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Discrimination of cloud and rain liquid water path by groundbased polarized microwave radiometry

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Abstract. We propose a new approach for groundbased remote sensing of liquid water path (LWP) in the presence of precipitating clouds. Dual polarized groundbased microwave radiometers are capable of detecting the unique scattering signature of nonspherical precipitation sized particles. This polarization signal is only produced by the precipitation particles for which the brightness temperature emission has a different sensitivity to LWP than the smaller cloud drops. By using the information that is contained in the polarization difference of the downwelling brightness temperature the cloud and rain liquid water fractions can be estimated independently. Future retrieval algorithms based on our proposed approach will enable the detection of small precipitation fractions in thick clouds and also allow for estimates of cloud and rain LWP in raining conditions.

Introduction

The path-integrated liquid water content (liquid water path, LWP) is of considerable interest to the meteorological community for a number of applications, ranging from climate research to radio telecommunications. Measurements of LWP can be provided by different methods, such as satellite imagery, cloud radar, and groundbased passive microwave radiometry. The latter is the most precise method for LWP estimation over land surfaces. Thus, groundbased microwave radiometers are used operationally for the remote sensing of integrated water vapour and LWP, offering the capability of performing measurements in nearly all types of weather conditions [*Güldner and Spänkuch*, 1999]. The main limit on their capabilities is the occurence of rain, which reduces the precision of LWP retrievals by current microwave methods.

Recently, the EU-project CLIWA-NET (BALTEX cloud liquid water network, [*Crewell et al.*, 2000b]) has been established, aiming at the evaluation and improvement of cloud parametrizations in weather and climate forecast models. CLIWA-NET includes measurement campaigns with multichannel microwave radiometers. Participating state-of-the-art radiometers like the 22-channel MICCY (MIcrowave radiometer for Cloud Cartography) instrument simultaneously provide brightness temperatures with 1 K absolute precision, a RMS of 0.2 K, and a beamwidth of 0.9 degree for all channels between 22.235 and 90 GHz [*Crewell et al.*, 2000a]. Cloud process studies will be carried out with this instrument to obtain further insight into the microphysical processes within clouds.

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The retrieval techniques for LWP from brightness temperatures (TB) at microwave frequencies used so far are limited to cloud LWP (C-LWP) in the absence of rain LWP (R-LWP). The reason for this limitation is the varying sensitivity of emitted TB with drop size. Above a certain radius r the dependence of TB on radius slightly exceeds being proportional to r^3. The LWP (proportional to the third moment of the drop size distribution) is no longer unambiguously coupled to the TB signal if such large drops are mixed with smaller cloud droplets. As a consequence, a LWP retrieval in raining clouds is highly ambiguous with current methods. This fact not only reduces the operational utility if raining conditions are masked out, but also adds a possible error source to LWP retrievals in many clouds.

Radar measurements do not offer an advantage when cloud and rain particles simultaneously occur because the sensitivity of the radar signal to drop size is even worse: The radar reflectivity factor is proportional to the sixth moment of drop radius. Thus the signal will always be dominated by the largest drops in the sampled volume [*Fox and Illingworth*, 1997]. While a change of the drop size distribution (DSD) from a cloud drop spectra to a convective rain drop size distribution will increase the TB signal of a microwave radiometer by a factor of 2 to 3, the reflectivity factor will change by several orders of magnitude. Thus LWP values derived from the radar reflectivity factor depend more critically on the assumption of the true drop size distribution than those derived from microwave radiometry.

Up to now passive groundbased microwave measurements only used the brightness temperature information, which alone cannot deal with the ambiguity introduced by large raindrops within the cloud. New findings from radiative transfer models [*Czekala and Simmer*, 1998] suggest a possibility to resolve this size dependent ambiguity by measuring a second signal that is also related to raindrop size: The polarization difference (PD), which is defined as the amount of linear polarization $PD=TB_v-TB_h$. This scattering induced signal depends on drop deformation, and hence on drop size. The modeling of somewhat realistically shaped nonspherical rain drops has recently become possible due to advances in single scattering methodology and computer efficiency.

