A Refined Two-Channel Microwave Radiometer Liquid Water Path Retrieval for Cold Regions by Using Multiple-Sensor Measurements

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***Abstract*—Traditional two-channel microwave radiometers (MWRs) are widely used to measure cloud liquid water path (LWP); however, the retrieved LWPs are subject to relatively large uncertainties, particularly for low LWP clouds. By reformulating the statistical retrieval method with clear-sky measurements as a reference, a simple method is presented to significantly reduce uncertainties in the LWP retrieval due to errors in MWR calibration, uncertainties in the absorption coefficients of atmospheric gases, and variations in the vertical profiles of temperature and pressure. The improvement is illustrated by comparing the statistics of the erroneous clear-sky LWP for the Department of Energy's Atmospheric Radiation Measurement Program Climate Research Facility observations at the North Slope of Alaska site and by comparing LWP retrieved with a multiple-sensor algorithm and LWP retrieved based mainly on MWR measurements. This letter also demonstrates the importance of using correct water cloud temperature and temperature-dependent water absorption coefficients for MWR LWP retrieval over cold regions. This approach can be easily implemented for combined MWR, ceilometer, and surface meteorological measurements.**

***Index Terms*—Liquid water path (LWP), LWP retrieval, microwave radiometers (MWRs), multiple-sensor LWP algorithm.**

I. INTRODUCTION

GROUND-BASED two-channel microwave radiometers (MWRs) have a long history in the remote sensing of atmospheric liquid water and water vapor [1], [2]. Liquid water paths (LWPs) derived from two-channel MWRs are widely used to infer water cloud microphysical properties by combining the retrieved LWP with other ground-based measurements [3], to validate satellite retrievals of cloud LWP [4], and to study variations in cloud properties [5]. Thus, accurate LWP retrievals from MWR measurements are important for cloud studies in general. There are several ways to retrieve LWP from the measured two-wavelength brightness temperatures. Site-specific statistical retrievals, which are based on site-specific climatology from radiosonde measurements, are often used to retrieve LWP [6]. Such methods are easy to implement, but often result in significant errors in the retrieved LWP as evidenced by the existence of relative large clear-sky LWP values [7]. Based on the Department of Energy's Atmospheric Radiation Measurement Program Climate Research Facility (ACRF) long-term data, improved statistical methods are proposed using measurements of surface temperature, pressure, and relative humidity as well as cloud temperature [8]. This approach offers improved LWP retrieval; however, the uncertainty in LWP remains as large as 30 g/m^2. Although physically based retrieval methods can provide more accurate LWP [9], [10], these methods require many inputs, which would be difficult to obtain on an operational basis. Thus, we still have to deal with errors as large as 30 g/m^2 in LWP retrieved from MWR measurements, which could be a serious problem for clouds with low LWP values [11].

The errors in retrieved LWP come from several different sources [6], [8]. First, MWR calibration errors result in LWP biases for statistically and physically based methods, although these errors are only a few tenths of a degree kelvin. For long-term observations such as those from ACRF sites, dealing with calibration bias and drift is critical for generating a consistent long-term cloud data set. Second, the uncertainties in the absorption coefficients of liquid water, cloud water, and of other atmospheric gases also contribute to LWP retrieval errors. Several laboratory measurements of liquid water absorption coefficients are available for clouds warmer than 0°; however, few reliable measurements are available for supercooled water [12]. This presents a big challenge to the retrieval of LWP over cold regions where supercooled water clouds occur more frequently. Third, the lack of operationally available information about the vertical profiles of temperature and water vapor constitutes an additional source of error. Finally, random noise in the measured microwave brightness temperatures also translates into random errors in the retrieved LWP.

