Chapter 26

The Impact of ARM on Climate Modeling

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1. What is a climate model?

Climate models are among humanity's most ambitious and elaborate creations. They are designed to simulate the interactions of the atmosphere, ocean, land surface, and cryosphere on time scales far beyond the limits of deterministic predictability and including the effects of time-dependent external forcings. The processes involved include radiative transfer, fluid dynamics, microphysics, and some aspects of geochemistry, biology, and ecology. The models explicitly simulate processes on spatial scales ranging from the circumference of Earth down to 100 km or smaller and implicitly include the effects of processes on even smaller scales down to a micron or so. The atmospheric component of a climate model can be called an atmospheric global circulation model (AGCM).

In an AGCM, calculations are done on a three-dimensional grid, which in some of today's climate models consists of several million grid cells.[1] For each grid cell, about a dozen variables are "time stepped" as the model integrates forward from its initial conditions. These so-called prognostic variables have special importance because they are the only things that a model remembers from one time step to the next; everything else is recreated on each time step by starting from the prognostic variables and the boundary conditions. The prognostic variables typically include information about the mass of dry air, the temperature, the wind components, water vapor, various condensed-water species, and at least a few chemical species, such as ozone.

A good way to understand how climate models work is to consider the lengthy and complex process used to develop one. Let us imagine that a new AGCM is to be created, starting from a blank piece of paper. The model may be intended for a particular class of applications (e.g., high-resolution simulations on time scales of a few decades). Before a single line of code is written, the conceptual foundation of the model must be designed

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[1] The AGCMs used for weather prediction employ much finer grids.

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through a creative envisioning that starts from the intended application and is based on current understanding of how the atmosphere works and the inventory of mathematical methods available. The design process can be viewed as an ordered sequence of choices:

- Where (how high) should the top of the model be placed?
- What range of processes should be included? For example, what chemical and biological processes are needed?
- What horizontal and vertical resolutions are needed? The answers will strongly influence the choice of the continuous equation system and the nature of the physical parameterizations. The available computer power determines what range of resolutions can be considered.
- What set of continuous equations should be used to describe the fluid dynamics? For example, should vertically propagating sound waves be included or filtered out? What conservation properties should the continuous system have?
- What approach should be used to discretize the model's domain? For example, should we use a latitude–longitude grid or a cubed sphere grid or a geodesic grid? Should the vertical coordinate be terrain following or not? Should the vertical coordinate move up and down, following the air, as in the case of isentropic coordinates?
- What approach should be used to discretize the equations? Possibilities include spectral, finite-volume, semi-Lagrangian, and spectral-element methods.
- Which variables should be prognosed (time stepped)? For example, should the model prognose temperature or potential temperature? With the continuous system of equations the choice does not matter, but with the discrete system it does.
- How should the variables of the model be arranged on the horizontal and/or vertical grids? There can be good reasons to place different variables in different locations.
- What vertical resolution is needed, and how should it vary with height?
- What conservation properties of the continuous system should be carried over to the discrete system? Possibilities include the mass of dry air, the mass of total water, the total energy content of the air, and the potential vorticity. Conservation is known to be particularly important in long simulations, such as those needed to explore climate change scenarios.
- What order of accuracy should be built into the discrete system? High accuracy can be beneficial but is computationally expensive.
- How many prognostic variables are needed for the representation of clouds? For example, is information about particle size needed, in addition to information about condensed-water mass?
- How should the many important subgrid-scale processes be parameterized, and how should those parameterizations be coupled to each other and to the resolved-scale fluid dynamics? A key goal of the Atmospheric Radiation Measurement (ARM) Program has been to enhance and facilitate the process of parameterization development, especially for parameterizations of clouds and radiation. Parameterizations are important because they are needed to enable simulations with models and also because they are based on simplified models that encapsulate our understanding of how those processes interact with larger-scale weather systems. In some distant future, it may be possible to explicitly simulate many processes that are parameterized today; even then, parameterizations will be needed to understand why the simulations turned out as they did.

The answers to the questions listed above define the scientific architecture of the model, which should be documented in journal articles, technical reports, and web pages that explain not only what choices have been made, but why.

Next, the scientific architecture described above must be combined with and complemented by a computational architecture. The form of the computational architecture will be dictated in part by the scientific architecture and in part by the characteristics of the machines that will be used to run the model. This is where software engineering comes in.

2. Improving the models

Although AGCMs are sometimes created "from scratch," as outlined above, existing AGCMs are updated routinely to incorporate new understanding and to address inadequacies of their formulations (Jakob 2003). Key steps are to identify model deficiencies through comparison with observations, attribute these deficiencies to particular defects of the model's formulation, and test new modeling concepts at the component level, in the same way that the engines, airframe, and other components of a new type of aircraft are tested individually before an actual flight is attempted. The data collected by ARM are used primarily to test individual model components, especially parameterizations.

The ARM Program has a particular interest in the parameterization of atmospheric radiative heating and cooling. As discussed in the next section, ARM has supported the development of greatly improved radiation parameterizations, which are now in use at modeling centers throughout the world. Even a perfect radiation parameterization needs realistic inputs to produce realistic heating and cooling rates. The required inputs include information about cloudiness, water vapor, and aerosols. ARM has therefore devoted a lot of attention to the parameterization of clouds and aerosols and to the effects of cloud processes on the distribution of water vapor.

