DOE/SC-ASR-16-002

Atmospheric System Research Treatment of Convection in Next-Generation Climate Models: Challenges and Opportunities Workshop Report

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October 2016

U.S. DEPARTMENT OF ENERGY
Office of Science

ASR
Atmospheric System Research

DOE/SC-ASR-16-002

Atmospheric System Research Treatment of Convection in Next-Generation Climate Models: Challenges and Opportunities Workshop Report

3-5 February 2016
Pacific Northwest National Laboratory

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Work supported by the U.S. Department of Energy,
Office of Science, Office of Biological and Environmental Research

Executive Summary

A workshop sponsored by the U.S. Department of Energy (DOE) Atmospheric System Research (ASR) Program was held at the Pacific Northwest National Laboratory (PNNL) on 3-5 February 2016. This workshop was a response to the rapid approach of climate models with cloud-permitting (1- to 10-km grid spacing) resolutions. The expansion of computational resources and advances in numerical methods are making such models a reality. The workshop participants considered specifically the new set of challenges for representing convective cloud processes in this generation of models. The challenges arise from the fact that some aspects of convection are partly resolved. Short- and long-term strategies that would lead to accurately representing convection in these models were discussed, and opportunities for the ASR program to effectively leverage DOE's unique capabilities, high-performance computing resources, and Atmospheric Radiation Measurement (ARM) Climate Research Facility observational facilities to this end were identified. The workshop was organized around the premise that a strategy to accurately treat convection in the next generation of climate models comprises addressing challenges on three core themes and their integration. These are:

1) Basic understanding of cloud processes: Additional progress in understanding of several cloud processes was identified as a key ingredient of the strategy to better represent convective processes in climate models. The most critical processes include boundary-layer evolution, up- and downdraft dynamics, microphysical feedbacks, aggregation of clouds, inducement of mesoscale circulations, stochasticity, and transitions in cloud populations.

2) Parameterizations: The workshop participants agreed that the scale-separation assumption, commonly used in the past, must be replaced by an important and stringent requirement of scale awareness. Not only is model resolution increasing, but it is being increasingly recognized that convective cloud phenomena encompass a wide range of spatial scales, and that these phenomena are parts of a continuum. The workshop participants determined that six fairly distinct approaches to treating convection in high-resolution climate models in a scale-aware manner are now being developed. Their status, strengths, and limitations were discussed. In addition to the absence of a spectral gap in convective phenomena, the assumption made by most existing parameterization schemes that all deep convection arises from the boundary layer does not universally apply. Most notable is the existence of elevated intense convective systems, which are disconnected from the boundary layer and produce strong feedbacks to the large-scale circulation. Parameterizations must therefore not only be scale aware, but robust enough to include convection not rooted in the boundary layer.

3) Observational needs: Assessments of the states of both our understanding of basic cloud processes and parameterization development point to the importance of observing how convective clouds and the associated downdrafts relate to one another and occur in populations containing varying amounts of small and large clouds. Several observational approaches were identified as being most helpful to the design of future parameterizations. In the short term, data from existing and currently deployed ARM Facility instrumentation that are collected separately could be merged into multi-parameter products, and an adaptive observing strategy based on forecasts could be deployed at ARM's Southern Great Plains (SGP) site to collect process-study-quality data over a sustained time period. In the longer term, scanning S-band research radars will be essential for obtaining precise microphysical observations, and convection-penetrating aircraft would also be useful for collecting in situ collocated statistics on up- and downdrafts and microphysics. Finally, field campaign data using modern platforms and instruments are needed over the tropical oceans.

4) Integration: An effective strategy to better represent convection in climate models requires integration among 1)-3) so that observations can be meaningfully used for model validation and hypothesis testing. The continued development of instrument simulators is identified as an important way of bridging the gap between model variables and measured quantities. The workshop participants also noted that a hierarchical approach to modeling is essential, in which one takes full advantage of progress across the range of other modeling frameworks, such as Large-Eddy Simulation (LES), limited-area cloud-resolving models (CRMs), and variable-resolution and operational high-resolution models, as well as the various ways observations have been used to validate and improve them.

Acknowledgments

The workshop organizers thank all the participants for their contributions via whitepapers, presentations, active engagement in the discussions during the workshop, and contributions to this report. Angela Rowe and Zhe Feng took very detailed notes, which served as the basis for this report. Funding for the workshop was provided by the U.S Department of Energy's Atmospheric System Research Program. We thank the ASR Program Managers Shaima Nasiri and Ashley Williamson, as well as Jerome Fast, ASR Science Focus Area (SFA) Principal Investigator (PI) at PNNL, for their support and encouragement throughout the planning and execution of the workshop. We also thank Emily Davis and Alyssa Cummings, who provided logistical support to the workshop.

Acronyms and Abbreviations

AAF	ARM Aerial Facility
ACME	Accelerated Climate Model for Energy
AMIE	ARM Madden-Julian Oscillation (MJO) Investigation Experiment
ARM	Atmospheric Radiation Measurement Climate Research Facility
ASR	Atmospheric System Research
CAPE	Convective Available Potential Energy
CAM	Community Atmospheric Model
CFMIP	Cloud Feedback Model Intercomparison Project
CLOWD	Clouds with Low Optical Water Depths
CMIP5	Coupled Model Intercomparison Project Phase 5
COSP	CFMIP Observation Simulator Package
CPM	Cloud-Permitting Model
CRM	Cloud-Resolving Model
3D	three-dimensional
DOE	U.S. Department of Energy
DYNAMO	Dynamics of Madden-Julian Oscillation
ENSO	El Niño Southern Oscillation
GATE	Global Atmospheric Research Program's Atlantic Tropical Experiment
GCM	Global Climate Model
GFDL	Geophysical Fluid Dynamics Laboratory
GoAmazon	Green Ocean Amazon 2014/15
HOMME	High Order Method Modeling Environment
IOP	intensive operational period
ITCZ	Intertropical Convergence Zone
LES	large-eddy simulation
MC3E	Mid-latitude Continental Convective Clouds Experiment
MCC	mesoscale convective complex
MCS	mesoscale convective system
MJO	Madden-Julian Oscillation
MONEX	Monsoon Experiment
MPAS	Model for Prediction Across Scales
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NEXRAD	next-generation radar
NOAA	National Oceanic and Atmospheric Administration

NPOL	NASA S-band dual-polarimetric radar
NSF	National Science Foundation
OLYMPEX	Olympic Mountain Experiment
PBL	planetary boundary layer
PDF	probability density function
PECAN	Plains Elevated Convection at Night
PI	principal investigator
PNNL	Pacific Northwest National Laboratory
RHI	Range Height Indicator
ROCORO	Routine Atmospheric Radiation Measurement (ARM) Aerial Facility (AAF) Clouds with Low Optical Water Depths (CLOWD) Optical Radiative Observations (RACORO)
S2S	sub-seasonal-to-seasonal
SciDac	Scientific Discovery through Advanced Computing
SFA	Science Focus Area
SGP	Southern Great Plains
SPA	Storm-Penetrating Aircraft
SPCAM	Superparameterized CAM
TOGA-COARE	Tropical Ocean-Global Atmosphere Coupled Ocean Atmosphere Response Experiment
TRMM	Tropical Rainfall Measurement Mission
TWP	Tropical Western Pacific
TWP-ICE	Tropical Warm Pool International Cloud Experiment
WCRP	World Climate Research Programme
WRF	Weather Research and Forecasting Model
WWRP	World Weather Research Programme
X-SAPR	X-Band Scanning ARM Precipitation Radar
YOTC	Year of Tropical Convection

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1.0 Introduction

For decades, the development of convective cloud parameterizations in climate models implicitly or explicitly relied on a perceived spatio-temporal scale separation and statistical equilibrium between the resolved large-scale environment and unresolved cloud processes. By postulating a balance between the creation of instability by slowly evolving large-scale environment and its removal by a large number of convection cells, which cover a small fraction of a model grid box, the assumed time and space scale separation makes the problem of parameterization theoretically tractable (e.g., Arakawa and Schubert 1973). The continuum of scales and organization of convective phenomena shown by field programs and satellite remote sensing show that the assumption is not applicable for high-resolution models, in which a small number of large clouds can easily cover a grid box or even a single cloud system can span multiple grid boxes. The models need to represent convective clouds that encompass forms ranging from non-precipitating isolated shallow clouds to mesoscale convective systems (MCSs), and the transitions and upscale growth of smaller elements. Understanding and accurate representation of these processes involved in the transitions from shallow non-precipitating clouds to precipitating shallow clouds, to deep convection, to MCSs, and to planetary-scale phenomena such as the Madden-Julian Oscillation (MJO) are important for accurate representation of the mean state of the climate, its natural and forced variability, and for the prediction of drought and extreme precipitation events.

Interest in how the continuum of convective processes interacts with atmospheric circulation and climate intersects with the current state of climate modeling in which rapid expansion of computational resources is pushing climate model resolution into a "gray zone," where some aspects of convection are resolved and the traditional scale separation argument does not apply. The next-generation climate models, here defined as those with grid spacing of 1-10 km, urgently require novel strategies of combining parameterization and explicit representation of convection processes. This challenge is both important and unprecedented.

The scientific and technical challenges and the intellectual gaps in our understanding of atmospheric convection are punctuated by the convergent paths of the next-generation climate and weather models. In recent years, these issues have drawn international attention, e.g., World Climate Research Programme (WCRP) and the World Weather Research Programme (WWRP) activities aimed at “seamless prediction.”

Interaction of convection with larger-scale motions involves not only individual cloud processes but also the nature, development, and behavior of entire populations of convective clouds, in which isolated cumulus, cumulus congestus, individual cumulonimbus clouds, and MCSs occur in the same vicinity and act simultaneously in their interactions with larger scales of motion. The adjustment of large scales of motion to convective populations can be seen through potential vorticity conservation. The generation of potential vorticity is proportional to the vertical gradient of heating. The particular makeup of a cloud population therefore strongly influences how interaction with larger scales of motion occurs. For example, a cloud population with a disproportionate number of MCSs containing stratiform portions would be expected to produce a cloud-scale heating profile concentrated at upper levels. The top-heavy heating profile sharpens the vertical gradient of heating produced by the convection in mid-levels. The vertical gradient of heating in turn generates large-scale potential vorticity at that level. On the other hand, a population with an overabundance of moderate cumulonimbus clouds and less stratiform precipitation would produce a concentration of heating at lower levels. The maximum heating gradient and associated potential vorticity generation then occurs at low levels rather than mid-levels. Parameterizations and gray-zone simulations must be able to produce cloud populations and heating profiles according to the nature of populations of convective clouds. The cloud populations include a range of scales of clouds from small cumulus to MCSs and adaptive parameterizations must be able to handle all such scenarios as well as their combinations.

