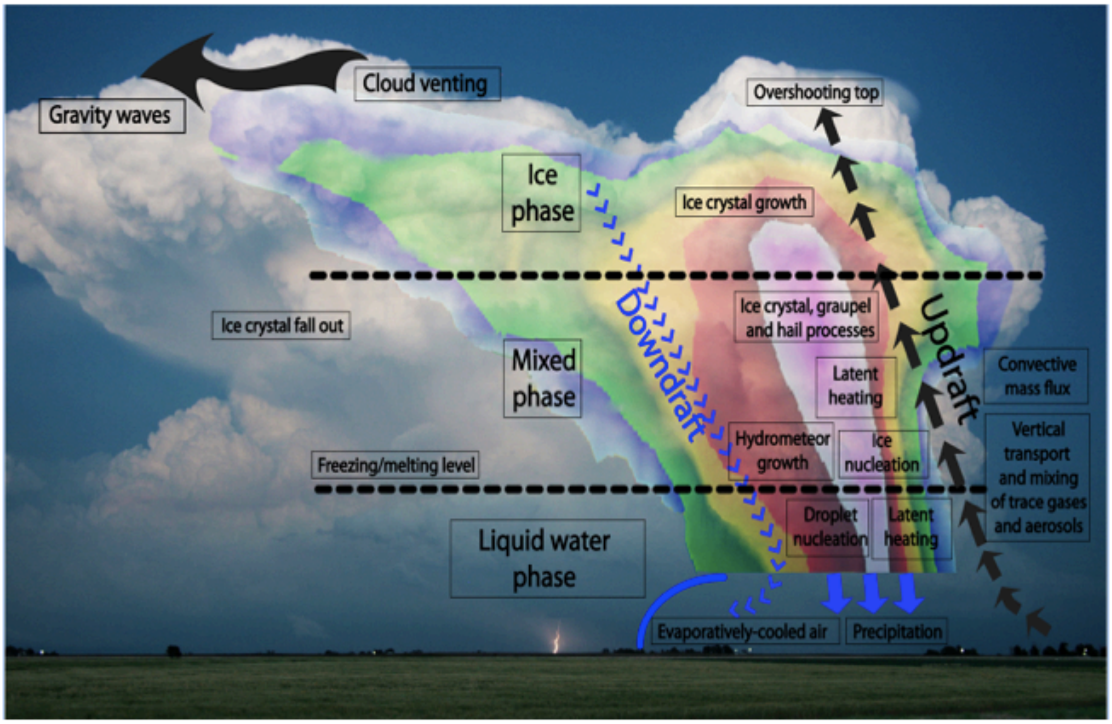

Figure 1: Complex dynamical processes within clouds that show that microphysical and dynamical processes of clouds are fundamentally linked. (From a presentation by Sue van den Heever)

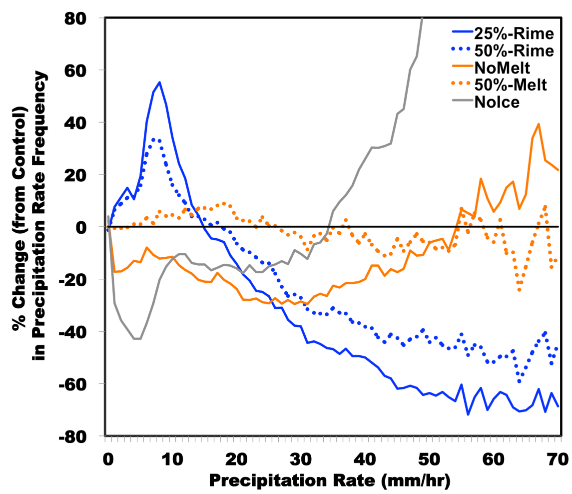

Figure 2: Percent change in microphysical tests from NuWRF CRM simulations of a squall line over Oklahoma that occurred May 20, 2011 during the Global Precipitation Measurement (GPM) field campaign called Mesoscale Continental Convective Cloud Experiment (MC3E, Petersen and Jensen 2012). Simulations were run to test sensitivity to changes in microphysics parameterizations. Shown: Percent change in the microphysics test simulations (Experiment - Control Run) of the precipitation rate frequency of occurrence binned by precipitation rate magnitude for simulations run with Nu-WRF. For example, the "25%-Rime" simulation revealed greater occurrence of weak precipitation rate (<20mm/hr) and reduced occurrence of heavy precipitation rate (>20mm/hr) relative to the control run.