During the first five years of ARM, the program's emphasis was on its first priority (i.e., precisely measuring the surface radiation field), the effect of clouds on radiation and the atmospheric state, and less on its second priority of measuring cloud properties (Stokes 2016, chapter 2). During that time, ARM provided crucial support for cloud parameterization development, but cloud observations and value-added products did not yet exist for most fields of interest to modelers. Within a few years, it became clear that, although global climate model (GCM) radiative transfer schemes were not as accurate as they needed to be (Ellingson et al. 1991; Mlawer et al. 2016, chapter 15), this source of simulated radiation errors was dwarfed by the effect of uncertainties in GCM predictions of the occurrence of clouds and their macrophysical and microphysical properties.

In the early years, only the ARM Southern Great Plains (SGP) site was operational (Cress and Sisterson 2016, chapter 5), which limited the ability of ARM data to address questions about clouds in the tropics, the global oceans, and the polar sea ice regions that are now known to account for most of the spread in GCM estimates of climate sensitivity (Bony and Dufresne 2005; Zelinka et al. 2012). The single-column modeling (SCM) concept (Randall et al. 1996; Zhang et al. 2016, chapter 24) was being implemented at the SGP, based on intensive observing periods (IOPs), during which frequent soundings over a GCM gridbox-sized area provided estimates of large-scale advective tendencies of temperature and humidity to force the parameterizations in a GCM column. It took several years for the limitations in the advective products to be understood (Ghan et al. 2000) and to develop a strategy to improve them (Zhang and Lin 1997). Early SCM case studies were used to understand how different ways of specifying the observed forcing (Randall and Cripe 1999) determined what could be learned and how nondeterministic behavior could develop as SCM solutions drifted from reality (Hack and Pedretti 2000).

Despite this, the early datasets shed light on several outstanding cloud-climate issues. As the SCM framework matured at the end of ARM's first decade, cloud-resolving models (CRMs) began to be used as intermediaries between ARM data and SCMs to identify parameterization deficiencies that were not obvious from the observations alone.

At the same time, the internationally based GEWEX Cloud System Study (GCSS) was also being planned (Randall et al. 2003). The idea of GCSS was that CRMs, which simulated spatial scales on which clouds form, could be compared more directly to observations than SCMs, while providing information on the small-scale motions that underlie stratiform cloud and cumulus parameterization assumptions. In this way, CRMs would serve as a bridge to identify and remedy parameterization errors. ARM and GCSS worked very well together; GCSS undertook model intercomparisons based on ARM data, and ARM benefitted from the expanded use of its data products by the international community at no direct cost to the program.

The use of ARM data by GCM developers also has been facilitated through ARM's sponsorship, along with the U.S. Department of Energy (DOE)'s Climate Change Prediction Program (CCPP), of the CCPP-ARM Parameterization Testbed (CAPT; Phillips et al. 2004). CAPT was designed to bridge the gap between ARM data used to develop, test, and improve parameterizations of physical processes and the GCMs where improved parameterizations are used. In CAPT, full atmospheric GCMs are integrated in weather forecast mode, like numerical weather prediction models, by initializing them with analyses produced by weather prediction centers. Short forecast simulations are performed, and simulation output is compared directly to ARM data to diagnose errors related to the parameterizations. By using results after short integration times, parameterization deficiencies can be identified before they are masked by compensations due to multiple error sources. Examining physical parameterizations in this way is a good complement to the use of SCMs because it allows for interactions between the large-scale dynamics and physics in ways that an SCM cannot do. Integrating GCMs in forecast mode has been applied widely to the Community Earth System Model (CESM; Williamson et al. 2005; Xie et al. 2008; Boyle and Klein 2010; to name just a few) and the Geophysical Fluid Dynamics Laboratory (GFDL) model (examples given below).

As active remote sensing cloud products emerged and IOPs began to be conducted at the other ARM sites during ARM's second decade, more direct evaluations of GCM fields were enabled. Some of these efforts have only borne fruit (as published papers and/or model improvements) since the ARM era ended in 2009 and the joint Atmospheric System Research (ASR)–ARM era began (Mather et al. 2016, chapter 4). However, papers continue to be published based on datasets acquired during the first 20 years of ARM. This attests to the continuing impact of the innovative ARM observational strategy.

3. The role of ARM in improving the Community Earth System Model

a. *Improved parameterization of radiative transfer*

One of the significant contributions from the ARM Program to climate studies is the development and introduction of highly accurate parameterizations of radiative processes into the CESM (Hurrell et al. 2013). These parameterizations, known as the Rapid Radiative Transfer Model for GCMs (RRTMG; Mlawer et al. 1997), are tested continuously against observations from the ARM Program (Oreopoulos et al. 2012). They also are updated routinely relative to benchmark line-by-line models of radiative transfer using the latest spectroscopic databases and empirical formulations of continuum absorption by water vapor and carbon dioxide (Clough et al. 2005; Mlawer et al. 2012, 2016, chapter 15). The RRTMG parameterizations are demonstrably more accurate than the traditional band models they replaced (Oreopoulos et al. 2012) and have thereby improved the simulation of both present-day climate and its response to future anthropogenic forcing (Iacono et al. 2008).

These changes are important for climate studies because the CESM, a model jointly developed by the DOE and the National Science Foundation (NSF), is used by over 3000 scientists and groups worldwide. The source code, input data, simulation output, and model documentation are freely available to the global community. The CESM supports a large community of researchers studying the dynamics and consequences of climate change and reporting these findings in major national and international reports. The CESM is one of several U.S. models used to produce the large suite of simulations analyzed by the Intergovernmental Panel on Climate Change (IPCC) in their assessment reports [e.g., the Fourth and current Fifth Assessment Reports (AR4 and AR5; IPCC 2007, 2013)]. Projections from the CESM also represent a key source for the most recent U.S. National Assessment (Melillo et al. 2014). The introduction of RRTMG represents an important enhancement to the physical fidelity of the Community Atmosphere Model, version 5 (CAM5), the component of CESM that simulates atmospheric processes (Gettelman et al. 2012).

