The Retrieval of Radiative Heating Rates in Cloudy Atmospheres: Test Cases Using ARM CART and IOP Data Results

A. C. Huffman III, G. L. Stephens, R. T. Austin, C. M. R. Platt, and R. F. McCoy
Department of Atmospheric Science
Colorado State University
Fort Collins, Colorado

Introduction

Understanding the variability of the hydrological cycle and prediction of its change are the foremost science and policy issues of global change. Intergovernmental Panel on Climate Change (IPCC) 1995 conjectures that "warmer temperatures will lead to a more vigorous hydrological cycle; this translates into prospects of more severe droughts and/or floods in some places." The hydrological cycle changes referred to are governed by feedbacks that in one way or another involve clouds. Lack of understanding these feedbacks is considered as one of the major obstacles confronting prediction of climate change.

Goal

The goal of this research is to answer two questions about cloud feedback. First, we must understand to what extent clouds affect the radiative heating of the atmosphere (i.e., given clouds, what of radiation?). Second, the influence of this heating on the general circulation of the atmosphere and, in turn, cloudiness must be understood (i.e., given radiation, what of circulation and hence clouds?). Two factors are key to answering these questions. Radiative heating by clouds and the effects on general circulation are the fast components. Slower components include the effects of clouds on the surface radiation budget.

Approach

Our observing system is considered as follows:

$$y = F(x, b) + Ky \qquad (1)$$

where y is a vector of the available measurements (to be defined); Ky is the measurement error (including instrument noise and calibration uncertainties); F is the forward function, which in this case is the two-stream broadband radiative transfer model and a model of the lidar/radar observations; b is a vector of parameters that define F and will be assumed to be known (such as asymmetry parameter); and x is the retrieval vector, in this case the profile of radiative heating.

We invoke estimation theory to invert Eq. (1). This estimation approach determines x such that the difference between y and F is minimized. In practice, most problems are ill-posed and some form of constraint is required, usually in the form of constraining x via a priori information. Minimization is constructed in terms of a suitable cost function (e.g., Menke 1989; Rodgers 1976)

$$\Phi = \Phi\left(\underline{x} - x_a, y - F(\underline{x}, b), S_a, S_y\right) \qquad (2)$$

where x_a is the a priori estimate of $\underline{x}$, S_a is the error covariance of this a priori and S_y is the error covariance of the forward model, which contains both the estimate of the forward model error and the measurement error. These covariance matrices define both the total error of the retrieval and the extent that the retrieval relies on the a priori.

Preliminary Results

The key to this estimation theory are the sensitivities, namely $K = \partial x/\partial y, \partial x/\partial b$. Shown in Figure 1 are these sensitivities for a 1% change in particle effective radius, number density, asymmetry parameter, cloud optical depth, water vapor, and a 0.5-km change in cloud height. These sensitivities are derived using the 5 December 1995 Maritime Continent Thunderstorm Experiment (MCTEX) case study as the base state (see Austin et al. 1998). Two conclusions can immediately be made from Figure 1. The most important parameter is vertical cloud distribution (i.e., height). Second, there is a smaller dependence on optical depth, thus the profile information is critical to the heating rate retrieval. An example of a cloud profile from MCTEX is given in Figure 2, along with the corresponding heating rate profile.

