A Boundary-Layer Cloud Study Using Southern Great Plains Cloud and Radiation Testbed (CART) Data

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Introduction

Boundary layer clouds—stratus and fairweather cumulus—are closely coupled to the water and energy budgets of land surfaces. This coupling involves the radiative impact of the clouds on the surface energy budget and the strong dependence of cloud formation and maintenance on the turbulent fluxes of heat and moisture in the boundary layer. The continuous data collection at the Southern Great Plains (SGP) Cloud and Radiation Testbed (CART) site provides a unique opportunity to study components of the coupling processes associated with boundary layer clouds and to provide descriptions of cloud and boundary layer structure that can be used to test parameterizations used in climate models. But before the CART data can be used for process studies and parameterization testing, it is necessary to evaluate and validate data and to develop techniques for effectively combining the data to provide meaningful descriptions of cloud and boundary layer characteristics. In this study we use measurements made during an intensive observing period (IOP) conducted at the SGP CART site in April 1994 for data validation and technique development. During this period we consider a case where low-level stratus were observed at the site for about 18 hours. This case is being used to examine the temporal evolution of cloud base, cloud top, cloud liquid water content, surface radiative fluxes, and boundary layer structure. A method for inferring cloud microphysics from these parameters is currently being evaluated.

Results

The clouds observed during this study were associated with a weak cold front that passed over the site. During this period the flow was dominated by a large high pressure center that moved from the Great Lakes at 1200 UTC 22 April to the Carolina coast by 1200 UTC 24 April. At about 0800 UTC (0200 LST) on 22 April 1994 a shallow layer of cool, moist air moved southwest over the CART site. This front was associated with a wind shift and a 3 °C decrease in temperature. Shallow stratus clouds were first observed at the time of the frontal passage and persisted for another 18 hours. The initial analysis presented here focuses on a four-hour period near the beginning of the event and a five-hour period near the end.

Although the energetics of the clouds that were observed in the event may be more strongly controlled by the surface heat fluxes than marine boundary layer clouds, the mean thermodynamic structure is well characterized by a mixed layer structure. The boundary layer deepened slightly during the day and the potential temperature jump across the inversion increased from about 2 K during the initial period to about 6 K during the second observing period. Since the above-inversion air was relatively moist, during the entire event equivalent potential temperature increased with height across the inversion. Future work will consider the detailed evolution of the boundary layer structure using wind profiler and radio-acoustic sounding system measurements.

The cloud characteristics for the event were obtained from the CART (Belfort) ceilometer, microwave radiometer, narrow band infrared (IR) (Heimann) radiometer and the Penn State 94-GHz radar. For this initial analysis the 94-GHz reflectivity data were analyzed subjectively to estimate cloud base and top at 10-minute intervals. These estimates are shown in Figure 1 and indicate a cloud thickness of 200-400 meters during the first analysis period with clouds thinning to about 200 meters during the second period. The cloud-top heights agree well with the inversion heights obtained from the soundings. The cloud-base heights from the ceilometer (Figure 2) are correlated with the radar cloud-base heights, but are systematically about 100 m higher than the radar estimates. As the cloud thins during the second analysis period, the ceilometer cloud bases are about 200 meters higher than the radar cloud bases and are occasionally higher than the cloud top. The cloud-top estimates, however, may only be accurate to about 75 meters. Furthermore, estimates of cloud-base heights from radar reflectivity are also uncertain. But as the cloud continues to thin after 2400 UTC (not shown here), the ceilometer no longer detects a cloud even though returns are still obtained from the radar.

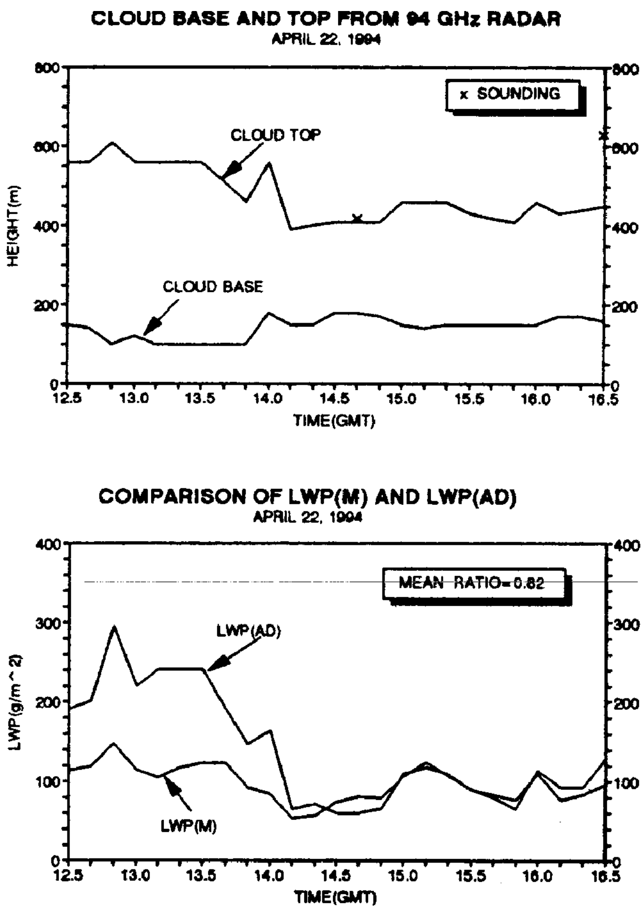

Figure 1. Cloud base and cloud top from 94-GHz reflectivities. Liquid water path (LWP) from microwave radiometer. Adiabatic LWP calculated using cloud-top and -base heights.

