UCRL-MI-224010
ARM-06-012

ARM's Support for GCM Improvement: A White Paper

Stephen A. Klein, Anthony Del Genio

August 25, 2006

Disclaimer

This work was performed under the auspices of the U.S. Department of Energy by University of California, Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.

ARM's Support for GCM Improvement

A White Paper

October 2004

Stephen A. Klein
Lawrence Livermore National Laboratory
Livermore, California

Anthony Del Genio
NASA-Goddard Institute for Space Studies
New York, New York

Introduction

The Atmospheric Radiation Measurement (ARM) program has been operating for approximately 10 years collecting data related to radiation and clouds at three primary sites – the Southern Great Plains (SGP) of the USA, the North Slope of Alaska, and the Tropical West Pacific (Ackerman and Stokes 2003). A key goal of the ARM program is to use this increased observational database to improve the representation of clouds and related processes in Global Climate Models (GCMs). This is a high priority for the U. S. Global Change Research Program because uncertainties in the representation of clouds and their sensitivities are largely responsible the high degree of uncertainty associated with the magnitude of climate change induced by human modification of carbon dioxide, other trace gases, and aerosols.

In this white paper, the progress towards this goal is reviewed. This progress can be divided into two parts – methodologies which allow modelers to use the data collected by ARM and actual improvements in climate models made by ARM supported scientists. Four examples of these GCM improvements are discussed in detail.

Before detailing this progress, some perspective is needed. ARM has been collecting data for approximately 10 years – a scientifically short period of time. For any new data to have a marked impact, it must (a) exist for a sufficiently long period of time to be climatically representative, (b) be quality-controlled and used by people for a long enough time for them to understand its strengths and weaknesses, and (c) speak to something that the modeling community has been or should be worrying about. In addition, the ARM approach to data collection was new and entailed the use of new instruments, such as the millimeter wavelength cloud radar. Thus, much of the early science effort was devoted to understanding instrument performance, improving measurement accuracy, and developing methods to retrieve physical quantities of interest from the measurements. The ARM program has matured to the point that the data are now primed to be used by modelers.

Viewed in this way, the actual improvements in GCMs detailed below may seem modest – but this should not be the case in the next 5 years. This significant delay between data collection and model improvement has been true of other experiments and data production programs. There is no reason to think that ARM would be exempt from this experience.

Connecting Data to GCMs

Given the nature of the data collected by ARM – detailed observations from a few fixed sites, it was not obvious how to connect the data to climate models which do not directly forecast the day-to-day weather. ARM has been extraordinarily successful in developing methodologies to apply data to climate model questions. The key technique that ARM has used is the Single Column Model (SCM) approach (Randall et al. 1996). The SCMs represent the column physics of the GCMs – this physics includes the cloud, turbulence, and convection parameterizations which are the most uncertain parts of the GCM and which are the major source of uncertainty to climate change (Figure 1). In the SCM approach you give the model the initial state above an ARM site and the dynamical tendencies from observations and then simulate the response of the column physics. The clouds, radiation, and other things predicted by the SCMs can then be directly compared to the observations taken by ARM. This directly overcomes the problem that GCMs lack the complicated data assimilation schemes that numerical weather predictions centers (e.g., NCEP or ECMWF) use to simulate day-to-day weather.

Another significant advantage of this approach is that Cloud Resolving Models (CRMs) can be run in the same way as SCMs. CRMs are limited area models with typical horizontal resolutions of 1 kilometer which "resolve" the clouds directly (Figure 2). While they still contain parameterizations of significant uncertainty (e.g. cloud microphysics), they may be used with care to study cloud processes and assess errors in the SCM cloud parameterizations.

The challenging part of this modeling strategy is the analysis of observations to determine the dynamical forcing. The dynamical forcing represents the impact of flow into and out of the single column which can be thought of as the horizontal size of a GCM grid cell. The analysis effort has focused on Intensive Observing Periods (IOPs) that have occurred at the ARM SGP site in Oklahoma. The analysis method, developed by ARM scientist Prof. Minghua Zhang (SUNY-Stonybrook), performs small adjustments to the data consistent with measurement uncertainties so that the physical conservation laws of mass, momentum, heat and moisture are obeyed and consistent with the observations of the radiation leaving the column and precipitation falling out of the column (Zhang and Lin 1997, Zhang et al. 2001). This has been very successful and this method is now the community standard for analysis methods and is being applied to other field campaigns (e.g. TOGA-COARE).

