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Title: Satellite Remote Sensing of Tropical Precipitation and Ice Clouds for GCM Verification

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This project, supported by the NASA New Investigator Program, has primarily been funding a graduate student, Darren McKague. Since August 1999 Darren has been working part time at Raytheon, while continuing his PhD research. Darren is planning to finish his thesis work in May 2001, thus some of the work described here is ongoing.

The proposed research was to use GOES visible and infrared imager data and SSM/I microwave data to obtain joint distributions of cirrus cloud ice mass and precipitation for a study region in the Eastern Tropical Pacific. These joint distributions of cirrus cloud and rainfall were to be compared to those from the CSU general circulation model to evaluate the cloud microphysical and cumulus parameterizations in the GCM. Existing algorithms were to be used for the retrieval of cloud ice water path from GOES (Minnis) and rainfall from SSM/I (Wilheit). A theoretical study using radiative transfer models and realistic variations in cloud and precipitation profiles was to be used to estimate the retrieval errors.

Due to the unavailability of the GOES satellite cloud retrieval algorithm from Dr. Minnis (a co-PI), there was a change in the approach and emphasis of the project. The new approach was to develop a completely new type of remote sensing algorithm - one to directly retrieve joint probability density functions (pdf's) of cloud properties from multi-dimensional histograms of satellite radiances. The usual approach is to retrieve individual pixels of variables (i.e. cloud optical depth), and then aggregate the information. Only statistical information is actually needed, however, and so a more direct method is desirable.

We developed forward radiative transfer models for the SSM/I and GOES channels, originally for testing the retrieval algorithms. The visible and near infrared ice scattering information is obtained from geometric ray tracing of fractal ice crystals (Andreas Macke), while the mid-infrared and microwave scattering is computed with Mie scattering. The radiative transfer is performed with the Spherical Harmonic Discrete Ordinate Method (developed by the PI), and infrared molecular absorption is included with the correlated k-distribution method. The SHDOM radiances have been validated by comparison to version 2 of DISORT (the community "standard" discrete-ordinates radiative transfer model), however we use SHDOM since it is computationally more efficient.

The model for the cloud profile consists of a liquid cloud layer and an ice cloud layer. For these two cloud layers, height of cloud top and base, and linear profile of liquid water content and effective droplet/ice crystal radius are free parameters. A vertically uniform rain layer with an exponential drop size distribution is also included between the liquid cloud base and the surface.

We designed an algorithm to perform the cloud property probability density function (pdf) retrieval from histograms of satellite radiances. This method considers three multi-dimensional spaces (see Fig. 1):

1. **cloud profile:** This high-dimensional space contains all the cloud profile parameters that are input to the radiative transfer model to simulate radiances.
2. **satellite radiance:** A low-dimensional space of satellite channels and known parameters (e.g. viewing angle).
3. **retrieved parameters:** The desired two-dimensional probability density function of cloud properties (e.g. ice water path and particle size).

Random points in the atmospheric profile space are mapped to the satellite radiance space with the radiative transfer model. The rate determining step is the radiative transfer calculations, so there is a limit to how many can be performed. Too few atmospheric space points, however, will degrade the cloud pdf retrieval. These atmospheric profile points are also mapped to the low-dimensional retrieval space (perhaps as easily as just pulling out two of the cloud parameters). Thus there is now a mapping of a number of points between the retrieval space and the radiance space. The mapping is nonunique – a small spot in the retrieval space may spread out to a larger area in the radiance space, and separate spots in the retrieval space may map to partially overlapping areas in the radiance space.

The probability distribution in the retrieval space is constructed by mapping the frequency (fraction of total pixels) in each satellite radiance bin to the retrieval space using the random points. The random cloud profiles are distributed according to a prior pdf. The prior pdf represents a priori information about the cloud and atmosphere profile, which is then refined by the additional information added by the satellite measurements. We used Bayes Theorem to provide a mathematical basis for the pdf retrieval algorithm.

The algorithm also provides uncertainty estimates of the cloud propery pdf's. This is important for comparison of retrieved and GCM cloud pdf's. We identified four sources of uncertainty in the pdf retrieval: 1) Uncertainty in the estimation of the observed radiance pdf, 2) Errors due to the finite number of random state vectors, 3) Errors in the observed radiances and the forward radiative transfer, and 4) Non-uniqueness in the inversion from radiance to atmospheric state. The algorithm has procedures to estimate the uncertainties from all of these error sources.