Before the introduction of RRTMG, radiative processes at CESM had been treated using parameterizations based upon traditional band formulations developed by the National Center for Atmospheric Research (NCAR; Kiehl and Briegleb 1991, 1993). While periodic updates (Collins 2001; Collins et al. 2002a) to these parameterizations maintained reasonable absolute accuracy relative to benchmark radiative codes (Feldman et al. 2011), these parameterizations suffered from several shortcomings inherent in their band formulation. First, it proved difficult to maintain and continually update the accuracy of most of the radiatively active species in the longwave parameterization because of the complex formulation of the absorptivity and emissivity terms in that scheme. The computation of these same terms scaled quadratically with the number of vertical levels, thereby imposing a major barrier to increasing the vertical resolution of CAM. In addition, the band formulations in both the shortwave and longwave proved quite difficult to extend to incorporate additional radiatively active compounds [e.g., volcanic and speciated anthropogenic aerosols (Meehl et al. 2012; Collins et al. 2002b, 2006b)]. Finally, several groups had demonstrated the appreciable technical, computational, and scientific advantages readily available from an alternate formulation of radiative transfer (Lacis and Oinas 1991; Fu and Liou 1992). This alternative is based upon the correlated-k formalism for the spectral integrations required to compute broadband fluxes. Correlated-k treatments can be readily derived and updated from line-by-line codes applied to periodically updated spectroscopic databases, such as the HITRAN compilations of line properties (Rothman et al. 2013). It is also much easier to extend correlated-k parameterizations to include new radiatively active species (e.g., NF_3) as their potential climatic significance is demonstrated (Prather and Hsu 2008).

In response to these considerations, members of the ARM community introduced the RRTMG family of parameterizations into the Community Climate Model (CCM; the predecessor to CAM) on an experimental basis. Simulations run with the band codes and with RRTMG were compared to quantify the impact of RRTMG on the radiative fluxes and climatological state simulated by CCM (Iacono et al. 2000). These comparisons demonstrated that introduction of RRTMG would appreciably improve the longwave fluxes by reducing the outgoing longwave radiation by 6–9 W m^2, enhance longwave atmospheric cooling rates by 0.2–0.4 K d^{-1}, and thereby reduce a number of systematic temperature biases in the model. These changes were attributed to the updated treatment of spectral and continuum absorption by water vapor in RRTMG relative to the band models. Changes of comparable magnitude were obtained when the effects of near-infrared absorption by water vapor were updated in accordance with modern spectroscopic databases and continuum formulations (Collins et al. 2006a). The sensitivity of CCM, CAM, and other GCMs to the radiative properties of water vapor follows from its roles as both the most important greenhouse gas, accounting for roughly 60% of the clear-sky greenhouse effect and the most important absorber of near-infrared radiation, contributing almost 75% of the clear-sky shortwave atmospheric heating rate (Kiehl and Trenberth 1997).

ARM also has improved radiation transfer under cloudy-sky conditions. At the beginning of the ARM era, the optical properties of liquid water clouds were well described by Mie theory with suitable parameterizations thereof (e.g., Slingo 1989), but radiation transfer through ice clouds [which cover about 19% of the planet (Chen et al. 2000; Hartmann et al. 1992)] posed a serious challenge, since no theory of radiation–particle interactions addressed the complex geometry of atmospheric ice particles. Not only are the optical properties of single ice crystals a challenge; so are the optical properties of the ice particle size distribution (PSD) that are not parameterized easily even with perfect knowledge of the former (Mitchell et al. 2011).

Over a decade of ARM research yielded an accurate means of treating ice cloud optical properties in terms of the physical attributes of both the PSD and the ice particles (for any given shape) within an analytical framework. This produced a considerable improvement over the previous ice optics scheme in CCSM in regards to LW radiation, where the mass absorption coefficient in the atmospheric window region was reduced by ~50% for cirrus clouds (Mitchell et al. 2006). This is primarily a consequence of optically describing a particle in terms of its volume-to-projected-area ratio instead of describing it as an equivalent-area sphere (appropriate only for extinction), as was done before in CCSM.

These results, along with the advantages of a modern correlated-*k* formulation, led the CESM Atmospheric Model Working Group (AMWG) to adopt the RRTMG parameterizations for CAM5 in the first version of the new CESM (CESM1). While several other teams developing weather and climate codes had already adopted the longwave component of RRTMG [e.g., the European Centre for Medium-Range Weather Forecasts (ECMWF), as described in Ahlgrimm et al. (2016, chapter 28)], CESM1 was the first climate model to adopt the shortwave component as well. The first comprehensive suite of historical and future climate simulations produced with CESM1 for the fifth phase of the Coupled Model Intercomparison Project (CMIP5) was assessed as part of the IPCC AR5.

The RRTMG family of parameterizations is now one of the core physical parameterizations in the CAM and CESM. Its adoption by the CESM science team, as well as by leading international groups such as the ECMWF, represents a significant advance in the treatment of radiative processes in numerical forecasts. This advance represents a major contribution from the ARM Program to the operational weather and Earth system modeling communities.

b. The early development of superparameterizations

Grabowski and Smolarkiewicz (1999) described a simplified GCM in which the physical processes associated with clouds were represented by running a simplified cloud-resolving model within each grid column of a low-resolution AGCM. Parameterizations of radiation, cloud microphysics, and turbulence (including small clouds) are included in the CRM, which explicitly simulates the larger clouds and some mesoscale processes. The model successfully simulated some aspects of organized tropical convection, which many other models had failed to capture. In particular, the model produced a signal resembling the Madden–Julian oscillation (MJO; Madden and Julian 1971, 1972), which is an eastward-propagating tropical disturbance characterized by a large zonal extent and a period of about 40–50 days. The MJO has proven very difficult to simulate with AGCMs (e.g., Lin et al. 2006; Kim et al. 2009).

