Factors Determining the Temperature Dependence of the Optical Thickness of Low Clouds

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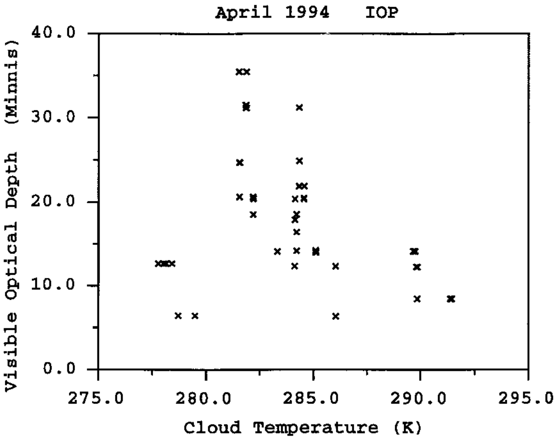
The factors that control changes in cloud optical thickness are among the major uncertainties in climate model predictions of sensitivity to increasing greenhouse gas concentrations. Simple thermodynamic arguments (Betts and Harshvardhan 1987) and *in situ* observations (Feigelson 1978) suggest that cloud liquid water content should increase with temperature for low and middle level clouds, leading to a negative cloud optics feedback (Somerville and Remer 1984). But International Satellite Cloud Climatology Project (ISCCP) satellite retrievals indicate that low cloud optical thickness increases with temperature only in cold regions, and more so over land than ocean. Over most of the world, optical thickness decreases instead (Tselioudis et al. 1992). There are several possible explanations: Increased precipitation efficiency or entrainment at warmer temperatures, systematic decreases of cloud physical thickness with temperature, or very large increases of cloud droplet effective radius with temperature.

The Goddard Institute for Space Studies (GISS) general circulation model (GCM), which includes a prognostic cloud water budget parameterization for stratiform clouds (Del Genio et al. 1996), reproduces the transition from increasing to decreasing low cloud optical thickness with temperature as temperature increases. To understand why, we consider the factors contributing to the parameterized optical thickness. For homogeneously distributed cloud water, optical thickness τ is related to liquid water content μ, cloud physical thickness Δz, and droplet effective radius r_e by the relation $\tau = (3/2)\mu\Delta z/(\rho_w r_e)$, where ρ_w is the density of liquid water. In the GCM, liquid water content generally increases/decreases with temperature at warm/cold temperatures, the opposite of that needed to explain the optical thickness behavior. But cloud physical thickness tends to decrease with temperature, more so at warm temperatures, accounting for most of the simulated temperature dependence of optical thickness. This is partly the result of the GCM's parameterization of vertically subgrid scale physical thicknesses, which depend on the degree of thermodynamic stability. (Effective radius variations, which track cloud water variations through an assumed constant number concentration, also contribute to the optical thickness behavior.) The GCM temperature dependence of optical thickness in the current climate turns out to be a good proxy for the doubled CO_2 cloud optics feedback. A climate change simulation with low cloud optical thickness feedback exhibits less polar amplification of warming than a simulation with fixed low cloud optics and has different impacts on the general circulation.

Data from the Atmospheric Radiation Measurement (ARM) Southern Great Plains (SGP) Cloud and Radiation Testbed (CART) site can be used in principle to validate the satellite finding and test the GCM hypothesis that appears to explain it. We have used collocated (as nearly as possible) data from four instruments for this purpose: 1) Microwave Water Radiometer (MWR) liquid water path (LWP) retrievals; 2) Belfort ceilometer cloud base heights; 3) Geostationary Operational Environmental Satellite (GOES) IR cloud top temperatures and visible optical thicknesses, the latter obtained from Pat Minnis' retrieval; 4) radiosonde temperature profiles to convert cloud top temperature to altitude and to define mean cloud temperature. Effective radius is estimated (subject to biases caused by subpixel cloud inhomogeneity) from the ratio of LWP to optical thickness, and liquid water content is estimated from the ratio of LWP to cloud physical thickness (top minus base altitude). The bulk of our analysis has been done on the April 1994 intensive observation period (IOP) data set because the Minnis retrievals are available for this time period, because sonde coverage is relatively dense, and because a sufficient sample of isolated low clouds exists in this month for patterns to emerge. The SGP CART site was quite warm during April 1994, putting it well into the regime in which ISCCP indicates that optical thickness decreases with temperature.

