Observed and Simulated Temperature Dependence of the Liquid Water Path of Low Clouds

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Disagreements among climate models as to the sign and magnitude of cloud feedback to be expected in a warming climate arise largely because of their differing treatments of cloud optics feedbacks. Models with prescribed/diagnosed cloud optical properties tend to give positive/negative cloud feedback, while those with prognostic cloud water budgets can give feedback of either sign depending on the details of the parameterization. Available observations provide conflicting evidence about the temperature dependence of cloud optical thickness in the current climate, at least for low-level clouds. Simple thermodynamic arguments (Betts and Harshvardhan 1987) and in situ observations (Feigelson 1978) suggest that liquid water content should increase with temperature. But satellite retrievals from the International Satellite Cloud Climatology Project (ISCCP) indicate that the optical thickness of low clouds increases with temperature only at cold temperatures and primarily over land; at warm temperatures, optical thickness decreases with temperature (Tselioudis et al. 1992).

The most recent version of the Goddard Institute for Space Studies (GISS) general circulation model (GCM) includes a prognostic cloud water budget parameterization for stratiform clouds (Del Genio et al. 1996). Unlike the previous version of the GCM, which prescribes cloud optical properties, the prognostic cloud water version successfully reproduces the ISCCP-observed transition from increasing to decreasing low cloud optical thickness with temperature as temperature increases. Assuming that this behavior is real and not an artifact of subpixel cloud cover variations, there are three possible explanations: 1) Microphysical sinks of cloud water such as precipitation or entrainment become more efficient in warmer environments, 2) The physical thickness of clouds systematically decreases with temperature, and 3) Droplet effective radii are much larger in warmer clouds. Sensitivity tests designed to suppress variations in each of these parameters in the GCM suggest that optical thickness decreases with temperature are most sensitive to cloud physical thickness variations, but observational confirmation is lacking.

Data being acquired at the Atmospheric Radiation Measurement (ARM) Southern Great Plains (SGP) Cloud and Radiation Testbed (CART) site can be used to examine the factors determining the temperature dependence of cloud optical thickness. Although cloud droplet effective radius variations may also be important for the satellite-observed optical thickness behavior, we focus initially on cloud liquid water and physical thickness variations, which can be derived from existing routine ARM measurements. For the analysis, we require nearly coincident data from four ARM instruments: 1) Microwave Water Radiometer (MWR) retrievals of vertically integrated cloud liquid water path; 2) ceilometer estimates of cloud base height; 3) Geostationary Operational Environmental Satellite (GOES) infrared brightness temperatures, which indicate cloud top height; and 4) radiosonde temperature profiles, which allow us to translate infrared (IR) brightness temperature into cloud top height and also indicate the mean cloud temperature. We restrict the analysis to low-level clouds with no IR-detectable clouds overhead by selecting only data for which the nearest (in time) colocated satellite pixel indicates a cloud top pressure >680 mb (the ISCCP definition of low clouds), and we ignore differences between IR brightness temperature and actual cloud top temperature, which should be small for clouds whose liquid water signature is detectable in the microwave. We also restrict analysis to cloud top temperatures >273 K, to eliminate biased impressions caused by the insensitivity of the MWR to cloud ice.

The MWR data set is routinely reported as 5-minute average liquid water paths (although higher resolution is available with decreased signal/noise ratio). Typical horizontal wind speeds at the SGP site in the lower troposphere are 5-10 m/s, implying an effective spatial resolution of 1.5-3.0 km, slightly better than ISCCP. Averaging the data on 10- or 15-minute time intervals does not qualitatively change the observed behavior. Ceilometer data, which are reported every 30 seconds, are averaged over the coincident 5-minute intervals to obtain the average cloud base height. Satellite data are available only at half-hour intervals; the nearest observation to each MWR time is used. The biggest limitation is the radiosonde, which is often available only once a day and must be used for all observations during a 24-hour period when this is the case.

