Determining Tropical Cirrus Particle Size Distributions from Remote Sensing with Lidar, Millimeter Radar and Infrared and Microwave Radiometry

C.M.R. Platt and R. T. Austin
Department of Atmospheric Science
Colorado State University
Fort Collins, Colorado

S. M. Sekelsky
Department of Electrical and Computer Engineering
University of Massachusetts
Amherst, Massachusetts

D. L. Mitchell
Atmospheric Sciences Center, Desert Research Institute
Reno, Nevada

S. A. Young
Commonwealth Scientific and Industrial Research Organization
Atmospheric Research Division
Aspendale, Victoria, Australia

Introduction

Clouds and their interactions with radiation still represent a significant (in our view, the greatest) uncertainty in climate models. The aim of this study is to evaluate and develop methods for measuring effective particle sizes in cold tropical cirrus clouds from the surface with a multi-instrument capability.

Two methods are considered. The first is the radar/lidar method discussed by Intrieri et al. (1993) for cloud particles larger than about 20 μm. For smaller particles that the radar cannot detect, the method of Platt et al. (1998b) is used and extended.

Small cloud particles have on occasion been found experimentally (Heymsfield and Jahnsen 1974; Knollenberg et al. 1993), and predicted (Jensen et al. 1996), to have maximum dimensions in the region of 10 μm. The presence of only small particles less than 20 μm in a cloud is significant because the solar reflectance in the cloud will be amplified compared to the infrared (IR) emittance, which will be reduced. Thus such clouds will not necessarily cause a warming effect in the climate context.

Here, theoretical methods are discussed briefly and then applied to some experimental data that were taken as described below.

Ground-based Remote Sensing

Cirrus clouds were observed in the Maritime Continent Thunderstorm Experiment (MCTEX) by the Commonwealth Scientific and Industrial Research Organization (CSIRO) visible lidar (0.532 μm) and infrared fast narrow-beam spectral radiometer (10.86 μm ± 0.5 μm), the University of Massachusetts millimeter radar (33 GHz, 95 GHz) and the Atmospheric Radiation Measurement (ARM) Microwave Radiometer (23.8 GHz, 31.4 GHz). The characteristics of these instruments have been described previously (Platt et al. 1998a; Sekelsky et al. 1999; Liljegren 1994). The instruments were situated close together at Garden Point, Melville Island, N. Territory, Australia. For the purposes of this study, data were taken with all instruments observing in the zenith. Time-clocks were synchronized carefully between the various instruments. Observational periods were dictated by the need for a clear atmosphere below the cirrus, at least for the lidar. The experiment lasted from November 15 to December 8, 1995.

Theoretical Values of the Lidar/Radar Ratio and Visible Extinction/IR Absorption Ratio

Using a single gamma function to represent the size distribution, Intrieri et al. (1993) showed that the radar reflectivity-lidar backscatter ratio was extremely sensitive to particle size in the cirrus size range. Similar functions calculated using hybrid size distributions (Platt 1997) are shown in Figures 1a and 1b. The size spectra employed (Heymsfield, private communication) were measured in mid-latitude frontal cirrus at the temperatures shown. Curves based on the same spectra were used to determine effective radii in typical MCTEX cirrus clouds.

Mitchell and Platt (1998) calculated values of α, the ratio between the lidar visible extinction coefficient and the IR absorption coefficient, and compared these with experimental values obtained in the ARM Pilot Radiation Observation Experiment (PROBE) (Platt et al. 1998a). Mitchell used a model of a bi-modal gamma function for his size distributions and a new treatment of extinction efficiency of ice crystal habits (Mitchell and Arnott 1994). Their values are shown in Figure 2, where α is seen to be sensitive to cirrus particle sizes less than about 20 μm in effective radius. The values of α shown in Figure 2 are used here to estimate effective radii in cold (~ -80 °C to -60 °C) MCTEX cirrus when the radar reflectivity was below the level of detection of the University of Massachusetts millimeter radar. Thus, the radar/lidar and α methods are seen to be complementary, and allow a wide range of particle sizes to be retrieved.

