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A 25-month database of stratus cloud properties generated from ground-based measurements at the Atmospheric Radiation Measurement Southern Great Plains Site

Xiquan Dong,[1] Patrick Minnis,[2] Thomas P. Ackerman,[3] Eugene E. Clothiaux,[4] Gerald G. Mace,[1] Charles N. Long,[4] and James C. Liljegren[5]

Abstract. A 25-month database of the macrophysical, microphysical, and radiative properties of isolated and overcast low-level stratus clouds has been generated using a newly developed parameterization and surface measurements from the Atmospheric Radiation Measurement central facility in Oklahoma. The database (5-min resolution) includes two parts: measurements and retrievals. The former consist of cloud base and top heights, layer-mean temperature, cloud liquid water path, and solar transmission ratio measured by a ground-based lidar/ceilometer and radar pair, radiosondes, a microwave radiometer, and a standard Eppley precision spectral pyranometer, respectively. The retrievals include the cloud-droplet effective radius and number concentration and broadband shortwave optical depth and cloud and top-of-atmosphere albedos. Stratus without any overlying mid or high-level clouds occurred most frequently during winter and least often during summer. Mean cloud-layer altitudes and geometric thicknesses were higher and greater, respectively, in summer than in winter. Both quantities are positively correlated with the cloud-layer mean temperature. Mean cloud-droplet effective radii range from 8.1 μm in winter to 9.7 μm during summer, while cloud-droplet number concentrations during winter are nearly twice those in summer. Since cloud liquid water paths are almost the same in both seasons, cloud optical depth is higher during the winter, leading to greater cloud albedos and lower cloud transmittances.

1. Introduction

Low-level stratiform clouds play a critical role in regulating the Earth's radiation budget and hence have important climate effects over both land and ocean [*Ramanathan et al.,* 1989]. Low-level stratus have also been widely recognized as a key component in predicting any potential future climate change [*Wielicki et al.,* 1995]. Because various climate models have different representations of cloud radiative properties and processes, an intercomparison of 19 general circulation models (GCMs) produced a variety of cloud feedback results, ranging from positive to weakly negative to nearly neutral cloud radiative forcings [*Cess et al.,* 1990]. Most early global climate models prescribed cloud optical depth as a function of altitude and/or temperature, which limited the ability of changes in cloud properties to feedback into the climate system [*Del Genio et al.,* 1996]. The prognostic parameterization of cloud optical properties, such as cloud liquid water content, is a fairly recent trend for global climate models. However, this approach requires the parameterization of complex microphysical, dynamic, and radiative processes, thus introducing degrees of freedom into the parameterization that are absent in the simpler approaches [*Del Genio et al.,* 1996]. Therefore we must improve the observational database of cloud properties, together with measurements of the associated dynamic and thermodynamic fields, in order to improve both these new prognostic parameterizations and the global climate models in which they are embedded.

The Department of Energy Atmospheric Radiation Measurement (ARM) program established the ARM Southern Great Plains (SGP) research site to obtain long-term records of surface radiation data and to de-

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[1] Meteorology Department, University of Utah, Salt Lake City.

[2] NASA Langley Research Center, Hampton, Virginia.

[3] Pacific Northwest National Laboratory, DOE, Richland, Washington.

[4] Department of Meteorology, Pennsylvania State University, University Park.

[5] Ames Laboratory, DOE, Ames, Iowa.

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termine the impact of clouds on radiation fields [*Stokes and Schwartz,* 1994]. One of the primary purposes 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 complement the surface data, provide large-scale averages, and bound the radiation budget at the top of the atmosphere (TOA) [*Minnis et al.,* 1995], ARM also includes a satellite measurement component to determine cloud properties and radiative fluxes. The ARM surface measurements serve as a valuable resource for validating the concurrent satellite retrievals. To begin the process of evaluating cloud parameterizations against observed data and verifying satellite data, we have developed a 25-month database of stratus cloud macrophysical, microphysical, and radiative properties using data collected at the ARM SGP central facility from November 1996 through November 1998. The database provides fundamental statistical information about stratus clouds for climate model parameterization evaluation and serves as the ground truth for satellite validation.

