Ice Cloud Bulk Scattering and Absorption Models: Refinement Through Comparison of Hyperspectral, Narrowband, and Polarization Sensors

FINAL REPORT
Contract number: NNX11AF40G
Activities: February 2011 - August 2014

Bryan A. Baum (PI)
Space Science and Engineering Center
University of Wisconsin-Madison
Madison, WI 53705
bryan.baum@ssec.wisc.edu

Dr. Ping Yang (Co-I)
Department of Atmospheric Sciences
Texas A&M University
College Station, TX 77843
Email: pyang@ariel.met.tamu.edu

Dr. Andrew Heymsfield (Co-I)
National Center for Atmospheric Research
Boulder, CO
Email: heyms1@ucar.edu

Introduction

Specific goals of this proposal are to:

- Continue to improve the accuracy of existing numerical models for computing the optical properties of ice crystals, including the enhancement of the modeling capabilities for complex particle habits, surface roughness, and the Rayleigh-to-geometric-optics transition (i.e., the so-called resonant regime) size parameter region.
- Include ice particle polarization and surface roughness in the models.
- Include microphysical data from more field campaigns and take advantage of new probes that measure size distributions and shapes for particles smaller than 50 microns.
- Update the suite of ice cloud bulk scattering models as knowledge is gained from their application in various research efforts,
- Continue to collaborate with different groups to investigate multisensor intercomparison studies, and
- Conduct studies to evaluate our models and their uncertainties.

This final report summarizes results for the entire grant period February 2011 – August 2014. This team has essentially accomplished the goals outlined above, and our models are available on-line at http://www.ssec.wisc.edu/ice_models. Our models are fully documented in the literature, and a list of journal articles is provided below that were developed with full or partial support under this grant.

We would especially like to thank NASA for making this research possible. This has been an incredibly rewarding and productive experience, and our models are now being used widely around the world.

Journal papers for which this grant is explicitly listed in the Acknowledgments section of the published article:

Wang, C., P. Yang, B. A. Baum, S. Platnick, A. K. Heidinger, Y.-X. Hu, and R. E. Holz: Retrieval of ice cloud optical thickness and effective particle size using a fast infrared radiative transfer model. *J. Appl. Meteor. Clim.*, **50**, 2283-2297.

Zhou, C., P. Yang, A. E. Dessler, Y.-X. Hu, and B. A. Baum, 2012: Study of horizontally oriented crystals based on CALIPSO observations in conjunction with Monte Carlo radiative transfer simulations. *J. Appl. Meteor. Clim.*, **51**, 1426-1439.

Wang, C., S. Ding, P. Yang, A. E. Dessler, and B. A. Baum, 2012: A new method to retrieving cirrus cloud height with a combination of MODIS 1.24– and 1.38–µm channels. *Geophys. Res. Lett.*, 39, L24806, doi:10.1029/2012GL053854.

Yang, P., L. Bi, B. A. Baum, K.-N. Liou, G. Kattawar, and M. Mishchenko, 2013: Spectrally consistent scattering, absorption, and polarization properties of atmospheric ice crystals at wavelengths from 0.2 µm to 100 µm. *J. Atmos. Sci.*, **70**, 330-347.

Cole, B., P. Yang, B. A. Baum, J. Riedi, L. Labonnote, F. Thieuleux, and S. Platnick, 2013: Comparison of PARASOL observations with polarized reflectances simulated using different ice habit mixtures. *J. Appl. Meteor. Clim.*, **52**, 186-196.

Wang, C., P. Yang, S. L. Nasiri, S. Platnick, B. A. Baum, A. K. Heidinger, and X. Liu, 2013a: A fast radiative transfer model for visible through shortwave infrared spectral reflectances in clear and cloudy atmospheres. *J. Quant. Spectrosc. Radiant. Transfer*, **116**, 122-131.

Wang, C., P. Yang, S. Platnick, A. K. Heidinger, B. A. Baum, T. Greenwald, Z. Zhang, and R. E. Holz, 2013b: Retrieval of ice cloud properties from AIRS and MODIS observations based on a fast high-spectral resolution radiative transfer model. *J. Appl. Meteor. Clim.*, **52**, 710-726, doi:10.1175/JAMC-D-12-020.1.

