A 25-Month Data Base of Stratus Cloud Properties Generated from Ground-Based Measurements at the ARM SGP Site

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Introduction

Boundary layer stratiform clouds are important in the regulation of the earth's radiation budget and play an important role in climate over both land and ocean (Ramanathan et al. 1989). Boundary layer stratus has also been widely recognized as a key component in predicating any potential future climate change (Wielicki et al. 1995). Since different climate models have different representations of cloud radiative properties, an intercomparison of 19 general circulation models (GCMs) produced quite different results in regards to cloud feedback, ranging from positive to weakly negative to nearly neutral cloud radiative forcings (Cess et al. 1990). Most early GCMs had the cloud optical depth as a function of altitude and/or temperature, which limited the ability of changes in cloud properties to feedback to the climate system (Del Genio et al. 1996). The prognostic parameterization of cloud optical properties, such as cloud liquid water content (LWC), in terms of GCM-resolved variables is a fairly recent trend. However, this approach requires the parameterization of complex microphysical, dynamic, and radiative processes, thus introducing a number of degrees of freedom into the parameterization absent from the simpler approaches (Del Genio et al. 1996). Therefore, we must improve the observational data base of cloud properties, together with measurements of the associated dynamic and thermodynamic fields, in order to improve both these new prognostic parameterizations and the GCMs in which they are embedded.

The U.S. Department of Energy (DOE) Atmospheric Radiation Measurement (ARM) Program established the ARM Southern Great Plains (SGP) research site to obtain long-term records of surface radiation data and the impact of clouds on these data (Stokes and Schwartz 1994). The purpose of the ARM Program is to improve the representation of radiation and clouds in GCMs so that these models can produce more accurate climate change simulations. The general approach adopted by the ARM Program is to use surface observations to develop, test, and improve cloud parameterizations in the context of a single-column model (SCM), and then to transfer the resulting parameterizations into full three-dimensional GCMs (Randall et al. 1996). To begin the process of evaluating cloud parameterizations against observed data, we have developed a 25-month data base of stratus cloud macrophysical, microphysical, and radiative properties using data collected at the ARM SGP central facility from November 1996 through November 1998. The data base includes two parts: measurements and retrievals. The measurements consist of cloud base and top heights, layer-mean temperature, liquid water path (LWP), and the transmission ratio measured by a ground-based lidar/ceilometer and radar pair, radiosondes, a microwave radiometer, and a PSP pyranometer, respectively. The retrievals, based on the parameterization of Dong et al. (1998), include the cloud droplet effective radius and number concentration, optical depth, and cloud and top-of-atmosphere (TOA) albedos. The data base provides fundamental statistical information about stratus clouds for climate model parameterization evaluation.

Method

Dong et al. (1997, 1998) have demonstrated that the combined measurements from a radar, lidar, microwave radiometer, PSP pyranometer, and radiosonde can provide basic information on stratus cloud properties, including cloud boundaries, cloud LWP, and downward solar flux through the cloud. To retrieve the microphysical and radiative properties of stratus clouds, Dong et al. (1997) used a 2-stream radiative transfer model in conjunction with ground-based measurements. The cloud LWP is obtained from microwave radiometer brightness temperature measurements, while the cloud-droplet effective radius is a free parameter. The cloud-droplet effective radius, together with the measured cloud LWP, is used to specify the cloud properties in the 2-stream radiative transfer model. The cloud-droplet effective radius is subsequently varied in the radiative transfer calculations until the computed cloud shortwave transmission matches what is measured.

The uncertainties in the retrieved cloud radiative properties using this technique are generally less than 5%, while the errors in the retrieved cloud droplet effective radius and number concentration are about 15% and 30%, respectively. In the retrieval, the cloud droplets are assumed to have a lognormal size distribution with a logarithmic width of 0.35. From sensitivity studies, we find that the variation of the cloud-droplet size distribution width has no effect on the retrieved cloud-droplet effective radius, while the number concentration changes by 15% to 30% as the logarithmic width varies from 0.2 to 0.5. These results are consistent with the results of both Hu and Stamnes (1993), who demonstrated that the cloud transmission primarily depends upon the cloud LWP and cloud-droplet effective radius, and Miles et al. (1999), who show the extreme sensitivity of the cloud-droplet number concentration to changes in the cloud-droplet size distribution width.

