New Technique for Retrieving Liquid Water Path over Land using Satellite Microwave Observations

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Abstract

We present a new methodology for retrieving liquid water path over land using satellite microwave observations. As input, the technique exploits the Advanced Microwave Scanning Radiometer for earth observing plan (EOS) (AMSR-E) polarization-difference signals at 37 and 89 GHz. Regression analysis performed on model simulations indicates that over variable atmospheric and surface conditions the polarization-difference signals can be simply parameterized in terms of the surface emissivity polarization difference ($\Delta\varepsilon$), surface temperature, liquid water path (LWP), and precipitable water vapor (PWV). The resulting polarization-difference parameterization (PDP) enables fast and direct (non-iterative) retrievals of LWP with minimal requirements for ancillary data. Single- and dual-channel retrieval methods are described and demonstrated. Data gridding is used to reduce the effects of instrumental noise. The methodology is demonstrated using AMSR-E observations over the Atmospheric Radiation Measurement (ARM) Southern Great Plains (SGP) site during a six day period in November and December, 2003. Single- and dual-channel retrieval results mostly agree with ground-based microwave retrievals of LWP to within approximately 0.04 mm.

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Introduction

Measurements of cloud liquid water properties are important in a wide range of disciplines including climate change, numerical weather prediction (NWP), and aircraft icing. A variety of remote sensing techniques have been developed to address this need, including both visible/infrared (Dong et al. 2002) and microwave methods. Unlike visible and infrared radiation, microwaves with frequencies less than about 90 GHz are insensitive to non-precipitating cloud ice particles, and are unaffected by the liquid cloud particle size distribution. Both of these features are desirable for characterizing cloud LWP. Microwave techniques are particularly mature for (1) ground-based LWP retrievals (Liljegren et al. 2001) and (2) satellite-based LWP retrievals over the oceans (Greenwald et al. 1993). Satellite-based methods for retrieving LWP over land are less mature. The main issue inhibiting satellite-based microwave retrievals of LWP over land so far has been discriminating cloud features from surface effects.

The "Normalized Polarization Difference" (NPD) technique developed by Greenwald et al. (1997, 1999) exploits the Special sensor microwave/imager (SSM/I) 37- and/or 85-GHz polarization-difference signals ($\Delta T_B = T_B^V - T_B^H$). The technique relies on (1) the small (but finite) difference in land-surface emissivity associated with the V and H polarization states and (2) the depolarizing effect of absorption of microwaves by liquid clouds. Compared to techniques based on a single SSM/I signal, the NPD technique was shown to be much less sensitive to cloud vertical location, surface temperature variability, and systematic instrumental errors. Drawbacks of the NPD technique (as presented by Greenwald et al.) included the need for synchronized surface and radiosonde measurements as ancillary input data, a computationally expensive iterative retrieval algorithm, and a need for independently retrieved values of surface emissivity polarization difference ($\Delta\varepsilon = \varepsilon^V - \varepsilon^H$).

We are developing a parameterization-based technique for retrieving LWP over land. Like the NPD technique, our method exploits polarization-difference signals from a conical-scanning satellite microwave sounder. Compared to the NPD technique, however, our method incorporates additional features which simplify retrieval processing. In this paper, we demonstrate first that the relationship between ΔT_B, $\Delta\varepsilon$, surface temperature (T_S), LWP, and PWV can be parameterized in a simple analytical form. The resulting PDP facilitates direct (non-iterative) LWP retrievals with minimal ancillary data requirements. Second, retrievals are performed on a two-dimensional (2D) grid, which permits spatial averaging of the polarization-difference signals before retrievals are performed. This feature significantly reduces the effects of random instrumental errors on the retrievals of $\Delta\varepsilon$ and LWP. Finally, we show that if the frequency dependence of $\Delta\varepsilon$ is negligible (at least relative to the 37- and 89-GHz channels), LWP may be retrieved in a "standalone" retrieval algorithm (i.e., with no requirement for independent cloud information).