The addition of a high-frequency channel to traditional two-channel MWR provides better accuracy in the LWP retrieval; however, it cannot reduce all sources of error such as calibration bias and drift. Therefore, it is still worth to explore alternative approaches, particularly considering the climatological importance of ACRF long-term MWR data set. This letter describes a refined statistically based LWP retrieval based on lidar and two-channel MWR measurements. This new approach uses clear-sky MWR measurements as a reference, thereby allowing us to reformulate the statistical retrieval to systematically minimize errors due to errors in calibration, uncertainties in the gas absorption coefficients, and lack of information regarding the vertical profile of temperature and water vapor. LWP can be accurately retrieved from multiple remote sensor

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measurements [13] for cloud LWP smaller than 40 g/m^2. Thus, the multiple-sensor-retrieved LWP could be used to validate MWR LWP retrieval, thereby providing a way to check the accuracy of the absorption coefficients for supercooled water used for the retrieval. The results presented here show that the refined algorithm significantly reduces the clear-sky LWP values and provides an accurate cloud LWP.

II. OBSERVATIONS

The observations used in this letter are long-term surface observations from the ACRF site in the North Slope of Alaska (NSA) [14]. The two-channel MWR used in ACRF uses wavelengths of 23.4 and 31.8 GHz. The combined internal blackbody and tipping-curve method is used to calibrate the brightness temperatures for the MWR. The internal blackbody (with a 0.12-K uncertainty) eliminates larger errors due to drift in the MWR receiver. The accuracy of the brightness temperature measurements is $\sim$0.3 K with a resolution of 0.25 K, which affects LWP retrieval accuracy to some extent. More information about the MWR used in this letter can be found at the ACRF website (http://www.ACRF.gov/instruments/instrument.php?id=mwr). ACRF's current LWP retrievals from MWR measurements are based on a statistical method (referred to as ACRF's archived LWP hereafter).

LWP can also be retrieved from other ground-based measurements [13], [15] collected at the ACRF sites. A multiple-sensor LWP retrieval algorithm was developed for low LWP clouds (water or mixed-phase, LWP $<$ 40 g/m^2) based on micropulse lidar [16], millimeter cloud radar (MMCR) [17], and interferometer measurements of atmospherically emitted radiance. Such low LWP values are typical of arctic boundary layer clouds and midlevel altocumulus [13]. This multiple-sensor-based LWP has an accuracy of $\sim$15%, making it more reliable than current MWR retrievals for low LWP clouds. Hence, the multiple-sensor retrieved LWP can be used to validate and refine MWR retrievals for low LWP.

An intercomparison of the ACRF's archived LWP and multiple-sensor retrieved LWP, which is based on $\sim$150 days of measurements from the NSA site, is presented in Fig. 1(a). Several differences between the LWP retrievals are evident in this figure. First, the ACRF's archived LWP values are statistically higher than the multiple-sensor retrievals as indicated by the means of MWR-retrieved LWP. Second, the slope of the means is larger than unity. When the data set is separated into winter and summer seasons, different slopes, which also depart from unity, are found. Finally, there is a large scattering range in ACRF's archived LWP values for a given multiple-sensor LWP. To generate a high-quality group-based data set for climate research and satellite validation, we need to understand and resolve these differences to provide consistent and reliable LWP measurements over a large range of LWP as encountered in nature.

As described in Section III, these differences can be resolved by applying an improved MWR LWP retrieval method, which uses clear-sky MWR observations as a reference and incorporates the correct temperature dependencies of water absorption coefficients for supercooled water clouds.

