Cloud Parameterization and Modeling Working Group Accomplishments

Development of the means for climate and cloud resolving models to simulate the conditions at all ARM sites

A challenge for ARM has been relating data taken at a few points to global climate model simulations. The program has taken the lead in the development of “forcing” datasets that permit single-column versions of the climate models (Figure 1) and cloud resolving models (Figure 2) to simulate the weather that occurs at the ARM sites and thus permit direct comparison of model simulations to observations. A “forcing” dataset quantifies the impact of the regions adjacent to the ARM site on conditions at the ARM site.

Previous work had produced “forcing datasets” only for Intensive Observing Periods at the SGP site. These IOPs were costly due to the requirement of frequent measurements from an array of sounding stations that enclose the ARM site. A recent development has been the creation of forcing datasets for the SGP that do not require Intensive Observing Periods *[Xie et al. 2004a]*. Three years of data has been created that permit the evaluation of single-column and cloud resolving models in a statistical way against ARM data. A statistical evaluation is necessary because ARM instruments typically measure only a small fraction of the area of a grid box at a single time *[Jakob et al. 2004]*. A second recent development has been the creation of the first forcing datasets for sites other than SGP. In particular, a dataset for the North Slope of Alaska site for the ARM Mixed-Phase Arctic Cloud Experiment (M-PACE) has been created *[Xie et al. 2006]*. Additionally a forcing dataset is currently being developed for the TWP Darwin site for the recently completed TWP-ICE experiment.

While single-column models are useful to evaluate new cloud parameterizations developed in the ARM program, it is necessary to understand the interactions of new parameterizations with atmospheric dynamics. This can only be done in the context of global integrations of a climate model. As a result, ARM (together with the DOE CCPP) created the CAPT program *[Phillips et al. 2004]* – a program that pioneered the use of climate models as weather prediction models. The CAPT program performs weather forecasts by integrating the climate models of NCAR and GFDL after they have been initialized with analyses from weather prediction centers such as NCEP, ECMWF, or the Goddard DAO. As an example, Figure 3 shows the vertical profile of clouds for the ARM NSA site during M-PACE as observed by the ARM remote sensors (“ARSCL”) and that as simulated by the NCAR and GFDL climate models. The CAPT program provides a direct way for scientists to use ARM data to test new parameterizations *[Xie et al. 2004b]*.

References

Jakob, C., R. Pincus, C. Hannay, and K. Xu (2004), Use of cloud radar observations for model evaluation: A probabilistic approach, *J. Geophys. Res.*, *109*, D03202, doi:10.1029/2003JD003473.

Phillips, Thomas J., Gerald L. Potter, David L. Williamson, Richard T. Cederwall, James S. Boyle, Michael Fiorino, Justin J. Hnilo, Jerry G. Olson, Shaocheng Xie and J. John Yio. (2004), Evaluating Parameterizations in General Circulation Models: Climate Simulation Meets Weather Prediction, *Bulletin of the American Meteorological Society*, *85*, 1903–1915.

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 Community Atmosphere Model, Version 2, simulations: Results from short-range weather forecasts, *J. Geophys. Res.*, *109*, D14102, doi:10.1029/2004JD004692.

Xie, S., S. A. Klein, M. Zhang, J. J. Yio, R. T. Cederwall, and R. McCoy (2006), Developing large-scale forcing data for single-column models and cloud-resolving models from the Mixed-Phase Arctic Cloud Experiment. *J. Geophys. Res.*, in press.

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 courtesy of Sam Iacobellis)

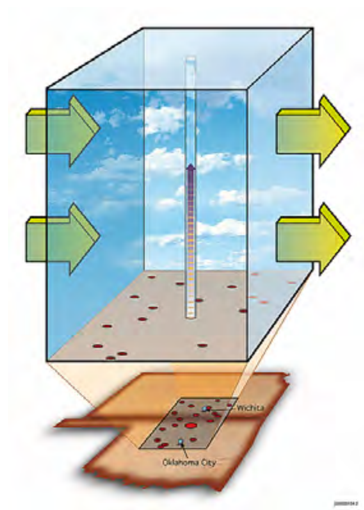


Figure 2. Illustration of a cloud field from a Cloud Resolving Model (CRM). A CRM is a limited area model which typically has horizontal resolutions of one kilometer. The figure shows the distribution of cloud condensate in green, and the strong radiative heating and cooling rates in red and blue, respectively, that occur because of the presence of the anvil cloud that is generated by deep convection. 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.

