Combining Microwave Radiometer and Millimeter Cloud Radar to Improve Integrated Liquid Water Retrievals

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Introduction

The present statistical retrieval, with which the integrated liquid water (ILW) path is derived from the microwave measurements, relies heavily on local climatology. A separate retrieval (and an *a priori* data set) is required for each instrument location. Neither the variations in the oxygen contribution to the microwave signal nor the strong dependence of microwave emission by clouds on the temperature of the cloud water (and therefore on cloud height) are accounted for.

The objective of this research has been to develop a retrieval for ILW that 1) is independent of local climatology and may thus be used at any location, 2) accounts for the variations in the oxygen contribution, and 3) accounts for the dependence on cloud temperature.

Background

The atmospheric opacity τ at the measured microwave frequencies is due to the sum of a "dry" contribution τ_{dry} from the far wing of the 60-GHz oxygen band, a contribution τ_{vap} from the water vapor resonance centered at 22 GHz, and (for cloudy skies) a contribution τ_{liq} from liquid water

$$\tau = \tau_{dry} + \kappa_{vap} V + \kappa_{liq} L \tag{1}$$

where $\kappa_{vap} = \tau_{vap} / V$ and $\kappa_{liq} = \tau_{liq} / L$ are the (frequency-dependent) path-averaged mass absorption coefficients and $V = \int \rho V \, dz$ and $L = \int \rho L \, dz$ are, respectively, the integrated water vapor (IWV) and the integrated cloud liquid water. If the dry contribution is determined separately and subtracted such that $\tau^* = \tau - \tau_{dry}$, then the two equations (one for each frequency) corresponding to Eq. (1) can be solved for the estimates of V and L

$$V = v_1 \tau_1^* + v_2 \tau_2^* \tag{2a}$$

$$L = l_1 \tau_1^* + l_2 \tau_2^* \tag{2b}$$

where v_1, v_2, l_1, and l_2 are the "retrieval coefficients," which may be expressed in terms of the mass absorption coefficients. The subscripts 1 and 2, respectively refer to the vapor- and liquid-sensitive frequencies (23.8 GHz and 31.4 GHz). At each frequency, the opacity is calculated from the measured sky brightness temperature T_{sky} with $\tau = \ln[(T_{mr}-T_{bg})/(T_{mr}-T_{sky})]$ where T_{bg} is the cosmic background radiating temperature (2.73 K) and T_{mr} is the atmospheric mean radiating temperature. In order to apply this retrieval T_{mr}, τ_{dry}, and v_1, v_2, l_1, and l_2 must be determined.

Retrieval Development

Extensive radiosonde data from polar (Barrow, SHEBA [Surface HEat Budget of the Arctic Ocean]), tropical (Manus Island), and continental (Oklahoma, Kansas, Albuquerque) sites were used in order to span the full range of the parameter space for the new retrieval.

The dry contribution is proportional to $(P-e)^2/T$, where P is the barometric pressure, e is the water vapor pressure, and T is the absolute temperature, as shown in Figure 1. The scatter is primarily due to temperature inversion conditions for which the surface data are less correlated with the vertical column. Nevertheless, the oxygen contribution may be estimated for any location with an accuracy of about 2% root mean square (rms) with this relationship.

For a wide range of locations and sky conditions T_{mr} can be estimated from surface temperature and humidity with an accuracy of ~1% as evident from Figure 2.

The vapor coefficients v_1 and v_2 exhibit a weak dependence on surface pressure and a weaker dependence on surface temperature and vapor pressure. Fitting v_1 and v_2 to the surface pressure, temperature and vapor pressure permits them to be estimated to within 2% rms for most locations. This

