DOE ARM Program

Accomplishments of the
Cloud Properties Working Group (CPWG)

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Cloud Radiative Forcing at the ARM Climate Research Facility: Using ARM Data to Establish Testable Metrics for GCM Predictions of Cloud Feedback

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The scientific underpinning of the Atmospheric Radiation Measurement (ARM) Program is largely based on the premise that long term ground-based measurements of certain quantities provide information sufficient to test the skill of general circulation models (GCMs) to predict radiative heating and cloud feedbacks (Stokes and Schwartz, 1994; Ackerman and Stokes, 2003). This hypothesis is based on the assumption that some set of long-term ground-based measurements provide sufficient information to characterize the physical state of the atmospheric column. In Mace et al. (2006a and b), this assumption is critically evaluated. Beginning with the basic measurements collected by the ARM Program at the ARM Climate Research Facility (ACRF) during the year 2000, the physical state of the atmosphere, including cloud occurrence, cloud properties, and radiative heating, is characterized, validated, and shown to provide a useful quantitative description of the cloud radiative heating profiles on annual time scales. This first validated characterization of the atmospheric physical state over a full annual cycle establishes a benchmark against which GCM predictions can be evaluated and improvements measured. As an example, Figure 1 shows the annually averaged vertical profiles of cloud radiative heating and their uncertainties in units of heating rate (Kelvins per day) for all non precipitating overcast clouds along with the cloud radiative effects (W m^{-2}) at the surface, top of atmosphere, and within the atmosphere. While GCMs are generally able to match top of atmosphere (TOA) cloud radiative effects, it is also known that matching TOA cloud radiative effects is not sufficient to establish the validity of model predictions because the proper radiative balance at TOA can easily be induced through compensating errors within the atmosphere (Webster and Stephens, 1984). Mace et al. (2006a and b) show that analysis of ARM data can provide the annually averaged vertical distribution of cloud-induced radiative heating with sufficient quantitative detail for establishing the skill of GCMs to predict a quantity known to be of first order importance in the climate system but is yet highly uncertain.

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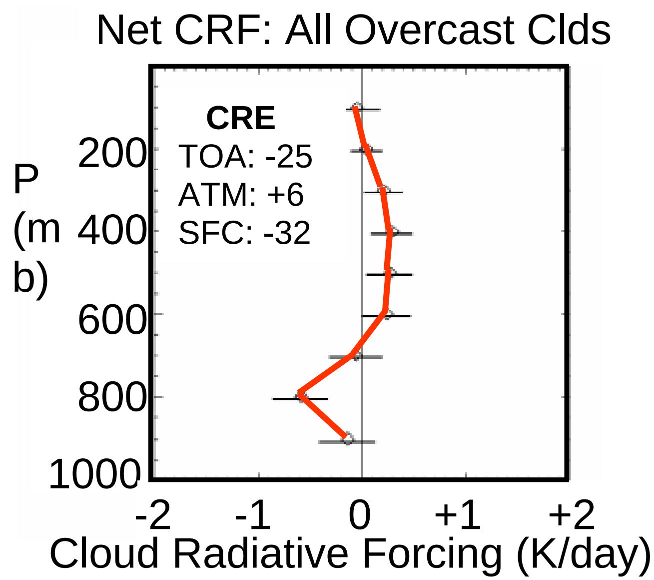
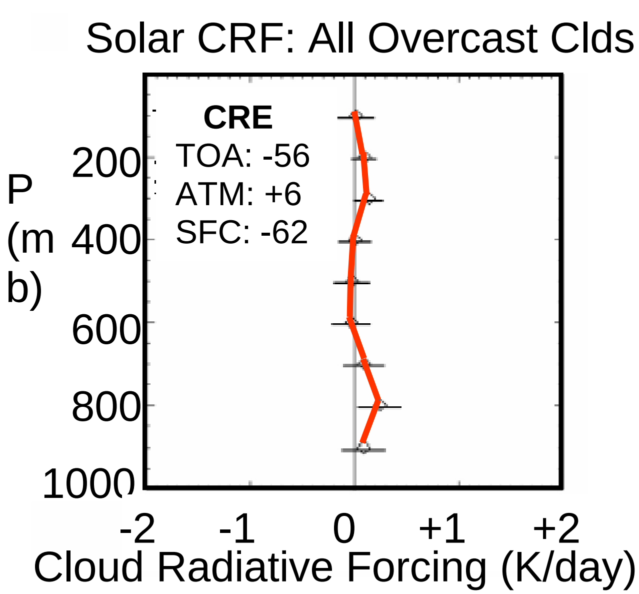
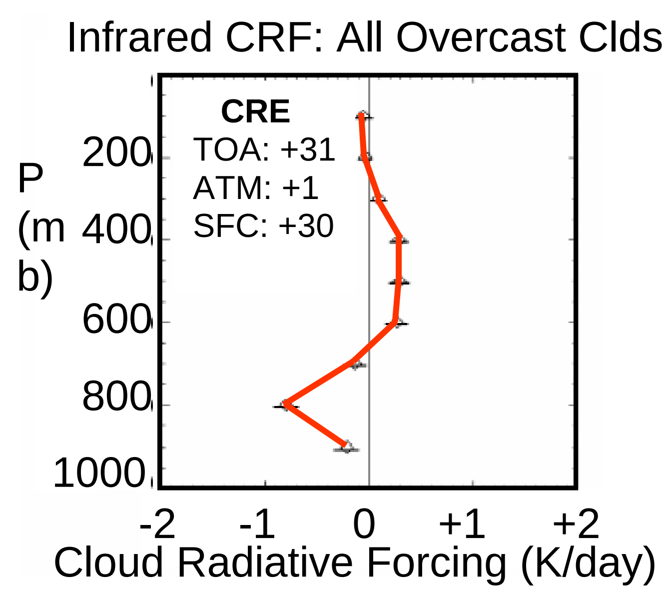
Figure 1. **Annually-Averaged Cloud Radiative Forcing** (CRF) Profiles (K/day) and **Cloud Radiative Effect** (CRE – inset – uncertainty +/- 3 W/m^2) at SGP for Top of Atmosphere (TOA), Atmosphere (ATM) and Surface (SFC) derived from ARM Measurements.







Improving the Treatment of Ice Clouds in GCMs

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New treatments for ice cloud size distributions (SD), ice sedimentation rates and optical properties were incorporated into NCAR's Community Atmosphere Model (CAM), part of the Community Climate System Model version 3 (CCSM3). The SD schemes were developed from aircraft measurements using the 2DC and FSSP probes and were parameterized as two SD modes; one gamma distribution representing small ice crystals (D < 80 microns) and another mode representing the larger ice particles. The ice cloud sedimentation rates and optical properties were formulated in terms of SD parameters and ice particle shape (i.e. mass- and area-dimensional power law relationships), thus coupling the new microphysics-radiation physics. All three of these schemes (SD, sedimentation and optical) were developed completely under the ARM program (Ivanova et al., 2001; Mitchell, 1996; Mitchell and Heymsfield, 2005; Mitchell et al., 2006). Incorporating these schemes in the CAM did not have a strong impact on model output fields, but the main improvement was more realistic physics that are sensitive to microphysical processes. At this time, it appears likely that the ice cloud optical property and sedimentation schemes will become part of the next version of the CCSM, that is, CCSM4.

To test the CAM's sensitivity to the representation of small ice crystals, two one-year CAM simulations were performed: one using a SD scheme developed for synoptic mid-latitude cirrus clouds (applied globally), and one using a SD scheme developed for convectively generated tropical anvil cirrus (also applied globally). The main difference between the two simulations was the representation of small ice crystal concentrations, with the anvil cirrus SD scheme yielding higher concentrations with decreasing temperature (see upper figures). In the tropics, the short-wave cloud forcing zonal means differed between the two runs by up to 25 W m^{-2} and 20 W m^{-2} for long-wave cloud forcing (see lower figures). Cloud forcing was greater using the anvil cirrus SD scheme. Corresponding differences in heating rates produced temperature differences over 3 ^{o}C in the tropical upper troposphere. Such differences may affect model dynamics and performance in general. These results underscore the need to accurately assess the concentrations of small ice crystals in ice clouds.