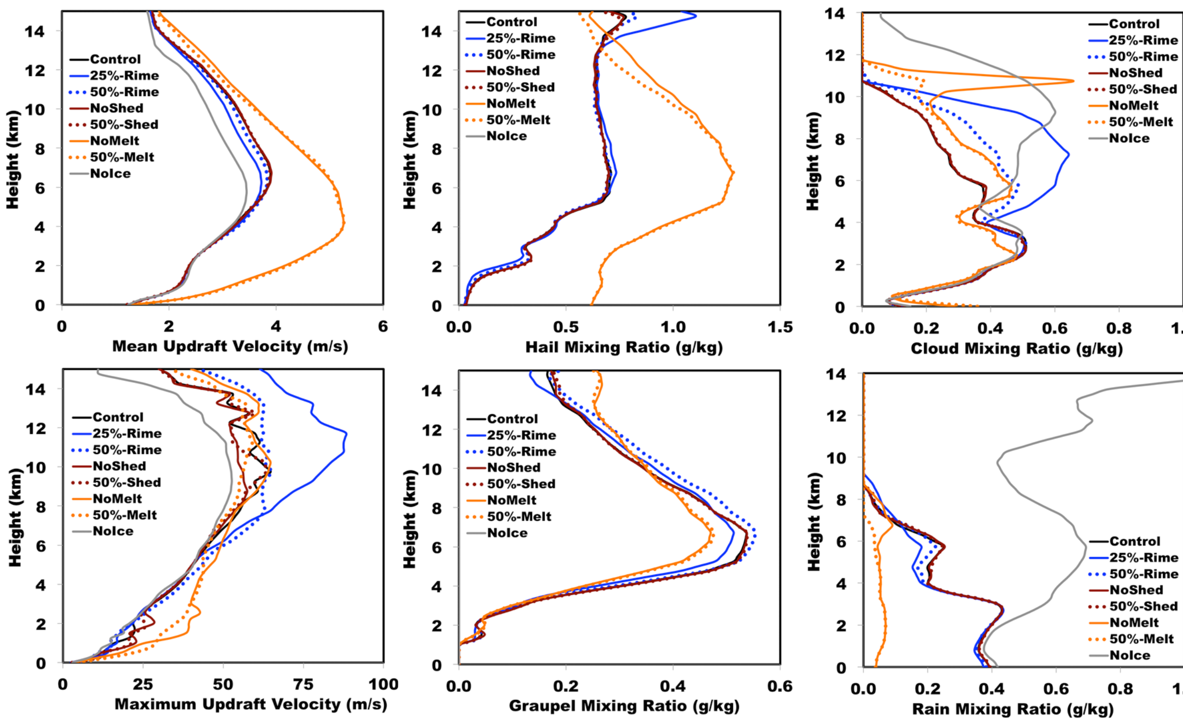

Figure 3: Vertical profiles of various quantities from a Regional Atmospheric Modeling System (RAMS) model simulated squall line that occurred on May 20, 2011 during the MC3E field project. All quantities except "Maximum Updraft Velocity" are mean quantities averaged horizontally and temporally. Model domain was centered over Oklahoma with 1.0 km grid spacing. The color legend is given on the plots. "Control" is the control simulation. The "Rime" tests used altered riming efficiencies relative to the control. The "Shed" tests reduced the shedding of raindrops from hail by the given amount. The "Melt" tests reduced the melting rate of hail by the given amount. The "NoIce" tests used only warm rain microphysics. These plots show variability in microphysical characteristics in models when there are limited observational constraints.

