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SURFACE-BASED REMOTE SENSING OF THE OBSERVED AND THE ADIABATIC LIQUID WATER CONTENT OF STRATOCUMULUS CLOUDS

Bruce A. Albrecht, Christopher W. Fairall, Dennis W. Thomson, and Allen B. White

Department of Meteorology, Penn State University

Jack B. Snider

NOAA/ERL/WPL

Wayne H. Schubert

Department of Atmospheric Science, Colorado State University

Abstract. A laser ceilometer, an acoustic sounder, and a microwave radiometer were used to estimate cloud thickness and the adiabatic and integrated liquid water content of shallow stratocumulus clouds continuously for three days using two-minute averages. Although the observed liquid water path was close to the theoretical adiabatic value for most of the three days, there was one four-hour period when the liquid water content dropped to about 50% of the adiabatic value. Hourly-averaged values for a 19-day period of intensive observations show that the cloud water content was generally close to the adiabatic value. Occasionally there were clouds greater than 300 m in depth in which the water content was clearly less than adiabatic.

Introduction

Measurements of cloud liquid water are central to many aspects of cloud microphysics research. The observed liquid water content is often compared with the adiabatic value to infer the effects of precipitation and entrainment on cloud structure. Observations from aircraft in cumulus clouds, for example, give a ratio of the liquid water content to the adiabatic value that decreases upward from cloud base to about 0.2 near the tops of clouds 3000 m in depth [Warner, 1955]. The liquid water content from aircraft measurements in stratocumulus generally decreases from values close to adiabatic near cloud base to values as low as 0.3 of the adiabatic near cloud top [Albrecht et al., 1985; Nicholls and Turton, 1986].

There are, however, uncertainties in estimating the ratio of the observed liquid water to the adiabatic value using aircraft. These are due to uncertainties in a) measuring cloud liquid water, b) estimating cloud base height and c) sampling clouds that vary in space and time. Hot-wire devices [e.g., Neel, 1973] and cloud-droplet spectrometers [e.g., Knollenberg, 1981] are commonly used to make cloud liquid water estimates. These sensors have relatively small sampling volumes and can suffer from systematic biases [Baumgardner, 1983]. Since the adiabatic liquid water content at any level in the cloud can be estimated if the cloud-base height is known, temporal and spatial variations in cloud-base height result in uncertainties in the adiabatic water content. Since several passes at different levels are required to obtain the vertical distribution of the liquid water content using an aircraft, the cloud structure can change over the duration of the measurements.

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In this paper we demonstrate the use of surface-based remote sensors to estimate the ratio of the observed liquid water path to the adiabatic value in marine stratocumulus clouds. A laser ceilometer is used to estimate cloud base height, and a sodar that senses C_T^2 is used to estimate cloud top. To estimate the integrated liquid water content a microwave radiometer is used. The adiabatic water content of the cloud is calculated from the cloud thickness. Although this technique does not give the vertical distribution of cloud water, it does define the temporal evolution of the integrated liquid water content at a single location with a resolution of approximately two minutes and eliminates many of the difficulties in making similar estimates with aircraft.

Description of the Experiment and Instrumentation

The measurements shown in this paper were made from the northwest tip of San Nicolas Island (located about 100 km southwest of Los Angeles, CA) during the First International Satellite Cloud Climatology Project Regional Experiment (FIRE) from 1-19 July 1987. The instruments used in this study were part of a suite of instruments that was operated continuously from the island [Albrecht et al., 1988]. In addition, soundings were obtained with a cross-chain Loran atmospheric sounding system (CLASS) as described by Schubert et al. [1987a]. Surface meteorological data were collected during the experiment. In this paper we focus on observations from 13-15 July, a period with persistent stratocumulus clouds and a well-established marine flow from the northwest.