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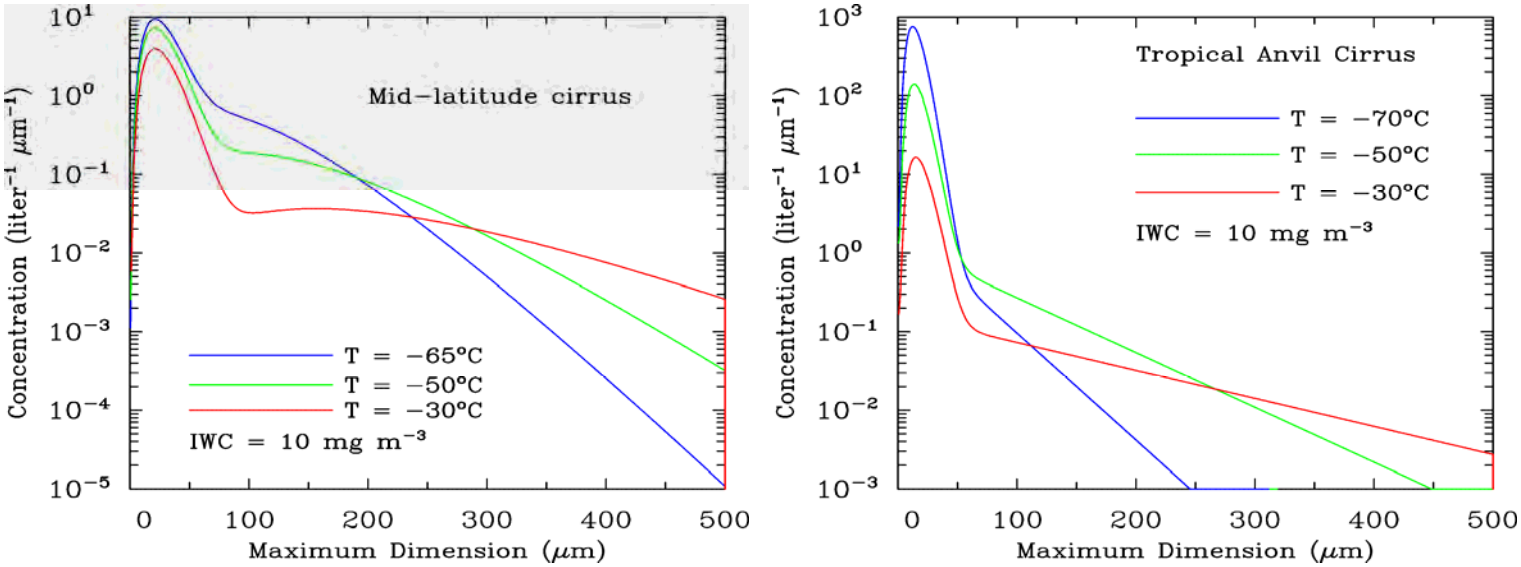
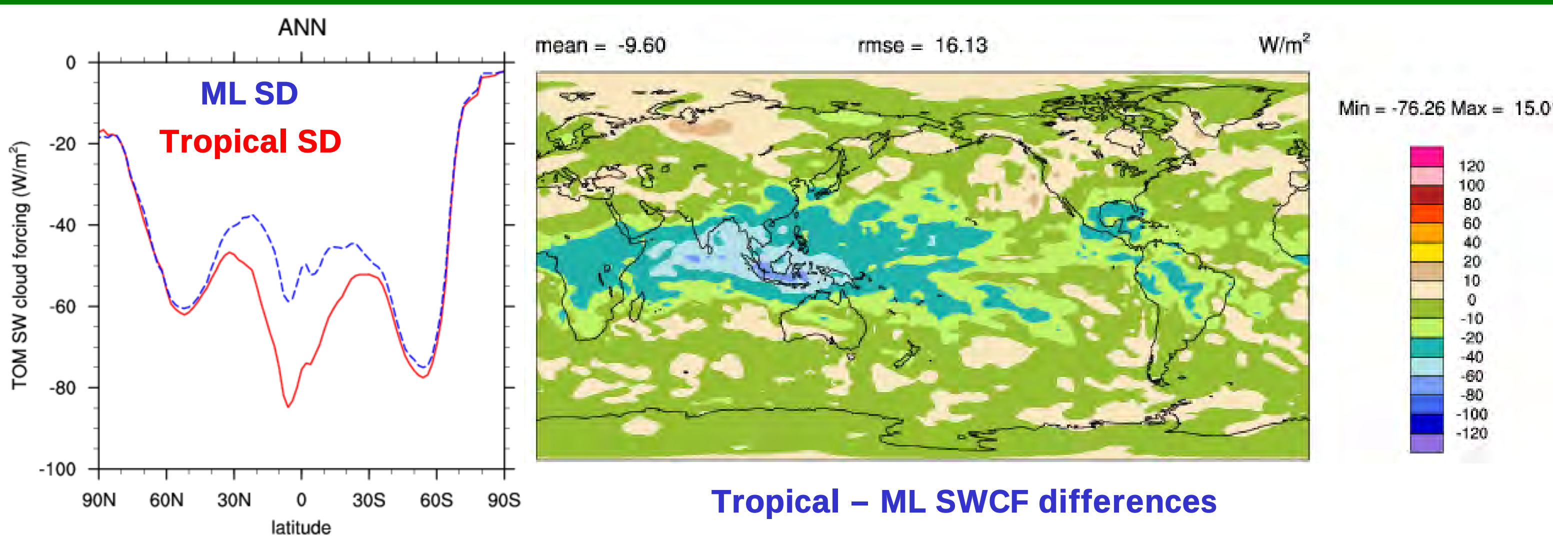
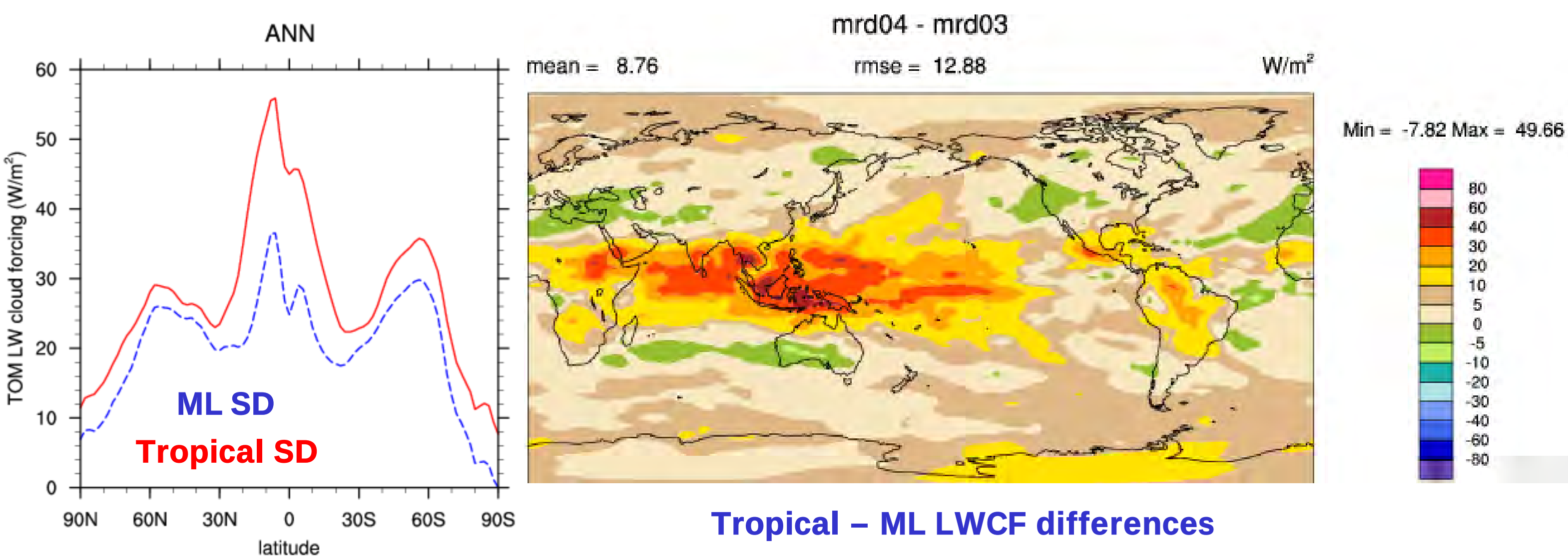


Small mode enhancement with decreasing T for tropical anvil cirrus; Opposite for ML cirrus.

CAM simulations: Tropical - midlatitude size distributions



Tropical – ML SWCF differences



Tropical – ML LWCF differences

Physically Based Parameterizations of Cloud Microphysics and Applications for Climate Models

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Using information about the size and shape distributions of ice crystals acquired during Intensive Operations Periods (IOPs) by aircraft over the ARM surface sites and at other locations, improved representations of the mean scattering properties of distributions of ice crystals (McFarquhar et al., 2002; Nousiainen and McFarquhar, 2004; McFarquhar et al., 2005) and of effective particle sizes of ice crystals (McFarquhar et al., 2003) have been developed. These schemes improve upon previous parameterizations in that they include realistic contributions of the number concentrations of previously unrepresented small crystals, they include the representation of the deviation of scattering and microphysical properties about their mean values in addition to the mean values themselves, they are based upon observed distributions of crystal habits rather than assuming single crystal habits, and they used libraries of scattering properties for individual shapes and sizes of ice crystals based upon an improved geometric ray-tracing method (Yang et al., 2000). Figure 1 shows an example of these improved representations for the effective particle radius in terms of ice water content, and in terms of ice water content and temperature.