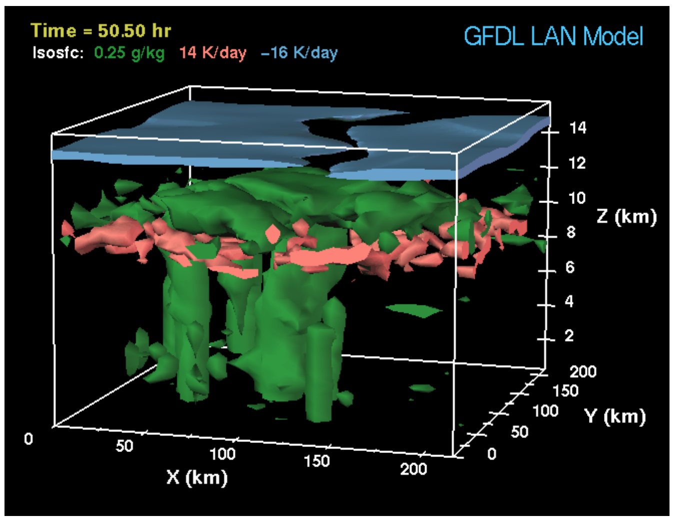
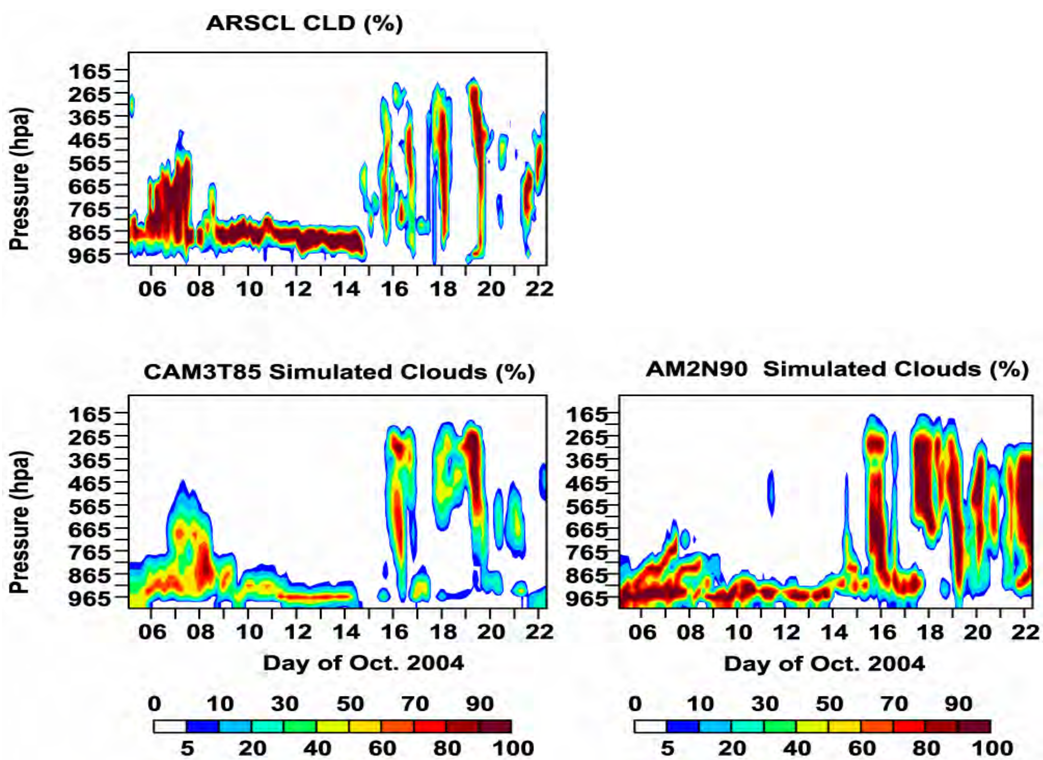


