The Synergistic Use of Passive Microwave and Infrared Observations to Retrieve Liquid Water Cloud Properties

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ABSTRACT

There are very few reliable observational methods that accurately measure Liquid Water Path (LWP) in **low-LWP** (0-100 gm^{-2}) clouds. However, it is well known that these clouds have a very high radiative impact in both the shortwave and longwave portions of the spectrum. To achieve an accurate measurement of LWP, the combination of passive microwave (MW) and infrared (IR) observations offers a high and largely unexploited potential for cloud property retrieval of effective radius, cloud optical depth and LWP. Here we propose a method combining typical microwave radiometer channels with two broadband infrared thermometer channels (IRT) to improve LWP accuracy. Simulations are shown for LWP values below 40 gm^{-2} which demonstrate that two IRT channels in addition to two standard microwave channels can reduce the LWP error from ~50% down to ~20%.

1. IMPORTANCE OF LOW-LWP CLOUDS

Long-term observations at different sites worldwide reveal a common feature concerning liquid clouds: the dominant occurrence of LWP with values smaller than 100 gm^{-2} (Fig. 1). If the two Atmospheric Radiation Measurement (ARM) program sites at the North Slope of Alaska (NSA) and Southern Great Plains (SGP) are considered, maximum occurrence of LWP is around 40 gm^{-2} or less. These clouds have a maximum effect on cloud radiative forcing (Fig. 2) and thus accurate retrieval of these clouds and their variability is of high importance for cloud-radiative impacts in the climate system.

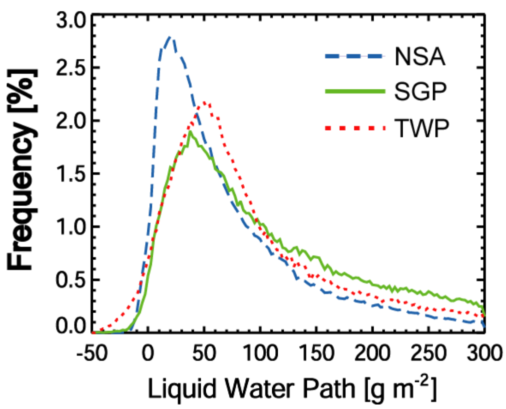

Figure 1*: Frequency distribution of LWP at the ARM sites NSA, SGP and TWP. Source: [1].*

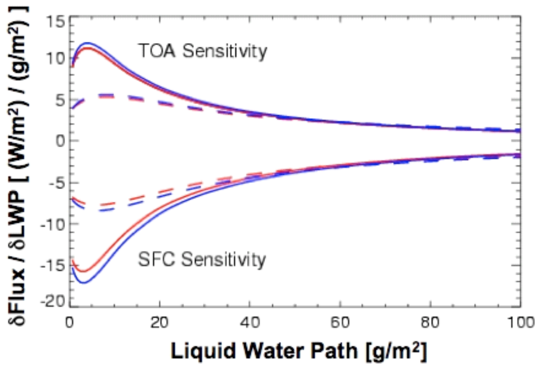

Figure 2*: Sensitivity of top of the atmosphere TOA and surface SFC shortwave radiative fluxes to LWP of a liquid cloud with effective radius of 6µm (solid) and 12µm (dashed), blue: mid-latitude winter, red: mid-latitude summer. Source: [2]*

2. MICROWAVE POTENTIAL

It is well known that ground-based microwave radiometers present the most reliable method for deriving accurate and high temporal resolution time series of LWP. For standard two-channel radiometers measuring at 23.8 and 31.4 GHz overall accuracies of LWP are expected to be on the order of ~30 gm^{-2} when mean LWP ranges are on the order of ~150 gm^{-2} corresponding to a relative accuracy of ~20% [1,3]. Accuracies can be reduced to the order of 10% when a 90 GHz channel is added, which is on the order of 5-times more sensitive to liquid water than frequencies in the 30 GHz microwave window [3]. However, LWP errors using standard microwave radiometers for LWP smaller than 50 gm^{-2} can be on the order of 50% and higher because the typical sensitivity of a standard two-channel radiometer is approximately 30 gm^{-2}. At these low LWP amounts cloud temperature, water vapour effects and instrumental uncertainty make the retrieval results unsatisfactory. An option in this LWP region is again to include 90 GHz measurements and/or passive infrared measurements. However, it needs to be noted that current gas absorption models differ by several Kelvin at 90 GHz which can lead to bias errors also for low LWP values.