Simulations incorporating these improved parameterizations into the Scripps single column model (McFarquhar et al., 2003; Iacobellis et al., 2003) over the Tropical Western Pacific and Southern Great Plains have shown that the variability in particle sizes and scattering properties can sometimes play a greater role in cloud-radiation interactions than the more obvious changes in the parameterizations themselves. For instance, simulations conducted by randomly choosing the effective radius at each time step within one or two standard deviations of the mean parameterized value showed that the shortwave reflection was enhanced by up to 4.9 W m^{-2}, showing that a simulation based upon an average parameterization does not give the same result as the average of a series of parameterizations. Further, differences in longwave heating rates, predicted by the different microphysical parameterizations, feed back upon the cloud water content which in turn affects the cloud radiative forcing in a way that either amplified or reduced the change in cloud radiative forcing that is directly associated with a modification of the microphysical or single-scattering properties. These findings have important ramifications for the way future parameterizations of cloud-radiation interactions should be developed.

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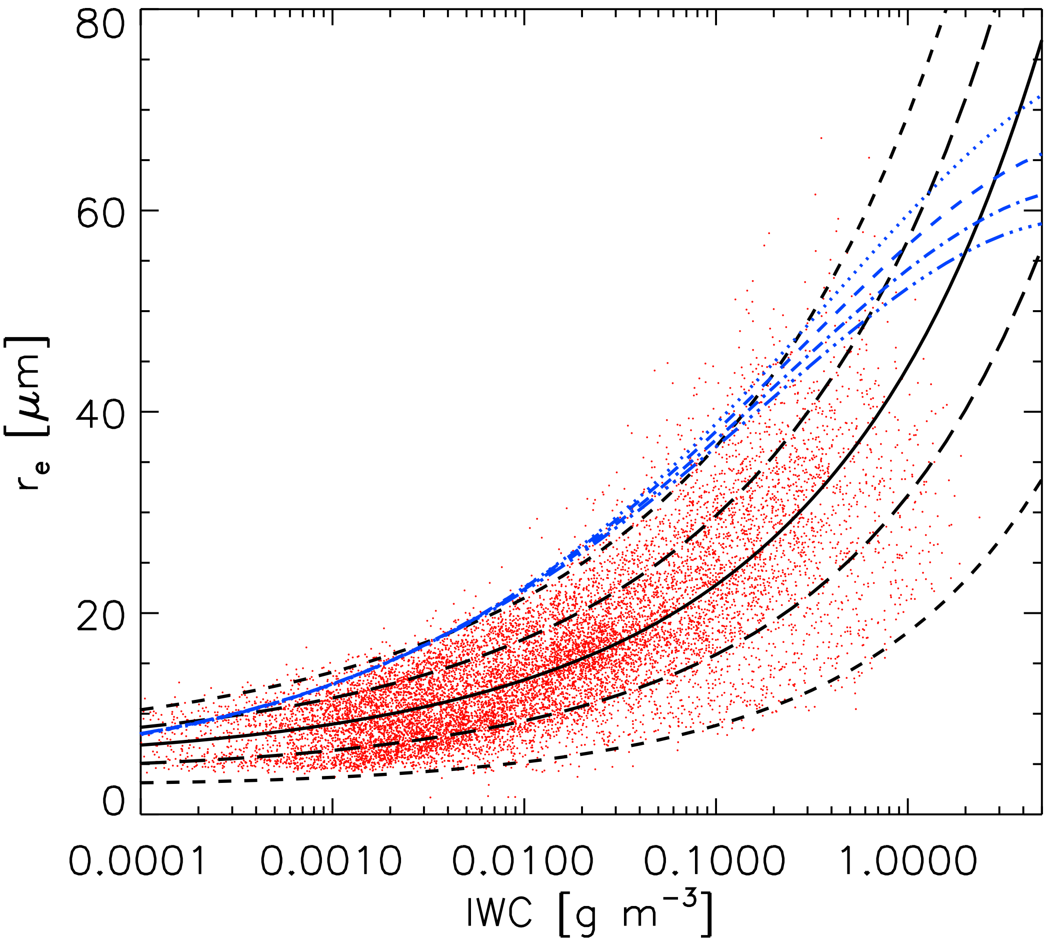

Figure 1: The effective radius, re, as function of ice water content IWC, derived from in-situ observations in tropical anvils. Each red dot represents a 10 s (2 km along the flight path) averaged size distribution. Solid black line represents best fit to data, thin long black dashes and thin short black dashes represent plus and minus one and two standard deviations from mean relation. Blue lines represent relationships determined by McFarquhar (2001): dots, -65^{o}C, dashes, -55^{o}C, dashes and dots, -45^{o}C, dashes and 3 dots, -35^{o}C (adapted from McFarquhar et al., 2003).

Aerosol Regulation of Arctic Cloudiness

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Johannes Verlinde, Pennsylvania State University, University Park, Pennsylvania
(for the M-PACE participants)

The Mixed-Phase Arctic Cloud Experiment (M-PACE), conducted from late September 2004 through October 2004 in the vicinity of the Department of Energy North Slope of Alaska field site, successfully documented the microphysical structure of Arctic mixed-phase clouds (Verlinde et al., 2006). Liquid was found in clouds with cloud-top temperatures as cold as -30 ^{o}C, the coldest cloud-top temperature warmer than -40 ^{o}C sampled by the aircraft. Observations in widely different forcing conditions suggest that the cause of the persistent liquid in these cold, ice-precipitating clouds is not in their dynamical characteristics, but must be microphysical in origin. The prevalence of liquid down to these low temperatures potentially could be explained by the relatively low ice nuclei concentrations measured (Prenni et al., 2006).

Ice nuclei (IN) concentration measurements were made using a continuous flow diffusion chamber (CFDC) on the University of North Dakota Citation II aircraft. Results are presented in composite form in Figure 1 (from Prenni et al., 2006). The data are presented as IN concentrations, binned into unit ranges of processing temperature, water supersaturation and ice supersaturation. These averaged concentrations include a substantial contribution (~87%) from measurements for which no IN were detected. Also shown is the parameterization of Meyers et al. (1992) that is used in many models, often without regard to the location, season or altitude being modeled. It is clear that this parameterization is not representative of average IN behavior as assessed during M-PACE flights in the vicinity of lower level Arctic stratiform clouds, and the use of this parameterization will impair our ability to predict cloudiness and related radiative forcing in this region.

Several recent studies suggest that the Arctic climate is more sensitive to changes in climate forcing than other regions on Earth, while global climate models are less reliable in this region (ACIA, 2004). Clouds play a particularly important role for the surface energy balance in the Arctic and are difficult to model. One possible reason for this is the difference in the aerosol properties of the Arctic atmosphere compared to lower latitudes. The global climate models that form the basis for assessments, such as the ACIA report, use the same cloud and aerosol descriptions in the Arctic as anywhere else on Earth, and are calibrated to provide a reasonable global climate. For the global climate, ice clouds such as found in tropical cirrus anvils are probably more important; however, applying formulations optimized for mid-latitude and tropical conditions to the Arctic, where conditions are clearly different, results in a poor representation of this apparently very sensitive region. It also means that global models which under-predict liquid-water clouds may feature a larger shift from ice to liquid clouds as the model climate warms. This constitutes an enhanced, unrealistic, positive feedback on climate change and may partly explain some of the models very large sensitivity to such features as projected ice cover. An important conclusion from these results is a necessity to include a realistic treatment of aerosols and aerosol/cloud interactions in future climate simulations (Prenni et al., 2006).

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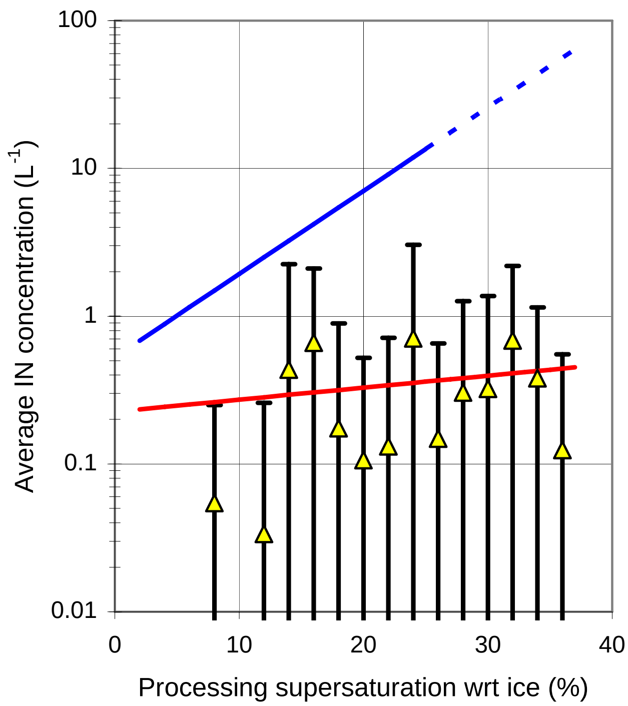

Figure 1: M-PACE ice nuclei concentration data processed for project-average concentrations (60 s integrated values) in finite bin intervals of CFDC processing ice supersaturation. Error bars indicate one standard deviation. The ice nucleation parameterization of Meyers et al. (1992), used as a standard in many cloud-resolving models, is shown for comparison as a solid blue line for the supersaturation range for which it can be strictly applied. (The dashed blue line extends it to higher supersaturations.) A best fit for the current binned and weighted data is shown as a solid red line, using the same functional form as in Meyers et al. (1992). (From Prenni et al., 2006).