Other than the relatively sparse sampling of the sonde and satellite, the biggest problem is eliminating erroneous MWR liquid water retrievals, since the microwave is not sensitive to low liquid water amounts. Frequency histograms of LWP in the presence of clear skies as defined by the ceilometer have a standard deviation of 0.004 cm, comparable to published satellite microwave LWP uncertainties; we thus eliminate all points whose LWP is smaller than this. When we plot r_e versus LWP for the remaining points, a well-defined population of unrealistically large particle sizes at values of LWP just slightly greater than our cutoff emerges; these are points with low optical thicknesses mismatched to the retrieved LWP. We therefore eliminate points with LWP < 0.010 cm and r_e > 15 µm as well, which removes most but not all of this population. A handful of anomalous points remains at mean cloud temperatures < 280 K. Comparison with Minnis' cloud top temperature retrievals when available indicates that at least some of these low LWP clouds extend above the freezing level and may be partly composed of ice. We include these points on the accompanying figures for completeness but ignore them in the interpretations that follow.

Aside from the anomalous cold temperature clouds, fairly clear patterns are evident. Both optical thickness and LWP decrease with temperature (Figure 1), indicating that the ISCCP result is real and not the product of subpixel cloud fraction biases. Cloud physical thickness decreases dramatically with increasing temperature, while the derived liquid water content and effective radius exhibit only a weak temperature dependence, and none at all at the warmest temperatures (Figure 2). LWP is well correlated with both cloud top and cloud base altitude, but only cloud top altitude varies systematically with temperature (Figure 3); brighter low-level clouds are thus primarily clouds with higher cloud tops. It remains to determine why clouds get thinner at warmer temperatures. The CART site data correlate to some extent with moist static energy gradient when synoptic low pressure prevails, suggesting perhaps increased compensating subsidence as the controlling factor.



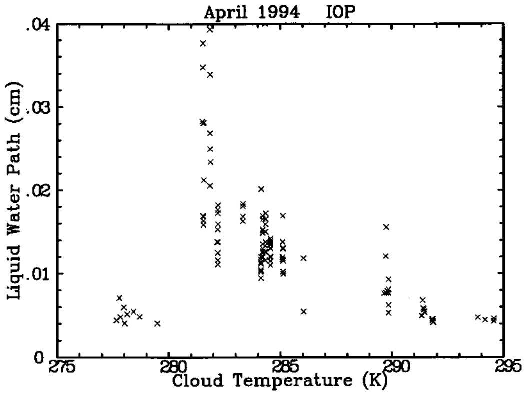


Figure 1. Minnis GOES visible optical thickness (upper) and MWR liquid water path (lower) vs. cloud temperature for low clouds during the April 1994 IOP at the SGP CART site.

All of the retrieved parameters used in this analysis will be made available to ARM investigators via the World Wide Web at URL in the near future. In particular, we view this

http://www.giss.nasa.gov/Research/Modeling/hydro.html

data set as one possible figure of merit for cloud parameterizations being tested in single-column models.

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.*, **9**, 270-304.

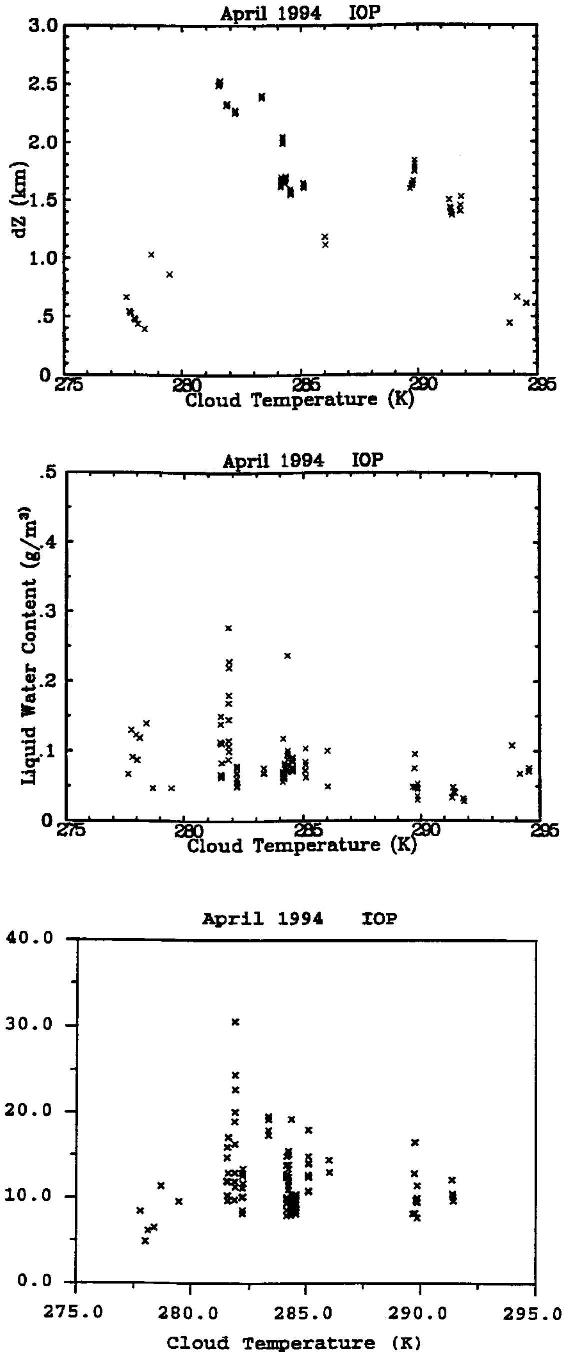


Figure 2. Derived cloud physical thickness (upper), liquid water content (middle), and droplet effective radius (lower) vs. cloud temperature at the SGP CART site during the April 1994 IOP.

