Stratus Sensing in the CloudSat Antecedent Validation Experiment (CAVEX99)

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Introduction

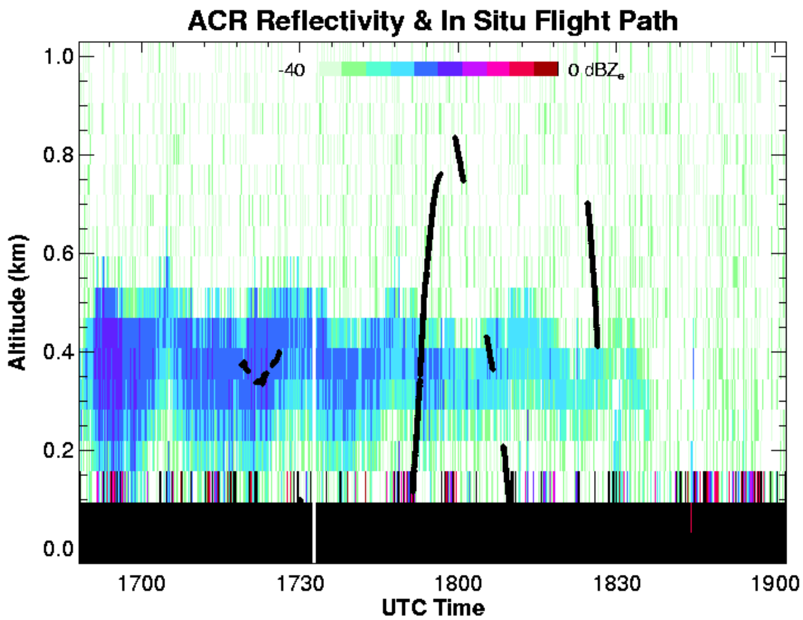
The CloudSat Antecedent Validation Experiment (CAVEX99) was one component of the Monterey Coastal Stratus Experiment (MCSE), a multi-experiment study of maritime stratus conducted off the Pacific coast near Monterey, California, in June and July 1999. MCSE was proposed and organized by Professor Bruce Albrecht of the University of Miami and Professor Qing Wang of the Naval Postgraduate School; it was supported by the Office of Naval Research. CAVEX was proposed as an add-on to MCSE and was designed to take advantage of planned MCSE flights inside the stratus layers by adding an additional aircraft for remote sensing measurements looking down from above the cloud layers. The remote sensing instruments were selected to simulate measurements by sensors on the CloudSat platform following its launch in 2003. CAVEX was supported by National Aeronautics and Space Administration (NASA) and the Atmospheric Radiation Measurement (ARM) Program.

CAVEX Measurements

Remote observations during CAVEX used the Jet Propulsion Laboratory (JPL)/UMass Airborne Cloud Radar (ACR) (Sadowy et al. 1997) and the Colorado State University Scanning Spectral Polarimeter (SSP) (Stephens et al. 2000) to remotely sense maritime stratus clouds beneath the ARM unmanned aerospace vehicle (ARM/UAV) Twin Otter aircraft, which was flying at an altitude of approximately 8000 feet (2440 m) above mean sea level (MSL). The ACR measures cloud reflectivity at 95 GHz; the SSP measures upwelling radiance and fluxes in the visible and near-infrared wavelengths. Second radar, the ARM UAV radar, was also flown on some flights for testing and comparison.

The MSCE Twin Otter aircraft, operated by the Naval Postgraduate School's Center for Interdisciplinary Remotely-Piloted Aircraft Studies (CIRPAS), flew inside the stratus layers performing in situ measurements of cloud properties while maintaining a stacked flight formation with the ARM/UAV aircraft above. The CIRPAS aircraft carried a Particle Measuring Systems Forward Scattering Spectrometer Probe (FSSP-100X) and a Gerber Scientific Particle Volume Monitor (PVM-100A) probe for the direct measurement of cloud liquid water content and particle size. Global Positioning System (GPS) geolocation data from both aircraft allow in situ cloud properties to be matched to specific radar bins as seen by the remote sensing aircraft. A sample time-height diagram of radar reflectivity with superimposed in situ flight track is shown in Figure 1a. Retrieved values of visible optical depth were calculated from the 583 nm and 609 nm channels of SSP data using the technique of (Miller et al. 2000). Values of optical depth corresponding to the reflectivity data in Figure 1a are shown in Figure 1b.

