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DEVELOPMENT OF METHODS FOR INFERRING CLOUD THICKNESS AND CLOUD-BASE HEIGHT FROM SATELLITE RADIANCE DATA

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INTRODUCTION

Cloud-top height is a major factor determining the outgoing longwave flux at the top of the atmosphere. The downwelling radiation from the cloud strongly affects the cooling rate within the atmosphere and the longwave radiation incident at the surface. Thus, determination of cloud-base temperature is important for proper calculation of fluxes below the cloud. Cloud-base altitude is also an important factor in aircraft operations. Cloud-top height or temperature can be derived in a straightforward manner using satellite-based infrared data. Cloud-base temperature, however, is not observable from the satellite, but is related to the height, phase, and optical depth of the cloud in addition to other variables. This study uses surface and satellite data taken during the First ISCCP Regional Experiment (FIRE) Phase-II Intensive Field Observation (IFO) period (November 13 - December 7, 1991) to improve techniques for deriving cloud-base height from conventional satellite data.

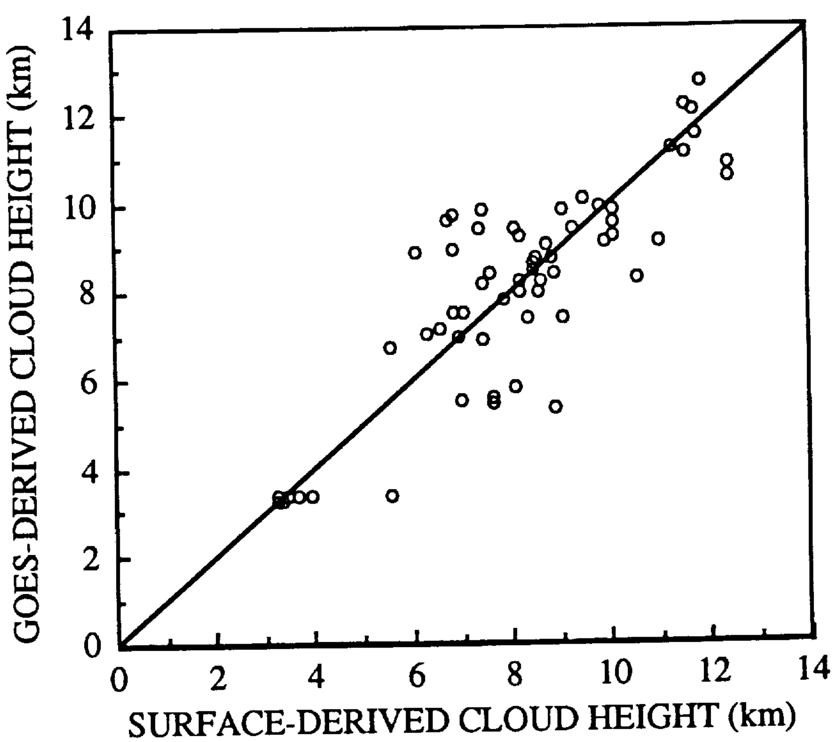

Fig. 1. Comparison of GOES-derived cloud center heights and surface-derived mean cloud heights.

DATA AND METHODOLOGY

Cloud base and cloud top altitudes were derived from several active remote sensor datasets taken during the FIRE-II IFO. The NASA Langley 8-inch visible wavelength lidar was operated on a regular basis throughout the experiment from Parsons, Kansas east of the hub at Coffeyville. The NOAA WPL 8.66-mm radar was located at the hub and operated from November 13 - 28. Both the NOAA WPL infrared lidar and Penn State University 95 GHz radar took data at the hub from November 11 to datasets whenever the cloud top could be clearly defined. Typically, the lidars were only used for cirrus clouds with visible optical depths $\tau < 4$. The Parsons lidar data were analyzed manually from graphical data. An automated digital threshold method was used to determine cloud boundaries from the radar and the infrared lidar data (Uttal et al., 1993). Cloud thickness is $\Delta z = z_t - z_b$.