Dong et al. (1998) parameterized the retrieved cloud-droplet effective radius and radiative properties as a function of cloud LWP, the transmission ratio (the ratio of surface irradiance during cloudy conditions to the expected clear-sky surface irradiance), and the cosine of the solar zenith angle. The parameterization enables estimation of stratus cloud microphysical and radiative properties using ground-based measurements that are readily available at a number of locations. To evaluate the retrieved and parameterized cloud microphysics, approximately 5 hours of data on October 24, 1996, from the Pennsylvania State University surface remote sensing site located at Rock Springs, Pennsylvania, were analyzed and compared to collocated in situ measurements made by a Forward Scattering Spectrometer Probe aboard the University of Wyoming King Air aircraft. On average, the retrieved values of the cloud-droplet effective radius and the cloud-droplet number concentration differed from the corresponding aircraft measurements by 7% and 27%, respectively, while the parameterized values differed from the aircraft measurements by 15% and 32%, respectively. Averaging all of the data to 30-min. resolution (Figure 1) significantly reduced the differences between the aircraft data and the retrieved and parameterized results, suggesting that at this averaging scale both the aircraft and the ground-based data are capable of characterizing the cloud microphysics, and the temporal and spatial statistics are converging. The parameterization of stratus shortwave radiative properties is generally within 5% of Slingo's (Slingo 1989) four-band, model-derived parameterization when absorption above cloud top was incorporated into the Slingo parameterization.

To further test the accuracy of the Dong et al. (1998) parameterization, the Dong et al. (1997) retrieval was applied to 3 months (December 1997 through February 1998) of data from the ARM SGP central facility and subsequently compared to estimates from the parameterization. Differences between the retrieved and parameterized values were generally within 3%. On average, the TOA albedo is 84% of cloud albedo, and the ratio of each 5-min. TOA albedo to cloud albedo never departed by more than 2% from the average value. Consequently, in the data base TOA albedo is not sensitive to the vertical profile of the atmosphere and one can take the TOA albedo to be 84% of the cloud albedo obtained from the parameterization.

Results and Discussions

Using the Dong et al. (1998) parameterization, a 25-month (November 1996 through November 1998) data base of stratus cloud properties at the ARM SGP central facility has been generated. The data base includes two parts: measurements and retrievals. The measurements consist of cloud base and top heights, layer-mean temperature, LWP, and the transmission ratio measured by a ground-based lidar/ceilometer and radar pair, radiosondes, a microwave radiometer, and a PSP pyranometer, respectively. The retrievals include the cloud-droplet effective radius and number concentration, cloud optical depth, and cloud and TOA albedos. The five criteria for choosing the periods when a retrieval was performed are: 1) there is only a single stratus cloud layer present, 2) the cosine of the solar zenith angle is larger than 0.2, 3) the range of transmission ratios is 0.1 to 0.7, 4) the cloud LWPs range from 20 to 600 g m^{-2}, and 5) the cloud top height is less than 3 km.