2. Method

Dong et al. [1997, 1998] have demonstrated that the combined measurements from a radar, lidar, microwave radiometer, standard Eppley precision spectral pyranometer (PSP), and radiosonde can provide basic information on stratus cloud properties, including cloud boundaries, cloud liquid water path (LWP), and downward solar flux through the cloud. To retrieve the microphysical and radiative properties of stratus clouds, *Dong et al.* [1997] used a δ2-stream radiative transfer model in conjunction with ground-based measurements. The retrieved microphysical properties include the cloud-droplet effective radius r_e and number concentration N. The radiative properties consist of broadband shortwave optical depth τ and cloud and TOA albedos R_{cldy} and R_{TOA}. The cloud LWP is obtained from microwave radiometer brightness temperature measurements, while r_e is a free parameter. Effective radius and the measured LWP are used to specify the cloud properties in the δ2-stream radiative transfer model. The retrieval scheme is based on an iterative approach that varies the r_e in the radiative transfer calculations until the model-computed transmission ratio (the ratio of surface solar flux during cloudy conditions to the expected clear-sky surface solar flux) matches the measured value. The motivation for using the transmission ratio instead of downward solar flux at the surface is to account for the biases between the measured and modeled surface downward solar flux [*Kato et al.,* 1997]. An empirical curve-fitting technique developed by *Long and Ackerman* [1999] has been used to estimate the expected clear-sky downward solar flux at the surface if there were no clouds.

The uncertainties in the retrieved cloud radiative properties using this retrieval scheme are generally less than 5%, while the errors in the retrieved r_e and N are about 15 and 30%, respectively, which are mainly contributed by the "expected" errors of surface measurements in cloud LWP and downward solar flux [*Dong et al.,* 1997, 1998]. In the retrieval the cloud droplets are assumed to have a lognormal size distribution with a logarithmic width of 0.35. Sensitivity studies showed that the variation of the cloud-droplet size distribution width has no effect on the retrieved r_e, while the N changes by 15 to 30% as the logarithmic width varies from 0.2 to 0.5 [*Dong et al.,* 1997]. These results are consistent with those of both *Hu and Stamnes* [1993] and *Miles et al.* [1999]. The former demonstrated that the cloud transmission primarily depends upon the cloud LWP and r_e, while the latter showed the extreme sensitivity of N to changes in the cloud-droplet size distribution width.

Dong et al. [1998] parameterized the retrieved r_e and radiative properties as a function of the cloud LWP, the transmission ratio γ, and the cosine of the solar zenith angle μ_0. 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 surface data were analyzed and compared to collocated in situ measurements made by a Forward Scattering Spectrometer Probe (FSSP) aboard the University of Wyoming King Air aircraft. The surface data were taken between 1200 and 1900 UTC during October 24, 1996, from the Pennsylvania State University surface remote sensing site located at Rock Springs, Pennsylvania, underneath an overcast stratus deck. On average, the retrieved values of r_e and N 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 a 30-min resolution (Figure 1) significantly reduced the differences between the aircraft data and the retrieved and parameterized values. The temporal and spatial statistics are converging for the 30-min averages, suggesting that, at this scale, both the aircraft and the ground-based data are capable of characterizing the cloud microphysics. The parameterization of stratus shortwave radiative properties is generally within 5% of *Slingo*'s [1989] four-band, model-derived parameterization when absorption above cloud top is 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