Radiative Transfer Simulations and Regression Analysis

The AMSR-E brightness temperatures were simulated for the general area around the ARM Climate Research Facility (ACRF) SGP site for December 2001. This region was selected primarily because of the wealth of ancillary data available, including frequent ground-based remote sensing retrievals of LWP and PWV. Retrieved profiles of temperature, water vapor, and LWC based on measurements by the ground-based twelve-channel microwave radiometer profiler (MWRP) (Liljegren et al. 2001), were used to simulate AMSR-E brightness temperatures for the 37- and 89-GHz channels. The radiative transfer model used in the simulations was described previously (Deeter and Vivekanandan 2004).

For observations of non-precipitating clouds, microwave brightness temperatures generally depend on vertical profiles of temperature, water vapor, and LWC, as well as surface temperature and emissivity. Brightness temperatures are generally different for the V and H polarizations because of the polarization dependence of the surface emissivity. Previous theoretical and experimental work on the NPD method demonstrated the exact proportionality of ΔT_B and $\Delta\varepsilon$, and showed that LWC vertical distribution (i.e., geometrical cloud boundaries) had only minor effects on ΔT_B. Similarly, the vertical distribution of water vapor should be expected to be much less significant than the vertically integrated value (i.e., PWV). Thus, we expect that the atmospheric influence on ΔT_B to be dominated by LWP and PWV. Moreover, with respect to both LWP and PWV, ΔT_B decreases exponentially towards zero with increasing absorber amount. Together, these observations indicate the feasibility of parameterizing the ratio ($\Delta T_B/\Delta\varepsilon$) in terms of T_S, LWP and PWV. (The inclusion of T_S in this parameterization is actually not essential, but does slightly reduce the overall parameterization errors.) Specifically, we find that the following parameterization (which hereafter we refer to as the polarization-difference parameterization, [PDP]) accurately represents the dependence of ΔT_B on all relevant geophysical quantities:

$$(\Delta T_B/\Delta\varepsilon) = \exp\left[\beta_0 + \beta_1 T_S + \beta_2 LWP + \beta_3 PWV\right] \tag{1}$$

Parameterization coefficients β_i were determined by applying multiple linear regression to the set of MWRP profiles and corresponding simulated brightness temperatures for all profiles acquired during December 2001. Results of the parameterization (including the exact computed ΔT_B values for each MWRP profile used in the regression) are presented in Figure 1. Equation (1) is equally valid for land and ocean surfaces, and therefore serves as the foundation for globally-applicable retrieval algorithms.