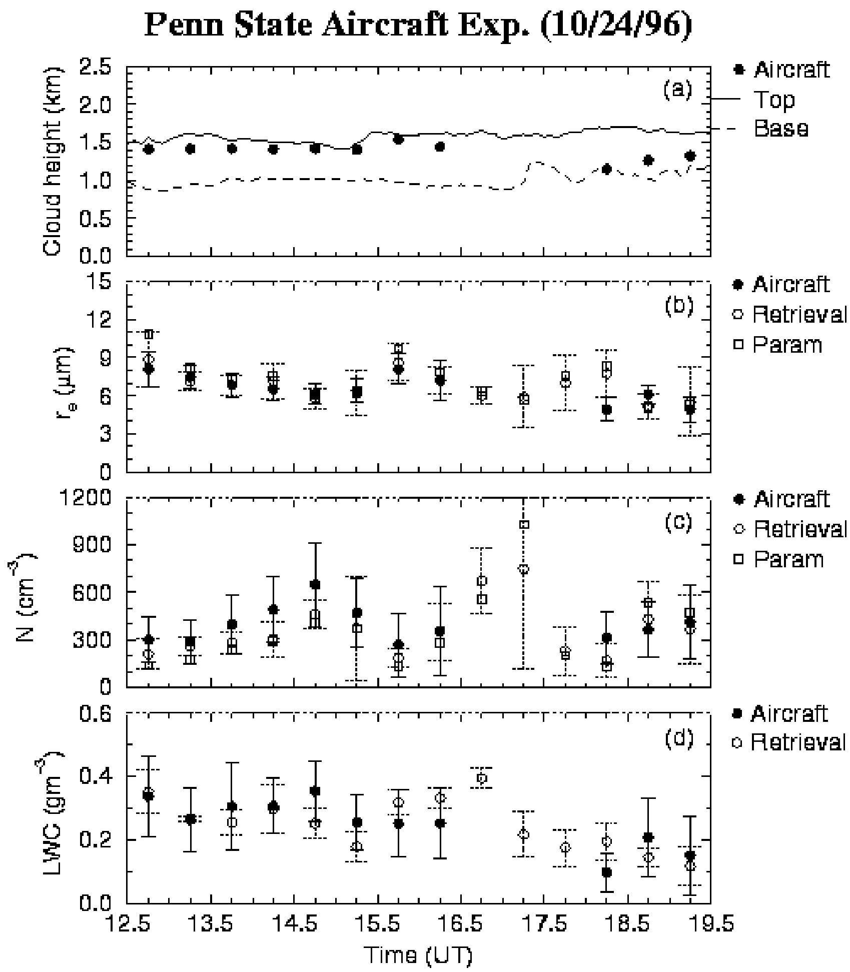

Figure 1. (a) Cloud base and top heights from ceilometer and 94-GHz cloud radar, and the aircraft altitude. The retrieved, parameterized, and in situ measured cloud droplet effective radii (re), cloud droplet number concentrations (N) and cloud liquid water contents (LWCs) at 30-minute temporal resolution are illustrated in (b), (c), and (d), respectively. The solid standard deviation bars are for the aircraft data, while the dashed standard deviation bars are for the retrieval.

Approximately 500 hours (more than 6000 samples at 5-min. resolution) of stratus occurred during the study period that satisfied these five criteria. The peak occurrence of isolated stratus occurred during the winter, whereas the minimum amount of stratus occurred in the summer (Figure 2). The mean and standard deviation of the measurements for each month are illustrated in Figure 3, whereas Figure 4 illustrates the frequency of occurrence of each measurement value. As a result of limited samples, the monthly means and standard deviations in Figure 3 might not represent the true values, especially during the summer season. The cloud layer heights and geometric thicknesses in summer are generally higher