Yi, B., P. Yang, B. A. Baum, T. L'Ecuyer, L. Oreopoulos, E. J. Mlawer, A. J. Heymsfield, and K.-N. Liou, 2013: Influence of ice particle surface roughening on the global cloud radiative effect. *J. Atmos. Sci.*, **70**, 2794-2807.

Baum, B. A., P. Yang, A. J. Heymsfield, A. Bansemer, A. Merrelli, C. Schmitt, and C. Wang, 2014: Ice cloud bulk single-scattering property models with the full phase matrix at wavelengths from 0.2 to 100 µm. *J. Quant. Spectrosc. Radiant. Transfer,* **146**, 123-139, doi: 10.1016/j.jqsrt.2014.02.029.

Bi, L., P. Yang, C. Liu, B. Yi, B. A. Baum, B. van Diedenhoven, and H. Iwabuchi: Assessment of the accuracy of the convenctional ray-tracing technique: Implications in remote sensing and radiative transfer involving ice clouds. *J. Quant. Spectrosc. Radiat. Transfer*, **146**, 158-174, doi:10.1016/j.jqsrt.2014.03.017.

Cole, B. H., Yang, P., Baum, B. A., Riedi, J., and C.-Labonnote, L., 2014: Ice particle habit and surface roughness derived from PARASOL polarization measurements, *Atmos. Chem. Phys*., **14**, 3739-3750, doi:10.5194/acp-14-3739-2014.

Wang, C., P. Yang, A. Dessler, B. A. Baum, and Y.-X. Hu, 2014: Estimation of the cirrus cloud scattering phase function from satellite observations. *J. Quant. Spectrosc. Radiant. Transfer,* **138**, 36-49*,* doi: 10.1016/j.jqsrt.2014.02.001.

Highlights of Tasks Completed During the Course of the Grant

Many research advances have been incorporated in our work recently.

1. Microphysical data are now available and *for the first time are now available on a web page* from almost a dozen field campaigns. The web site developed for this purpose is http://www.ssec.wisc.edu/ice_models/microphysical_data.html. Dr. Andy Heymsfield and colleagues published an article detailing the in situ data (Heymsfield et al. 2013). We note that the 2D-C data were reprocessed to mitigate the impact of large particle breakup at the probe inlets. In addition to the advent of new field campaign data, a new particle habit distribution was developed and adopted that more closely aligns with atmospheric particle observations. Now, the particle habit percentages vary as a function of particle maximum dimension to more accurately the types of ice particles present in each size range. The habits correspond more closely to those observed in the top layers of clouds as passive satellite remote sensing instruments get the most information from those layers. (Drs. Andrew Heymsfield and Carl Schmitt, NCAR).
2. Dr. Ping Yang and colleagues have completed the development of a new library (Yang et al., 2013) that provides the single-scattering properties for a variety of different ice particle habits, including droxtals, hollow/solid columns, hollow/solid bullet rosettes, plates, aggregates of columns, and small/large aggregates of plates. The libraries encompass wavelengths from 0.2 – 100 µm (ultraviolet to far-infrared), and includes the full phase matrix so that models can be built for polarization sensors such as CALIOP (Cloud-Aerosol Lidar with Orthogonal Polarization) and PARASOL (Polarization & Anisotropy of Reflectances for Atmospheric Sciences coupled with Observations from a Lidar). Additionally, the library contains single scattering properties for smooth,

moderately roughened, and severely roughened particles. (Ping Yang and Lei Bi, a post-doctoral student at Texas A&M).