Figure 3. Illustration of the CAPT approach. CAPT facilitates the use of ARM data by the climate modeling community by integrating the climate models in weather prediction mode. This figure shows the time-height plots of cloud fraction from ARM observations (ARSCL CLD) and CAPT forecasts of the climate models of NCAR (CAM3T85) and GFDL (AM2N90) for October 2004 at ARM's Barrow, Alaska site. During this period, the ARM Mixed-Phase Arctic Cloud Experiment occurred. Note that the model output is plotted as a concatenated time series of data from hours 12 to 36 of forecasts that begin every day. (Figure courtesy of Shaocheng Xie)



Development of improved convection parameterizations for the NCAR climate model with use of ARM data

A key uncertainty for climate models is the representation of sub-grid scale cumulus convection. Existing parameterizations of convection are known to lead to significant model errors that hinder the application of climate models to many important problems. ARM-funded scientists have used ARM data to identify a problem with the convection scheme of the NCAR climate model and have developed modifications to that convection scheme which improve the model's climate.

Over the SGP site, summertime precipitation produced by the default convection scheme of the NCAR model occurs nearly every day contrary to the observations (Figure 1b). This occurs because the parameterization triggers convection whenever the atmospheric column is unstable to moist convection and convective available potential energy ("CAPE") is present. The observations clearly show that this condition is not sufficient (Figure 1a) for convective precipitation. ARM scientists developed modifications to this parameterization that also require that the large-scale circulation be generating CAPE for convection to occur *[Xie and Zhang 2000, Zhang 2002]*. Figure 1c shows that the time series of the rate of generation of CAPE by large-scale processes ("DCAPE") is well correlated with precipitation. ARM estimates of the effects of the large-scale circulation were computed from data ARM collected during the Intensive Observing Period that happened at this time. Figure 1d shows that the modifications of *Xie and Zhang [2000]* lead to a significantly improved simulation in the NCAR single-column model.

An improved simulation in a single-column model may not indicate actual improvement in the full global climate model. However, improvements have been noted with the modifications of *Xie and Zhang [2000]* in global climate model simulations in CAPT or weather forecast mode *[Xie et al. 2004]*. Improvements have also been found with the modifications of *Zhang [2002]* in the simulation of tropical convection. In particular, the simulation of the Madden-Julian Oscillation, a very important mode of tropical variability, has been improved *[Zhang and Mu 2005]* and the tendency of the atmospheric model to produce an erroneous "double-ITCZ" when coupled with an ocean has been reduced (Figure 2) *[Zhang and Wang 2006]*.

References

Xie, S., and M. Zhang (2000), Impact of the convection triggering function on single-column model simulations, *J. Geophys. Res.*, *105*(D11), 14,983–14,996.

Xie, S., M. Zhang, J. S. Boyle, R. T. Cederwall, G. L. Potter, and W. Lin (2004), Impact of a revised convective triggering mechanism on 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, G. J. and Mingquan Mu. (2005), Simulation of the Madden–Julian Oscillation in the NCAR CCM3 Using a Revised Zhang–McFarlane Convection Parameterization Scheme. *Journal of Climate*, *18*, 4046–4064.

Zhang, G. J., and H. Wang (2006), Toward mitigating the double ITCZ problem in NCAR CCSM3, *Geophys. Res. Lett.*, *33*, L06709, doi:10.1029/2005GL025229.

Figure 1. Illustration of the effect of convection parameterization on the simulation of summertime precipitation at the SGP site. The plots show the evolution of conditions at the ARM SGP site during the summer of 1997. Each panel compares the time series of observed precipitation to another field. The fields shown are the time series of convective available potential energy "CAPE" in Figure 1a, precipitation simulated by the single column model of the NCAR CCM3 model with the default convection parameterization in Figure 1b, the time tendency of CAPE due to the effects of the large-scale atmospheric circulation "DCAPE" in Figure 1c, and precipitation simulated by the CCM3 single-column model with the modifications developed by *Xie and Zhang [2000]* in Figure 1d. By altering the conditions under which the convection occurs and the amount of convection when it occurs, atmospheric simulations can be significantly improved. (Figure from *Xie et al. [2004]*)