An example of this methodology is shown in Figures 3 and 4. Figure 3 shows the observations from a careful analysis of the measurements taken by the millimeter wavelength cloud radar, lidar, and ceilometers that ARM has been operating continuously at the SGP site since 1996. The ARM data shows the evolution over 2 days of the height profile of 3-hour averaged cloud occurrence, and cloud liquid and ice water mass mixing ratio. This data are the output of complicated retrieval algorithms ARM has developed to analyze the raw output that the instruments collect (Clothiaux et al. 2000, and many others). While considerable uncertainty remains in these algorithms, these ARM retrievals are extremely valuable because current satellites cannot resolve the vertical distribution of clouds – they typically only sense the highest cloud layer. [The CloudSat and Calipso instruments to be launched into space in 2005 will provide a partial solution this problem. (Stephens et al. 2002)]. ARM scientists are currently processing the multi-year dataset that has been collected at the SGP and the other ARM sites in Alaska and the Tropical West Pacific. These extended records of cloud properties can be combined with extended analyses of forcing to yield improved knowledge of how clouds vary with the large-scale environment (Xie et al. 2004a). As this is achieved in the next few years this data will be extremely important. As is shown in Figure 4, SCMs run with the forcing produced by ARM yield very different distributions of cloud liquid water (or ice water). [Note that for this frontal cloud case 2-dimensional CRMs are not superior (Figure 5) suggesting that care should be exercised in deciding when to trust CRMs.] The ARM data should be very useful in weeding out model parameterizations *in both SCMs and CRMs* which produce unrealistic cloud simulations.

Examples of GCM improvements

Improved Radiative Transfer Parameterizations

It is no surprise that a program with radiation in its title would have produced improvements to radiative transfer modeling. ARM measurements and field campaigns have been central to reducing the remaining uncertainties of radiative transfer modeling – specifically the parameterization of the amount of longwave radiation absorbed by the water vapor continuum (Clough et al. 1989; Mlawer et al. 2004) or the amount of solar radiation absorbed by clouds (Ackerman et al. 2003). (Some uncertainties still remain such as the representation of the 3 dimensional effects of cumulus clouds on radiative transfer.) These reduced uncertainties have been encapsulated in a radiative transfer model developed by Dr. Tony Clough and his collaborators at AER. This radiative transfer model, known as RRTM, includes a significant computation advance as well. The amount of computer time needed for the normal method used to compute longwave radiative transfer increases as the square of the number of model levels – that is a doubling of the number of vertical levels would require four times as many computations. As GCMs are increasing the number of levels to better resolve many processes (e.g. boundary layer or stratosphere-troposphere interactions), the increased computational burden of radiative transfer will be unacceptable as radiation codes already consume about 20-40% of a GCM's computational intensity. The advance in RRTM is the use of new methods which increase only linearly with the number of vertical levels in a model. This is so attractive that RRTM has been incorporated into the weather prediction model of the ECMWF which now has 60 vertical levels. The RRTM longwave code has also been incorporated in the latest version of the GCM of the Max Planck Institute for Meteorology in Hamburg Germany (this model is known as ECHAM5). The benefit of better radiative transfer is not limited to these two models. The parameterization of the water vapor continuum developed by Tony Clough which has been tested carefully against ARM measurements has been incorporated in radiation codes for several GCMs including those from the NCAR and GFDL.

Cloud Overlap and the Representation of Clouds in GCM Radiative Transfer Models

Because the horizontal resolution of GCMs is much coarser than the scale of clouds, GCMs parameterize the fractional area of a grid box that contains clouds. Because the cloud fraction is determined at every vertical level of a GCM, this poses an uncertainty for radiative transfer. For example, if the cloud fraction of a high and low cloud in the same grid box is 50%, does the high cloud overlap the low cloud or do they exist in separate parts of the grid box? The assumption made about this – called the 'cloud overlap' assumption – is rather uncertain and impossible to verify until the advent of cloud radars which determine the vertical distribution of clouds (Figure 3). The ARM cloud radar record is now long enough to determine the appropriate cloud overlap assumption.

