1. INTRODUCTION

Our ARM funding began in 1991, with the overall purpose to exploit measurements in clouds sampled during several field programs, especially from experiments in tropical regions, in a four-component study to develop and validate cloud parameterizations for general circulation models, emphasizing ice clouds. The components were:

1. **Parameterization of basic properties of mid- and upper-tropospheric clouds, such as condensed water content, primarily with respect to cirrus from tropical areas.** Data from research aircraft served as a basis for developing and validating our parameterizations.

2. The second component was to develop parameterizations which express cloud radiative properties in terms of basic cloud microphysical properties, dealing primarily with tropical oceanic cirrus clouds and continental thunderstorm anvils, but also including altocumulus clouds.

3. The third component was to validate the parameterizations through use of ground-based measurements “calibrated” using existing and planned in-situ measurements of cloud microphysical properties and bulk radiative properties, as well as time-resolved data collected over extended periods of time.

4. The fourth component was to implement the parameterizations in the National Center for Atmospheric Research (NCAR) community climate model (CCM) II or in the NOAA-GFDL model (by L. Donner GFDL) and to perform sensitivity studies. This component was also to include conducting numerical simulations of mesoscale ice clouds for selected cases, primarily those from tropical cirrus (data collected near Kwajalein and during TOGA/COARE) which contain high quality data. The purpose of this numerical study was to gain an understanding of the physical processes responsible for the formation and development of ice clouds and their impact on climate simulations. Based on our improved knowledge of these physical processes we...
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planned to address the problems with parameterizing cirrus clouds in GCMs noted by Heymsfield and Donner (1990), and to modify and improve their GCM cirrus cloud parameterizations.

2. RESULTS OF RESEARCH
A. Tropical Cirrus Data

Objective 1 was to learn more about the microphysics of ice clouds, especially those in the tropics that formed as a result of deep convection. We proposed to analyze existing tropical cirrus data and to make measurements in tropical cirrus through participation in the NASA component of the TOGA COARE. We now have results from thunderstorm anvils using existing data collected (by A. Heymsfield) at Kwajalein, Marshall Islands, and new data collected in association with the Central Equatorial Pacific Experiment (CEPEX), which field-tested the thermostat hypothesis of Ramanathan and Collins (1991). These results are published in Heymsfield and McFarquhar (1996) and McFarquhar and Heymsfield (1996). Additional anvil microphysical data were collected in the Central Western Pacific during TOGA COARE.

The CEPEX and Kwajalein data are primarily from anvils removed from convection, although some of the Kwajalein data were collected within, and immediately adjacent to, convective cells. We examined the vertical and horizontal distributions of microphysical properties for individual case studies, including three cases from CEPEX and two cases from Kwajalein. These data are especially useful for our anvil modeling studies, as discussed later. We have also examined the statistical distributions of the microphysical parameters of the entire CEPEX and Kwajalein data sets.

The size spectra data used to derive the microphysical parameters are acquired with Particle Measuring Systems' (PMS) 1 and 2D probes which begin to size above about 30 μm. The PMS forward and axial scattering size spectrometer probes (FSSP) and (ASSP) on the aircraft measured in the size range 2 to 30 μm. However, these probes sense a combination of large ice crystals which transit through an unknown sample volume outside of the probe’s sample volume, and small ice crystals which are contained within the sample volume but are incorrectly sized, and hence inaccurate. We also collected data with a Video Ice Particle Sampler (VIPS) during CEPEX which sized crystals between 5 and above 150 μm and an ice crystal replicator at Kwajalein which could detect particles 5 μm and above. The analysis of these data is time-intensive and laborious so only a subset of the available data has been analyzed.

Analysis of the CEPEX VIPS data showed that for small IWCs, especially prevalent
at cloud tops, small crystals make substantial, but variable, contributions to the total IWC and cross-sectional area $A_c$. Smaller particles become relatively more important in the distributions of mass and cross-sectional area as altitude increases and in general when IWC decreases. Since we observed that $A_c$, closely related to cloud radiative properties, was at least one order of magnitude larger near the cloud base than the top, it was suggested that larger particles near the bottom of thick anvils or near intense convective cores were just as important in determining radiative properties as the smaller crystals near the top.

To further investigate how small crystals impact the mass and radiative properties of anvil clouds, we evaluated what the ice water content from 2 to 30 μm might have been if the FSSP had measured ice crystals accurately during CEPEX, assuming that each ice crystal detected was spherical with a density of 0.9 g cm$^{-3}$. The calculations showed that whenever the ice water content was below about $10^{-3}$ g m$^{-3}$, IWCs from the 1 and 2D probes may have been appreciably underestimated. When the IWC was above about $10^{-2}$ g m$^{-3}$, the contribution by the small ice crystals was about 20%, but this is a significant overestimate because in these instances significant numbers of large ice crystals are erroneously sensed by the FSSP.