The cloud pdf retrieval algorithm was tested using numerical cloud model output. Two fields, a squall line scene and a scattered convection scene, were obtained from a GATE simulation of Clark's three-dimensional cloud resolving model (Grabowski et al., 1998). GOES radiances were simulated from the hydrometeor fields using the radiative transfer model described above. The cloud pdfs retrieved with the algorithm were compared to those obtained from the cloud model fields. Figures 2 and 3 show results of these tests for two-dimensional

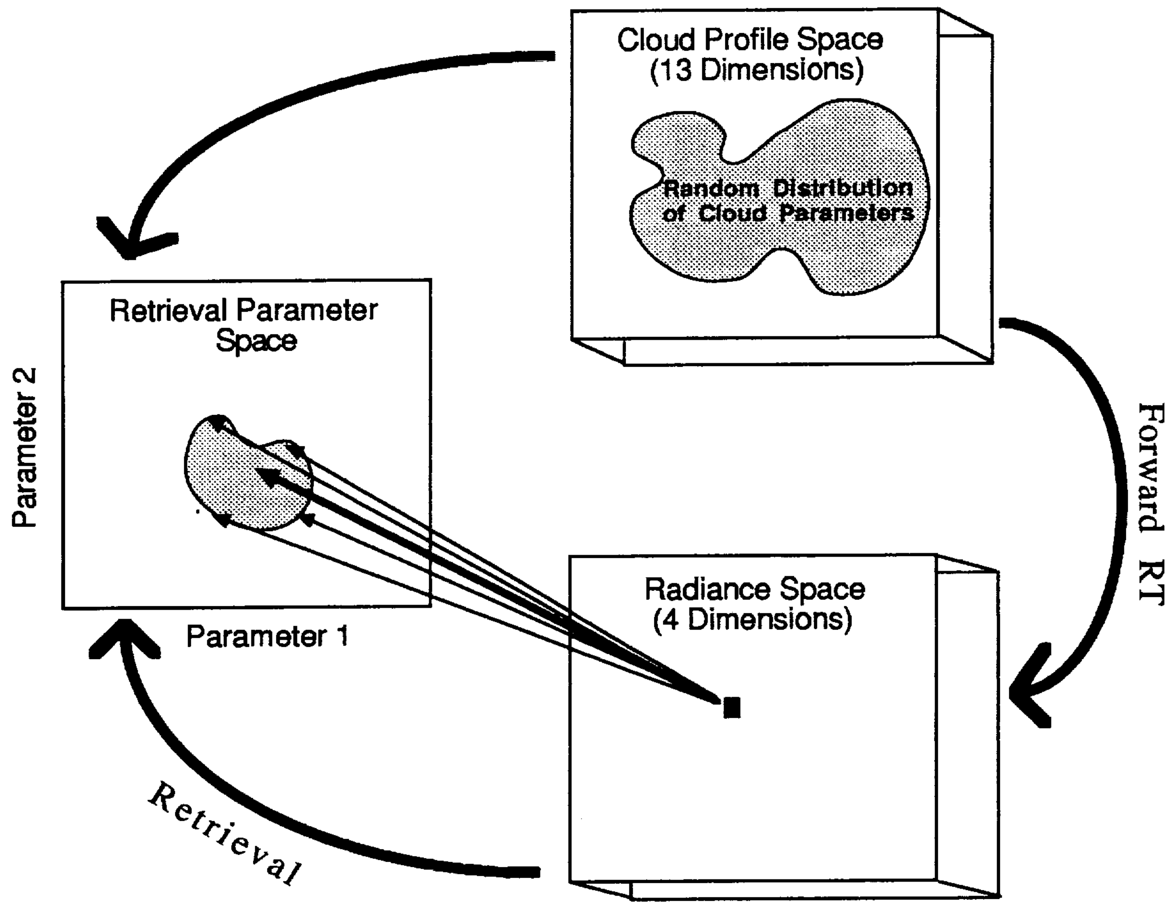

Figure 1: The PDF retrieval concept. Forward radiative transfer maps the random cloud profiles into radiance space. Retrievals use this mapping and the mapping from cloud profile space to retrieval space to go from a measured radiance bin to the retrieval parameters. Due to uncertainty in the measured radiances and the non-uniqueness of the mapping, a single radiance bin maps into a range of retrieval parameters.

joint distributions of cloud top height and optical depth and one-dimensional distributions of each. It is apparent, especially for the 1D distributions that the pdf retrieval works well, although the algorithm may over estimate the error bars. The cloud pdf retrieval algorithm was also applied to GOES data from the eastern tropical Pacific that we obtained in 1996 and 1997 from CIRA at Colorado State University.

