

# **Refinement of Ice Cloud Bulk Optical Models: From Microphysical Measurements to Global Retrievals Using Multiple Satellite Instruments**

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Final Report

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## **Introduction**

The goals of this work were to:

- Extend the spectral range of the calculations to encompass 0.45 through 2.25  $\mu\text{m}$  at a spectral resolution of 0.01  $\mu\text{m}$  for both (a) smooth-faced particles, and (b) particles with “roughened” surfaces. Particles with roughened surfaces are more representative of those found in cirrus, and the scattering phase function is featureless at visible wavelengths.
- Extend the calculations to a much broader set of particle size distributions that encompass more climatic regimes.
- Extend theoretical scattering calculations to new habits that better capture the physical attributes and complexity of ice particles found in nature.
- Improve the computational capabilities for simulating the single-scattering properties of ice crystals, e.g., develop a physically-based approach to treat the delta-transmission when the size parameter is large and incorporate the edge effect in computing the extinction and absorption efficiencies.

This report summarizes results for the proposed effort. We are pleased to report that our goals were met. This team was quite productive in both the development of the models and also the number of journal articles that resulted during the course of this effort.

Specifically, a paper by Zhang et al. (2009) discusses the implication of the ice cloud retrievals of optical thickness and particle size in the global MODIS products. We worked with a graduate student of Prof. B. J. Sohn in South Korea, who used our ice models to investigate the ability of a radiative transfer model to simulate MODIS radiances for ice clouds: Ham et al. (2009). Ding et al. (2009) discusses aspects of the Legendre decomposition of the scattering phase functions for ice clouds as well as water clouds and dust. The Legendre decomposition process is required for radiative transfer calculations. Hong et al. (2009) developed a parameterization of shortwave and longwave radiative properties of ice clouds for use in climate models, also based on our ice models. In a study on the color ratio (for CALIPSO) that used our single scattering properties, Bi et al. (2009) discussed a number of improvements to the calculation of ice particle scattering properties. Schmitt and Heymsfield (2007) and Heymsfield et al. (2008) discuss progress regarding hollow bullet rosettes and microphysical measurements in various ice cloud environments. These papers provide a rough idea of the breadth of our work and how it is percolating through the scientific community.

### **Status of Current Libraries of Ice Particle Single Scattering Properties**

In previous work, we used two different extensive libraries (one solar, one infrared) of the microphysical and single-scattering properties that were developed for a variety of ice crystal habits, including droxtals, three-dimensional bullet rosettes, solid and hollow columns, plates, and aggregates. One of these databases covered solar wavelengths although there were some spectral gaps. These gaps complicated our effort to build spectral models of ice cloud single-scattering properties for the solar spectral flux radiometer (SSFR, Peter Pilewski, University of Colorado-Boulder). These gaps also prevent us from developing broader band models for use in shortwave radiance/flux calculations. The other database covered the near infrared to far infrared wavelength spectrum. However, some aspects (e.g., aspect ratio) of the previous database of the scattering properties were not consistent over the solar and infrared spectral regions. Our team's focus was on improving the description of ice cloud scattering properties at solar wavelengths.

### **Detailed progress over the course of this effort**

A number of research advances regarding the light scattering calculations were made since the advent of the ice models detailed in Baum et al. (2005a, 2005b, 2007).

1. Andy Heymsfield and Carl Schmitt (both of NCAR) noted that ice particles are predominately hollow rather than solid (Schmitt and Heymsfield, 2007). By hollow bullet rosette, we mean a particle in which each bullet crystal of the rosette contains a cone-shaped hollow intrusion at its end. However, the scattering properties of hollow bullet rosettes are quite different from those of solid bullet rosettes, as shown in Yang et al. (2008). We now have available a new ice habit that will be more realistic and have incorporated it into our calculations.
2. It has also been noted by Andy Heymsfield and Carl Schmitt that our aggregate particle is not an optimal choice. Our current aggregate is basically a number of solid columns attached randomly, but with very little open space. Thus, this