Another limitation is the uncertainty involved in microwave liquid water retrievals. Histograms of MWR liquid water paths indicate a small but fairly uniform population of points at paths > 0.1 cm, which corresponds to optical thicknesses >150 for a 10 µm droplet effective radius. These are probably erroneous and are eliminated from the analysis. The microwave also has difficulty with small liquid water paths because of varying water vapor contents, cloud temperatures, etc., that are not adequately taken into account in the retrieval algorithm; negative liquid water paths are possible. The frequency distribution of liquid water paths at the SGP site for observation times at which the ceilometer indicates clear skies is centered near zero but with a standard deviation of 0.004 cm; we thus eliminate points below this threshold as well. Neither cutoff qualitatively affects the results we present here.

Unfortunately, difficulties in the ARM Programs ability to retrieve data from the ARM archive, combined with the satellite data being taken offline since mid-1994 for revision, have prevented us from obtaining coincident data from all four instruments for even a single full month thus far. To get started, we have therefore focused on June 1993, for which all instruments but the ceilometer are available, and have explored several approximations to substitute for an actual cloud base observation. The simplest assumption is that cloud base does not vary systematically with temperature. We thus define a proxy cloud thickness as the pressure difference between the surface and cloud top, and define the mean cloud temperature accordingly. Figure 1 (left) shows the resulting variations of liquid water path with temperature, both for individual points (top) and binned into 1 K temperature intervals (bottom). Liquid water path clearly exhibits a tendency to decrease with increasing cloud temperature, consistent with the ISCCP optical thickness behavior in midlatitude summer. To see whether this is caused by liquid water content or cloud physical thickness variations, we normalize the liquid water path by the proxy pressure thickness and plot it versus temperature (Figure 1, right). This quantity increases with temperature at a rate of about 0.05/K, somewhat larger than but qualitatively consistent with the theoretical rate of increase of cloud liquid water content for a lifted parcel. This suggests that water content changes are close to adiabatic and the observed satellite optical thickness behavior can be explained by a systematic decrease of cloud physical thickness with temperature. But other explanations are possible, depending on cloud base behavior.

To try to estimate cloud base variations in the absence of the ceilometer data, we use radiosonde relative humidity profiles to identify cloud base. Sensitivity tests for other months in which the ceilometer data are available suggest that a relative humidity threshold of 94% results in the highest percentage of reasonably accurate identifications of cloud base. With this approximate definition of cloud base, we examine several different hypotheses for the cause of liquid water path variations: 1) cloud thickness variations dominated by cloud top changes, 2) cloud thickness variations caused by cloud base variations, and 3) constant cloud thickness, but systematic changes in mean cloud pressure (and temperature, implying changes in liquid water content). Preliminary results are shown in Figure 2. Liquid water path decreases with increasing cloud top pressure, but only for top pressures >800 mb. On the other hand, liquid water path increases with cloud base pressure to some extent, but only for base pressures <875 mb. One possible explanation is that different physics operate for low clouds within and above the planetary boundary layer. If anything, there is a slight tendency for liquid water paths to *decrease* with increasing mean cloud pressure and pressure thickness, just the opposite of expectations.

Further examination reveals, though, that our results are compromised by the necessity of using the radiosonde to estimate cloud base. Data from the 5-month period September 1994 -January 1995, when ceilometer data exist, show a clear decrease of liquid water path with increasing cloud base height. But when cloud base is estimated from the radiosonde, there is no obvious dependence on cloud base. This may be due both to inaccuracies in radiosonde relative humidity estimates and to the sparse sampling of radiosonde data, which precludes coincident liquid water path and cloud base estimates for most of the data set. Nonetheless, the preliminary results are encouraging enough to conclude that the ISCCP result is probably realistic and that we will be able to differentiate the roles of liquid water, cloud thickness, and cloud height variations once a statistically significant sample of data from all four instruments is made available. The next phase of the research will address the more difficult question of whether the observed temperature dependence is indicative of the feedback to be expected in a climate change. For this purpose, we will need to investigate the large-scale conditions that give rise to the observed correlations (e.g., static stability, synoptic scale pressure variations, aerosol variations). Ultimately, we will have to document the role of cloud droplet size variations as well.