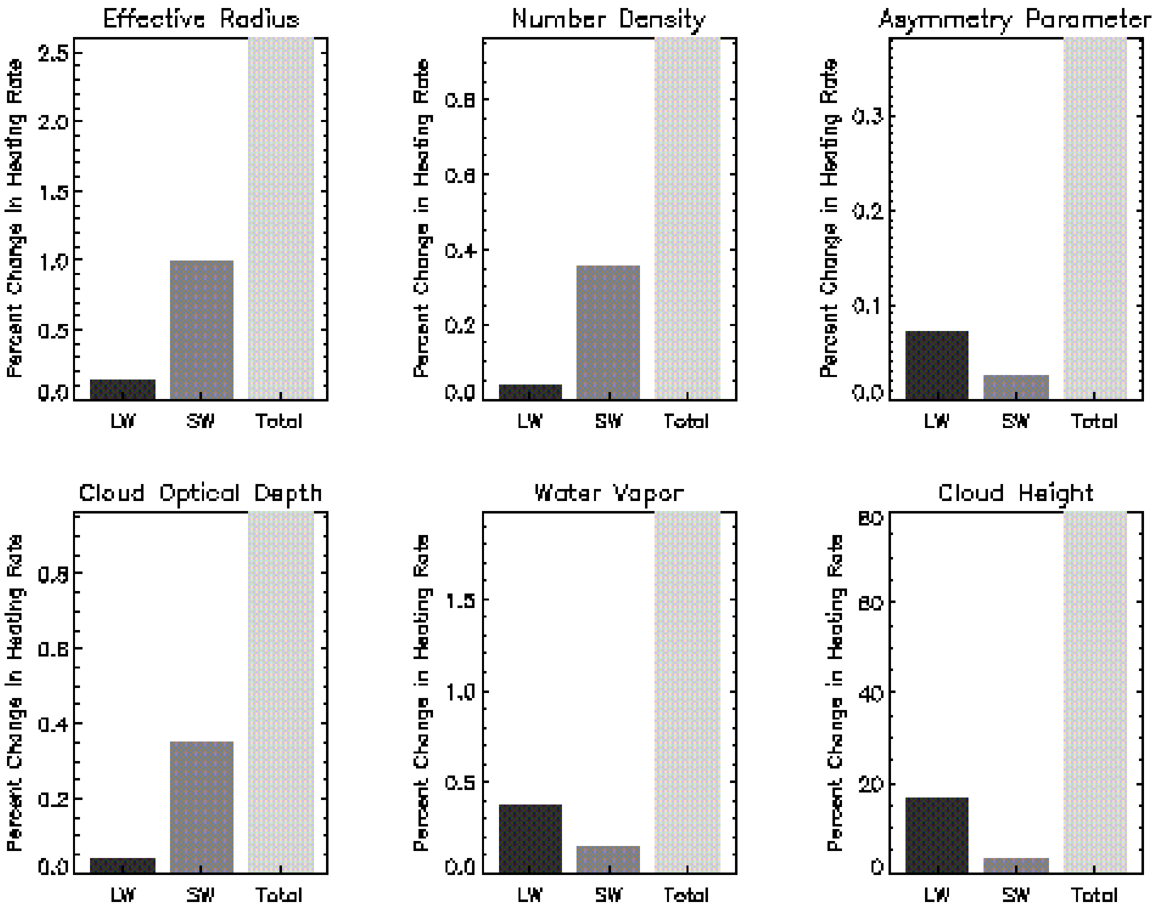

Figure 1. Sensitivities of heating rate from a 1% change in effective radius, number density, asymmetry parameter, cloud optical depth, and water vapor, and to a 0.5-km change in cloud height. These results are computed using the 5 December 1995 MCTEX case.

Further constraints on the heating rate retrievals are flux measurements at the ground. Shown in Figure 3 is a comparison between downwelling infrared (IR) flux from ground-based measurements and model calculations from the 5 December 1995 MCTEX case.

Summary and Conclusions

As determined from heating rate calculations from the radar and lidar data collected during MCTEX, the heating rate retrieval is most sensitive to the cloud profile. Changes in cloud height produce the largest changes in the heating rate profile. Second, small changes in other parameters (a priori information) such as effective radius, number density and asymmetry parameter result in much smaller variations in the heating rate profile. Finally, the radiative heating of the atmosphere and related cloud feedback mechanisms are critically related to the accurate determination of cloud height in the column.

References

Austin, R. T., C. M. R. Platt, S. A. Young, S. M. Sekelsky, and R. E. McIntosh, 1998: Optical depths and microphysics of tropical clouds - results from the MCTEX. This proceedings.

Intergovernmental Panel on Climate Change (IPCC), 1995: *Climate change, 1994; radiative forcing of climate and evaluation of the IPCC 1992 emission scenarios*. Cambridge University Press, Cambridge, United Kingdom.

