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**FINAL REPORT FOR THE DOE/ARM PROJECT TITLED
IMPROVEMENTS IN MODELING THE MICROPHYSICAL AND RADIATIVE PROPERTIES
OF CIRRUS CLOUDS USING THE REGIONAL ATMOSPHERIC MODELING SYSTEM (RAMS)**

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David L. Mitchell¹, John M. Edwards² and Darko Koracin¹

1. Atmospheric Sciences Center, Desert Research Institute
University of Nevada System, Reno, Nevada

2. Hadley Centre for Climate Prediction and Research,
United Kingdom Meteorological Office, Bracknell, U.K.

This is the final report to the Department of Energy's Atmospheric and Radiation Measurement (ARM) Program for grant DE-FG03-94ER61775. This covers the period 1 December 1993 to 30 November 1997, which includes the no-cost extension of this grant. The results herein focus on work conducted from July 1996 through November of 1997. This includes the six month period in which the P.I. was on sabbatical in Europe, stationed at the U.K.'s Hadley Centre for Climate Prediction and Research, and at the University of Oslo, Norway. Also, four journal articles (mentioned in previous reports) are now published, and reprints are attached. These reprints address earlier activities not mentioned in this report. Also attached is our extended abstract for the ARM '97 Science Team Meeting, which discusses key findings obtained during the above period which is the focus of this report.

1. Application of ARM Research to GCMs and Satellite Remote Sensing

The main work activity during this period was the refinement and GCM parameterization of the treatment of ice cloud radiative properties, developed for this project (Mitchell et al. 1996). The treatment has now been rigorously tested and improved, and can now be used with confidence in radiation transfer schemes. The ARM project titled "Refinement, Validation and Application of Cloud-Radiation Parameterization in a GCM", Graeme Stephens P.I., is now using the above radiation scheme for ice clouds, as well as a Mie theory parameterization for water clouds developed under this (our) ARM project. A version of NCAR's CCM3 GCM containing a new prognostic cloud water scheme, currently under development by Jon Egill Kristjansson (University of Oslo, Norway) and Phil Rasch (NCAR), is using our ice cloud radiation scheme to perform various sensitivity tests to ultimately decide on an optimal formulation of this scheme for GCM work. Work at the Hadley Centre with John Edwards and Tony Slingo, conducted over a 4 month period, has resulted in a number of sensitivity tests using the new ice cloud radiation scheme, as well as some fundamental improvements in the performance of the Unified Model (the GCM developed and used at the Hadley Centre). This will be discussed in a separate section below.

The above ice cloud radiation scheme has also proven useful in satellite remote sensing, and has now been extensively used at the U.K. Meteorology Office, especially in retrieving characteristic ice particle sizes from tropical anvils (e.g. Baran et al. 1997). The radiation scheme differs from others in the thermal infrared, where it is assumed that photon tunneling does not occur for real ice particles (tunneling can be viewed as a process by which photons outside a particle's area-cross section can still be absorbed). Single particle T-matrix and Mie calculations suggest that a particle's ability to capture

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energy through tunneling depends on surface morphology, with more tunneling the more circular (or less angular) a surface is. This assumption leads to retrievals of mean particle size which are similar to those observed in tropical cirrus by optical imaging probes, whereas retrieved sizes using Mie theory are about 1/3 those predicted by this scheme. The retrieval method requires channels in the 8-9 μm and 11-12 μm ranges. This assumption about tunneling, as well as treating size distributions in the radiation scheme as bimodal, allows retrievals over a broader range of mean particle size than previous schemes permitted, making such size retrievals applicable to most types of cirrus clouds. This fact was recognized by Dr. Claudia Stubenrauch at Laboratoire de Meteorologie Dynamique, Paris France, who has a Ph.D. student implementing this radiation scheme/retrieval method on 3I cloud data (satellite data based on channels in the thermal IR). The goal is to construct a global climatology of cirrus particle size using this method, although for thick cirrus, particle sizes will be most representative of the upper cloud.

