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Can liquid water profiles be retrieved from passive microwave zenith observations?

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[1] The ability to determine the cloud boundaries and vertical distribution of cloud liquid water for single-layer liquid clouds using zenith-pointing microwave radiometers is investigated. Simulations are used to demonstrate that there is little skill in determining either cloud base or cloud thickness, especially when the cloud thickness is less than 500 m. It is also shown that the different distributions of liquid water content within a cloud with known cloud boundaries results in a maximum change in the brightness temperature of less than 1 K at the surface from 20 to 150 GHz, which is on the order of the instrument noise level. Furthermore, it is demonstrated using the averaging kernel that the number of degrees of freedom for signal (i.e., independent pieces of information) is approximately 1, which implies there is no information on vertical distribution of liquid water in the microwave observations.

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1. Introduction

[2] Water clouds interact strongly with infrared and visible radiation, making them an important modulator of the Earth's radiation budget. Profiles of liquid water content (LWC) are required in order to accurately compute the radiative heating of the atmosphere caused by the cloud. Furthermore, LWC is a prognostic variable in most weather prediction and climate models, and thus LWC observations are needed to evaluate and improve these models and the processes within them. Due to the small absorption coefficient of liquid in the microwave region of the spectrum, clouds are semi-transparent in this spectral region and thus observations in this region are used to characterize the cloud properties. Microwave and millimeter-wave cloud radars, which transmit pulses of energy into the atmosphere at frequencies between 10 and 100 GHz, measure the radar reflectivity factor Z, which is proportional to the sixth moment of the droplet size distribution (DSD). Due to microphysical processes the relation between Z and LWC, i.e. the third moment of the DSD, varies over a wide range depending on atmospheric and cloud conditions. For example, the presence of even a few drizzle drops in the radar volume will dominate the Z observation even though these drops contribute negligibly to the LWC, and since drizzle is commonly observed in liquid water clouds, even the detection of cloud base by cloud radar can be problematic. Therefore multi-sensor algorithms combining cloud radar with microwave radiometer and/or lidar have been suggested [*Frisch et al.*, 1998; *Löhnert et al.*, 2008] in order to reduce LWC uncertainty to about 20%.

[3] Passive microwave radiometry has been used for decades to retrieve the vertically integrated liquid water path (LWP) with reasonable accuracy [e.g., *Westwater*, 1978]. LWP can be retrieved from atmospheric brightness temperature observations in the microwave region because in this spectral region the liquid water contribution increases with frequency (the emission is proportional to the frequency squared) and the absorption has no dependence on the DSD since the droplets are considerably smaller than the wavelength and thus are in the Rayleigh regime. A standard technique to measure LWP is to observe the atmospheric emission at two frequencies; a window channel that is away from gaseous absorption lines where the emission is dominated by the liquid water emission (e.g., at 31 GHz) and at a channel that is near a transparent water vapor absorption line (e.g., at 24 GHz) to correct for the water vapor contribution to the window channel. The addition of window channels at higher frequencies, such as 90 GHz where the liquid water absorption is significantly larger than at 31 GHz, can further constrain the retrieval and improve the accuracy to better than 15 g/m^2 [*Crewell and Löhnert*, 2003] compared to the 20–30 g/m^2 uncertainty in the retrievals from dual-channel retrievals that use observations between 22 and 32 GHz [*Turner et al.*, 2007].

[4] It is very desirable to be able to retrieve LWC with some fidelity from a single passive remote sensing instrument, as these instruments are typically more affordable than active remote sensors. *Solheim et al.* [1998] have suggested that a 12-channel microwave profiler that makes observations at K-band (22–32 GHz) and V-band (51–59 GHz), which is augmented with a narrowband infrared observation at 10 μm, can be used to retrieve profiles of temperature, humidity, and LWC. *Ware et al.* [2003] showed a comparison between LWC profiles retrieved from such a profiling microwave radiometer with cloud liquid sensors flown on balloons during a field experiment and found an agreement of 50%. Recently, *Knupp et al.* [2009] used "equivalent" liquid water profiles derived from a microwave profiler during a snowfall event for analyzing cloud physics, where "equivalent" was used to indicate that the effects of scattering by the ice particles (which are no longer in the Rayleigh scattering regime) are not taken into account by their LWC retrieval algorithm. These studies have assumed that there is significant information content in the microwave observations to the LWC profile; however,