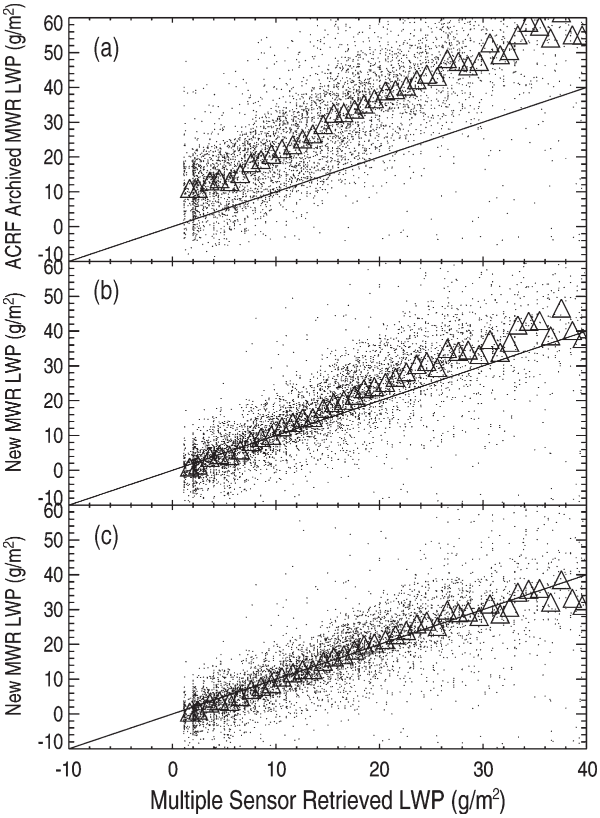

Fig. 1. LWP comparison between the multiple-sensor retrievals and two-channel MWR retrievals based on $\sim$150 days of measurements at the ACRF NSA site. (a) ACRF's archived MWR LWP. (b) MWR-retrieved LWP with clear-sky measurements as a reference. (c) MWR-retrieved LWP with clear-sky measurements as a reference, temperature dependency of liquid absorption coefficient in [12], and lidar-identified liquid layer temperature. Note that triangle symbols represent the means of MWR retrievals. The solid lines are 1 : 1 lines.

III. METHODOLOGY AND RESULTS

A. MWR LWP Retrieval With Clear-Sky Measurements as a Reference

In this section, we reformulate the statistical retrieval method of [8] by introducing clear-sky MWR measurements as a reference. Based on the measured microwave brightness temperatures T_{sky} at 23.8 and 31.4 GHz, the atmospheric opacity τ can be estimated with

$$\tau(\nu) = \ln\left(\frac{T_{\mathrm{mr}}(\nu) - T_{\mathrm{bg}}}{T_{\mathrm{mr}}(\nu) - T_{\mathrm{sky}}(\nu)}\right) \tag{1}$$

where T_{bg} is the cosmic background radiation temperature (2.73 K), and $T_{\mathrm{mr}}(\nu)$ is the mean atmospheric radiative temperature. The frequency-dependent atmospheric opacity τ includes contributions from dry air τ_{dry}, water vapor τ_{vap}, and liquid water τ_{liq}, i.e.,

$$\tau(\nu) = \tau_{\mathrm{dry}}(\nu) + \tau_{\mathrm{vap}}(\nu) + \tau_{\mathrm{liq}}(\nu) + \varepsilon(\nu) \tag{2}$$

where $\varepsilon(\nu)$ is an error term including contributions from calibration errors, measurement uncertainties, and uncertainties introduced by (1).

The $\tau_{\rm vap}$ and $\tau_{\rm liq}$ can be related to the vertical integrated water vapor (PWV) and liquid water (LWP) with path-averaged mass absorption coefficients for water vapor $\kappa_{\rm vap}(\nu)$ and liquid water $\kappa_{\rm liq}(\nu)$, i.e., $\tau_{\rm vap}(\nu) \approx \kappa_{\rm vap}(\nu)\text{PWV}$ and $\tau_{\rm liq}(\nu) \approx \kappa_{\rm liq}(\nu)\text{LWP}$.

To retrieve PWV and LWP from two-channel MWR measurements based on (2), we need to know $\kappa_{\rm vap}$ and $\kappa_{\rm liq}$ and estimate $\tau_{\rm dry}$ and $T_{\rm mr}$ [8]. In this traditional approach, LWP retrieval accuracy is sensitive to the accuracy of $\tau_{\rm dry}$, $\kappa_{\rm vap}$, and $\kappa_{\rm liq}$, the various error sources aggregated in $\varepsilon(\nu)$, and the magnitude of PWV, particularly for small LWP values. To minimize errors due to $\tau_{\rm dry}$, $\varepsilon(\nu)$, and $\kappa_{\rm vap}$, we propose to use clear-sky MWR measurements as a reference. In a clear-sky period (CLR), $\tau_{\rm CLR}$ can be expressed as

$$\tau_{\rm CLR}(\nu) = \tau_{\rm dry,CLR}(\nu) + \tau_{\rm vap,CLR}(\nu) + \varepsilon_{\rm CLR}(\nu). \tag{3}$$