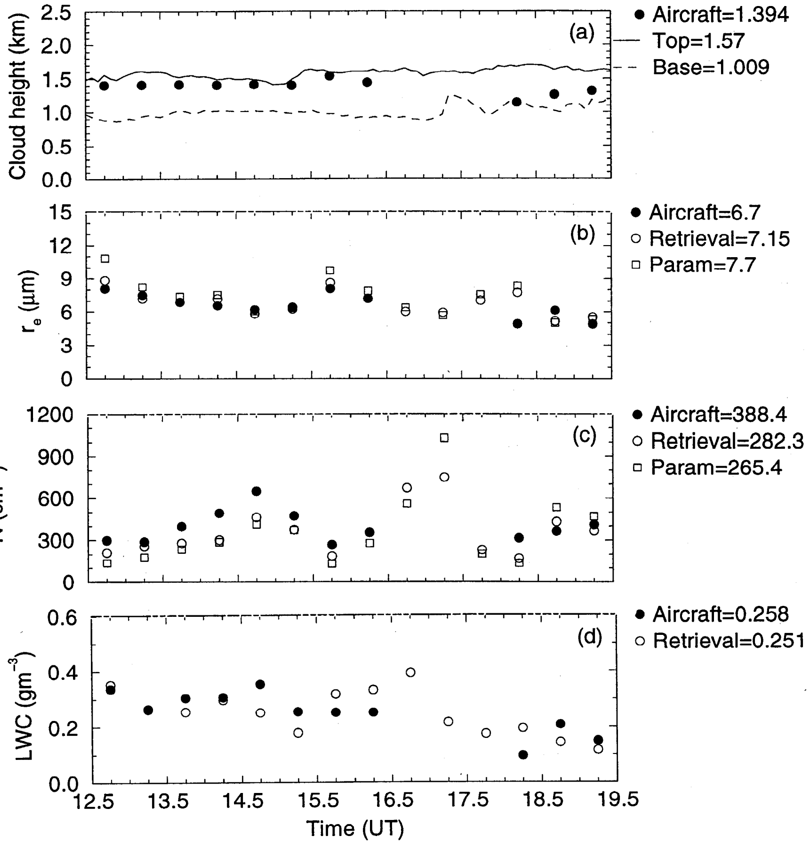

Figure 1. Pennsylvania State University aircraft expedition (October 24, 1996): (a) cloud base and top heights from ceilometer and 94-GHz cloud radar, and the aircraft altitude. Retrieved, parameterized, and in situ measured (b) cloud-droplet effective radii r_e, (c) cloud-droplet number concentrations N, and (d) cloud liquid water contents L_{wc} at a 30-min temporal resolution.

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 the top-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 database TOA albedo is not sensitive to the vertical profile of the atmosphere and one can obtain the TOA albedo by multiplying the parameterized cloud albedo by 0.84.

The *Dong et al.* [1998] parameterization was used to generate the retrieval part of the database for the period from November 1996 through November 1998 at the ARM SGP central facility. The database (5-min resolution) includes two parts: measurements and retrievals. The former consist of cloud base Z_{base} and cloud top Z_{top} heights, layer-mean temperature T_{cldy}, LWP, and γ measured by a ground-based lidar/ceilometer and radar pair, radiosondes, a microwave radiometer, and a PSP, respectively. The retrieval products include the r_e, N, τ, R_{cldy}, and R_{TOA}, respectively. The five criteria for choosing the periods for performing a retrieval are (1) only low-level stratiform clouds are present, (2) μ_0 is larger than 0.2, (3) the range of γ is 0.1 to 0.7, (4) LWP is between 20 and 600 $\text{g}\,\text{m}^{-2}$, and (5) Z_{top} is less than 3 km.

The physical reasons for using these five criteria are briefly discussed below. Since a plane-parallel radiative transfer model and the measured solar flux have been used in the retrieval, any broken low-level clouds or any mid and high-level clouds above low-level stratus clouds could affect the solar flux computation in the radiative transfer model and the interpretation of the surface measurement. Therefore only isolated, overcast, and daytime low-level stratus clouds were chosen in this study. Criterion 2 was used to maximize the accuracy of the empirical curve-fitting technique that calculates the solar transmission ratio [*Long and Ackerman,* 1999] and to minimize the effects of deviations from the horizontally homogeneous cloud layer assumption in the retrieval [*Dong et al.,* 1997]. Criteria 3 and 4 are always negatively correlated with each other; that is, higher cloud LWP relates to lower γ. In this study, the lower limit of cloud LWP is based on the retrieval accuracy of microwave radiometer, and the upper limit roughly corresponds to the precipitation conditions in which large drizzle or raindrops can reach the ground. The range (0.1-0.7) of γ, in general, relates to the upper

