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NEW METHOD FOR RETRIEVING LIQUID WATER PATH OVER LAND USING AMSR-E OBSERVATIONS

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1. 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 and microwave methods. Unlike visible and infrared radiation, microwaves with frequencies of 90 GHz and less 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 properties such as liquid water content (LWC) and liquid water path (LWP). Passive microwave techniques are particularly mature for (1) ground-based LWP retrievals and (2) satellite-based LWP retrievals over the oceans. 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.

Because of the high atmospheric transmittance of microwaves (even in the presence of clouds), land-surface temperature and emissivity variations directly modulate observed satellite microwave brightness temperatures. Moreover, the relatively high mean surface emissivity values typical of land surfaces (compared to ocean surfaces) result in poor thermal contrast conditions. Thus, at microwave frequencies, the same liquid cloud would produce a much larger radiative perturbation (in terms of the observed brightness temperature, T_B) over the ocean than over land. The "Normalized Polarization Difference" (NPD) retrieval technique was developed specifically to overcome these limitations (Greenwald et al. 1997, Greenwald et al. 1999, Combs et al. 1998). This technique exploits the Special Sensor Microwave/Imager (SSM/I) 85 or 37 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 height, surface temperature and systematic instrumental errors. Drawbacks of the NPD technique (as presented by Greenwald et al.) included the need for synchronized radiosonde measurements and visible/infrared satellite observations as ancillary input data, the need for prior knowledge of the surface emissivity polarization difference ($\Delta\epsilon = \epsilon^V - \epsilon^H$), and a computationally expensive iterative retrieval algorithm. These issues have so far prevented the development of an operational satellite product.

In the following, we describe a new regression-based technique for retrieving LWP in non-precipitating clouds over land. The technique is applied specifically to the Advanced Microwave Scanning Radiometer for EOS (AMSR-E) instrument, but could be easily adapted to exploit SSM/I observations. The retrieval methodology exploits polarization-difference signals, like the NPD technique, but incorporates additional features which circumvent the main problems of the NPD technique listed above. Specifically, the new method involves no coordinated measurements from any other instruments (either ground-based or satellite-based), does not depend on prior knowledge of $\Delta\epsilon$, and is based on a simple analytical expression.

2. RETRIEVAL ALGORITHM

The foundation of the new retrieval algorithm lies in a new parameterization for the AMSR-E polarization-difference signals. Parameters in this new "Polarization-Difference Parameterization" (or PDP) include $\Delta\epsilon$, surface temperature (T_S), LWP and precipitable water vapor (PWV). The PDP takes the form

$$\Delta T_B \approx \Delta\epsilon \exp[\beta_0 + \beta_1 T_S + \beta_2 \mathrm{LWP} + \beta_3 \mathrm{PWV}]$$

where the coefficients β_i may be obtained by applying multiple linear regression (after properly recasting the PDP equation above) to radiative transfer simulations. Training sets used as the basis of the regression were formed independently using observations from a twelve-channel ground-

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based microwave radiometer and synthetic profiles produced from NCEP Reanalysis. Brightness temperatures for each profile were calculated using an absorption/emission model (Deeter and Vivekanandan 2005). Retrieval results do not appear to be strongly sensitive to the method used to form the training sets. The fit of the regression for the radiometer-based training set is shown graphically in Figure 1.

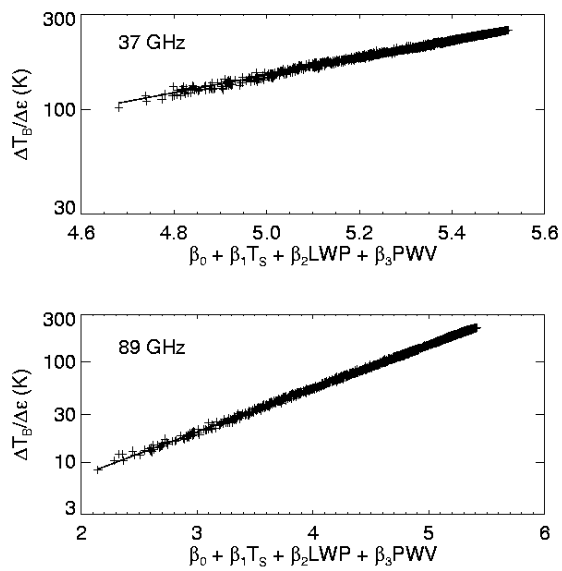

Figure 1. Results of applying multiple linear regression to the PDP equation for both the 37 and 89 GHz AMSR-E polarization-difference signals. Plotted points indicate results of radiative transfer simulations. Solid line indicates best fit as determined by regression analysis.