The cloud base height was estimated using a laser ceilometer (Väisälä model CT 12K) that uses a low-powered GaAs laser diode operating at a wavelength of 0.904 μm. The system seeks to maintain a constant average power by automatically selecting a pulse repetition rate between 620 and 1120 Hz. The received signal is averaged over many pulses and the resulting intensity profile is used to define the cloud base height every 30 s with a resolution of 15 m. Data from the ceilometer were saved on a microcomputer system [Schubert et al., 1987b].

A sodar was used to estimate inversion height as determined by the virtual temperature profile. This particular Doppler sodar is a three-beam, monostatic system with 25 transducers in its phased array antenna. The operating frequency is 1600 Hz. The nominal peak acoustical power is 176 W in each transmitted pulse of 200 ms duration. The back-scattered acoustic signals were averaged over two-minute intervals and saved at 128 heights from 38 m to 1129 m on a microcomputer system. A time series of maximum reflectivity heights was extracted from the raw data and smoothed using a 5-point running median filter in time. This filtering process removed most of the noise peaks from local sources without seriously affecting small scale variability in the data. The error of the height estimate due to the size of the scattering volume is equivalent to one-half the acoustic pulse length in space, or about 34 m.

The height of maximum acoustical reflectivity corresponds to the height of maximum temperature variance, C_T^2. It in turn corresponds to the altitude of maximum temperature gradient, which occurs above the inversion base. Hourly estimates of inversion height were compared with height of the inversion base estimated from 22 soundings from the CLASS system [Schubert et al., 1987a]. The base of the inversion (cloud top) defined from the soundings was on average 44 m below the maximum in the reflectivity. In addition, two-minute smoothed sodar values were compared with estimates of the inversion height obtained from four high-vertical resolution temperature and moisture profiles from some tethered balloon measurements made during FIRE (personal communication, Phil Higgnet, 1989). The height of the inversion base from the balloon measurements was on average 56 m below the level of maximum sodar reflectivity. Based on these comparisons we will specify the cloud top to be 50 m below the maximum in the reflectivity and estimate the uncertainty in the cloud-top height to be 10-20 m.

The total liquid water measurements were made using a three-frequency (20.6, 31.65, and 90.0 GHz) microwave radiometer of the type described by Hogg et al. [1983]. The integrated liquid water from this system was obtained from measurements at the two lower frequencies using an antenna system with a beamwidth of 2.5 deg that was pointing toward the zenith during FIRE. Radiometric brightness temperatures were converted to path-integrated liquid water (liquid water path) using the statistical retrieval technique described by Hogg et al. [1983]. Data were averaged and collected for 60 s intervals during the experiment. The absolute uncertainty in the measured liquid water path is estimated to be 20 percent.

Observations

The integrated liquid water and the cloud-base height were averaged to give two-minute values that were combined with the filtered two-minute inversion heights from the sodar for 13-15 July. The cloud base and top heights for this period (Figure 1) were obtained from a well-defined stratocumulus deck with no breaks after the cloud deck formed around 0300 UTC on 13 July. The cloud was relatively thin during most of 13 July and only about 100 m thick during the afternoon of 13 July (2000-2400 UTC). The cloud deck deepened to 300 m during the night but then thinned again on the afternoon of 14 July. The cloud deck on the morning of 15 July was almost 400 m thick. Some drizzle was observed on this day both at San Nicolas and at the ship Point Sur, which was then located about 60 km northwest of the island. In general, on all three days there was greater variability in the cloud-base height than in the cloud-top height. On 13 and 15 July there was an appreciable increase in the cloud base variability just after local sunrise (1200 UTC). This unexplained behavior was observed on several other days during the extended experiment.