3. Based on the ice cloud microphysical data and the new single-scattering property library, Dr. Bryan Baum developed and applied methodology to build spectral and narrowband ice cloud bulk scattering models. These models are available on-line at http://www.ssec.wisc.edu/ice_models/polarization.html. A paper is available that documents these new models (Baum et al., 2014).
4. In addition, we were able to begin investigating the impact of the new ice models on broadband radiance simulations, with an initial paper published by Yi et al. (2013) that employed the RRTMG and Fu-Liou broadband models. The use of roughened ice particle models has a significant impact on the global fluxes obtained in the NCAR GCM runs we performed in this study.
5. Our models or ice libraries are being used by the MODIS, VIIRS, CERES, and AIRS teams, and also in investigations with the CALIPSO, AirMSPI and SSFR groups among others. Additionally, our models/libraries are being used in NOAA operational retrievals for both polar-orbiting and geostationary satellites. The models are also percolating into various spectral and broadband models such as CRTM, RRTMG, libRadTran, and LBL-DIS. As projects go, this one is having a large and positive impact.

Research Highlights

In our first year annual report, we discussed how a comparison of ice cloud optical thickness (τ) retrievals between PARASOL and MODIS revealed significant differences that were attributed to the assumed single scattering properties. The primary difference between the optical thicknesses obtained by the two teams was traced to the assumption that MODIS uses smooth ice particles, while PARASOL adopted a hexagonal ice particle model that contained air bubbles, which acted to reduce the maxima in the scattering phase function (i.e., reduced halos and other maxima). PARASOL polarization measurements were used to improve our new ice models. In other words, the use of polarized reflectance measurements provides another constraint on our models in addition to our previous work comparing microphysical properties and also CALIOP backscattering data.

In our second year annual report, we demonstrated how ice models based on smooth or roughened particles could be used to derive simulated polarized reflectivities for comparison to PARASOL measurements over ocean. We demonstrated that use of models based on severely roughened ice particles resulted in more consistent comparisons with PARASOL measurements (Cole et al. 2013; 2014).

We know that the optical thickness values from MODIS Collection 5 are higher than those from PARASOL. We have also found that MODIS Collection 5 cirrus optical thicknesses are higher than those obtained using infrared (IR) window channels. To make a long story short: the optical thicknesses can be brought into greater harmony by assuming the ice particles are roughened. A case study is provided to illustrate the solar and IR τ retrievals for a MODIS Aqua granule recorded over the Bay of Bengal at 0745 UTC on 2 August, 2010 as shown in Fig. 1. For this analysis, two different fast models are employed to infer τ– we note that these fast models were developed partially in support of this grant. The solar–based method [Wang et al., 2013b] infers optical thickness τ by minimizing the differences between model simulations and observations at 0.86 and 2.13 μm (MODIS bands 2 and 7, respectively). The IR–based method [Wang et al., 2011] computes optical thickness by minimizing the difference between measured and computed radiances in the 8.5, 11, and 12 μm bands (MODIS bands 29, 31, and 32 respectively).

Before showing results from the fast models, it is useful to look at the asymmetry parameter at 0.65 μm for four different habit models, as shown in Fig. 2. The MODIS Collection 5 (C5) model used a mixture of habits, but assumed that the particles were smooth. Comparisons with CALIPSO and PARASOL indicated that the MODIS C5 optical thickness was higher by about 30% than from CALIOP (i.e., a lidar) or polarization measurements. Our research indicates that inclusion of particle roughening mitigates this issue. In Fig. 2, we show the asymmetry parameter for three new models in addition to C5. For Collection 6, MODIS adopted a single habit, the severely roughened aggregate of solid columns (or ASC). The CERES team now bases their ice cloud retrievals on the use of roughened solid columns (or SC), although earlier products used a smooth column model. Our team believes that there is much value in using a general habit mixture (or GHM) rather than a single habit. As shown in Fig. 2, the MODIS Collection 5 model has the highest asymmetry parameter values overall due to the assumption of smooth particles, and the values increase with particle size. The other three models assume the use of severely roughened particles, and the asymmetry parameter is lower for these models relative to the MODIS Collection 5 model. The model based on the aggregate of solid columns has the lowest values. Note that the value is fairly constant at 0.76 and invariant with particle size. A higher value of the asymmetry parameter means that there is more energy in the forward scattered direction and less at side- and backscattering angles. This means that more scattering will be required from the cloud to match a given reflectivity, which in turn results in a higher inferred optical thickness. For a given set of measured reflectivities, the use of the MODIS Collection 5 model will result in higher inferred optical thicknesses than those inferred using the aggregate of solid column model, which is now being used for Collection 6.