A paper describing the cloud pdf retrieval work has been submitted, reviewed, and is now under revision:

McKague, D. S., and K. F. Evans, 2001: *Multichannel satellite retrieval of cloud parameter probability distribution functions.* Submitted to J. Atmos. Sci.

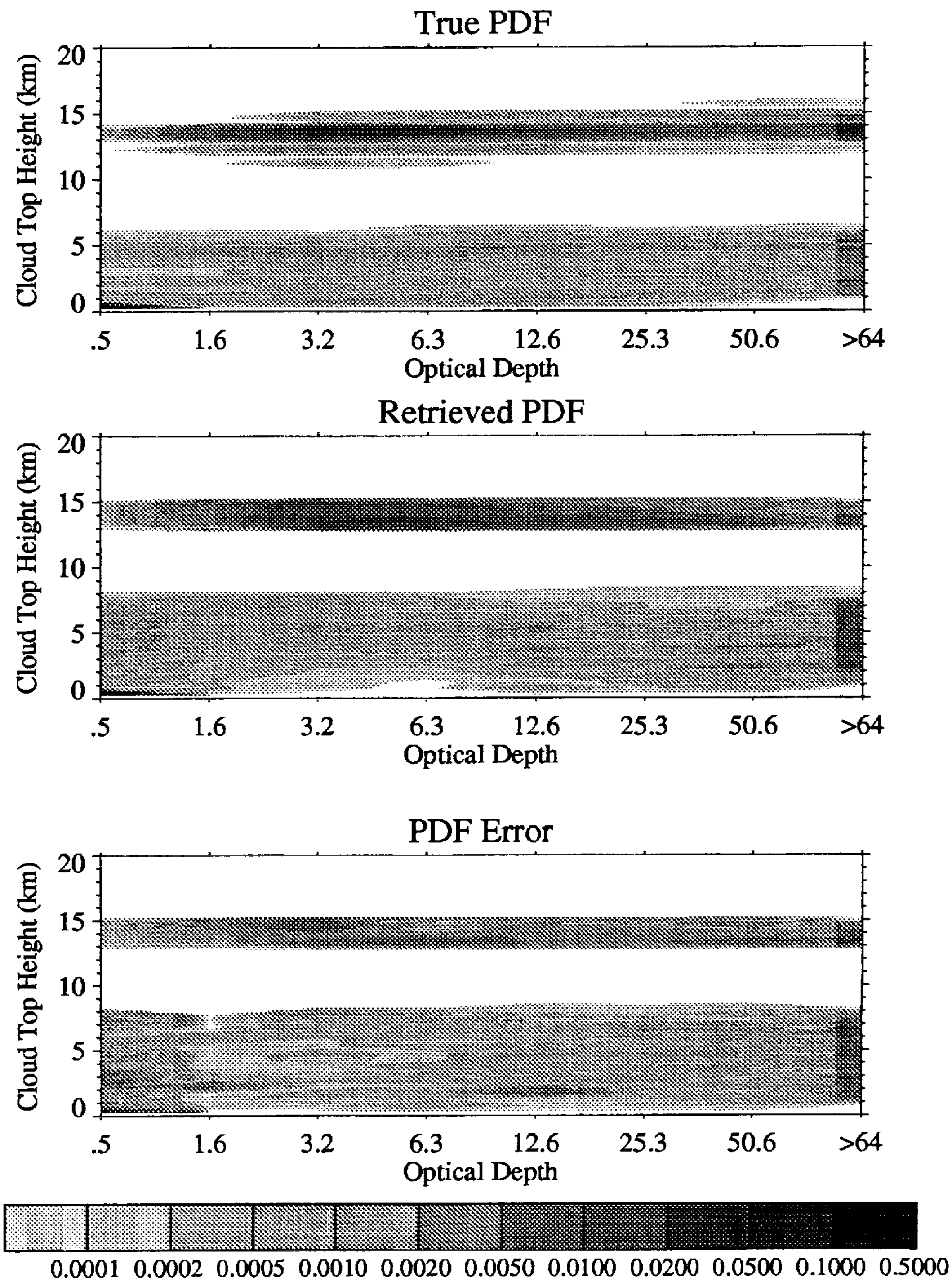

Figure 2: True, retrieved, and algorithm estimated errors for the joint pdf of optical depth and cloud top height.

