RECENT RESULTS FOR THE PROJECT “Development and Comparison of Ground and Satellite-Based Retrievals of Cirrus Cloud Physical Properties”

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This report is the final update on ARM research conducted at DRI through May of 2006. A relatively minor amount of work was done after May, and last month (November), two journal papers partially funded by this project were published. The other investigator on this project, Dr. Bob d’Entremont, will be submitting his report in February 2007 when his no-cost extension expires. The main developments for this period, which concludes most of the DRI research on this project, are as follows:

- 1) Further development of a retrieval method for cirrus cloud ice particle effective diameter (D_e) and ice water path (IWP) using terrestrial radiances measured from satellites.
- 2) Revision and publication of the journal article "Testing and Comparing the Modified Anomalous Diffraction Approximation".
- 3) Revision and publication of our radar retrieval method for IWC and snowfall rate.

Regarding (1), a 13 page paper was written and published in the proceedings of the 12th AMS Conference on Atmospheric Radiation (Passive Thermal Retrievals of Ice and Liquid Water Path, Effective Size and Optical Depth and Their Dependence on Particle Size and Size Distribution Shape). This paper describes the current version of our satellite-based retrieval method for D_e , IWP and cirrus cloud optical depth. This retrieval scheme employs the modified anomalous diffraction approximation (MADA), which is formulated in terms of (1) gamma distribution parameters that describe the ice particle size distribution (PSD) and (2) ice particle mass- and projected area-dimensional power-laws that define the ice particle shape. This allows the ice optics scheme (MADA) to explicitly couple with the cloud microphysics. Advantage is gained in a retrieval sense by coupling the MADA scheme with the best current microphysical assumptions regarding the temperature dependence of the PSD and ice particle shapes. Our retrieval method contains temperature-dependent PSD schemes for (1) synoptic mid-latitude cirrus and (2) for anvil cirrus generated from deep convection. The percentages of different ice particle shapes occurring at various temperatures, based on many flight hours through cirrus of types (1) and (2), has been provided to us by SPEC, Inc. We have parameterized this information with polynomial fits so that an ice crystal shape “recipe” can be obtained for any given temperature, and from this recipe we calculate the appropriate mass- and area-dimensional relationships for use in our retrieval scheme.

This microphysical information on the PSD and ice particle shape can easily be updated in the retrieval algorithm.

One important finding we made during this period was that the retrieval of the ice particle effective diameter, D_e , depends on the shape or bimodality of the PSD. When the Ivanova et al. (2001) PSD scheme is used (which predicts a bimodal PSD at warmer cirrus temperatures), non-unique solutions for D_e are obtained, at least for retrievals based on thermal IR wavelengths. This potential for multi-valued D_e retrievals has not previously been recognized. Better PSD measurements will hopefully resolve this question.

During September we received a large PSD data-set from SPEC, Inc., and, as part of another project, a new method for expressing these PSD as gamma functions was developed. The gamma distribution fits to these PSD are now being parameterized in terms of temperature and IWC. The PSD are of higher quality and differ significantly from those in our current mid-latitude scheme at colder temperatures. Once this new PSD scheme is incorporated into our retrieval algorithm, we will reprocess several case studies and include these retrieval results in the paper noted above. The paper will then be submitted to the Journal of Atmospheric and Oceanic Technology.

Regarding (2), the paper "Testing and Comparing the Modified Anomalous Diffraction Approximation" is now published in the November 2006 issue of the Journal of Atmospheric Sciences. The MADA scheme was developed under two ARM projects and further improved upon under this project. This paper clearly demonstrates that it is at least as accurate as other ice optical property parameterizations currently in use. It was necessary to make the assumption that ice crystals are hexagonal columns in order to compare with the different ice optic schemes. As noted, MADA has the advantage of being formulated in terms of any ice particle and PSD shape. The validation of the MADA scheme was critical for this project since our treatment of ice cloud radiative properties, and hence our retrievals, are based on MADA.