Extending ARM Remote Sensing Capabilities to Measuring Vertical Profiles of Precipitation

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Since its earlier days, the Atmospheric Radiation Measurement (ARM) Program put a special emphasis on deriving long-term vertical profiles of water vapor and cloud parameters from ground-based measurements performed with a suite of passive and active instruments deployed at the ARM Climate Research Facilities (ACRF). The characterization of the atmospheric column above the ACRF sites constitutes one of the ARM priorities and is intended to help in the assessment of the climate and cloud models. Precipitation is a very crucial component of the global water cycle; however, until recently, there have been no attempts to quantitatively retrieve precipitation parameters with standard ARM instruments which presented a certain inadequacy in characterizing the vertical atmospheric column. To address this problem, a novel attenuation-based remote sensing method to retrieve vertical profiles of rain rates from ARM vertically pointing 8–mm (K_a-band) wavelength cloud radars (MMCR) has been developed (Matrosov, 2005). These radars were designed for remote sensing of non-precipitating clouds and were not initially intended for the quantitative use in rainfall because of high attenuation of K_a-band frequencies in rain. Traditional precipitation radars (which are not part of the standard ARM instrumentation) operate at C-band (5 cm wavelength) or S-band (10 cm wavelength) where attenuation in rain is small and they usually use absolute reflectivity methods or polarimetric methods to infer rainfall rate, R. These traditional precipitation radar methods are not applicable to MMCR measurements. Our new ARM retrieval method is actually based on attenuation effects and uses K_a-band vertical reflectivity *gradients* which are then related directly to R using a tight relation that is unique to the K_a-band. The rainfall rate profiles can be obtained where MMCR signals are neither in saturation nor in the noise. The attached figure shows comparisons of MMCR retrieved rainfall rates with traditional estimates based on absolute reflectivity and polarimetric estimates from a nearby precipitation C-band (C-Pol) radar at the Darwin ACFR site. A vertical plane scanning mode was employed by the C-Pol radar to obtain vertical rain profiles over the ACFR site. The results show that MMCR estimates are within uncertainties of precipitation radar estimates using the two C-band approaches. It indicates that MMCR measurements can be effectively used to retrieve rainfall profiles over ACRF sites, thus noticeably improving the characterization of the atmospheric column above those sites.

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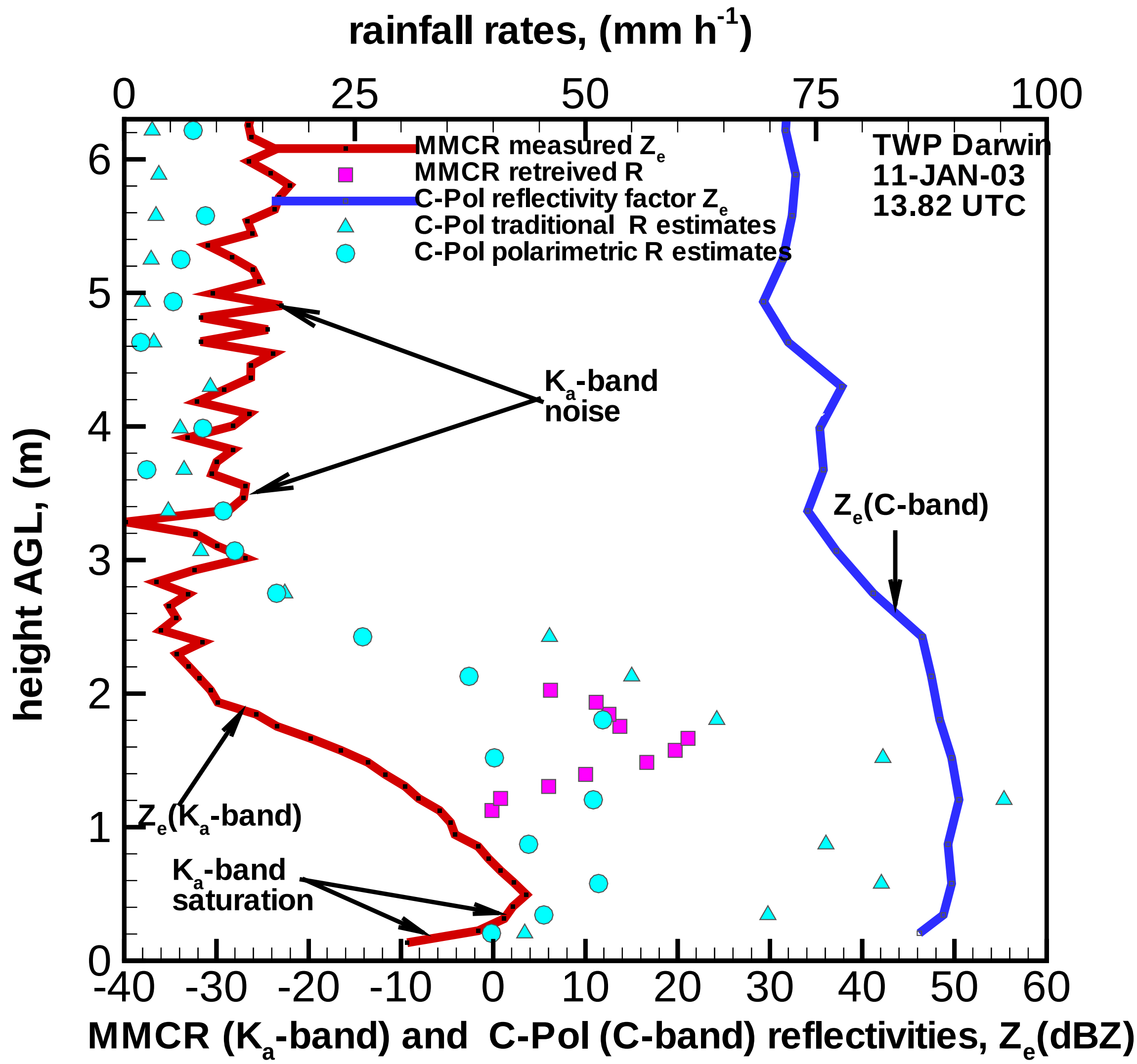

Figure 1: Comparisons of ARM MMCR attenuation-based estimates of rainfall with traditional precipitation radar (C-Pol) measurements. Reflectivities are plotted along the lower X-axis while the rainfall rates are plotted along the upper X-axis.

ARM Observations Validate Climate Model for Tropical Cirrus Clouds

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In a study funded by the U.S. Department of Energy's Atmospheric Radiation Measurement (ARM) Program, researchers used ground-based observations to assess simulations of tropical cirrus derived from the European Climate Model for Weather Forecasting (ECMWF). As described in Geophysical Research Letters (May 2004) the researchers used lidar and radar measurements of cirrus occurrence obtained between April and November 1999 from ARM's instrumented field site on Nauru Island to assess the accuracy of the ECMWF model in predicting tropical cirrus. Using a subdivided model grid box of 100 independent samples to represent cloud variability, comparisons of cloud top height and optical depth over the eight month period indicated good agreement between the model and measurements. Additionally, both the model and observations showed that tropical cirrus fall into two distinct categories: cirrus near convection (anvils) and cirrus detached from convection.

Thin cirrus clouds near the tropopause layer - the layer of the Earth's atmosphere where the troposphere turns into the stratosphere - can have significant impacts on radiative heating in the upper troposphere. This is due, in part, to the ice crystals that make up tropical cirrus clouds; these crystals tend to absorb and re-emit infrared radiation, which can increase warming in the atmosphere. Because of the important role of tropical cirrus in modulating the radiation budget, the ability of large-scale models to correctly simulate their occurrence is important in predicting the role of these clouds on climate. This is especially true in the tropics, where deep convection, heavy precipitation, and consistently warm temperatures act as a "breeding ground" for extensive and persistent cirrus cloud sheets.