The aim of this paper is to propose a new approach for LWP retrieval in the presence of raining clouds by adding polarization information to the current unpolarized measurement systems and retrieval methods. We will illustrate the physical processes which relate the TB and PD signal to the varying partitioning of total LWP between cloud and rain. We will show how the information content due to the unique scattering signature of nonspherical rain drops can be used to improve the accuracy of widely used LWP retrieval techniques. However, we do not propose a complete retrieval algorithm for a specific instrument. At this stage we focus on explaining the general method and its possible advantage for obtaining a LWP retrieval without restriction to non-raining clouds.

Such improvements are expected to have significant impact on future operational services as well as cloud process studies which may be based on the new retrieval approach. Such studies offer the opportunity to gain knowledge about internal structures and cloud microphysical properties. The onset of precipitation, specifically the transition from small particle dominated cloud DSD to precipitation sized DSD (which is very important in cloud parametrizations in numerical weather prediction models), should be detectible. A systematic bias in LWP retrieval is expected if rain drops are not considered.

Polarization signal

The shape of raindrops is known to be nonspherical due to wind stress, surface tension and internal hydrostatic pressure. *Chuang and Beard* [1990] describe the shape of raindrops falling at terminal velocity by a series of Chebyshev polynomials. The radiative transfer results of *Czekala and Simmer* [1998] revealed remarkable differences between the effects of (commonly assumed) spherical and oblate spheroid shapes on polarized microwave brightness temperatures. The latter shape is used as a close approximation to the Chebyshev shape. While the brightness temperature (TB, defined as the average brightness temperature calculated from the vertically and horizontally polarized brightness temperatures according to $(TB_v+TB_h)/2$) showed only a weak dependence on the hydrometeor shape, the polarization difference for downwelling radiation (as seen by a groundbased sensor) was altered from small positive values (always well below 2 K) in the case of spherical raindrops to large negative values (down to -15 K) in the case of oblate spheroids. The polarization in both cases is only produced by drops that are large enough (compared to wavelength) to cause a significant amount of scattering.

The precise amount of negative PD varied with the optical thickness within the observed volume. Specifically, the amount of precipitation, the chosen frequency, and the elevation angle of the hypothetical groundbased observation, and the cloud top and cloud base height controlled the amount of PD predicted by the radiative transfer model. The theoretically predicted signal of negative PD arising from precipitation sized water drops has recently been validated with groundbased measurements [*Czekala et al.*, 2000].

Model calculations

The above mentioned studies [*Czekala and Simmer*, 1998] imply that polarization measurements might be exploited to learn more about the amount of precipitation sized particles within clouds. In order to illustrate the radiometric sensitivities to the partitioning of water between cloud and rain in a clear and simple way, we carried out a sensitivity study. Within an atmospheric column with a fixed vertical profile of temperature and humidity we positioned a cloud between 1 and 2 km height with a specified fraction of cloud water and rain water. For reasons of simplicity we assume a constant vertical profile of cloud and rain water within the cloud. This model is meant to simulate situations like a viewing of an isolated rain event from outside the rain cell or a cloud with no observed surface rain rate. Precipitating clouds with no surface rain rate frequently occur when precipitation starts to evolve within the cloud, but evaporates below the cloud base before reaching the surface.

Cloud and rain fractions were varied independently so that the resulting C-LWP ranges from 0.0 kg/m^2 to 2.5 kg/m^2 and the R-LWP from 0.0 kg/m^2 to 2.5 kg/m^2. The total LWP simply is the sum T-LWP = C-LWP + R-LWP. All possible combinations of both kinds of LWP were calculated, resulting in total LWP ranging from 0.0 to 5.0 kg^{2}m. Although the pure rain cases without any C-LWP make sense for observations where the rain shaft of isolated showers is observed against a clear sky background, some of the C-LWP/R-LWP combinations (especially those with large C-LWP) are certainly unrealistic for the given vertical cloud extension. Nevertheless, the complete coverage of all possible combinations is well suited for explaining the nature of the signal expected from raining clouds, even in the presence of severe rain events.