Before May of 2005, the efficiency of the photon tunneling process as a function of ice particle shape was not understood by anyone. Photon tunneling is the process by which radiation beyond the physical cross-section of a particle "tunnels" to the surface of the particle and then is either absorbed or scattered outside the forward diffraction peak. The tunneling efficiency, T_e , is 1.0 for spheres and less than 1.0 for non-spherical particles. Tunneling can contribute up to 40% of the absorption in cirrus clouds at terrestrial wavelengths and is strongest when the real index of refraction is large and the wavelength and particle size are comparable. By comparing MADA with the Finite Difference Time Domain (FDTD) results of Ping Yang for six different ice crystal shapes, T_e was parameterized as a function of ice particle shape and mean size (maximum dimension) of the PSD. Thus, T_e is no longer a free parameter in the MADA scheme; we can say the MADA scheme now has closure. Tunneling can now be treated for any ice crystal shape recipe. This represents a major advancement. This work on tunneling was funded by NSF and the current ARM grant, and is described in MADA paper cited below.

Regarding (3), a new radar method for retrieving the IWC in cirrus clouds was proposed for this project. While the emphasis of this project was on satellite remote sensing using IR wavelengths, preliminary testing of the radar-IWC retrieval algorithm yielded IWCs consistent with CVI measurements of IWC during the 9 March 2000 ARM IOP. The operating principle is that relatively accurate estimates of IWC can be obtained if one has ice cloud measurements of radar reflectivity (Z) and corresponding temperature. From temperature, the slope parameter of the PSD can be estimated and used in a new equation expressing IWC in terms of Z and PSD slope. The IWC also depends on ice particle shape (the mass-dimension relationship), which represents a source of uncertainty.

This radar algorithm for retrieving the IWC was used to initialize a recently developed and published snow growth model, or SGM (see below under ARM articles published). The development of this analytically formulated SGM was partially funded under ARM (but not this project), and the model represents a unique, accurate and computationally inexpensive way of predicting the evolution of the PSD in ice clouds. As described in the paper, the radar algorithm developed for this project was used to initialize the model by estimating the IWC at the lowest radar echo (which is often about 1-2 km above ground level for the National Weather Service WSR-88D radars sited in the mountainous western United States). Since much or most of the snowfall rate may develop within a few kilometers of the surface, snowfall rate estimates by these radars cannot be based strictly on the lowest radar echo. By using the IWC retrieval from the lowest radar echo to initialize the SGM, the SGM can predict the evolution of the snowfall rate from the lowest radar echo to the surface (including sublimation below cloud base). This is demonstrated for a case study in the paper, with validation from snow-gage measurements. Thus our IWC retrievals from NWS radar have been used to estimate the snowfall rates at ground-level.

Finally, the theoretical basis for our radar retrieval was fully described in the SGM paper, which cites ARM support under acknowledgments.

PUBLICATIONS

The papers cited below (supported by ARM funding) are described above under recent results. It might be noteworthy that the paper describing the snow growth model appears in a special issue of Atmospheric Research featuring selected papers from the International Conference on Clouds and Precipitation (ICCP). This paper is the first paper featured in the special issue.

Mitchell, D.L., R.P. d'Entremont and R.P. Lawson, 2006: Passive thermal retrievals of ice and liquid water path, effective size and optical depth and their dependence on particle size and size distribution shape. Proceedings, 12th AMS Conference on Atmospheric Radiation, 10-14 July, Madison, Wisconsin, paper 12.5.

Mitchell, D.L., A.J. Baran, W.P. Arnott and C. Schmitt, 2006: Testing and comparing the modified anomalous diffraction approximation. *J. Atmos. Sci.*, 63, 2948-2962.

Mitchell, D.L., A. Huggins, V. Grubisic, 2006: A new snow growth model with application to radar precipitation estimates. *Atmos. Research.*, **82**, 2-18.