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STRATOCUMULUS CLOUD HEIGHT VARIATIONS DETERMINED FROM SURFACE AND SATELLITE OBSERVATIONS

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1. Introduction

Determination of cloud-top heights from satellite-inferred cloud-top temperatures is a relatively straightforward procedure for a well-behaved troposphere. The assumption of a monotonically decreasing temperature with increasing altitude is commonly used to assign a height to a given cloud-top temperature. In the hybrid bispectral threshold method, or HBTM, Minnis et al. (1987) assume that the lapse rate for the troposphere is -6.5 Kkm^{-1} and that the surface temperature which calibrated this lapse rate is the 24-hour mean of the observed or modeled clear-sky, equivalent blackbody temperature. The International Satellite Cloud Climatology Project (ISCCP) algorithm (Rossow et al., 1988) attempts a more realistic assignment of height by utilizing interpolations of analyzed temperature fields from the National Meteorological Center (NMC) to determine the temperature at a given level over the region of interest. Neither these nor other techniques have been tested to any useful extent. The First ISCCP Regional Experiment (FIRE) Intensive Field Observations (IFO) provide an excellent opportunity to assess satellite-derived cloud height results because of the availability of both direct and indirect cloud-top altitude data of known accuracy. This paper examines the variations of cloud-top altitude during the Marine Stratocumulus IFO (MSIFO, June 29 - July 19, 1987) derived from surface, aircraft, and satellite data.

2. Data

The soundings taken by the NCAR Electra during the IFO are used to characterize the vertical temperature and moisture structure of the lower troposphere (surface to 850 mb) over the California marine stratocumulus (MS) area. These soundings also reveal the location of the cloud top by providing the altitude of the inversion base. The Electra flights used here were confined to the Pacific between 30°N and 34°N and 119.5°W and 125.1°W. A nominal low-level lapse rate, Γ_{BL}, was constructed by averaging the lapse rates between 1000 mb and the inversion base. Average temperatures, T, and specific humidities, q, were computed for each of six levels: the surface

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(1000 mb), inversion base, inversion top, 850 mb, 700 mb, and 500 mb. NMC analyses from the IFO time period were used to determine T and q at 700 and 500 mb. The six levels define five layers which are simplified to three for discussion purposes: the boundary layer BL (surface to inversion base), the above-cloud layer AL (inversion base to 850 mb), and the upper layer UL (850 mb - 500 mb). The mean temperature and humidity of each layer are the averages of T and q at the boundaries of the layer.

Continuous data taken from San Nicolas Island (SNI) with the Pennsylvania State University sodar were used to measure cloud-top altitude over the island. The instantaneous data were first averaged over all cloudy, 30-minute intervals between July 1 and 19. A mean diurnal cycle of cloud-top altitude, z_c, was computed from these interval averages.

Cloud amount C, cloud-top temperature T_c, cloud albedo, and clear-sky temperature T_{cs}, were derived from hourly GOES data using the HBTM on a 0.5° grid (Young et al., 1989). Surface temperature, T_g, was derived from T_{cs} using a simple five-layer radiative transfer model employing the parameterization for absorption in the 11.5 μm window region used by the ISCCP (Rossow et al., 1988). It is assumed that attenuation by the atmosphere above 500 mb is negligible for this area. The resulting values of T_g were generally 1.5 to 2.5 K warmer than those for T_{cs}. The effect of atmospheric attenuation on cloud-top temperature was also examined with the model. In general, the warm AL increased the outgoing radiance canceling the attenuation by the UL so that the resulting value of T_c was ~ 0.1 K colder than the original value. Therefore, it is assumed that the satellite-measured value of T_c is representative of the actual radiating temperature of the cloud top. Satellite cloud-top altitude, z_{sc}, was determined by two techniques: (1) using Γ_{BL} and the 24-hour average of T_s to compute the variation of T with height and (2) using the HBTM approach.