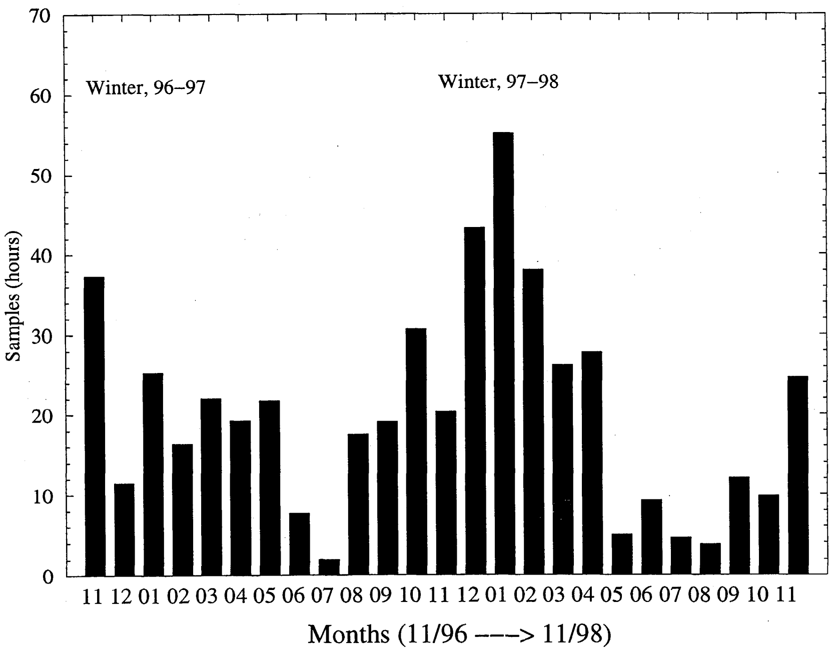

Figure 2. Isolated, overcast, and daytime low-level stratus cloud amount from November 96 to November 98 at ARM SGP site (total 504 hours).

and lower limits of cloud LWP, respectively. Criterion 5 selects the low-level stratus clouds.

3. Results and Discussions

Approximately 500 hours (more than 6000 samples at 5-min resolution) of data satisfied the criteria for low-level stratus clouds during the study period. Other low-level stratus clouds that occurred during the period with mid and high-level clouds are not included in this database. *Ackerman et al.* [1998; available at http://www.arm.gov/docs/documents/technical/] used the combined measurements of the ARM cloud radar, Belfort ceilometer, and micropulse lidar from October 1 to December 31, 1997, to determine cloud occurrence and location using the algorithm of *Clothiaux et al.* [1999]. The cloud fractions for the 3-month period are 0.57, 0.18, 0.39, 0.18, and 0.16 for total, multilayered, low, mid, and high clouds, respectively. Note that it is possible to have both low and high cloud fraction layers present at the same instant so that low, mid, and high cloud fraction will not equal the total cloud fraction. Combining the Belfort ceilometer detected boundary layer stratus clouds with large-scale synoptic conditions during the period of entire 1996, *Gottschalk et al.* [1998; available at http://www.arm.gov/docs/documents/technical/] classified stratus clouds into five categories: overrunning/stationary front, warm front advected from Gulf of Mexico, cold front, building high pressure, and miscellaneous. The cloud fractions for the five categories are 0.15, 0.26, 0.14, 0.18, and 0.27, respectively, relative to the total cloud amount. In this database the peak occurrence of isolated stratus occurred during the winter, whereas the minimum amount of stratus occurred in the summer (Figure 2), which is consistent with the data of *Warren et al.* [1986] that comprise an average of surface cloud observations taken from 1971 through 1981 in a 5° region centered near the ARM SGP site. 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.