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

Somerville, R.C.J., and L. A. Remer. 1984. Cloud optical thickness feedbacks in the CO_2 climate problem. *J. Geophys. Res.*, **89**, 9668-9672.

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

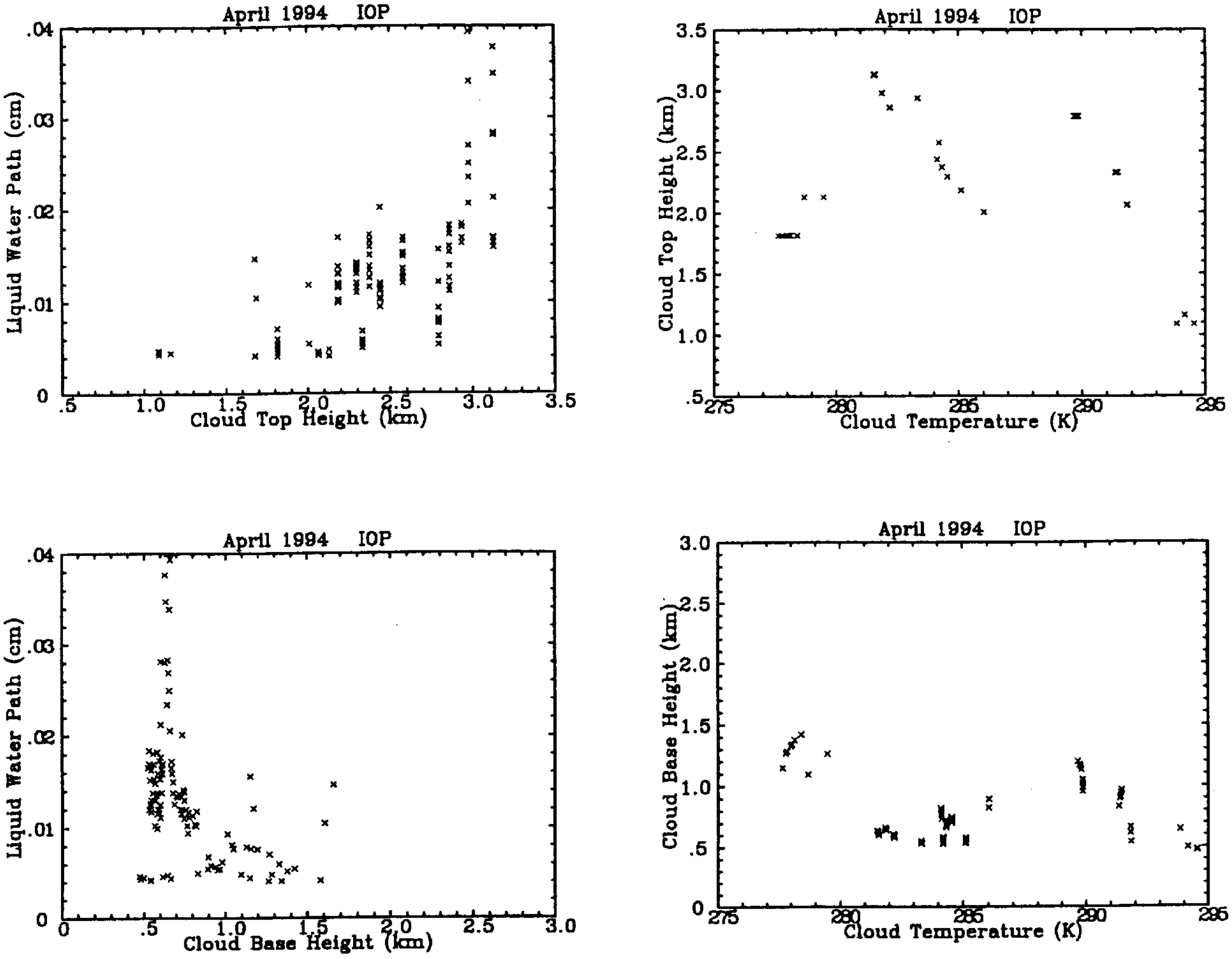


Figure 3. MWR liquid water path versus cloud top height (upper left) and versus cloud base height (lower left) for low clouds at the SGP CART site during the April 1994 IOP; corresponding cloud top height versus, cloud temperature (upper right) and cloud base height versus cloud temperature (lower right).