To examine the conditions under which the specific cirrus forms, the researchers also conducted a case study of measured and modeled typical thin cirrus in the tropopause over Nauru. Of the 32 cases examined, 56% were associated with convection, and 66% were influenced by tropospheric waves, as determined in the model's vertical velocity field. These waves occur just below cloud base and appeared to modulate cirrus cloud cover and ice water content.

Ground-based measurements provided by ARM's instrumented field sites allow comparisons such as these to assess strengths and weaknesses in climate models. Although there is some difficulty in comparing a model grid box with single point measurements (such as those provided by ARM instruments), this research showed that the model predicts both convective anvils and isolated tropopause cirrus reasonably well. In this case, the model exhibited sufficient skill in simulating tropical cirrus characteristics such that it may be useful as a tool for identifying and understanding cirrus formation mechanisms and large-scale features of tropical cirrus over time.

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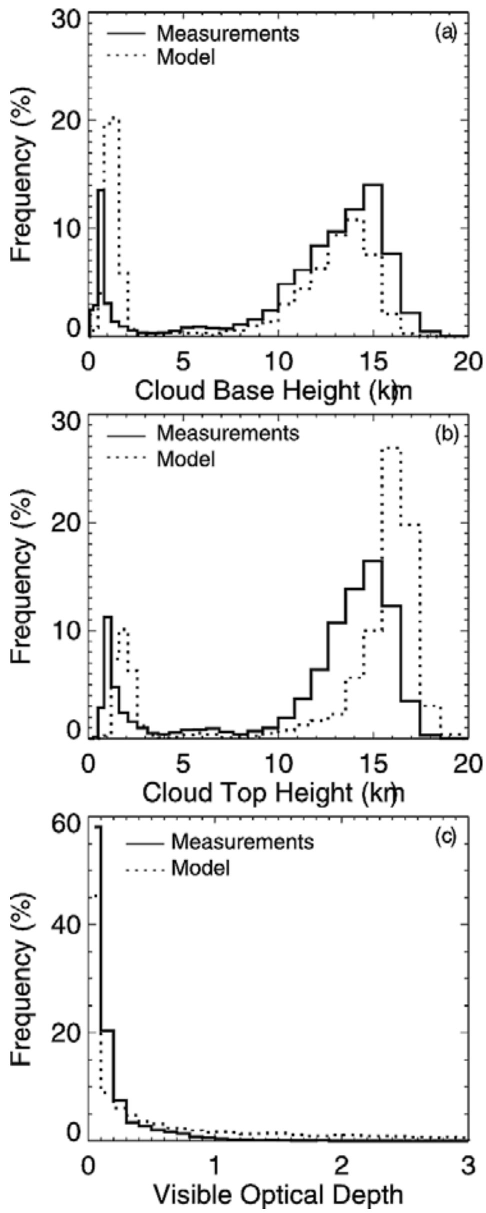

Composite statistics compare ARM measurements and ECMWF model- derived cloud properties of (a) base height, (b) cloud top height, and (c) high cloud visible optical depth for tropical cirrus clouds.

Continuous Dataset of Water Vapor Measurements Throws Water on Assumptions of Cirrus Cloud Formation

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To study the link between water vapor, cirrus cloud formation (homogeneous and heterogeneous) mechanisms, and their potential climatic impacts, researchers sponsored by the Department of Energy's Atmospheric Radiation Measurement (ARM) Program analyzed a one-year dataset of water vapor measurements obtained by a Raman lidar at the program's Southern Great Plains (SGP) site in Oklahoma. Signals from the Raman lidar can be used to distinguish ice and water in optically thin clouds (such as cirrus clouds). In addition, this lidar provides continuous, high resolution water vapor profiles with an accuracy of 5%, while simultaneously detecting the presence of clouds. As reported in *Geophysical Research Letters* in June 2004, the long-term continuous dataset provided by the Raman lidar at SGP allowed the researchers to provide the first analysis of reliable upper tropospheric water vapor profiles measured from a single location. Their findings confirmed one aspect of cirrus formation, while raising questions about another.

As the single largest percentage of greenhouse gases in the Earth's atmosphere, water vapor (or "humidity") is a critical component of climate change research. Because of its ability to absorb energy, water vapor plays an essential role in radiative feedback mechanisms and cloud formation. This is especially true in the upper troposphere — the highest point of weather conditions in Earth's atmosphere, at about 10 km high. At this altitude, small changes in moisture can significantly impact the amount of outgoing radiation, as well as influence the formation of ice-crystals in cirrus clouds. However, accurately measuring water vapor amounts in the upper troposphere (where cirrus clouds occur) is very difficult, particularly on a continuous basis. This is due to the effect of extremely cold temperatures on traditional measurement instrumentation and the irregular schedule of their deployment, as well as the lack of resolution in satellite measurements for studying cirrus nucleation processes.

Using the Raman lidar data from SGP, the ARM researchers were able to analyze a significant climate sample (about 300,000 data points, or 9,500 profiles) of continuous upper tropospheric water vapor concentrations. As quantified by aircraft in situ measurements, typical ice-generating cirrus clouds are structured with an ice-generating region near the top, an ice crystal growth or deposition region in the middle, and a sedimentation or sublimation region near the cloud base. Using this structure in their analysis, the researchers examined the relative humidity with respect to ice (RHI) in the three regions. They found that ice supersaturation (RHI >100%) occured most frequently in the ice crystal formation region where cloud updraft velocities are typically the strongest, but also occurred frequently in the growth region.

Specifically, their study showed that ice supersaturation occurred about 31% of the time in cirrus clouds, confirming existing assumptions regarding the frequency of homogeneous (non-aerosol related) cirrus formation. However, they also found that ice supersaturation often occurred at temperatures warmer than -40C, when heterogeneous (aerosol-related) cirrus formation typically occurs. This type of ice formation results in smaller ice particles, thereby increasing the resulting reflectivity of the cloud. This implies that heterogeneous formation may play a larger role in the impact of cirrus clouds on the Earth's radiative energy budget than previously thought. These findings, and the dataset used to reach them, represent an important link between the measurement and modeling communities as they continue to improve scientific understanding of the effect of cirrus clouds on the Earth's global climate.

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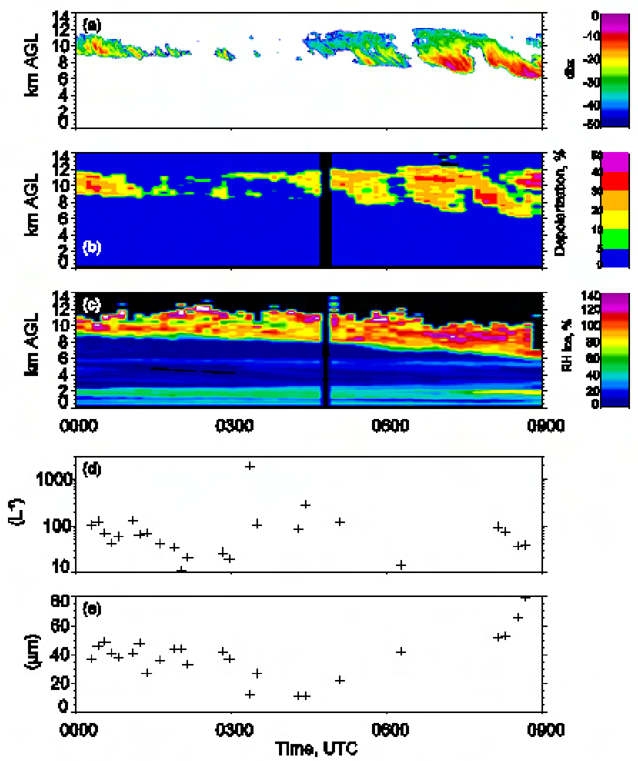

Height vs. time display of 35 GHz radar reflectivity (a), lidar depolarization ratio (b), and relative humidity with respect to ice (c) derived from DOE-ARM measurements on 15 November 2000 at the Southern Great Plains Site. Also shown are time series of mean layer number concentration (d) and effective radius (e).

To illustrate their findings, a continuous nine-hour segment of Raman lidar measurements showed upper tropospheric RHI measurements ranging from 120% near cloud tops and decreasing to about 70% at cloud base.

New Capabilities to Characterize Mixed-phase Cloud Microphysical Properties at the ARM Climate Research Facility

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A key goal of the Atmospheric Radiation Measurement (ARM) Program is to improve cloud parameterizations in general circulation models (GCMs) (Stokes and Schwartz, 1994; Ackerman and Stokes, 2003). Among different phase clouds, mixed-phase clouds are the least understood and studies show that parameterizations of mixed-phase clouds in GCMs have significant impacts on climate sensitivity (Gregory and Morris, 1996; Fowler et al., 1996). Our poor understanding of mixed-phase clouds is mainly the result of our limited observational capabilities. However, during the last few years, the ARM Cloud Property Working Group has made significant progress in this area by developing new capabilities at the ARM Climate Research Facility for characterizing mixed-phase cloud microphysical properties (Wang et al., 2004; Shupe et al., 2004; Turner, 2005). These new algorithms use either single instrument measurements, such as those from the AERI or the MMCR, or multiple sensor measurements to retrieve liquid- and ice-phase cloud microphysical properties (e.g., water content and effective particle size).