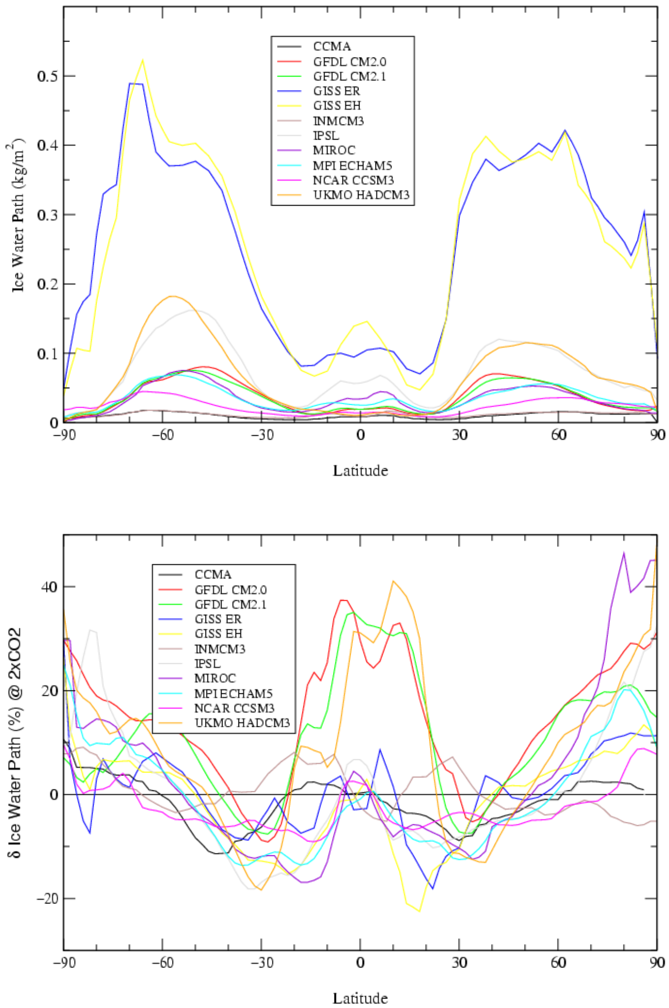

Figure 4. Top: The climatology of zonal, annual mean IWP from the various models in the IPCC AR4 data archive. Bottom: The percent change in zonal, annual mean IWP after a CO2 doubling in the model. These figures demonstrate the large variations in model produced IWP and the sensitivity of the model simulated IWP to a changing climate. CAPPM observations are needed to assess these model differences.