The initial analysis uses data for a 0.3° region containing Coffeyville. Collocated 8-km visible and infrared radiances from the Geostationary Operational Environmental Satellite (GOES) were analyzed with the method of Minnis et al. (1993) to determine cloud optical depth and cloud-top height for the region. A bidirectional reflectance model having an effective radius of 10 µm was used to derive optical depth for clouds with a derived top temperature $T_c > 253K$. A cirrostratus ice crystal model was used for clouds having $T_c \leq 253K$. The cloud-top height is found from T_c and the Coffeyville sounding.

RESULTS

The mean cloud center heights derived from the surface and satellite data are shown in Fig. 1. The mean difference of 0.1 km and the rms difference of 1.3 km are almost identical to the same quantities found by Minnis et al. (1993) for FIRE-I data taken only for cirrus clouds. This dataset contains both cirrus and liquid water clouds. Cloud thicknesses Δz from the surface-based sensors were correlated

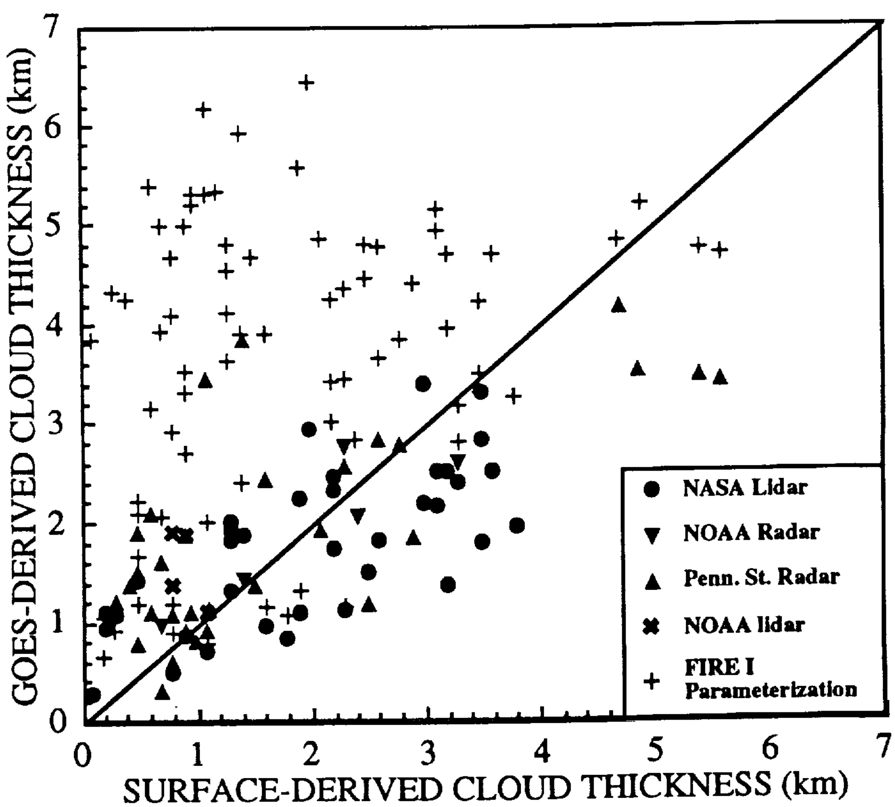

Fig.2. Comparison of GOES-derived and surface-derived cloud thickness.

with the GOES optical depths τ and cloud-center temperatures T_c to obtain the following parameterization.

$$\Delta z = 7.5 - 0.026\,T_c + 0.85\ln\tau. \qquad (1)$$

The thicknesses computed with this parameterization are compared with the corresponding surface-based values in Fig. 2. The line of agreement in Fig. 2 indicates that (1) tends to underestimate thicker clouds and overestimate the thinner ones. The rms difference is 0.92 km. The parameterization derived by Minnis et al. (1990) from the FIRE-I cirrus data results in an overestimation of cloud thickness for almost all of the FIRE-II data. These differences between the FIRE-I and FIRE-II results are not unexpected. The FIRE-I analysis included only cirrus clouds but multiple layer cirrus were included. In the present analysis, only single layer clouds are used. Both liquid and ice water clouds are used here. Water droplet clouds tend to be more compact than cirrus so there should be less thickness for a given optical depth for liquid water clouds than for ice crystal clouds. Some of that effect may be causing some of scatter in the data plotted in Fig. 2.

