Temperature Dependence of Low Cloud Liquid Water Path: SGP Observations and Climate Implications

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Introduction

The International Satellite Cloud Climatology Program (ISCCP) observations indicate that the optical thickness of low clouds over midlatitude land decreases with increasing temperature during summer (Tselioudis and Rossow 1994). This is at odds with the assumption made in many general circulation models (GCMs) that liquid water content (LWC) increases adiabatically with temperature while cloud geometric thickness is invariant. Atmospheric Radiation Measurement (ARM) Southern Great Plains (SGP) data can verify and explain this finding. We use four data sets: microwave radiometer (MWR) [liquid water path (LWP)], Belfort laser ceilometer (BLC) (cloud base height), Geostationary Operational Environmental Satellite Infrared (GOES IR) (low cloud identification and cloud top temperature), and balloon-borne sounding system (BBSS) (cloud/surface temperature, cloud top height, meteorological structure). Each is available for the long periods of time necessary to deduce climatological relations. From these data streams, secondary variables (cloud geometrical thickness, LWC) are calculated as well. We select months for which all four instruments produced data and in which isolated low cloudiness was common. Over a 4-year period, this gives us a total of 3394 observations in 18 months that we divide into warm and cold season ensembles. We also classify clouds synoptically by grouping data according to the sign of deviation of the instantaneous lower troposphere meridional wind and temperature from the seasonal and mean diurnal cycle.

Temperature is only one of the factors affecting cloud properties in a dynamic atmosphere. Furthermore, observation times for individual instruments at the SGP are not always coincident, and each instrument has a non-negligible retrieval uncertainty. These combine to produce considerable scatter in any regression, and only a small fraction of the total variance (15% to 25%) of any quantity is explained by its temperature dependence. Nonetheless, the data are clearly consistent with the ISCCP finding. In the warm season, when $T > 280°$ K, the LWP of low clouds tends to decrease with warming, being highly variable at the colder temperatures but almost always small when temperatures are warm (Figure 1). Defining $f(A) = A^{-1}dA/dT$ for any parameter A, we find

$$f(LWP) = -.08/K$$

with a correlation coefficient r = -.39 (r = .06 is significant at the 99% level). LWC is almost uncorrelated with T, indicating subadiabatic behavior. Instead, cloud geometric thickness (dz) is found to decrease clearly with T [f(dz) = -.05/K, r = -.51, Figure 1], mostly due to rising cloud base height but partly due to descending cloud top height. In the cold season, LWP is almost uncorrelated with T.

The behavior of cloud base height is easily explained. There is a fairly good relationship between the lifting condensation level (LCL) of surface air and observed cloud base heights (Figure 2), typical of a convective planetary boundary layer (PBL). The LCL rises with temperature because the relative humidity (RH) of surface air decreases with temperature (Figure 2). Without a constant surface moisture source (unlike the ocean), warming drives the PBL away from saturation, and parcels must ascend more to form cloud, making warm clouds optically thinner than cold clouds. Cloud top height behavior is more difficult to understand. Neither surface pressure nor pressure tendency decreases with temperature, arguing against subsidence as a cause for cloud top suppression with warming. Instead, the presence of drier air above cloud top under warm conditions (see discussion of Figure 3) may increase the effectiveness of entrainment dilution of the cloud. This may also explain the failure of LWC to increase adiabatically with warming. Whether entrainment strength itself increases with warming is not well understood, although cloud top jumps in moist