While much has been learned from observations about how the different forms of convection make up cloud populations around the globe, how environmental factors such as wind shear, thermal stratification of the atmosphere, humidity, surface conditions, and the diurnal cycle control the convective population is not well understood. Even less understood are how environmental factors related to internal deterministic as well as stochastic dynamics within the convection populations affect the populations' evolution. For example, boundary-layer organization prior to the formation of precipitating convection and cold-pool dynamics produced by the clouds themselves contribute substantially to stochasticity and initiation of convection. The radiative environment adds to the complexity via diurnal pulsing and self-aggregation of smaller clouds adjusting toward radiative equilibrium.

For the next generation of climate models to take full advantage of rapidly increasing computational resources and to alleviate many of the shortcomings of the current generation in representing the mean climate, its natural and forced variability, and the occurrence of extreme precipitation and hazardous weather, they must represent convective populations and their variants accurately. Processes on 1-10-km scales must be accounted for in ways that are consistent with observations of how cloud populations evolve from domination by first shallow, then deep, and finally mesoscale, convection. The spatio-temporal extent of influences of convection populations on circulation during each stage of their evolution must be clearly understood. Meeting this challenge is a matter of both increasingly robust theory and parameterization architecture. Some of the challenges require improved and more complete observational documentation of microphysical and dynamical processes to which convective population development is especially sensitive.

The premise of this workshop is that a complete strategy for improving the treatment of convection in next-generation climate models can be organized into three intersecting core themes:

- Basic understanding of cloud processes;
- Parameterization; and
- Collection, processing, and analysis of observational data.

Equally important is that these three themes be approached in a coordinated way, with particular attention to the integration of each of the three core themes with the others, as depicted in Figure 1. With this framework in mind, the workshop brought together 30 experts to address the following questions:

- What are the challenges in each of the three core themes and their integration?
- Given DOE capabilities (e.g., ARM and high-performance computing resources), how can ASR help meet these challenges?

- What can be done in the short term (~3 years) using existing resources and what new capabilities and/or long-term (~10 years) investments are required to address these challenges?

This report is intended to serve as a consensus among workshop participants that summarizes science priorities involving integrated research and development activities that the ASR Program could consider as part of its strategic planning. In the remainder of the report, convection-related issues in current climate models as seen by the workshop participants are reviewed, and the challenges in the three core themes and their integration are identified and strategies for meeting them are laid out. Finally, the report concludes by summarizing short-term and long-term activities that would improve the understanding and climate model representation of convective clouds.

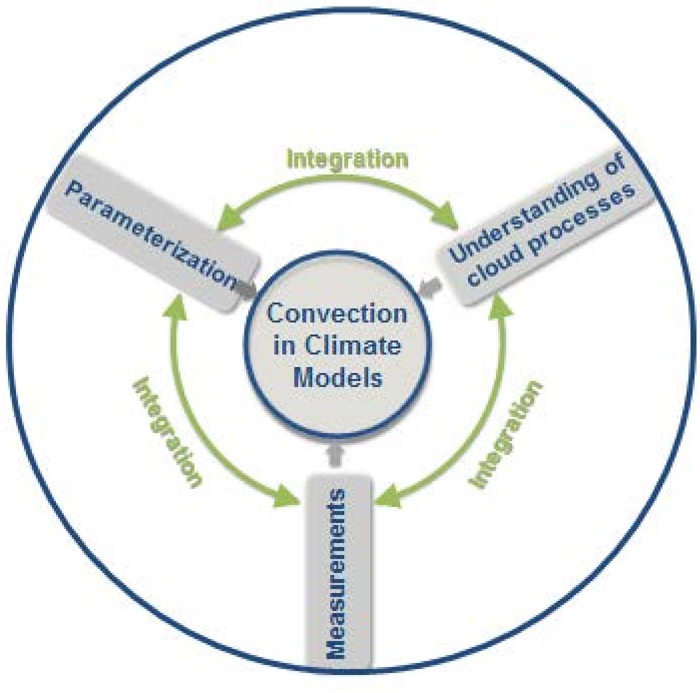

Figure 1. The core themes on which progress is required for accurate treatment of convection in next-generation climate models and their integration.

2.0 Issues Associated with Convection in the Current Climate Models

As a primary mechanism of heat transport between the surface of the earth and the upper atmosphere, convection is a critical component of the climate system and its variability. As a result, limitations in our understanding and representation of convection in climate models are manifested in biases in the simulated climate. The list of convection-related biases in present-day climate models is extensive and covers all spatio-temporal scales. Highlighted below are a few of the most prominent ones.

2.1 Diurnal Cycle

Convection over land often initiates as shallow cumulus clouds in response to solar forcing and may gradually grow into deep convection in early afternoon if humidity in the lower free troposphere is sufficiently high. Subsequently, the shallow clouds may or may not grow to large mesoscale convection depending on environmental conditions. Some deep convective cells peak in the late afternoon and decay near the area of the clouds' initiation, while others organize into MCSs, propagate over long distances, and precipitate well into the next morning. Thus, the diurnal cycle of precipitation varies with the scale of the convective entity and can manifest differently between land and ocean and from one region to another (e.g., Chen and Houze 1997, Romatschke and Houze 2010).

Figure 2 shows the diurnal cycle of precipitation over the Southern Great Plains (SGP) of the United States from observations, Coupled Model Intercomparison Project Phase 5 (CMIP5) models, and the seasonal cycle of surface temperature. These models do not account for mesoscale convection. As a result, nocturnal convective precipitation is essentially absent in the CMIP5 models and many of the models have peak precipitation just before or after noon. The underestimated propagating nocturnal precipitation has important implications for land-atmosphere interactions and the seasonal cycle of temperature such that the models have a warm bias in summertime near-surface temperatures due to low precipitation and dry soil, notably over the central U.S. (Fig 2b). Some indications suggest that cloud-permitting simulations run at sub-10-km grid spacing have the potential to alleviate this problem (Trier et al. 2014).

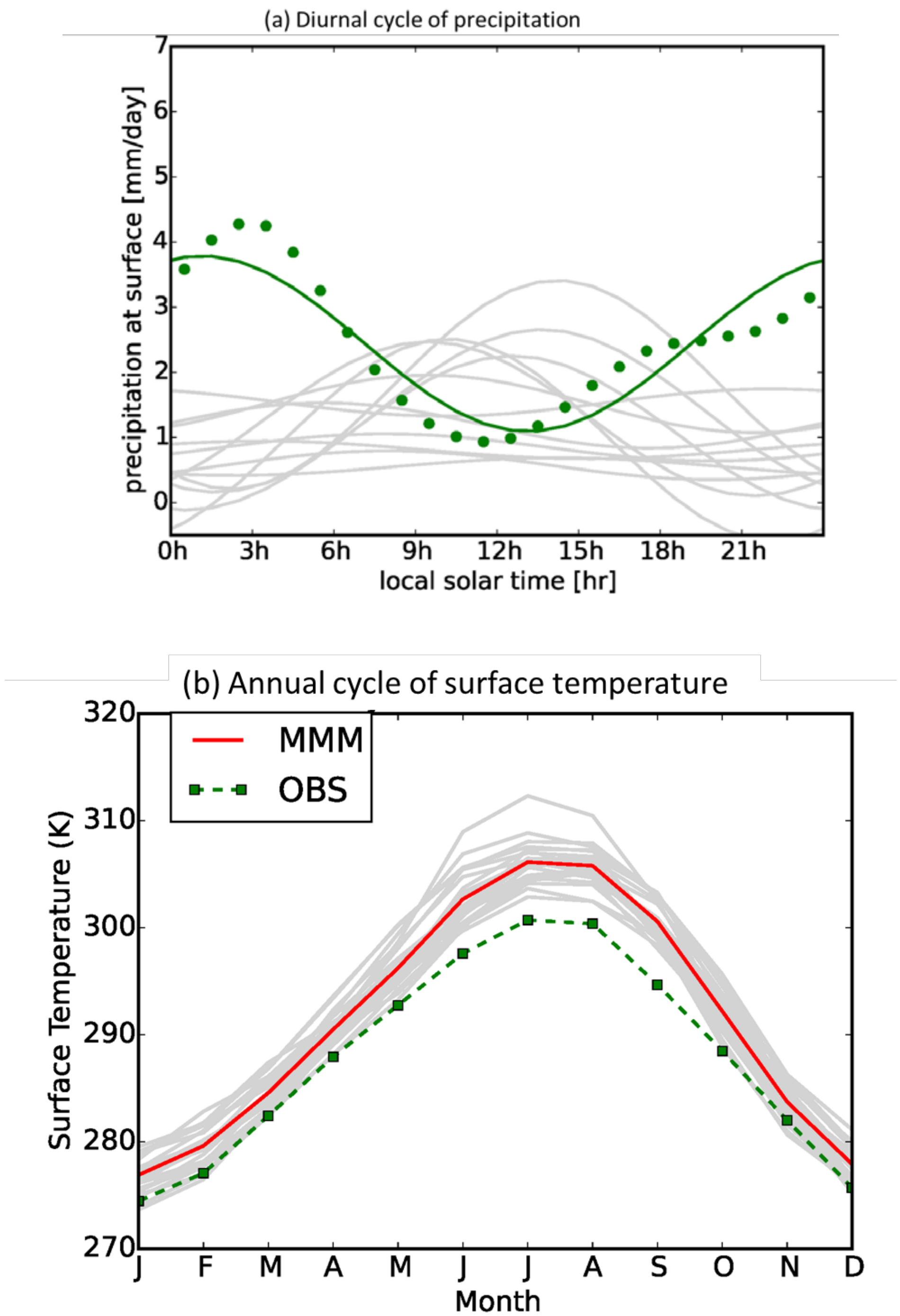

Figure 2. (a) Diurnal cycle of June-July-August precipitation from observations and CMIP5 models (Courtesy of Chengzhu Zhang, Lawrence Livermore National Laboratory) and (b) the seasonal cycle of surface temperature at ARM's Southern Great Plains site (Adapted from Zhang et al. 2016).

2.2 Madden-Julian Oscillation

The Madden-Julian Oscillation (MJO) is a major component of tropical intra-seasonal variability with far-reaching impacts on regional extremes such as tropical cyclone activity, atmospheric rivers, heat waves, and floods (Zhang 2005, 2013). Despite extensive research over the last four decades, fundamental understanding and accurate representation of MJO initiation, propagation, and interaction with other regional processes remain unmet challenges. The main reason for the slow progress is thought to be the multiscale nature of the cloud processes involved and associated difficulties in parameterizing these processes. As noted above, parameterizations are as yet unable to handle multiscale aspects of the convection. The consequence of this problem is apparent in the comparison of MJO variance between CMIP models and observations (Figure 3). While CMIP5 has been improved over CMIP3, these models generally continue to underestimate the variance and tend to have more persistent precipitation over equatorial regions than is observed (Hung et al. 2013). Several ASR-supported studies have highlighted the importance of cloud interactions involving entrainment in the simulation of MJO (Zhang and Song 2009, Zhu et al 2009) and radiative feedbacks (Del Genio et al. 2015) that are poorly represented in many parameterization schemes. Another aspect of MJO that challenges global models is the "MJO prediction barrier" over the maritime continent (Neena et al. 2014, Kim et al. 2009), where problems of representation of convection in MJO are compounded by interactions with diurnal cycle and complex topography (Hagos et al. 2016).