Inspired by the results of Grabowski and Smolarkiewicz (1999), and with the support of the ARM Program, Khairoutdinov and Randall (2001) created a superparameterized version of the CAM (SP-CAM), in which the CAM's parameterizations were replaced, in each CAM grid column, by a simplified version of Khairoutdinov's CRM (Khairoutdinov and Randall 2003). One copy of the CRM runs in each grid column of the CAM. The CRM is two-dimensional (one horizontal dimension, plus the vertical) and uses periodic lateral boundary conditions.

The ARM Program's early support of the SP-CAM made it possible to explore the behavior of the model in more detail. In 2006, the National Science Foundation created a Science and Technology Center (STC) focused on continuing development and applications of the SP-CAM. In effect, the STC was incubated by ARM. Over the past decade, the SP-CAM has been coupled with an ocean model (Stan et al. 2010) and used in studies of the MJO (Benedict and Randall 2009, 2011), monsoons (DeMott et al. 2011, 2013), the diurnal cycle of precipitation (Pritchard and Somerville 2009 a,b; Pritchard et al. 2011; Kooperman et al. 2013), African easterly waves (McCrary 2012), and climate change (Wyant et al.

2006, 2012; Arnold et al. 2013). Further discussion is given by Randall (2013).

4. The role of ARM in improving the GISS model

ARM data have strongly influenced parameterization evaluation and development in the Goddard Institute for Space Studies (GISS) AGCM. Here, we discuss how the data have been used for model components relating to low-cloud feedbacks, cloud phase, and convective entrainment and downdrafts.

a. *Low-cloud feedbacks*

At the dawn of the ARM era, cloud optical property feedbacks were just being recognized as a serious climate issue. Early GCMs had fixed cloud optical thicknesses or albedos. However, Somerville and Remer (1984) and Betts and Harshvardhan (1987) argued that liquid water content (LWC) and thus cloud albedo should increase with temperature, providing a negative cloud feedback. In the first Atmospheric Model Intercomparison Project (Cess et al. 1989), a number of GCMs assumed such behavior as a parameterization. Meanwhile, several GCMs were implementing prognostic cloud water budgets, producing different cloud feedbacks depending on specific process representations (e.g., Mitchell et al. 1989; Roeckner et al. 1987). Satellite datasets were showing that, except at cold temperatures, liquid water path (LWP) and low-cloud optical thickness were correlated negatively with temperature (Tselioudis et al. 1992; Greenwald et al. 1995), although there were concerns that this might be an artifact of the satellite sensors' resolution. The GISS GCM reproduced the satellite behavior because of liquid water sinks (cloud-top entrainment and precipitation) and varying cloud physical thickness (Tselioudis et al. 1998), but it was not known whether these were responsible for the observed behavior. The resulting positive optical thickness feedback increased the climate sensitivity by 0.35°C (Yao and Del Genio 1999).

Although cloud radars had not yet been deployed at the SGP, early ARM data permitted a preliminary study of continental midlatitude low-cloud optical properties (Del Genio and Wolf 2000). The ARM microwave radiometer (MWR) was used to obtain LWP, the ceilometer for cloud-base height, satellite brightness temperatures and soundings for cloud-top height, surface meteorology observations for relative humidity, and surface weather reports of cloud type. From these, cloud physical thickness and LWC were derived, along with indices of boundary layer structure.

The results documented the midlatitudes as a transition region between the satellite-observed low- and high-latitude behaviors. Low-cloud LWP was invariant with temperature during winter but decreased with temperature in summer. LWC showed no temperature dependence, but clouds physically thinned with temperature, especially during summer and in the warm sector of baroclinic waves. This was due primarily to a rising cloud base with warming as relative humidity decreased and the lifting condensation level increased. The temperature dependence of cloud thickness only occurred in well-mixed or decoupled boundary layers and was, in part, the result of a shift in the relative frequency of convective and stable boundary layers. Dong et al. (2005) revisited this analysis with accurate radar-derived cloud-top heights and a more recent MWR processing and found that LWC decreased with increasing temperature instead, but overall they agreed with the conclusions of Del Genio and Wolf (2000).

b. *Cloud phase*

Changes in the relative occurrence of cloud ice and liquid as climate warms exert a negative feedback on climate change, because of their different particle sizes and scattering phase functions and thus in the condensate retained rather than precipitated out (Mitchell et al. 1989). The feedback depends on the temperature range over which the transition (in a statistical sense) from liquid to ice occurs. In principle, both phases can exist from temperatures ~0°C down to the homogeneous ice nucleation threshold of ~−38°C. Which phase exists at a given temperature within this range depends on the cloud-scale dynamics, the resulting degree of supersaturation, the availability of ice nuclei, and the age of the cloud. Some GCMs use single-moment cloud microphysics parameterizations that diagnose cloud phase from grid-scale properties. Others use two-moment schemes that determine phase from parameterized microphysical processes that estimate nucleation rates of liquid and ice and conversions between them. Model comparisons to ARM observations during the Mixed-Phase Arctic Cloud Experiment (M-PACE) IOP at the ARM North Slope of Alaska (NSA) site in 2004 showed significant scatter in the amounts of ice and liquid and a tendency for the liquid phase to be underpredicted in boundary layer stratocumulus (Klein et al. 2009) but overpredicted in a frontal multilayer cloud (Morrison et al. 2009).