The adiabatic liquid water path was calculated by assuming adiabatic ascent of a parcel from cloud base to cloud top. Since these clouds are thin, we can assume that the adiabatic liquid water mixing ratio w_l varies linearly with height z as $w_l = \Gamma_l (z - z_B)$, where z_B is the height of cloud-base. The quantity $\Gamma_l = dw_l/dz$ defines the vertical variation of the adiabatic liquid water mixing

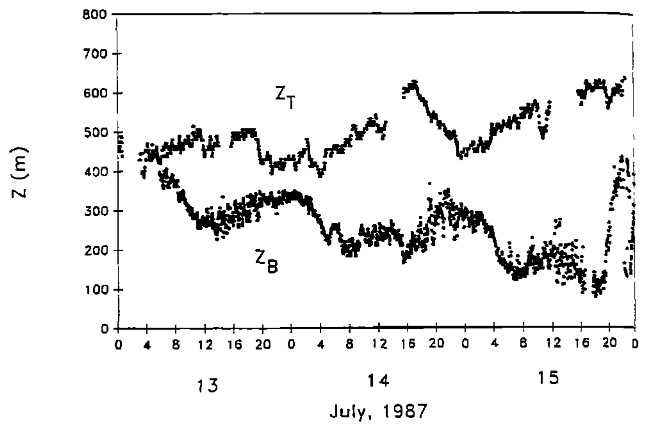

Fig. 1. Cloud-top height and cloud-base height of clouds over San Nicolas Island from 13-15 July 1987. Each point represents a two-minute average. Time is in UTC.

ratio with height and is the negative of the change in saturation mixing ratio with height. The variation of the saturation mixing ratio with height is easily calculated by applying the Clausius-Clapeyron equation and assuming moist adiabatic ascent. Thus from the definition of saturation mixing ratio $w_s = \varepsilon e_s/(p - e_s)$ it follows that

$$\Gamma_l = -\frac{dw_s}{dz} = \frac{(\varepsilon + w_s) w_s l_v}{R_d T^2}\Gamma_w - \frac{w_s p}{(p - e_s)H} \quad (1)$$

where $\varepsilon = 0.622$, l_v is the latent heat of vaporization, R_d is the specific gas constant for dry air, Γ_w is the moist adiabatic lapse rate, and H is R_d T/g.

The integrated liquid water path $(\Delta z)_l$ may then be written as

$$(\Delta z)_l = \frac{1}{\rho_l}\int_{z_B}^{z_T} \rho\, w_l\, dz\,, \quad (2)$$

where ρ_l is the density of water, ρ is the density of the air, and z_T is cloud-top height. The approximation sign is used since w_l is defined as the ratio of the mass of water to the mass of the dry air.

Since the layers are shallow we simplify (2) as

$$(\Delta z)_l = \frac{\bar{\rho}}{\rho_l}\bar{\Gamma}_l \frac{1}{2}\left(z_T - z_B\right)^2, \quad (3)$$

where $\bar{\rho}$ and $\bar{\Gamma}_l$ are averages in the cloud layer. The temperature and pressure needed to evaluate (1) were obtained from the average temperature and pressure in the cloud layer as extracted from hourly averages of surface temperature and pressure. The cloud values were obtained by assuming a dry adiabatic lapse rate below cloud base and a moist adiabatic lapse rate in the cloud layer and then applying the hydrostatic equation. Conditions were relatively constant for the 19 days of the experiment with $\bar{\rho}$ in the cloud layer ranging from 1.14 to 1.21 gm^{-3} and $\bar{\Gamma}_l$ ranging from 1.99 to 2.14 g kg^{-1}km^{-1}. For the 13-15 June cases $\bar{\rho}$ = 1.20 kg m^{-3} and $\bar{\Gamma}_l$ = 2.10 g kg^{-1}km^{-1}.

The time series of the observed and the adiabatic liquid water path are shown in Figure 2 (the adiabatic values have been shifted upward for clarity). Excellent correlation between the adiabatic and the liquid water content is clearly defined on all time scales and is illustrated further in Figure 3. Although the five to ten minute variations in the cloud-base height observed on 13 July resulted in variations in the adiabatic content of only about 0.04 mm, corresponding variations in the cloud water could be resolved with the microwave radiometer. The less than adiabatic values on 15 July (Figure 3b) are observed from about 1500-1900 UTC and may be due to drizzle observed during this period. In addition, the ceilometer trace shows evidence of a double cloud layer around 2230 UTC that would indicate some decoupling of the layer.