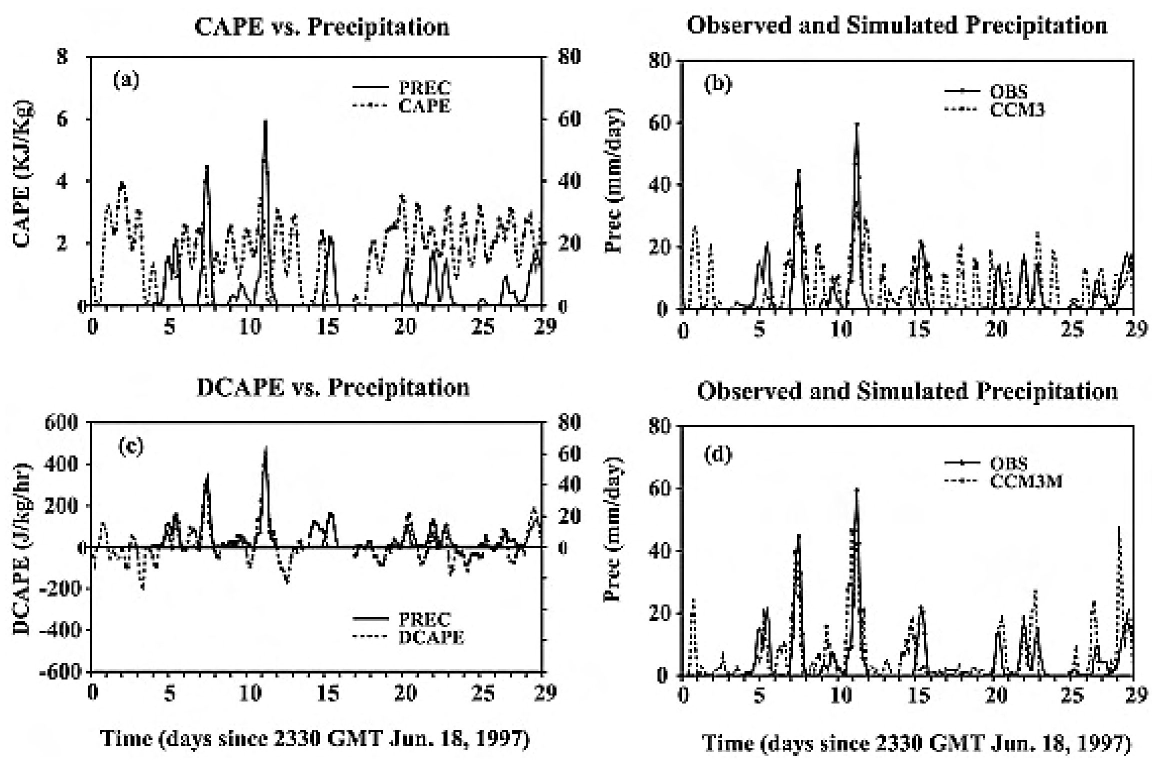
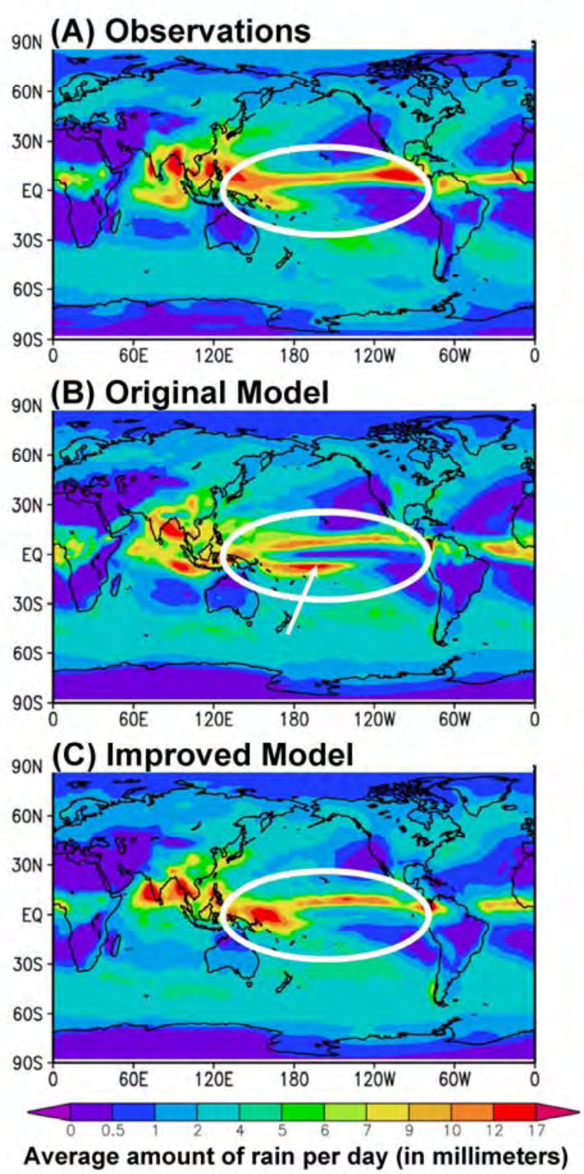