3. INFRARED POTENTIAL

Turner [4] demonstrated that a LWP relative error of ~4% is possible in the low-LWP range below 50 gm^{-2} when a standard two channel microwave radiometer and observations from a high-resolution infrared spectrometer (AERI: Atmospheric Emitted Radiance Interferometer) are combined within an optimal estimation retrieval scheme. However, the AERI instrument is an instrument that generally requires sophisticated calibration, near-real-time monitoring and careful data post-processing. In this study we show that two “easy-to-handle” infrared thermometers (manufactured by Heitronics) can also significantly enhance the LWP accuracy in critical low-LWP regions where typical MW radiometers do not show satisfactory efficiency.

In order to address this issue, the new microwave profiler HATPRO G2 (Humidity And Temperature PROfiler Generation 2) of the University of Cologne (manufactored by Radiometer Physics) has been equipped with two broadband infrared radiometers (IRT), in addition to the 7 channels between 22 and 32 GHz and 7 channels between 51 and 58 GHz that were already part of the HATPRO. The first IRT has a maximum sensitivity at ~11 µm (bandpass 10.2 – 11.9 µm) and the second one a maximum sensitivity at ~12 µm (bandpass 11.1 – 12.8 µm).

In order to assess the effect of IRT brightness temperature on LWP, we have simulated microwave and infrared brightness temperatures using data from the ARM mobile facility deployment in the Black Forest in 2007. Between October 22 and November 4 the cloud situation was very frequently dominated by low-level liquid stratus clouds occurring between 500 and 1000 m height. For this time period AERI data was carefully post-processed and – in combination with microwave measurements at 23.8 and 31.4 GHz – used to retrieve cloud optical depth, effective radius and LWP. These retrievals, in addition to the profiles of temperature, pressure and humidity from four-times daily radiosonde ascents, were used to calculate microwave and infrared brightness temperatures. More than 5000 retrievals were available from which we randomly chose 730 cases to perform the following sensitivity studies and proto-type retrieval development. Although these retrievals do not necessarily represent the “ground truth”, they do help us in interpreting the MW and IRT brightness temperature signals of low-LWP clouds.

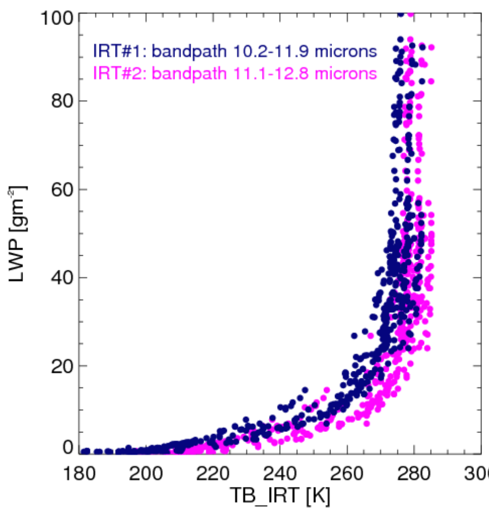

***Figure 3**: LWP as a function of the two IRT brightness temperatures*

Following the above described simulations, both IRT brightness temperatures show a significant sensitivity to LWP from about 5 to 20 gm^{-2} (Fig. 3). At values above 20 gm^{-2} liquid clouds start to show saturation effects in both channels leading to a strongly reduced LWP-sensitivity. At these larger LWP amounts, the cloud base temperature dominates the signal. However if the difference of both IRT brightness temperatures is plotted against the LWP, a clear signal can still be indentified up to 40-50 gm^{-2} (Fig. 4). Thus an accurate LWP retrieval should be possible up to this LWP threshold. Note that the scatter in the brightness temperature difference plot versus LWP is due to the sensitivity to the effective radius of the cloud droplets.