The cloud LWP was modeled with a DSD given by a modifed gamma distribution with a modal radius of 5.5 micron and an integration interval from 0.1 to 100 μm. The rain LWP was produced by a Marshall-Palmer distribution and an integration interval from 100 μm to 5 mm. Oblate spheroids with a fixed orientation and a size dependent aspect ratio were used for rain, spheres for cloud particles. The T-Matrix code from Mishchenko [*Mishchenko*, 2000] was used to calculate the amplitude scattering function for these particles. The surface emission, which has hardly any effect on the downwelling radiation, was set to 0.9, a reasonable value for land surfaces.

Figure 1 shows the brightness temperature obtained at 19 GHz with an elevation angle of 30.7 degrees for a hypothetical groundbased observation. The amount of LWP due to rain is indicated by the size of the symbols. Smallest symbols are assigned to zero R-LWP, thus the lower line in Fig. 1 indicates the result for clouds without rain. The reverse situation (all LWP is made from R-LWP) is indicated by the upper line which shows a stronger increase with LWP and a saturation at large LWP values where the atmosphere (sum of gas and liquid constituents) becomes opaque. It is obvious from the different slopes of both extreme cases that a TB measurement can only be converted to a LWP if the

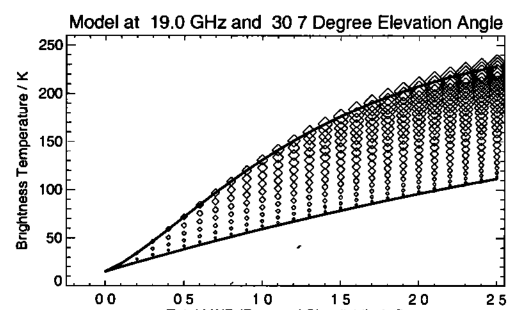

Figure 1. Modeled TB versus total LWP. The R-LWP fraction within the total LWP is indicated by the symbol size. The extreme cases of pure cloud (lower line) and pure rain (upper line) indicate the higher sensitivity of TB to rain.

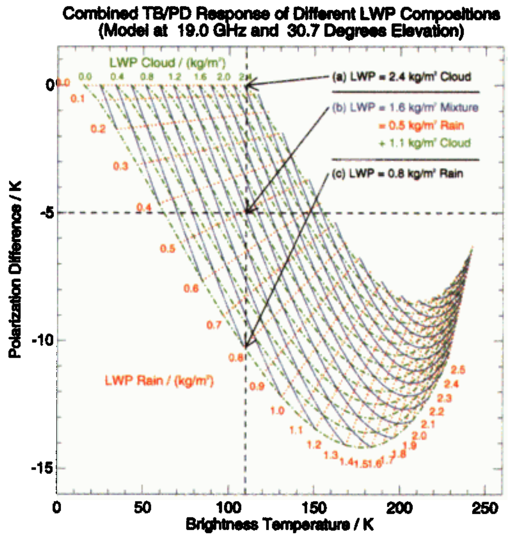

Figure 2. Resulting TB and PD for different combinations of C-LWP and R-LWP at 19 GHz. For more details see text.

mixture of rain and cloud fraction is known. Realistic cloud conditions are represented by a point somewhere between both limiting cases.

Proposed Retrieval Method

Combining the information of TB and PD that refer to a specific combination of cloud LWP and rain LWP into one diagram (Fig. 2) shows that the information contained in the two signals is complementary. Figure 2 gives the response of all calculated mixtures of cloud and rain LWP in terms of their radiative response. Isolines of constant LWP are given for three different LWP variables: Dotted red lines indicate calculations with the same R-LWP but varying C-LWP, dash-dotted green lines show the results for same C-LWP, but with varying R-LWP. The solid blue lines are lines of constant total LWP, which may be formed by any mixture of C-LWP and R-LWP.