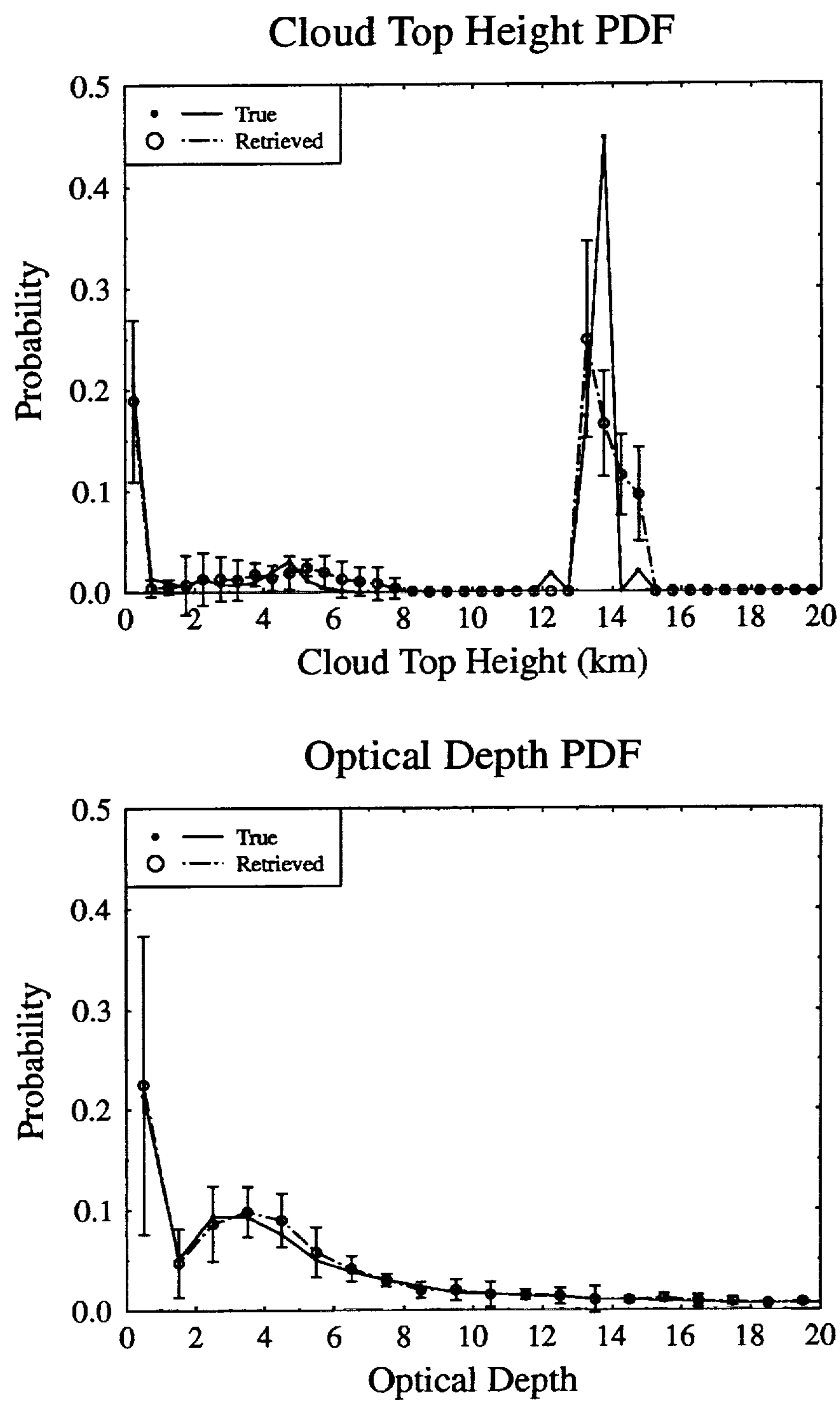

Figure 3: True, retrieved, and algorithm estimated errors for the one- dimensional pdf of cloud top height (top) and optical depth (bottom).