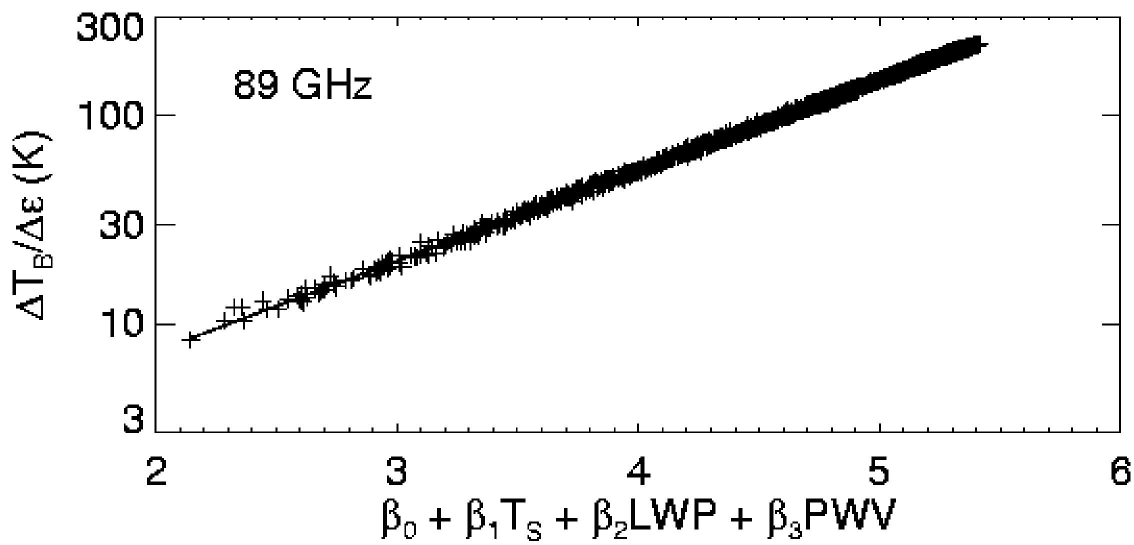

Figure 1. Results of multiple linear regression for 89-GHz AMSR-E polarization-difference signals. Plotted points (+ symbols) indicate results of radiative transfer simulations described in Section 2. The solid line indicates best fit as determined by regression analysis.

PDP-based Retrieval Strategies

The PDP serves as the basis for both single- and dual-channel LWP retrieval algorithms. In both types of retrieval algorithms, a priori knowledge of both T_S and PWV is assumed; these quantities may be adequately predicted or estimated using reanalysis, NWP models, or other satellite remote sensing products. Thus, determination of $\Delta\varepsilon$ is the main obstacle to retrieving LWP from measured values of ΔT_B.

Single-channel PDP retrievals require ancillary data (e.g., visible/infrared satellite observations) collocated with the satellite microwave observations to separate clear and cloudy scenes. Clear-sky observations, where LWP may be assumed to be exactly zero, are processed using Eq. (1) to determine $\Delta\varepsilon$. Cloudy scenes yield LWP retrievals by exploiting $\Delta\varepsilon$ values retrieved during previous clear-sky overpasses, and assume negligible temporal variability of $\Delta\varepsilon$. (In the case study presented in Section 4, clear/cloudy determinations are made on the basis of ground-based observations.)

Dual-channel PDP retrievals exploit the observed weak frequency dependence of $\Delta\varepsilon$. Specifically, if $\Delta\varepsilon$ is assumed to be frequency independent, simultaneous measurements of ΔT_B at 37 and 89 GHz may be processed to directly retrieve LWP. Since no independent clear/cloudy determination is required, the dual-channel strategy is much simpler to implement than the single-channel strategy. And, although it is more restrictive than the single-channel method in terms of the assumed frequency dependence of $\Delta\varepsilon$, it requires no assumptions with regard to $\Delta\varepsilon$ temporal variability. For the ACRF SGP site, results of a case study (presented in Section 4) indicated highly correlated values of $\Delta\varepsilon$ at 37 and 89 GHz.

For both single- and dual-channel PDP methods, data gridding suppresses the effects of random instrumental error. Currently, we grid T_B observations to a rectangular 0.25 by 0.25° latitude/longitude grid before retrieving LWP.

Southern Great Plains Case Study

A time-series plot of LWP recorded from five microwave radiometer instruments in the SGP region from November 28 to December 4, 2003, is shown in Figure 2. Microwave radiometer data from instruments stationed at the SGP C1 (36.605N, 97.486W), B1 (38.305N, 97.301W), B4 (36.071N, 99.218W), B5 (35.688N, 95.856W), and B6 (34.985N, 97.522W) facilities were used in this study. As indicated in Figure 2, liquid clouds were not detected over the SGP region from November 28 through December 1, 2003. This clear period was followed by three days during which a passing cold front produced liquid water-bearing clouds and precipitation. As indicated by NEXRAD radar and surface meteorological data (including the microwave radiometer data wet-flag fraction), precipitation associated with this front fell in the SGP region primarily between 0000 and 0900 Universal Time Coordinates (UTC) on December 3. Surface temperatures throughout the SGP region were well above freezing during the entire period from November 28 through December 4; any precipitation presumably fell to the surface as rain.