Cirrus Data

Retrieved Values of r_{eff} From Measured Radar/Lidar Ratios

Profiles of lidar backscatter, radar reflectivity and effective radii r_{eff} for a cirrus cloud of typical optical depth in MCTEX are shown in Figures 3a to 3c, obtained from hybrid curves similar to those shown in Figure 1. These values are compared with those obtained from a size distribution represented by a single gamma function (Austin et al. 1998) in Figure 3d. The differences represent the sensitivity of the method to assumed size distributions. In this case, the hybrid distributions, being bi-modal, are considered to be a better representation of the available observational data.

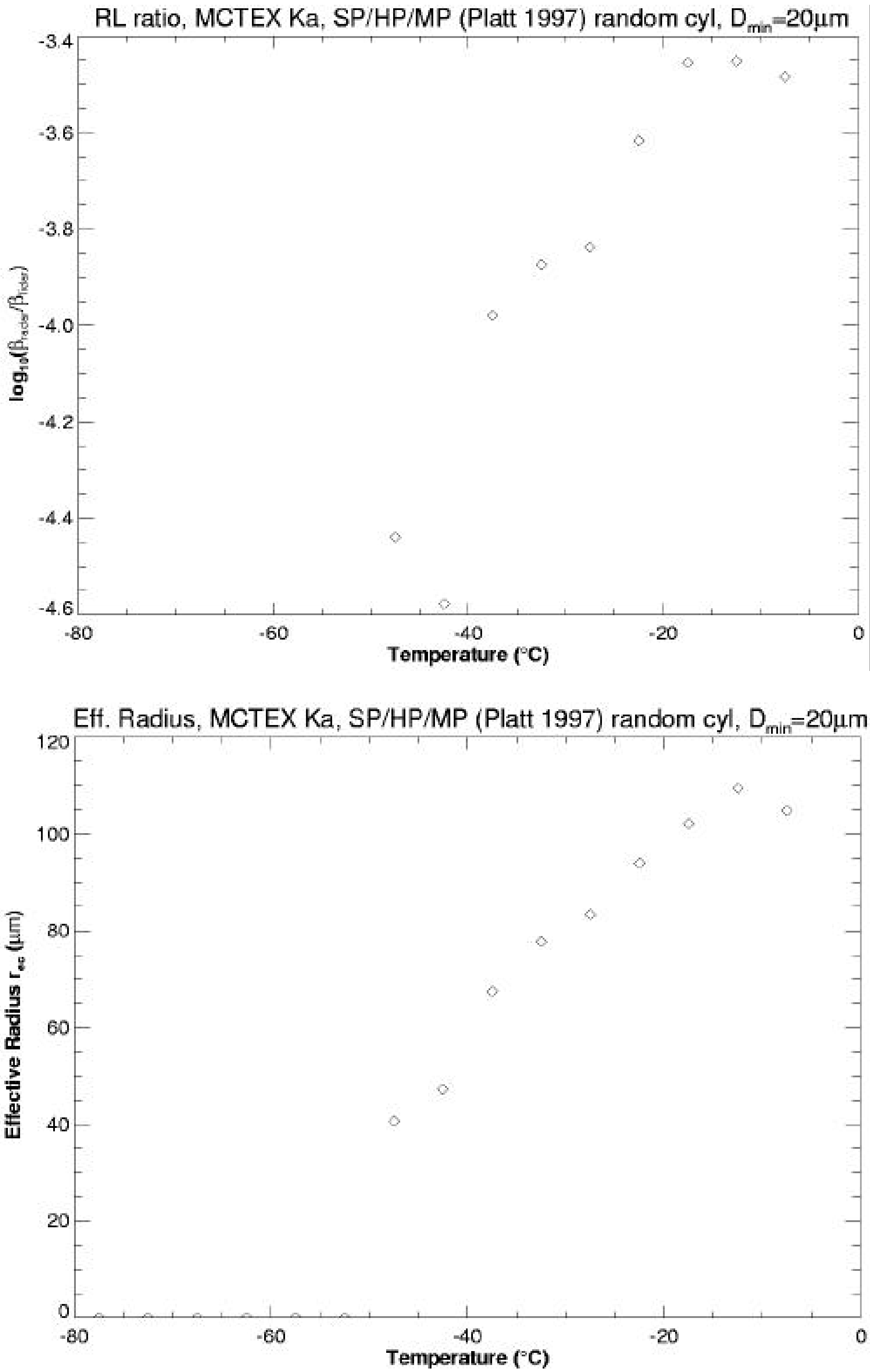

Figure 1. Radar/lidar ratio (a) and effective radius (b) of hybrid size distributions based on Platt (1997).