It has become clear that the accuracy of the cloud ice water path retrieval from GOES is too poor to allow joint distributions of cirrus cloud ice mass and precipitation from satellite and the GCM to be compared (as originally intended). Therefore, as a final part of his thesis research Darren is applying the pdf retrieval method to the SSM/I data we collected for the eastern tropical Pacific. The idea is to compare the rain rate distributions obtained from the single pixel microwave algorithms of Wilheit and Liu and Curry with ones generated by our pdf retrieval algorithm.

To make the prior pdf of random atmosphere and precipitating hydrometeors realistic we are using 3D fields from a GATE squall line simulation by Tao's Goddard Cumulus Ensemble (GCE) model. There are 7 fields with significant precipitation having a grid size of $170 \times 140 \times 31$ (2 km spacing) at half hour simulation intervals. The microwave brightness temperatures simulated from the hydrometeor fields are convolved with the SSM/I beam pattern, ranging in size from 15 km at 85 GHz to 65 km at 19 GHz. This provides too few independent cloud/radiance profiles for the pdf retrieval method. Therefore we are pursuing an innovative approach of simulating stochastic hydrometeor fields having the same vertical and horizontal statistics as the cloud model fields. The stochastic simulation method uses Empirical Orthogonal Functions to represent the vertical self and cross-correlations between five hydrometeor parameters (rain, snow, and hail mass content, and snow and hail mean particle diameter). The horizontal structure is represented with Fourier transforms having the same power spectra as the input fields. Random independent numbers with the correct statistics are used for the EOF/Fourier components. The ensemble of stochastic fields are then transformed back to the hydrometeor space. As a final step the ensemble single point statistics of each of the five hydrometeor fields is forced to match the input histograms.

Figure 4 shows an example rain water path field from the GCE simulation and one of the stochastic rain water path fields. The stochastic field has reasonable horizontal correlations, which are critical for obtaining the correct beam filling effect in the simulated SSM/I brightness temperatures.

The pdf retrieval algorithm has been used to retrieve the one-dimensional pdf of precipitation rate from SSM/I data collected for June, July, and August 1997 over the eastern tropical Pacific. Preliminary results are shown in Figure 5 for two retrievals: one with the SSM/I brightness temperatures simulated at the 2 km scale and another with the brightness temperatures averaged over the SSM/I antenna beam patterns. Thus, the second retrieval includes the effect of beam filling (in this case the retrieved rainrate is that averaged over the SSM/I 37 GHz beam pattern). Figure 6 shows the one-dimensional pdf of precipitation rate retrieved with the Liu and Curry single pixel algorithm for the same data. Both the Liu and Curry and the pdf retrieval with antenna beam averaging methods have a strange secondary peak in rainrate around 9 mm/hr. Retrieval tests with simulated SSM/I brightness temperatures from the GCE and Clark models will be used to test the pdf rain retrieval algorithm and determine whether this secondary peak is a robust result.