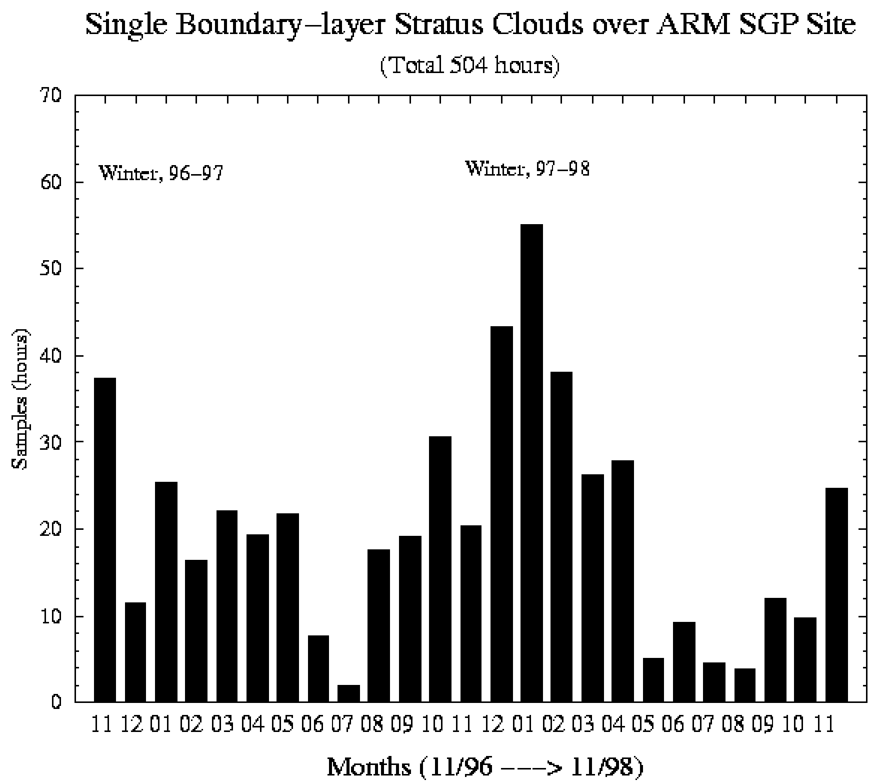

Figure 2. A single layer stratus cloud amount from November 1996 to November 1998 at ARM SGP site.

and greater, respectively, than those in winter. Both cloud height and cloud thickness is positively correlated with cloud-layer mean temperature. Most cloud base heights are less than 0.6 km with a mean value of 0.47 km and a standard deviation of 0.39 km. Cloud top heights range from 0.8 to 1.4 km with a mean value of 1.32 km and a standard deviation of 0.51-km mean.

We found that the cloud top heights from the cloud radar were overestimated during the summer season compared to the radiosonde soundings. This was most likely due to insect contamination of the radar power returns at these low altitudes (Clothiaux et al. 1999). So, the radar-estimated cloud top heights in this data base have been modified by setting the cloud top height to that altitude in the radiosonde soundings where the relative humidity drops below 94% (Keihm 1989). From the cloud-layer temperature distribution illustrated in Figure 4, we expect most of the stratus clouds in the data base to be in the liquid phase and only approximately 16% to be in a mixed phase with liquid water droplets still dominant. Most monthly mean cloud LWPs range from 50 to 200 g m^{-2} with a modal frequency of occurrence between 50 and 100 g m^{-2}. The mean and standard deviation of LWP were 134 g m^{-2} and 86 g m^{-2}, respectively. The transmission ratio has a negative correlation with cloud LWP (Figure 3) and a broad frequency of occurrence histogram (Figure 4).

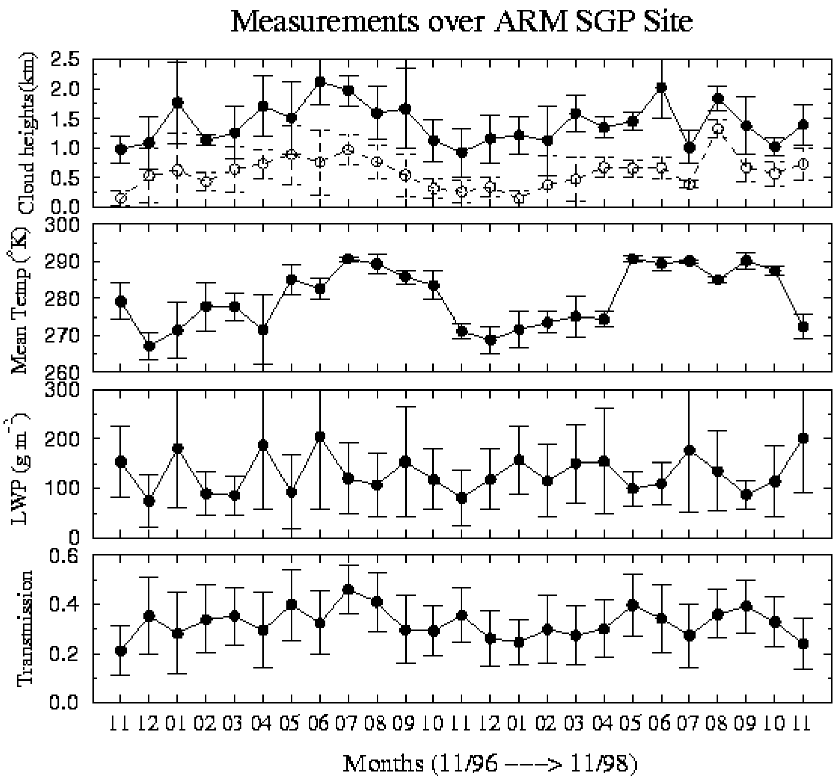

Figure 3. Monthly mean and standard deviation values of measurements.