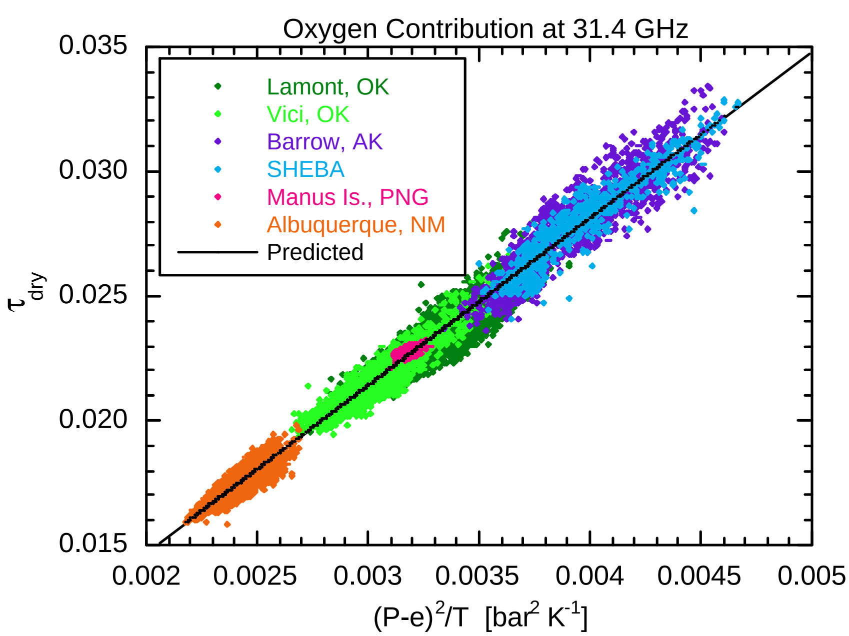

Figure 1. The "dry" contribution due to oxygen at 31.4 GHz for several sites as a function of dry pressure and temperature. 23.8 GHz is similar.

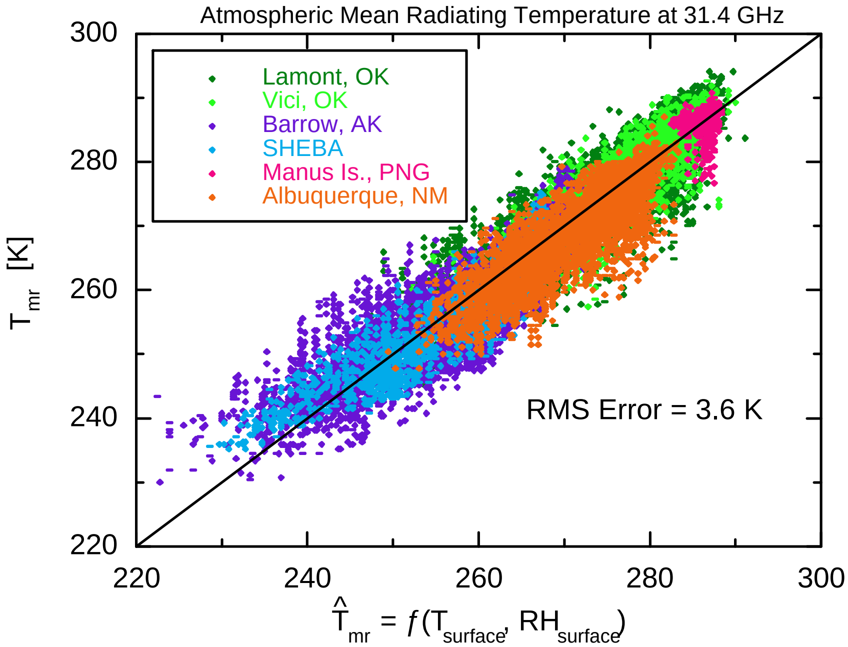

Figure 2. The mean radiating temperature at 31.4 GHz for several sites as a function of the predicted value. Results at 23.8 GHz are similar.

in turn permits the IWV to be determined with an rms accuracy of 0.5 mm or better for any site. (Compare this with 0.6 mm to 1.0 mm rms for the statistical retrieval used at the Southern Great Plains [SGP].)

Retrieval of the ILW is complicated by the fact that κ_{liq} decreases exponentially as the mean cloud water temperature increases, as illustrated in Figure 3, and thus depends strongly on the height and thickness of the cloud, as do the liquid water retrieval coefficients l_1 and l_2.

The Millimeter Cloud Radar (MMCR) is used to provide a weighting function proportional to the distribution of cloud water that can be used to find the cloud temperature:

$$T_{cloud} = \int w(z)\, T(z)\, dz \,/ \int w(z)\, dz. \tag{3}$$

The weighting function, as shown in Figure 4, is the square root of the radar reflectivity. (The reflectivity is proportional to the 6th moment of the droplet radius whereas the mass is proportional to the 3rd moment.)

