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# Quality Control and Analysis of Microphysical Data Collected in TRMM Aircraft Validation Experiments

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## Final Report

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This report summarizes our efforts on the funded project "Quality Control and Analysis of Microphysical Data Collected in TRMM Airborne Validation Experiments", NASA NAG5-9663, Andrew Heymsfield, P. I. We begin this report by summarizing our activities in FY2000-FY2004. We then present some highlights of our work. The last part of the report lists the publications that have resulted from our funding through this grant.

### SUMMARY OF ACTIVITIES

In *FY2000-2001*, we focused on analyzing data from the TRMM field campaigns TEFLUN-B, LBA and Kwajex. Seminars reporting on the results of our analysis were presented by Andy Heymsfield at NASA GSFC, Colorado State University, and at the National Center for Atmospheric Research. A talk describing the results was presented at the European Geophysical Society (EGS) meeting in Nice.

In *FY2001-2002*, progress was made in five areas. We completed a manuscript that described the microphysical properties of the stratiform ice cloud regions observed during the TRMM field campaigns. (See Reference List, Heymsfield et al., 2002). The study also developed parameterizations for these properties for use by the remote sensing and modeling communities, as described in the section on "Primary Findings" below. The results were presented at the TRMM Workshop in October 2001. We also worked with Jeff Stith to incorporate some of our findings in a paper, which he published (Stith et al., 2002).

The data from the stratiform ice cloud regions were used to study the relationship between the radar reflectivity at various radar wavelengths and the precipitation rate, for ice clouds. The wavelengths include those of the TRMM radar and those proposed for the Global Precipitation Mission (GPM). The results of this work were presented at the TRMM Science Meeting during July 2002.

The data from the stratiform ice cloud regions were used to characterize the fall velocity characteristics of tropical ice cloud populations. Two papers describing these activities appear in the list of references (Heymsfield, 2003).

We assisted with the software development effort for the Common Microphysics Product (CMP) definition. Specifically, we helped to debug the software that was developed by Alexei Korolev, and assisted Jeffrey Stith and Julie Haggerty with the quality control. This work led to a publication (Kingsmill et al., 2004, see below).

In *FY2003-2004*, we continued our work on a project that related properties of the particle size distributions and particle habits during the periods defined by the CMP effort to coincident measured radar reflectivity. We derived gamma fit coefficients that described the intercept, slope, and dispersion that characterize the particle size distributions. These size distributions were related to those measured in hurricanes during CAMEX-4 and also in midlatitude storms. A publication describing this work appears in the reference list (Heymsfield et al., 2004).

We also worked on a characterization of the properties of the particle size distributions in convective cells sampled by the Citation aircraft during LBA and KWAJEX. This and associated work led to a publication (Stith et al., 2004). Seminars describing our activities were presented at NCAR, Colorado State University, and at Cal Tech University.

## PRIMARY FINDINGS

Some of the main findings from our analysis of the TRMM microphysical data were reported in the articles identified in the reference list. The measurements of particle size distributions (PSDs) and ice particle habits we helped to acquire during slow, Lagrangian-type spiral descents through deep subtropical and tropical stratiform cloud layers in Florida, Brazil and Kwajalein, Marshall Islands were examined and synthesized. Our purpose with this type of flight pattern was to learn more about how the PSDs evolved with height in the cloud layer, and to develop parameterizations for the resulting observations. Most of these spirals began at cloud top, with temperatures (T) as low as -50C, and they ended at cloud base or below the melting layer (ML). Our analysis has shown that the PSDs broadened downwards, with the diameters of the largest particles increasing from several millimeters at cloud top to one centimeter or larger at the top of the ML. There was some continued particle growth in the ML. The concentrations of the sub-1 mm size particles decreased with vertical distance from the top to bottom of the cloud layer. The result was a consistent change in the PSDs in the vertical. Aggregation, as ascertained from both the changes in the PSDs and evolution of particle habits, was responsible for these trends.

Until recently, we found that the PSDs were generally well represented by exponential curves. However, our conclusions are changing, and the resulting analysis is taking quite a bit of time. We searched for a better representation of the PSDs over the size range from tens of microns to few cm than could be provided by exponentials, as the latter did a poor job of representing the PSDs below 500 or so microns. We are progressing very well on this issue, and are now using a gamma distribution with a variable order that depends primarily on temperature.