3. Results

Average soundings derived from the Electra results and corresponding NMC data are shown in Fig. 1. The NMC data lack the vertical resolution necessary to detect the BL inversion. In general, the NMC humidities are higher than expected from the aircraft data, but the 1000- and 850-mb temperatures were within ± 2 K of the Electra data. It was found that $\Gamma_{BL} = 7.1$ Kkm^{-1} with a standard deviation of ± 1.5 Kkm^{-1} for 23 soundings. Satellite-derived cloud-top heights using methods (1) and (2) are compared to the inversion base heights from the Electra in Fig. 2. The values of z_{sc} are taken from the 0.5° region containing the flight track of the Electra. The average difference in cloud-top heights are 0.2 ± 0.2 km and 0.3 ± 0.2 km for methods (1) and (2), respectively. The average value of T_c is quite close to the mean temperature of the inversion base.

The average diurnal variations of z_c and cloud-base altitude over SNI during the IFO are shown in Fig. 3. Maximum cloud-top height occurs near 1000 LST with a broad minimum around sunset. The cloud base is lowest around 0430 LST before rising steadily to a peak value of ~ 0.5 km shortly after noon. Cloud thickness is relatively constant at ~ 0.25 km between 0200 and 1000 LST. The clouds thin rapidly to about half the maximum thickness by late afternoon before thickening again during the night. Diurnal variations of z_{sc} from both methods are superimposed on the SNI results in Fig. 4. SNI is situated between two of the 0.5° regions. The results shown in Fig. 4 were derived from the combined averages for the two regions. Data from hours with $C < 10$ percent were not used in these comparisons. The relative changes in z_{sc} are similar to those for z_c, except for the minimum in z_{sc} near 1400 LST. The diurnal range in cloud-top height is greater for the satellite data. The satellite data also appear to be noisier. Some of the noise may be due to missing data (up to 7 days of data were lost at some hours) and navigation errors (Young et al., 1989). Average cloud heights from (1) are 0.08 ± 0.1 km lower than the SNI results, while the method (2) heights are 0.15 ± 0.8 km lower than z_c. Between 0 and 10 LST, the mean values of z_{sc} are within ± 0.02 km of the sodar results. During the day, the differences increase steadily while the cloud depths decrease (Fig. 2). After sunset, the differences decrease.

4. Discussion

The differences in cloud-top heights shown in Fig. 2 appear to be due to a 0.8-K underestimate in the derived surface temperature. It is not known, however, if the actual surface temperature is the same as the 1000-mb temperature. Over SNI at night (Fig. 4), there is excellent agreement suggesting that there is no problem with the satellite-derived surface temperature. During the day, the underestimate of cloud-top height may be due to several factors. Clear-sky contamination of the cloudy radiances is more likely during the day when the clouds break up. This effect would be manifest in lower values of T_{cs} during the day. The observed clear-sky temperatures, though, increase during the day. Since the clouds thicken at night and thin during the day (Fig. 3), there may be some variation in the cloud infrared opacity. Figure 5 shows a correlation of cloud thickness and the difference between the sodar and method-1 cloud-top altitudes. These data reveal that the two height values agree for cloud thicknesses greater than 250 m. The differences increase almost linearly with decreasing thickness. The diurnal variation of the mean visible cloud albedo (Minnis et al., 1989) is also consistent with the cloud thinning during the day. Initial estimates, however, indicate that the reduced opacity can account for only ~ 0.02 km of the observed daytime differences. Other potential effects include sampling differences and island heating during the day.

5. Concluding Remarks

The results presented here clearly show the problems associated with using temperature soundings with low vertical resolution to convert cloud-top temperature to cloud-top altitude over regions with significant inversions. It is clear that the average value of z_{sc} would have been closer to 680 mb instead of 913 mb if the NMC data had been used in the analysis. Estimation of the vertical profile using a simple lapse rate and a measurement of surface temperature appears to be an effective solution to the difficulties of boundary-layer inversions. The differences between the island and satellite-derived cloud-top heights are currently unresolved. A closer comparison using a smaller area corresponding to SNI and one-to-one sampling is required to properly examine the differences.