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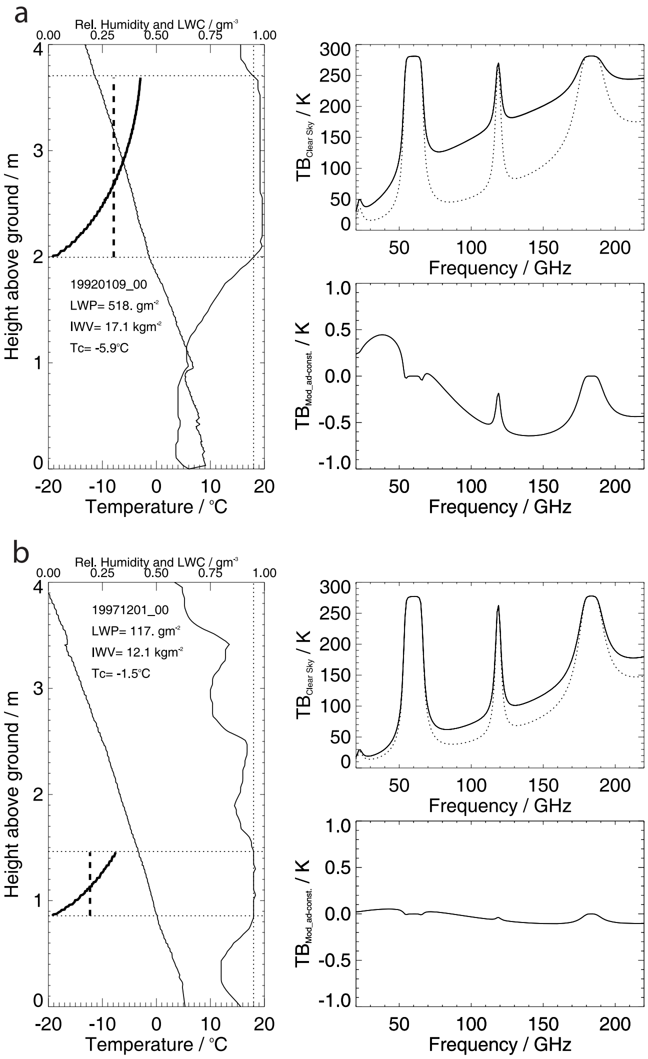

Figure 1. Radiosondes launched (a) on 1 Dec 1997 at 10 UTC and (b) on 9 Jan 1992 at 00 UTC at Payerne, Switzerland. (left) Cloud boundaries are diagnosed by 95% threshold in relative humidity and a modified adiabatic profile. In addition, a constant liquid water content yielding the same LWP is indicated. (right) The simulated brightness temperatures (TB) with (solid) and without (dotted) cloud contribution (top) and the difference in TB between the calculations with the modified adiabatic and the constant LWC profile (bottom) are shown.

the actual amount of information in the observations has never been quantified. The aim of this paper is to investigate the information content of ground-based zenith-pointing multi-spectral (i.e., profiling) microwave radiometer observations with respect to LWC.

2. Sensitivity of Microwave Observations to LWC

[5] We start the analysis by investigating the spectral response of microwave radiation that would be observed at the surface to different cloud structures (i.e., vertical distributions of liquid water). For that purpose, we have selected two single-layer liquid cloud cases that were diagnosed from radiosonde profiles collected at Payerne, Switzerland (46.82°N, 6.95°E, 491 m AGL). The cloud boundaries were determined using a threshold of 95% for the relative humidity (RH) profile. The LWC was assumed to be a modified adiabatic profile using the empirical relationship that was derived from aircraft observations [*Karstens et al.*, 1994]. The two cases were selected to represent "average" cloud (LWP and thickness are approximately 100 g/m^2 and 500 m) and a "thick" cloud (LWP and thickness are approximately 500 g/m^2 and 1700 m).