The $Z_{\rm top}$ altitudes and cloud-layer geometric thicknesses ΔZ in summer are generally higher and greater, respectively, than those in winter. Both $Z_{\rm top}$ and ΔZ are positively correlated with $T_{\rm cldy}$, probably as a result of the seasonal variation of $Z_{\rm top}$. Most values of $Z_{\rm base}$ are less than 0.6 km with a mean value of 0.47 km and a standard deviation of 0.39 km, and $Z_{\rm top}$ range from 0.8 to 1.4 km with a mean value of 1.32 km and a standard deviation of 0.51 km. During summer, $Z_{\rm top}$ from the cloud radar was overestimated compared to the radiosonde soundings, whereas $Z_{\rm base}$ detected by lidar and soundings agreed very well for all data sets. The disagreement during summer was most likely due to insect contamination of the radar power returns at these low altitudes [*Clothiaux et al.,* 1999]. Therefore the radar-estimated $Z_{\rm top}$ in this database have been modified by setting $Z_{\rm top}$ to the altitude in the radiosonde soundings where the relative humidity drops below 94% [*Keihm,* 1989]. To account for the sparse temporal sampling by the radiosondes, the sounding-observed ΔZ at balloon launching time were linearly interpolated and added to the lidar-detected $Z_{\rm base}$ for times when the radar-detected $Z_{\rm top}$ were overestimated. $Z_{\rm top}$ overesti-

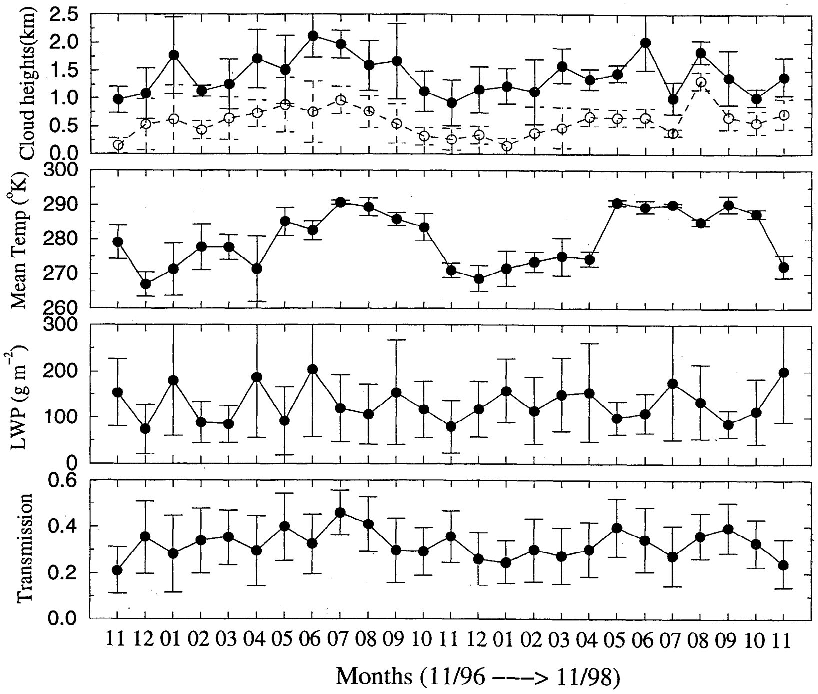

Figure 3. Monthly mean and standard deviation values of measurements over ARM SGP site.

mation could usually be identified by the occurrence of a sudden drop of radar reflectivity in the radar images. The T_{cldy} distribution illustrated in Figure 4 indicates that most of the observed stratus clouds are entirely in the liquid phase and only approximately 16% may be in a mixed phase with liquid water droplets still dominant [*Curry et al.,* 1999].

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 and 86 g m^{-2}, respectively. LWP was derived from the microwave radiometer brightness temperatures measured at 23.8 and 31.4 GHz using a statistical retrieval method based on 5 years of National Weather Service (NWS) soundings from Oklahoma City [*Liljegren,* 1999; available at http://www.arm.gov/docs/documents/technical/]. The root-mean-square (RMS) accuracies of the retrieval are about 20 g m^{-2} and 10% for cloud LWP below and above 200 g m^{-2}, respectively. The γ is negatively cor-