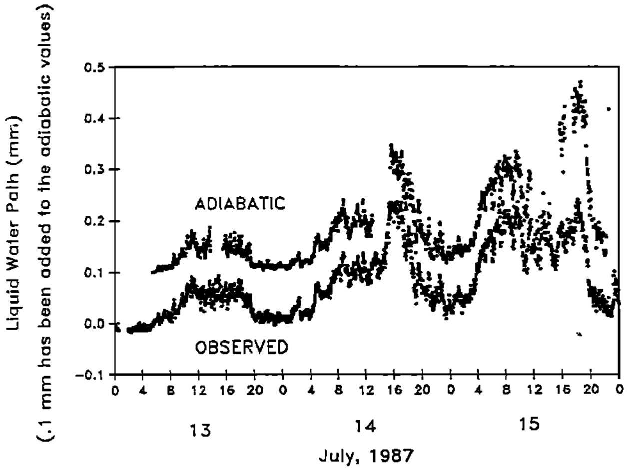

Fig. 2. Time series of the observed liquid water path from the radiometer and the adiabatic liquid water values calculated with the cloud base height from the ceilometer and cloud top from the sodar for 13-15 July. Each point represents a two-minute average. A constant 0.1 mm was added to the adiabatic values to aid in the visualization.

Although there is excellent agreement between the adiabatic and the calculated values (Figure 3a), it is possible that the close agreement could be due to systematic biases in any one of the three required independent measurements. For example, a 20 m uncertainty in the depth of a 200 m deep cloud results in a 0.004 mm or a 10% uncertainty in the adiabatic liquid water content. The precision of the radiometer is estimated to be 0.005 mm and its accuracy, as noted previously, is about 20%. Although systematic errors may contribute to the good agreement between the observed and the adiabatic liquid water, it is unlikely that such a constant ratio of the observed to the adiabatic value could be maintained. In addition, as noted previously, not all the clouds exhibited the adiabatic behavior.

Data from the three remote sensing systems used in this study were collected for the entire 19-day period of the FIRE stratocumulus IFO. Hourly estimates of the inversion height and the cloud-base height were used to estimate the adiabatic values from these data. A comparison as a function of cloud depth of the adiabatic values with the hourly-averaged observed values is shown in Figure 4. There is clearly an envelope of points that follows the adiabatic values for clouds as deep as 400 meters. Using hourly-averaged values in the quadratic expression for the adiabatic liquid water path, however, results in a slight underestimate of the hourly-averaged adiabatic content and may account for the slight deviation of the observed liquid water from the adiabatic values.

As mentioned previously, if the good agreement between the observed values and the adiabatic content should be fortuitously due to systematic instrument errors, it still is difficult to explain why the ratio of the observed to the adiabatic liquid water path is so constant over a wide range of cloud depths. There were several cases for clouds deeper than 300 m in which the water content was clearly less than adiabatic. Work is in progress to determine how conditions differ between the adiabatic and the nonadiabatic cases.