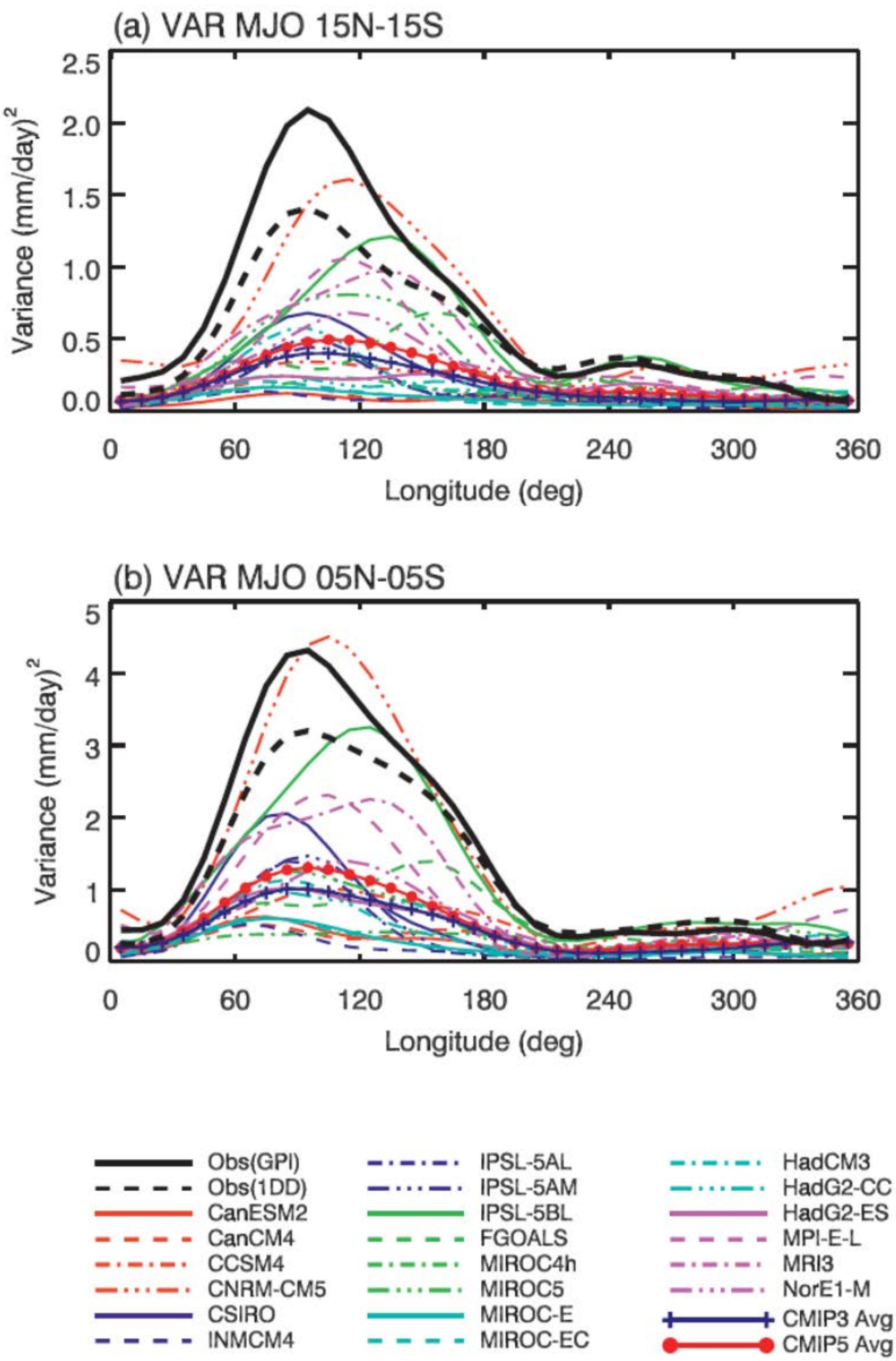

Figure 3. Variance of the MJO mode along the Equator averaged between (a) 15°N and 15°S and (b) 5°N and 5°S (Adapted from Hung et al. 2013). The different line styles represent different CMIP models.

2.3 South Asian Summer Monsoon

In general, there are two precipitation issues in CMIP5 models: spread, which pertains to large differences among the models and limits the confidence level in their projections, and bias, which represents consistent deviations of the model results from observations. These two forms of uncertainty are especially apparent in monsoon environments. Consider, for example, the seasonal cycle of precipitation in the South Asian monsoon. Figure 4a shows the seasonal cycle of precipitation averaged over all of India, while Fig. 4b shows the same data normalized by the annual mean precipitation. The CMIP5 ensemble has a very large spread in seasonal cycle amplitude, and when the precipitation is normalized, it is also apparent that the onset of the monsoon is delayed in most of the models. The convection in the South Asian monsoon exhibits a broad range of forms, including extremely deep intense convection in the region of Pakistan and northwest India, convective systems with extremely large stratiform components in northeastern India and Bangladesh, and large fields of weak to moderate convection and stratiform precipitation upstream of western coastal mountain ranges (Houze et al. 2015). All these forms of convection interact differently with large-scale motions, and models that do not account for these different forms could be biased in various ways.

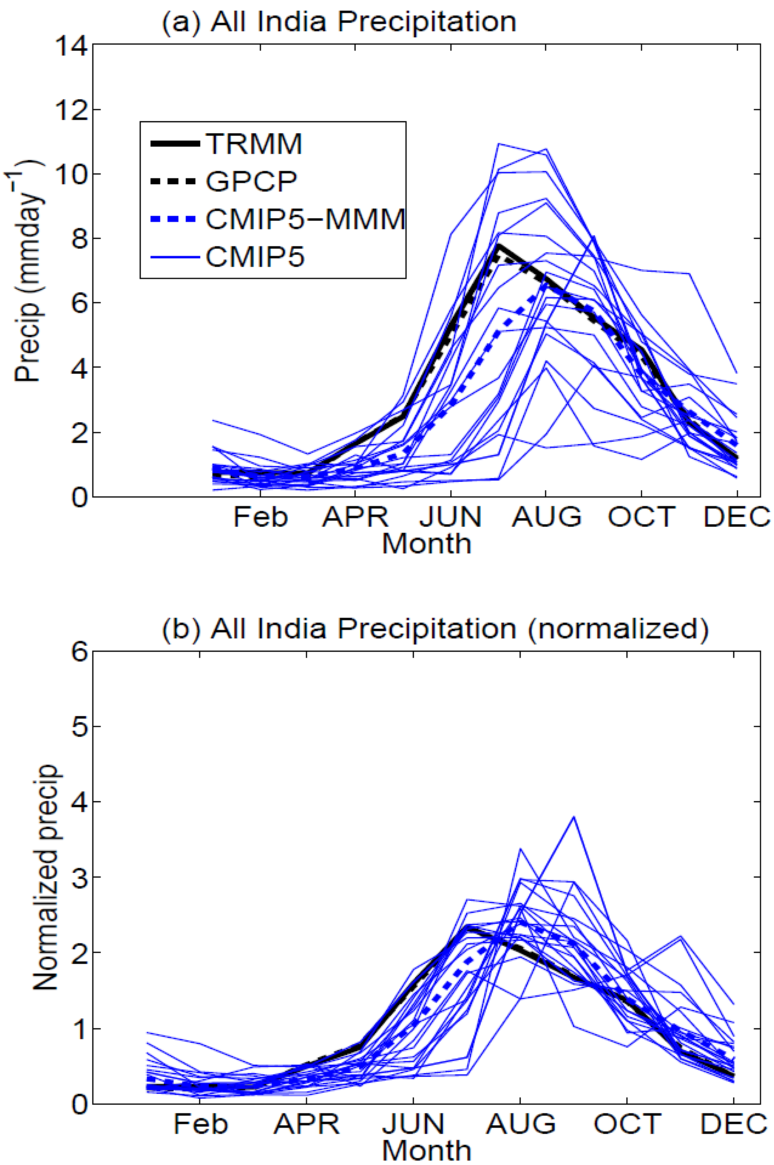

Figure 4. (a) Annual cycle of all-India rainfall derived from satellite observations (black) and from 20 CMIP5 models (blue) and (b) same but normalized by the annual mean precipitation. The dashed blue curve represents the multi-model mean.

3.0 Strategy of Representing Convection in the Next-Generation Climate Models

After reviewing the convection-related model biases in key features of climate variability, the workshop identified specific challenges in each of the three core themes depicted in Figure 1 and in their integration, and then proposed strategies for how the ASR Program could address them. The following summarizes discussions.

3.1 Improving the Basic Understanding of Convective Cloud Processes

In order to highlight the gaps in our understanding of convection, we consider the full lifecycle of convection as a starting point, which can be treated as a series of four transition processes:

1. Boundary-layer variability and the development of precipitating shallow cumulus clouds.
2. Transition to deep convection.
3. Upscale growth from deep convective cells to MCSs.
4. Organization into large-scale features with time and spatial scales beyond individual MCSs.

These transitions take place under certain environmental conditions but not others, and these transition processes are often linked as forcing-response and feedback mechanisms for each other. The overarching question is: *which environmental conditions and internal feedback processes control these transitions?* Each of the transitions listed above and the specific scientific questions related to them are discussed individually below.

3.1.1 Boundary-Layer Disturbance and the Development of Precipitating Shallow Cumulus Clouds

The processes that determine whether boundary-layer dynamics will lead to the formation of a field of cumulus clouds that evolve into a regime containing deeper and larger precipitating convective clouds is not well understood. The boundary layer contains internal instabilities that produce rolls, hexagonal cells, and other mesoscale patterns of enhanced convergence that organize clouds into patterns and make some of the clouds more robust. Such dynamical transitions can occur without external forcing, whereas in some situations vertical wind shear plays a crucial organizing role. ASR-funded analysis of data from highly sensitive radars deployed in the ARM MJO Investigation Experiment (AMIE) and cloud-resolving modeling studies have led to some advances in understanding these processes in a tropical ocean environment; Rowe and Houze (2015) have shown how the boundary layer develops rolls (due to internal instability), which encourage some clouds to grow larger, starting a chain reaction that concludes with a cloud population containing deep convection and MCSs. Weckwerth et al. (1999) and others have shown observations of similar boundary-layer evolution over land (Florida, Illinois, Kansas). Recent ASR-funded studies have shown the important role of cold-pool dynamics as a link between rain microphysics and the development of secondary shallow clouds through both mechanical and thermodynamic forcings (Del Genio et al. 2012, Hagos et al. 2014a, Feng et al. 2015, and Torri et al. 2015). Further observations need to be obtained, analyzed and reproduced in LES models to achieve the level of understanding necessary to inform parameterization development.