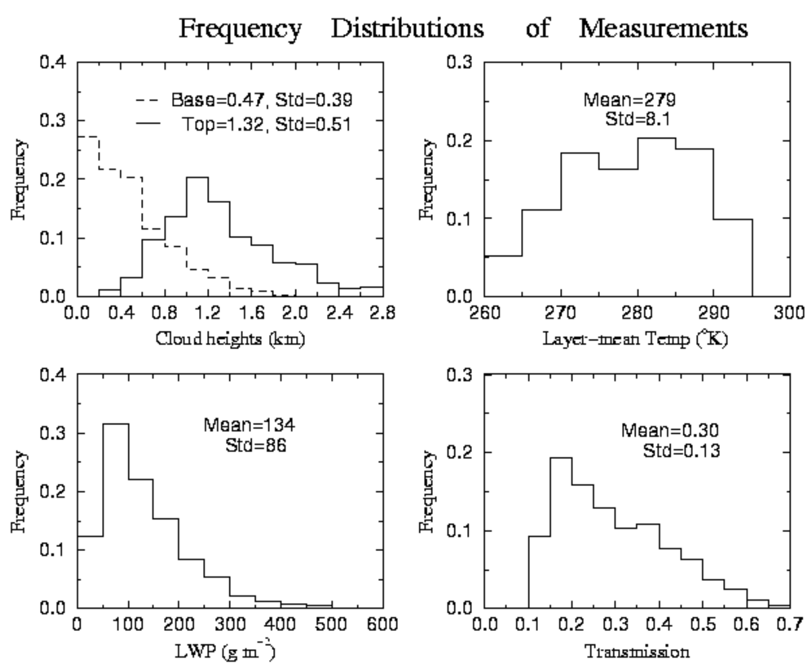

Figure 4. Frequency distributions of measurements from all data sets (>6000 samples).

The mean and standard deviation of the retrieved parameters for each month are illustrated in Figure 5; whereas Figure 6 illustrates the frequency of occurrence of each retrieved value. Although the monthly mean values of cloud-droplet effective radius do not exhibit a strong seasonal trend, there does appear to be a slight variation from the winter of 1996-1997 to the winter of 1997-1998. During this period, the monthly mean value of the cloud-droplet effective radius increased from winter to summer and then decreased monotonically from summer to the ensuing winter. This trend is not as strong in the data from the winter of 1997-1998 to the winter of 1998-1999. Overall, the effective radii during the summer are generally larger than those during the winter. There are at least two physical reasons that might explain this seasonal variation. First, more water vapor is present in the summer season atmospheric column. Therefore, if cloud condensation nuclei (CCN) concentrations are the same during the summer and winter seasons, one might expect the cloud droplets to grow to larger sizes during the summer. And second, mean cloud-droplet sizes increase monotonically with height above cloud base and this growth process is dominated by condensation rather than coalescence. Therefore, larger cloud droplets might be expected to occur in the geometrically thicker clouds of summer.