The observational analyses show that clouds are more maximally overlapped if the vertical distance separating two cloud layers is decreased. Conversely as the vertical separation distance increases, clouds tend to be randomly overlapped (Hogan and Illingworth 2000; Mace and Benson-Troth 2002). Because the transition between these two overlap types is usually smooth, it is useful to parameterize the degree of cloud overlap as a function of the physical separation distance of model levels. Doing this in a GCM represents an improvement over the currently popular "maximum-random" overlap assumption which states that clouds in adjacent layers are maximally overlapped and clouds separated by clear layers are randomly overlapped. The improvement occurs because the degree of overlap in the "maximum-random" assumption depends on how the models vertical coordinate is discretized through the "adjacent" layers criterion. If you add more vertical levels between the same physical distance, the degree of overlap would artificially change. The new parameterization based on the cloud radar observations uses the actual physical separation distance of model levels which is therefore insensitive to how many vertical levels separate a given physical distance in the atmosphere. This new parameterization is currently being adopted by several GCMs (e.g. GFDL). In addition, new methodologies have been developed by ARM scientists to represent this new cloud overlap parameterization statistically in GCMs (Pincus et al. 2003).

While these improvements are important, the major uncertainties in the representation of clouds and their radiative impacts are probably not contained in these areas. The greater uncertainty is associated with providing the correct clouds for radiation calculations. This in turn is dependent on the other physical parameterizations of clouds, convection, and turbulence. The following two examples touch on these uncertainties.

Representing the Aerosol Indirect Effect in GCMs

While future radiative forcing of climate by carbon dioxide may dominate that by aerosols, the interpretation of climate change over the 20th century is complicated by the uncertainty associated with the impact of aerosols on clouds.

The indirect effect of aerosols is that an increase in aerosol abundance (which has resulted from industrialization), may be expected to lead to a greater number of cloud condensation nuclei - the sites on which clouds form. If there are greater abundances of cloud condensation nuclei, then there will likely be a greater number of cloud droplets formed when water vapor is condensed in updrafts. Because the total mass of water condensed into clouds is controlled by thermodynamics, a greater number of droplets for the same mass of cloud water means that the average size of the cloud droplets will be smaller. This has two important effects. The first is that smaller drops leads to more reflective clouds, which tends to cool the climate system. The second effect is that smaller droplets will be less likely to produce drizzle or rain. As a result the cloud will live longer which also tends to produce a cooling of the system. The degree to which these effects occur in nature is a topic of great uncertainty.

Representing this effect in GCMs is complicated because it is requires two new parameterizations. The first parameterization relates aerosol properties to the number of cloud droplets nucleated at cloud base. The second parameterization describes the evolution of cloud drop number as processes other than nucleation also affect its evolution. A successful form of both these parameterizations has been developed by ARM researcher Dr. Steven Ghan (PNL) (Ghan et al. 1997, Abdul-Razzak and Ghan 2000). These parameterizations have been tested in ARM SCM simulations with a modified version of the NCAR SCM and shown to produce sensitivities to aerosol similar to those simulated by a CRM which should be expected to produce a more realistic simulation of this effect (Ovtchinnikiov and Ghan 2004). These parameterizations have also been tested in the NCAR GCM CAM3 and they have been shown to produce a realistic simulation of the mean climate (Ghan 2004). Although these parameterizations are not part of the default CAM3, if NCAR were to adopt these parameterizations, it would be able to treat the indirect effect of aerosols – something the current CAM3 does not.

Improving GCM Deep Convection Parameterizations

The deep convection parameterization of GCMs is perhaps the parameterization with the greatest uncertainty in how to represent it. The ARM program has devoted many IOPs to observing deep convection over the SGP site and the resultant data has provided new insights into how deep convection behaves.

Through an intercomparison study, scientists using the NCAR SCM noticed that the frequency of deep convection in their model was far greater than that observed. Specifically, the deep convection scheme would convect nearly every afternoon when it diagnosed convective instability. However, in the real world the presence of instability is not sufficient for convection to occur; usually convection over the SGP requires a large-scale disturbance to initiate. ARM scientist Prof. Guang Zhang (UCSD) analyzed the observations collected by ARM and from this deduced a new convective trigger and closure parameterization (Zhang 2002) (The closure parameterization is that which determines how much precipitation occurs in a given convective event.) Other ARM scientists Dr. Shaocheng Xie and Prof. Minghua Zhang developed a convective trigger similar to that proposed by Prof. Guang Zhang. This modified convective trigger was implemented into the NCAR SCM and was shown to yield an improve simulation (Xie and Zhang 2000). To then test this parameterization in the full GCM, Dr. Xie made use of another DOE project – the CCPP-ARM Parameterization Testbed project in which climate models are integrated as forecast models (Phillips et al. 2004). Two noticeable improvements in the forecasts with Xie's parameterization were a reduction of the "double" Intertropical Convergence Zone problem and a reduced incidence of tropical cirrus clouds (as a result of the greater inhibition applied to the deep convection parameterization) (Xie et al. 2004b). As climate integrations with this parameterization also appear successful, this parameterization would seem to be ready for adoption by NCAR into the core model.