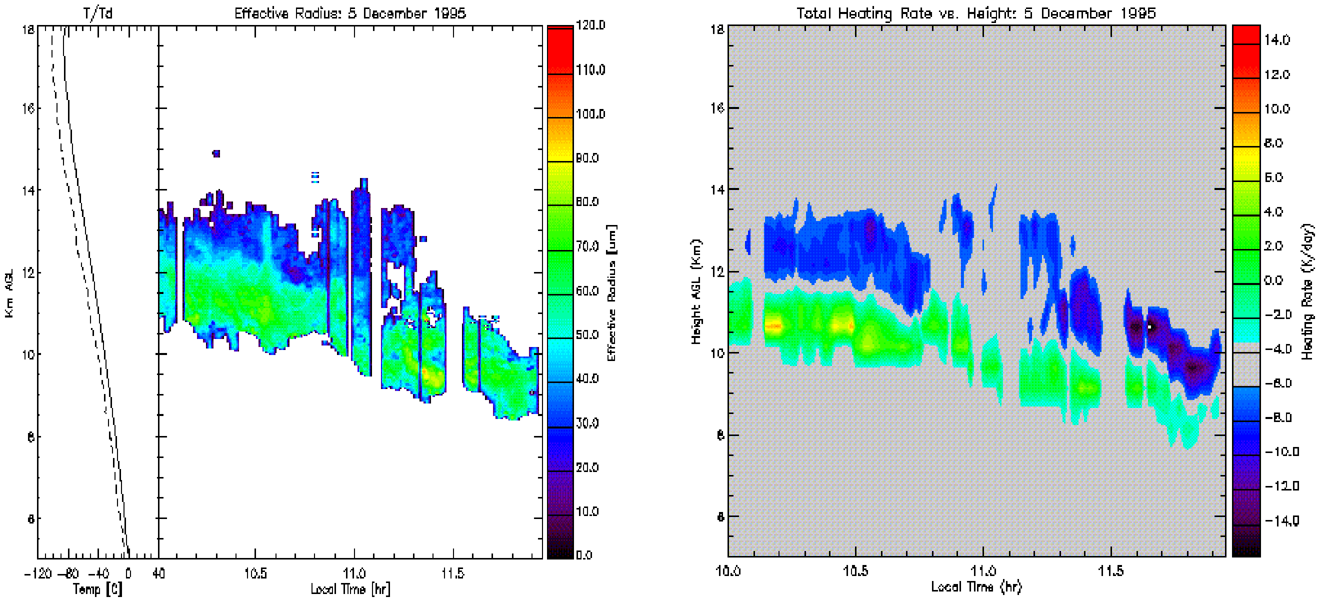

Figure 2. Plot of effective radius and heating rate derived from the 5 December 1995 MCTEX case. The temperature and dewpoint profile is provided on the left edge of the figure for reference. (For a color version of this figure, please see *http://www.arm.gov/docs/documents/technical/conf_9803/huffman-98.pdf*.)

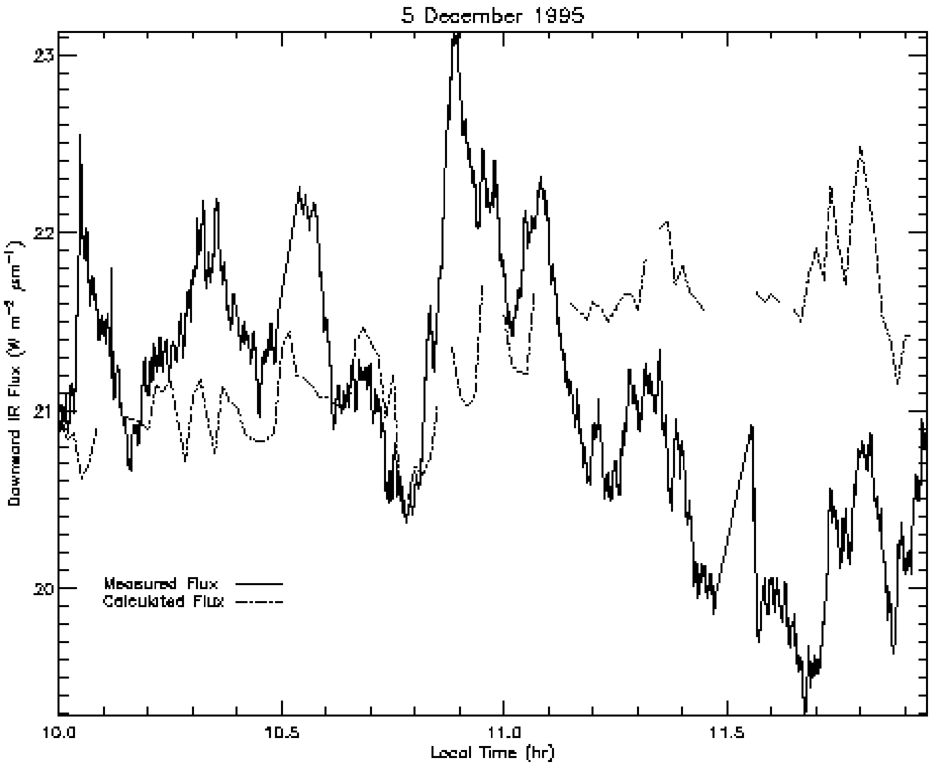

Figure 3. A comparison of downward IR flux measured at the surface, and calculated using the two-stream model.

Menke, W., 1989: *Geophysical data analysis: Discrete inverse theory*. Academic Press, San Diego, California, 289 p.

Rodgers, C. D., 1976: The limitations of remote sounding. In *Proceedings of the Symposium on Meteorological Observations from Space: Their Contribution to the First GARP Global Experiment*. NCAR, Boulder, Colorado, pp. 1-6.