Figure 2. Illustration of the impact of the convection parameterization on global climate simulations. Each panel shows the global distribution of the climatological amount of precipitation for the months of June, July, and August (JJA). The precipitation from the NCAR coupled ocean-atmosphere model with and without the modifications to the convection scheme developed by *Zhang [2002]* are shown in panels B and C. The modifications reduce the incidence of the "double-ITCZ" problem in coupled-ocean atmosphere models and is an improvement in comparison to the observations in panel A. The "double-ITCZ" problem, endemic to most coupled ocean-atmosphere models, is when precipitation occurs in two Inter-Tropical Convergence Zones (ITCZs) north and south of the equator when observations typically indicate only one ITCZ. This problem is highlighted by the white circle and arrows. (Figure from *Zhang and Wang [2006]*)



Advancement of cloud resolving models to address climate change problems via the Multi-scale Modeling Framework

Intercomparison studies of the ARM Cloud Parameterization and Modeling working group have established that cloud resolving models (CRMs) are superior to single-column models (SCMs), particularly for the simulation of deep convection, for which SCMs rely on convection parameterizations. CRMs should be superior since they explicitly simulate convection with their high resolution.

The superior quality of cloud-resolving models motivates the desire to use them to address climate directly. One possibility is to simulate the entire globe with the resolution of a CRM. Japanese scientists have done this on the Earth Simulator, but they are not able to do many climatologically significant simulations due to the computational expense *[Tomita et al. 2005]*. An alternative and less-computationally expensive approach is the incorporation of a cloud resolving model at each grid-point of today's low-resolution climate models. Essentially the parameterization of cumulus convection, and other physical processes such as large-scale condensation, radiation, and turbulence, are removed from the climate model and replaced with a low-resolution 2-dimensional cloud resolving model (Figure 1). This approach called "super-parameterization" or more recently "Multi-scale Modeling Framework" has been intensively developed by Dave Randall and Marat Khairoutdinov at Colorado State University with seed money from ARM following the original idea of Wojiech Grabowski of NCAR *[Randall et al. 2003, Khairoutdinov et al. 2005]*. (Although ARM continues to fund efforts in MMF, future funding will primarily come from the NSF Science and Technology Center which has been chartered in Summer 2006) The initial MMF simulations appear to yield an improved simulation of the Madden-Julian Oscillation and the diurnal cycle of precipitation over land, two features that are difficult for conventional climate models to simulate.

ARM data has been used in the development of the cloud resolving model used in the MMF *[Khairoutdinov and Randall 2003]* and in the evaluation of the MMF simulations *[Ovtchinnikov et al. 2006]*. As example, Figure 2 shows the height dependence to the histogram of cloud condensate as retrieved from the ARM instruments at the TWP sites Manus and Nauru and simulated by the MMF and the NCAR climate model "CAM" with the conventional parameterizations *[McFarlane et al. 2006]*. Because the retrievals of cloud condensate are restricted to times of no precipitation, the MMF data must be sampled for times of no precipitation and when this is done better agreement is found. The conventional NCAR CAM overestimates the occurrence of cirrus clouds, consistent with other studies.

An important goal of the ARM program is to narrow of the uncertainty of climate change predictions due to uncertain cloud feedbacks. A first investigation of the cloud feedbacks from the MMF shows a surprisingly low climate sensitivity. Intriguingly, the global CRM of the Japanese also appears to show a similarly low climate sensitivity *[Miura et al. 2005]*. However, the low sensitivity is mainly due to cloud types such as boundary layer stratocumulus and mid-latitude frontal cloud systems for which the MMF simulations are not necessarily superior to those of conventional climate models *[Wyant et al. 2006]*. A more significant result is that the MMF simulates a positive water vapor feedback similar to conventional models, thus providing increased confidence in the water vapor feedback, which is the largest of the known positive feedbacks in the climate system.