Cloud base heights derived using the difference between cloud-top height and cloud thickness are shown in Fig. 3. The mean and rms differences are 0.3 and 1.3 km, respectively. These statistics reflect the errors in cloud-top height (Fig. 1). If the thickness parameterization errors and the cloud-top height errors were independent, the rms difference in cloud base altitude should be ~1.6 km. The derived rms difference is lower suggesting that some compensating effects are occurring in the techniques for deriving cloud-top height and cloud thickness. The slight bias in cloud base would translate to a 3% underestimate of the downwelling radiative flux for a cloud base at 253K. The rms uncertainty would be ~ ± 10%.

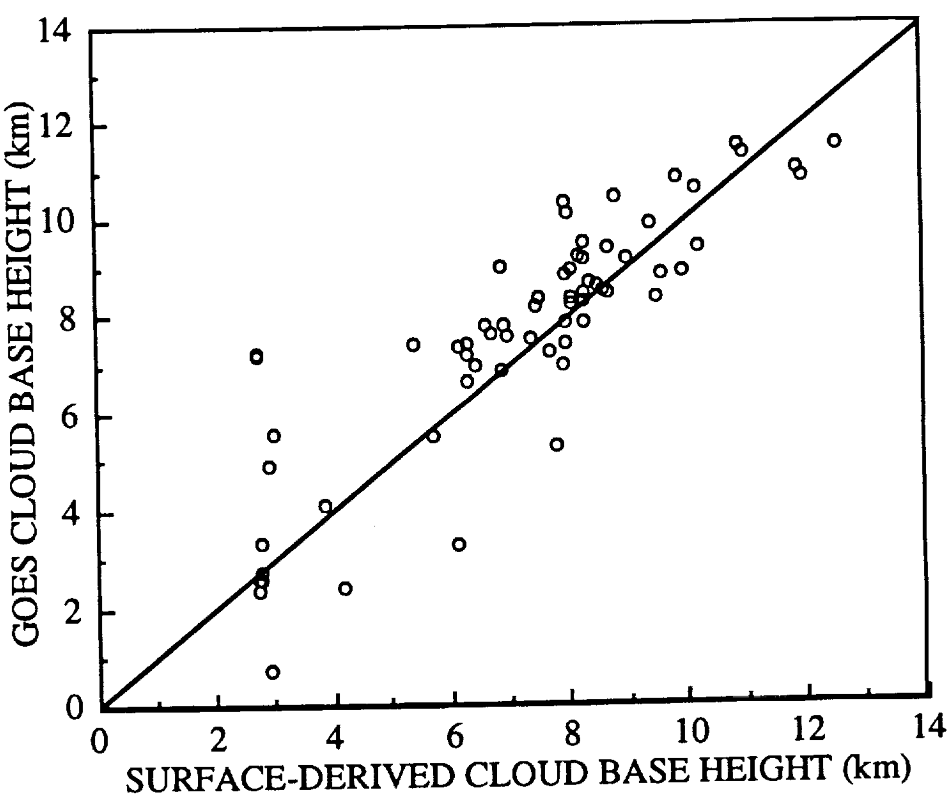

Fig. 3. Comparison of GOES-derived and surface-derived cloud base.

DISCUSSION AND CONCLUDING REMARKS

The uncertainties in the derived values due to the satellite data were noted above. Some additional uncertainty may be introduced by mixing the different surface datasets. Because of differences in the characteristics of the lidars and radars, Uttal et al. (1993) found some systematic differences between the cloud boundaries observed using the NOAA lidar and radar and the Penn State radar. These differences are not apparent in Fig. 2. The data points do not appear to line up according to the sensor. The greatest outliers in this dataset, however, are from the PSU radar indicating that the sensor effect needs to be examined more closely.

The results from this preliminary study and others are encouraging for the development of parameterizations of cloud thickness based on cloud optical depth, temperature, and, perhaps, the phase of the clouds. These parameterizations may have applications to mesoscale and larger scale climate models in addition to the remote sensing applications. Future analyses of the combined satellite-lidar-radar datasets need to examine the effects of phase and cloud layering. Additional data from the ER-2 would also help expand the number of samples for developing the cloud thickness parameterizations.

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