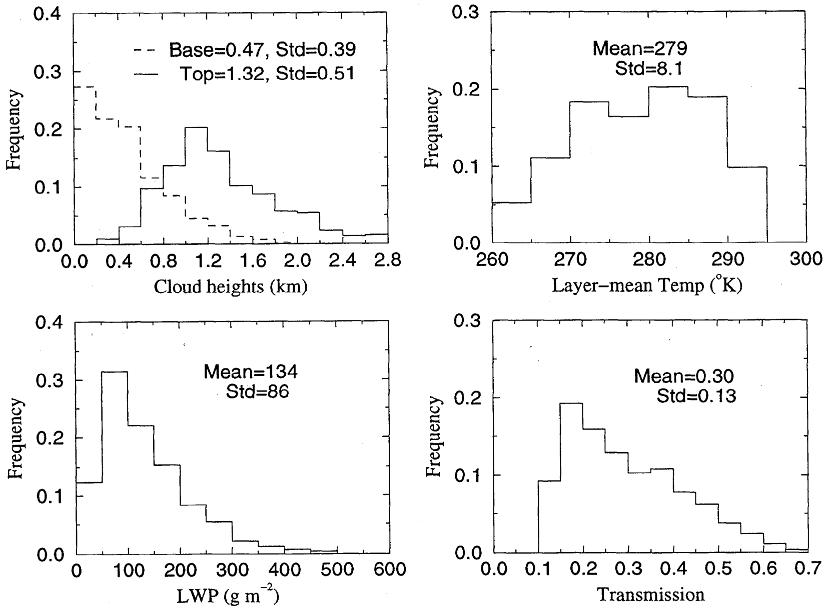

Figure 4. Frequency distributions of measurements from all data sets (~ 6000 samples).

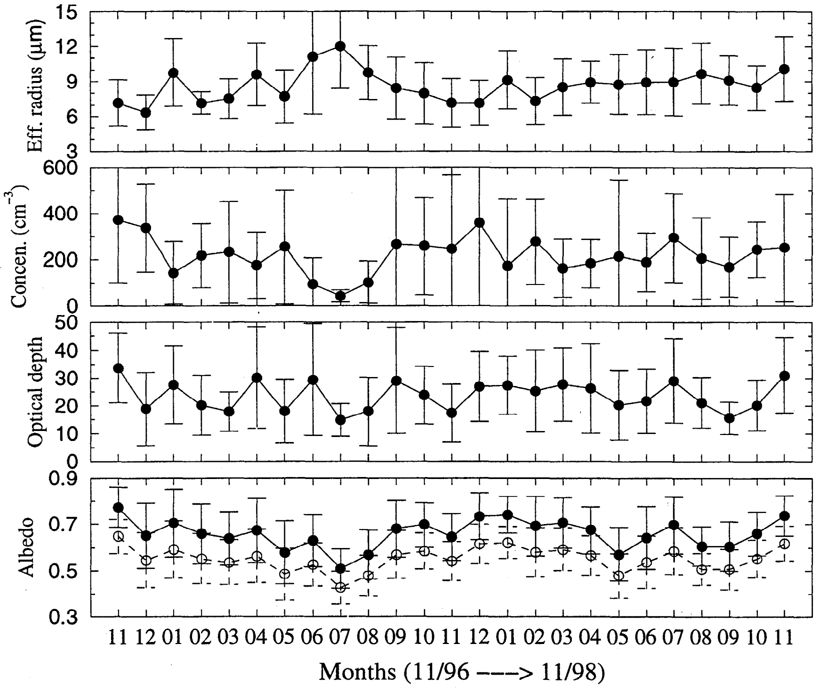

Figure 5. Monthly mean and standard deviation values of retrievals.

related with LWP (Figure 3) and has a broad frequency of occurrence histogram (Figure 4).

The means and standard deviations of the retrieved parameters for each month are illustrated in Figure 5, whereas Figure 6 shows the frequency of occurrence of each retrieved value. Between December 1996 and December 1997 the monthly mean value of r_e increased from winter to summer, then decreased monotonically from summer to the ensuing winter. This trend is not as strong between the 1997-1998 winter and 1998-1999 winter. Overall, r_e is generally larger during the summer than in the winter. There are at least two physical reasons that might explain this seasonal variation. First, more water vapor is present in the summer atmospheric column. Therefore, if cloud condensation nuclei (CCN) concentrations are the same during summer and winter, the cloud droplets should grow larger during the summer. Second, mean cloud-droplet sizes increase monotonically with height above Z_{base}. This growth process is dominated by condensation rather than coa-