Final comments

The ARM program is now producing datasets of great value to the modeling community and has developed several methodologies to apply these data to climate model evaluation. Of particular note are the existing multi-year observations of the effects of clouds on the surface radiation budget and the vertical distributions of cloud occurrence and incipient observations of cloud microphysics – cloud water mass and characteristic cloud drop sizes. In combination with the SCM forcing datasets which are being extended in time, ARM scientists can now test new parameterization ideas and rule out unrealistic cloud parameterizations. It is expected that the next 5 years will yield many more examples of climate model improvements than those listed in this white paper. Because the ARM data are freely available to the broad scientific community, we also expect that some of these improvements will come from uses of ARM data by scientists not directly funded by ARM. In addition, ARM is developing a new mobile facility that will produce new datasets in under-sampled regions of the globe which will also promote testing and evaluation of model simulations of the climate of these areas. It is thus expected that ARM efforts in the coming years will play a significant role in reducing uncertainties associated with the representation of clouds in GCMs.

Acknowledgements. *This paper was motivated by a meeting of the sub-committee on Global Change Research Programs of the DOE Office of Science Biological and Environmental Research Advisory Committee (BERAC). The meeting dealt with the question of how DOE should invest in the "super-parameterization" modeling approach. Tom Ackerman, Bill Collins, Steve Ghan, Jean-Jacques Morcrette, and Hualu Pan are thanked for their input.*

References

Abdul-Razzak, H. and S. J. Ghan, 2000: A parameterization of aerosol activation. 2. Multiple aerosol types. *J. Geophys. Res.*, **105** (D5), 6837-6844.

Ackerman, T. and G. Stokes. 2003: The Atmospheric Radiation Measurement Program. *Physics Today*, **56**, 38-45.

Ackerman, T. P., D. M. Flynn, and R. T. Marchand, 2003: Quantifying the magnitude of anomalous solar absorption. *J. Geophys. Res.*, **108** (D9), 4273, doi: 10.1029/2002JD002674.

Clough, S. A., F. X. Kneizys, and R. W. Davies, 1989: Line shape and the water vapor continuum. *Atmos. Res.*, **23**, 229-241.

Clothiaux, E. E., and co-authors, 2000: Objective determination of cloud heights and radar reflectivities using a combination of active remote sensors at the ARM CART sites. *J. Appl. Met.*, **39**, 645-665.

Ghan, S. J., L. R. Leung, R. C. Easter, and H. Abdul-Razzak, 1997: Prediction of cloud droplet number in a general circulation model. *J. Geophys. Res.*, **102**, 21,777-21,794.

Ghan, S. J., 2004: Prediction of cloud droplet number in CAM. Presentation to the 2004 Spring Meeting of the NCAR Atmosphere Model Working Group.

Hogan, R. J. and A. J. Illingworth, 2000: Deriving cloud overlap statistics from radar. *Q. J. Roy. Met. Soc.*, **126** (569), 2903-2909.

Mace, G. G. and S. Benson-Troth, 2002: Cloud-layer overlap characteristics derived from long-term cloud radar data. *J. Clim.*, **15** (17), 2505-2512.

Mlawer, E. J., D. C. Tobin, and S. A. Clough, 2004: A revised perspective on the water vapor continuum: the MT_CKD model, in preparation.

Ovtchinnikov, M. and S. J. Ghan, 2004: Parallel simulations of aerosol influence on clouds using a cloud resolving model and a single column model. *J. Geophys. Res.*, in press.

Phillips, T. J., G. Potter, D. L. Williamson, R. Cederwall, J. Boyel, M. Fiorino, J. Hnilo, J. Olson, J. J. Yio, and S. Xie, 2004: Evaluating parameterizations in general circulation models: Climate simulation meets weather prediction. *Bull. Amer. Met. Soc.*, **84**, in press.