The use of exponential size distributions did reveal some very interesting results. The slope $\lambda$ of the exponentials varied systematically with temperature, and conformed to previous studies for mid-latitude frontal and cirrus layers. However, the temperature did not appear to be the fundamental factor controlling $\lambda$. Rather it depended on such factors as the collection kernel for aggregation and the time available for this process to occur. A direct relationship was found between $\lambda$ and the intercept $N_0$ .This relationship was not found clearly in earlier studies because the PSDs in our observations had better fidelity with less scatter. In the ice regions and upper part of the ML, the $N_o$ and $\lambda$ decreased, and in the lower part of the ML they began to increase as the largest particles melted. Figure 1 shows an example of the $N_o$ vs. $\lambda$ relationship assuming an exponential distribution; this will change somewhat when our investigation of the gamma functional form is completed.

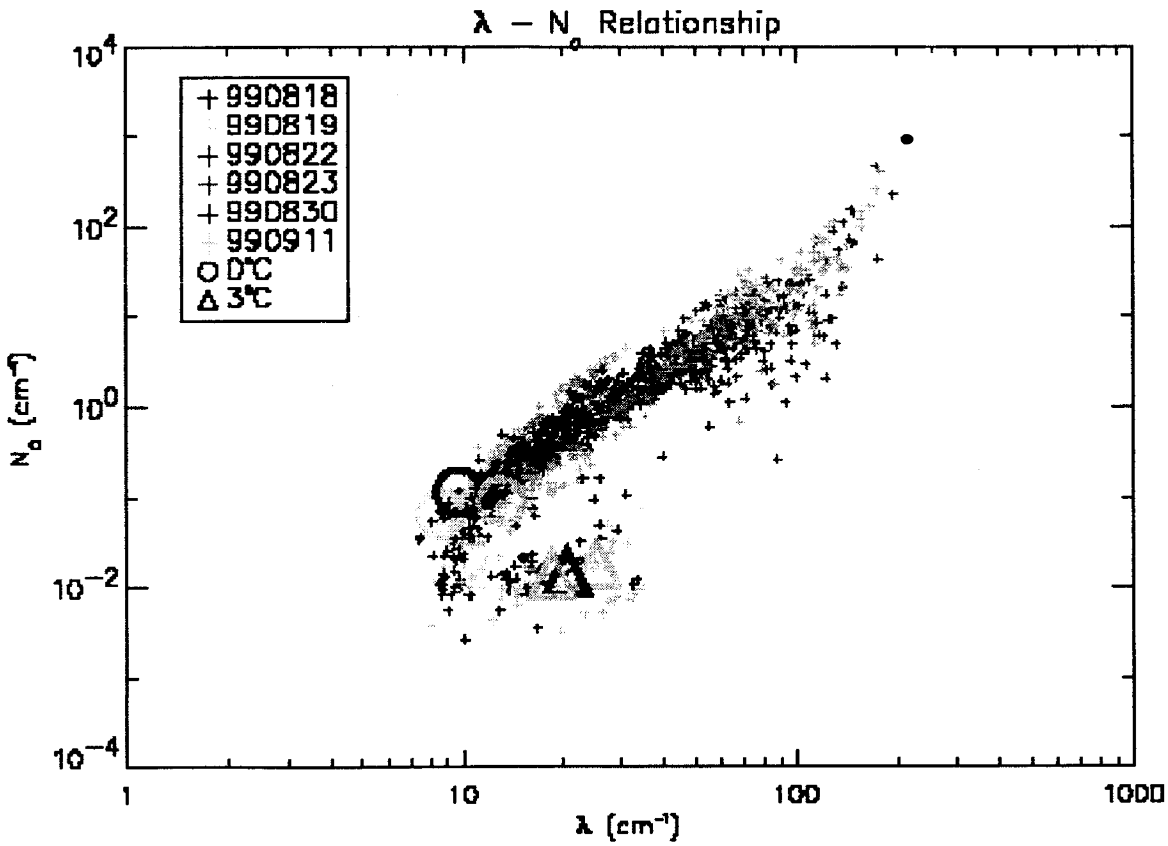


Figure 1 $N_o$ vs. $\lambda$ relationship for spirals on six days during KWAJEX. Different colors represent different spirals. Large symbols represent data points at temperatures of 0 and 3°C