Diurnal variations of cloud-top height and thickness deduced from the satellite data are reasonably representative of the changes actually occurring in the cloud field over the course of the day. The clouds thicken and rise during the night and sink and break up while they thin out during the day. This diurnal variation in cloud structure was also observed by Minnis and Harrison (1984) from similar satellite measurements taken over the southeastern Pacific during November 1978 as well as over other parts of the California marine stratocumulus area (Young et al., 1989). These intercomparisons are encouraging for the capabilities of satellite retrieval algorithms to accurately determine low-level cloud properties.

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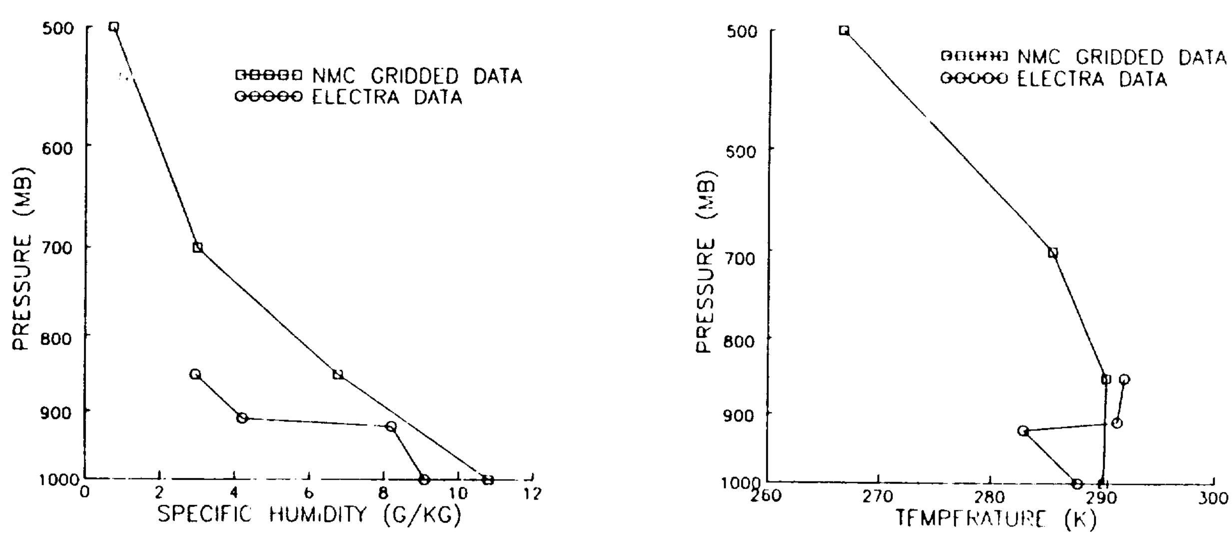

Fig. 1. Comparison of mean temperatures and humidities for IFO Electra flights and corresponding NMC analyses.

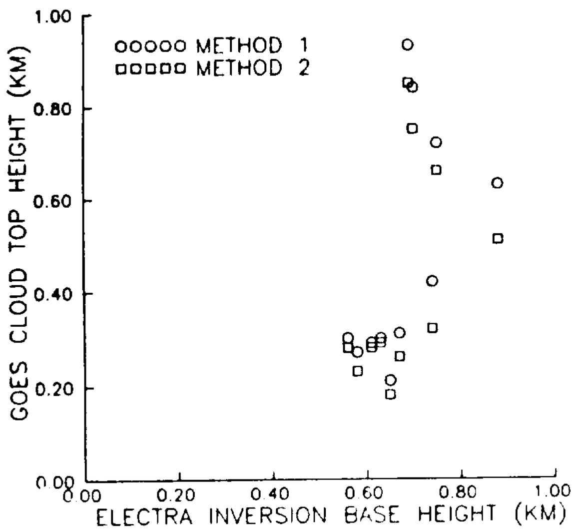

Fig. 2. Comparison of Electra-derived inversion base heights and corresponding satellite-derived cloud-top heights during IFO period.