In addition to internal instabilities, environmental factors determine boundary-layer structures that affect the formation and development of cumulus clouds. For example, land-use heterogeneity, lake or nearby ocean surface conditions, topographic features, and large-scale wind shear and thermodynamic instability can lead to certain patterns of boundary-layer dynamics and cloud patterns.

Once precipitating convective clouds form, they often replace boundary-layer air with downdraft air on the scale of the precipitation. The resulting downdraft creates cold pools that may then dominate the formation of subsequent convection, but important details of this process remain poorly understood and are imperfectly handled in simulations. Where the cold pools intersect, the enhanced boundary-layer convergence often results in secondary convection (Feng et al. 2015), and a chain reaction may occur that leads to aggregation of convective cells, MCSs, and cold pools that can prolong MCS lifetimes.

Several subtle factors may affect the sequence of boundary-layer development from undisturbed to disturbed, whether due to external or internal factors. Some steps in this evolution may be difficult to forecast because when the boundary-layer physical system is close to the edge of a transitional state, noise (physical or numerical) could lead to the boundary layer going into another state. The question of what determines how far the boundary-layer system is from a transition point is therefore critical. Another subtle factor is the microphysical feedback that occurs once the clouds form, especially for shallow warm clouds. Yet another subtle factor affecting feedback to the boundary layer is the entrainment process in shallow clouds. Microphysics and entrainment both are factors in determining whether shallow clouds triggered by boundary-layer convergence will or will not produce cold pools. While the parameterization considerations in this document naturally focus on convection and microphysical parameterizations, such considerations emphasize that we must also be prepared to reconsider the boundary-layer parameterizations. Therefore we have to better understand interactions among parameterization within climate models. For example, it should be recalled that the boundary layer itself begins to enter a “gray zone” for its representation when the grid length is of the order of a few times the boundary-layer height.

3.1.2 Transition to Deep Convection

General convergence producing mean upward motion ("lift") in a boundary layer that is sufficiently moist, deep, and buoyantly unstable is a primary prerequisite for a field of shallow convection to become populated with deeper convective clouds. As deeper clouds form, some begin to precipitate and may begin to interact with each other via cold pools, which, in turn, can lead to further clustering of convection at the cold-pool edges. Recent analysis of the predictive capacity of various common atmospheric parameters (buoyancy, dilution, mean upward motion, and convective inhibition) for the transition to deep convection over the continental U.S. indicates that they fail to consistently distinguish transitional from non-transitional boundary layers (Lock and Houston 2014), pointing to the potentially important role of stochasticity. Land-surface conditions and their associated fluxes and gradients may be missing factors contributing to stochasticity. Thus there is still much to learn about the transition to deep convection and the factors influencing it such as 1) when, where, and how convection initiates; 2) the roles of internal boundary-layer dynamics and instabilities; 3) influence of atmospheric mean conditions, especially shear, instability, humidity, and mean vertical motion; 4) land-surface heterogeneities; and 5) reorganization of the boundary layer by cold pools through precipitating convective elements.

One of the key challenges that continues to impede our understanding of how convective clouds deepen is our inability to determine the characteristics of updrafts as well as their interactions with the environment (especially via entrainment) and microphysical processes. Statistics of the intensity, size, and variation of updrafts with the height of convective towers are inadequate to non-existent under many key environmental conditions. As a result, the factors determining the behavior of drafts in convective clouds at all stages of development remain far from clear. Aircraft data (e.g., Zipser and LeMone 1980) and Tropical Rainfall Measurement Mission (TRMM) radar observations (Zipser et al. 2006) show that precipitating convection differs between land and ocean. Moreover, the tendency toward upscale growth differs between open oceans, arid lands, rainforests, and monsoons (Houze et al. 2015). The most powerful, nearly undiluted towers occur mainly over a few land areas (relatively dry regions near major mountain ranges). Even though Convective Available Potential Energy (CAPE) is often very large over tropical oceans, observations from field programs show that undiluted ascent from the boundary layer is extremely rare over tropical oceans.

As a feedback to the environment, latent heat release is a key factor. It depends on both the width and intensity of updrafts, i.e., on the vertical mass flux. For this reason, it is important to know the concurrent statistics of both width and intensity of drafts. However, the latent heating also depends on the nature of the microphysical processes in updrafts, which are strongly tied to vertical velocity intensity on very small scales within updraft regions. Therefore, the spatial variability of the vertical velocity within the width of drafts is also a crucial factor. For example, ASR-funded theoretical and modeling studies showed that entrainment rate per unit height of a plume is related to a parcel's vertical velocity and its distance from the edge of the updraft of which it forms part (Tian and Kuang 2016), and that the mean vertical velocity, in turn, is related to the size of the updraft (Morrison 2016). The modelled relationships among the width, intensity, and internal turbulent characteristics of drafts have to be verified by observations.

This leads to the question: how well do models determine vertical velocity? Comparing with the multi-Doppler radar retrievals, Varble et al. (2014) showed that CRMs with bulk microphysics overestimate the upper-tropospheric vertical velocity by up to 250% for a tropical convection case from the Tropical Warm Pool International Cloud Experiment (TWP-ICE; Figure 5a), and Fan et al. (2015) showed that results did not improve with a more detailed but computationally expensive bin microphysics scheme. However, for mid-latitude convection during MC3E, in spite of overestimation by CRMs, the differences between model and the retrieved updraft velocity are much smaller compared to the differences in the tropical convection case (Fig. 5b, Fan et al. 2015). It is also worth noting that while useful studies continue to be conducted on the sensitivity of high-resolution CRMs to their resolution, there is rather little evidence that vertical velocities and other convective cloud properties within current CRMs converge with resolution, much less to observations (e.g., Stein et al. 2015). A novel strategy for untangling the interactions of microphysical processes with vertical velocity is being pursued under ASR support: it involves “piggybacking” of multiple microphysics schemes in a single simulation in order to compare their responses to the same environment (Grabowski 2015).

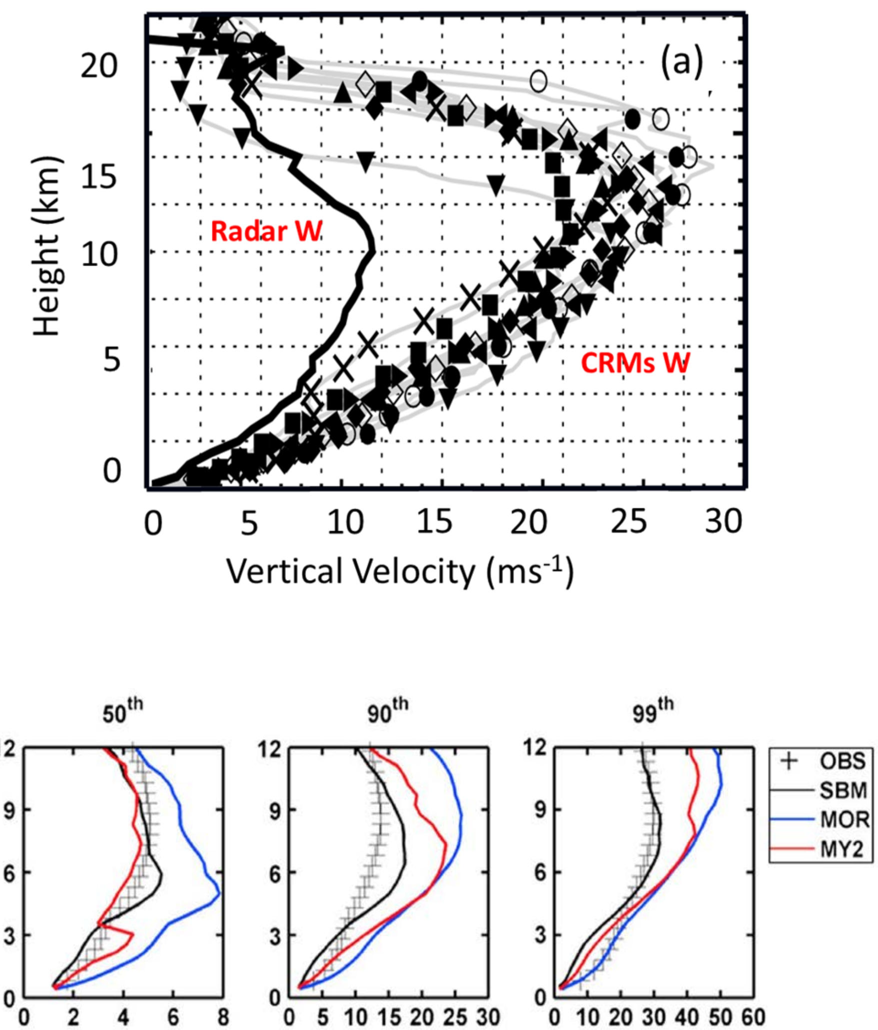

Figure 5. TOP: Median profiles of maximum vertical velocity for three-dimensionally defined convective updrafts beginning below 1 km and ending above 15 km for the period of 1310*Z* to 1750*Z* on 23 January, 2006. Gray lines with symbols and the dashed black lines represent simulations. Observations are represented by the solid black line (adapted from Varble et al. 2014). BOTTOM: Comparison of vertical velocity from bulk and spectral bin microphysics schemes with the multiple Doppler retrievals for the mesoscale convective complex (MCC) case on May 23 during the MC3E field campaign (adapted from Fan et al. 2015).

3.1.3 Upscale Growth from Deep Convective Cells to MCSs

About 30-70% of warm-season rain over the U.S. east of the Rocky Mountains (Fritsch et al. 1986, Nesbitt et al. 2006) and 50-60% of all tropical rainfall (Yuan and Houze 2010) is produced by MCSs. An MCS begins when convective clouds rooted in the boundary layer aggregate into a unit that is an order of magnitude larger than an individual convective cloud. The net heating by the aggregated convection induces mesoscale circulations in the form of layered sloping-up and downdraft circulations. The mesoscale circulation is not necessarily rooted in the boundary layer; a lower tropospheric layer several kilometers in depth may feed the sloping updraft, and the sloping downdraft begins in the midtroposphere. Pandya and Durran (1996) showed that the sloping mesoscale circulations are a gravity wave response to the net heating by the aggregated convection. Moncrieff (1992) showed that the geometry of the mesoscale updraft and downdraft are determined as an adjustment of the mesoscale motions to the environmental temperature and wind profiles (see also Chapter 9 of Houze 2014). Thus, the MCS is not simply a group of convective elements in close proximity. It is a mesoscale dynamical entity. Convective-scale buoyant updrafts are embedded within the mesoscale circulation. A typical aspect of an MCS is that it contains a stratiform cloud and precipitation area that evolves from the outflow or remains of its embedded convective elements. The stratiform region contains active condensation/deposition and latent heating at upper levels and melting, evaporation, and associated cooling at lower levels. The stratiform region thus gives the MCS a top-heavy heating profile that strongly influences the larger-scale circulation in which it is embedded. It is essential to represent the top-heavy heating by convection in parameterizations used in climate models.