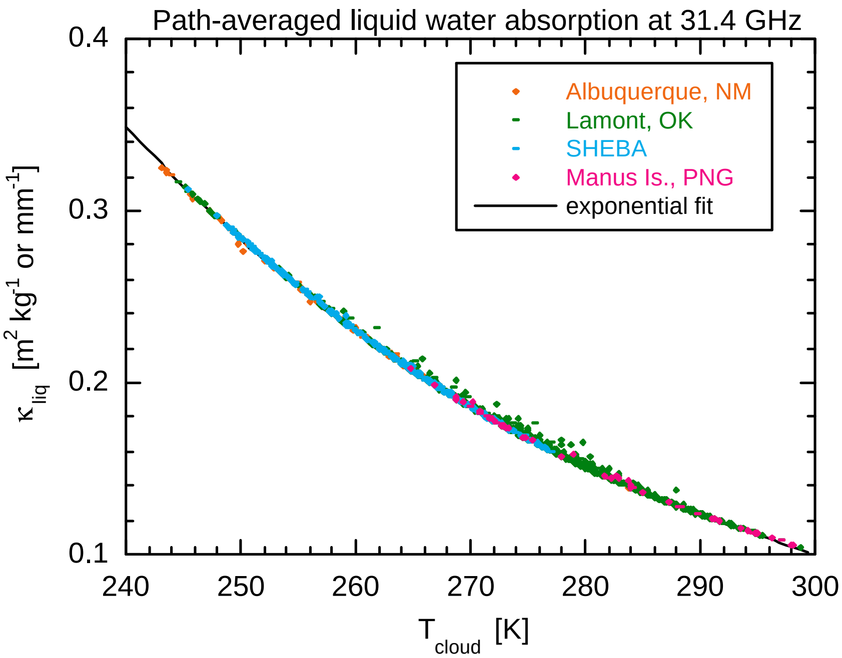

Figure 3. The path-averaged liquid water absorption coefficient at 31.4 GHz as a function of liquid water-weighted cloud temperature.

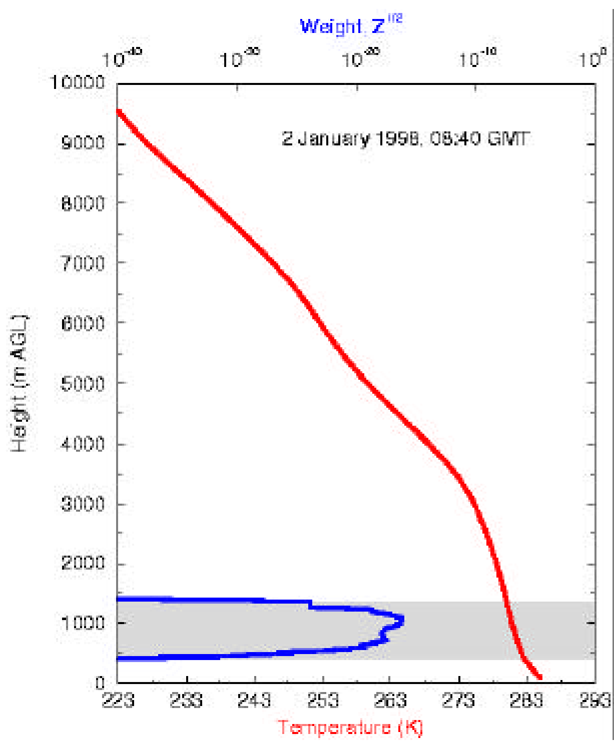

Figure 4. A sample radar-derived weighting function and a temperature profile for a low stratus cloud case on January 2, 1998.

Results

Figure 5 shows mean cloud temperatures calculated according to Eq. (3) for January 2, 1998, when low stratus clouds were present. The cloud base temperature derived from cloud base height, and the surface temperature are shown for comparison.

Figure 6 compares the ILW and IWV for January 2, 1998, from the new retrieval with the statistical retrieval currently in use. When T_{cloud} from the radar is less than the climatological value implicit in the statistical retrieval, the ILW is also less (because κ_{liq} is larger). Clear-sky episodes are also better resolved with the radar. Note that the IWV from the new site-independent retrieval agrees very well with the site-specific statistical retrieval and the radiosondes.

The advantage of specifying T_{cloud} occurs primarily at larger values of ILW as shown in Figure 7. For small values of ILW, an error in κ_{liq} due to using a climatological value for T_{cloud} results in a small absolute error in ILW (even though the relative error may be substantial).

Mixed-phase clouds present a problem when using the radar to determine T_{cloud}. If the weighting from the ice is substantial, the derived value for T_{cloud} will be too low and the ILW will be underestimated. This problem has been encountered using the MMCR at SHEBA. The addition of polarization to the Atmospheric Radiation Measurement (ARM) MMCRs should help discriminate ice and liquid water phases.