The next step is to focus on the low optical thickness results to compare the IR- and solar-based optical thicknesses as shown in Fig. 3. The comparisons are shown as histograms of frequency of occurrence for τ values on a log10 scale, with red indicating the highest frequencies of occurrence. A comparison of MODIS Collection 5 τ values between the solar and IR approaches is shown in this figure. In Figs. 3a–c, the solar-based retrievals tend to be higher than the IR-based retrievals. However, given that the asymmetry parameter for the solid column, aggregate of solid column, and general habit mixture models are lower than that for Collection 5, the differences between the solar– and IR–based models decrease as expected. The solar-based results obtained with the aggregate of solid columns (Fig. 3d) compares best with the IR–based retrievals, although the results indicate that the differences might increase as optical thickness increases.

What this case study suggests is that with our new models that adopt particle roughening, the optical thickness obtained from different types of measurements may not agree, but will be more in harmony.

Summary

The enthusiastic response of the remote sensing community to our ice models has been tremendously gratifying, and the models are being used and cited by an increasing number of different communities. A number of our published studies compare ice cloud products from different sensors available in the A-Train constellation. These studies are instrumental in driving the advances necessary for building the models. Our work has recently been summarized in three articles: (1) the microphysical data are available on-line, with a paper published documenting the data (Heymsfield et al., 2013); (2) the ice particle single-scattering library has been completed and published (Yang et al. 2013), and (3) bulk ice cloud spectral and narrowband models are now available to the public with a paper published (Baum et al., 2014). The bulk optical models include both satellite sensors that are currently in orbit as well as historical polar-orbiting and geostationary sensors. This team has been quite productive, and we worked quite well together. All in all, this has been a really rewarding experience.

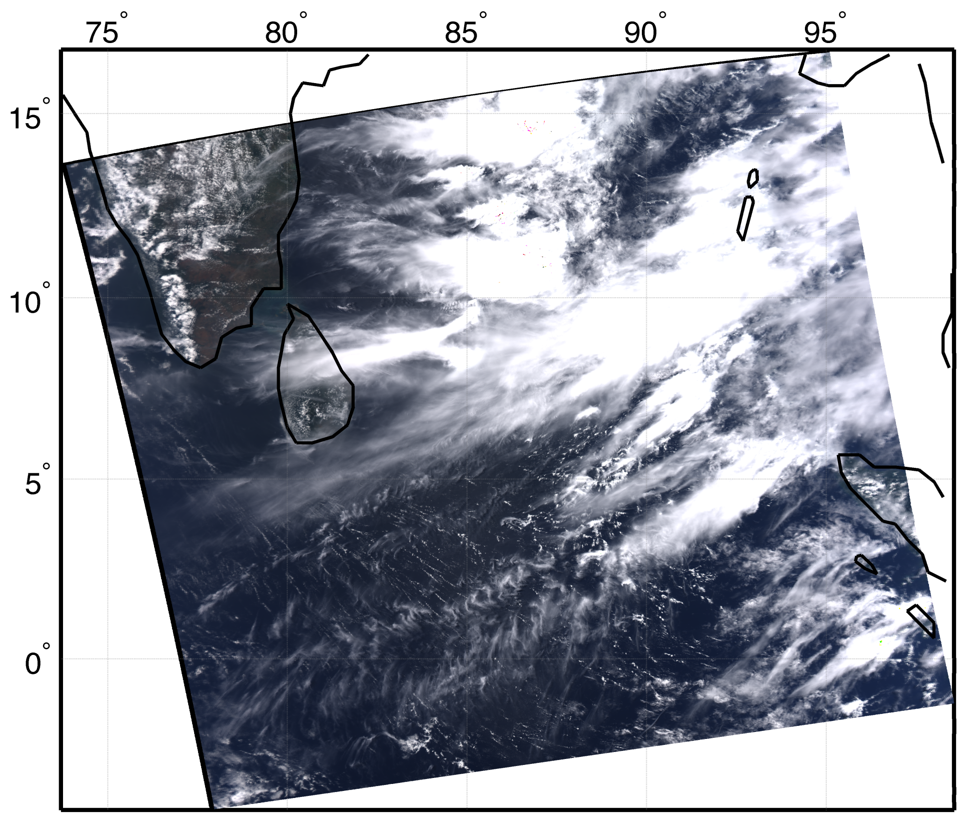

Figure 1: Aqua/MODIS scene from August 2, 2010, recorded over the Bay of Bengal at 0745 UTC.