[6] The change in the brightness temperature relative to the cloud-free scene in three window regions (Figure 1) is 6 (27) K at 31 GHz, 25 (89) K at 90 GHz, and 34 (96) K at 150 GHz for the average (thick) cloud case. The noise level of a typical ground-based radiometer is in the order of 0.05 K for these frequencies, so the change in the signal between the cloud and cloud-free case is well above the instrument noise level. The larger sensitivity to LWP at 90 and 150 GHz have resulted in the manufacture and deployment of microwave radiometers that make observations at these frequencies, since over 50% of the clouds in the Arctic, Tropics, and mid-latitudes have LWP less than 100 g/m^2 [*Turner et al.*, 2007]. These high frequency channels are not standard on commercially available microwave profiler radiometers, and at high water vapor amounts and large LWP these higher frequency channels will saturate before the observations at 22–32 GHz.

3. Cloud Boundary Determination

[7] The retrieval of LWC first requires that the cloud boundaries (e.g., cloud base and cloud top) can be properly determined. Retrievals that utilize microwave radiometer data are typically based upon simulations that use a large number of radiosonde ascents that span the range of expected atmospheric conditions, which are used to generate synthetic observations with radiative transfer model calculations. Typical radiosondes do not measure cloud liquid directly, and therefore a diagnosis of cloud boundaries from the thermodynamic profiles and a theoretical cloud model, such as the modified adiabatic technique listed above, have been used to generate LWC profiles. The two cases in Figure 1 represent situations where clouds can be diagnosed from the thermodynamic profiles relatively clearly. In general, however, cloud boundary determination from RH profiles is problematic because inherent uncertainties and non-representativeness in the RH field can lead to large scatter between the observed RH and cloud presence. For example, cloud radar and lidar observations show multi-layer clouds at a mid-latitude site less than 10% while the modeling technique described above yields about 40% (Table 1); thus we will simplify our analysis to focus purely on the single-layer cases.

[8] We have developed cloud boundary (base and top) retrieval algorithms using the methodology of *Löhnert and Crewell* [2003]. For this purpose, we have used 14 years of high vertical resolution radiosonde profiles (over 10 000 ascents) from Payerne, which is representative of a central European site. We diagnosed that 1812 of these profiles had single-layer liquid water clouds using the 95% RH threshold. We used this subset of radiosondes, using the modified adiabatic model of liquid water, as input for a radiative transfer model to compute the downwelling brightness

Table 1. Single-Layer Liquid Water Cloud Characteristics Derived From 941 Radiosondes Using the Modified Adiabatic Method and Simultaneously Observed by Microwave Radiometer, Cloud Radar and Lidar at the ARM Mobile Facility Deployment to the Murg Valley in Southwestern Germany in 2007[a]

	Clouds Modeled From RS	Observations at Sounding Times	Observations Whole Period
Number	941	28025	746164
Cloudy cases/%	69.3	50.6	49.9
Multi-layer clouds/%	39.1	8.2	7.5
Single layer water clouds (all/no drizzle)/%	30.2	42.4/23.2	42.3/23.0
Median LWP of single layer water clouds/gm^{-2}	27.4	78.8	76.7
Single layer water clouds with LWP > 500 gm^{-2}/%	1.0	6.5	6.4
Median thickness of single layer water clouds/m	238.0	300.0	300.0
Single layer water clouds:			
thicker than 500 m (all/no drizzle)/%	6.8	12.7/3.7	12.2/3.5
thicker than 1000 m (all/no drizzle)/%	2.3	7.0/0.7	6.4/0.8
Correlation between LWP and cloud thickness	0.97	0.35	0.30

[a] RS is radiosonde. Observations are at 15 min interval past launch. For better representativity also the observations at all times are given.