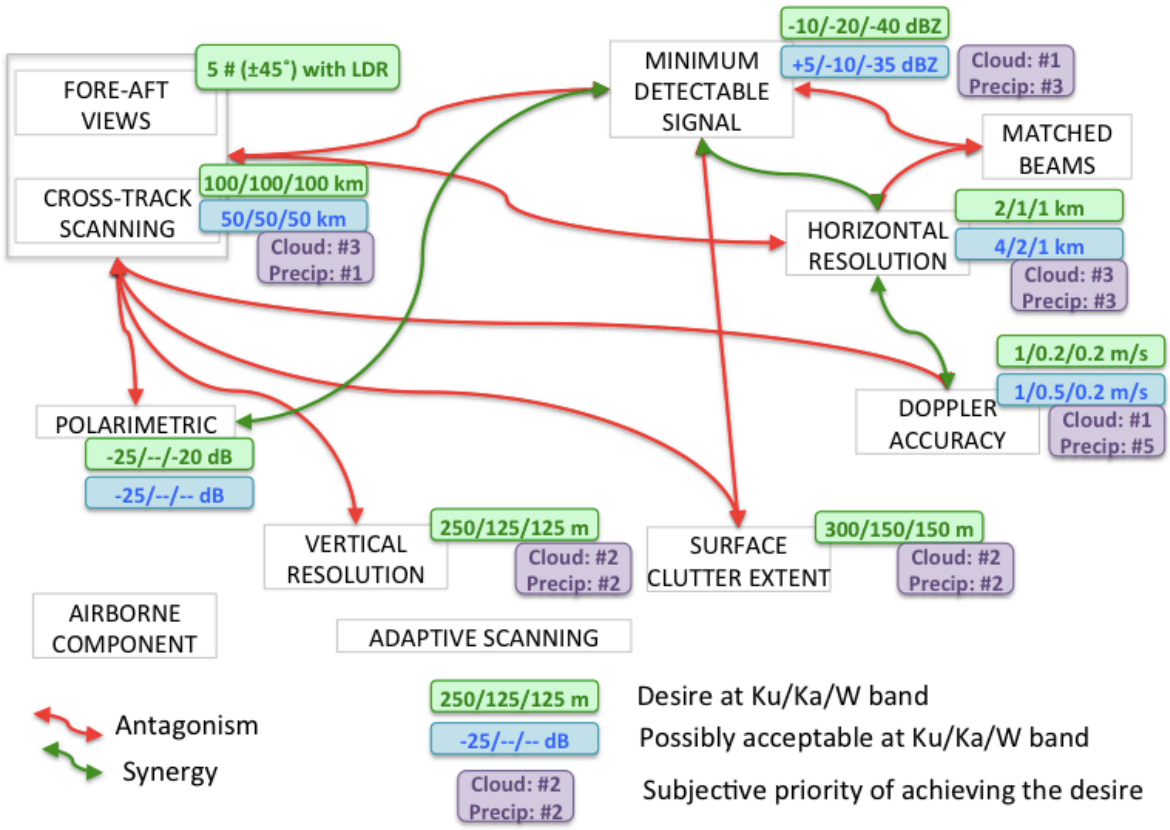

Figure 5: A baseline radar system would comprise a triple-frequency system centered upon scanning Ku, Ka and W-band (13, 35 and 94 GHz) radars, with Doppler capability at all frequencies. To retrieve cloud parameters the system needs high-sensitivity, fine range resolution capabilities. Specifications are negotiable based on final configuration, partner instrument availability and scientific needs. This figure shows the relationship between synergistic parameters by green arrows and antagonisms are shown by red arrows. At very high level, by imposing more stringent requirements on one performance parameter one can expect an increase in mission cost in order to preserve other parameters connected via a red arrow. On the other hand, improved feasibility in mission implementation can result through judicious selection of performance requirements for parameters connected via green arrows. This figure summarizes the team's initial dialogue (in July 2013) on performance sought for key radar parameters that address the full extent of the science goals of the observations. The resulting performance desires at nadir are captured in the green boxes (where the x/y/z format corresponds to the desires expressed for the Ku, Ka and W band, respectively). A possible "dual-requirement" approach is where one set of performance requirements (green boxes) are stated for nadir measurements and a more relaxed set of requirements (blue boxes) are given for off-nadir measurements.

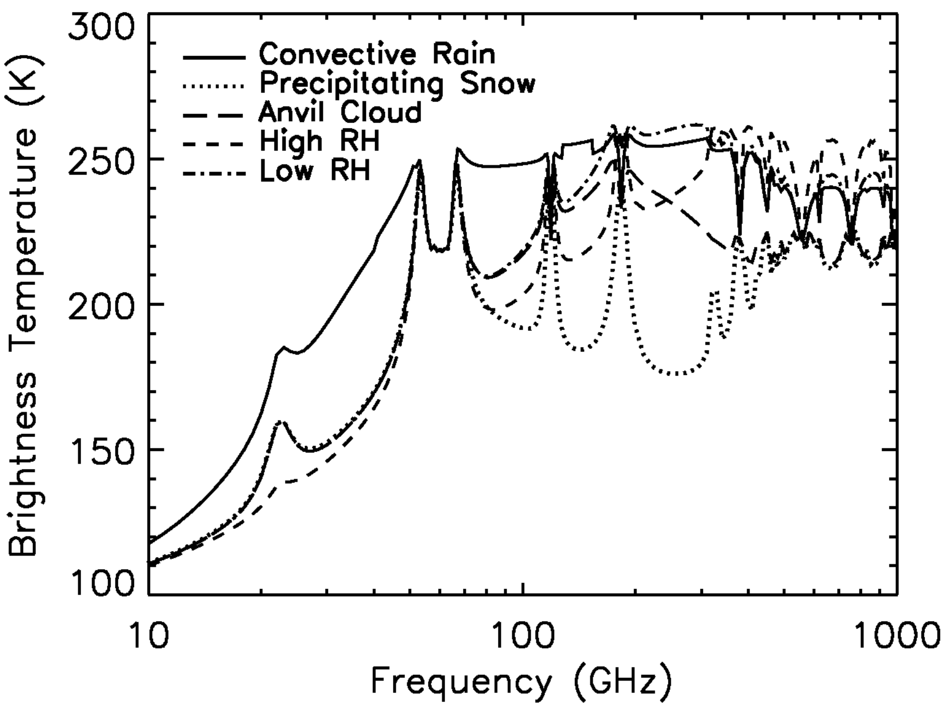

Figure 6: For extended spatial coverage, a multi-channel, wide-swath, multi-frequency range microwave radiometer will provide crucial profiling information from surface characteristics to thin cirrus clouds. The above figure shows the passive microwave response to five different cloud/precipitation parameterizations from 10-1000 GHz. Frequencies of interest for CAPPM include: 10-89, 50-60, 118, 183-640 GHz, with V and H polarizations as appropriate. These channels also provide solid integral constraints for profile retrievals to help resolve vertical processes as measured over narrow radar swaths. TMI, GMI, AMSR-E, AMSR-2 and the ESA Ice Cloud Imager provides heritage for this instrument. This radiometer may serve other purposes for snow pack, sea ice, SST, and other geophysical parameters. Ultimate channel selection is negotiable. Note that there is a second copy of GPM's GMI in parts in storage that could be used here. [From Skofronick-Jackson, 2004]