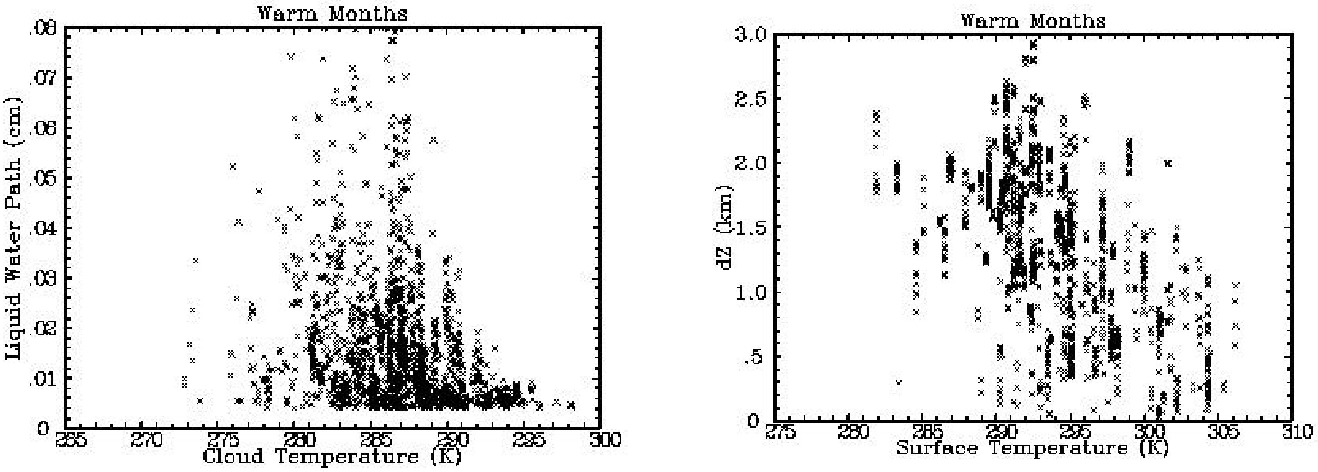

Figure 1. Warm season temperature dependence on low cloud (left) LWP and (right) dz at the SGP.

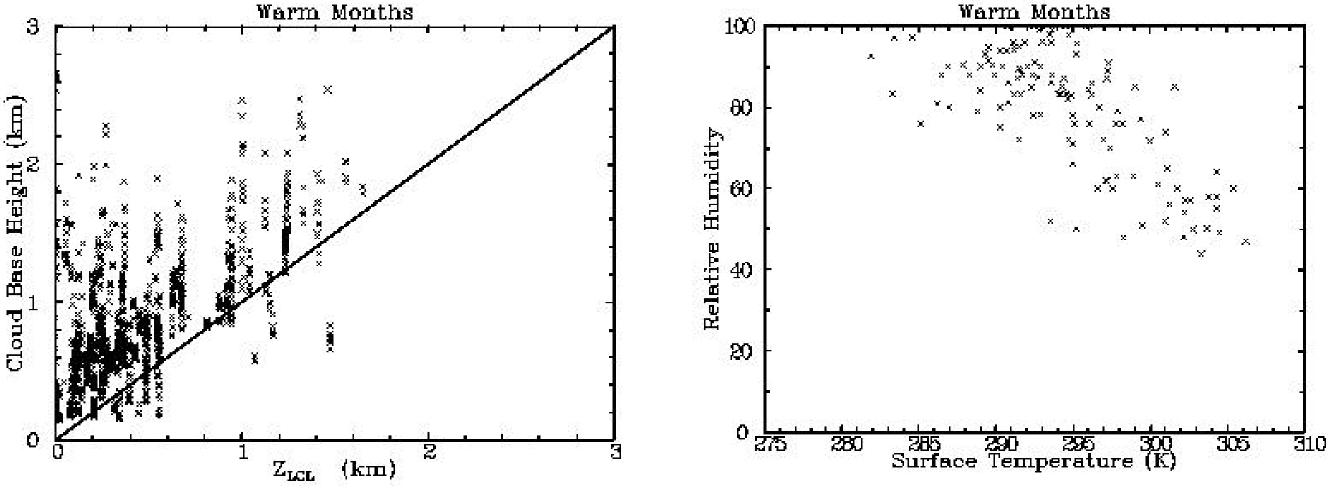

Figure 2. (Left) Belfort laser ceilometer cloud base height vs. LCL of surface air; (right) surface RH vs. surface temperature.

static energy and total water content vary with T in a manner consistent with increasing tendency toward cloud top entrainment instability.

To help assess the climatic significance of the results, we separate the variability by time scale. Seasonal variations in the warm sector of baroclinic waves (v´ > 0, T´ > 0) show a large decrease in both LWP and dz from the cold to the warm season. This is also seen in conditions of building high pressure under warmer than normal conditions (v´ < 0, T´ > 0). Cold sector/wraparound flow conditions (v´ <0, T´ < 0) and pre-warm frontal flow (v´ > 0, T´ < 0) are associated with LWP either constant or increasing from winter to summer instead. Seasonal change consists of a temperature increase and meridional temperature decrease, analogous to long-term greenhouse climate change predictions, so the seasonal variation may be a good proxy. When data are composited over diurnal cycle phase, clouds are also seen to thin with warming. When the seasonal and diurnal cycles are removed, isolating synoptic time scale variations, again clouds thin with warming.