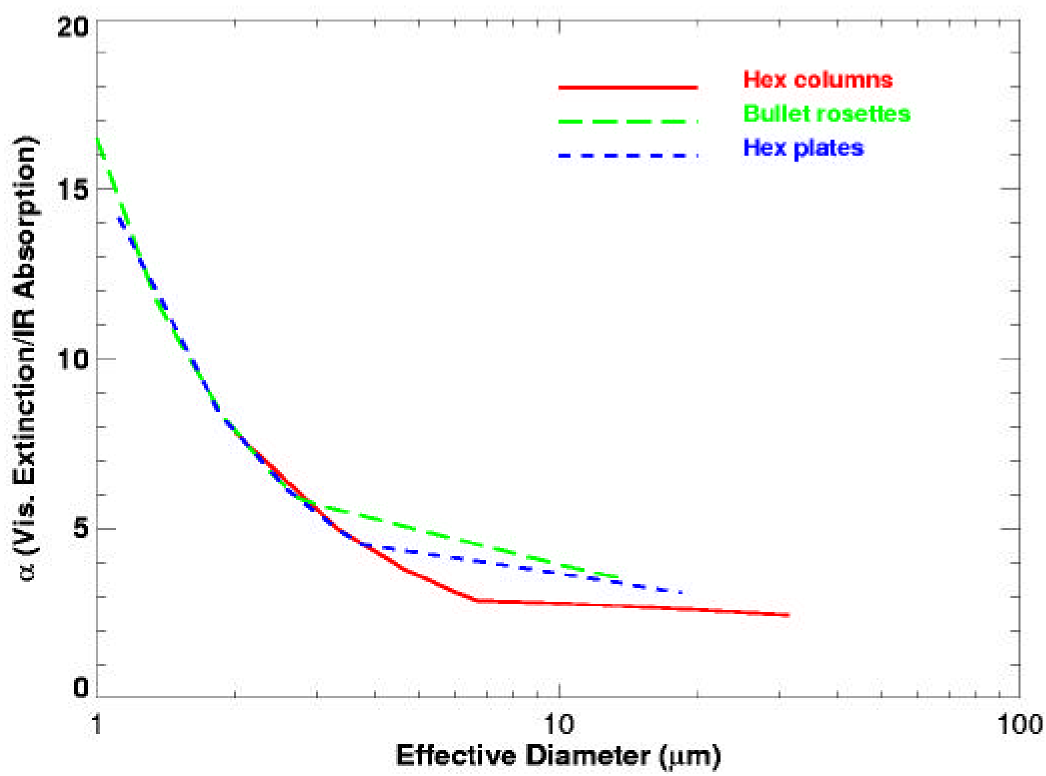

Figure 2. Visible extinction/IR absorption ratio for several habits calculated using a bi-modal size distribution.

Values of r_{eff} From Measured Values of α

Some analyzed lidar/radiometer (LIRAD) data for one case from MCTEX are shown in Figures 4 and 5. Shown in Figure 4a to 4f are the time-height lidar backscatter, cloud temperature, IR optical depth, radiance and water path, lidar integrated backscatter and retrieved values of the quantity $2\alpha\eta$, where η is a multiple scattering factor described in Platt et al. (1998b). Equivalent values of α are shown in Figure 5. The multiple scattering factor for the cloud is given values between 0.2 and 0.4 (Platt et al. 1998b), depending on mid-cloud temperature. Unlike the lidar/radar ratios, which give profiles of r_{eff} through the cloud, the value of α is an effective integrated value for the cloud depth.

Uncertainties in the value of α from various causes have been estimated. Both random errors in radiometer radiance and water vapor path (e.g., Liljegren 1994, and private communication) and systematic uncertainties in radiometer calibration are included. Also included are systematic uncertainties (for each case) in visible optical depth retrieval and in multiple scatter. It can be seen that the systematic uncertainties dominate.