A striking and potentially significant finding relates to a strong temperature dependence noted in the microphysical properties of the CEPEX and Kwajalein composite data sets. The ice water content (IWC) decreases systematically with decreasing temperature. The large scatter noted in the measurements in each temperature interval can be attributed to variations in storm updraft intensity and distance and time from anvil formation. The median diameters of the particle mass-size distributions, $d_m$, as determined from particle size spectra data and their conversion to mass based on the observed ice crystal habit (Heymsfield 1977) also show a systematic decrease with decreasing temperature. Frequency plots of particle cross-sectional area per size spectrum, a direct measurement from the 2D probes, and effective diameter (ratio of particle volume to area) also decrease systematically with temperature.

We have examined the dependence of particle habit on temperature, using CEPEX and Kwajalein data collected at temperatures from -15 to -83°C. Habit information is crucial for calculations of cirrus cloud radiative properties, and hence for assessing the importance of cirrus clouds on climate (Stephens et al. 1990). In general, below -45°C, plates and columns predominated, from -30 to -45°C bullet rosettes and other complex spatial forms dominated, and above -25 or -30°C planar crystals, including dendrites, and aggregates dominated. However, there is wide variability in habits at each level, reflecting both crystallographic effects and intensity of convection, among others.
We have begun an assessment as to whether the CEPEX size distributions can be parameterized in a relatively simple form as dependent on temperature and ice water content. Preliminary results are encouraging. We followed the approach of Heymsfield and Platt (1984), who parameterized the size distributions by a curve of the form

\[ N(D) = A(T,IWC) \cdot D^{B(T,IWC)} \]

where \( N(D) \) is the number distribution function and

- \( A \) and \( B \) are temperature-dependent (T) best fit curves to data observed during several different field campaigns.

An article on this subject has been submitted by McFarquhar and Heymsfield (1997). It is important to have a good knowledge of such a parameterization because of the many different circumstances in which such a parameterization is required. For example, Ebert and Curry (1992) parameterized cloud optical properties using such parameterized spectra. It is also important for the calculation of heating rates in tropical anvils.

B. Mesoscale and Numerical Modeling Calculations

In this part of our research we emphasized calculations which lead to an understanding the physical processes (microphysical and dynamical) that determine an anvil’s lifetime, and to an understanding of the anvil’s radiative properties. Our approach involved the numerical modeling of particle growth processes with the uniqueness that we made no assumptions about the evolving ice particle size distributions, using explicit microphysical measurements from CEPEX.

Recent studies have shown that anvils are not inert, passive outflows, but instead are dynamically active systems (Lilly 1988) hosting further precipitation development, perhaps driven by destabilizing radiative heating forces (Webster and Stephens, 1980). In-situ data for related modeling studies have been lacking until recently. As mentioned above, the needed microphysical and radiative measurements of tropical convection were made during CEPEX (McFarquhar and Heymsfield, 1993).

We built a simple framework in which to study the evolution of hydrometeors in a convectively-generated cirrus anvil. The simple two-dimensional system consisted of a specified flux of ice particles, buoyancy, and momentum into the model domain in the upper left-hand side, representing the outflow from a convective core into the resultant spreading stratiform anvil. While the flux into an anvil depends intimately on the convective region’s properties, we did not attempt to model the complex convective region itself nor did we address the complicated issue of ice nucleation in the convective updraft. Instead, we used the momentum, vapor, and ice fluxes that a convective region would generate to carry ice particles into the anvil. The ice particles are initially distributed with size using CEPEX...
measurements from an anvil near the convective core. From there, we predicted the anvil's structure and radiative properties using a dynamical model, showing how the interaction of dynamical and microphysical processes (including diffusional growth and sedimentation) affected the ice particle size distributions. (We used data collected in tropical anvil clouds because it was already available; this technique could be applied to the ARM SGP CART site data when the microphysical data needed to initialize and validate the model become available.)

The anelastic, nonhydrostatic, time-dependent model is used to numerically solve a system of finite difference equations for the conservation of momentum, mass, thermodynamic energy, water vapor mixing ratio, cloud water mixing ratio, and two variables that represent the ice particle size spectrum. We used a discrete representation of the ice particle size distribution, classifying ice particles into 10 independent size categories having a maximum particle diameter of 1000 μm; particles in the ith category have radius \( R \) and number concentration \( N \). Two prognostic equations describe each category – one for \( N \) and another for \( NR^3 \), which yields particle size. This treatment allows particles to sediment and sublimate at their individual rates, making no assumptions about the evolving ice particle size distribution. The boundary conditions are a closed, free-slip upper boundary, a no-slip lower boundary, and an open outflow (downstream) boundary. The numerical scheme is a forward-time, modified upstream method suggested by Soong and Ogura (1973), which conserves scalar variables in a closed domain, is positive definite, and advects quantities only downstream, but suffers from numerical diffusion. The model domain is a 2-dimensional slab (height 13 km, length 40 km), representing the outflow downwind region of a deep convective cloud. Our experiments used a 200 m grid size.