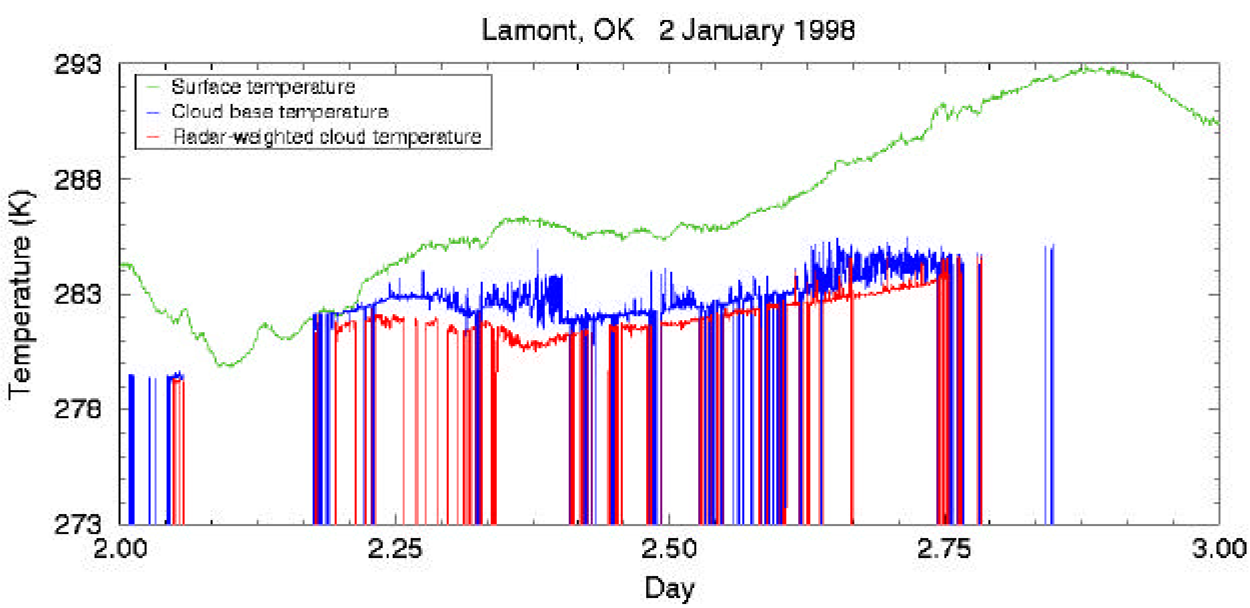

Figure 5. Mean cloud temperature, cloud base temperature, and surface air temperature for January 2, 1998.