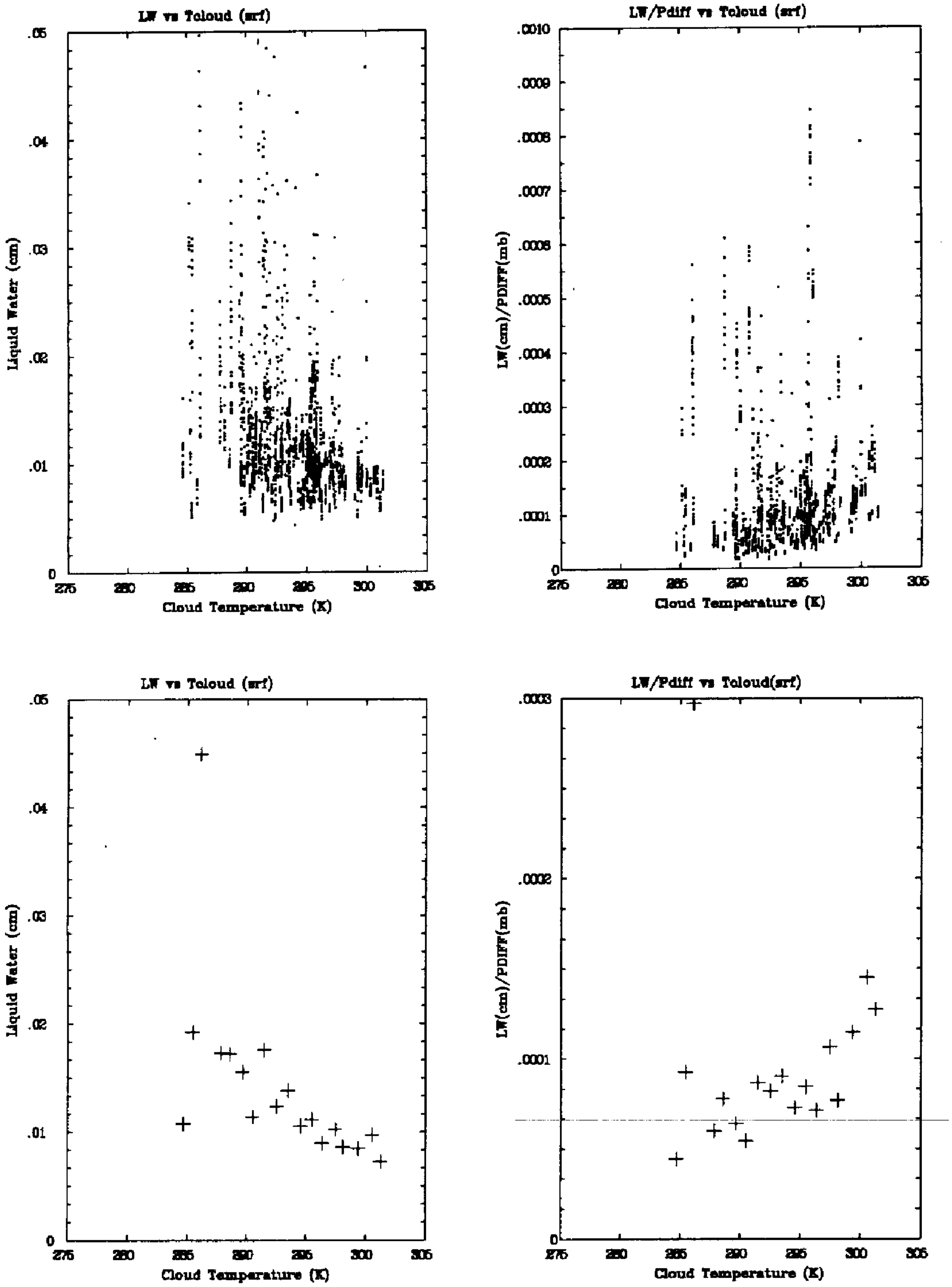

Figure 1. June 1993 MWR liquid water path variations as a function of cloud temperature (left), plotted as individual observations (top) and binned into 1 K temperature intervals (bottom), and analogous plots of liquid water path divided by proxy cloud pressure thickness (right).