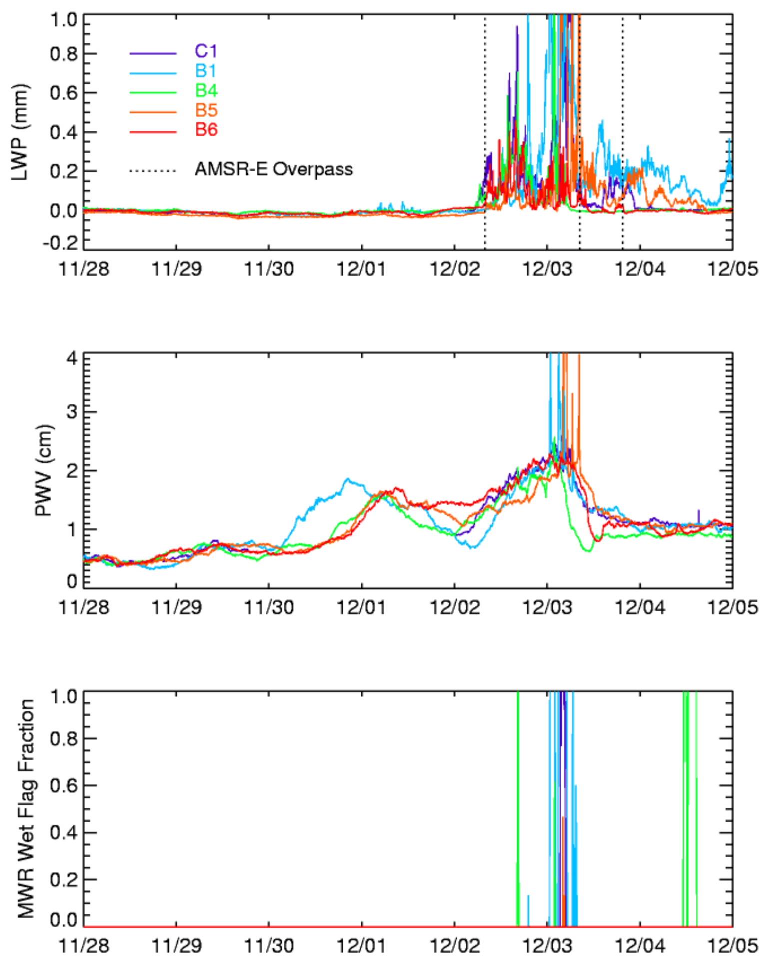

Figure 2. Time series of LWP, PWV, and wet-flag fraction recorded by five ground-based microwave radiometers at the ACRF SGP site between November 28 and December 5, 2003. AMSR-E overpass times on December 2 and 3 are indicated by vertical dotted lines in top panel.

All AMSR-E observations over the study area from November 28 through December 1 were processed as clear-sky observations, resulting in gridded Δε values for each overpass. Next, all overpasses for this period were averaged for each grid cell, producing gridded four-day mean Δε values. A total of at least seven overpasses contributed to the mean Δε values for each grid cell. Gridded temporal mean Δε values calculated this way for both the AMSR-E 37- and 89-GHz channels are shown in Figure 3. The figure generally indicates that, for the ARM SGP region, Δε values for 37 and 89 GHz are highly correlated and similar in magnitude. A least-squares fit of Δε values at 37 and 89 GHz yielded a slope of 0.91 and a correlation coefficient of 0.89.

