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PROPERTIES OF TROPICAL AND MIDLATITUDE ICE CLOUD PARTICLE ENSEMBLES: OBSERVATIONS AND PARAMETERIZATIONS

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1. INTRODUCTION

Advances in the treatment of ice clouds in general circulation models (GCM) will require not only better horizontal and vertical model resolution but also a better description of the microphysical and radiative properties of ice clouds. Increased emphasis on the properties of ice cloud particle ensembles rather than the properties of individual ice particles is needed for GCM and cloud and mesoscale models. In this study, we are concerned primarily with characterizing the properties of midlatitude and tropical ice PSDs, determining how they relate to the bulk properties of the particle size distributions (PSD), including the median mass diameter and median mass-weighted terminal velocity; we hope to develop an understanding of the factors that influence the dependencies. This study adds to the results from earlier studies through the use of data from both midlatitude and tropical ice clouds, as well as the use of new instrumentation to provide better habit, size spectra, and IWC information.

2. DATA SETS AND INSTRUMENTATION

Data used in this study were acquired from aircraft Lagrangian spiral descents and balloon-borne ascents through ice cloud layers that averaged more than 3 km in depth. The goals of this sampling strategy were to characterize the vertical structure of ice cloud microphysical properties between cloud top and base and to follow particles as they grew and descended through cloud layers. Temperatures for the midlatitude clouds ranged between –20 and –63°C and for the tropical clouds between 0 and -50°C .

All 19 spiral descents commenced at cloud top and ended at cloud base or below the melting layer. A group of eight spirals were obtained in synoptically-generated clouds in Wisconsin during FIRE I in the fall of 1986. A group of six spirals were conducted in anvils or stratiform regions associated with convection during the Tropical Rain Measuring Mission campaign near Kwajalein (Kwajalein Experiment, KWAJEX, summer 1999). Two spirals were obtained in synoptically-produced cirrus during the ARM field campaigns in Oklahoma during March 2000. Data were acquired during three balloon-borne ascents by the NCAR ice crystal replicator (Miloshevich and Heymsfield, 1997) through synoptically generated cirrus during FIRE II in Kansas.

Size-spectra measurements were obtained in sizes from about 50 to 1,000 μm with Particle Measuring Systems (PMS) 2D-C probes. The 2D-C resolution was 25 μm for FIRE I and 33 μm for the other field campaigns. For sizes from 1,000 μm to more than 3mm for FIRE I and the ARM campaigns, PMS 2D-P probes were used. The 2D-P probe resolution was 100 μm for the FIRE I and 200 μm for the ARM campaign. The PSDs in sizes from 1 mm to more than 3 cm for the TRMM field campaign were obtained from a Stratton Park Engineering Company (SPEC) high volume precipitation spectrometer (HVPS) probe; probe resolution was 0.2 mm. Average size distributions were measured over 5-to 7-second intervals, or about 1 km of horizontal flight distance.

Our balloon-borne replicator measurements provide information on the PSDs at temperatures

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below −50°C where a significant fraction of IWCs and particle cross-sectional areas may be below the 2D-C probe's size-detection threshold. The NCAR balloon-borne replicator collects ice particles larger than 10 to 20 μm in size, and provides detailed imagery of the particles with a resolution of a few microns.

Ice water content was measured directly by a counterflow virtual impactor (CVI) probe during the ARM field campaign and for the other field programs was calculated from the PSD and cross-sectional area, as described in Heymsfield et al. (2002).

High-resolution particle imagery was collected during the ARM and TRMM field campaigns with a SPEC cloud particle imager (CPI) probe, which obtains images of particles above about 10 to 20 μm diameter with a resolution of 2.3 μm.

3. PARAMETERIZATION OF THE PARTICLE SIZE DISTRIBUTIONS

Gamma equations of the form $N = N_0 D^{\mu} e^{-\lambda D}$ were fitted to the measured particle size distributions (PSDs) over sizes(D) from as small as tens of microns to as large as 1.5 cm using a moment-matching technique. The intercept parameter N_0 and the slope λ were related to each other (Fig. 1A), with λ and N_0 values decreasing monotonically with height. The μ values tended from positive values of 2 to 4 at large λ to –1 to –2 at small λ. The maximum measured diameter, D_{max}, increased with decreasing λ (not shown). These trends are consistent with aggregational growth and mirror qualitative trends and quantitative values found by earlier investigators for midlatitude clouds at temperatures above –25°C . The N_0 values from the midlatitude clouds were about an order of magnitude lower than those for the tropical PSDs. The λ parameter showed a weak dependence on temperature, (not shown) ranging from about 300 cm^{-1} at temperatures near -50°C to about 10 cm^{-1} near 0°C.