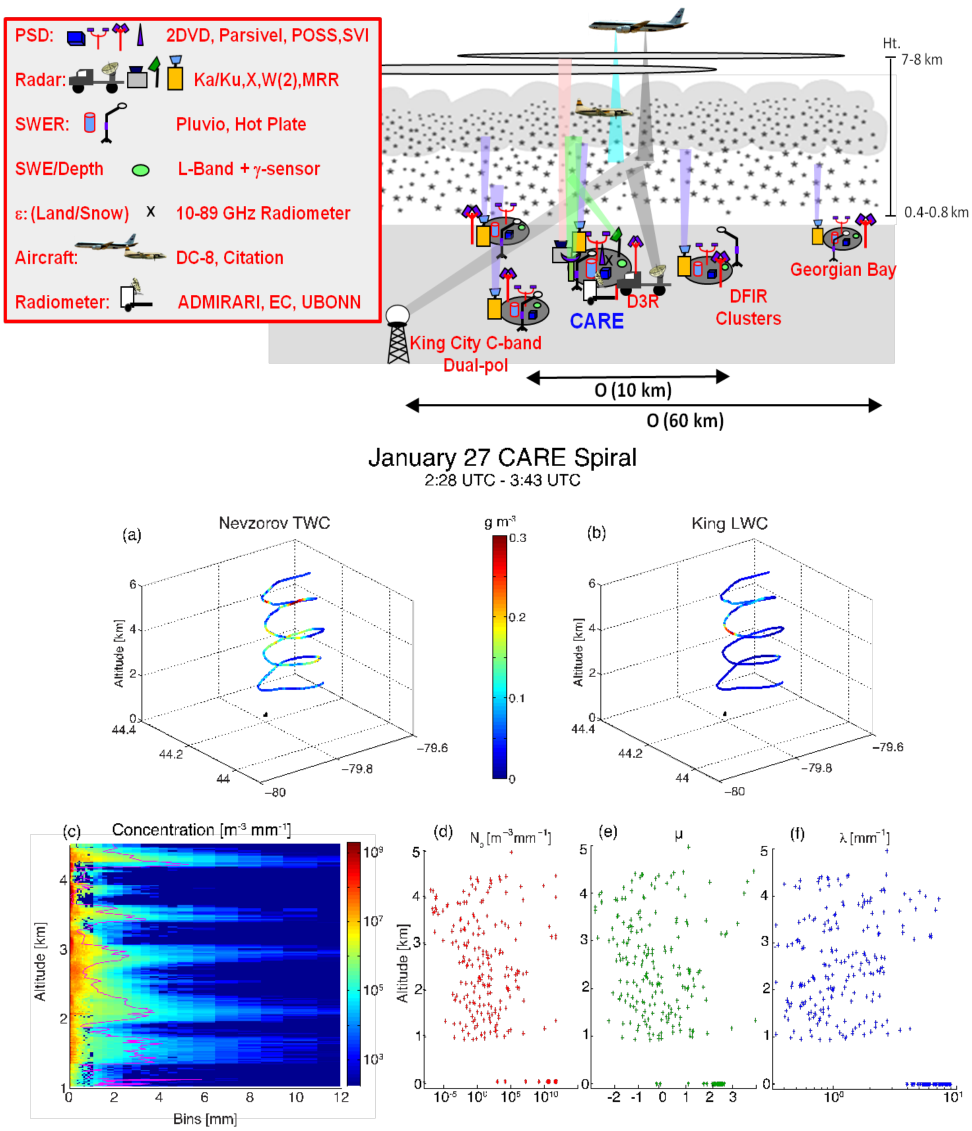

Figure 7: Well-outfitted detailed and focused aircraft and ground-based observations can assist in CAPPM objectives. Top image is probable sampling strategy with stacked aircraft plus ground based instruments. Detailed observations of cloud particle size, shape and phase distributions, bulk mass contents, bulk extinction, single-scattering properties, concentrations of cloud condensation nuclei and ice nucleating particles, and compositions of aerosols are possible on scales of hundreds of meters (as partially evidenced in the lower panel from the field campaign described in Skofronick-Jackson 2015). If aircraft data are targeted to regions where existing cloud processes do not agree with satellite derived microphysics, and processed in a consistent manner, it is possible to determine how probability distribution functions of microphysical properties vary with environmental conditions (e.g., temperature, location, cloud formation mechanism, aerosol concentrations, vertical velocities, supersaturation, atmospheric stability, etc.). Microphysical schemes typically use gamma functions to represent cloud particle size distributions, and the aircraft observations allow one to determine how the parameters of the gamma distribution vary with environmental conditions. Where possible prior field campaign observations will be used in order to elucidate the required observations for CAPPM. Note that GPM's IPHEX and OLYMPEX field campaigns obtained 4-radar aircraft observations of 3D precipitation and cloud particles. [From Skofronick-Jackson, et al., 2015]

Table 3: References

Adams-Selin, R.D., S.C. van den Heever, and R.H. Johnson, 2013: Quantitative evaluation of bow echo microphysical sensitivity. *Wx. and Forecasting*, 28, 1188-1209.