An important question is what determines the scale of MCSs. One way to ask this question is: how does the initial group of convective cells that grow into an MCS originate? One hypothesis is that of "self-aggregation" (e.g., Wing and Emanuel 2013) whereby radiative-convective interactions, even if they are consistent with an equilibrium on the largest scales, nonetheless drive an initially dispersed area of small convective clouds to concentrate in a mesoscale area and intensify through radiative/dynamic feedback. Houze et al. (2015) have noted that precipitating cloud populations observed by the TRMM radar suggest that self-aggregation probably applies over tropical oceans; however, it is not yet clear whether it applies in the same way over land. Over both land and ocean, vertical shear fundamentally affects the formation, organization, and propagation of MCSs due to the interaction of vertical shear with the baroclinic generation of vorticity by the horizontal gradient of convective heating.

Another factor that plays a role in upscale growth of convection to form MCSs is the dynamics of cold pools, which have long been known to be affected by lower-tropospheric vertical shear (Thorpe et al. 1980), evaporative cooling, etc. For example, cold-pool depth partially controls gust-front speed and the subsequent updraft. Johnson and Houze (1987) described cold pools as the mode of communication between precipitating convective elements. As precipitating convective cells deposit cold pools in the boundary layer, they trigger new convection in the vicinity of older convection. Several questions related to cold pools have yet to be answered. Among those are: what determines whether or not convection is initiated due to cold pools? How long do cold pools last? How deep are they? How strong are the updrafts they induce? And what is the inter-relationship among the natures of primary updrafts, downdrafts, cold pools, and secondary updrafts in the process of organization? Ice microphysical processes (melting, evaporation, riming, ice multiplication, graupel-hail production), which impact organization both through latent heat release and radiative feedbacks, are also identified as the key areas of uncertainty. Along with knowledge gaps related to ice initiation and properties specifically, what are the roles of dynamical-microphysical feedbacks affecting vertical velocity in particular ice processes?

Cold pools are not necessarily always the proximate cause of MCSs. An important aspect of MCSs related to parameterization is that they can form above a shallow layer of stable air (Marsham et al. 2011), physically separated from cold pools and other boundary-layer processes. Parameterizations usually are surface-based convection being forced from the boundary layer, and as such cannot apply easily or directly to the formation of elevated MCSs, which can strongly feedback to the larger-scale circulation over the U.S. The observational data collected from the recent field campaign over the Central U.S., Plains Elevated Convection at Night (PECAN, Geerts et al. 2015), is expected to provide some insight into the development of nocturnal elevated MCSs over the Central U.S.

3.1.4 Organization into Large-Scale Features with Time and Spatial Scales beyond Individual MCSs

The large-scale convective features at mid-latitudes are often organized by large-scale dynamics (e.g., those of fronts, extratropical cyclones) that exist independently of convection. In the tropics, there are two types of large-scale convective phenomena: those that are governed by independent large-scale dynamics (e.g., equatorial waves, monsoons, the Hadley cell) with convective feedback as their main energy sources, and those that are governed by the convection-circulation interaction, which is essential to their very existence in the absence of independent large-scale dynamics (e.g., the MJO, tropical cyclones). In either case, mesoscale dynamics of shallow-deep-MCS transition alone would not explain the large-scale characteristics; interaction between convection and its environment takes place over a much larger scale than individual convective systems, and air-sea interaction is also likely to be involved. Faithfully reproducing these large-scale convective features by global climate models, the ultimate test of their fidelity requires not only adequate representations of cumulus convection, but also how they work together with parameterization of other processes (e.g., radiation, air-sea fluxes, and upper-ocean mixing).

In summary, the key challenges in our understanding of shallow to deep and upscale growth of convection and its organization into large-scale convective features primarily lie in:

1. how boundary-layer processes evolve in a way that leads to cloud populations containing deep and mesoscale convection, including cold-pool dynamics;
2. size, intensity, and internal variability of updraft/downdrafts;
3. microphysical feedbacks;
4. aggregation of convection;
5. inducement of mesoscale circulation, especially gravity-wave response to aggregated convective elements;
6. adjustment of mesoscale motions to environment profiles of stability and shear; and
7. the role of stochastic processes.

3.2 Paths towards Improving the Treatment of Convection in High-Resolution Climate Models

As noted in the introduction, the representation of convection in traditional global models, with grid spacing ~100 km, implicitly or explicitly relied on the assumption that the areas of up- and downdrafts are much smaller than those of the grid boxes. In that case, scale separation and statistical quasi-equilibrium is assumed between the resolved circulation that destabilizes the atmospheric column and the aggregate of convective updrafts that work to stabilize it (Arakawa and Schubert 1974). Furthermore, parameterizations implicitly require that the grid box is large compared to the mean distance between updrafts in order for the box to contain a meaningful sample size of updrafts. The breakdown of the mean-distance assumption means that stochastic effects start to be relevant (e.g., Plant and Craig 2008), whereas the breakdown of the area assumption means that convection enters a so-called “gray zone” that is further discussed below. Furthermore, in comparison to the slow evolution of the forcing, convection is often assumed to respond almost instantaneously and deterministically, with little memory or internal variability of its own. However, it has been known since the Global Atmospheric Research Program’s

Atlantic Tropical Experiment (GATE) that long-lasting MCSs are important, and scale separation is not present in either time or space.

Advances in computational resources have made possible operational global weather and experimental climate models that have spatial resolution ≤ 10 km, which allows mesoscale circulations to be at least partially resolved. As a result, fundamental rethinking of the objective of, approach to, and assumptions in convection parameterizations are taking place. First of all, simulations at sub-10-km scales could easily have organized convection systems with an area of updrafts and downdrafts that are comparable to and even greater than the grid spacing and could last longer than the often assumed adjustment time-scale of cumulus convection. In such cases, organized convective clouds cannot be treated as aggregate responses to the environment, but must be part of the now resolved, more rapidly evolving dynamics.

This does not obviate parameterization; instead it gives it new purpose and definition. Parameterizations must *represent the sub-grid states, processes, and transitions discussed in the last section and their interactions with resolved dynamic and thermodynamic processes, which include mesoscale processes*. In this case, the *resolved dynamics* and the *sub-grid states and transitions* are parts of the same continuum and the separation is arbitrarily imposed by the model resolution. Note that MCSs themselves contain subgrid-scale processes; i.e., parts of the mesoscale systems are resolved and some parts are parameterized. Therefore as scale separation (and statistical quasi-equilibrium assumption) disappears, an important and stringent constraint emerges: the requirement for *scale awareness.* That is, the results should be insensitive to arbitrary changes in grid spacing. Parameterizations must be aware of the processes that are unresolved, partially resolved, or fully resolved and adjust their operations accordingly. Scale awareness thus implies that the sums of resolved and parameterized parts of key quantities (e.g., mass flux) should not vary with resolution for the range of resolutions of interest.

This requirement has some practical implications for regionally refined models. Currently, models that are too expensive to run at high resolution globally are increasingly using regional refinement, where a certain region of interest is treated with higher resolution than other regions. If a parameterization is not scale aware, the increased resolution over a limited area introduces an anomalous localized forcing that could propagate globally and affect the model climatology and undermine the benefits of the increased resolution. The seriousness of this issue in "scale-incognizant" parameterizations has been demonstrated using models with regionally-refined grids that are run in aqua-planet mode. Figure 6 shows the circulation and precipitation anomalies associated with refined resolution in the Model for Prediction Across Scales (MPAS)-Atmosphere (Skamarock et al. 2012) with Community Atmospheric Model 4 (CAM4) physics. The global grid spacing is 120 km, but the resolution in a circle centered at the Equator is 30 km. The increased resolution results in enhanced precipitation and associated localized heating near the refined resolution region that excites erroneous Rossby waves which, in turn, propagate around the globe affecting circulation patterns elsewhere (Hagos et al. 2013).

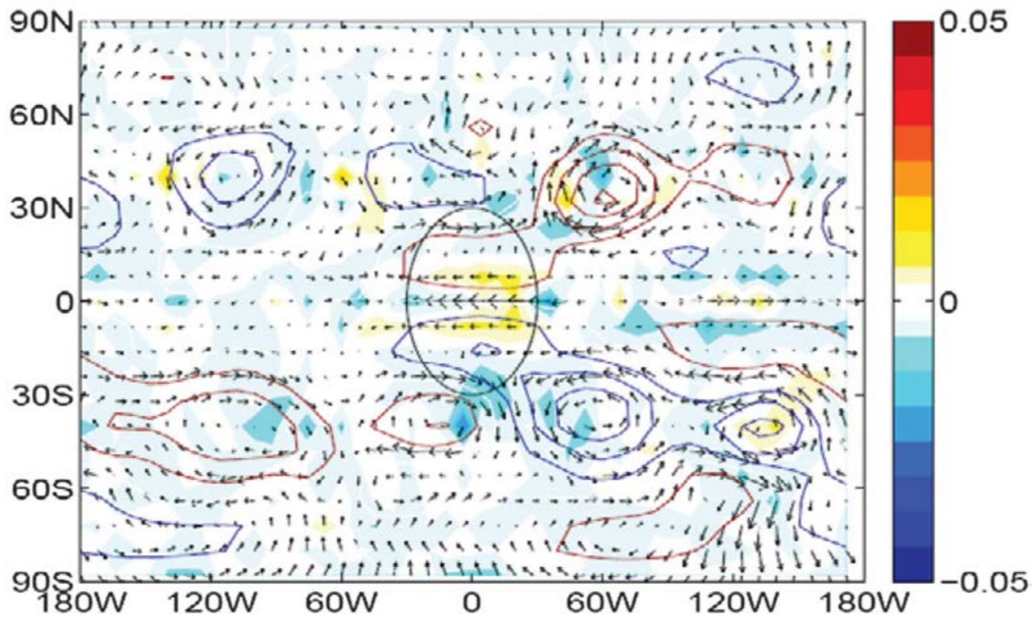

Figure 6. Anomalous streamlines, non-divergent wind (m/s), and vertical velocity (Pa/s) in a regionally refined aqua-planet MPAS-Atmosphere simulation. The grid spacing is 120 km global gradually reduced to 30 km in the black circle (adapted from Hagos et al. 2013).

In the absence of scale separation, the requirement for scale awareness cannot be treated as an afterthought that can be addressed by tuning some parameters in order to produce a desired outcome at a given resolution; rather (like statistical quasi-equilibrium before it), scale awareness has to be built in as a fundamental constraint on the design of robust parameterizations.