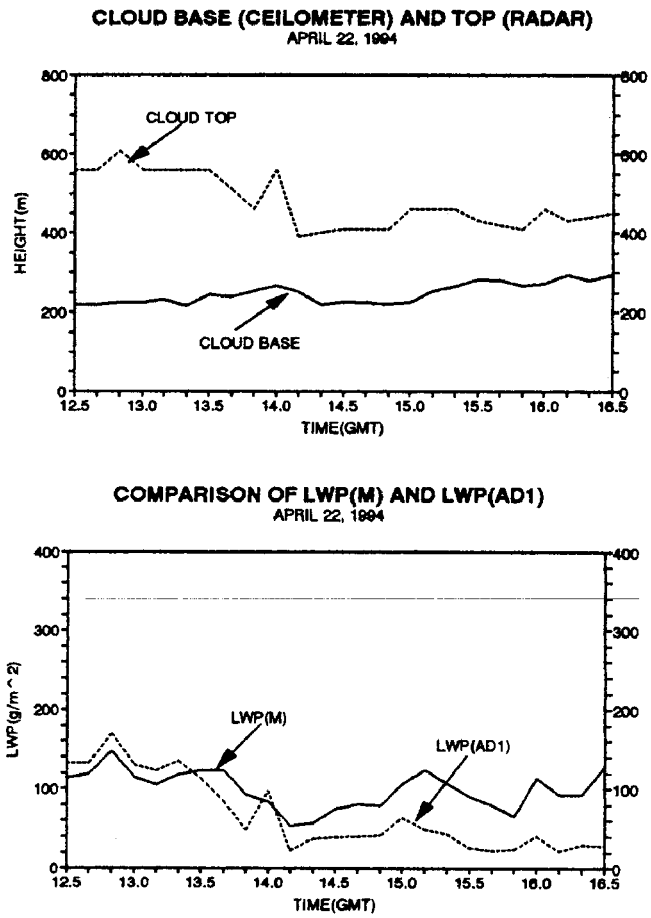

Figure 2. Cloud base from CART ceilometer. Liquid water path (LWP) from microwave radiometer. Adiabatic LWP calculated using cloud-top and -base heights.

The cloud thicknesses from the radar and the ceilometer were used to calculate the adiabatic liquid water path. A comparison of the calculated liquid path with liquid water path retrieved from the microwave radiometer is also shown in Figures 1 and 2. A positive clear-sky bias of $46gm^{-3}$ was removed from the microwave data. The adiabatic values obtained using the cloud radar to estimate cloud base show reasonable correlation with the measured values. For the thicker cloud observed during the beginning of the first analysis period, the observed water path is substantially less than the adiabatic values. From 1410 UTC to 1630 UTC the observed values are very close to adiabatic. During the second analysis period it is also found that the deeper clouds have liquid water paths that are less than the adiabatic value, but more closely match the adiabatic value when the cloud thins to about 200 meters. The adiabatic liquid water path calculated using the radar cloud tops and ceilometer cloud bases is almost always less than the observed liquid water path. These results further indicate that the ceilometer may underestimate cloud-base heights for these relatively thin clouds. The causes for this discrepancy are being explored. Although the clouds observed during this period are relatively thin, they have a substantial impact on the downward solar radiation observed at the surface. Although the downward shortwave flux shows considerable variability, the IR emission remains relatively constant as indicated by the IR radiometer cloud-base temperatures. Work is in progress to retrieve cloud microphysical properties by using the cloud boundaries, liquid water path, and surface solar flux in conjunction with a two-stream radiative transfer model.

Conclusions

Data collected at the SGP CART site during an IOP in April 1994 were used to study low-level stratus clouds and their effects on the surface radiation budget. Although the analysis focuses on a one-day case associated with persistent stratus observed during the April 1994 IOP, the emphasis is on the synergism of the diverse data sets collected at the site and the development of strategies for routinely characterizing cloud, boundary layer, and radiation conditions from the CART data for low-cloud situations.

Although the clouds during this period were relatively thin, estimates of cloud-base height, cloud-top height, and liquid water content provide a consistent description of the evolution of the clouds and one that may be very useful for model verification and process studies. Work is in progress to couple the surface radiative fluxes to the observed cloud properties. Although this case study provides a prototype for how the CART analyses can be effectively used to produce cloud and radiation characterizations useful for testing climate model parameterizations, additional effort is needed to derive these cloud properties routinely from the CART data. Furthermore, the data from the CART site should be carefully evaluated to determine any systematic biases in ceilometer cloud-base heights and microwave radiometer estimates of liquid water path. The utility of using a millimeter radar for the definition of the properties of boundary layer clouds is clearly documented. Work is in progress to refine objective techniques for defining cloud-top heights. Routine observations from millimeter wavelength radars would be invaluable for studying boundary layer clouds and identifying multi-layered cloud systems that might complicate the interpretation of bulk measures of cloud properties such as liquid water path and surface solar fluxes.