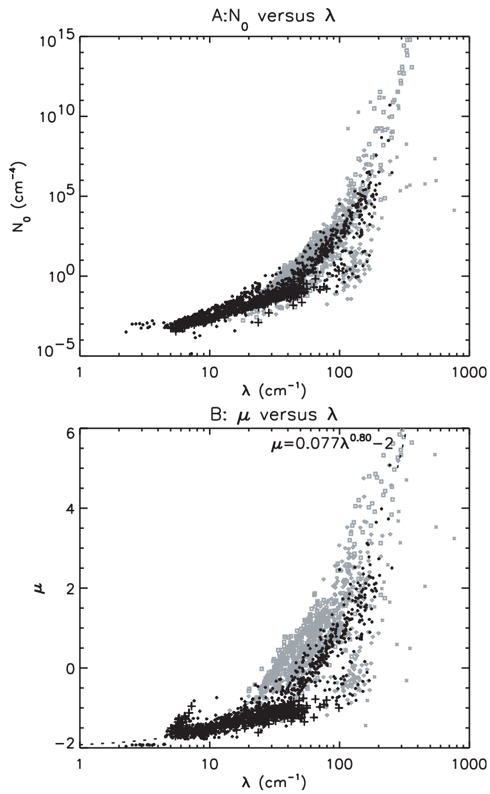

Figure 1. Gamma fit parameters to PSD observations in midlatitude (light symbols) and tropical clouds (dark symbols).

4. BULK PROPERTIES

Bulk properties are derived from the fitted PSDs. The ice water content, IWC, was derived from an analytic solution to the equation IWC $= \int_0^{D_{max}} N(D)m(D)dD$, where the particle mass m is based on Heymsfield et al. (2002) and depends both on particle dimension and cross-sectional area. The IWC is shown as a function of λ in Fig. 2A. The IWC ranged from 0.0005 to 1 g m^{-3} and were about an order of magnitude higher for the tropical than for the midlatitude data set, because the midlatitude N_0 (and total particle concentration) values are lower.

The median mass diameter (D_m) was derived from the point at which the cumulative distribution of IWC with size is 50% of the total IWC. The D_m values are highly correlated with IWC (Fig. 2B).

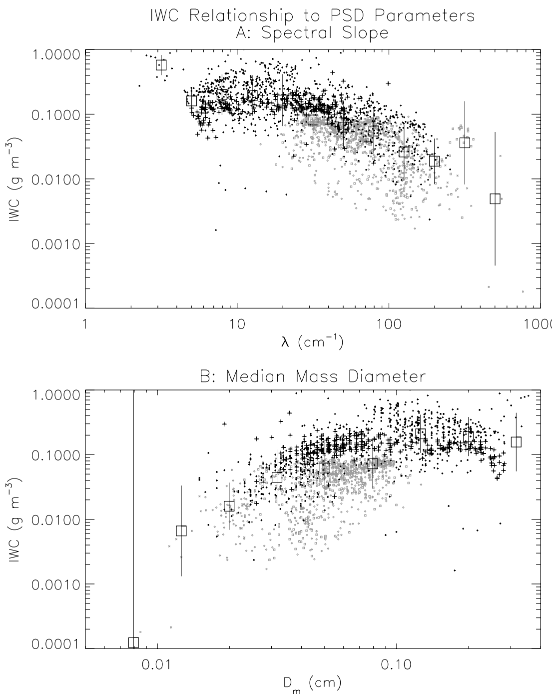

Figure 2. Top: IWC vs λ, with symbols same as in Fig. 1. Bottom: IWC vs median mass diameter.