temperature; note that a ground-based profiling microwave radiometer typically makes 12–14 observations from 22 to 60 GHz. We then used the *Löhnert and Crewell* [2003] method, after applying random instrumental noise of 0.5 K on the computations, to construct algorithms to retrieve cloud base and top. The assumed instrumental noise of 0.5 K should be interpreted as a random absolute error of the instrument due to calibration offsets and long-term drifts. Application of these algorithms to the simulated observations reveals very little skill (Figure 2), with an RMS error between the retrieved and true cloud boundaries of more than 800 m with a correlation coefficient of 0.59 (0.71) for cloud base (top). This relatively poor result in determining the cloud boundaries from microwave observations is not surprising because the weighting functions are generally smooth and broad, and therefore have difficulties detecting sharp transitions such as cloud boundaries. Furthermore, even an indirect determination of cloud location using a RH threshold approach on a humidity profile retrieved from a profiling radiometer is limited because there are only 2 to 3 pieces of independent humidity layers that can be retrieved from microwave observations in the 22–60 GHz band [*Löhnert et al.*, 2009]. The addition of the 10 μm infrared radiometer (IR) improves the prediction of cloud base; however, these observations must account for the attenuation by water vapor between the cloud and the surface and the contribution from above the cloud if the LWP is below $\sim$60 g/m^2 when the cloud is semi-transparent in the infrared [*Turner*, 2007]. Finally it must be assumed that the temperature profile retrieved from the profiling radiometer is accurate.

[9] If we provide the cloud base height to the boundary retrieval algorithm (assuming cloud base from there is perfect or alternative ceilometer is available), there is a significant improvement in the retrieval of cloud top height with the RMS reducing from more than 800 m to approximately 70 m with the correlation between the retrieved and true cloud top being nearly perfect (Figure 2). However, the median cloud thickness of the simulated observations is 293 m and the RMS difference implies a median uncertainty in the cloud thickness of 27%. Additionally, these results must be interpreted w.r.t. the modified adiabatic assumption, where we have a good correlation (0.97) between cloud thickness and LWP (Figure 2). The correlation between cloud thickness and LWP determined from real observations using a synergistic sensor approach [*Illingworth et al.*, 2007] at a mid-latitude site is much poorer (0.35; Table 1) and thus, in reality, we expect significantly higher uncertainty in cloud top retrieval.

4. LWC Profiles

[10] Our main objective is to analyze the information content in microwave observations concerning the vertical distribution of liquid water within the cloud. The hypothesis is that the temperature dependent emission by liquid water (as a function of height) and the differential absorption of liquid water at different frequencies provides enough information to retrieve LWC with some skill. As we have already demonstrated the low skill at determining the vertical position of the liquid water from passive microwave zenith observations, we simplify the problem and assume that the retrieval algorithm knows both the base and top of the single-layer cloud. We used two simplified profiles of liquid water in this sensitivity study: a modified adiabatic profile and a profile of constant LWC. Figure 1 illustrates that at frequencies between 20 and 60 GHz the modified adiabatic profile produces slightly higher brightness temperatures than the constant LWC profile; this is because the emission is stronger at colder temperatures and there is more mass higher in the cloud where it is colder. The brightness temperature (T_b) difference between the two LWC profiles is a maximum of approximately 0.1 (0.5) K for the average (thick) cloud. These T_b differences are close to the assumed noise level of $\sim$0.5 K of a typical ground-based microwave radiometer (see section 3).

[11] The optimal estimation framework [*Rodgers*, 2000] provides a method for calculating the degrees of freedom for signal (DGF), which is equivalent to the number of independent pieces of information in the observations, in the retrieval of the profile of LWC. The method utilizes the covariance of *a priori* profiles of LWC with altitude, $\mathbf{S}_a$, together with the covariance matrix for the observations, $\mathbf{S}_e$, and the Jacobian of the forward model with respect to