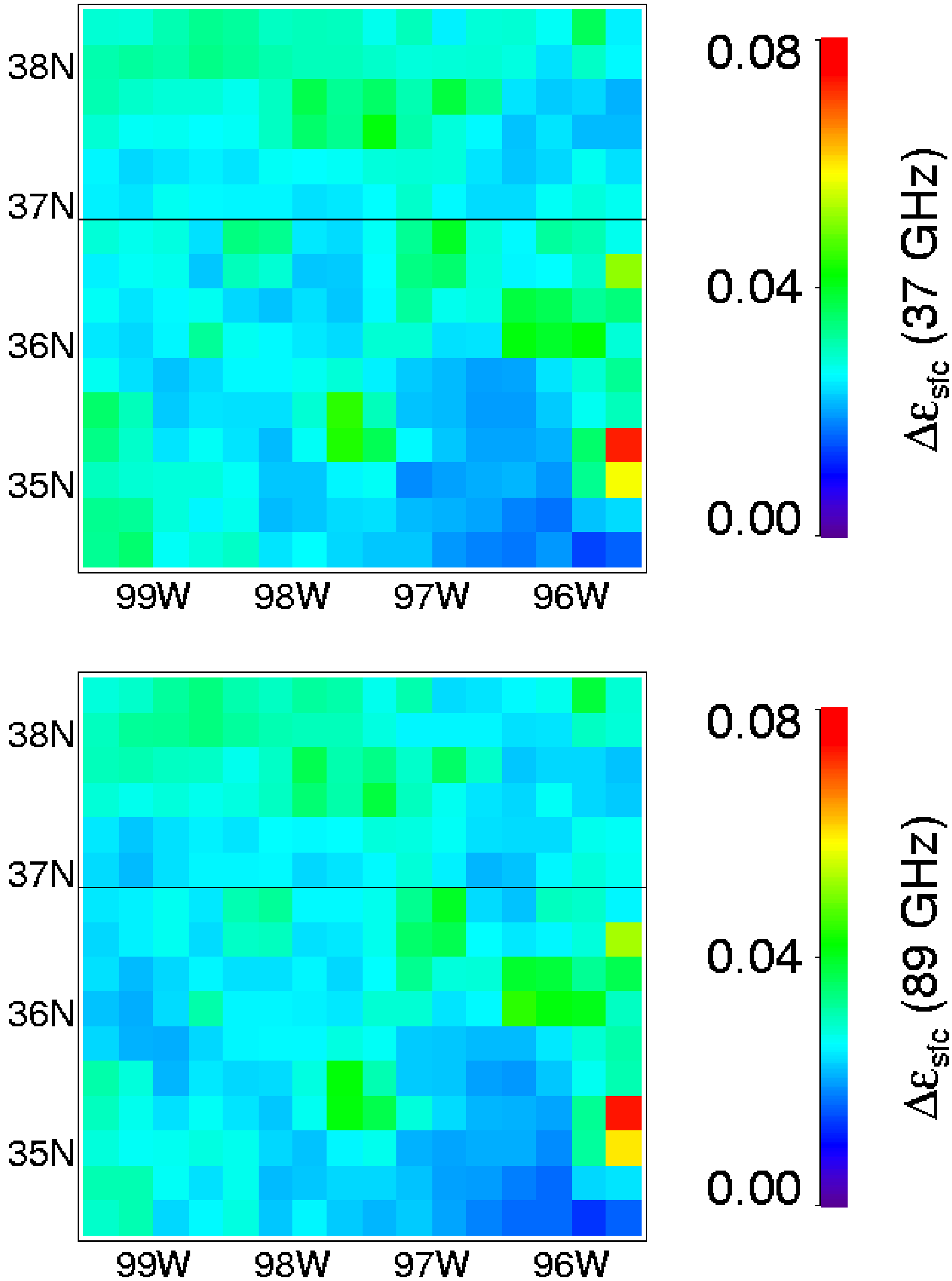

Figure 3. Gridded maps of surface emissivity polarization difference at 37 and 89 GHz retrieved using clear-sky AMSR-E observations between November 28 and December 1, 2003.

AMSR-E overpasses of the SGP region at approximately 0750 UTC on December 2 and 0830 and 1930 UTC on December 3 were processed to produce LWP retrievals. Only a single AMSR-E overpass occurred over the SGP region on December 2, and none occurred on December 4. As indicated by the five SGP MWR instruments, liquid clouds first became evident in the SGP region at approximately 0500 UTC on December 2. Surface temperature and PWV values needed to retrieve LWP were obtained from NCEP Reanalysis interpolated to the midpoints of the retrieval grid cells and AMSR-E overpass times. $\Delta\varepsilon$ values for each grid cell were obtained using clear-sky AMSR-E observations as described in the previous paragraph. Maps of single-channel (89 GHz) and dual-channel LWP retrievals for the 1930 UTC overpass on December 3 are presented in Figures 4 and 5. Dual-channel LWP retrievals were performed by assuming frequency independence of $\Delta\varepsilon$, which is justified by the strong correlation of $\Delta\varepsilon$ at 37 and 89 GHz apparent in Figure 3. Locations of the five ground-based radiometers are indicated in Figures 4 and 5 as red asterisks.