2. Unified Model Preliminary Findings

The fact that input to this radiation scheme consists of the mean maximum dimension ($\bar{D}$) of the physical size distribution (not an effective radius), as well as ice particle shape and a few other inputs, allows us to link this scheme to a historical data base of ice cloud size distribution measurements. As discussed in the attached ARM article, for purposes of global climate modeling, historical data show $\bar{D}$ is reasonably well correlated with temperature. This temperature correlation was used to define size spectra in the Unified Model (U.M.) and in CCM3. This results in ice-containing frontal clouds having much different radiative properties (larger ice particles) than typical cirrus clouds (having $T < -25^\circ\text{C}$). This had a substantial impact on global albedo and outgoing longwave radiation (OLR), relative to the common assumption of constant ice particle size.

The following U.M. results pertain to a 15 month run, assuming planar polycrystals, beginning December 1, 1978, evaluated 6-9 months into the run for June-August (experiment aakzb in Fig. 1b & 2b). The control run, experiment aalib (an AMIP integration), assumes all ice particles are 30 μm spheres, but is otherwise identical to experiment aakzb regarding all aalib-aakzb comparisons. The control run is also compared with observations, in which case the control run results (aalib) and observations were averaged over ten June-August periods.

In Fig. 1a, the upper panel gives reflected shortwave (SW) radiation predicted in the control run minus that observed during the Earth Radiation Budget Experiment (ERBE). The same is done for OLR in the lower panel. It is seen that *the control run tends to underestimate reflected SW and overestimate OLR, especially in the tropics where solar fluxes are greatest.* In Fig. 1b, the upper panel gives reflected SW for the planar polycrystal run (aakzb) minus the control, while the lower panel gives the same comparison for OLR. *In general, the polycrystal run tends to predict more reflected SW and less OLR relative to the control run, especially in the tropics.* Contrasting Fig. 1a and 1b, there is a general improvement in both the reflected SW and OLR. While not all regions show improvement (such as OLR in the Indian Ocean/Arabian Sea), this is to be expected, as other aspects of the U.M. (such as treatment of the Indian Monsoon) may be deficient.

Figure 1a. See report for details.

Figure 2a. See report for details.

Change in Reflected SW Radiation
 Polycrystals - 30 μm -spheres
 aakzb-aalib: JJA 1979

Change in Outgoing Longwave Radiation
 Polycrystals - 30 μm -spheres
 aakzb-aalib: JJA 1979

Figure 1b. See report for details.

Change in Zonal Mean Temperature
 Polycrystals - 30 μm -spheres
 aakzb-aalib: JJA 1979

Figure 2b. See report for details.

One of the principal problems with the U.M. and other GCMs is the tropical cold bias (predicted temperatures in the tropical upper troposphere are colder than observed by a few degrees K). This is seen in Fig. 2a, where mean zonal temperatures from the control run are differenced with summer mean temperatures based on ECMWF reanalysis data (our best estimate of "ground truth"). This cold bias can overstimulate the Hadley circulation, thus effecting the atmospheric circulation in general. The planar polycrystal run reduced the U.M.'s cold bias by about 1°K, as shown in Fig. 2b, primarily due to a reduction in longwave (LW) cooling. Similar results were obtained with other ice crystal shapes, although the warming from hexagonal columns was more modest. Combined with an engineering improvement regarding the shape of cumulonimbus clouds, the cold bias currently appears virtually absent, although these results are preliminary.

The improvement regarding the non-spherical ice treatment is relatively simple to understand - for a given ice water path, real ice crystals exhibit far more surface area than do spheres having the same maximum dimension. This fact, combined with the temperature dependence of $\bar{D}$, increases optical depth (τ) in the tropics, while having variable effects elsewhere. This generally results in more SW radiation being reflected, especially in the tropics, while trapping more LW, and, to a lesser extent, absorbing more SW radiation. The higher τ of relatively high, cold tropical anvils also results in enhanced warming of the upper tropical troposphere, due to enhanced LW trapping and SW absorption. Another factor effecting the reflected SW is that more radiation is scattered into a particle's rear hemisphere for polycrystals than for ice spheres.

Finally, GCM sensitivity studies indicate the global radiation balance is sensitive to what ice crystal shape is assumed. This is discussed in the attached article from the last ARM meeting. Since global net radiative forcing due to changing crystal shapes may be on the same order as the 4 W m^{-2} forcing due to a CO_2 doubling, satellite retrieval schemes should include dominant ice crystal shape as a retrieved quantity.

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PROJECT FUNDED PUBLICATIONS

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