References

Khairoutdinov, Marat and David A. Randall (2003), Cloud Resolving Modeling of the ARM Summer 1997 IOP: Model Formulation, Results, Uncertainties, and Sensitivities. *Journal of the Atmospheric Sciences*, *60*, 607–625.

Khairoutdinov, Marat, David Randall and Charlotte DeMott (2005), Simulations of the Atmospheric General Circulation Using a Cloud-Resolving Model as a Superparameterization of Physical Processes. *Journal of the Atmospheric Sciences*, *62*, 2136–2154.

McFarlane, S. A., J. H. Mather, T. P. Ackerman, (2006) Analysis of tropical radiative heating profiles in the Multi-scale Modeling Framework: A comparison to ARM observations. *Proceedings of the 16th ARM Science Team Meeting*, Albuquerque, New Mexico.

Miura, H., H. Tomita, T. Nasuno, S. Iga, M. Satoh, and T. Matsuno (2005), A climate sensitivity test using a global cloud resolving model under an aqua planet condition, *Geophys. Res. Lett.*, *32*, L19717, doi:10.1029/2005GL023672.

Ovtchinnikov, Mikhail, Thomas Ackerman, Roger Marchand and Marat Khairoutdinov (2006), Evaluation of the Multiscale Modeling Framework Using Data from the Atmospheric Radiation Measurement Program. *Journal of Climate*, *19*, 1716–1729.

Randall, David, Marat Khairoutdinov, Akio Arakawa and Wojciech Grabowski (2003), Breaking the Cloud Parameterization Deadlock. *Bulletin of the American Meteorological Society*, *84*, 1547–1564.

Tomita, H., H. Miura, S. Iga, T. Nasuno, and M. Satoh (2005), A global cloud-resolving simulation: Preliminary results from an aqua planet experiment, *Geophys. Res. Lett.*, *32*, L08805, doi:10.1029/2005GL022459.

Wyant, M. C., M. Khairoutdinov, and C. S. Bretherton (2006), Climate sensitivity and cloud response of a GCM with a superparameterization, *Geophys. Res. Lett.*, *33*, L06714, doi:10.1029/2005GL025464.

Figure 1. Illustration of the Multi-scale Modeling Framework or "super-parameterization". The figure shows a single grid-box of a global climate model (GCM). In this case the grid box has sides with approximate length of 300 km. For each grid box, a cloud resolving model is used to simulate the cloud, convection, radiation, and turbulence processes. The figure shows a cloud-resolving model in the configuration that has been used most often; namely, the cloud resolving model is 2-dimensional and consists of 64 columns which have a horizontal spacing of 4 kilometers. (Figure courtesy of Tom Ackerman)

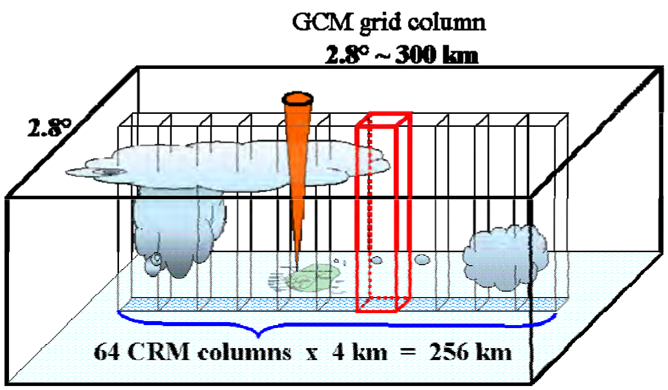


Figure 2. Comparison of the distributions of cloud condensate for the ARM TWP sites Manus and Nauru. Each panel consists of the histogram of cloud condensate which is computed separately for each altitude bin and then displayed as a function of height. The upper left panel ("ARM") consists of the retrievals of cloud condensate from the ARM remote sensors. The MMF panel is shown twice – once for all grid columns and once for grid columns that do not contain precipitation. Note that ARM retrievals are not performed in columns with precipitation. The results of the conventional NCAR CAM climate model are shown in the lower right. (Figure from *McFarlane et al. [2006]*)