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Subject: Final Report for "Radiation Parameterization for Three-Dimensional Inhomogeneous Cirrus Clouds Applied to ARM Data and Climate Models" (UCLA Award No. DE-FG03-00ER62904, ending date September 30, 2003)

Scientific Goal(s): The primary goals of our project are (a) characterization of the three-dimensional (3D) cirrus cloud fields (including thin cirrus) using satellite and ground-based radar and lidar data available from the ARM program; and (b) development of the radiation parameterization programs for inhomogeneous clouds (1D and 3D) with a specific emphasis on cirrus for incorporation in the UCLA GCM for process studies.

2. Accomplishments:

- (a) Development of a 3D inhomogeneous radiative transfer model for clouds with a particular focus on cirrus based on a delta diffusion approach for 3D radiative transfer for both broadband solar and thermal infrared radiation.
- (b) Incorporation of radiation and cloud parameterizations developed by Fu and Liou (1993) and Gu and Liou (2001) in the UCLA atmospheric GCM for the ENSO type simulation.
- (c) Innovation of a methodology for the construction of a 3D field of inhomogeneous cirrus clouds in terms of ice water content and ice crystal size from a unification of satellite and ground-based cloud radar data.
- (d) Development of a thin cirrus detection threshold method using MODIS channels with validation from the ARM cloud radar data.

3. Progress Description:

- (a) We developed a 3D radiative transfer model to simulate the transfer of solar and thermal infrared radiation in inhomogeneous cirrus clouds. The model utilized a diffusion approximation approach (four-term expansion in the intensity) employing Cartesian coordinates. The required single-scattering parameters,

including the extinction coefficient, single-scattering albedo, and asymmetry factor, for input to the model, were parameterized in terms of the ice water content and mean effective ice crystal size. The incorporation of gaseous absorption in multiple scattering atmospheres was accomplished by means of the correlated k -distribution approach. In addition, the strong forward diffraction nature in the phase function was accounted for in each predivided spatial grid based on a delta-function adjustment. The radiation parameterization developed herein is applied to potential cloud configurations generated from GCMs to investigate broken clouds and cloud-overlapping effects on the domain-averaged heating rate. Cloud inhomogeneity plays an important role in the determination of flux and heating rate distributions. Clouds with maximum overlap tend to produce less heating than those with random overlap. Broken clouds show more solar heating as well as more IR cooling as compared to a continuous cloud field (Gu and Liou, 2001).

- (b) We incorporated a contemporary radiation parameterization scheme in the UCLA atmospheric GCM in collaboration with the UCLA GCM group. We first transferred the GCM code from the DEC computer to a number of Sun Workstations that were available in our Computer Lab, and successfully made the code operational. The version of the UCLA GCM that we adopted for cloud/radiation studies included prognostic equations for liquid/ice water contents. However, it predicted 0 and 1 cloud covers based on a threshold humidity method over a 4° by 5° grid (for ENSO and other climate simulations). In conjunction with the cloud/radiation process studies, we developed a physically-based cloud cover formation scheme in association with radiation calculations. The model clouds were first vertically grouped in terms of low, middle, and high types. Maximum overlap was then used for each cloud type, followed by random overlap among the three cloud types. Fu and Liou's 1D radiation code with modification was subsequently employed for pixel-by-pixel radiation calculations in the UCLA GCM. We showed that the simulated cloud cover and OLR fields without special tuning are comparable to those of ISCCP dataset and the results derived from radiation budget experiments. Use of the new radiation and cloud schemes enhances the radiative warming in the middle to upper tropical troposphere and alleviates the cold bias in the UCLA atmospheric GCM. We also illustrated that ice crystal size and cloud inhomogeneous are significant factors affecting the radiation budgets at the top of the atmosphere and the surface (Gu et al. 2003).
- (c) An innovative approach has been developed to construct a 3D field of inhomogeneous clouds in general and cirrus in particular in terms of liquid/ice water content and particle size on the basis of a unification of satellite and ground-based cloud radar data. Satellite remote sensing employing the current narrow-band spectro-radiometers has limitation and only the vertically integrated cloud parameters (optical depth and mean particle size) can be determined. However, by combining the horizontal cloud mapping inferred from satellites with the vertical structure derived from the profiling Doppler cloud radar, a 3D

cloud field can be constructed. This represents a new conceptual approach to 3D remote sensing and imaging and offers a new perspective in observing the cloud structure. We applied this novel technique to AVHRR/NOAA satellite and mm-wave cloud radar data obtained from the ARM achieve and assessed the 3D cirrus cloud field with the ice crystal size distributions independently derived from optical probe measurements aboard the University of North Dakota Citation. The retrieved 3D ice water content and mean effective ice crystal size involving an impressive cirrus cloud occurring on April 18, 1997, are shown to be comparable to those derived from the analysis of collocated and coincident in situ aircraft measurements (Liou et al. 2002).

- (d) Detection of thin cirrus with optical depths less than 0.5, particularly those occurring in the tropics remains a fundamental problem in remote sensing. We developed a new detection scheme for the identification of thin cirrus based on a combination of the 1.38 and 0.65 μm reflectance ratio and 8.6-11 μm brightness temperature difference. Results calculated from a radiative transfer model and the data obtained from MODIS onboard the Terra satellite were employed to illustrate the applicability of this approach for the regional mapping of thin cirrus. The mm-wave radar data that was coincident and collocated with the satellite data available at the ARM site was used for validation. In all cases selected, the new method was able to detect more than 85% of the thin cirrus clouds estimated to have optical depths between 0.1 and 0.9 (Roskovensky and Liou 2003b).

5. Publications Acknowledging the Grant:

Gu, Y., and K. N. Liou, 2001: Radiation parameterization for three-dimensional inhomogeneous cirrus clouds: application to climate models. *J. Climate*, **14**, 2443-2457.

Rolland, P., and K. N. Liou, 2001: Surface variability effects on the remote sensing of thin cirrus optical and microphysical properties. *J. Geophys. Res.*, **106**, 22965-22977

Liou, K.N., and Y. Takano, 2002: Interpretation of cirrus cloud polarization measurements from radiative transfer theory. *Geophys. Res. Lett.*, **29**, 10.1029/2001GL014613, 27-1-27-4.

Liou, K.N., S.C. Ou, Y. Takano, J. Roskovensky, G. Mace, K. Sassen, and M. Poellot, 2002: Remote sensing of three-dimensional inhomogeneous cirrus clouds using satellite and mm-wave cloud radar data. *Geophys. Res. Lett.*, **29**, 10.1029/2002GL014846, 74-1-74-4.

Roskovensky, J., and K.N. Liou, 2003a: Detection of thin cirrus using a combination of 1.38 μm reflectance and window brightness temperature difference. *J. Geophys. Res.*, **108**, D18, AAC 4-1-4-16.