Parameterizations of cloud phase during the ARM era had been influenced by midlatitude aircraft observations in the frontal regions of baroclinic storms (Bower et al. 1996). These data suggested that liquid water was rare at temperatures <−15°C, whereas earlier aircraft data (Feigelson 1978) had liquid present down to −40°C. Naud et al. (2010) used the ARM SGP Raman lidar and

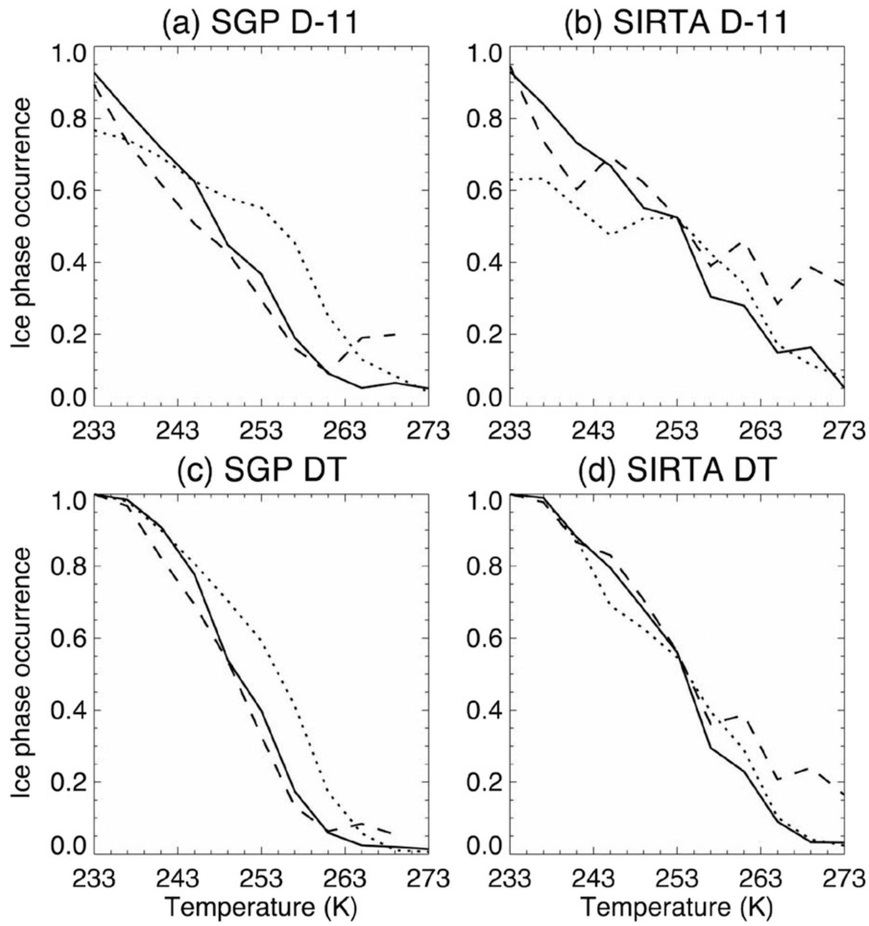

FIG. 26-1. Lidar-based temperature dependence of the fractional occurrence of the ice phase in optically thin clouds at the (a),(c) SGP and (b),(d) SIRTA sites (Naud et al. 2010). (top), (bottom) Two different approaches to specifying the depolarization ratio threshold that separates ice from liquid are represented. The solid curves show the temperature dependence at the median level of the cloud, while the dashed and dotted curves represent the phase at cloud top and cloud base, respectively.

the SIRTA lidar in France (Haeffelin et al. 2016, chapter 29) to compile statistics of cloud phase based on the lidar depolarization ratio. Lidar phase profiles are restricted to optically thinner clouds, such as altocumulus that often occur behind fronts, a different sampling than that of Bower et al. (1996).

Naud et al. (2010) found that liquid persists in these clouds down to ~−40°C, depending on the lidar and depolarization threshold used (Fig. 26-1), much colder than in the Bower et al. data. Likewise, the temperature at which ice and liquid occur equally is much colder in the lidar data (~−20°C) than in the Bower et al. data (−6.5°C). The GISS GCM at that time used a hybrid diagnostic scheme (Del Genio et al. 1996) in which cloud phase at nucleation varies probabilistically with temperature down to −38°C, but with Bergeron–Findeisen glaciation of supercooled cloud liquid by falling snow possible as the cloud ages. The overall resulting dependence of cloud phase on temperature in the GCM appears realistic, but the GCM analysis was not performed separately for thick frontal and thinner postfrontal clouds.

c. *Convective downdrafts*

The GATE field experiment showed that convective downdrafts are important to the energy and water budgets of convective systems (Houze and Betts 1981). Downdrafts were neglected in early cumulus parameterizations, though. By the time ARM began, some GCMs had included simple representations of downdrafts, including GISS (Del Genio and Yao 1988).

The first GCSS case study to examine midlatitude continental convection was based on the ARM summer 1997 SCM IOP. CRMs diagnosed updraft and downdraft mass fluxes (Xu et al. 2002), and these were compared to those parameterized in 15 SCMs (Xie et al. 2002). The SCM and CRM updraft mass fluxes were in reasonable agreement. Downdraft mass fluxes were much weaker in the SCMs than in the CRMs, however. Several possible reasons for this were suggested by Xie et al. (2002). First, the cumulus parameterizations only accounted for convective downdrafts, while the CRMs included both convective and mesoscale downdrafts. Second, some parameterizations (including that used by GISS) prescribed a single downdraft with a prescribed fraction of the updraft mass flux and/or did not allow downdrafts below cloud base.