Values of r_{eff} at varying times in the above cloud are shown in Figure 6. The range of values at one time is a measure of the difference in values quoted for different ice crystal habits. Despite the uncertainties, it is clear that small particles can be present in the colder tropical cirrus clouds. Of course, small

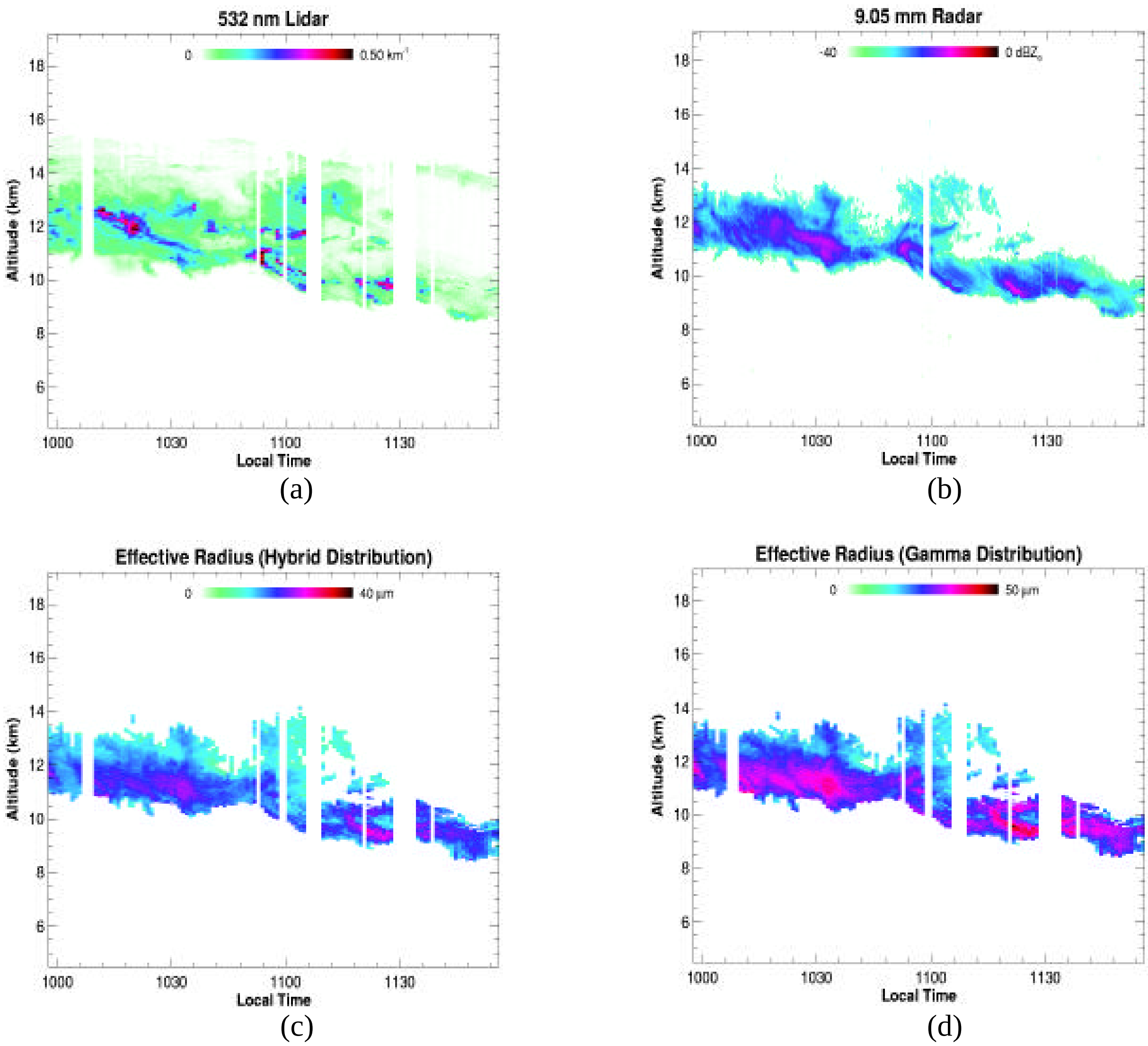

Figure 3. Time-height diagrams of (a) lidar backscatter, (b) radar reflectivity, (c) retrieved particle size using a hybrid distribution, and (d) retrieved particle size using a gamma distribution for a single MCTEX case.

particles are also present in the lidar time-height image in Figure 3a near the cloud tops, where they are below the radar threshold reflectivity shown in Figure 3b.