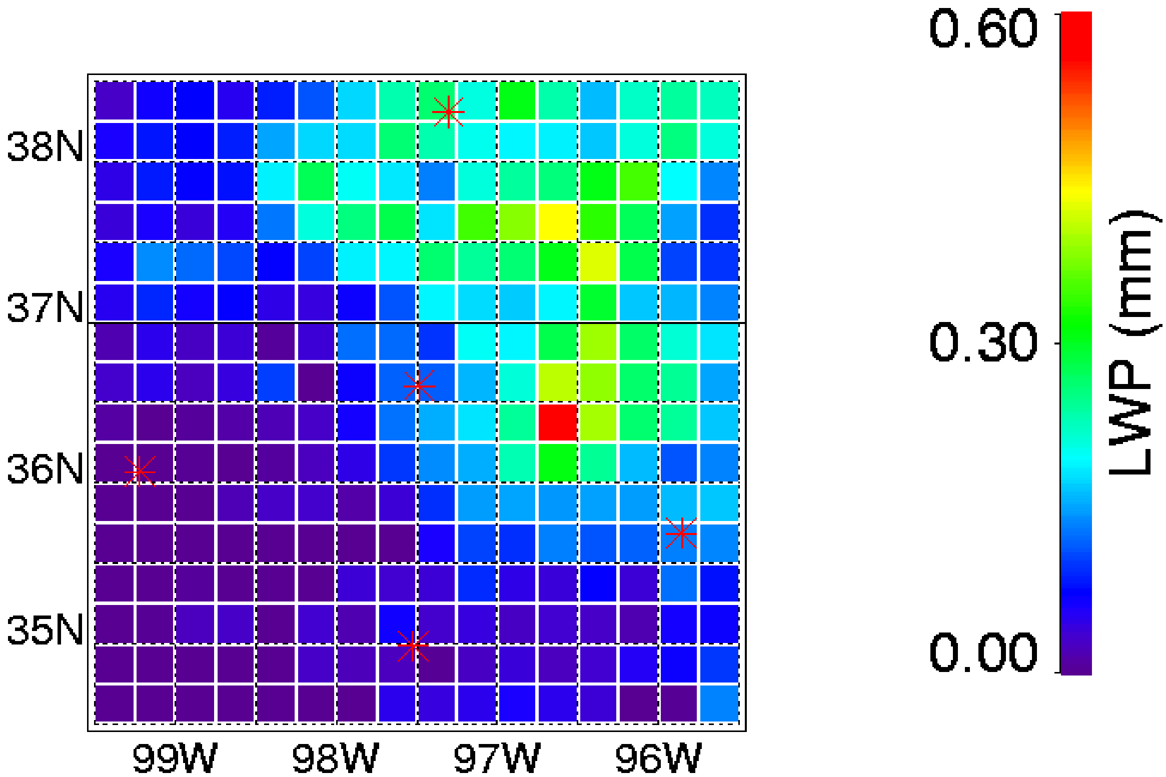

Figure 4. Single-channel (89 GHz) LWP retrievals for AMSR-E overpass at 1930 UTC on December 3, 2003.