Most cloud-droplet effective radii ranged from 5 to 12 μm with a long tail toward the larger sizes. The mean cloud-droplet effective radius was 8.3 μm, which is almost identical with the value obtained by Han et al. (1998) for Northern Hemisphere continental locations using International Satellite Cloud Climatology Project (ISCCP) data. The variation of cloud-droplet number concentration was always opposite to that of the effective radius (Figure 5). The large standard deviations for the number concentrations in Figure 5 result from both uncertainties in the observed cloud boundaries and assuming a constant lognormal size distribution width of 0.53 that was obtained from aircraft in situ measurements over the ARM SGP site during the fall of 1997. The number concentration frequency of occurrence histogram is similar to the one for the effective radius as it too has a much longer tail toward higher values. The number concentration mean value of 235 cm^{-3} for this study is similar both to the in situ value (243 cm^{-3}) obtained from aircraft probe measurements during the fall of 1997 and to the value (288 cm^{-3}) obtained in the climatology study of Miles et al. (1999). The variations in the monthly mean values of cloud optical depth; cloud albedo and TOA albedo follow the trend in the cloud LWP. Most cloud optical depths are between 5 and 45 with a mean value of 25.1. The mean values for cloud and TOA albedos are 0.69 and 0.58, respectively, with frequency of occurrence modal values of 0.75 and 0.65, respectively.

A summary of both measured and retrieved cloud properties in the data base as a function of season is illustrated in Table 1. As Table 1 shows, cloud layer heights and geometric thicknesses in summer are generally higher and greater, respectively, than those in winter. Both of these quantities are positively correlated with the cloud-layer mean temperature. Cloud-droplet effective radii are generally larger, while cloud-droplet number concentrations are generally smaller, during summer as compared to winter, which is consistent with the findings of Han et al. (1998). Applying a student-T test to the cloud-droplet effective radii for the two seasons, we find with a certainty of 99.9% that the cloud-droplet effective radii for the two seasons are significantly different. Since cloud LWPs are almost the same in both seasons, cloud optical depth is higher during winter, leading to higher cloud albedos and lower cloud transmissions.

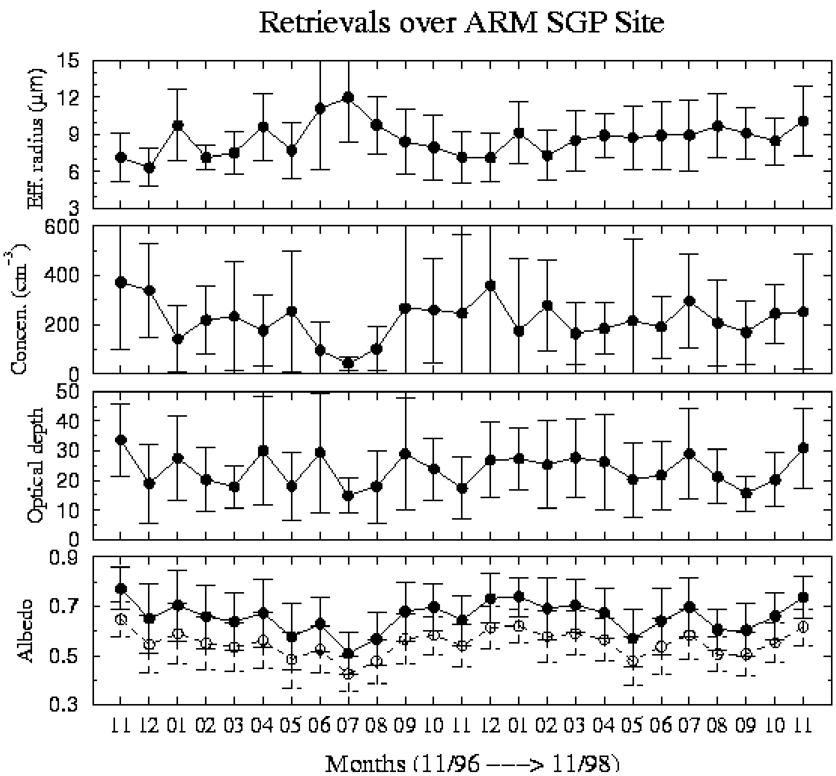

Figure 5. Monthly mean and standard deviation values of retrievals.