(a)



(b)

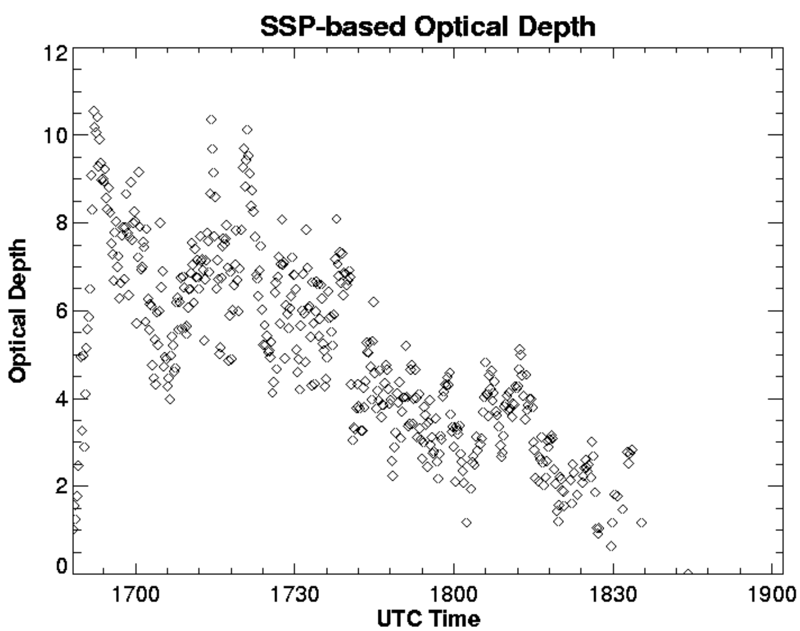


Figure 1. Sample measurement data from a single CAVEX99 flight on June 19, 1999: (a) Time-height diagram of radar reflectivity, with the in situ aircraft flight track superimposed for periods of horizontal coincidence, and (b) visible optical depth retrievals for the same flight.

Retrieval Algorithm

The forward model developed for the retrieval assumes a lognormal size distribution of cloud droplets:

$$N(r) = \frac{N_T}{\sqrt{2\pi}\sigma_{log} r} \exp\left[\frac{-\ln^2(r/r_g)}{2\sigma_{log}^2}\right]$$

where N_T is the droplet number density, r is the droplet radius, r_g is the geometric mean radius, and σ_{log} is the natural log of the geometric standard deviation. The liquid water content and effective radius are defined in terms of moments of the size distribution. The model assumes that no significant drizzle is present.

Using an estimation theory approach (Rodgers [1976] and later works), we retrieve a state vector consisting of a geometric mean radius profile and a constant value of N_T. We let N_T and σ_{log} be constant through the cloud column, similar to (Frisch et al. 1995); we also specify the value of σ_{log} based on a developing database of cloud microphysical data (e.g., Miles et al. 2000). The retrieval algorithm obtains an optimal solution based on measurements, forward model parameters, and a priori data, together with specified uncertainties for each of these quantities. The particular parameters used in the case shown here are summarized in Table 1. A detailed description of the retrieval algorithm is found in an upcoming paper (Austin and Stephens 2000).

Table 1. Retrieval parameters used in this analysis.

Parameter	Value	Uncertainty
A priori r_g	6.55 μm	70%
A priori N_T	74 cm^{-3}	45 cm^{-3}
Model σ_{log}	0.38	0.13
Measured Z	-----	1.0 dBZ
Measured τ	-----	varies

The estimation theory framework provides valuable information on the relative influence of measurement data and a priori information and the uncertainties in these quantities. For example, Figure 2 shows a partition of the standard deviation in the retrieved r_g profile for a single radar measurement during a case study flight.