Changes in thermodynamic structure of the PBL seem to account for much of the behavior we observe. Sounding composites for the cold (280° K to 290° K) and warm (300° K to 305° K) ends of the warm season distribution exhibit structures characteristic of the midlatitude and subtropical marine PBLs, respectively (Figure 3). At the cold end, where the thicker clouds are observed, the PBL is often highly stratified, and RH is high at the surface and persists to 1.5 km (2.0 km in the coldest cases) before decreasing. Five of seven of these soundings with World

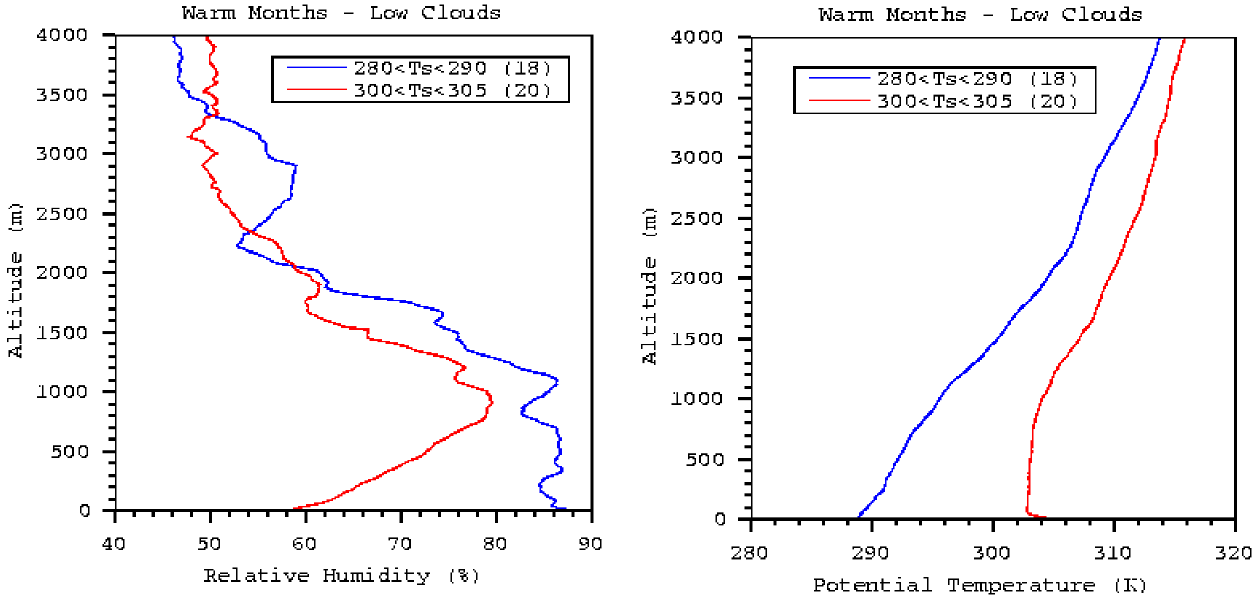

Figure 3. Warm season soundings of (upper) potential temperature, (lower) RH when low clouds are present at the SGP for cold (280-290 K) and warm (300-305 K) subsets of the population. (For a color version of this figure, please see *http://www.arm.gov/docs/documents/technical/conf_9803/delgenio-98.pdf*.)

Meteorological Organization (WMO) cloud classifications available were classified as bad-weather stratus, with mean cloud cover of 79%. At the warm end, where clouds are uniformly thin, well-mixed and detached PBLs below inversions are the rule, and RH increases up to about 1.0 km before dropping sharply above the inversion level. Seven of nine WMO-classified soundings were classified as stratocumulus, cumulus, or cumulus-under-stratocumulus, with mean cloud cover of 49%. Two features of the continental cloudy PBL differ from its marine counterpart: 1) surface RH in warm conditions is much lower than over the oceans, not surprisingly; and 2) over the oceans, stratocumulus and cumulus tend to occur under cold advection, while bad-weather stratus is usually associated with warm advection. The opposite is true at the SGP: The mean meridional wind is –2 m/s for the cold subset and +4 m/s for the warm subset. Plausibly this can be explained by the fact that the PBL's thermal response time is faster than that of the ocean mixed layer but slower than that of the land surface. Strength of detachment of the PBL, as measured by fractional specific humidity differences between subcloud and near-cloud top air, does not seem to explain the temperature dependence of LWP; frequency of occurrence of convective PBLs appears to be a better candidate.

These results have implications for estimates of the range of possible climate sensitivities. Most GCMs with low sensitivity to a doubling of CO_2 achieve this result via a negative low cloud optical thickness feedback. Our results, however, combined with the near-global tendency for clouds to thin with warming seen by ISCCP, argues for a positive low cloud optical thickness feedback instead. In fact, the GISS GCM, which makes cloud geometrical thickness a function of both RH and stability, obtains positive low cloud optical thickness feedback and a sensitivity of 3.1° C (Yao and Del Genio 1998). The observations therefore suggest that a more credible lower limit to climate sensitivity is 2.0° C to 2.5° C instead.

References

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