Conclusions

It is demonstrated that cloud particle sizes over a wide range can be measured by the techniques described. The techniques are certainly worth pursuing, but it is equally important that aircraft validation data are obtained simultaneously, both with particle counters and impactor studies. Advances

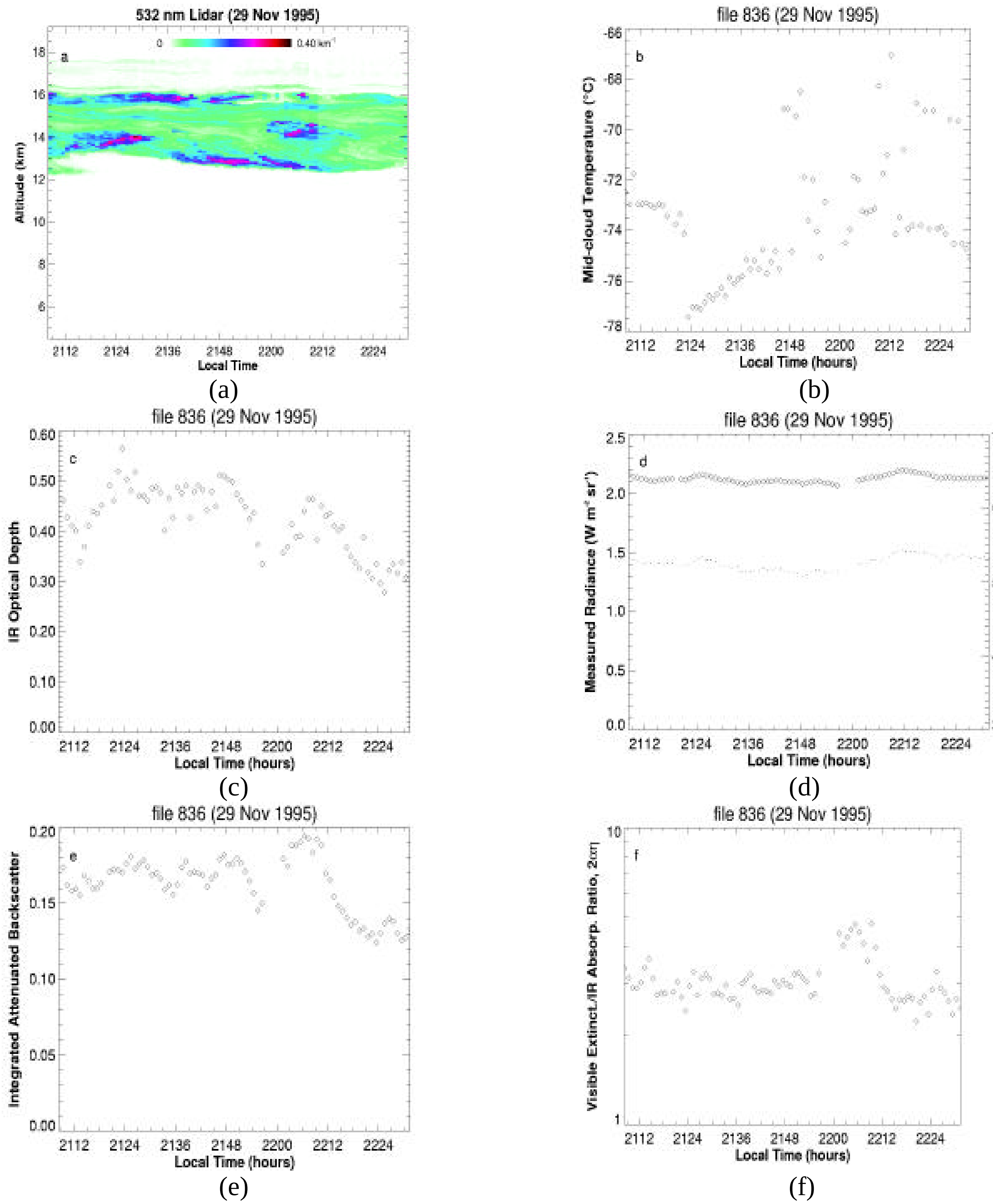

Figure 4. LIRAD data and results for a single MCTEX case: (a) time-height diagram of lidar backscatter, (b) mid-cloud temperature, (c) IR optical depth, (d) measured IR radiance and water vapor path, (e) integrated attenuated backscatter, and (f) visible extinction/IR absorption ratio multiplied by 2η.