Third, and perhaps most important, is that in most GCMs a stronger downdraft erroneously suppresses future convection. This occurs because in most GCMs, low moist static energy downdraft air immediately mixes with the ambient high moist static energy boundary layer air that gave rise to the convection, prematurely stabilizing the boundary layer. Downdrafts actually form boundary layer cold pools that remain distinct from the ambient air for hours (Houze and Betts 1981; Tompkins 2001). As the cold pools spread, high moist static energy air at the cold pool leading edge is lifted, triggering the next generation of convection rather than shutting it down. Indeed, several years earlier Mapes (2000) had made the point that GCM downdraft parameterizations were perhaps doing more harm than good because of this behavior.

The Xie et al. (2002) result led to several attempts to strengthen the GISS downdraft. For CMIP3 (Schmidt et al. 2006), the downdraft mass flux was increased by adding entrainment and extending the downdraft below cloud base. For CMIP5 (Schmidt et al. 2014), multiple downdrafts were added whenever an equal mixture of cloud and environment air was negatively buoyant. Buoyancy was based only on temperature, rather than on virtual temperature with precipitation loading, because the latter created an excessive downdraft mass flux. Post-CMIP5, as part of an effort to create realistic GCM intraseasonal variability, convective rain reevaporation was strengthened. This sufficiently moistened the environment that downdraft negative buoyancies were reduced, and it finally became possible to include the precipitation loading effect (Del Genio et al. 2012). Recently, a downdraft cold pool parameterization has been developed (Del Genio et al. 2013), with some effect on convective occurrence frequency.

d. Convective entrainment and vertical velocities

By 2006, cloud radars were standard at all ARM sites, and the Active Remotely Sensed Cloud Locations (ARSCL) value-added product (Clothiaux et al. 2000; Kollias et al. 2016, chapter 17) had become ARM's signature contribution to the evaluation of GCM cloud parameterizations. That year ARM conducted its first full-scale tropical IOP in Darwin, Australia, the Tropical Warm Pool–International Cloud Experiment (TWP-ICE; May et al. 2008). During TWP-ICE, Darwin experienced changes in weather regime that are characteristic of the Australian winter monsoon season: an active monsoon period of onshore flow and extensive rain; a suppressed monsoon period with drier midlevel conditions and isolated, moderate depth convection; an even drier fully suppressed period of mostly clear skies; and a monsoon break period of building instability and occasional but vigorous deep convection. These regime shifts provided an ideal opportunity to test model convection behavior, and intercomparisons of SCMs (Davies et al. 2013), CRMs (Varble et al. 2011; Fridlind et al. 2012), and GCMs (Lin et al. 2012) followed.

Before TWP-ICE, convective entrainment had been identified as a glaring shortcoming of cumulus parameterizations. This was based on a GCSS case study of the ARM summer 1997 IOP (Guichard et al. 2004) that showed that SCMs triggered continental deep convection too early in the day and a tropical ocean case study (Derbyshire et al. 2004) that showed that CRM convection depth was much more sensitive to environmental humidity in CRMs than SCMs. This behavior was traced to weak entrainment, a remnant of early cumulus parameterization history in which simulating convection that reached the tropopause was one of the few observational constraints. ARM ARSCL data at the Nauru Island site had verified that the depth of cumulus congestus was indeed sensitive to midtropospheric humidity (Jensen and Del Genio 2006).

By the time of TWP-ICE, the GISS GCM was using the Gregory (2001) entrainment parameterization, which is based on convective turbulence scalings. The Gregory scheme diagnoses updraft speed w and parameterizes entrainment ε as a function of parcel buoyancy B and updraft speed: $\varepsilon = CB/w^2$. The proportionality constant C indicates the fraction of buoyant turbulent kinetic energy available for use by entrainment. TWP-ICE data documented the more maritime character of active period convection (lower radar reflectivities and less graupel above the melting level, less lightning) relative to the stronger, more continental convection during the break period. Wu et al. (2009) showed that the Weather Research and Forecasting (WRF) Model, run at convection-resolving resolution, simulated stronger updraft speeds during the break period than during the active period, consistent with the indirect observational inferences.

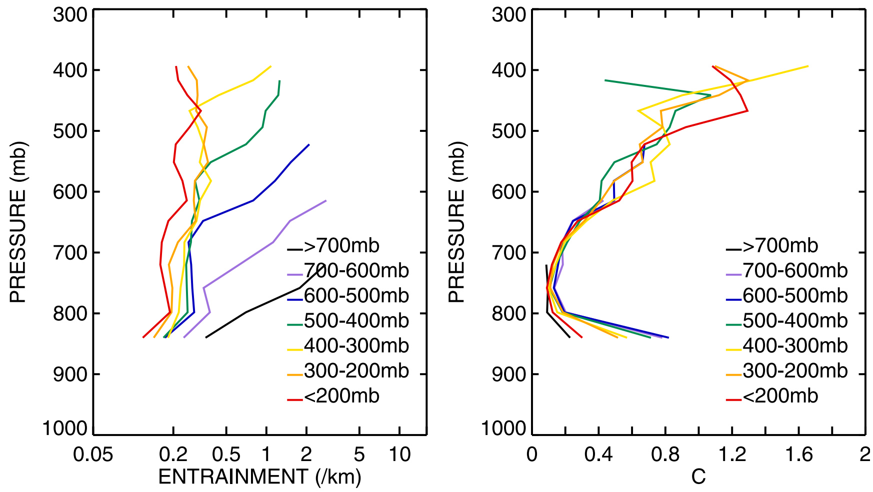

FIG. 26-2. (left) Entrainment rates inferred from the moist static energy profile within convective columns penetrating to different pressure levels, as simulated by the WRF Model for the TWP-ICE break period (Del Genio and Wu 2010). (right) Parameterization test from the same simulation showing that a single vertical profile of the proportionality constant in the Gregory (2001) entrainment parameterization works generally for all types of convection.