Results

Time-height plots of retrieved values of cloud liquid water content (LWC) and effective radius are shown in Figures 3a and 3b for the June 19, 1999, case study. Correlation plots of these retrieved values and corresponding in situ measurements by the FSSP and PVM cloud probes are shown in Figures 3c and 3d. Points in these plots are restricted to periods when the in situ aircraft was within 500 m of the horizontal position of the radar aircraft. Agreement between the retrieved and in situ values of LWC is

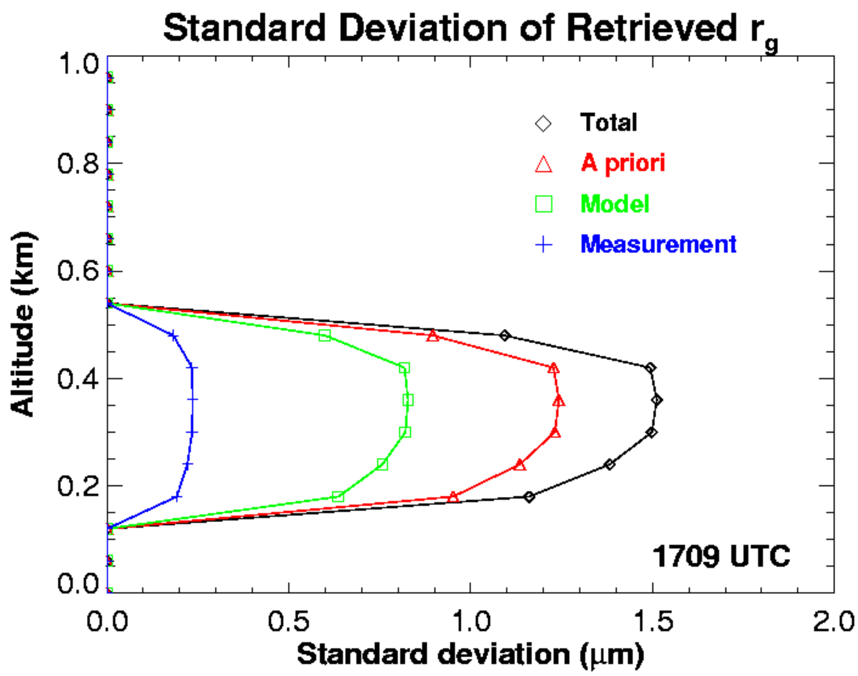


Figure 2. Partition of standard deviation in r_g for 1709 Universal Time Coordinates (UTC) retrieval of June 19.

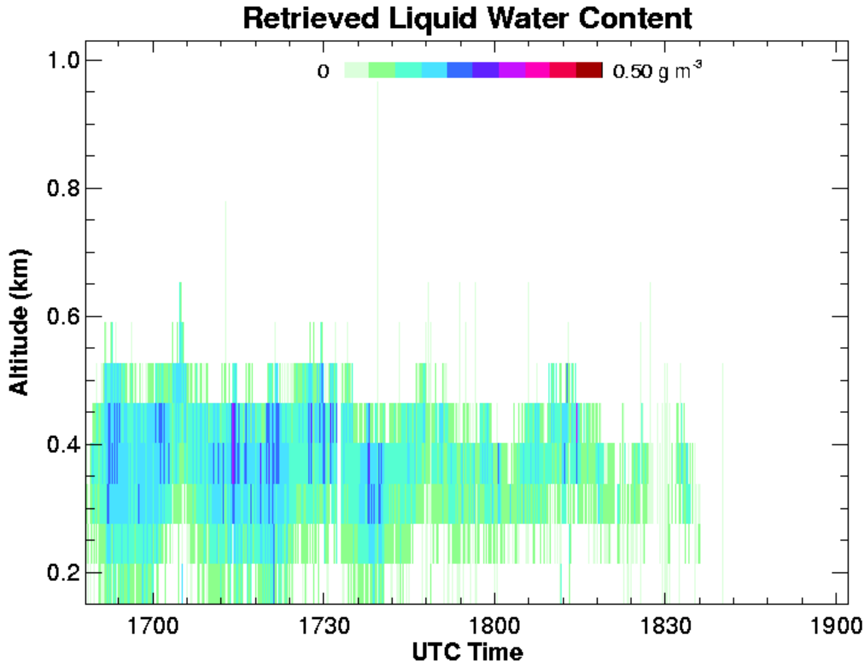
generally good. The spread about the 1:1 line is likely due (at least in part) to sampling differences, i.e., the difference in sampling volume seen by the cloud probes and the radar, which was using a 60 m vertical bin. Effective radius values show a bias; the retrieved values tend to exceed the in situ values by approximately 20%. The origin of this bias is under study.