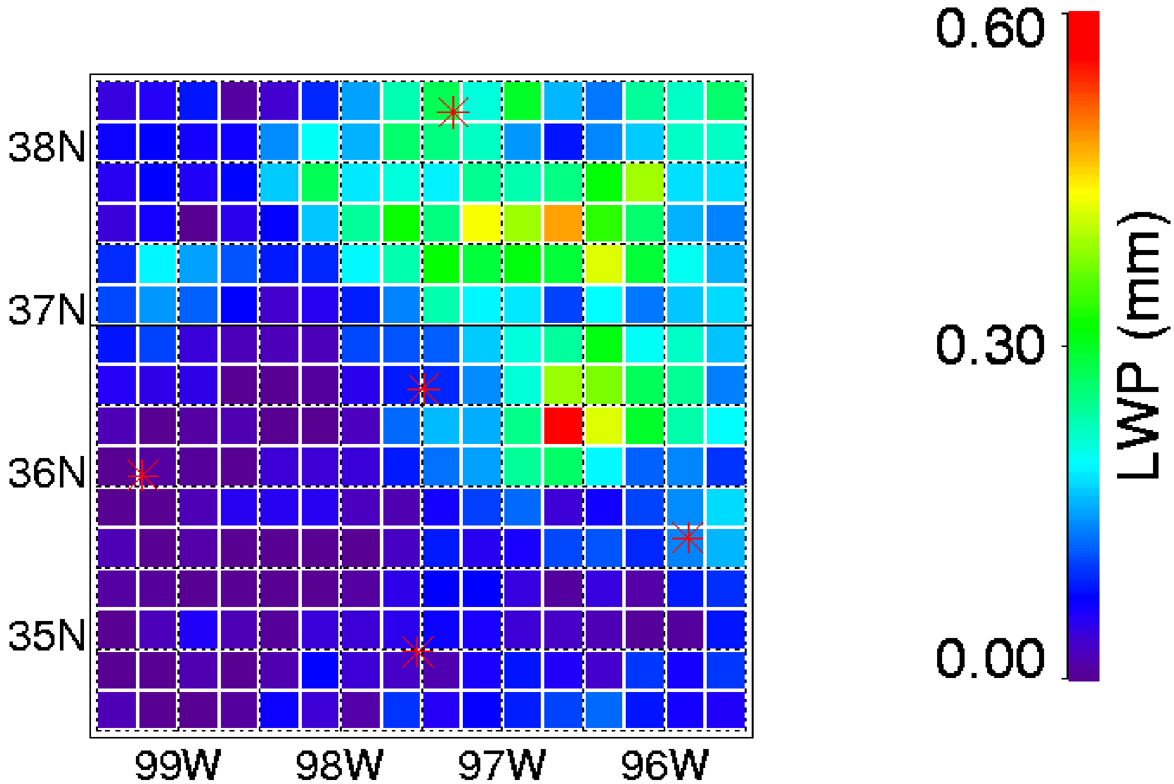

Figure 5. Dual-channel LWP retrievals for AMSR-E overpass at 1930 UTC on December 3, 2003.

Single-channel and dual-channel AMSR-E LWP retrievals for the three overpasses on December 2 and 3 are compared with corresponding values from the five ground-based MWR instruments in the scatterplot shown in Figure 6. MWR LWP values indicate the mean LWP value over a 30-min period spanning the time of the AMSR-E overpass; associated error bars indicate the LWP standard deviation over the same period. Plotted AMSR-E LWP values and error bars indicate the statistics (mean and standard deviation) over five grid cells including the grid cell containing the MWR site and the grid cells immediately north, south, east and west. Thus, MWR LWP error bars describe the local measured temporal LWP variability whereas AMSR-E error bars are related to spatial variability. In both cases, error bars provide a measure of the expected disparity in retrieval results due to differing instrument sampling characteristics in addition to other sources of retrieval error. Root mean square (RMS) retrieval errors (taking the MWR results as "truth") are 0.04 and 0.05 mm for the single- and dual-channel algorithms respectively. We suspect these values are at least in part the result of mismatched sampling area (as described above) and therefore overestimate the fundamental retrieval uncertainty. Validation studies in the future should avoid this problem by concentrating on horizontally homogeneous cloud systems.