Pure cloud conditions are indicated by the uppermost horizontal dotted red line (no rain fraction). The increase in cloud liquid water path from 0.0 to 2.5 kg/m^2 leads to an increase in the corresponding TB, but no polarization is produced. Pure rain conditions (in the absence of cloud) produce the lower limit of the PD signal (indicated by the lowest dash-dotted green line). When mixing rain into the cloud, increasing amounts of rain LWP shift the horizontal line of pure cloud response towards negative PD. However, the lines of constant rain LWP do not remain horizontal. This means that a variation of C-LWP in the presence of considerable R-LWP (e.g. 0.7 kg/m^2) not only results in a change of TB, but also affects the PD signal: Increasing amounts of cloud water damp the PD. With further increase of R-LWP the PD signal ceases to increase in amplitude (beginning saturation due to increasing optical thickness) and then drops back towards zero. It is worth while to note that in the region of initial saturation (beginning of curvature in the dash-dotted green isolines of the C-LWP) the isolines of C-LWP and R-LWP remain roughly orthogonal. This means that C-LWP and R-LWP affect the TB/PD response in different ways, which is a prerequisite for a simultaneous retrieval of both properties. If the isolines of both quantities were parallel then a distinction of both quantities would be impossible. This would be the case when assuming spherical particles for all kinds of hydrometeors since spherical rain produces a TB signal with a different sensitivity than cloud drops and only very small positive PD (always below 2 K).

The advantage of our proposed new approach of LWP retrieval by using the PD signal in addition to only the TB signal is obvious when looking at a hypothetical measurement of 110 K brightness temperature and -5 K polarization difference (indicated by the dotted black lines in Fig. 2). The TB result of 110 K refers to 2.4 kg/m^2 liquid water path when assuming a pure cloud particle size distribution (retrieval (a), uppermost dotted red line) or 0.8 kg/m^2 liquid water path when assuming a composition of pure rain without clouds (retrieval (c), lowest dash dotted green line). These numbers give a good estimate about the uncertainty in LWP retrieval in the presence of raining clouds when only TB measurements are used. In comparison, when the supplementary PD information is used (measurement (b) in Fig. 2) the total LWP is reliably estmated to be 1.6 kg/m^2. Furthermore, we are now able to separate the LWP between the fraction of cloud water (1.1 kg/m^2) and the fraction of rain water (0.5 kg/m^2).

Discussion

The above results are idealized model calculations that neglect the precise vertical distribution of the hydrometeors and use simplified cloud microphysical assumptions. For example the variability of drop size distribution functions and the effect of the melting layer need to be considered in more detail before a practical retrieval scheme can be based upon such radiative transfer calculations. In order to assess to impact of drop size distribution on the above calculations we re-calculated the results from Fig. 2 with the Willis drop size distribution. This distribution is a modified Gamma distribution (alpha=2.5) with significantly less drops at larger radii. The maximum difference in rain generated PD reaches -1.5 K (with very similar TB results). These differences are obtained for the high rain LWP of 1.6 kg/m^2. At smaller rain amounts the differences are much smaller. At 30 GHz the results agree even better, at 40 GHz there is almost no difference between the results for the two drop size distributions. This suggests that multifrequency observations re-

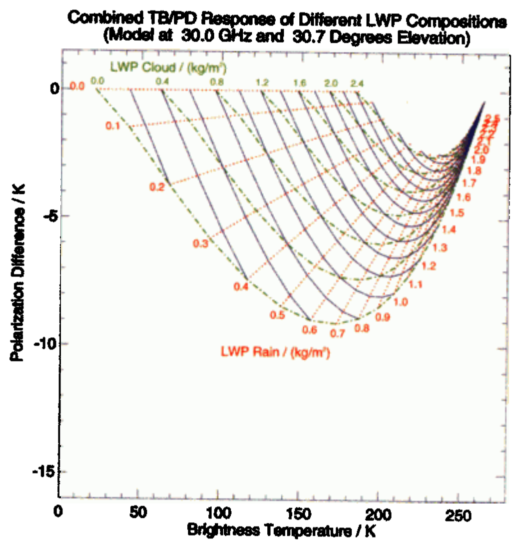

Figure 3. Increased sensitivity of PD to R-LWP at 30 GHz (all other parameters as in Fig. 2).

solve the ambiguity introduced by the unknown drop size distribution.