By combining (2) and (3), we have

$$\begin{aligned}\Delta\tau(\nu) &= \tau(\nu) - \tau_{\rm CLR}(\nu)\\ &= [\tau_{\rm dry}(\nu) - \tau_{\rm dry,CLR}(\nu)] + [\tau_{\rm vap}(\nu) - \tau_{\rm vap,CLR}(\nu)]\\ &\quad + \tau_{\rm liq}(\nu) + [\varepsilon(\nu) - \varepsilon_{\rm CLR}(\nu)]\\ &\approx [\tau_{\rm vap}(\nu) - \tau_{\rm vap,CLR}(\nu)] + \tau_{\rm liq}(\nu) + \Delta\varepsilon(\nu). \end{aligned} \tag{4}$$

Normally, the clear-sky period to be used as a reference can be found within 12 h of the cloudy measurements. Temporal changes in PWV and atmospheric temperature and pressure profiles are usually smooth and relatively small within this time period. Thus, $(\tau_{\rm dry} - \tau_{\rm dry,CLR})$ is very close to zero and $\Delta\tau_{\rm vap} = (\tau_{\rm vap} - \tau_{\rm vap,CLR})$ is much smaller than $\tau_{\rm vap}$ or $\tau_{\rm vap,CLR}$. Similarly, $\Delta\varepsilon$ is also much smaller than $\varepsilon(\nu)$ or $\varepsilon_{\rm CLR}(\nu)$. The frequency-dependent $\Delta\tau$ given in (4) therefore results mainly from the contribution from liquid cloud, although this contribution is a relatively small term in (2).

For the two-channel MWR measurements, neglecting $\Delta\varepsilon$, we have

$$\Delta\tau_1 \approx \kappa_{\rm vap,1}\Delta\text{PWV} + \kappa_{\rm liq,1}\text{LWP} \tag{5a}$$

$$\Delta\tau_2 \approx \kappa_{\rm vap,2}\Delta\text{PWV} + \kappa_{\rm liq,2}\text{LWP} \tag{5b}$$

where ΔPWV is the difference in precipitable water vapor between the retrieval time and the clear-sky reference period. Combining (5a) and (5b), LWP can be written as

$$\text{LWP} = L_1\Delta\tau_1 + L_2\Delta\tau_2 \tag{6}$$

where L_1 and L_2 are coefficients determined by the following equations:

$$\begin{aligned} -L_1 &= \left(\kappa_{\rm liq,2}\frac{\kappa_{\rm vap,1}}{\kappa_{\rm vap,2}} - \kappa_{\rm liq,1}\right)^{-1}\\ L_2 &= \left(\kappa_{\rm liq,2} - \kappa_{\rm liq,1}\frac{\kappa_{\rm vap,2}}{\kappa_{\rm vap,1}}\right)^{-1}. \end{aligned} \tag{7}$$

Equation (6) is the same as [8, eq. (4b)], with $\Delta\tau_1$ and $\Delta\tau_2$ replacing $\tau_1 - \tau_{\rm dry,1}$ and $\tau_2 - \tau_{\rm dry,2}$. To estimate LWP based on (6), we need to know $T_{\rm mr}$, $\kappa_{\rm liq,1}$, $\kappa_{\rm liq,2}$, and $\kappa_{\rm vap,1}/\kappa_{\rm vap,2}$. Because the results are less sensitive to the accuracy of $T_{\rm mr}$, calibration errors in $T_{\rm sky}$, and uncertainties in the water vapor absorption coefficient, we can use the formulation introduced by [8] to estimate $T_{\rm mr}$. Similarly, we can directly use L_1 and L_2 introduced by [8]. The sensitivity of the LWP retrieval to the liquid water absorption coefficients at the microwave region can be examined by using (7) to calculate L_1 and L_2. The temperature dependencies of $\kappa_{\rm liq,1}$ and $\kappa_{\rm liq,2}$ are calculated based on the formulations in [12].