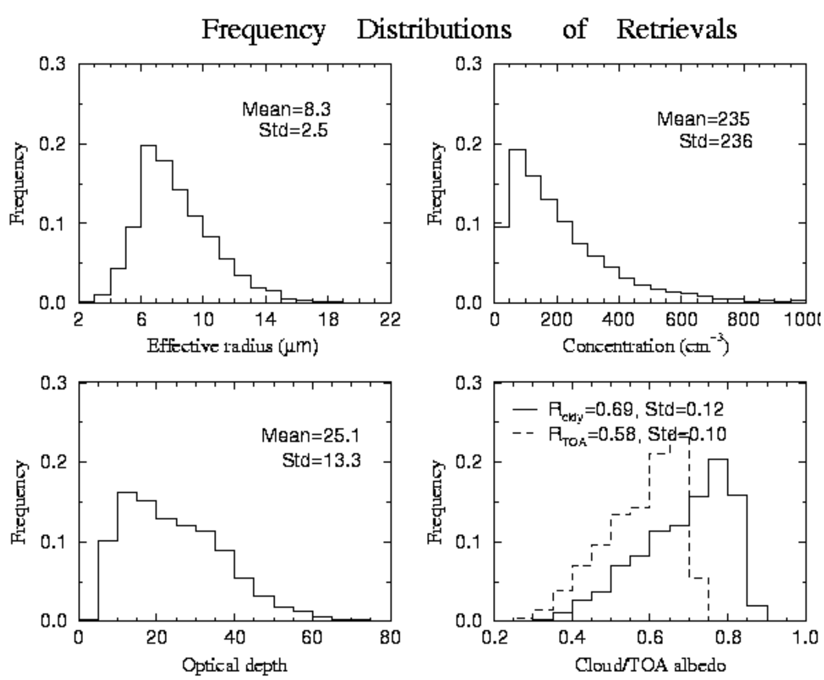

Figure 6. Frequency distributions of retrievals from all data sets (>6000 samples).

Table 1. Seasonal mean values of cloud properties.

	Winter	**Spring**	**Summer**	**Fall**	**Year**
Fraction	0.385	0.25	0.09	0.271	1
Zb (km)	0.343	0.671	0.756	0.404	0.474
Zt (km)	1.241	1.475	1.751	1.183	1.316
Temp (K)	271.7	278.5	287.6	281.6	278.8
LWP (g m^{-2})	131.6	134.2	128.9	136.9	133.6
Transmission	0.278	0.318	0.369	0.283	0.296
re (μm)	8.06	8.46	9.73	8.17	8.28
N (cm^{-3})	243.8	202.9	131.4	275.5	235.3
τ	25.5	24.1	21.3	26.3	25.1
R_cldy	0.712	0.659	0.605	0.703	0.689
R_TOA	0.597	0.553	0.507	0.589	0.577

Conclusions

A 25-month data base (November 1996 through November 1998) of the macrophysical, microphysical, and radiative properties of isolated boundary layer stratus at the ARM SGP central facility has been generated. The data base provides fundamental statistical information about stratus for use both in GCM cloud parameterization development and the evaluation of satellite stratus cloud retrievals. The stratus cloud properties in the data base have been examined and summarized in Table 1 as a function of season. The measurement component of the data base provides a fairly self-consistent set of values, presenting few apparent problems for the current application. The one exception is the radar overestimates of stratus cloud top height during summer as a result of severe insect and clutter contamination of the radar power returns at this time of year.

Based on sensitivity studies (Dong et al. 1997) and comparison with aircraft data (Dong et al. 1998), the retrieved and parameterized cloud radiative properties should be accurate to about 5%, while the cloud-droplet effective radii have an uncertainty of approximately 15%. The uncertainty in the retrieved and parameterized cloud-droplet number concentrations can be up to 30% as a result of both assuming a constant size distribution and uncertainty in the observed cloud boundaries. Note that for the 2-stream retrieval of Dong et al. (1997) the sensitivity of the cloud-droplet number concentration to errors in the width is much less than for radar-based techniques, such as the one by Frisch et al. (1995).

More studies are needed to investigate the day-to-day and season-to-season variations of the cloud microphysics in the data base. For example, knowledge of short- and long-term variations in aerosol column concentrations at the ARM SGP site would enable studies on the relationship between aerosol properties and cloud microphysics. Analysis and classification of the large-scale synoptic conditions may be an important step in understanding the source of the seasonal variations in the cloud microphysics.

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