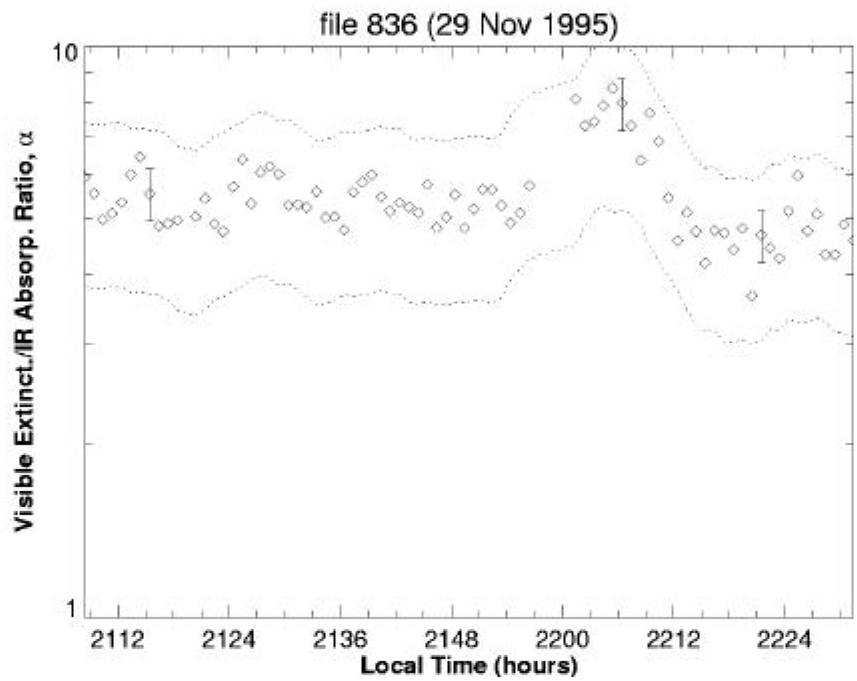

Figure 5. Retrieved values of α (diamonds) are shown for the same MCTEX case as Figure 4. The error bars on three of the points show the random errors, while the dotted lines indicate systematic uncertainties.

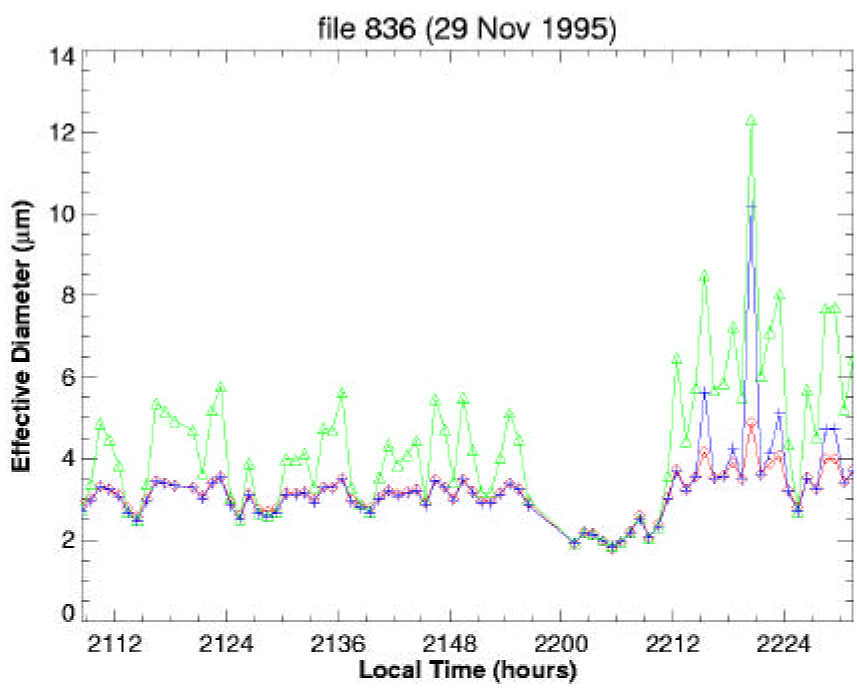

Figure 6. Values of effective radius for the same MCTEX case, calculated for the three ice crystal habits shown in Figure 2.

in the calculation of the multiple scattering factor η are also necessary. With new data appearing on cirrus particle phase functions for a wide range of ice crystal habits and deformations, such data should soon be available.