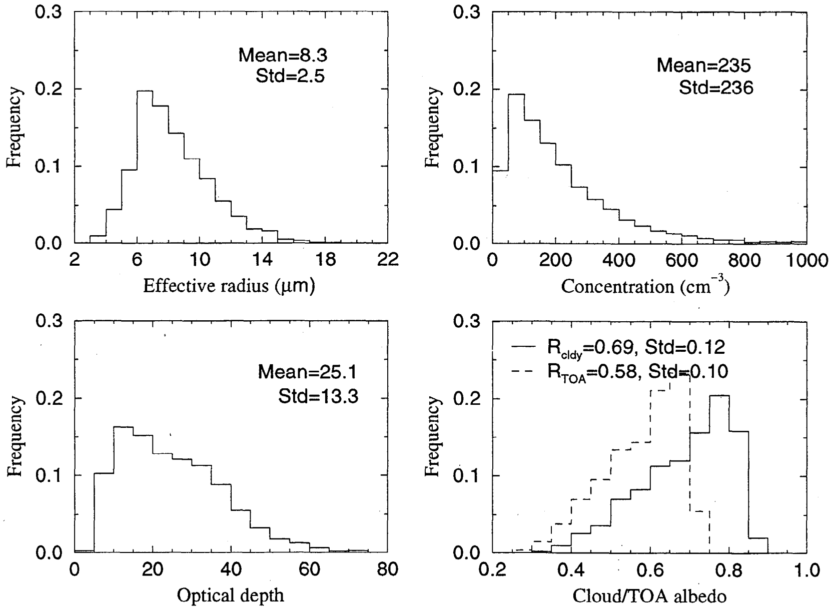

Figure 6. Frequency distributions of retrievals from all data sets (~ 6000 samples).

Table 1. Aircraft in Situ Measurements Over ARM SGP Site

Date	Period, UT	Distance, km	$r_e, \mu\text{m}$	N, cm^{-3}	σ
Sept. 20, 1997	1712-1755	X=-0.24, Y=-4.0	4.2	249	0.462
Sept. 21, 1997	1845-1934	X=0.30, Y=-1.14	7.2	184	0.553
Sept. 24, 1997	1910-2100	X=0.50, Y=-1.64	5.6	288	0.537
Total	~ 3.5 hours	X=0.33, Y=-1.74	6.1	243	0.534

lescence. Therefore larger cloud droplets might be expected to occur in the geometrically thicker clouds observed during the summer.

Most retrievals of r_e ranged from 5 to 12 μm with a long tail toward the larger sizes. The mean value of r_e was 8.3 μm, which is almost identical to the value obtained by *Han et al.* [1998] for Northern Hemisphere continental locations using International Satellite Cloud Climatology Project (ISCCP) data. The variation of N was always complementary to that of r_e (Figure 5). The large standard deviations for N in Figure 5 result from uncertainties in the observed cloud boundaries and from assuming a constant lognormal size distribution width of 0.53 that was obtained from aircraft in situ measurements taken over the ARM SGP site during the fall of 1997. The distribution of frequency of occurrence of N is similar to that for r_e, as it too has a much longer tail toward higher values. The mean N of 235 cm^{-3} for this study is similar to the in situ values (243 cm^{-3}) obtained from aircraft FSSP measurements during the fall of 1997 and (288 cm^{-3}) obtained in the climatology study of *Miles et al.* [1999]. Table 1 lists the mean values of r_e, N, and the logarithmic width σ of droplet size distribution derived from the aircraft FSSP data taken in stratus clouds over ARM SGP central facility during September 1997 (Y. Liu, personal communication, 1999). The aircraft flew at a distance indicated by X (east-west) and Y (north-south) during each flight. While these aircraft data cannot be used to compare directly with the ground-based retrievals due to the occurrence of cirrus over the stratus (September 20 and 21, 1997) and the presence of broken stratus (September 24, 1997), they provide additional evidence that the mean value of 235 cm^{-3} is reasonable for the ARM SGP stratus clouds.