Variations in water vapor and temperature profile will also affect our numerical results, mainly by an additional shift along the TB axis. However, the results presented here clearly illustrate the profit of adding the polarization signal that is produced by nonspherical precipitation sized particles to the retrieval process. In addition, multifrequency observations will help to overcome uncertainties that may arise from unknown drop size distributions. Modern multichannel microwave radiometers [*Solheim et al.*, 1998; *Crewell et al.*, 2000a] can determine the temperature (RMS $< 2\,\mathrm{K}$) and humidity (RMS $< 0.3\,\mathrm{gm}^{-3}$) profile in the cloudy (non-raining) troposphere. Even though the applied retrieval algorithms normally fail in the presence of precipitation, there is still residual information about atmospheric temperature contained in the observations. Estimating the cloud base temperature (even with limited accuracy and lacking vertical profile) will significantly improve the LWP retrieval.

For this purpose, a final retrieval scheme may also rely on secondary information, such as surface temperature, cloud base height, and humdity profile data from numerical weather prediction models. For semi-transparent situations (less than $1.5\,\mathrm{kg/m^2}$ R-LWP at 19 GHz) the vertical distribution of the hydrometeors is of minor importance and will not degrade the general dependence of TB and PD on the different LWP fractions.

Figure 3 shows the resulting TB/PD response at 30 GHz (instead of 19 GHz used in Fig. 2). At higher frequencies the saturation of the PD signal begins at lower rain rates compared to the 19 GHz results. However, the sensitivity of PD to small amounts of R-LWP is significantly increased. This is partly due to the change in the size parameter (the ratio of particle size to the wavelength under consideration). Another reason is the increased optical thickness due to the frequency dependence of the refractive index.

A lower total optical thickness (e.g. at 10 GHz) decreases the dynamic range of the TB signal, but prevents saturation of the PD and TB signal. Since the accuracy of TB measurements is in the range of 1 K this reduction of the TB signal range is not a severe problem. The insensitivity of 10 GHz observations to smaller drops leads to a total signal that is dominated by the rain generated PD.

Similar changes in sensitivity to R-LWP can also be achieved by variation of the observation angle. Since the total optical thickness increases with increased geometrical path lengths through the atmosphere at lower elevation angles, the saturation of the PD is observed at different R-LWP fractions. This effect is not the same as a variation in frequency because elevation angle affects the radiation only by changing the optical thickness (due to varied path length). Changes in frequency induce a similar change in optical thickness, but additionally change the ratio of particle size to wavelength and thus lead to different single scattering parameters.

Finally, the development of practical retrieval methods also needs to incorporate instrument noise and antenna characteristics, thus leading to instrument specific algorithms. Current research microwave radiometers have a sufficiently narrow beamwidth (less than 1 degree) to reveal cloud inhomogeneities in process studies [*Crewell et al.*, 2000a]. With an absolute accuracy of 1 K and a relative calibration of the PD to 0.2 K with clear sky conditions it will be possible to detect the discussed signal.

Conclusions

The presence of precipitation sized rain drops within clouds inhibits a precise remote sensing of LWP by currently used groundbased microwave methods. The brightness temperature is related to LWP, but if the drop size distribution is unknown it is not possible to partition the LWP between cloud droplets and rain drops using such measurements. We have presented a new approach to discriminate between the different contributions to total LWP by exploiting the additional information contained in the negative polarization difference caused by nonspherical rain drops. This signal depends on the drop size and therefore reduces the uncertainty that arises from the unknown partitioning of total LWP between the cloud and rain fractions of the drop size distribution. Future retrieval algorithms that use simultaneous measurements of brightness temperatuıe and polarization difference will allow for a more accurate retrieval of total liquid water path. In addition, we expect that it will be possible to estimate independently the contributions by rain drops and cloud drops to the total LWP. The uncertainties that may arise from insufficient knowledge of cloud microphysics and vertical distribution of the hydrometeors will be partly mitigated by the additional information that is gained by multifrequency and making multiangle measurements.

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