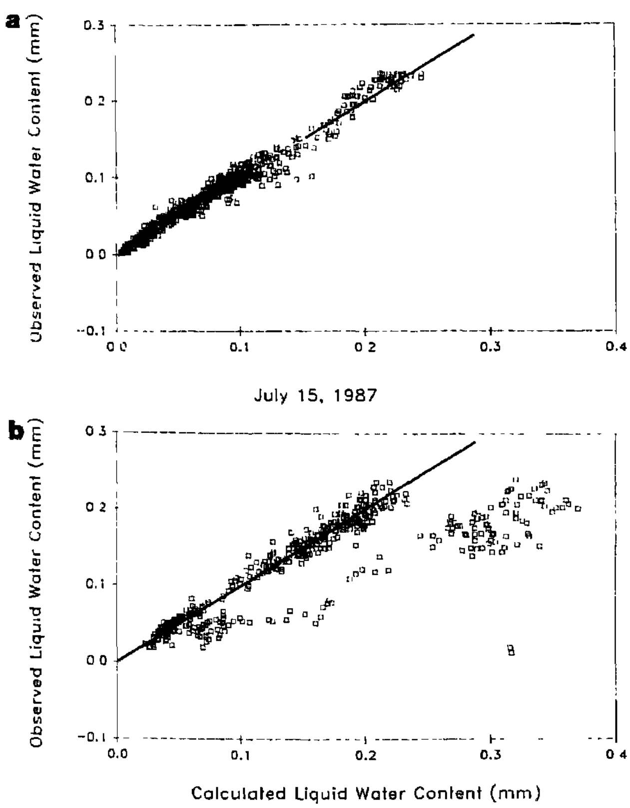

Fig. 3. The observed liquid water path as a function of the adiabatic path for a) 14 July and b) 15 July.

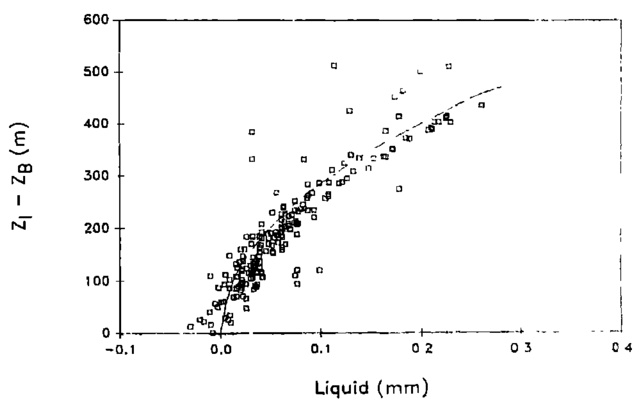

Fig. 4. The observed liquid water path for hourly-averages obtained from 1-19 July as a function of cloud depth. The thin line represents a polynomial fit to the adiabatic values for the entire period.

Most aircraft observations in stratocumulus show values that are less than adiabatic [Albrecht et al., 1985; Nicholls and Turton, 1986]. The clouds over San Nicolas during FIRE were generally shallower than those observed by aircraft over the open ocean. In addition the clouds over San Nicolas Island may be affected more by continental aerosols than those over the open ocean and may be less influenced by drizzle processes.

Conclusions

We have demonstrated that combined measurements from a sodar, a laser ceilometer, and a microwave radiometer can be used to compare the observed and adiabatic values of integrated cloud liquid water on time scales as short as two minutes. Stratocumulus clouds observed from 13-15 July over San Nicolas Island during FIRE were studied in detail using two-minute data. The cloud water contents were found to be close to adiabatic, although a four-hour period when the clouds were clearly less than adiabatic was observed. A similar analysis made with hourly values taken during the 19 days of the experiment indicated that the liquid water content was close to the adiabatic, although several periods when the clouds were less than adiabatic were observed for clouds greater than 300 m thick. The technique described here should prove to be useful in the development of an observational base that can extend much beyond the limited measurements that have been made from aircraft. The technique may be extended to deeper clouds by using sensitive cloud radars operating at 35 or 94 GHz to define cloud top.

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B.A. Albrecht, C.W. Fairall, D.W. Thomson, and A.B. White, Dept. of Meteorology, Penn State University, University Park, PA, 16802.

J.B. Snider, NOAA/ERL/WPL, 325 Broadway, Boulder, CO, 80303.

W.H. Schubert, Dept. of Atmospheric Science, Colorado State University, Ft. Collins, CO, 80523.

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