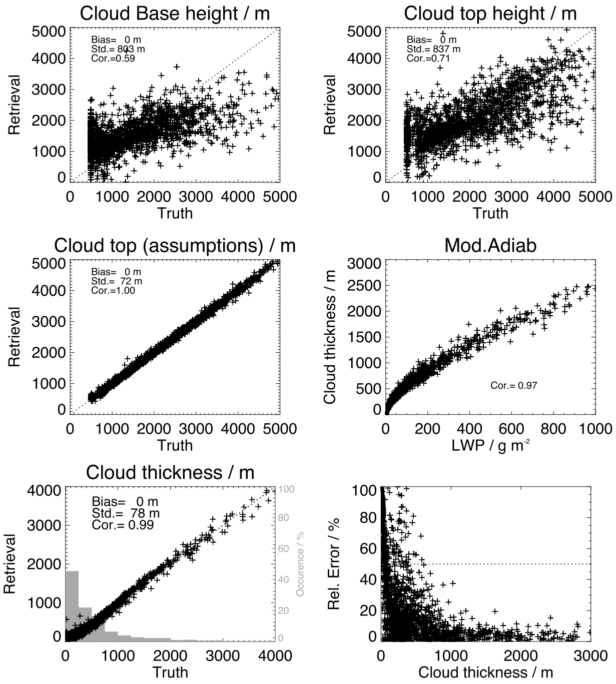

Figure 2. Retrieval results for (a) cloud base height and (b) cloud top height derived from simulated 14-channel microwave profiler observations for 1812 profiles of single-layer water clouds. The retrieved results for (c) cloud top height and (e) cloud thickness (the occurrence of cloud thickness is indicated in grey) include the specification of cloud base height as an additional input parameter into the retrieval algorithm. (d) The relationship between LWP and cloud thickness within the training data set that uses the modified adiabatic model and (f) the resulting relative error of cloud thickness given cloud base information.

perturbations in the LWC profile, $\mathbf{K}$, to provide the error covariance of the optimal solution, $\mathbf{S}$, as $\mathbf{S} = (\mathbf{K}^T\mathbf{S}_e^{-1}\mathbf{K} + \mathbf{S}_a^{-1})^{-1}$.

[12] The diagonal elements of $\mathbf{S}$ provide an estimate of the mean quadratic error of LWC, whereas the off-diagonal elements provide information on the correlation of retrieval errors of LWC at different heights. The averaging kernel matrix $\mathbf{A}$, which is computed as

$$\mathbf{A} = \mathbf{S} \cdot \left(\mathbf{K}^T\mathbf{S}_e^{-1}\mathbf{K}\right),$$

is the sensitivity of the retrieved to true state, or in other words, $\partial \mathrm{LWC}_{\mathrm{retrieved}}/\partial \mathrm{LWC}_{\mathrm{true}}$. The trace of $\mathbf{A}$ is the degrees of freedom for signal (independent pieces of information) in the observations. To simplify the analysis, we have assumed that the microwave observations are uncorrelated and that the uncertainties in the *a priori* data at different levels are also uncorrelated; this makes $\mathbf{S}_e$ and $\mathbf{S}_a$ diagonal matrices. The diagonal elements of $\mathbf{S}_e$ have been set to $(0.5\ \mathrm{K})^2$, with 0.5 K representing the noise level of the observed $\mathrm{T_b}$ measurement. The components of the error covariance matrix of the solution $\mathbf{S}$ have been converted to relative error in LWC (in %).

[13] Figure 3 shows the trade-off between the relative error in LWC and DGF for the average and thick liquid water clouds in Figure 1. The different points represent different uncertainty levels of the a priori profile ($\mathbf{S}_a$), where very small uncertainties in the a priori result in a low number of DGF while large uncertainties in the a priori result in larger DGF. If only channels from 22–32 GHz are considered, Figure 3 clearly shows that there is essentially only 1 piece of independent information in the retrieval; this single piece of information is the LWP and implies that there is no information in the observation about the vertical distribution of LWC for either average or thick clouds. However, if higher frequencies (e.g., 90 and 150 GHz) are additionally included in the retrieval, then there is some limited amount of information on the profile of LWC in the thick cloud with resulting LWC accuracies ($\mathbf{S}$) on the order of 30–100%, but there is still only one piece of information on the profile of LWC in the average cloud. Note, that in case of the thick cloud, a small amount of additional information is obtained when using 22–32 GHz and 51–59 GHz channels simultaneously. However, an accurate a priori knowledge of the temperature profile is essential in this case. Summarizing: for both average and thick clouds,