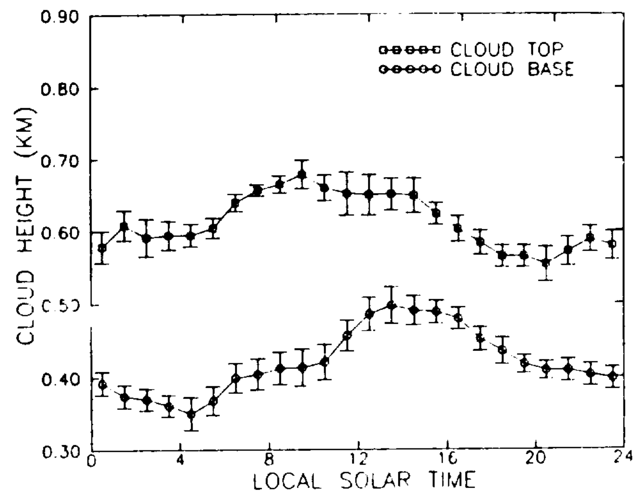

Fig. 3. Diurnal variations of mean sodar-derived cloud-base and cloud-top heights over SNI for July 1-19, 1987.

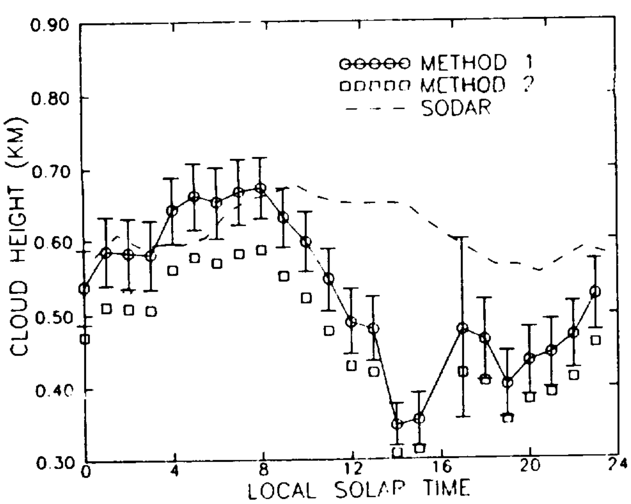

Fig. 4. Comparison of mean GOES-derived cloud-top heights over 1.0° x 0.5° region centered on SNI and mean sodar-derived cloud-top altitudes over SNI for July 1-19, 1987.

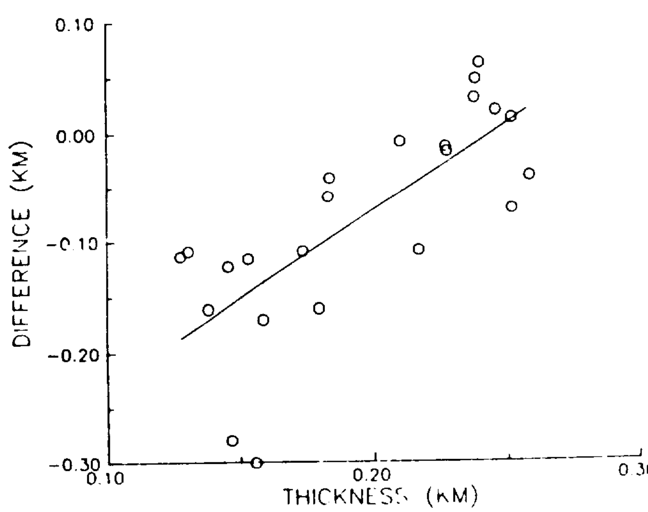

Fig. 5. Correlation of mean sodar-derived cloud thicknesses and differences in satellite-island-derived cloud-top altitudes over SNI for July 1-19, 1987.