## 5.14 THE CHANGE OF CLOUD LIQUID WATER PATH ON TEMPERATURE OVER POLAR AREAS

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### 1. INTRODUCTION

The variations of cloud properties have important impacts on climate. However, many interactions of clouds within the climate system are not well understood nor accurately characterized. To date, most cloud feedback observations have focused on low clouds over low and middle latitudes (*Del Genio and Wolf*, 2000; *Tselioudis et al.*, 1992). In polar regions, the temperatures are generally close to or colder than the freezing point even during warm seasons (e.g. *Minnis et al.*, 2001). The changes of cloud properties with temperature play a fundamental role in the cloud-radiative feedback system. Thus, it is important to more accurately quantify the sensitivity of Arctic stratus clouds to changes in the cloud temperature.

Combining the Surface Heat Budget of the Arctic Ocean (SHEBA; October 1997 - October 1998) and First ISCCP Regional Experiment Arctic Cloud Experiment (FIRE ACE; May - July 1998) ground-based data with satellite observations, this study investigates the dependence of cloud liquid water path *LWP* on temperature in the Arctic, and the physical mechanisms of the *LWP* variations.

### 2. DATA AND RETRIEVAL ALGORITHMS

The microwave radiometer (MWR) at the SHEBA site measured downwelling radiances at frequencies of 23.8 and 31.4 GHz. Cloud *LWP* and column water vapor (*CWV*) were retrieved from the MWR measurements using the algorithm developed by *Lin et al*. (2001). This algorithm properly accounts not only for the temperature and pressure dependence of atmospheric gas absorption at the microwave wavelengths, but also the variation of water absorption with the cloud water temperature (*Lin et al*., 1998; *Lin et al*., 2001). The root mean square (rms) *LWP* errors are about 0.024 mm (or 25%), which is larger than the uncertainties in the retrieval algorithm. The spatial and temporal mismatches between MWR retrievals and in situ measurements probably contribute significantly to the rms errors.

Cloud top and base heights were estimated from the cloud-top and base temperatures derived from the Advanced Very High Resolution Radiometer (AVHRR) data (*Minnis et al*., 2001]) and ground-based infrared (IR) thermometer (IRT) measurements, respectively, with SHEBA atmospheric profile information. To verify the relationship of cloud *LWP* and temperature *T*, 10-minute averaged cloud-base height estimates from the SHEBA Depolarization and Backscatter Unattended Lidar (DABUL) were analyzed. The DABUL data provide the opportunity to separate liquid and ice phase clouds and to detect single and multi-layer clouds. The current study uses only cloud-base heights for single-layered water clouds (absolute depolarization ratio < 0.05). Comparison of the IRT and lidar cloud-base heights shows that the two techniques yield consistent results with a 0.4-km mean difference and a 0.5-km standard deviation.

### 3. RESULTS

Significant amounts of liquid water during SHEBA were not observed until the spring thaw was well underway (i.e., May 1998). Figure 1 shows the relationships between *LWP* and cloud height for overcast cases. Generally, *LWP* increases with increasing cloud-top height (1a) and with decreasing cloud-base height (1b). Thus, increasing cloud thickness is mainly responsible for the enlarged *LWP* (1c). Despite the changes in *LWP* with both cloud-top and base heights (or cloud thickness), cloud liquid water content (*LWC*) varies little with *LWP* (1d).

To further confirm the *LWP* variations with cloud temperature, the DABUL cloud-base height data were analyzed. The lidar data exhibit very similar *LWP* changes with the environmental conditions to those in Figure 1. Figure 2 plots the relationship between *LWP* and DABUL cloud-base height for all single-layered water clouds. Potential fog cases (or cases with surface relative humidity ≥ 100%) were eliminated from the original DABUL data to avoid height detection errors caused by lidar minimal range. The figure clearly shows that the *LWP* values decrease with increasing cloud-base height. Since the DABUL depolarization ratio is used in the analysis for these single-layered clouds, the results are not

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affected by ice clouds, mixed phase conditions, or cloud ice water path (*IWP*) values.

If the rate of change with temperature for *LWP* is defined as $f\,(LWP) = LWP^{-1}dLWP/dT$, then for the SHEBA dataset, *f* (*LWP*) is about 0.033 /K. The *LWP* temperature dependence over the ice sheet has some similarities to that in winter midlatitude land regions, as seen by DelGenio and Wolf (2000). Both regions have limited heat capacity and column water vapor relative to the ocean. When *LWP* is averaged for each 1-K temperature interval, the estimated *f* values for these monthly-scale *LWP* changes are about 0.07 /K, which is about two times larger than that (~0.033 /K) estimated from short-time-scale data. The assumption for obtaining this stronger cloud feedback factor with temperature is that the water clouds are equally distributed over the considered temperature range. Similar calculations by previous studies also yielded slightly higher *f* values (0.04 ~ 0.05 /K). For climate studies, the estimation from the original *LWP* samples, which is equivalent to cloud water path weighted by cloud population in each temperature bin, may be more realistic.

The decrease of cloud-base height with *T* is directly connected to a lower cloud lifting condensation level (LCL). As the surface air temperature increased from 255 K to 275 K during FIRE ACE period, the surface relative humidity changed on average from ~78% to ~95%, and the specific humidity increased sharply from ~0.7 g/kg to ~4.0 g/kg. When lifted and cooled, surface air parcels with elevated surface relative humidity at high temperatures condense water vapor more quickly than those with lower humidity at low temperatures. As a consequence, the LCL of surface air estimated from the SHEBA surface humidities and temperatures and atmospheric vertical profiles decreased from ~0.5 km at low temperatures to altitudes just above or at the surface for warm temperatures (Fig. 3). Because of the humidity, again, the moist static energy of the surface air parcel is higher at warmer rather than lower temperatures, which, at least partly, causes the increase in cloud top heights, especially in moist convection cases. Deepening boundary layers may be another reason for increased cloud-top heights in warm and humid environments. Thus, the cloud physics that causes *LWP* to increase with *T* is the increase of cloud thickness resulting from warmer and moister environments.