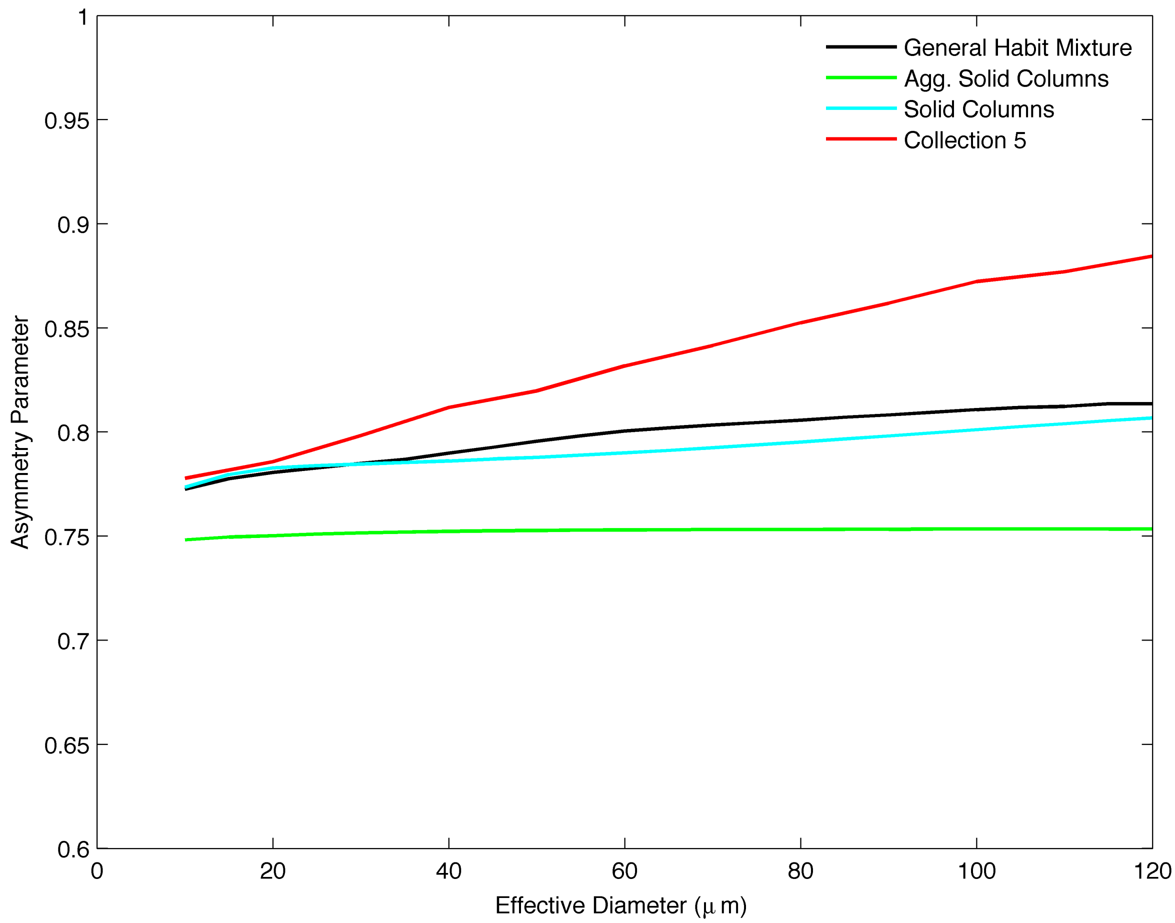

Figure 2: The asymmetry parameter at 0.65 μm as a function of effective diameter for MODIS Collection 5 (red), the general habit mixture (black), solid columns (cyan), and the aggregate of solid columns (green).