In the view of the workshop participants, efforts at representing convection in higher-resolution models have been progressing along six general directions, each with its unique strengths and challenges. These directions are briefly summarized below.

3.2.1 Modifications to Quasi-Equilibrium Mass Flux Schemes

As mentioned above, one of the key assumptions in statistical, quasi-equilibrium-based mass flux schemes is that updraft area fraction $\sigma << 1$ and compensating subsidence area fraction is $\sim \mathbf{1}$. This assumption has never been accurate in the presence of MCSs, and with increased resolution it breaks down even for convective-scale drafts. Arakawa et al. (2011) proposed an approach to address this issue by requiring that the parameterized mass flux be rescaled as $M = (1-\sigma)^2 M_{adj}$. Thus, M matches the quasi-equilibrium adjustment value M_{adj} when $\sigma << 1$ and gradually decreases to zero in situations for which $\sigma \sim 1$ when the mass flux is fully resolved. Implementation and evaluation of quasi-equilibrium parameterizations with this and similar modifications are currently being actively pursued both within the ASR Program (Suhas and Zhang 2015, Wang et al 2016, Xiao et al. 2015) and elsewhere (Grell and Freitas 2013, Wu and Arakawa 2014, Liu et al. 2015). Key issues arising for this approach are how one should actually diagnose the value of σ within partially resolved convection and, moreover, how one should diagnose M_{adj} given that the grid-scale atmospheric state traditionally supplied input to a scheme cannot by construction be considered as representative of a quasi-equilibrium state. While, by design, such models attempt to account for the changes in the overall mass flux with resolution, they do not address underlying issues related to the resolution dependence of the nature of the interactions between the environment and convection, or to the differences in the resolved and unresolved components of convective clouds. Another approach to these issues is the so-called “perturbation formulation” approach of Gerard (2015), which advocates that no existing approach to mass-flux (or cloud-fraction) closure would be likely to prove satisfactory, and so advocates a mixed or hybridized form as a practical alternative.

3.2.2 Prognostic Parameterization of Processes

In contrast to the quasi-equilibrium-based approach discussed above, this prognostic approach aims to treat certain key processes involved in convection—that is, convective updraft, convective downdrafts, and the sub-grid circulations associated with them—in a prognostic and unified manner (Park 2014). This methodology incorporates the interactions of multiple plumes within a grid box; aims to predict the initiation, temporal evolution, and advection of plume and environmental properties; allows convection to propagate; and includes aspects of cold pools. This approach is scale-adaptive in the sense that it only aims to represent sub-grid-scale motion with respect to the resolved motions, which allows the parameterized mass flux to vanish as σ approaches 1. Currently this approach does not include convection originating from above the boundary layer or the impacts of wind shear on convection. Furthermore, the effects of the parameterized sub-grid circulations on surface fluxes are not included. Other studies that have experimented with prognostic approaches include Pan and Randall (1998) (recently revisited by Yano and Plant 2012), Gerard et al. (2009), and Grandpeix and Lafore (2010). A key issue in this area is to establish which quantities have to be treated as explicitly prognostic in order to yield what benefits, and which quantities may reasonably continue to be handled diagnostically. Another issue that deserves systematic investigation is how one might choose to handle (or perhaps not to handle) the advection of extra prognostic variables, particularly if those are two-dimensional quantities and/or not obviously properties of an air parcel.

3.2.3 Non-Local Parameterization of Processes

An important feature of MCSs is propagation, in that they move from one grid element to another. Therefore, information on aspects requiring parameterization may have to be passed from one grid element to another. Such a necessity will likely require gray-zone, scale-aware methods to distinguish between the grid scale and the resolved scale at every grid element. Up to now there has been little consideration of such issues. This reticence may be due to the potential computational challenges related to parallelization in non-local approaches. Preliminary investigations of some possible aspects of non-local parameterization inputs and outputs have been made by Keane and Plant (2012) and Kuell and Bott (2011), respectively.

3.2.4 PDF-Based Turbulent Schemes

This approach can be considered as an incomplete, third-order, turbulence-closure parameterization, for it uses a family of assumed probability density functions (PDFs) to obtain a self-consistent closure for the second-order Reynolds equations (Golaz et al. 2002, Larson and Golaz 2005). It involves a three-step process beginning with the second-order turbulence equations that solve for the second-order moments of vertical velocity, moisture, and potential temperature, as well as their covariances. The predicted moments are then used to construct PDFs of these variables. Finally, the PDFs are used to calculate the third-order moments and provide closure for the second-order equation. The current version uses a double Gaussian family of PDFs. This approach has been successfully implemented in Global Climate Models (GCMs): CAM and Accelerated Climate Model for Energy (ACME) with the Zhang and McFarlane (1995) deep-convection scheme (Bogenschutz et al. 2013) and the Geophysical Fluid Dynamics Laboratory (GFDL) AM3 with the Donner (1993) deep-convection scheme. The approach performs well for shallow cumulus and stratocumulus clouds (Guo et al. 2014). Its development into a unified scheme that does not specifically refer to cloud category (i.e., shallow versus deep) is in progress. However, it is computationally expensive and the strategies for implementing organization mechanisms (such as shear and cold-pool dynamics) in such a scheme are only beginning to be developed and ASR is contributing to that development (Storer et al. 2015, Griffin and Larson 2016). One feature of this approach is that it predicts largely prescribed probability distributions of vertical velocity, temperature, moisture, and hydrometeor-mixing ratios. These quantities are not directly obtainable from existing observations. However, useful statistics of closely related quantities can be derived from ARM instruments such as cloud radars. Such observations need to be obtained as much as possible concurrently so that covariances can be obtained. This requirement implies that some quantities need to be measured at higher frequency (especially temperature, wind, and water vapor content) than they are currently measured, and others such as vertical velocity may require as yet unavailable platform or instruments (e.g., vertical air motion). Nonetheless, PDF methods have the advantage of predicting the terms in budgets of higher-order moments that can be compared in a one-to-one manner with LES. That is in contrast to traditional mass-flux models that have conceptual foundations precluding direct comparison with LES.

3.2.5 Explicit Approaches: Superparameterization and Global CRMs

In the original superparameterization approach, instead of cloud parameterizations (and boundary-layer parameterizations for temperature and moisture), two-dimensional cloud-resolving models are embedded in the climate-model grid boxes. The GCM provides the large-scale forcing and the CRM runs typically at 4 km-1-km grid spacing with periodic lateral-boundary conditions (Randall et al. 2013) to provide the convective tendencies to the GCM. Evaluation and improvement of this approach is an active area of research. It has been shown to improve the propagation of MCSs over the central U.S. compared to that of the same model with traditional parameterization (Prichard et al. 2011, Kooperman et al. 2013, and Elliott et al. 2016). Furthermore a superparameterization version of NCAR's CAM model (SPCAM) has been shown to have better skill in representing MJO than several other models (Kim et al. 2009), as well as the conventional version of CAM (Benedict and Randall 2009). However, as is often also the case with changes in cumulus parameterizations (Kim et al. 2012), the improvement comes with biases in the mean state and in the boundary-layer interactions. Along with microphysics issues that are typical in CRMs, lack of communication among the embedded CRMs has been pointed out as a challenge for the superparameterization of convection and convective organization. For instance, when MCSs are generated in a CRM domain, they are confined to that domain by periodic lateral-boundary conditions. Although MCSs can be generated across contiguous climate model domains on the parent climate model grid as a result of the joint effects of latent heating and vertical shear, circulation structure of the MCSs is compromised (Pritchard et al. 2011). The two-dimensional assumption is also limiting because most real MCSs are not two-dimensional. Although 3D CRMs can be used because of the added computational expense, it has only been attempted in very small domains (e.g., Khairoutdinov et al. 2005). New acceleration algorithms emerging from an ongoing DOE Scientific Discovery through Advanced

Computing (SciDac) project may lead to affordable large-domain 3D CRM superparameterization in the near future.

The global cloud-permitting modeling (CPM) approach is more physically realistic than superparameterization because the simulated mesoscale-cloud systems are three-dimensional and are not confined by periodic lateral-boundary conditions. The pioneering global CPM simulations conducted on Japan's Earth Simulator had 3.5-km, 7-km, or 14-km computational grids according to the length of the simulation (e.g., Miura et al. 2005, Satoh et al. 2008). When compared to TRMM observations, the 7-km grid-spacing simulation successfully captured not only the MJO but also the clusters of MCSs in it (Miyakawa et al. 2012). While they are computationally extremely expensive, such models are now being run for short periods at cloud-resolving, sub-kilometer-grid spacing (Miyamoto et al. 2013).

3.2.6 Dynamically Based Parameterization for Organized Convection

The main messages from the previous items are that we are at the crux of a new era of mesoscale-permitting global weather and climate models in which we can no longer neglect organized convection, defined as underlying multiscale order in a turbulent environment, in parameterization development. This issue points to the need to bring mesoscale dynamics to parameterization, where it is presently conspicuous only by its absence. An excellent example is the effects of vertical shear on organized convection, with particular attention to MCSs. Along those lines, two parameterization developments are underway that share a common physical-dynamical basis: the multi-cloud model (Khouider and Majda 2006) and the slantwise layer-overturning model (Moncrieff 2010, Moncrieff and Waliser 2015). The multi-cloud model represents the diabatic heating and the associated circulations as three cloud types observed to dominate the diabatic heating in tropical convection: congestus, deep convection, and stratiform cloud (Johnson et al. 1999). Slantwise layer overturning is a simple computationally efficient paradigm for the parameterization of organized convection based on multiscale coherent structures in a turbulent environment. Cumulus clouds in the environment are treated by traditional parameterization. Rooted in the nonlinear dynamics of convection in a sheared environment, the slantwise overturning approach readily represents top-heavy heating and mesoscale circulations in a scale-invariant manner. The coherent structure paradigm implies the existence of dynamical instability mechanisms for tropical convection shown by the multi-cloud model (Khouider and Moncrieff 2015). Finally, the turbulent environment noted in the definition of organized convection means that small-scale cumulus convection is intimately involved.

In summary, while all these approaches differ in the formulation of the problem and the technical design of the actual schemes, they are fundamentally related in that they aim to represent details of processes of convective cloud systems with resolved dynamic and thermodynamic states. Thus, their successful implementations fundamentally depend on the answers to the basic science questions discussed in the previous section and, as detailed in the next two sections; ASR is uniquely positioned to tackle some of these issues. Parameterization issues that follow the basic science questions include how can one reconcile parameterization schemes, many of which focus on convection rooted at the planetary boundary layer (PBL), with occurrence of elevated MCSs? How can cumulus parameterizations work compatibly with the parameterization of other processes and allow them to collectively be scale-aware when their individual roles vary with model resolution? These are only some of the issues that require a deliberate integration of basic understanding of cloud processes with parameterization development.