Pincus, R., H. W. Barker, and J. J. Morcrette, 2003: A fast, flexible, approximate technique for computing radiative transfer in inhomogeneous cloud fields. *J. Geophys. Res.*, **108** (D13), 4376, doi:10.1029/2002JD003322.

Randall, D. A., K.-M. Xu, R. J. Somerville, and S. Iacobellis, 1996: Single-column models and cloud ensemble models as links between observations and climate models. *J. Clim.*, **9**, 1683-1697.

Stephens, G. L., and co-authors, 2002: The CloudSat Mission and the A-train. *Bull. Amer. Met. Soc.*, **83**, 1771-1790.

Xie, S. and M. Zhang, 2000: Impact of the convection triggering functioin on single-column model simulations. *J. Geophys. Res.*, **105** (D11), 14983-14996, doi:10.1029/2000JD900170.

Xie, S., R. T. Cederwall, and M. Zhang, 2004a: Developing long-term single-column model/cloud system-resolving model forcing data using numerical weather prediction products constrained by surface and top of the atmosphere observations. *J. Geophys. Res.*, **109**, D01104, doi:10.1029/2003JD004045.

Xie, S., M. Zhang, J. S. Boyle, R. T. Cederwall, G. L. Potter, and W. Lin, 2004b: Impact of a revised convective triggering mechanism on the Community Atmosphere Model Version 2 simulations: Results from short-range weather forecasts. *J. Geophys. Res.*, **109,** D14102, doi:10.1029/2004JD004692.

Zhang, G. J., 2002: Convective quasi-equilibrium in midlatitude continental environment and its effect on convective parameterization. *J. Geophys. Res.*, **107** (D14), 4220, doi:10.1029/2001JD001005.

Zhang, M. H., and J. Lin, 1997: Constratined variational analysis of sounding data based on column-integrated budgets of mass, heat, moisture, and momentum: Approach and application to ARM measurements. *J. Atmos. Sci.*, **54**, 1503-1524.

Zhang, M. H., J. L. Lin, R. T. Cederwall, J. J. Yio, and S. C. Xie, 2001: Objective analysis of ARM IOP Data: Method and sensitivity. *Mon. Wea. Rev.*, **129**, 295-311.

Figure 1. Illustration of a Single Column Model (SCM). An SCM represents the evolution of the atmosphere in a single grid box of a Global Climate Model (GCM). To run an SCM, you give the SCM the horizontal flow of mass, water, and energy in and out of the single point and the physical parameterizations of the GCM computes the evolution of clouds and other properties. When the horizontal flow is specified from observations, the SCM can be directly compared to the observations from a fixed point. This matches the observing strategy of ARM which takes intense observations from a few fixed sites.

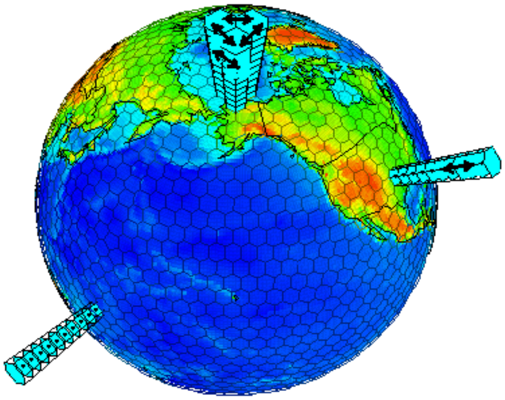

Figure 2. Illustration of a cloud field from a Cloud Resolving Model (CRM). A CRM is a limited area model which typically has horizontal resolutions of one kilometer. When a CRM is driven with the same observed horizontal flow as is used to drive SCMs, the output of the two models may be directly compared to each other and ARM data. While CRMs still contain parameterizations of great uncertainty (e.g. cloud microphysics and small-scale turbulence) and therefore should not be thought of as “ground-truth”, they may carefully be used in some circumstances to diagnose errors in GCM parameterizations.