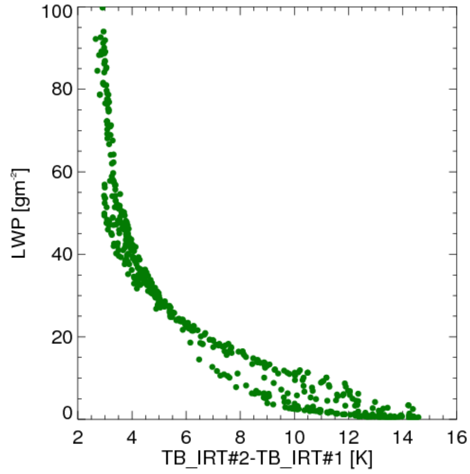

***Figure 4**: LWP as a function of the difference of the two IRT brightness temperatures.*

4. RESULTS OF RETRIEVAL PROTO-TYPE

The above-mentioned data have been used to create retrieval algorithms on a multi-linear regression basis following [2]. 50 % of the data were used for statistical minimization and the other 50 % were used for retrieval testing. The RMS errors of LWP for different LWP ranges and different channel combinations are shown in Tab. 1.

***Table 1**: Absolute (in gm^{-2}) and relative (in %) RMS accuracies of LWP for different channel combinations and LWP ranges. Note that the relative RMS was calculated by dividing the absolute RMS by the mean LWP values of the corresponding LWP range.*

Channel combination	RMS LWP < 40 gm^{-2}	RMS LWP < 100 gm^{-2}	RMS all LWP
23.8 + 31.4 GHz	6.2 (52 %)	9.1 (37 %)	12.4 (19 %)
IRTs only	2.5 (21 %)	9.2 (37 %)	42.3 (64 %)
23.8 + 31.4 GHz + IRTs	2.1 (18 %)	7.1 (29 %)	12.9 (20 %)
23.8 + 31.4 + 90 GHz	4.4 (37 %)	5.2 (21 %)	5.8 (9 %)
23.8 + 31.4 + 90 GHz + IRTs	2.1 (18 %)	4.6 (19 %)	5.4 (8 %)
Mean LWP [gm^{-2}]	11.9	24.7	65.7

When retrieving LWP in the range below 100 gm^{-2} Tab. 1 shows how important the inclusion of the two IRT brightness temperatures can be. Especially if no 90 GHz channel is included the IRTs can be very beneficial, e.g. for LWP smaller than 100 gm^{-2} the RMS error can be reduced by ~8 % while for LWP below 40 gm^{-2} the error can even be reduced by more than 30 %. This demonstrates the high value of including IRT channels to microwave channels for low-LWP retrieval. For values below 40 gm^{-2} the IRTs perform excellent themselves (21 % accuracy), however LWP is highly variable in time and space so that alternating small and large values of LWP may appear on very short time or space scales. Thus, a combined retrieval is strongly desired to guarantee accurate LWP values throughout all LWP ranges.

The advantage of a 90 GHz channel for LWP retrieval must again be underlined in this case study. Adding a 90 GHz channel to a standard two-channel MW-radiometer results in 50% more accurate LWP retrievals. However, especially for the low-LWP cases below 40 gm^{-2}, an additional pair of IRTs can still significantly increase the retrieval accuracy.

5. OUTLOOK

The results obtained in this study show that the combination of microwave and broadband infrared channels show potential for significantly increasing LWP accuracy of liquid clouds with the highest sensitivity on cloud radiative forcing. We are currently testing the "robustness" of our results by creating a larger and more representative data set of low-LWP clouds. Additionally we will take into account detailed calibration issues of the IRTs and examine the influence measurement errors of larger than 0.5 K (as assumed here) have on our results. If these results can be generalized, the addition of IRT instruments to a LWP microwave radiometer should become a standard. First observations by HATPRO-G2 are currently undertaken and allow the assessment of real data.

The detection of small amounts of LWP is not only important for the assessment of cloud radiative effects but also for the profile retrieval of temperature and humidity from remote sensing instruments. Especially when using spectrally highly resolved infrared or lidar measurements it is of high importance to know a priori if even small amounts of liquid water are present.

Based on this work and the work of [5], where the potential of deriving temperature and humidity profiles for a MW & IR combination in clear sky cases has been shown, we are currently building a retrieval approach for combing HATPRO and AERI to synergistically retrieve profiles of temperature and humidity as well as mean cloud layer optical depth, effective radius and LWP. This work is currently on-going and first results will be discussed at ISTP 2009.

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