Del Genio et al. (2007) implemented the Gregory parameterization in the GISS GCM, with different values of the proportionality constant to represent more- and less-entraining parts of the cumulus spectrum. The parameterization was evaluated by Wu et al. (2009) in SCM tests against the WRF-derived TWP-ICE updraft speeds. The SCM reproduced the difference in convection strength between the active and break periods but overestimated updraft speeds in the upper troposphere. A WRF study of the TWP-ICE break period diurnal cycle tested various proposed parameterizations of entrainment (Del Genio and Wu 2010). The entrainment rate inferred from the thermodynamic structure in convecting grid boxes decreased over the afternoon as shallow convection gradually gave way to congestus and then predominantly deep convection (Fig. 26-2, left panel). To see whether these variations were consistent with the Gregory scheme, w, B, and ε were derived from the WRF fields and the implied values of C for different convection depths calculated from these. The results (Fig. 26-2, right panel) suggest that a single profile of C applies to convection of varying depths, except near cloud base, where the deeper events have smaller C than the shallow events. This suggests that the Gregory scheme is, in general, a good predictor of entrainment but that the SCM shortcomings seen by Wu et al. (2009) may be due to changes in convective parcel properties that the Gregory scheme by itself cannot anticipate (e.g., larger parcel sizes or nonturbulent sources of lifting as convection deepens). If so, then the operational GISS GCM approach of allowing weakly and strongly entraining plumes (smaller and larger C) to coexist at all times needs to be reconsidered. Tests with the cold pool parameterization (Del Genio et al. 2013), in which the less-entraining plume exists only after cold pools form, is more in keeping with the WRF inferences and produces some improvement, but entrainment remains an ongoing focus of research.

5. The role of ARM in improving the GFDL model

During the ARM era, the AGCM of the GFDL has undergone extensive development. The ARM data were particularly important for the research that led from the earlier version of the model, called the Atmospheric Model version 2 (AM2), to the newer version, called AM3.

As described above, observations of temperature and moisture advection, and their refinement to provide forcing for SCMs, were among the key achievements of ARM during the late 1990s. In addition to forcing observations, ARM has provided increasingly comprehensive characterization of other aspects of the atmospheric state, including important details of the microphysical and dynamical structure of clouds. In-cloud vertical velocities for both shallow and deep convective systems have recently become available, based on profiling and multiple Doppler radars (Collis et al. 2013). These observations have been used to evaluate and develop parameterizations for clouds and convection in GFDL models, with the goal of driving cloud microphysics and aerosol–cloud interactions with physically realistic vertical velocities.

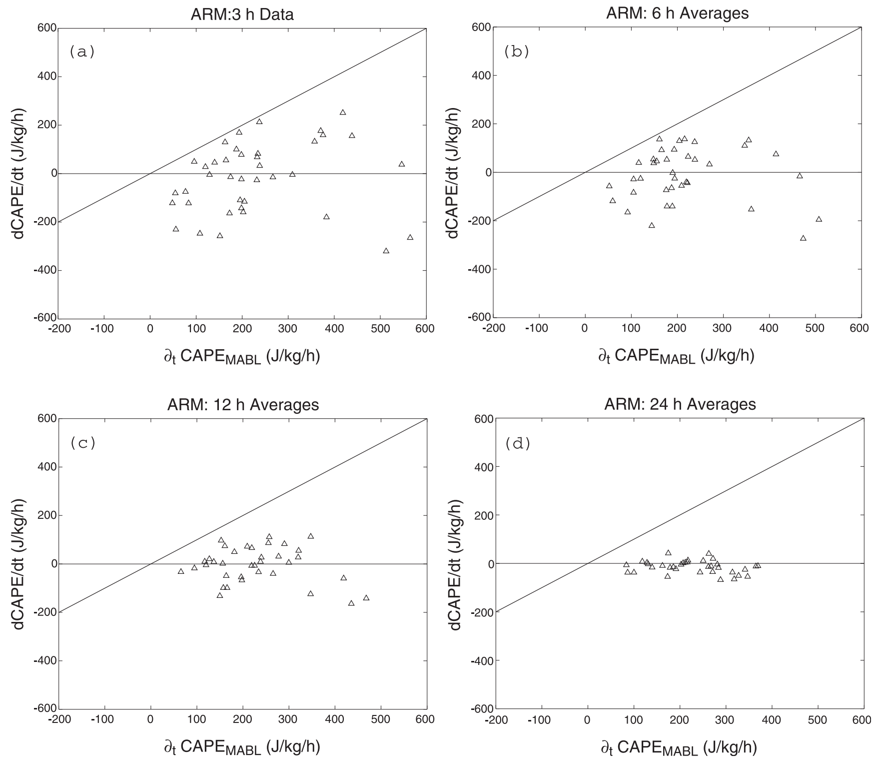

FIG. 26-3. Observations from the ARM SGP site have been used to examine quasi equilibrium for deep convection (Donner and Phillips 2003). Under quasi equilibrium, the rate at which CAPE changes, plotted on the vertical axis, should be small relative to the rate at which CAPE changes by advection averaged over large spatial scales and by boundary layer processes, plotted on the horizontal axis. At the ARM SGP, quasi equilibrium holds over daily time averages, but less so over shorter, subdiurnal periods. A consequence is that cumulus parameterizations using quasi-equilibrium closures often do not simulate the diurnal cycle of convection well. Results like these have motivated the development of closures that recognize the importance of nonequilibrium convection (Bechtold et al. 2014).