The June 19, 1999, case was deemed to possess no drizzle based on the structure and magnitude of the radar measurements. A case considered to have drizzle (June 24) was also examined. The drizzle violates the forward model assumptions and results in degradation in both liquid water content and effective radius retrievals. The case studies mentioned here are examined in more detail in an upcoming paper (Austin et al. 2000).

Conclusions

CAVEX99 provided a valuable data set for the development of retrieval algorithms in preparation for the CloudSat mission, scheduled for launch in 2003. The algorithm shown here shows definite promise for use in stratus retrievals. Drizzle remains a challenge; an initial step is use of the retrieval to indicate the presence of drizzle. The structure of the algorithm facilitates the addition of complementary data streams, which is anticipated by the formation flight of CloudSat, PICASSO-CENA (Pathfinder Instruments for Cloud and Aerosol Spaceborne Observations - Climatologic Etendue des Nuages et des Aerosols), and Aqua.

(a)



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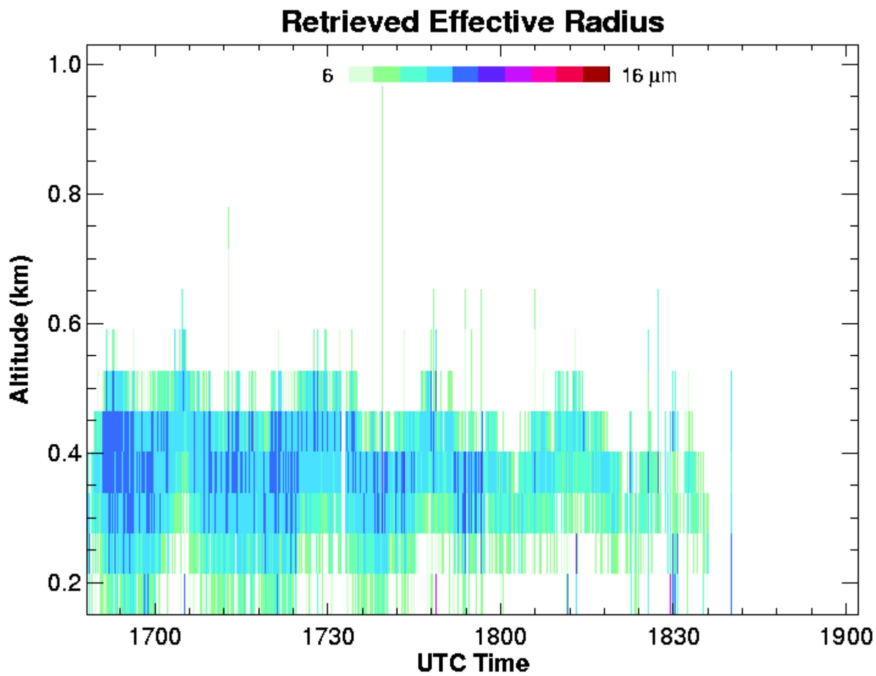
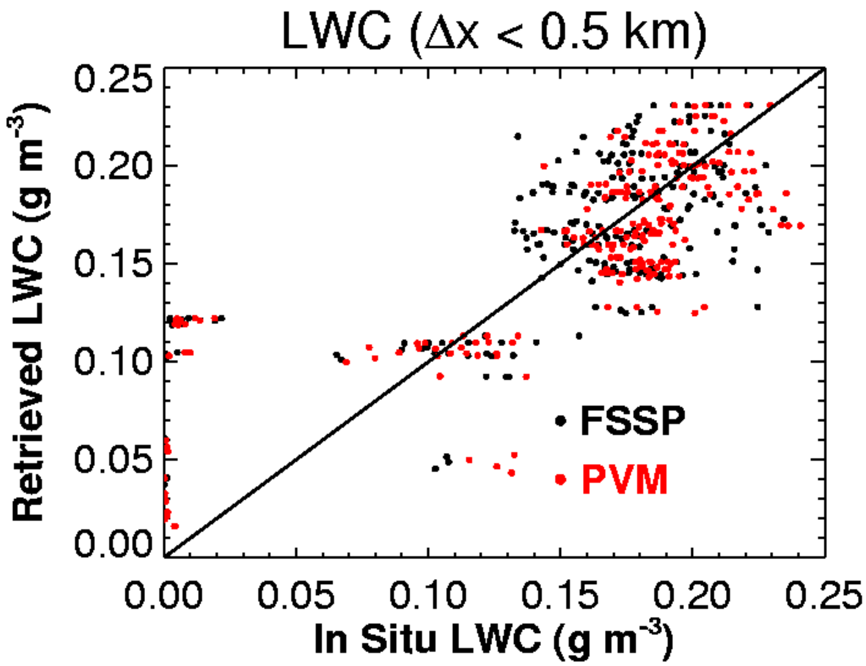