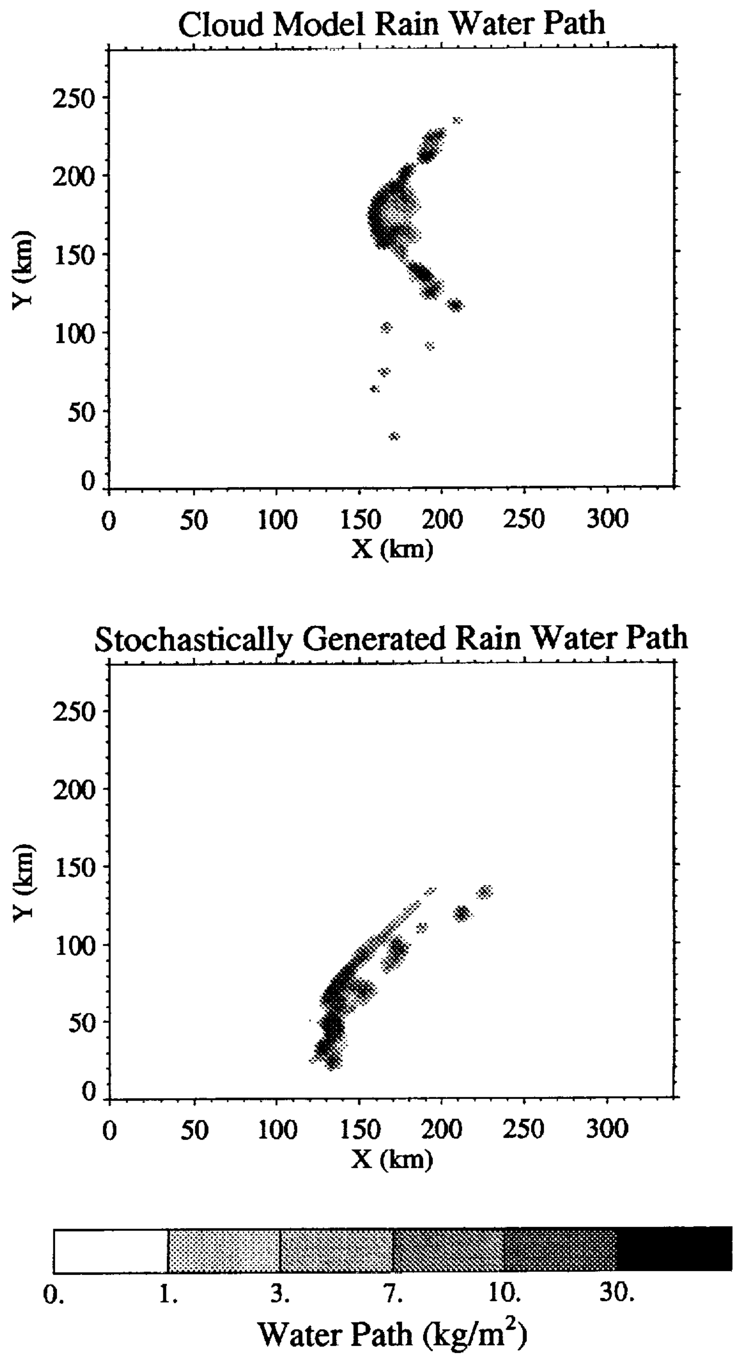

Figure 4: The integrated rain mass content for one of the GCE cloud model simulated fields (top panel) and one of the stochastic fields (bottom panel).