## 4. CONCLUSIONS

Over the SHEBA site during FIRE-ACE, cloud liquid water path increased with temperature due primarily to an increase of cloud thickness. The observed temperature dependence of *LWP* was ~3.3% /K. These observed cloud variations have significant effects on the polar climate and should be taken into account in climate models.

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Figure 1. *LWP* dependence on cloud top height (a), cloud base height (b), cloud thickness (c) and cloud liquid water content *LWC* (d).

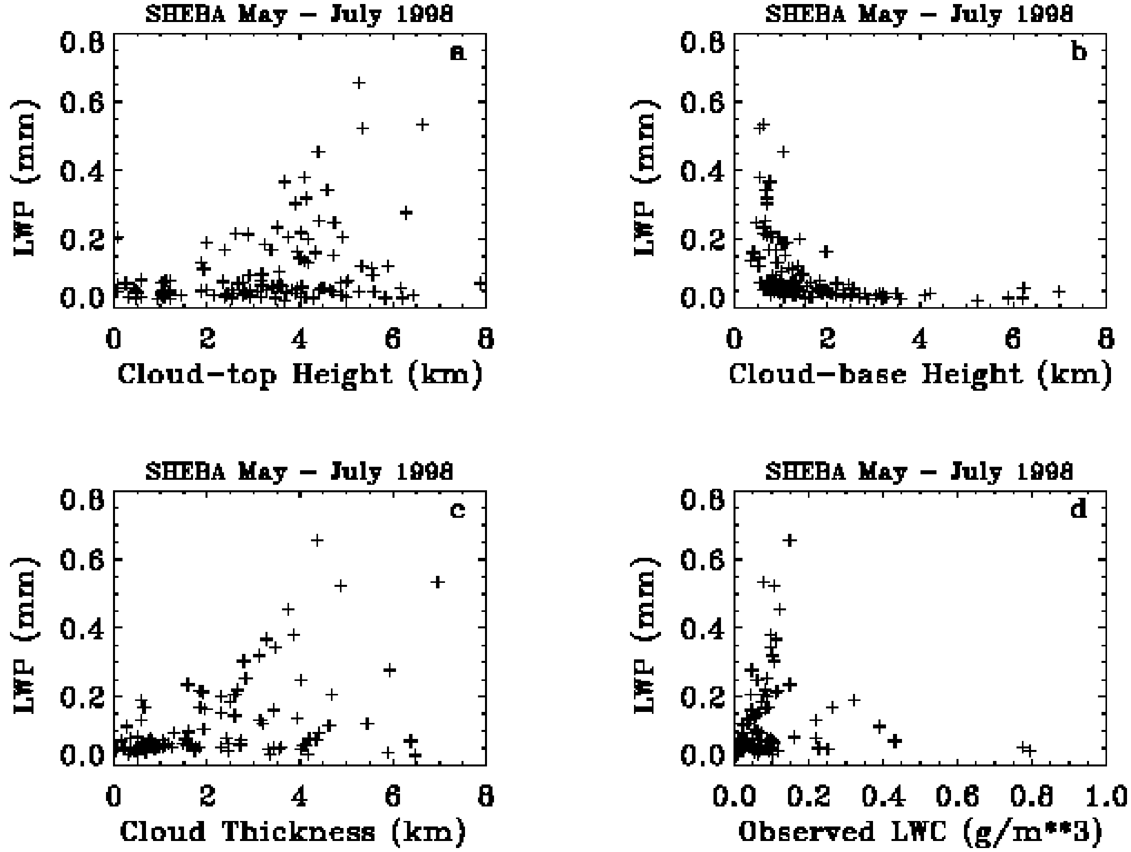


Figure 2. The relationship between *LWP* and cloud base height observed by DABUL.

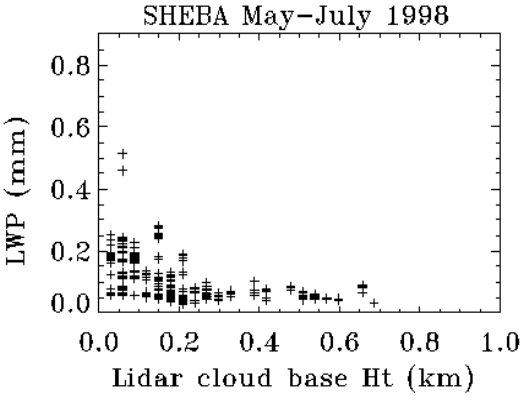
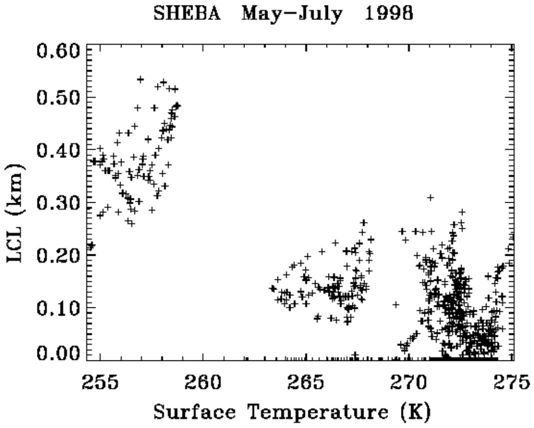


Figure 3. Temperature dependence of cloud lifting condensation level (LCL).



Note: The LCL values were theoretically estimated from surface meteorological measurements of temperature and humidity and atmospheric profile.