Adams-Selin, R.D., S.C. van den Heever, and R.H. Johnson, 2013: Impact of graupel parameterization schemes on idealized bow echo simulations. *Mon. Wea. Rev.*,141, 1241-1262.

Bassill, N. P. *(*2014*),* Accuracy of early GFS and ECMWF Sandy (2012) track forecasts: Evidence for a dependence on cumulus parameterization*, Geophys. Res. Lett.,* 41*,* 3274–3281*, doi:*10.1002/2014GL059839.

Bengtsson, Lennart, Kevin I. Hodges, and Erich Roeckner. "Storm tracks and climate change." *Journal of Climate* 19, no. 15 (2006): 3518-3543.

Berg, Neil, and Alex Hall. "Increased interannual precipitation extremes over California under climate change." *Journal of Climate* 28, no. 16 (2015): 6324-6334.

Bryan, George H., and Hugh Morrison. "Sensitivity of a simulated squall line to horizontal resolution and parameterization of microphysics." *Monthly Weather Review* 140, no. 1 (2012): 202-225.

Cheng, L, M Hoerling, A AghaKouchak, B Livneh, X-W Quan, and J Eischeid. "How Has Human-Induced Climate Change Affected California Drought Risk?" *J. of Climate* 29, no. 1 (2016): 111-120.

Durden S. L., S. Tanelli, L. Epp, V. Janmejad, E. Long, R. Perez, A. Prata. "System Design and Subsystem Technology for a Future Spaceborne Cloud Radar," in *IEEE Geoscience and Remote Sensing Letters*, vol. 13, no. 4, pp. 560-564, April 2016. doi: 10.1109/LGRS.2016.2525718

Fan, Jiwen, Yi-Chin Liu, Kuan-Man Xu, Kirk North, Scott Collis, Xiquan Dong, Guang J. Zhang, Qian Chen, Pavlos Kollias, and Steven J. Ghan. "Improving representation of convective transport for scale-aware parameterization: 1. Convection and cloud properties simulated with spectral bin and bulk microphysics." *Journal of Geophysical Research: Atmospheres* 120, no. 8 (2015): 3485-3509.

Frederiksen, Jorgen S., and Carsten S. Frederiksen. "Interdecadal changes in southern hemisphere winter storm track modes." *Tellus A* 59, no. 5 (2007): 599-617.

Hagos, S.*,* Z. Feng*,* C. D. Burleyson*,* K.-S. S. Lim*,* C. N. Long*,* D. Wu*, and* G. Thompson *(*2014*),* Evaluation of convection-permitting model simulations of cloud populations associated with the Madden-Julian Oscillation using data collected during the AMIE/DYNAMO field campaign, *J. Geophys. Res. Atmos.,* 119*,* 12,052–12,068*, doi:*10.1002/2014JD022143.

Hand T., M. Cooley, G. Kempic, D. Sall, P. Stenger, S. Woodworth, R. Park, P. E. Racette, G. Heymsfield, L. Li, 2013: Dual-Band Shared Aperture Reflector/Reflectarray Antenna Designs, Technologies and Demonstrations for NASA's ACE Radar. 2013 IEEE International Symposium on Phased Array Systems & Technology, Oct 2013

Lane, T.P., and M.W. Moncrieff, 2010: Characterization of momentum transport associated with organized moist convection and gravity waves. *Journal of the Atmospheric Sciences*, **67**, 3208–3225, DOI: 10.1175/2010JAS3418.1.

Tristan S. L'Ecuyer, H. K. Beaudoing, M. Rodell, W. Olson, B. Lin, S. Kato, C. A. Clayson, E. Wood, J. Sheffield, R. Adler, G. Huffman, M. Bosilovich, G. Gu, F. Robertson, P. R. Houser, D. Chambers, J. S. Famiglietti, E. Fetzer, W. T. Liu, X. Gao, C. A. Schlosser, E. Clark, D. P. Lettenmaier, and K. Hilburn, 2015: The observed state of the energy budget in the early twenty-first century, Journal of Climate 2015 28:21, 8319-8346

Palerme, C., Kay, J. E., Genthon, C., L'Ecuyer, T., Wood, N. B., and Claud, C.: How much snow falls on the Antarctic ice sheet?, The Cryosphere, 8, 1577-1587, doi:10.5194/tc-8-1577-2014, 2014.