A retrieval example of a multiple sensor based algorithm (Wang et al., 2004) is presented in Figure 1. The MMCR and MPL measurements (Figure 1a-c) display the general vertical structure of arctic mixed-phase clouds: liquid water dominated ice generating layer at the top and deep ice virga below. Combining MMCR and MPL measurements one can retrieve ice water content (IWC; Figure 1d) and particle effective radius (D_{ge}; Figure 1e) profiles for the ice phase cloud (Wang and Sassen, 2002). The liquid water path (LWP, Figure 1g) and layer mean effective radius (r_{eff}, Figure 1h) of the liquid-water phase cloud can be retrieved from AERI and MPL measurements together with retrieved ice phase properties. The algorithm developed by Wang et al. (2004) combines these different retrieval approaches and is capable of characterizing the microphysical properties of mixed-phase clouds, which have a high frequency of occurrence in the Arctic (Intrieri et al., 2002; Wang et al., 2005).

Global coupled atmospheric and oceanic model simulations indicate that the Arctic is one of the most sensitive areas to climate change due to the increase of greenhouse gases (Walsh et al., 2002; Covey et al., 2003), which indicates the importance of improving the simulation of arctic clouds in GCMs in order to predict accurately arctic climate change. Applying the new retrieval capabilities to the long-term ARM observations at the NSA site will provide reliable cloud properties and both lead to a better understanding of arctic clouds (Wang, 2006) and to validation and improvement of their simulated properties in GCMs.

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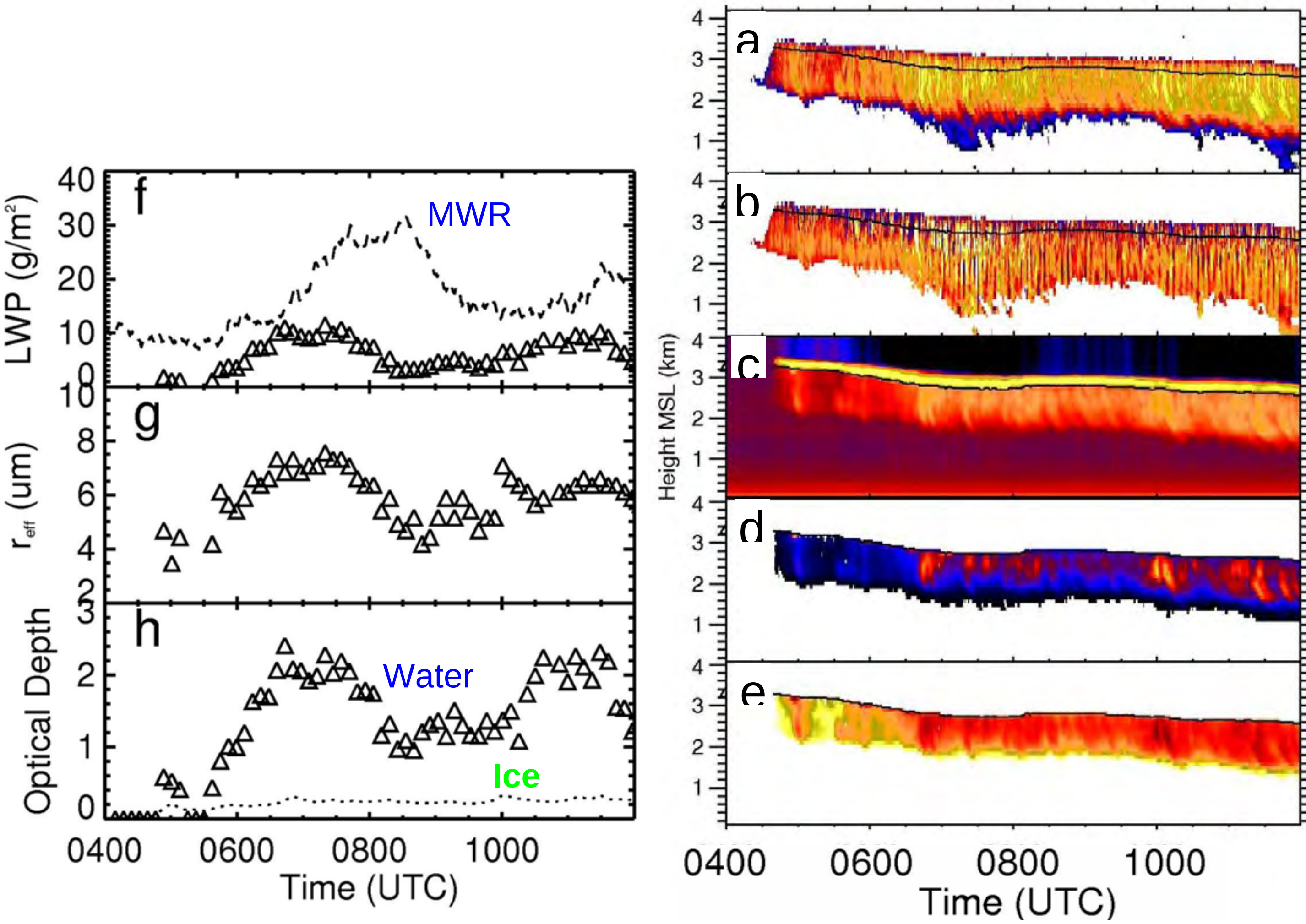
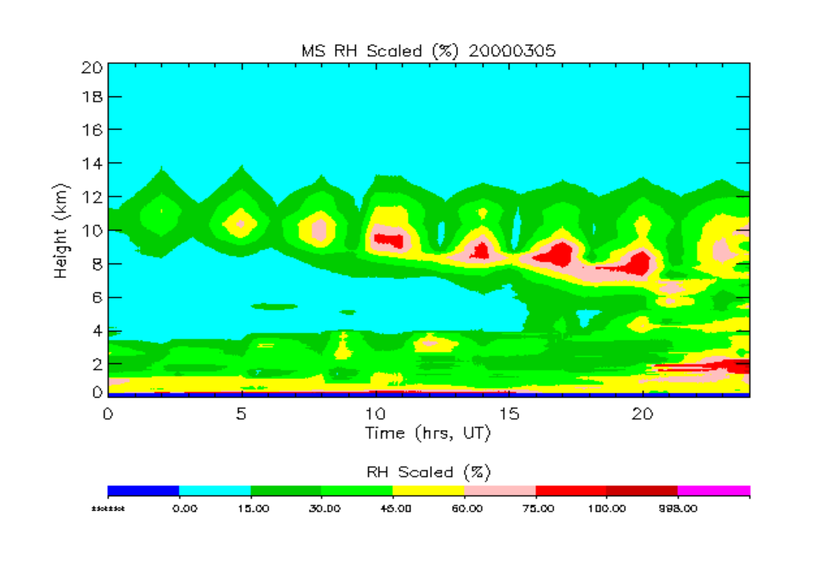
Figure 1: A multiple sensor mixed-phase cloud retrieval example observed between 0400 and 1200 UTC on January 18, 2000 at the NSA site. The radar Z_e (a) and mean Doppler velocity (b) and MPL return power (c) show the typical vertical structure of Arctic mixed-phase clouds. The algorithm provide IWC (d) and D_{ge} (e) profiles for the ice phase cloud, LWP (f) and layer mean r_{eff} (g) for the water phase cloud, and the optical depths of the water and ice phase clouds (h).