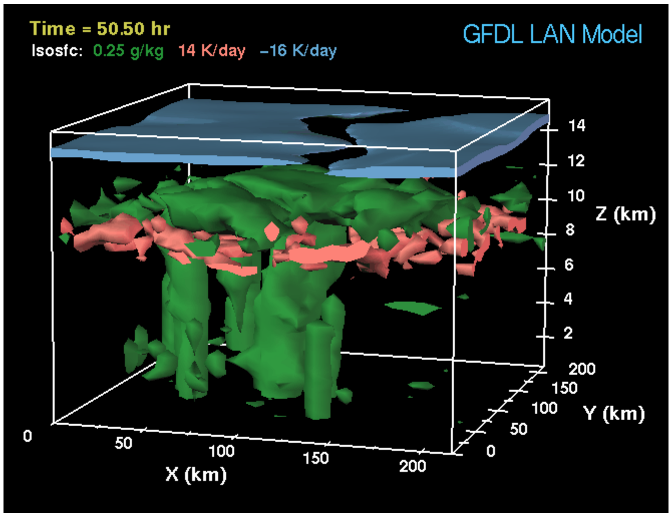

Figure 3. The time evolution of the vertical profiles of cloud amount (top) in percent, cloud liquid (middle) and cloud ice (bottom) water mixing ratios in grams of condensate per kilogram of air as retrieved from ARM cloud radar observations over ARM's Southern Great Plains site on March 2-3, 2000. The vertical profiles of cloud occurrence and cloud condensate mixing ratios are extremely valuable to SCM and CRM modelers who have not previously had access to such data.

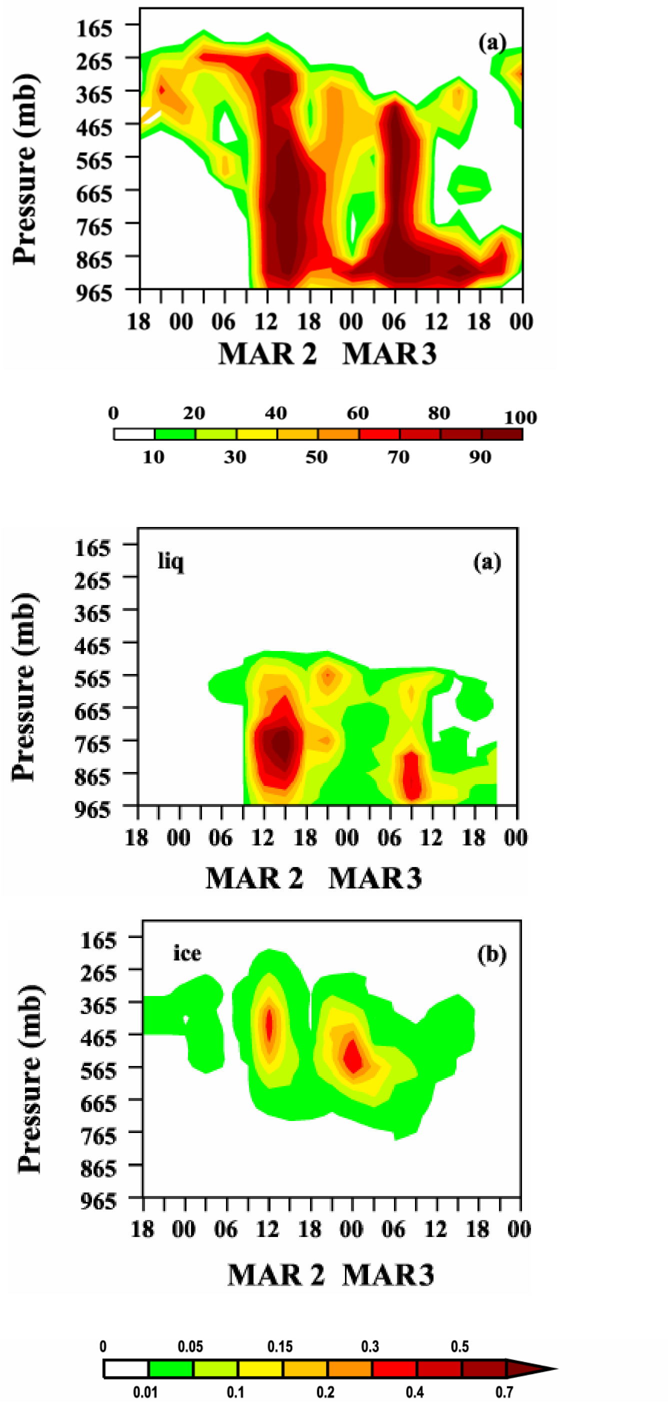

Figure 4. The time evolution of cloud liquid water mixing ratio as simulated by 9 SCMs on March 2-3, 2000. These simulations should be directly compared to the middle panel of Figure 3. The SCMs give variable liquid water contents underscoring why GCMs often give variable responses of clouds to climate change. The continued use of ARM observations will be very useful to improve these models and hopefully reduce the uncertainty associated the response of clouds to climate change.