3.3 Observational Data Needs

The scientific and parameterization challenges discussed in the previous section highlight the need for understanding how the size, intensity, and internal turbulent structure of updrafts/downdrafts relate to one another and associated microphysical and cold-pool processes, as well as the prevailing large-scale environmental *context*. This section discusses the specific implications for collection, analysis, and delivery of observational data for process studies and parameterization development. The necessity for developing integrated data sets from concurrent and collocated observations/retrievals of these key processes using previous ARM intensive operational periods (IOPs) and permanent sites, field campaigns, various satellite missions, and operational activities of other agencies is highlighted. Future short-term and long-term observation strategies and investments are proposed.

3.3.1 Merged Multi-Instrument or Multi-Datastream Products from Existing Data and Facilities

Merged and concurrent multi-instrument or multi-datastream products aimed at meeting the above-stated goals need to be made available for convection over both land and ocean. The contrast in convection properties is generally starker between land and ocean than between tropical and mid-latitude regions. Over land, different topography, aridity, vegetation, and land use introduce further variability into convective populations. It is important to obtain key parameters of microphysics, drafts, and environmental conditions concurrently in these various environments. Concurrency is the most egregious deficiency in existing data sets. Statistics on different parameters and processes are key for process-level understanding and for constraining model parameters (e.g., relationships between environmental water vapor and precipitation, between precipitation type and latent heating, between cloud structure and radiative processes; the impact of up- and downdrafts on microphysical processes and cold-pool formation) but they must be obtained concurrently in order to be most useful. Products that can realistically be obtained concurrently and would be very useful for process studies and guiding parameterization development and validation include:

- Vertical profiles of environmental moisture on synoptic, mesoscale, and convective timescales (available from frequent soundings and some advanced profiling instruments),
- Cloud and precipitation morphology and organization (from scanning and vertically pointing radars of multiple frequencies, specifically W-, K-, X-, C-, and S-band, and satellite remote sensing),
- Three-dimensional cloud and hydrometeor types and fall speeds in convective and mesoscale cloud systems (dual-polarization radar and algorithms, vertically pointing radar),
- Divergence and vertical air motions fields (Doppler radars, profilers, sounding arrays),
- Cold-pool properties, including horizontal gradients and vertical profiles of temperature, moisture, and wind (surface meteorology station network, dropsondes, radiometers, lidars, wind profilers), and
- Latent- and radiative-heating retrievals (scanning and vertically pointing cloud and precipitation radars).

Many of these products can be made available through current instrumentation at SGP. However, the absence of a research S-band scanning radar is a limitation. Historical and IOP data sets, such as those collected at the Tropical Western Pacific (TWP) site in Darwin, GoAmazon2014/15, and

DYNAMO/AMIE are available and could be exploited more fully. An example of using past data sets for statistical validation of updrafts velocities measured by scanning and vertically pointing radar systems at the TWP site is the work of Collis et al. (2013). Such an integrated approach has been demonstrated to be useful for studies of relationships of entrainment rate to vertical velocity, buoyancy, and turbulent dissipation rate in shallow clouds. Using data collected during the Routine Atmospheric Radiation Measurement (ARM) Aerial Facility (AAF) Clouds with Low Optical Water Depths (CLOWD) Optical Radiative Observations (RACORO) field campaign, Lu et al. (2016) were able to derive an improved representation of entrainment rate using variables from multiple platforms.

Augmented by external radar resources such as the operational S-band radar network, which includes radars in the SGP region (NEXRAD), investigation of storm morphology and microphysical characteristics of MCSs and smaller convective entities affecting the SGP can be pursued with these data sets. The operational network's usefulness is limited, however, by the operational scanning mode, which degrades vertical resolution. For more complete documentation of processes, a research S-band scanning radar is needed.

3.3.2 Short-Term Observation Strategy: Adaptive Measurements at SGP

Typical field projects that last only a few months or less do not generally provide statistically robust data sets, and repeating such campaigns over sequential years is expensive. This issue sheds light on the need for a new and more efficient approach to obtaining observations at the SGP site. A proposed solution involves adapting observation strategies based on forecasts. During the spring season, when MCSs tend to affect the region, the scan strategy of radars, lidars, sounding launches, and other measurements could vary according to the forecasted weather situation. The default pre-planned modes would be altered to ones best suited to sample properties of shallow clouds when deep clouds are absent, adjusting to the deepening cloud population, and finally to MCSs with time decisions could be made and implemented quickly through online communication among PIs and instrument mentors. This mode of operations adapts a field campaign approach to the permanent observations facilities to optimize their ability to provide concurrent observations of the details of convective systems that will be of optimal use to parameterization development. The NEXRAD operational S-band network can be used to document the evolution of larger convective systems as they move into and out of the SGP region.

The workshop participants highlighted the potential value of a field campaign approach to situationally adapt observational strategies. However, limitations remain. The NEXRAD S-band network is not adequate to fully document the physical processes within heavily precipitating convective systems because of the radar scan strategies. The existing SGP facilities are also limited for microphysical evaluations due to attenuation at W-, K-, X-, and C-band. Once again, we see the missing element at SGP being the S-band scanning radar.

3.3.3 Long-Term Observation Strategy: Additional Observational Needs

Some of the variables listed in Sec. 3.3.1 may be difficult or impossible to obtain satisfactorily even using the optimized adaptive approach at SGP, as described above. However, ARM can continue to partner with other agencies including the National Oceanic and Atmospheric Administration (NOAA; with NEXRAD radars, profilers, and aircraft resources), the National Aeronautics and Space Administration (NASA; with satellite, aircraft, radar, and a host of portable ground-site facilities), and the National Science Foundation

(NSF; NCAR facilities). Investments in long-term observations that would have significant impact include:

- *S-band dual-polarization scanning radar.* NEXRAD radars operate in a pre-defined, full-volume scanning mode that is optimized for nowcasting but does not provide sufficient vertical resolution to obtain precise distributions of microphysical particle characteristics indicated by dual-polarization technology. Highly sensitive S-band scanning radars such as NSF's S-Pol (e.g., used in AMIE/DYNAMO) and NASA's NPOL (e.g., used in the Mid-Latitude Continental Convective Clouds Experiment [MC3E] and Olympic Mountains Experiment [OLYMPEX]) are required for increased vertical resolution through frequent, adaptable Range Height Indicator (RHI) scan sectors. In addition, W-, K-, X-, and C-band radars can be severely, and at times completely, attenuated by heavy precipitation associated with MCSs, thus limiting the full spectrum of observations needed to understand upscale growth or precipitating systems. S-band radars are complex and expensive, but provide substantial benefits compared to higher-frequency radars, including minimal attenuation, reduced non-Rayleigh scattering, and improved sensitivity, especially for clear-air retrievals. Importantly, for understanding all phases of convective cloud development, Bragg echoes are more prominent at S-band and therefore an S-band radar can help detect thermals and small cumulus clouds. Among the advantages of S-band are reduced attenuation effectively extending the range of coverage, especially when heavy precipitation is near the radar, and elimination of non-Rayleigh scattering effects, which make interpretation of differential reflectivity and differential phase difficult, if not impossible. As a result, there is far less ambiguity in the application of hydrometeor identification algorithms at S-band, especially when strong convection is present, such as around the SGP site.

  At present, S-band radar can be obtained by partnering with other agencies, as in past campaigns. Because of competition, the availability of S-band research radars of NSF and NASA for ARM campaigns cannot be assured. In addition, other agency priorities and hence operations of these radars may differ from those of an ARM campaign. Therefore it is desirable that ARM operates its own transportable S-band radar facility for use at SGP in an ongoing virtual field campaign mode as well as for deployments elsewhere (see Section 3.4.1).

- *Convection-penetrating research aircraft.* As discussed above, there is a critically insufficient amount of information on updraft/downdraft intensities, dimensions, and internal turbulent characteristics, which need to be determined concurrently and statistically. The X-Band Scanning ARM Precipitation Radar (X-SAPR) network at SGP has provided a means to partially investigate these properties using multi-Doppler techniques, which are fraught with uncertainties, assumptions, and limited areal applicability. Vertically profiling radars provide some information on vertical air motions; however, because they must be corrected for hydrometeor fall speed, making them only useful for very large up- and downdrafts, they are useless in weaker convection or stratiform regions. Limitations of sampling and accuracy associated with these radar methods necessitate in situ targeting, which can best be obtained with an aircraft of suitable airframe, altitude capability, and instrumentation to obtain information on drafts of all strengths at all altitudes. A convection-penetrating research aircraft is needed in the atmospheric sciences community. The workshop participants acknowledged that the development of such a platform is complicated and expensive. For example, the NSF storm-penetration aircraft (SPA; A-10) development has proven challenging, and when it might be available for deployment is uncertain. When ready, such a facility would be invaluable, especially if used in connection with ARM facilities. However, this aircraft will likely be in heavy community demand. A proactive inter-agency cooperation will be necessary to assure that it is used to meet DOE objectives as an integral part of the broader national priorities.

- *Large-scale, multi-agency, international, tropical oceanic field campaigns.* Most of the vertical re-distribution of heat by convection occurs over the tropics, especially the tropical warm oceans, the Maritime Continent and monsoon regions of Asia and Africa. GATE, TOGA-COARE, and AMIE/DYNAMO have provided critical information over open ocean tropical environments (Atlantic, Pacific, and Indian Oceans, respectively). However, they did not fully address the scientific questions discussed in foregoing sections because of limited observational technology available in the earlier programs; only the recent AMIE/DYNAMO campaign benefitted from dual-polarization radar and cloud radars, but no direct vertical draft measurements were made by any of these campaigns. None of these prior projects had strong microphysical and vertical velocity components. Besides the open oceans of the tropics, the Maritime Continent is one of the largest convective heat sources in the atmosphere, with the most complex arrangement of ocean and land. It is known that the MJO is disrupted in its passage over this region, affecting its impact on global weather-climate. This behavior remains one of the greatest unsolved problems of tropical convection interacting with the large-scale atmospheric circulation and the ocean differently from over the open ocean because of the topography. Despite all these prior efforts, crucial unknowns remain in regard to the fundamental understanding of convection in these oceanic regions. The four aspects of fundamental knowledge delineated in Section 3.1 are particularly deficient in these regions. Mechanisms of convective triggering, convective lifecycles, upscale growth of convection, and the processes by which entire convective cloud fields become composed of different forms of convection all need to be better understood to improve model representations of convection over the open tropical ocean and the Maritime Continent, which are not all the same as those over areas of the major continents, such as the Great Plains. Yuan and Houze (2010) and Houze et al. (2015) have used satellite data to point out the existence of differences in the nature of convection between the eastern and western ends of Intertropical Convergence Zone (ITCZ) regions and between the Maritime Continent and open oceans. A long-term strategy will be required to address the problem of insufficient in situ observations over the tropical oceans and land masses. This group of experts considered that large-scale oceanic field campaign data will be needed ultimately to address the key science questions and for parameterization development issues discussed in this document. Advanced understanding of physical processes governing the interaction between atmospheric convection and the global circulation can no longer be achieved via observations collected by small-scale field campaigns focusing on a single process. Deployment of a single ARM mobile facility will most likely be inadequate, and a bigger cooperative (interagency, international) program can be envisioned. With its observational and modeling infrastructure and its emphasis on high-resolution global climate modeling, DOE is best positioned to draft a blueprint for such a long-term plan to tackle climate model biases related to tropical convection. At this juncture, the needed components of such a field program in the tropics would include in situ aircraft for microphysics and vertical motion measurements (the SPA would be needed for the over-land component), along with dual-Doppler/dual-polarization radars. C-band radars would be adequate for over the ocean, but at least one scanning S-band radar is needed for land-based convection.