- aggregate has a relatively high volume to area ratio. In Figure 1 is shown a collage of images of a more realistic aggregate provided by Heymsfield and Schmitt. What is striking about these images is the predominance of plates rather than columns, and also how much “open space” there tends to be with these aggregates, i.e., a much lower volume to area ratio. To address this development, Ping Yang and colleagues developed a mathematical representation for a new ice aggregate consisting of plates. Progress on this particle required further improvements to the improved geometric optics model (IGOM) that was detailed in Bi et al. (2009). A paper on the new aggregate of plates was developed, submitted and published (Xie et al. 2011).
3. The light scattering calculations performed by Ping Yang and colleagues depend on having an accurate database of the ice index of refraction. For our calculations, we have previously used the compilation published by Steve Warren in 1984. However, this compilation is being updated to use the new data in Warren and Brandt (JGR, 2008).
  4. Ping Yang and his colleagues have been improving the scattering computational models. For example, the delta-transmission term in the phase function caused some confusion within the user community. With a new treatment that considers a continuous distribution of scattered energy in the improved models, there will no longer be a delta transmission term in the models. The new computational package includes state-of-the-art models such as the PSTD, ADDA, and IGOM. Substantial effort has been made to intercompare these models. Given these developments, Dr. Ping Yang and colleagues are incorporating these advances and also improvements in the mechanics of actually performing the light scattering calculations, and are now in the midst of developing a new solar database for the various ice particle habits. The library will include calculations for smooth, moderately roughened, and severely roughened particles.
  5. Recent research to compare ice cloud properties from POLDER and MODIS suggests that the MODIS ice cloud scattering models do not work well with polarized measurements from POLDER (Zhang et al. 2009). The primary problem was traced to the assumption that our ice scattering properties are developed for particles having smooth facets rather than roughened facets. Use of smooth particles, such as for plates and columns, lead to the presence of halos in the forward scattering direction and also enhanced backscattering. POLDER polarization measurements tend to indicate that a roughened particle is more consistent. Roughened particles tend to have a smoother scattering phase function than smooth particles at visible wavelengths (i.e. no halos, reduced backscattering). Unfortunately, POLDER provides only up to 14 angles per observation, and this is not enough to fully intercompare the measurements with theoretical models. The angular and spectral information provided by GLORY would have been immensely useful to this effort. The new solar database provides the necessary phase matrix information necessary for intercomparison with POLDER/PARASOL data.
  6. A new particle habit distribution was developed to be more consistent with atmospheric particle observations (Baum et al. 2011) by Drs. Carl Schmitt and Andy Heymsfield at NCAR. The previous habit mixture (Baum et al. 2005a) was

chosen to minimize the uncertainty between measured and calculated bulk microphysical properties. The new habit recipe additionally attempts to portray more accurately the types of ice particles present in each size range. The habits have been chosen to correspond to those observed in the top layers of clouds as passive remote sensing instruments get the most information from those layers. The new habit distribution includes the use of hollow bullet rosettes, small aggregates of plates, and large aggregates of plates (see Baum et al. 2011).

## **In Situ Ice Cloud Microphysical Data**

### *a. Field campaign data used in MODIS Collection 5 cloud products*

While this investigator team used about 1,100 individual particle size distributions (PSDs) for our earlier studies, we now have about 13,000 PSDs, and the list is growing. Data are now incorporated from a number of recent field campaigns as shown in Table 1. The number of PSDs available for use has increased by more than an order of magnitude, from 1117 to 12,815, even when filtering the available data using the homogeneous freezing temperature, i.e.,  $T_{cld} \leq -40^\circ\text{C}$ . The IWC now ranges from  $10^{-6}$  to  $10^0 \text{ g m}^{-3}$ , an increase of three orders of magnitude from the Baum et al. (2005a) study. The IWC is obtained by applying an improved mass-dimensional relationship to each PSD.