Parazoo, N. C., A. S. Denning, J. A. Berry, A. Wolf, D. A. Randall, S. R. Kawa, O. Pauluis, and S. C. Doney (2011), Moist synoptic transport of CO2 along the mid-latitude storm track, Geophys. Res. Lett., 38, L09804, doi:10.1029/2011GL047238.

Peral E., S. Tanelli, Z. Haddad, O. Sy, G. Stephens and E. Im, "Raincube: A proposed constellation of precipitation profiling radars in CubeSat," *2015 IEEE IGARSS*, Milan, 2015, pp. 1261-1264. doi: 10.1109/IGARSS.2015.7326003.

Petch, J., Hill, A., Davies, L., Fridlind, A., Jakob, C., Lin, Y., Xie, S. and Zhu, P. (2014), Evaluation of intercomparisons of four different types of model simulating TWP-ICE. Q.J.R. Meteorol. Soc., 140: 826–837. doi: 10.1002/qj.2192.

Petersen, W. A., and M. Jensen. "The NASA-GPM and DOE-ARM Midlatitude Continental Convective Clouds Experiment (MC3E)." *The Earth Observer* 24, no. 1 (2012): 12-18.

Popkin, Gabriel, "Cloudy Forecast: The biggest source of climate uncertainty is white and fluffy", *Science News Magazine*, Vol. 185 No. 6, March 22, 2014.

Ruin, I, C Lutoff, B Boudevillain, J-D Creutin, S Anquetin, M. Bertran Rojo, L Boissier et al. "Social and hydrological responses to extreme precipitations: an interdisciplinary strategy for postflood investigation." *Weather, climate, and society* 6, no. 1 (2014): 135-153.

Sadowy G.A., M. Sanchez-Barbetty, S. Tanelli, B. Cannon, K.Vanhille, A.Brown and K.Brown, 2016: Development of a three-frequency spaceborne radar for cloud and precipitation measurement. *96th American Meteorological Society Annual Meeting, New Orleans,* Jan 13, 2016.

Saleeby, S. M., and W. R. Cotton. "A large-droplet mode and prognostic number concentration of cloud droplets in the Colorado State University Regional Atmospheric Modeling System (RAMS). Part I: Module descriptions and supercell test simulations." *Journal of applied meteorology* 43, no. 1 (2004): 182-195.

Saleeby, S.M., and S.C. van den Heever, 2013: Developments in the CSU-RAMS Aerosol Model: Emissions, Nucleation, Regeneration, Deposition, and Radiation. *J. Appl. Meteor. Climatol.*,, 52, 2601-2622.

Saleeby, S.M., S.R. Herbener, S.C. van den Heever, and T. L'Ecuyer (2015), Impacts of cloud droplet–nucleating aerosols on shallow tropical convection. *J. Atmos. Sci., 72,* 1369–1385. doi:10.1175/JAS-D-14-0153.1

Sheffield, A.M, S.M. Saleeby, and S.C. van den Heever (2015), Aerosol-induced mechanisms for cumulus congestus growth, *J. Geophys. Res. Atmos., 120,* 8941–8952, doi:10.1002/2015JD023743.

Skofronick-Jackson, G., M-J. Kim, J.A. Weinman, and D. Chang, 2004: "A Physical Model to Determine Snowfall over Land by Microwave Radiometry," *IEEE Transactions on Geoscience and Remote Sensing,* vol. 42, no. 5, pp. 1047-1058.

Skofronick-Jackson, G., W. Petersen, D. Hudak, S. Nesbitt, and others, "Global Precipitation Measurement Cold Season Precipitation Experiment (GCPEx): For Measurement Sake Let it Snow," *Bull. Amer. Meteor. Soc.*, **96**, 1719–1741, 2015. doi: http://dx.doi.org/10.1175/BAMS-D-13-00262.1.

Stephens, Graeme L., and Todd D. Ellis. "Controls of global-mean precipitation increases in global warming GCM experiments." *Journal of Climate* 21, no. 23 (2008): 6141-6155.

Tanelli S., G.M. Heymsfield, G.S. Stephens, S.L. Durden, E. Im, P. Racette, G.A. Sadowy and L. Li, 2010: Decadal Survey Tier 2 Mission Study: Summative Progress Report: ACE Radar. http://ntrs.nasa.gov/search.jsp?R=20120004215

Tao, W.-K., J.-P. Chen, Z. Li, C. Wang, and C. Zhang (2012), Impact of aerosols on convective clouds and precipitation, *Rev. Geophys., 50,* RG2001, doi:10.1029/2011RG000369.