  Such a field effort is essential for a holistic achievement of the goals discussed in 3.1.1-3.1.4. Global models must be able to distinguish and accurately represent convective processes over ocean, land, coastal zones, mountains, and large islands. Finally, the workshop participants appreciate the potential impact of DOE’s effort over the SGP, the Amazon, and Argentina in providing a comprehensive, comparative understanding of convection processes over these widely different regions. They also emphasized the value of similar efforts over tropical ocean and Maritime Continent environments for painting a more complete picture of global convection.

3.4 Integration

In the last three sections, key scientific and parameterization challenges, as well as observational needs, were examined individually. However, even if the technical aspects of process modeling, parameterization development, and observations are addressed, progress is not guaranteed unless the challenges of effectively using observations to validate modeling and parameterization development activity, as well as integrating analysis of observational data and model output to draw robust scientific conclusions, are addressed. Among the many challenges for integration are:

1. the observed and modeled quantities not being the same,
2. the spatiotemporal scales represented by the measurements being different than what the model represents, and
3. the uncertainties associated with observations not being well quantified, thus introducing additional uncertainties when evaluating model processes.

Specific approaches for bridging some of these gaps are discussed below.

3.4.1 4D Analysis for Deep Convection and Virtual Field Campaigns

To a certain degree, measurements from ARM and other agencies are being assimilated to better support high-resolution modeling. Variational analyses like those that have been done for various ARM and other agency field campaigns are useful. However, they are often one-dimensional and the short duration of field campaigns limits their value for determining climatological variability. Virtual field campaigns of the type done for the Year of Tropical Convection (YOTC; Moncrieff et al. 2012) can be used to fill gaps in characterizing convection over longer time periods. However, YOTC was conducted only with global model reanalyses and therefore did not connect readily with all of the processes on smaller time and space scales. DOE has shown leadership in the development of high-resolution 3D variational analysis. For example, recently such an analysis for atmospheric diabatic heating and derivative fields has been developed for an ARM SGP intensive operational period (Tang and Zhang 2015). Furthermore, there is an ongoing effort to incorporate more of the available observed fields from the ARM SGP megasite. With such integration, the diurnal cycle issues over the central U.S. discussed in section 2. 1 can be effectively tackled. Similar effort for other regions would be desirable, especially for the Maritime Continent where diurnal cycle processes are even more complicated and have far-reaching impact on general circulation.

3.4.2 Instrument Simulators

One crucial way of bridging the gap between observations and model variables is the use of instrument simulators. In contrast to the traditional approach of performing geophysical quantity retrievals, simulators calculate instrument observables such as radar reflectivity factor, dual-polarization parameters, satellite brightness temperature, and other measurements made by remote sensors that can be diagnosed from the model outputs. Radar simulators have been used in studies using cloud-permitting regional model simulations, LES, and GCM studies (e.g., Varble et al. 2011, Hagos et al. 2014). However, this effort would be more effective if it were expanded and improved. ARM is in the process of developing simulators for GCMs using the Cloud Feedback Model Intercomparison Project (CFMIP) Observation Simulator Package (COSP) framework. Coupled with the aforementioned traditional approaches, more advanced and adaptive simulators designed to support a range of high-resolution model (e.g., LES, Cloud-Resolving Model [CRM]) diagnostics are also being developed (e.g., http://radarscience.weebly.com/radar-simulators.html) and are expected to help address the key science questions related to interaction between convection and dynamics with microphysical processes.

3.4.3 Cross-Scale and Hierarchical Approach to Modeling

High-resolution global atmospheric models are often thought of as a high-resolution limit to traditional global modeling. Alternatively, one can view them as a large-domain limit to regional high resolution. This latter perspective enables evaluation of model physics in regional- and variable-resolution global modeling frameworks at a fraction of the computational cost of global high-resolution models. Some progress has been made with this approach. For example, the porting of CAM5 physics package into WRF provided a flexible and efficient platform for evaluation of CAM5 physics schemes at any resolution of interest (Ma et al. 2014, Ma et al. 2015). Thus, a relatively small investment in porting physics packages into a flexible regional mesoscale model for development and evaluation purposes across a range of multiple resolutions would benefit the broader community. On the other hand, the non-hydrostatic MPAS-Atmosphere has been run on NCAR and DOE machines at variable resolution with refined regional mesh, down to 3 km (e.g., Pilon et al. 2016). Evaluation and improvements of the model in variable-resolution mode will certainly benefit the eventual use of the model in a global cloud-permitting mode. The development of a non-hydrostatic version of the High Order Method Modeling Environment (HOMME; the future dynamical core for ACME), which is in progress, will likely benefit from a similar regionally refined mesh approach. The treatment of organized convection in the gray zone can move forward by using advances in knowledge of physical and dynamical processes gained from improved observations and from LES and CRM modeling that ASR has been particularly active in, as detailed in preceding sections of this report. Maximum impact could be achieved by enhancing the knowledge from these advances via collaboration with the broader atmospheric science community, e.g., the intersection of weather and climate at sub-seasonal-to-seasonal (S2S) timescales (Vitart et al. 2014, Moncrieff and Waliser 2015). Thus, high-resolution climate modeling activities should be designed whenever possible as integral parts of a modeling continuum that includes LES, CRM, limited-area cloud-permitting models, variable-resolution models, and operational global cloud-permitting models. Consideration is required of what can be learned through evaluation of one approach using specific observational data that can benefit other approaches up and down the hierarchy where direct evaluation using that specific observational data is not feasible.

4.0 Conclusion

This workshop was conceived in response to the need for the next generation of global climate models to represent the physics of the entire spectrum of convective clouds on 1-10 km grid spacing. These models will resolve many features of clouds while other aspects will remain parameterized depending on the nature of the cloud populations to be simulated. Thus, parameterizations will have to operate seamlessly across all the involved scales and phenomena. The workshop brought together 30 experts in atmospheric convection with specialties in field observations, satellite studies, LES models, CRMs, GCMs, convection parameterization, and microphysics parameterization. All sessions were consecutive such that modelers commented on observational approaches and observationalists contributed to the discussions of modeling and parameterization. As detailed in the foregoing sections of this report, a multitude of issues were examined. However, the consensus of the participants can be summarized in the following main points:

Science

- *Mesoscale organization of convection*. Significant model biases in mean climate and variability are related to problems in representing organized convection.
- *Convection as a sequence.* The processes leading to organized convection is a seamless sequence that begins with boundary-layer instability and is followed in order by formation of non-precipitating cumulus, development of showers and cold pools, aggregation of deepening convection into mesoscale units, and ultimately formation of MCSs.
- *Mesoscale air motions are important*. MCSs develop mesoscale circulations (specifically, midlevel inflows, mesoscale convective vortices, and quasi-steady, layered, slantwise ascent and descending circulations) fundamentally different from the transient convective towers rising out of the boundary layer.
- *Convective dynamics and microphysics and the interactions between them.* Convection consists of many parts, some of which are insufficiently known from observations: namely, boundary-layer instabilities related to cloud growth; intensities, widths, and internal turbulent structure of convective updrafts and downdrafts; cold-pool dynamics; and ice microphysics

Modeling

- *Hierarchical Approach*: As climate-modeling efforts approach cloud-permitting resolutions, they should take full advantage of advances in other modelling activities including LES, Limited Area CRMs, variable resolution, and operational high-resolution models.
- *Scale awareness*: Although several paths to representation of convection in the next generation of climate modeling are being pursued by different developers, the importance of built-in scale awareness as a constraint for parameterizations is emphasized.
- *Parameterization decoupled from the boundary layer*: Some of the major approaches to parameterization remain designed to represent convection arising from the boundary layer. This approach may not be sufficient or appropriate in view of the important role of MCSs that are decoupled from the boundary layer ("elevated MCSs").

Observational

Observational gaps needs to be addressed for parameterization development efforts to succeed. The consensus of the workshop was that these observational needs could be fulfilled in three stages:

- *Development of merged products:* To take full advantage of ARM observations relevant to convection and microphysical processes, development of integrated data sets from *existing* concurrent and collocated observations/retrievals of these processes using previous ARM IOPs and permanent sites, as well as field campaigns and operational activities of other agencies, is needed.

- *Short-term adaptive observations strategy:* The type of data that would fulfill the principal observational needs is a function of the nature of the weather systems affecting a data network. Therefore, it may be valuable if observational strategies at SGP and possibly other ARM deployments were proactively adapted to the weather in a way that addresses these problems in near-real time. It would be useful for the SGP to be operated in an IOP mode during the spring storm season by monitoring the weather and adapting the observational strategies on a day-to-day basis. Based on forecast conditions, scanning procedures and sounding launches, and supplemental aircraft (if available), can be scheduled to optimize instrument operations to the observational needs noted throughout this report.

- *Long-term*: The short-term program at SGP provides experience in instrument development, multi-faceted observations, and observation-modeling integration, which is needed for field observations in other parts of the world. The workshop participants anticipated future needs of an S-band radar that can conduct specialized dual-polarization scans, convection-penetrating aircraft, and other advanced observing technologies in multi-disciplinary and multi-platform field campaigns, especially over the critical convective regimes of tropical oceans and the Maritime Continent. To optimize the outcome of such field campaigns, it is desirable to have them conducted with inter-agency and international collaborations and coordination. The value of outlining a long-term observing strategy for tropical convection to meet the ultimate goal of realistically reproducing convection in global climate models was also noted.

Progress on the key science questions can be assessed through a review of scientific articles published over the defined period and examination of how/if they were influenced by the outcome of this workshop. Similarly, standard metrics for usage of ARM facilities can indicate the impact of the investment decisions informed by the outcome of the workshop (the merged products, adaptive observational strategy for SGP, S-band radar, convection-penetrating aircraft, IOPs over tropical environments, etc.). The ultimate metric, however, will have to be measurable improvement in the high-resolution climate model simulation of the important climatological features discussed in section 2 (diurnal cycle of precipitation over land, the MJO, monsoons, El Niño Southern Oscillation (ENSO), the structure of the ITCZ and others elements of the general circulation) as quantified using the standard metrics and improvement of confidence in the models' projections of the response of the water cycle and associated weather and hydrological extreme events to natural and anthropogenic climate forcing.

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