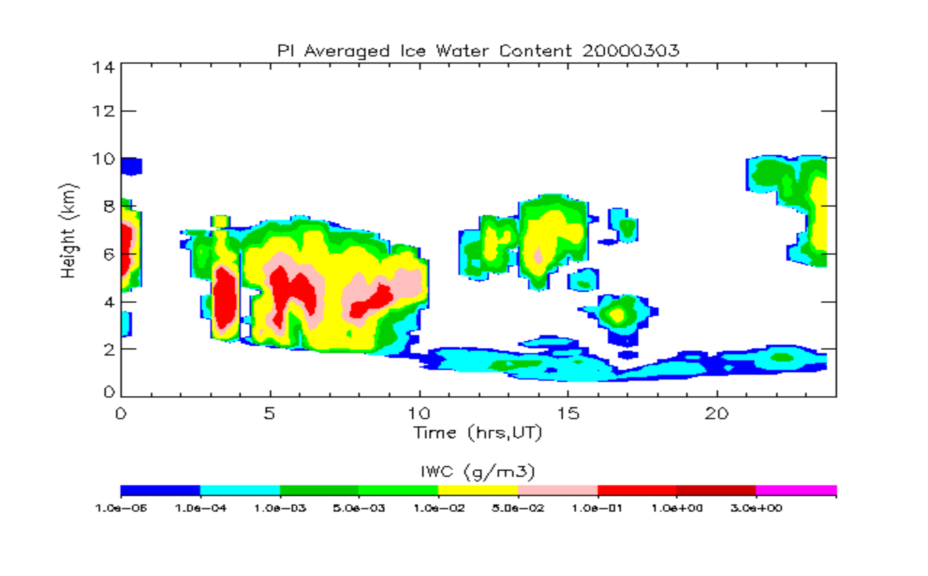


Development of Continuous Cloud and Atmospheric State Datasets for Radiation Studies



- Profiles of atmospheric temperature, humidity, and pressure at 1 minute time resolutions for one year have been developed using data from multiple instruments at each of the permanent ARM sites

- Profiles of cloud water content and particle sizes have been developed at 10 second time resolution for one year using multiple instruments at each of the permanent ARM sites



A New Model of Cloud Drop Distribution that Simulates Drop Clustering

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Yuri Knyazikhin, Boston University, Boston, Massachussetts
Warren Wiscombe, NASA Goddard Space Flight Center, Greenbelt, Maryland, and Brookhaven National Laboratory, Upton, Long Island, New York

Cloud droplet size distribution is one of the most fundamental subjects in cloud physics. Understanding of spatial distribution and small-scale fluctuations of cloud droplets is essential for both cloud physics and atmospheric radiation. For cloud physics, it relates to the coalescence growth of raindrops while for radiation, it has a strong impact on a cloud's radiative properties. Our ARM PI science team has developed size dependent models of spatial distribution of cloud drops that simulates the observed clustering of drops. In contrast to currently used models that assume homogeneity and therefore a Poisson distribution of cloud drops, these models show strong drop clustering, the more so the larger the drops. Clustering has vital consequences for rain physics, explaining how rain can form much faster than in homogenous models. It also helps explain why remotely sensed cloud drop size distributions are generally biased.

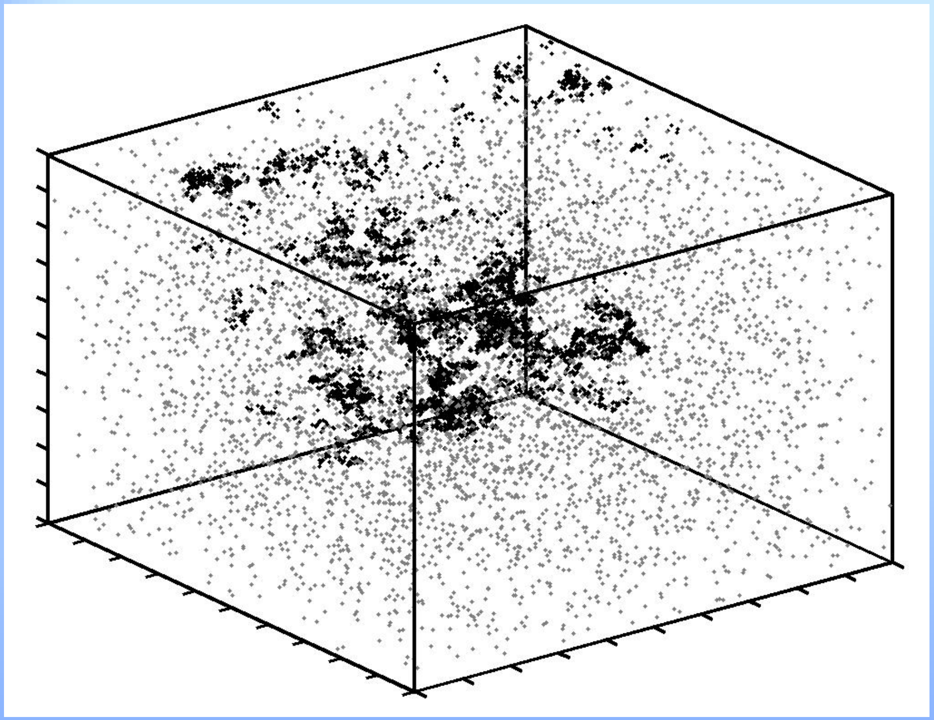
The PowerPoint figure illustrates a realization of the cloud drop distribution model that simulates drop clustering. It shows the different space-filling properties of large (black) and small (gray) cloud drop distributions. There are an equal number of drops colored gray and black. The gray drops are distributed randomly throughout the space whereas the black particles are strongly clustered. The image is based on analysis of the Forward Scattering Spectrometer Probe (FSSP) measurements in stratocumulus clouds over Oklahoma and Kansas.

References:

Marshak, A., Y. Knyazikhin, M. Larsen, and W. Wiscombe, 2005: Small-scale drop size variability: Empirical models for drop-size-dependent clustering in clouds. *J. Atmos. Sci.*, **62**, 551-558.

Knyazikhin, Y., A. Marshak, M. Larsen, W. Wiscombe, J. Martonchik, and R. Myneni, 2005: Small-scale drop size variability: Impact on estimation of cloud optical properties. *J. Atmos. Sci.*, **62**, 2555-2567.

A new model of cloud drop distribution that simulates drop clustering



Drop clustering has vital consequences for rain physics, explaining how rain can form much faster than in homogenous models and why remotely sensed cloud drop size distributions are generally biased.

ARM accomplishment:
We have pioneered the development of a new size dependent model of spatial distribution of cloud drops that simulates the observed drop clustering.

This image illustrates the different space-filling properties of large (black) and small (gray) cloud drop distributions. There are an equal number (5115) of drops colored gray and black. The gray drops are distributed randomly throughout the space whereas the black particles are strongly clustered. The image is based on analysis of the Forward Scattering Spectrometer Probe (FSSP) measurements in stratocumulus clouds over Oklahoma and Kansas.

For details, see two recently published papers:

Marshak et al., 2005: *J. Atmos. Sci.*, 62, 551-558 and Knyazikhin et al., 2005: *J. Atmos. Sci.*, 62, 2555-2567.

Investigating Issues Related to Sub-Grid Scale Variability Using ARM Value Added Products

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Under the auspices of the ARM Cloud Properties and Instantaneous Radiative Flux Working Groups, a gridded Value Added Product (VAP) has been developed for the Southern Great Plains (SGP) network area. The ARM SGP network is a unique array of surface sites intended to sample an area roughly the size of a 300 km resolution Global Climate Model (GCM) to investigate sub-grid scale variability for GCM development. The Surface Cloud Grid (SCG) VAP (Christy and Long, 2003) uses the 15-minute retrievals of clear-sky and measured downwelling shortwave (SW) radiation, as well as the estimated fractional sky cover, from the SW Flux Analysis VAP (Long and Ackerman, 2000; Long and Gaustad, 2004; Long et al., 2006). The individual site retrievals for the ARM SGP Central Facility and 20 Extended Facilities, covering the north central Oklahoma and south central Kansas area, are interpolated to a 0.25 degree latitude by 0.25 degree longitude grid.

Analyses of spatial and temporal representativeness and sub-grid variability have been presented by Long et al. (2002) using the ARM Surface Cloud Grid (SCG) VAP data. These analyses were aimed at the question of just how representative are measurements made in the center of a GCM-scale grid box to the sub-grid variability across the box. The results of the analyses show that even on monthly time scales:

- The monthly average for the SGP Central Facility often significantly differs from the monthly average values at other locations within the SGP network area.

- The measurements made at the SGP Central Facility even on monthly time scales are often only highly correlated (correlation > 0.8) within a radius of 75 km for fractional sky cover, and even less for the effect of clouds on the downwelling SW.

- As the area increases, statistics such as fractional sky cover frequency of occurrence derived from a point measurement site compared to the larger area naturally diverge (how often is the entire continental United States completely cloud free or cloud covered?). Thus comparison between GCM statistics and ARM Central Facilities must account for this natural scaling issue, i.e. that the statistics should not actually completely agree.

These results highlight several issues that must be addressed in our efforts to develop and improve parameterizations for GCMs. The SCG VAP, now produced as an operational product by ARM, can be a useful tool with which to study some of these issues.

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Christy, J. E. and C. N. Long, (2003): "The Surface Cloud Grid (SfcCldGrid) Value-Added Product: Algorithm Operational Details and Explanations", Atmospheric Radiation Measurement Program Technical Report, ARM TR-010, Available via http://www.arm.gov/publications/techreports.stm.