The number concentration of small particles that may be present in a given PSD has received much scrutiny in recent years. One question is: how many of the small particles are caused by large particles shattering at the inlet to the 2D-C (and similar) probe? Microphysical data have been reprocessed and incorporated from the ARM, TRMM, and CRYSTAL-FACE campaigns to mitigate the shattering issue for the 2D probes as described by Field et al. (2006). New data have been provided from Pre-AVE (Aura Validation Experiment, 2004), MidCiX (Midlatitude Cirrus Experiment, 2004), and from SCOUT (Stratospheric-Climatic links with emphasis On the Upper Troposphere and lower stratosphere) campaign held in November-December, 2005, in Darwin, Australia. For SCOUT, the targeted ice clouds were in the upper troposphere and lower stratosphere (deReus et al. 2009). The PSD data were obtained from a Forward Scattering Spectrometer Probe (FSSP). Because of the absence of particles of sizes several hundred microns and above, data from the small particle probes were less subject to shattered artifacts. The SCOUT data are from eight flights and span the temperature range  $-30^\circ\text{C}$  to  $-86^\circ\text{C}$ . Also from Darwin are microphysical data obtained during the ACTIVE (Aerosol and Chemical Transport in tropical conVEction) campaign in Darwin, Australia, from November, 2005, to February, 2006 (e.g., Jin et al. 2010). For ACTIVE, anvil cirrus were sampled at temperatures from  $-31^\circ\text{C}$  to  $-66^\circ\text{C}$ , from regimes including pre-monsoon, monsoon, and localized convection events such as a daily thunderstorm that forms over the Tiwi Islands near Darwin, Australia during the wet season that is so consistent that it has been given a name: “Hector”.

The National Center for Atmospheric Research (NCAR) Video Ice Particle Sampler (VIPS) probe is used to obtain particle size data down to sizes of about  $10 \mu\text{m}$ . The VIPS data do not have the same shattering issues that other small particle probes may have, but the data are obtained under more limited conditions because of the need for mostly small particles that do not shatter, such as in the pre-AVE and SCOUT campaigns. Based on

these new data, it is now possible to build models for much lower  $D_{eff}$  values without artificially increasing the number of small particles.

**Table 1: Number of particle size distributions for each field campaign. The total sample set has been filtered by the requirement that the cloud temperature be colder than  $-40^{\circ}\text{C}$ . A total of 12,815 PSDs are presently available.**

Field Campaign	Location and Year	Number of 5-sec averaged PSDs $T_{\text{cld}} \leq -40^{\circ}\text{C}$	Probes
ARM IOP	Oklahoma, USA	1420	2D-C, 2D-P, CPI
TRMM KWAJEX	Kwajalein, Marshall Islands	201	2D-C, 2D-P, CPI
CRYSTAL-FACE	Caribbean	62	CAPS, VIPS
SCOUT		553	FSSP, CIP
ACTIVE -Monsoons		4268	CAPS
ACTIVE -Squall Lines		740	CAPS
ACTIVE -Hectors		2583	CAPS
MidCiX	Oklahoma, USA	2968	CAPS, VIPS
Pre-AVE		20	VIPS

## Summary

The response of the remote sensing community to our ice models has been tremendously positive. Over the course of this proposal period, we have improved several aspects of the models that needed further development. A number of studies have been initiated to intercompare ice cloud products from different sensors on the A-Train, and these comparisons have been instrumental in illuminating the advances that the models must take in the future. Over the course of this effort, this team (Drs. Ping Yang, Andy Heymsfield, and Bryan Baum) has worked extremely closely to address the issues. Based on the new databases of ice particle scattering properties that now include more consistent properties across the spectrum from the UV through the Far-Infrared, we are now able to explore the differences between smooth and roughened particles, and incorporate new ice habits including the hollow bullet rosette and aggregate of plates.

## Relevant publications, funded primarily or in part under this proposal:

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