An ongoing challenge for the evolving GFDL climate models has been triggering and closure for cumulus parameterizations. Donner and Phillips (2003) used observations of changes in convective available potential energy (CAPE) due to boundary layer processes and large-scale-average advective tendencies from the ARM SGP site and other field programs focused on deep convection to provide empirical guidance for choosing closures for cumulus parameterization (Fig. 26-3). Fast changes in CAPE tied to boundary layer processes were found to violate quasi equilibrium, and a closure excluding boundary layer contributions to CAPE change was more consistent with ARM SGP observations, though not with observations from some of the other field programs. Benedict et al. (2013) incorporated this closure into GFDL AM3 (Donner et al. 2011) and found that it substantially improved AM3's simulation of tropical variability, including the MJO.

Both AM2 and AM3 use stochastically generated subcolumns to represent cloud structure, especially vertical overlap for clouds and radiation (Pincus et al. 2006). Its implementation was supported by ARM, as was much of the research that underpins the approach, including studies of the nonlinear effects of cloud heterogeneity on cloud microphysics (Pincus and Klein 2000), analysis of cloud overlap in CRMs (Pincus et al. 2005), analysis of total water variance and skewness in CRMs (Klein et al. 2005), and analysis of observed cloud heterogeneity at the SGP site (Kim et al. 2005).

AM3's parameterizations for shallow and deep convection provide multivariate probability density functions (PDFs) for in-cloud dynamics, thermodynamics, and microphysics. Vertical velocities play an especially important role in activating aerosols and the subsequent microphysical evolution of clouds, with important implications for cloud–aerosol and cloud–radiative interactions. The vertical-velocity PDFs in the Donner (1993) deep cumulus parameterization used in AM3 have been subject to only limited observational constraints, but the emergence of ARM vertical-velocity observations (Collis et al. 2013) will permit considerably more robust evaluation and enable further development of this parameterization approach.

AM3 includes PDFs of stratiform vertical velocity for aerosol activation, taken as normally distributed with a standard deviation related to turbulence. Experiments in AM3 with multivariate PDFs for stratiform clouds and boundary layers using higher-order closure with an assumed distribution have shown promising prospects for improving simulation of marine stratocumulus clouds (Guo et al. 2010) and aerosol–cloud interactions involving turbulence and cloud dynamics (Guo et al. 2011). PDFs of vertical velocity from ARM cloud radars at the ARM SGP site have been compared with those from AM3 and a modified version of AM3 that uses the boundary layer and cloud parameterizations of Guo et al. (2010). The latter agree with ARM radar observations in producing a binormal vertical-velocity PDF, in contrast to the normal distribution in AM3.

Relative to AM2 and AM3, GFDL's highest-resolution models adopt simplified parameterizations for cumulus convection and stratiform clouds. The simplified PDF cloud parameterization was developed with ARM support (Zhao et al. 2009).

AM2 (Anderson et al. 2004) has been evaluated extensively by comparing SCM integrations against ARM observations for deep convection at the SGP site during June 1995 and June–July 1997 (Xie et al. 2002), midlatitude stratiform frontal clouds at the SGP site (Xie et al. 2005), and mixed-phase clouds during M-PACE (Klein et al. 2009). AM2 also has been evaluated against ARM observations by integrating it in forecast (CAPT) mode for M-PACE (Xie et al. 2008); the Tropical Ocean Global Atmosphere Coupled Ocean–Atmosphere Response Experiment (Boyle et al. 2008); the east Pacific Investigation of Climate Cruise (Hannay et al. 2009); and, along with AM3, TWP-ICE (Lin et al. 2012). Simulations of cloud fraction and precipitation in AM2 and AM3 SCMs also have been compared against observations at the ARM SGP site (Song et al. 2013). These evaluations have yielded many insights on the behaviors of AM2 and AM3. For example, the summer forecast experiments using SGP observations revealed AM2's warm bias in that region to be due to its inability to simulate enough precipitation and not due to deficient soil moisture or unrealistic radiation (Klein et al. 2006). In another example, the forecast experiments during the dry period of TWP-ICE suggested that sensitivity of the cumulus parameterization to free-tropospheric humidity was important for successful simulation. Experiments with increased dependence of convective entrainment on humidity are currently underway at GFDL.

6. Concluding discussion

The main subject of this chapter is ARM's influence on climate model development. ARM has directly funded model development activities, and it has collected data that make it possible to test the models in ways that could only be dreamed of before ARM started.

We have presented a few examples to show how ARM data have led to improvements in climate models. Additional examples are provided in other chapters of this monograph (e.g., Ghan and Penner 2016, chapter 27).

It is important to recognize that the process that leads from data collected in the field to improvements in climate simulations is not at all straightforward or even predictable. The record shows that ARM data have suggested ideas, supported ideas, and ruled out ideas. Modelers have been challenged to devise ways of using the data to test the models, for example through the SCM strategy, which took years to develop and is still evolving. Climate modelers continue to use data collected in the early stages of the ARM Program, as well as the more detailed data collected later in the program. ARM will continue to influence climate model development and evaluation for many decades to come.

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