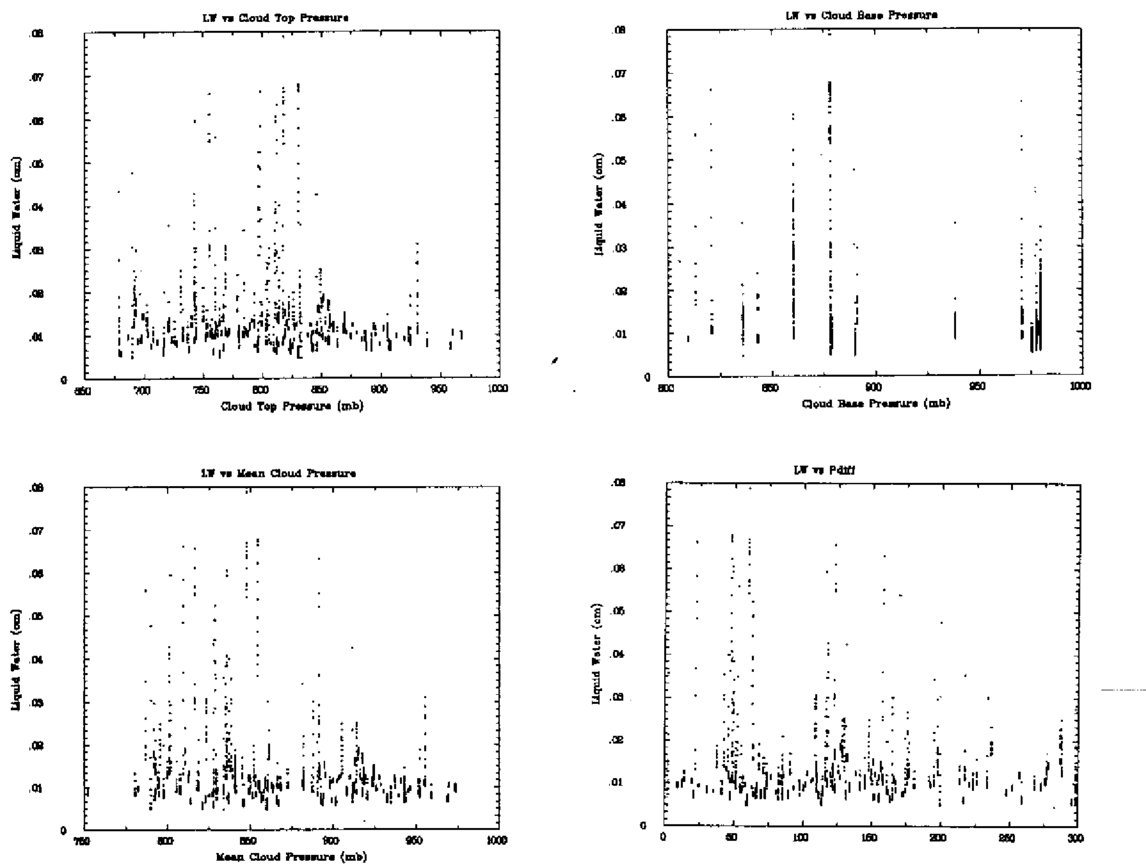

Figure 2. June 1993 MWR liquid water path vs. cloud top pressure (upper left), cloud base pressure (upper right), mean cloud pressure (lower left), and cloud pressure thickness (lower right). Cloud base is identified from radiosonde relative humidity profiles.

References

Betts, A. K., and Harshvardhan. 1987. Thermodynamic constraint on the cloud liquid water feedback in climate models, *J. Geophys. Res*., **92**, 8483-8485.

Del Genio, A. D., M.-S. Yao, W. Kovari, and K. K.-W. Lo. 1996. A prognostic cloud water parameterization for global climate models, *J. Clim*., submitted.

Feigelson, E. M. 1978. Preliminary radiation model of a cloudy atmosphere. 1: Structure of clouds and solar radiation, *Beitr. Phys. Atmos*., **51**, 203-229.

Tselioudis, G., W. B. Rossow, and D. Rind. 1992. Global patterns of cloud optical thickness variation with temperature, *J. Clim*., **5**, 1484-1495.