As our control experiment, we used microphysical and environmental state data collected during a case of deep tropical convection on April 4-5, 1993, north of Fiji. Penetrations upwind and downwind along the length of a cirrus anvil at 7 height intervals were made, collecting measurements of ice particle size spectra, ice water content, humidity, and temperature. These measurements were made from the source of the anvil throughout its length, providing excellent data source on the temporal and spatial evolution of ice particle size spectra within a tropical anvil. Based on these measurements, moist air laden with ice particles (0.2 g/kg) enters the anvil from the left side at 5 m/s at heights between 10 and 12 km.

This numerical model is being tied to a microphysical package developed by Heymsfield (1982) that considers the growth of the following particle types: water droplets, water drops, needles, plates and dendrites, columns, bullet rosettes, aggregates, graupel and hail.
This package considers processes such as diffusional and accretional growth, aggregation, sedimentation, evaporation, and melting. In light of the new demands by radiative transfer schemes, this package includes and tracks ice crystal habits, providing a more detailed description of particle sizes, phase, and shapes.

The model is limited currently in that (1) the growth of the cloud to its anvil-generating stage is not modeled explicitly, (2) it does not allow particle interactions that could affect the size distribution (some aggregates were noted by McFarquhar and Heymsfield, 1993), (3) the model is two-dimensional and therefore the results are not sheared, and (4) presently, radiative heating effects are not included, although likely to play a role in the anvil's life cycle. These topics will have to be avenues of further research.

A separate modeling study was done with the detailed microphysical model of Chen and Lamb (1994). The same April 4 1993 case was simulated, with reasonable agreement between the observations and model results. The details are described in a paper submitted to *Journal of Geophysical Research* (Chen et al. 1996).

C. Remote Sensing Parameterizations

Another research objective was to validate the microphysical and radiation parameterization thrusts using field data, in particular from ground-based remote sensors. We envisaged using radar at ARM CART sites, especially the tropical site, to measure radar reflectivity (dBZ), from which we could deduce ice water content, particle cross-sectional area, optical depth and albedo, using parameterizations developed from the microphysical measurements. We then intended to compare in-situ measurements over the site with those deduced from the radar.

While the necessary field data has not been collected to validate our parameterizations (the ARM tropical CART data will be available in the future), we did develop equations relating radar reflectivity dBZ to ice water content, and dBZ to ice particle cross-sectional area from the CEPEX and Kwajalein data sets. These are found to be highly temperature dependent, and such a temperature dependence has not been examined in earlier studies relating dBZ to IWC (Sassen 1984, Heymsfield 1977). We collaborated with Dr. Dave Atlas in a paper (Atlas et al. 1995) where equivalent radar reflectivity was written as a function of IWC and a moment of the size distribution such as median volume diameter $D_0$. We also collaborated with Phil Brown in a paper (Brown et al. 1995) where we assessed the potential of a spaceborne 94 GHz radar for providing useful measurements of the vertical distribution and water content of ice clouds on a global scale.

D. GCM Studies
One of the objectives of our research was to incorporate the Heymsfield and Donner (1990) ice water content parameterization into the NCAR CCM II and possibly the NOAA/GFDL GCM. This parameterization including both saturated and sublimating regions has now been incorporated into the NOAA/GFDL GCM (Donner 1994).

Preliminary studies showed that the radiative properties of ice clouds in the model are highly variable in height, latitude, longitude, and time. Thus, there is significant potential for feedbacks of various types involving ice clouds. Using the NOAA GCM we were able to determine that variations in both ice water path and particle size are important in determining the emissivity patterns. For example, for a typical sample at the .355 sigma surface, an ice cloud at 30° S with an ice water path of 15.4 g m⁻³ had an emissivity of 0.63, while at the same longitude at about 60°S, a cloud with a water path of 5.7 g m⁻² had an emissivity of 0.52. The difference could be attributed to differences in effective particle diameter (42μm vs. 93μm).

We also participated in a study where field measurements from CEPEX were used to study the link between water vapor, convection and sea surface temperature in the equatorial Pacific (Lohmann et al. 1995). Good agreement was found between the simulated and observed ice water content, in particular with respect to its increase with in-cloud temperature.

E. Radiation Studies

We have represented the particle cross-sectional area in terms of the ice water content from the tropical cirrus cloud data set as reported in Heymsfield and McFarquhar (1996). Given that we know IWC as a function of height from the Heymsfield and Donner (1990) parameterization we can derive particle cross sectional area, optical depth and cloud albedo.

Retrieved cirrus cloud optical depths and mean effective ice crystal sizes, using the polar orbiting NOAA satellite AVHRR data (at 0.63, 3.7 and 10.9 μm, have been compared with those derived from in-situ data for clouds studied during FIRE (Ou et al., 1995). While the data collection was funded through NASA/FIRE, the specific application of the in-situ data to this project was funded in part by our ARM grant.

It was found that the retrieved ice crystal mean effective size and optical depth compare reasonably well with those derived from the balloon-borne replicator measurements. This may in part be due to the much lower sizing threshold of these replicator measurements than those used in the earlier FIRE studies.
PUBLICATIONS

Resulting from Analyses using Research under DE-AI05-92ER61389


OTHER REFERENCES