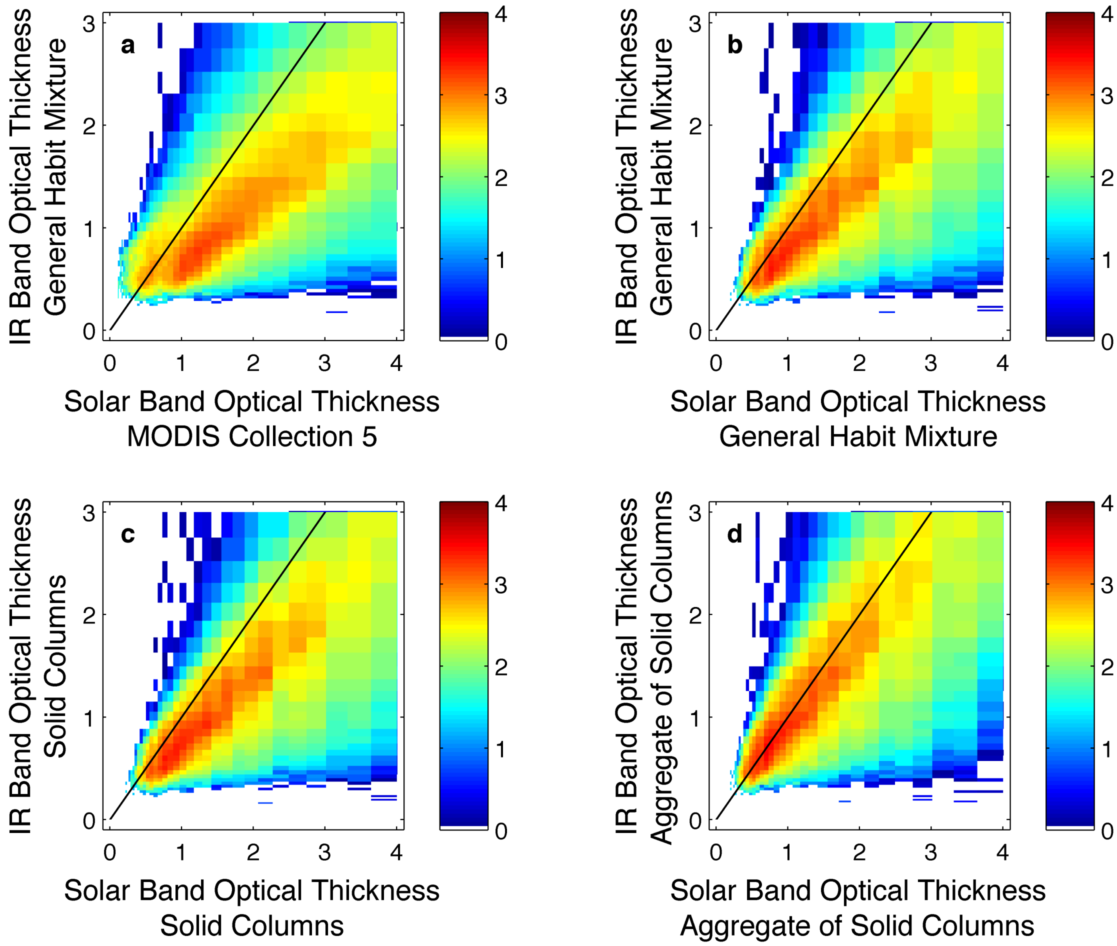

Figure 3: Comparison of ice cloud optical thicknesses inferred separately from MODIS solar and IR bands. The results are based on different ice habit models for the MODIS granule shown in Figure 1. Histograms are shown to compare results in (a) MODIS Collection 5 and the general habit mixture, (b) the general habit mixture, (c) the solid column model, and (d) the aggregate of solid column model. The histograms indicate frequencies of occurrence on a log10 scale, with red indicating the highest frequencies of occurrence.