Tao, W.-K., D. Wu, S. Lang, J.-D. Chern, C. Peters-Lidard, A. Fridlind, and T. Matsui (2016), High-resolution NU-WRF simulations of a deep convective-precipitation system during MC3E: Further improvements and comparisons between Goddard microphysics schemes and observations, J. Geophys. Res. Atmos., 121, 1278–1305, doi:10.1002/2015JD023986.

van den Heever, S.C., Wei-Kuo Tao, Stephen M. Saleeby, D. Wu, Steven Lang, and Gail Skofronick-Jackson, "A Multi-Model Multi-Microphysical Parameterization Experiment to Assess Simulated Cloud and Precipitation Sensitivities" to be submitted, 2016.

van den Heever, S.C., G.G. Carrió, W.R. Cotton, P.J. DeMott, and A.J. Prenni (2006), Impacts of Nucleating Aerosol on Florida Storms. Part I: Mesoscale Simulations, *J. Atmos. Sci. 63,* 1752–1775.

van den Heever, S.C., G.L. Stephens, and N.B. Wood (2011), Aerosol indirect effects on tropical convection characteristics under conditions of radiative-convective equilibrium, *J. Atmos. Sci., 68,* 699-718.

Varble, Adam, Edward J. Zipser, Ann M. Fridlind, Ping Zhu, Andrew S. Ackerman, Jean-Pierre Chaboureau, Scott Collis, Jiwen Fan, Adrian Hill, and Ben Shipway. "Evaluation of cloud-resolving and limited area model intercomparison simulations using TWP-ICE observations: 1. Deep convective updraft properties." *Journal of Geophysical Research: Atmospheres* 119, no. 24 (2014).

World Climate Research Programme, http://wcrp-climate.org/grand-challenges

Zhao, Ming, J-C. Golaz, I. M. Held, V. Ramaswamy, S-J. Lin, Y. Ming, P. Ginoux et al. "Uncertainty in model climate sensitivity traced to representations of cumulus precipitation microphysics." *Journal of Climate* 29, no. 2 (2016): 543-560.

Table of Contributing Participants since the start of discussions July 2013

Last Name	First	Affiliation
Bennartz	Ralf	Vanderbilt University
Braun	Scott	NASA Goddard Space Flight Center
Chandrasekar	Chandra	Colorado State University
Da Silva	Arlindo	NASA Goddard Space Flight Center
Durden	Stephen	Jet Propulsion Laboratory, California Institute of Technology
Eastwood	Im	Jet Propulsion Laboratory, California Institute of Technology
Haddad	Ziad	Jet Propulsion Laboratory, California Institute of Technology
Heymsfield	Gerald	NASA Goddard Space Flight Center
Hou	Arthur	NASA Goddard Space Flight Center (deceased 11/2014)
Houze	Robert	University of Washington-Seattle
Huffman	George	NASA Goddard Space Flight Center
Jackson	Gail S	NASA Goddard Space Flight Center
Joe	Paul	Environment Canada
Kidd	Chris	University of Maryland
Kollias	Pavlos	Stony Brook
L'Ecuyer	Tristan	University of Wisconsin, Madison
Lebsock	Matthew	Jet Propulsion Laboratory, California Institute of Technology
Li	Lihua	NASA Goddard Space Flight Center
Mace	Gerald	University of Utah-Salt Lake City
Meneghini	Robert	NASA Goddard Space Flight Center
Mohr	Karen	NASA Goddard Space Flight Center
Munchak	Stephen	NASA Goddard Space Flight Center
Petersen	Walter	NASA Marshall Space Flight Center
Racette	Paul	NASA Goddard Space Flight Center
Reid	Jeffrey	Naval Research Lab
Sadowy	Gregory	Jet Propulsion Laboratory, California Institute of Technology
Saleeby	Stephen	Colorado State University
Tanelli	Simone	Jet Propulsion Laboratory, California Institute of Technology
Tao	Wei-Kuo	NASA Goddard Space Flight Center
Turk	Joe	Jet Propulsion Laboratory, California Institute of Technology
van den Heever	Sue	Colorado State University
Vane	Deborah	Jet Propulsion Laboratory, California Institute of Technology
Wilcox	Eric	Desert Research Institute
Wu	Dong	NASA Goddard Space Flight Center
Zipser	Ed	University of Utah-Salt Lake City