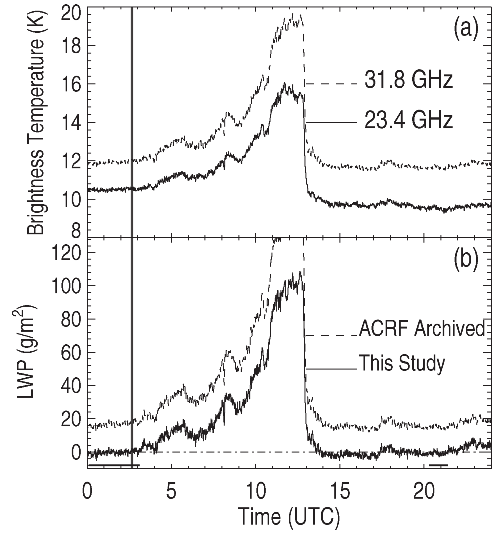

Fig. 2. Example of LWP retrievals with the current method. (a) Observed brightness temperatures at (solid line) 23.4 and (dashed line) 31.8 GHz on January 12, 2000 at the ACRF NSA site. (b) LWP retrieved with the new method and the comparison with ACRF's archived LWP. Note that the thick horizontal lines near the bottom of (b) indicate the clear-sky periods identified by lidar measurements; the vertical line indicates the clear-sky measurements used as a reference.

This approach requires that clear-sky MWR measurements be obtained for use as a reference. Clear-sky periods lasting more than an hour are identified based on ceilometer or lidar measurements and used to calculate average MWR signals. If the clear-sky periods are much longer than an hour, multiple references could be saved to form a reference database with date and time as index. To find a reference for given cloudy observations, we use the temporally closest clear-sky signals from the database.

B. Results and Discussion

An example of the LWP retrieval based on the method outlined in Section III-A is given in Fig. 2. In Fig. 2(b), ACRF's archived LWPs are shown to have clear-sky values up to 15 g/m^2. Using the clear-sky measurements as a reference, the new formulation reduces the erroneous clear-sky LWP values to within a ±5 g/m^2 margin. The residual clear-sky LWP is partly attributed to the random noise in the observed brightness temperatures that are displayed in Fig. 2(a). The benefits of using clear-sky MWR measurements as a reference are also evident in the LWP comparison given in Fig. 1(b); here, LWP is calculated with (6) using the L_1 and L_2 that were calculated in [8, eq. (17)]. It should be noted that the new method improves

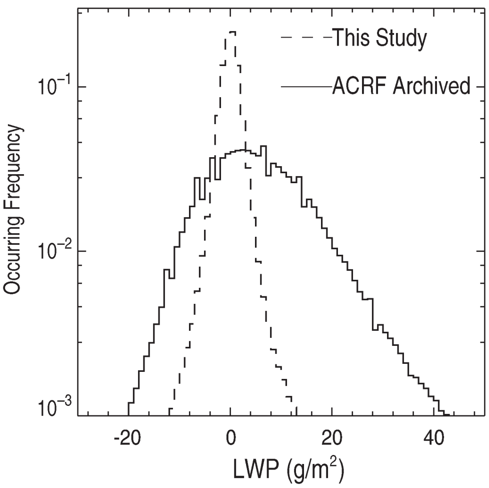

Fig. 3. Frequency distributions of retrieved clear-sky LWP values based on MWR observations at the ACRF NSA site during January 1999 and December 2004. Note that the solid line represents the new MWR retrievals discussed here and the dashed line represents ACRF's archived retrievals.

the correlation between an LWP retrieved by a multiple-sensor and MWR-retrieved LWP. The large bias in the MWR-retrieved LWP shown in Fig. 1(a) is significantly reduced and is scattered less than that in Fig. 1(a) for a given multiple-sensor LWP value.