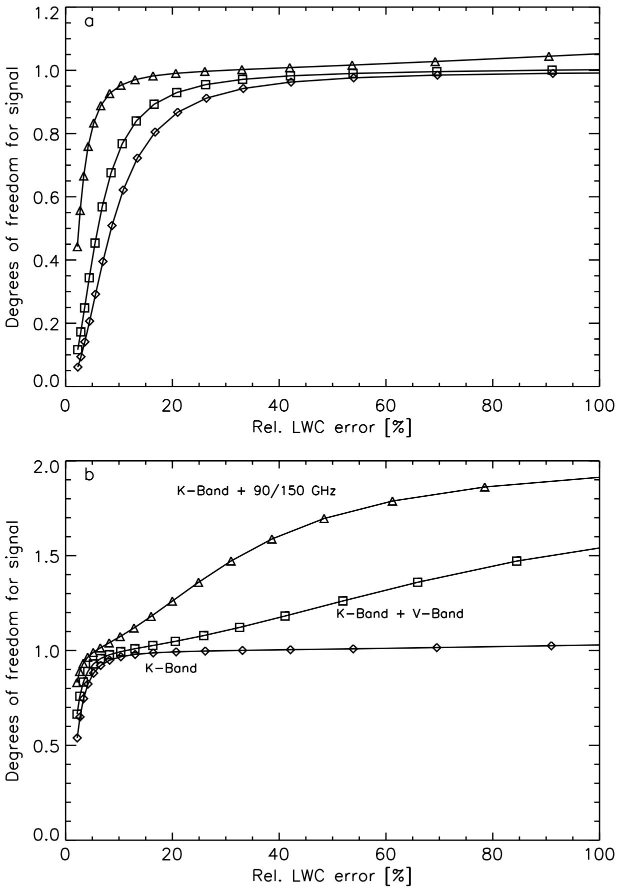

Figure 3. Degrees of freedom for signal as a function of the relative LWC error for (a) average and (b) thick clouds diagnosed from radiosondes in Figure 1. The two curves in each panel differentiate between seven K-band channels only (22 – 32 GHz) (diamonds), K-band channels plus 7 V-Band channels (51 – 59 GHz) (squares) and these channels plus 90 and 150 GHz channels (triangles).

though, the addition of the higher frequency channels adds more information to the retrieval of liquid water.

5. Conclusion

[14] We have investigated the ability to retrieve profiles of LWC from passive zenith-pointing microwave radiometer observations. We have demonstrated that there is little skill in the retrieval of the cloud boundaries from these observations, and even if the cloud base is provided that there is still significant uncertainty (78 m error at a mean cloud thickness of 293 m) in the retrieved cloud thickness. Note that these results are explicitly valid for the modified adiabatic model only and may be significantly higher in reality. Furthermore, we have analyzed the information content in the microwave observations to quantitatively determine the number of independent pieces of information that exist for the LWC profile under conditions where the cloud boundaries are known, there are no errors in the forward radiative transfer model, and that the radiometric uncertainties in the observations are uncorrelated and typical. For clouds of average LWP (order 100 g/m^2) there is NO information in the microwave radiometer observations on the vertical distribution of liquid. For a thick non-precipitating liquid cloud (order 500 g/m^2), a typical microwave profiler that makes observations in the 22–32 GHz range also has NO information on the profile of LWC. However, if the radiometer is equipped with higher frequency channels (e.g., 90 and 150 GHz), then there is limited information (up to 2 independent pieces of information) in the thick cloud but the uncertainty in the retrieved LWC is between 30% and 100%. Thus we conclude that the profiling of LWC using passive zenith microwave radiometers can only be done in very limited situations where the clouds have large LWP and observations at higher frequencies are available. However, the addition of new information, such as multi-angle T_b observations from multiple coordinated microwave radiometers (e.g., using a tomographic solution) or profiles from active remote sensing data (e.g., from cloud radar or lidar), to the multi-channel microwave radiometer observations may yield more independent pieces of information on the LWC profile.

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