Acknowledgments

The authors thank the Bureau of Meteorology MCTEX Science Team for their logistical and moral support of the ARM experiment. The research was supported under the U.S. Department of Energy, Office of Health and Environmental Research, Grants DE-FG03-94ER61748 and DE-FG03-98ER62569.

References

Austin, R. T., S. A. Young, C. M. R. Platt, G. R. Patterson, S. M. Sekelsky, and R. E. McIntosh, 1998: Retrieval of tropical cirrus cloud properties from ground-based lidar and millimeter-wave radar sensing at the Maritime Continent Thunderstorm experiment. In *Proceedings of the Seventh Atmospheric Radiation Measurement (ARM) Science Team Meeting,* CONF-970365, pp. 389-393. U.S. Department of Energy, Washington, D.C.

Heymsfield, A. J., and L. J. Jahnsen, 1974: Microstructure of tropopause cirrus layers. *Sixth Conference on Aerospace and Aeronautical Meteorology,* November 12-15, American Meteorological Society, 43-48.

Intrieri, J. M., G. L. Stephens, W. L. Eberhard, and T. Uttal, 1993: A method for determining cirrus cloud particle sizes using lidar and radar backscatter technique. *J. Appl. Meteor.,* **32,** 1074-1082.

Jensen, E. J., O. B. Toon, H. B. Selkirk, J. D. Spinhirne, and M. R. Schoeberl, 1996: On the formation and persistence of subvisible cirrus clouds near the tropical tropopause. *J. Geophys. Res.,* **101,** 21,361-21,375.

Knollenberg, R. G., K. Kelly, and J. C. Wilson, 1993: Measurements of high number densities of ice crystals in the tops of tropical cumulonimbus. *J. Geophys. Res.,* **98,** 8639-8664.

Liljegren, J. C., 1994: Two-channel microwave radiometer for observations of total column precipitable water vapor and cloud liquid water path. Preprints*: Fifth Global Change Studies,* January 23-28, 1994, Nashville, Tennessee.

Mitchell, D. L., and W. P. Arnott, 1994: Model predicting the evolution of ice particle spectra and radiative properties of cirrus clouds. II. Dependence of absorption and extinction on ice crystal morphology. *J. Atmos. Sci.,* **51,** 817-832.

Mitchell, D. L., and C.M.R. Platt, 1998: Microphysical interpretation of LIRAD extinction/absorption ratios using a microphysics-radiation scheme. In *Proceedings of the Eighth Atmospheric Radiation Measurement (ARM) Science Team Meeting*, DOE/ER-0738, pp. 495-498. U.S. Department of Energy, Washington, D.C.

Platt, C.M.R., 1997: A parameterization of the visible extinction coefficient of ice clouds in terms of the ice/water content. *Jour. Atmos. Sci.*, **54,** 2083-2098.

Platt, C.M.R., S. A. Young, R. T. Austin, G. R. Patterson, and S. Marsden, 1998a: The optical properties of tropical cirrus clouds in the Maritime Continent Thunderstorm Experiment from lidar and infrared radiometer retrievals. In *Proceedings of the Seventh Atmospheric Radiation Measurement (ARM) Science Team Meeting*, CONF-970365, pp. 493-497. U.S. Department of Energy, Washington, D.C.

Platt, C.M.R., S. A. Young, P. J. Manson, G. R. Patterson, S. C. Marsden, R. T. Austin, and J. Churnside, 1998b: The optical properties of equatorial cirrus from observations in the ARM Pilot Radiation Observation Experiment. *J. Atmos. Sci.*, **55,** 1977-1996.

Sekelsky, S. M., W. L. Ecklund, J. M. Firda, K. S. Gage, and R. E. McIntosh, 1999: Particle size estimation in ice-phase clouds using multi-frequency radar reflectivity measurements at 95 GHz, 33 GHz, and 2.8 GHz. *J. Appl. Meteor.*, **38,** 5-28.