The improvement that can be obtained using clear-sky measurements as a reference is illustrated by the retrieved LWP statistics observed at the ACRF NSA site during clear-sky periods from January 1999 to December 2004 (see Fig. 3). The clear-sky periods are identified using ceilometer measurements. For idealized MWR measurements and perfect retrievals, we expect to see zero LWP values during clear-sky periods; however, we have to deal with random noise in the measurements and we are able to minimize only the mean and standard deviation of the clear-sky LWP values retrieved from the MWR measurements. As shown in Fig. 3, ACRF's current archived LWP retrievals have a relatively wide distribution of LWP values and a significant positive mean bias during clear-sky periods. In contrast, the new method provides clear-sky LWP values with a narrower distribution and a mean of ~ 0.3 g/m^2. The range of clear-sky LWP values is indicative of some of the uncertainties in cloud LWP values. Fig. 3 suggests using clear-sky references, which were formulated in Section III-A, to provide more accurate LWP retrievals; this is particularly important for clouds with low LWP [11].

Although these are significant improvements, the slope of the means presented in Fig. 1(b) still differs slightly from unity. Over cold regions such as the arctic, most water clouds are supercooled. The temperature dependencies of the water absorption coefficients at 23.4 and 31.8 GHz, which were used for retrievals, have a noticeable impact on the retrieved LWP. We can calculate L_1 and L_2 in (6) and (7) based on the formulations of water absorption in the microwave region in [12]. The cloud temperatures were determined from lidar-derived cloud height. Although micropulse lidar data are available from the NSA site, we have chosen to use ceilometer data here to determine the cloud height because it has a better temporal coverage and is available for other places. Cloud base heights are determined from raw ceilometer data using the algorithm discussed in [18], which is capable of separating water cloud base from virga. The retrieved LWP values with the new L_1 and L_2 are slightly smaller than using L_1 and L_2 based on [8, eq. (17)]. The intercomparison of LWP retrieved by a multiple-sensor method and LWP retrieved using the new method is presented in Fig. 1(c), which clearly shows that the slope of the means is very close to the 1 : 1 line.

IV. SUMMARY

A simple approach for improving the accuracy of MWR LWP retrieval over cold regions is presented based on observations from the ACRF NSA site. The new LWP retrieval method is reformulated based on the traditional statistical retrieval using clear-sky MWR measurements as a reference. As illustrated in the new formulation, the LWP retrieval is less sensitive to errors in calibration, assumptions about the vertical structure of the atmosphere, and uncertainties in the gas absorption coefficients. The improvement in LWP retrieval is demonstrated with the clear-sky LWP value statistics. The mean and standard deviation of the retrieved clear-sky LWP values with the new method are $\sim$0.3 and 4.0 g/m^2, respectively. These are much smaller than current ACRF achieved results. The retrieved LWP from MWR for supercooled water clouds can be further improved by incorporating the temperature dependencies of the water absorption coefficients suggested in [12], combined with water cloud temperature estimates inferred from lidar measurements of cloud height. With these improvements, good agreement between MWR-retrieved LWP and the LWP retrieved by a multiple-sensor algorithm is achieved for LWP < 30 g/m^2. This makes it possible to combine MWR with other measurements to cover the whole range of water and mixed-phase clouds over a wide range of LWP.

The improved approach is based on [8] and can be easily implemented to ACRF-like observations. Although micropulse lidar and Raman lidar are better to identify cloud-free periods, ceilometer measurements are adequate to detect water clouds and low-level ice clouds in cold regions. Therefore, the approach can be applied to measurements where only MWR, ceilometer, and surface weather station are available. The importance of properly identifying the height of the water layer to infer water cloud temperature for LWP retrieval in cold regions should be emphasized. For supercooled clouds such as those observed over the arctic, deep ice virga or ice precipitation often falls below the supercooled water layer [13]. Without the proper separation of water and ice regions, a large error in estimated cloud water temperature may be introduced with lidar or MMCR measurements. Although this method is demonstrated based on ACRF NSA observations, the approach could also be applied to midlatitude and tropical MWR observations.

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