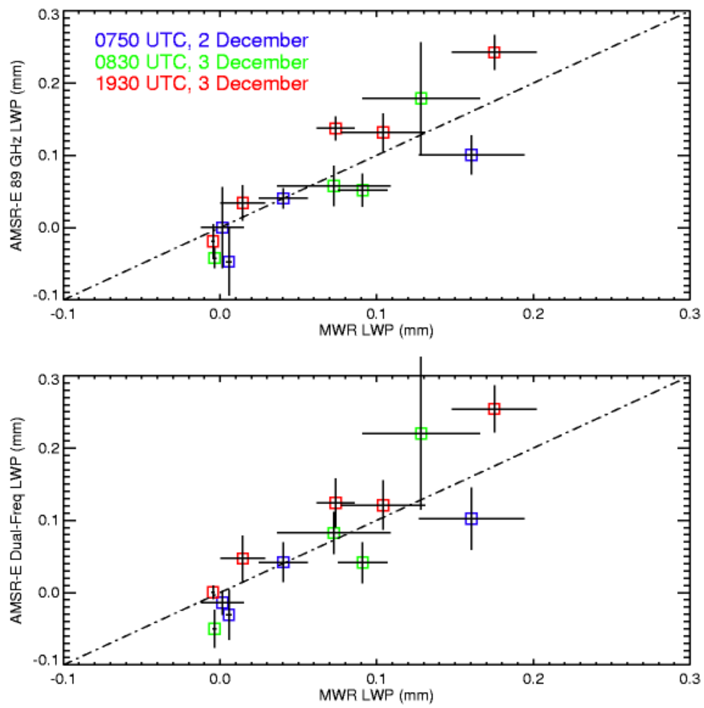

Figure 6. Scatterplot of AMSR-E single-channel (89 GHz) and dual-channel LWP retrieval results versus LWP retrieved by five ground-based microwave radiometers at the ACRF SGP site for AMSR-E overpasses on December 2 and 3, 2003.

Conclusion

New microwave-based satellite remote sensing techniques for retrieving LWP over land are being developed. Problems with low thermal contrast and surface emissivity variability prevent the extension of techniques developed for open ocean to land surfaces. The NPD technique partially overcomes these problems by exploiting the polarization dependence of the surface emissivity of land surfaces. Developments described in this report improve on operational aspects of the NPD technique and permit LWP retrievals over extended regions. First, a PDP was developed for the polarization-difference signal in terms of $\Delta\varepsilon$, T_S, LWP, and PWV. The PDP minimizes the need for ancillary data and results in simple retrieval algorithms based either on single- or dual-channel strategies. LWP retrievals based solely on the 89-GHz channel require independent cloud identification. Clear-sky observations are employed to retrieve $\Delta\varepsilon$ while cloudy scenes yield LWP retrievals. LWP retrievals based on simultaneous observations at 37 and 89 GHz require no independent cloud information, but do rely on the assumed frequency independence of $\Delta\varepsilon$. Under both strategies, data gridding is employed to suppress the effects of instrumental noise.

The new techniques were applied to AMSR-E observations over the ACRF SGP site during a six-day period in 2003. Ground-based microwave radiometers were used both to distinguish clear and cloudy periods and to validate the AMSR-E retrieved LWP values. Although quantitative validation of AMSR-E LWP retrievals using ground-based radiometers is hindered by LWP spatial variability, retrieval errors appear to be on the order of 0.04 mm. More validation studies concentrating on extensive stratus cloud systems (where the effect of retrieval sampling area is minimized) will be necessary to better quantify retrieval error statistics.

Several issues must be addressed before the PDP-based techniques described here could be used to retrieve LWP over land operationally. Characteristics of $\Delta\varepsilon$ which generally exhibits temporal, spatial, and spectral variability) that impact LWP retrieval quality must be analyzed for more surface types. Robust filters are needed to identify and discard AMSR-E observations that might be affected by precipitation. Finally, a rigorous error analysis is needed to quantify retrieval error contributions from all sources.

Although the techniques described in this paper exploits AMSR-E observations, they could be easily adapted to accommodate SSM/I observations. Currently, there are three operational SSM/I instruments. The use of all four instruments for LWP retrievals would greatly increase the frequency of observations and reduce retrieval errors due to temporal variability of $\Delta\varepsilon$. In addition, the techniques should be equally suitable for future conical-scanning microwave sounders such as the conical-scanning microwave imager and Gestalt photo mapper.

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