Figure 3. Retrieval results for June 19: (a) Retrieved liquid water content (LWC), (b) retrieved effective radius, (c) correlation of retrieved and in situ LWC for periods of horizontal coincidence, and (d) similar correlation of retrieved and in situ effective radius.

(c)



(d)

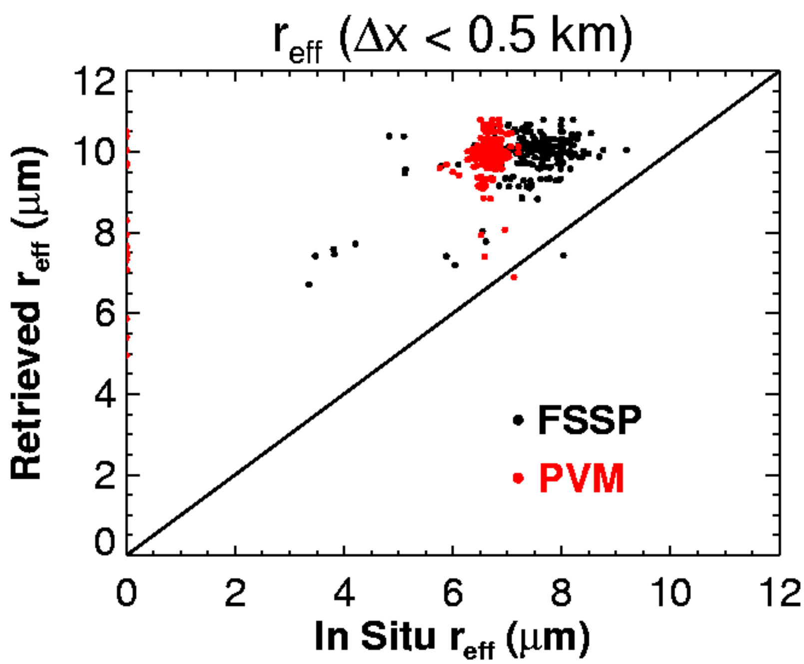


Figure 3 (contd.). Retrieval results for June 19: (a) Retrieved liquid water content (LWC), (b) retrieved effective radius, (c) correlation of retrieved and in situ LWC for periods of horizontal coincidence, and (d) similar correlation of retrieved and in situ effective radius.

Acknowledgments

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