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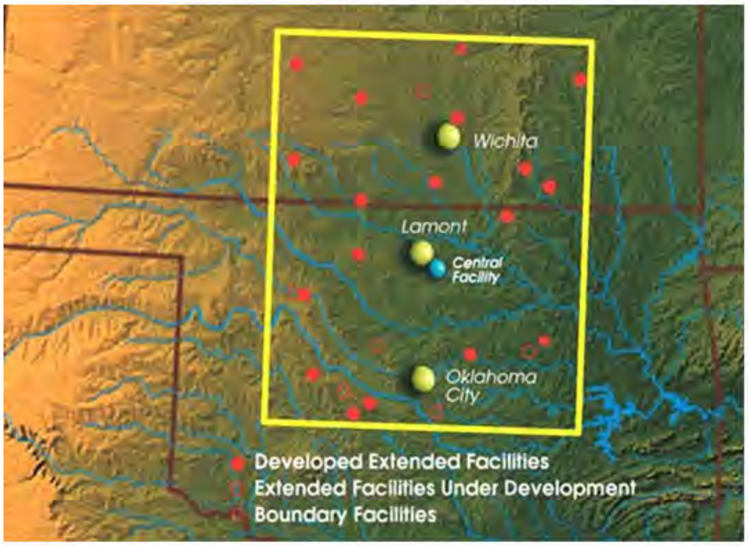
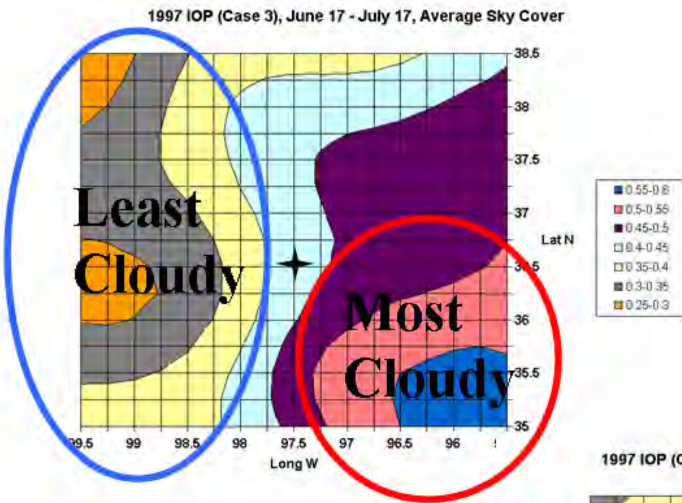
Surface Gridded VAP

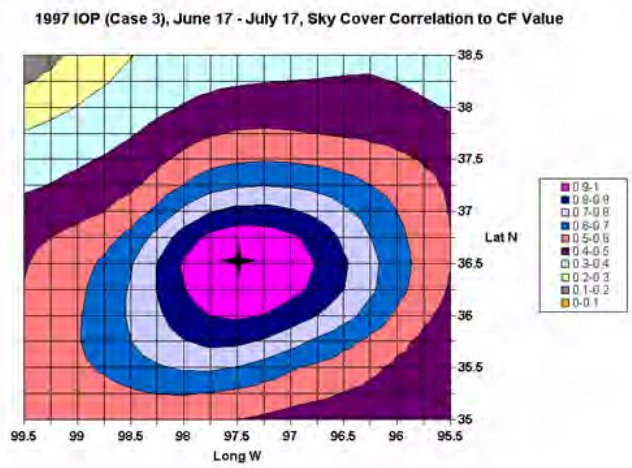


Output from the Shortwave Flux Analysis Value Added Product (VAP) for the SGP Central Facility and 20 Extended Facilities are used to produce a 0.25^{O} X 0.25^{O} Lat/Long grid product for the SGP network area. These include all downwelling all- and clear-sky SW components as well as fractional sky cover.

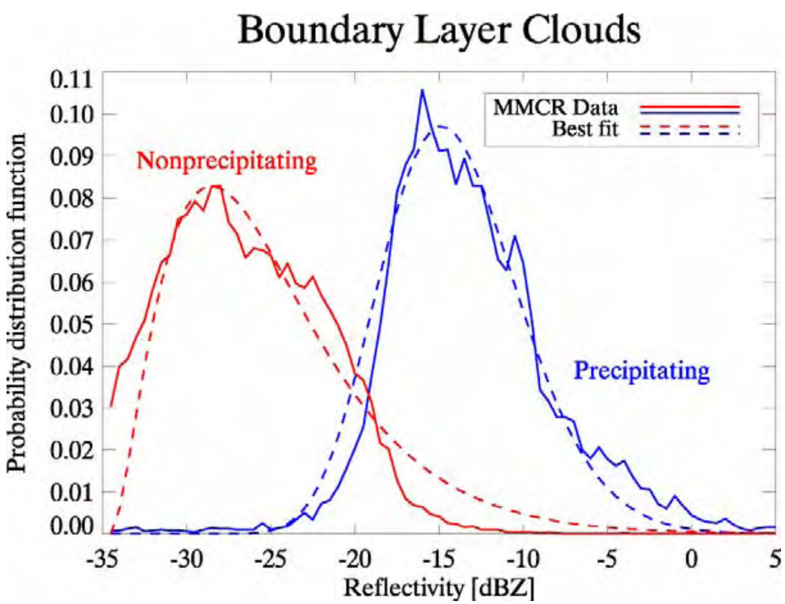


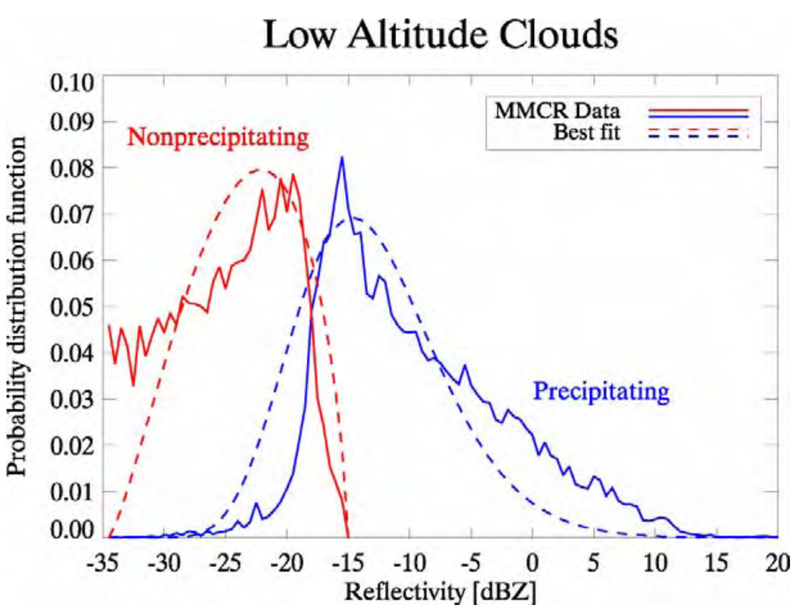
Analyses using the Surface Cloud Grid VAP data show that even on monthly time scales the measurements made in the center of the "box" do not well represent the variability inherent inside the box either for a monthly average sky cover (left) or for the sky cover time series (below) represented as a correlation analysis.

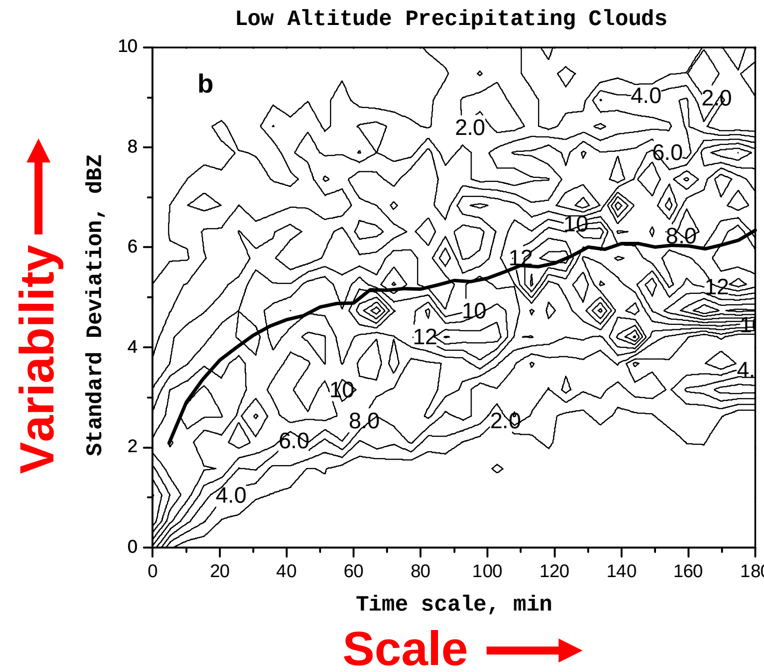
The type of analyses shown here suggest the gridded VAP to be a useful tool for the development of parameterizations to relate the larger-scale forcings resolvable by GCMs to the smaller scale features that drive the sub-grid scale dynamical processes.



Variability of low-altitude cloud systems over ACRF







ARM data suggest climate models need to take into account variability of cloud systems based on

- Cloud type
- Presence of precipitation/drizzle
- Scale

Kogan, Z. et al, 2005: JGR