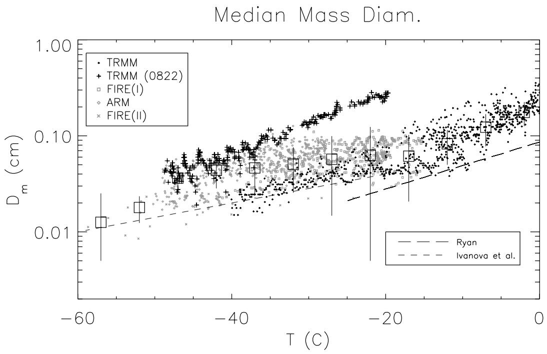

Figure 3. Median mass diameter as a function of temperature. Symbols same as in Fig. 1

On average, the D_m values increase from about 100 μm near –55°C to about ten times that value near 0°C (Fig. 3), but considerable variability is observed in this relationship. The leveling off of the average values of D_m (large squares) between –25 and –15°C results from higher than average D_m values at temperatures below –25°C for the 22 August 1999 KWAJEX case which was adjacent to convection (points markedly above the D_m values for the other tropical clouds in the figure and identified with larger symbols). D_m versus temperature values based on the exponential PSDs of Ryan (2000) are plotted in Fig. 3. The Ryan D_m curve drops more steeply with temperature than found in our observations— because the concentrations in small sizes are represented over this temperature range by an exponential– but overall, the agreement is quite good. The curve labeled Ivanova et al. (2001) relates D_m to temperature using gamma PSDs fit to measurements from midlatitude cirrus PSDs. This curve also produces lower values of D_m than we observed here except at the temperatures below –50°C .

The median mass-weighted terminal velocity (V_m) was derived using the cumulative distribution of ice mass flux with size, normalized by the IWC. The terminal velocities were calculated as in Khvorostanyov and Curry (2001), modified according to the experimental data reported in Heymsfield et al. (2002). The V_m generally increased with the IWC (Fig. 4). Much of the variability found in the figure (see $\pm$ 1 σ bounds) results from variability in the coefficient N_0, which influences IWC but not V_m. There is a great deal of variability in the tropical data set (Fig. 4A), largely because of the inclusion of points for the 0822 KWAJEX case that occurred in the proximity of convection; we believe that this variability reflects the wide range of conditions that may be sampled in association with convectively induced ice cloud layers. The scatter observed in the midlatitude data sets (Fig. 4B) is smaller. In the composite data set (Fig. 4C), on average, there is approximately an order of magnitude increase in V_m, from about 10 to 100 cm s^{-1}, with three orders of magnitude increase in IWC. The V_m are somewhat higher than those estimated by Heymsfield and Donner (1990) from midlatitude observations.

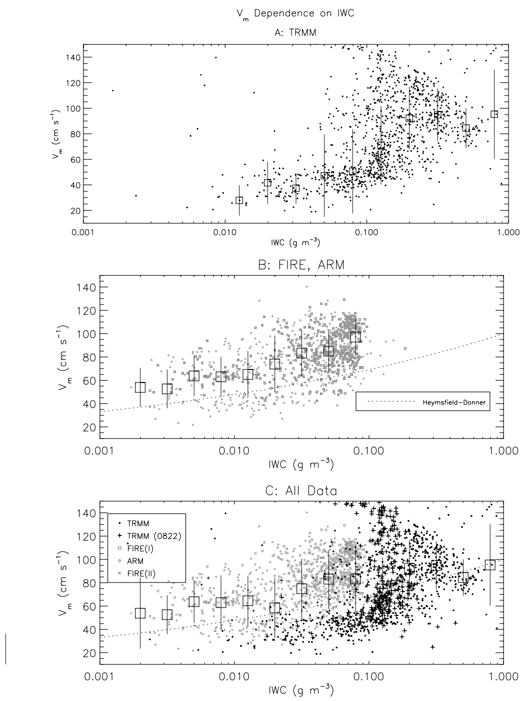

Figure 4. Median mass-weighted terminal velocity as a function of temperature for A: Tropical ice clouds, B: Midlatitude clouds, and C: Both combined.

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5. SUMMARY AND CONCLUSIONS

This study has sought to improve knowledge of mass and terminal velocity properties of ensembles of ice particles found in deep cirrus and stratiform ice cloud layers in midlatitude and tropical regions. The interpretations are based on gamma and exponential curves fitted to particle size distributions measured over the temperature range of –60 to 0°C . Relationships between ice water content, median mass diameter, and median mass-weighted terminal velocity were developed from the data, leading to the following equations for the midlatitude and tropical data sets combined (cgs):

- IWC = $1.17\lambda^{-0.76}$ r^2=0.94.
- IWC = $13.01{D_m}^{2.04}$ r^2=0.86.
- $V_m = 116\mathrm{IWC}^{0.16}$, r^2=0.84.

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