The variations in the monthly mean values of τ, R_{cldy}, and R_{TOA} follow the trend in LWP. Most values of τ are between 5 and 45 with a mean value of 25.1. The mean values for R_{cldy} and R_{TOA} are 0.69 and 0.58, respectively, with frequency of occurrence modal values of 0.75 and 0.65, respectively. Satellite observations [*Minnis et al.,* 1995; *Minnis and Smith,* 1998] have shown that cloud and TOA albedos are a function of the solar zenith angle; that is, higher albedos result from higher solar zenith angles. However, the albedos are not sensitive to the solar zenith angle in this study because some of the sensitivity to the solar zenith angle has been incorporated into γ. The albedo difference between winter (μ_0=0.447) and summer (μ_0=0.757) is only 2% or 0.02 calculated from the parameterization for the same τ. The albedos become more sensitive to the solar zenith angle in the parameterization if downward solar flux at the surface is used instead of γ.

The measured and retrieved cloud properties in the database are summarized as a function of season in Table 2. Z_{top} and ΔZ are generally higher and greater, respectively, in summer than in winter, and both quantities are positively correlated with T_{cldy}. Mean r_e values range from 8.1 μm in winter to 9.7 μm during summer, while N values during winter are nearly twice those in

Table 2. Seasonal Mean Values of Cloud Properties

	Winter	Spring	Summer	Fall	Year
Fraction	0.385	0.250	0.090	0.271	1
Z_{base}, km	0.343	0.671	0.756	0.404	0.474
Z_{top}, km	1.241	1.475	1.751	1.183	1.316
T_{cldy}, 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
γ	0.278	0.318	0.369	0.283	0.296
$r_e, \mu\text{m}$	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

summer. Since LWPs are almost the same in both seasons, τ is higher during the winter, leading to greater R_{cldy} and lower cloud transmittance.

It it important to note that the measured and retrieved cloud properties in the database can only represent isolated, overcast, and daytime lower-level stratus clouds because the solar flux was used in the retrieval. Daytime broken and nighttime stratus cloud properties are not included in the database. A new algorithm to retrieve cloud microphysical properties, which is independent of solar flux, should be developed. The retrievals from the new algorithm, as well as the measurements, will be integrated with the existing database to form a completed surface database that will be useful for studying some important atmospheric phenomena, such as the continental stratus diurnal cycle. The database described here is available publicly from the corresponding author.

4. Conclusions

A 25-month database (November 1996 through November 1998) has been generated to quantify the macrophysical, microphysical, and radiative properties of isolated and overcast low-level stratus at the ARM SGP central facility. The database provides fundamental statistical information about stratus for use in general circulation model cloud parameterization development and the evaluation of satellite stratus cloud retrievals. The stratus cloud properties in the database have been examined and summarized in Table 2 as a function of season. The measurement component of the database 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.

On the basis of sensitivity studies [*Dong et al.,* 1997] and comparison with aircraft data [*Dong et al.,* 1998], the retrieved cloud radiative properties should be accurate to about 5%, while the r_e values have an uncertainty of approximately 15%. The uncertainty in the retrieved N 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 δ2-stream retrieval of *Dong et al.* [1997] the sensitivity of the N 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 database. 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. The high temporal resolution and accuracy of this database will also provide numerous opportunities for comparison with satellite retrievals of similar cloud properties. The generated database will provide a ground truth data set for estimating errors in the satellite products and for validating satellite cloud retrieval algorithms, which should result in greater understanding of the satellite observations which will, in effect, extend the surface retrievals to a greater portion of the Earth's surface.

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T. P. Ackerman, Pacific Northwest National Laboratory, P.O. Box 999/MS K9-44, Richland, WA 99352. (Thomas.Ackerman@pnl.gov)

E. E. Clothiaux and C. N. Long, Department of Meteorology, 503 Walker Bldg., Pennsylvania State University, University Park, PA 16802. (cloth@essc.psu.edu; long@essc.psu.edu)

X. Dong and G. G. Mace, Department of Meteorology., 819 Wm. C. Browning Bldg., University of Utah, Salt Lake City, UT 84112. (xdong@met.utah.edu; mace@met.utah.edu)

J. C. Liljegren, Ames Laboratory, Center for Nondestructive Evaluation, 1915 Scholl Rd., Bldg. ASC II, Ames, IA 50011-3042 (jim@ultra1.cnde.iastate.edu)

P. Minnis, NASA Langley Research Center, Mail Stop 420, Hampton, VA 23681-0001.(p.minnis@larc.nasa.gov)

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