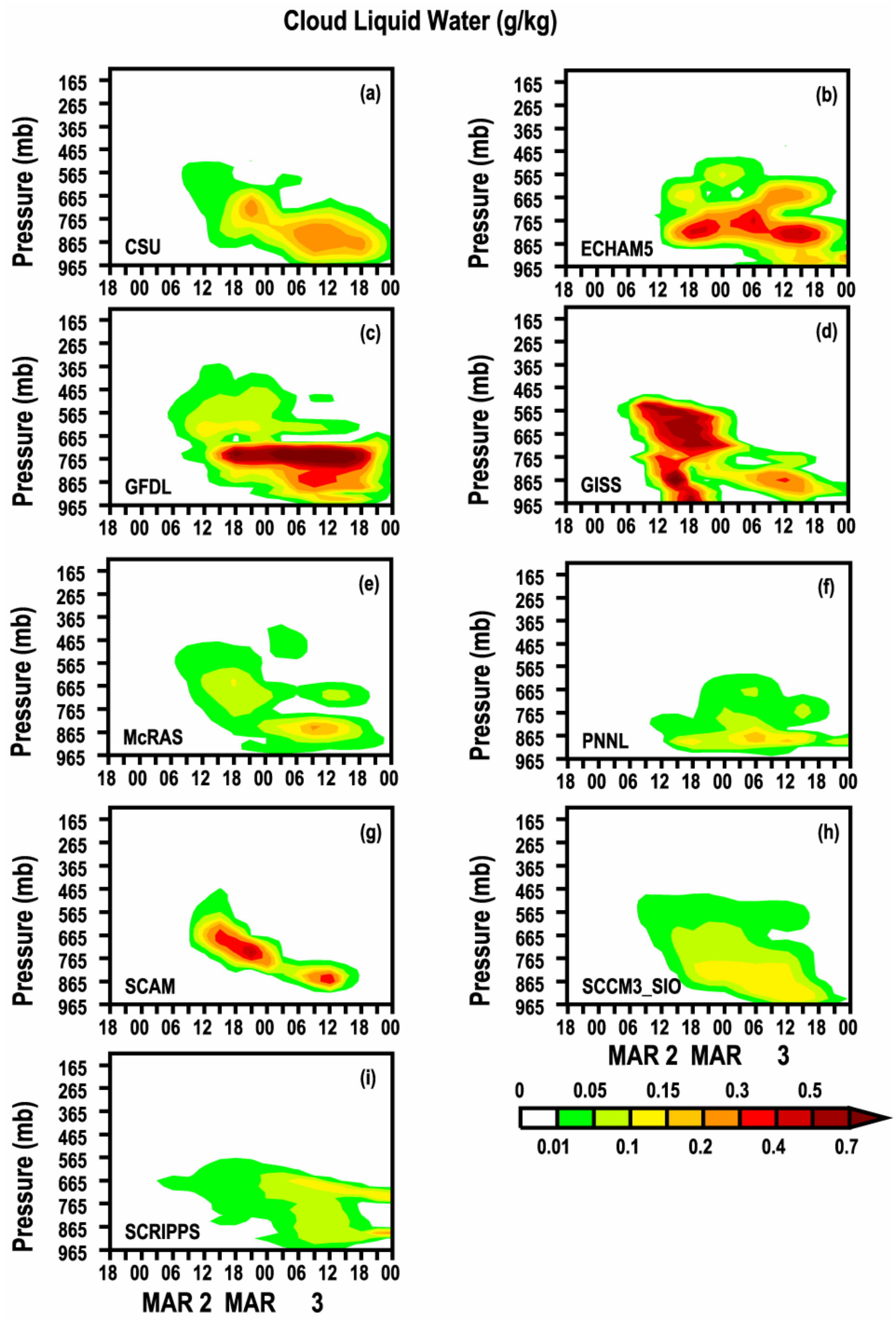

Figure 5. The time evolution of cloud liquid water mixing ratio as simulated by 4 CRMs on March 2-3, 2000. These simulations should be directly compared to the middle panel of Figure 3.