General expressions were developed relating $N_o$ to $\lambda$ for various bulk microphysical and radar variables, as shown below in Table 1. These expressions are undergoing minor revision to take into account our observations that the PSDs were better represented by gamma distributions than by exponentials (gamma of order 0). Nevertheless, we feel that it is useful to show the types of relationships that we developed. Relationships are included in Table 1 to obtain ice water content (IWC), radar reflectivity factor ($Z$), mass and reflectivity-weighted fall velocities ($Vm$ and $Vz$), precipitation rate ($R$), cross sectional area of the particle population ($A$), and effective radius ($r_e$). These expressions appear to apply to both tropical and mid-latitude clouds and facilitate the specification of $N_o$ and $\lambda$ for cloud and climate models. These expressions are also useful for interpreting vertically pointing radar data. Given $N_o$ and $\lambda$ other properties, e.g., mass-weighted fallspeed, can be derived. The approach is well suited to calculation of IWC, precipitation rate, and radar-related parameters where reflectivities are from 0 to 25 $dBZ_e$.

**Table 1**

**Equations to Derive $N_0$, $\lambda$ from Microphysical and Radar Variables**

| Variable | Full Spectrum | $N_0, \lambda$ Eq. | Spectrum Truncated at $D_{max}$* | $N_0, \lambda$ Eq. |
|---|---|---|---|---|
| **IWC** $[\frac{g}{m^3}]$ | $\frac{N_0 \pi k a^n \Gamma(4 + bn + \alpha)}{6\lambda^{(4 + bn + \alpha)}}$ | $\frac{1.5 \times 10^4 N_0}{\lambda^{3.4}}$ | $\frac{N_0 \pi k a^n \gamma(4 + bn + \alpha, \lambda D_{max})}{6\lambda^{(4 + bn + \alpha)}}$ | $\frac{5.3 \times 10^3 N_0 \gamma(3.4, 9.65\lambda^{0.1})}{\lambda^{3.4}}$ |
| **Z** $[\frac{mm^6}{m^3}]$ | $\frac{N_0 k^2 a^{2n} \Gamma(7 + 2bn + 2\alpha)}{\rho_w{}^2 \lambda^{(7 + 2bn + 2\alpha)}}$ | $2.2\frac{N_0 \times 10^9}{\lambda^{5.7}}$ | $\frac{N_0 k^2 a^{2n} \gamma(7 + 2bn + 2\alpha, \lambda D_{max})}{\rho_w{}^2 \lambda^{(7 + 2bn + 2\alpha)}}$ | $\frac{1.0 \times 10^8 N_0 \gamma(5.7, 9.65\lambda^{0.1})}{\lambda^{5.7}}$ |
| $\mathbf{V}_m$ $[\frac{cm}{s}]$ | $\frac{C\lambda^{(1 - \kappa)}\Gamma(\kappa + 3)}{\Gamma(4)}$ | $640\lambda^{-0.57}$ | $\frac{C\lambda^{(1 - \kappa)}\gamma(\kappa + 3, \lambda D_{max})}{\gamma(4, \lambda D_{max})}$ | $\frac{300\lambda^{-0.57}\gamma(4.a6, 9.65\lambda^{0.1})}{\gamma(4, 9.65\lambda^{0.1})}$ |
| $V_Z$ $[\frac{cm}{s}]$ | $\frac{C\lambda^{(1 - \kappa)}\Gamma(\kappa + 6)}{\Gamma(7)}$ | $900\lambda^{-0.57}$ | $\frac{C\lambda^{(1 - \kappa)}\gamma(\kappa + 6, \lambda D_{max})}{\gamma(7, \lambda D_{max})}$ | $\frac{300\lambda^{-0.57}\gamma(7.6, 9.65\lambda^{0.1})}{\gamma(7, 9.65\lambda^{0.1})}$ |
| **R** $[\frac{mm}{hr}]$ | $\frac{C N_0 \pi k a^n \Gamma(\kappa + 4 + bn + \alpha)}{6\rho_w \lambda^{(\kappa + 4 + bn + \alpha)}}$ | $\frac{3.2 \times 10^5 N_0}{\lambda^{3.9}}$ | $\frac{C N_0 \pi k a^n \gamma(\kappa + 4 + bn + \alpha, \lambda D_{max})}{6\rho_w \lambda^{(\kappa + 4 + bn + \alpha)}}$ | $\frac{5.8 \times 10^4 N_0 \gamma(3.9, 9.65\lambda^{0.1})}{\lambda^{3.9}}$ |
| **A** $[\frac{cm^2}{cm^3}]$ | $\frac{N_0 \pi a \Gamma(3 + b)}{4\lambda^{(3 + b)}}$ | $\frac{0.58 N_0}{\lambda^{2.9}}$ | $\frac{N_0 \pi a \gamma(3 + b, \lambda D_{max})}{4\lambda^{(3 + b}}$ | $\frac{0.31 N_0 \gamma(2.9, 9.65\lambda^{0.1})}{\lambda^{2.9}}$ |
| $\epsilon$ $[km^{-1}]$ | 2Ax$10^5$ | | | |