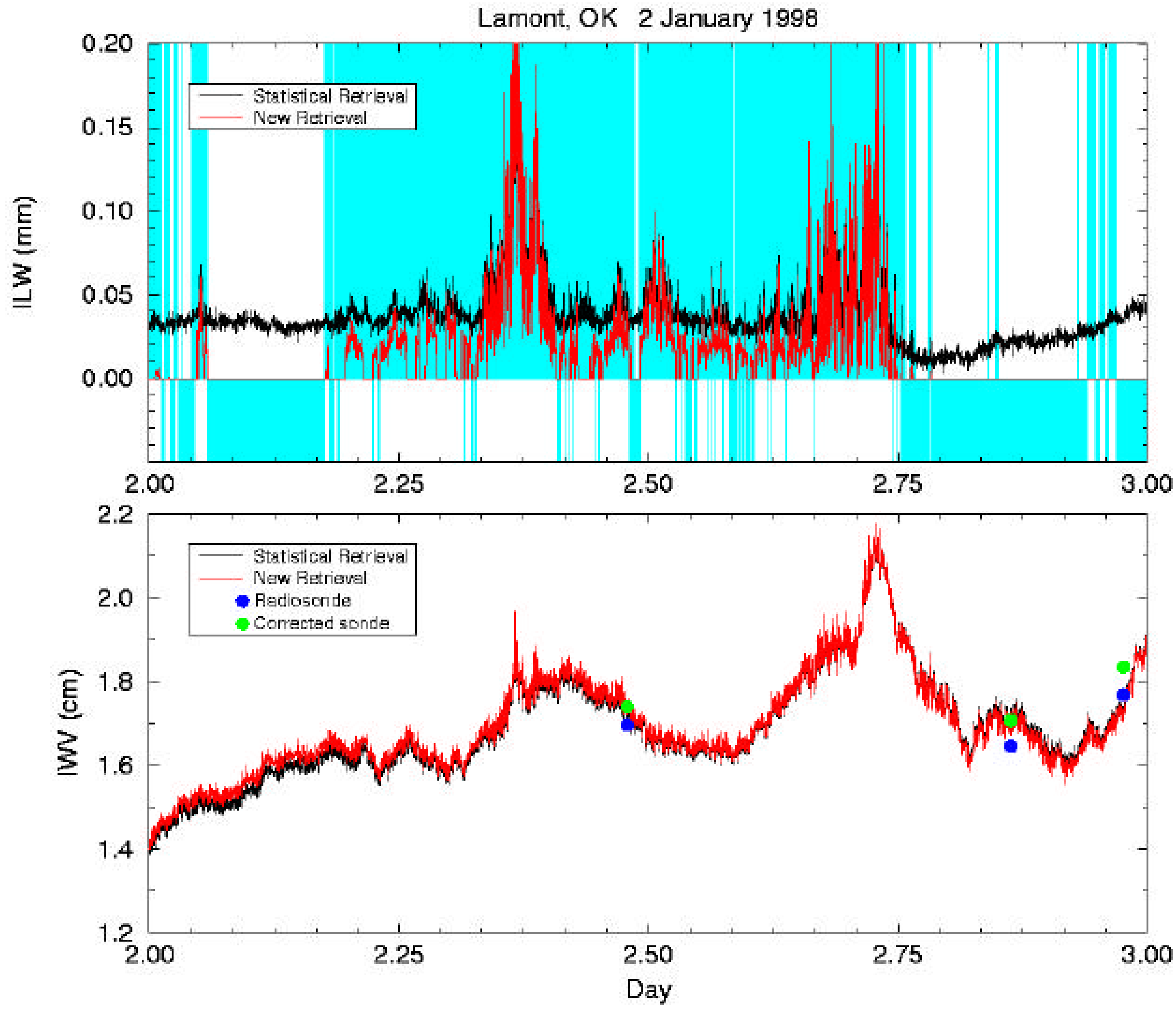

Figure 6. Upper panel: ILW from the site-specific statistical retrieval and the new site-independent retrieval accounting for cloud temperature. The light blue-shaded areas indicate clear/cloudy sky from the ceilometer. Lower panel: IWV from both retrievals and from radiosondes.

Conclusions

By accounting for the relevant physical processes, a new retrieval algorithm for ILW and IWV has been developed that is a) independent of local climatology, and b) offers improved accuracy.

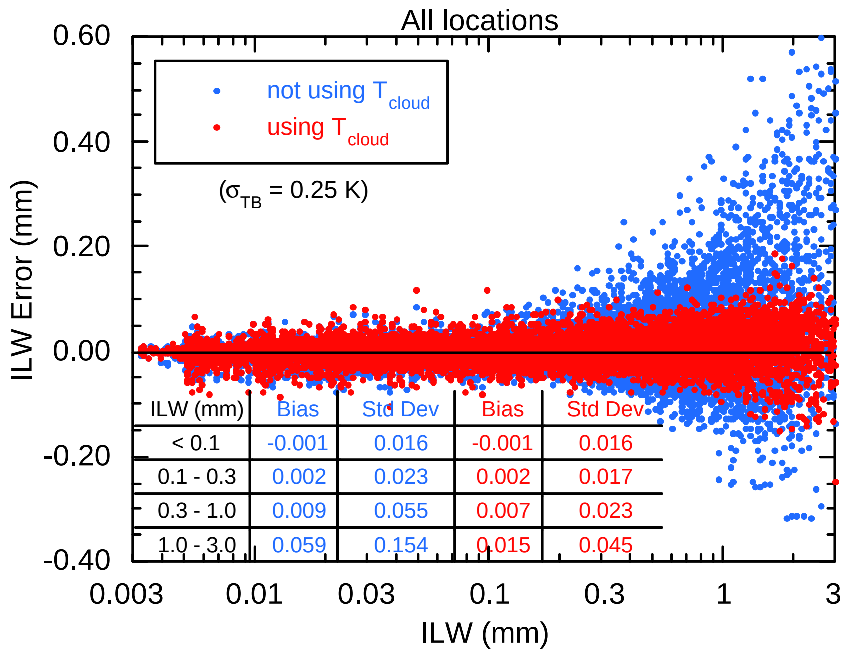

Figure 7. Comparison of ILW accuracy for site-independent retrievals that include and ignore the cloud temperature dependence.