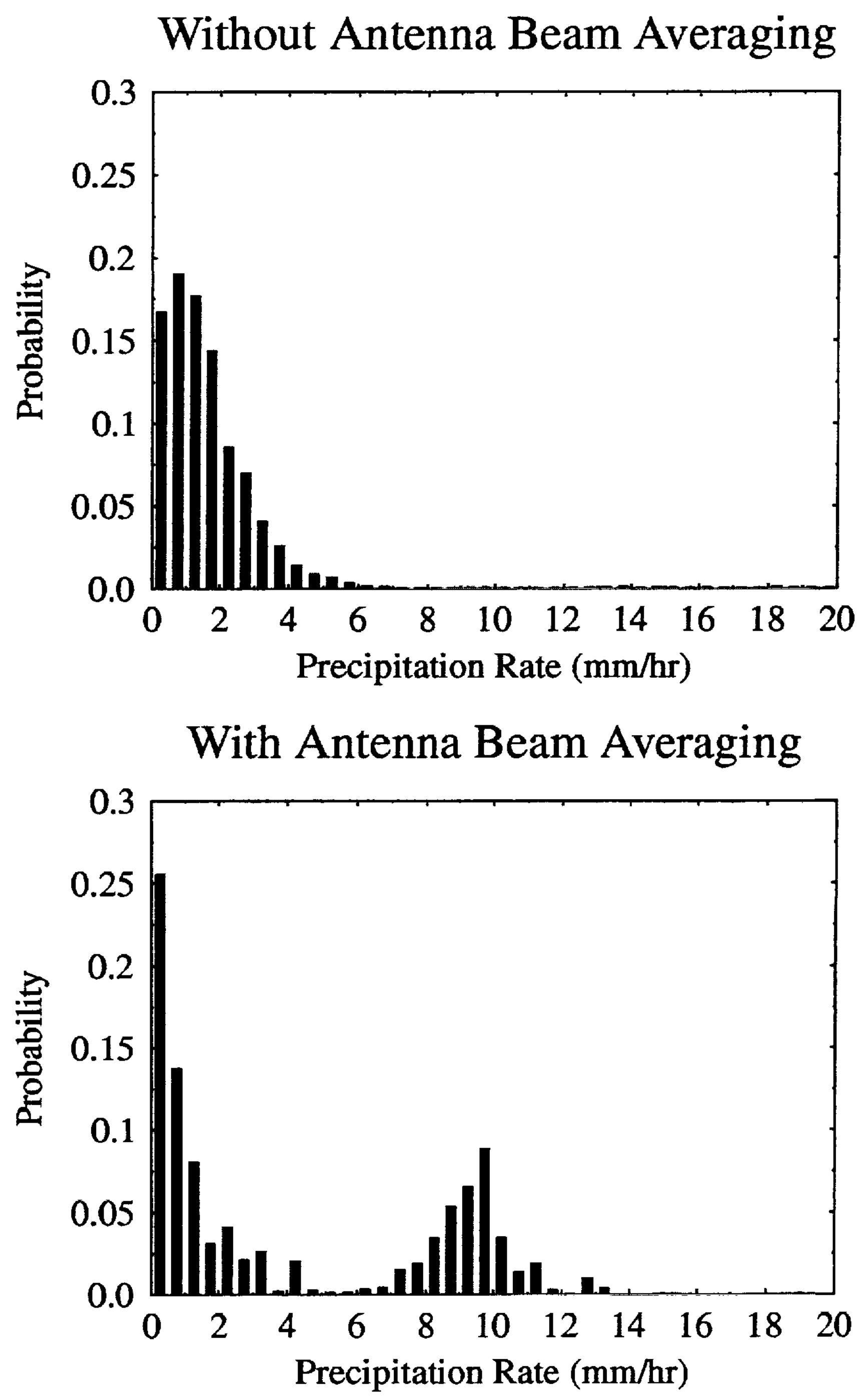

Figure 5: Retrieved precipitation rates from SSM/I data for June, July, and August of 1997 over the eastern tropical Pacific. The top panel is the retrieval using 2 km scale priors. The bottom panel is the retrieval using antenna beam averaged priors.

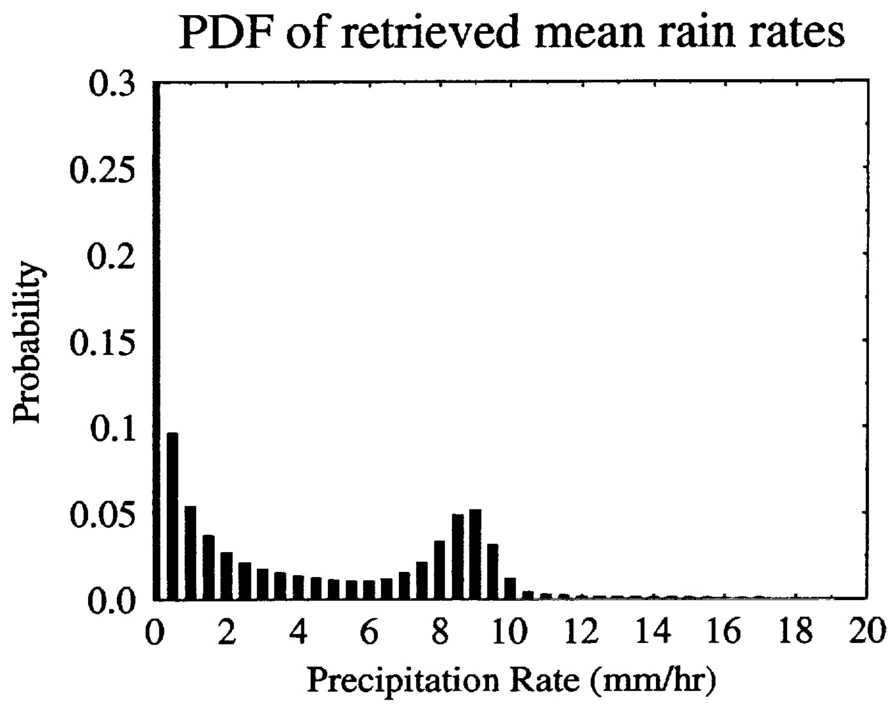

Figure 6: Retrieved precipitation rates from SSM/I data for June, July, and August of 1997 over the eastern tropical Pacific using the Liu and Curry algorithm.