* **Incomplete gamma function:** $\gamma(a,x) = \int_0^x t^{(a - 1)} e^{-t} dt$. **Units unless otherwise stated: cgs.**

**Equations based on the following relationships:**

**Mass:** $m = \frac{\pi}{6}\rho_e D^3$. **Effective density:** $\rho_e = k(A_r)^n D^\alpha$, $k = 0.4$, $n = 1.5$, $\alpha = -0.5$

**Area Ratio:** $A_r = aD^b$, $a = 0.40$, $b = -0.09$

**Terminal Velocity:** $V_t = a_f(\frac{4gk}{3\rho_a})^{b_f} \nu^{(1 - 2b_f)} D^{(3b_f - 1)} A_r^{(n - 1)b_f}$.

**Drag Coefficient Parameters:** $a_f = 1.653$, $b_f = 0.465$. **Kinematic viscosity:** $\nu$.

**Air density:** $\rho_a$

$\kappa = b_f[b(n - 1) + 3 + \alpha]$

$\mathbf{C} = \mathbf{a}^{b_f(n-1)} \mathbf{a}_f (\frac{4gk}{3\rho_a})^{b_f} \nu^{(1-2b_f)}$, **P = 500 hPa, T = 0°C**

The data used in this analysis was incorporated into calculations reported in the two papers on terminal velocity by Heymsfield (2003).

## LIST OF PUBLICATIONS

Heymsfield, A. J*, A. Bansemer, P. R. Field, S. L. Durden, J. Stith, J. E. Dye, W. Hall and T Grainger, 2002: Observations and parameterizations of particle size distributions in deep tropical cirrus and stratiform precipitating clouds: Results from in---situ observations in TRMM field campaigns. *J. Atmos. Sci.*, **59**, 3457--3491.

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Heymsfield, A. J. **, S. Matrosov, and B. Baum, 2003: Ice Water Path--Optical Depth Relationships for Cirrus and Deep Stratiform Ice Cloud Layers. *J. Appl. Meteor.*, **42**, 1369--1390.

Heymsfield, A. J., A. Bansemer, S. L. Durden, and T. P. Bui, 2004: Ice microphysics observations in Hurricane Humberto: Comparison with non-hurricane generated ice cloud layers. Submitted to *J. Atmos. Sci.*.

Stith, J. L., J. A. Hagerty, A. J. Heymsfield, and C. A. Grainger, 2004: Microphysical characteristics of tropical updrafts in clean conditions. *J. Appl. Meteor.*, in press.

Kingsmill, D., E., S. E. Yuter, A. J. Heymsfield, P. V. Hobbs, A. V. Korolev, J. L. Stith, A. Bansemer, and J. A. Haggerty, 2004: TRMM Common Microphysics Products: A tool for evaluating spaceborne Precipitation retrieval algorithms. *J. Appl. Meteor.*, in press.

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