In applications where $\Delta\epsilon$, T_S and PWV are known a priori, the PDP equation can be directly inverted to retrieve LWP using a single polarization-difference signal. Development of an LWP retrieval equation based on polarization-difference signals for two frequencies (specifically, 37 and 89 GHz) is also straightforward. Dividing the PDP expression for ΔT_B at 89 GHz by the expression for ΔT_B at 37 GHz and solving for LWP yields

$$LWP = [\ \ln(\Delta T_B^{89}/\Delta T_B^{37}) - \ln(\Delta\epsilon^{89}/\Delta\epsilon^{37}) - (\beta_0^{89} - \beta_0^{37}) - (\beta_0^{89} - \beta_0^{37})T_S - (\beta_0^{89} - \beta_0^{37})\ PWV\ ] / (\beta_0^{89} - \beta_0^{37})$$

Therefore, if the frequency dependence of $\Delta\epsilon$ is negligible (or, specifically, if $\Delta\epsilon^{89}/\Delta\epsilon^{37}$ can be shown to vary negligibly), LWP may be retrieved without any a priori knowledge of $\Delta\epsilon$. In practical terms, the dual-frequency methodology is an improvement over the single-frequency method because (1) it requires no independent clear/cloudy determination (which would involve measurements from a separate instrument) and (2) it involves no assumptions regarding the temporal variability of $\Delta\epsilon$. Moreover, as a "stand-alone" retrieval algorithm, the dual-frequency methodology is more generally applicable than the NPD method (which requires independent visible/infrared satellite observations to determine scene cloudiness). For example, the presence of overlying cirrus clouds does not directly inhibit LWP retrievals using the dual-frequency method. Further, the dual-frequency method is applicable to regions of persistent cloudiness, which would be problematic for the single-frequency method.

3. VALIDATION STUDIES

As part of the Atmospheric Radiation Measurements (ARM) program operated by the United States' Department of Energy, five ground-based microwave radiometers (MWR) distributed throughout the Southern Great Plains (SGP) field site provide near-continuous observations of LWP (Liljegren et al. 2001). MWR retrieval 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 acquired for the period between 1 November, 2003 and 31 January, 2004 in order to validate AMSR-E retrievals. All AMSR-E observations located within 0.25 by 0.25 degree latitude/longitude boxes centered on the coordinates of each MWR were extracted, processed with the dual-frequency retrieval methodology and matched with corresponding LWP values from the corresponding MWR. A total of 570 pairs of AMSR-E and MWR retrievals were produced for the three month period.

A comparison of AMSR-E based and MWR-based LWP retrievals for the SGP dataset is presented as a scatterplot in Fig. 2. In the figure, retrievals for which AMSR-E brightness temperatures indicated scattering (according to the Ferraro algorithm) are plotted in red; these account for approximately 5% of the SGP retrievals. Plotted MWR values indicate the mean LWP observed for a two-hour period around the corresponding AMSR-E observation time; error bars indicate the LWP standard deviation over the same period. Analysis of the various statistics for the SGP comparisons reveals only a marginal dependence on the training set used to produce the PDP regression coefficients.

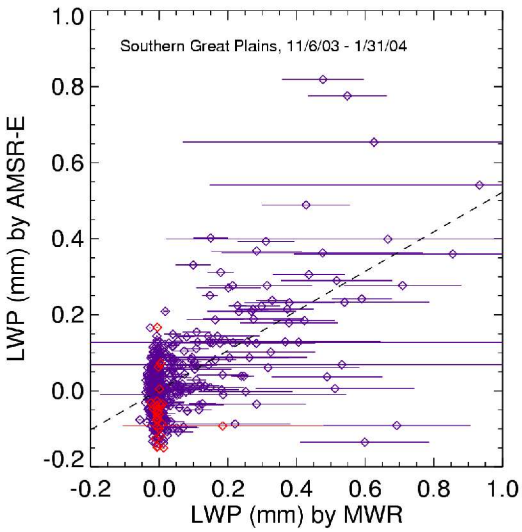

Figure 2. Scatterplot of LWP values retrieved using the AMSR-E dual-frequency method and corresponding MWR values in the Southern Great Plains region between November, 2003 and January, 2004. AMSR-E retrievals for which brightness temperatures indicated high scattering are plotted in red.

Analysis of AMSR-E and MWR LWP comparisons is much simpler in clear-sky conditions than during periods of significant cloudiness. Specifically, in clear-sky scenes, the "true" LWP is known to within a small uncertainty, and LWP spatial variability over the retrieval grid cell should be negligible. Other sources of retrieval error, including scattering from precipitating particles, are also minimized in clear-sky scenes. On the other hand, other important potential sources of retrieval error, including instrumental errors, ancillary data errors and variability of $\Delta\epsilon^{89}/\Delta\epsilon^{37}$ are not expected to be different during clear and cloudy conditions. Thus, analysis of AMSR-E retrieval errors in clear-sky scenes indicates the magnitude of at least an important subset of the entire set of retrieval error sources. For validation purposes, we define all scenes for which the mean MWR LWP over a two-hour period around the AMSR-E observation time was less than 0.05 mm as clear. We further assume that clear-sky conditions at the MWR location extended throughout the overlapping 0.25 by 0.25 degree latitude/longitude grid cell. Defined this way, clear-sky scenes constituted about 76% of all SGP scenes. Clear-sky bias and RMS error values for all SGP comparisons are typically about 0.01 and 0.06, respectively. These values are consistent with theoretically estimated uncertainty values.

Because of large differences in sampling area, comparisons of AMSR-E and MWR retrieval results in cloudy conditions depend on LWP variability over a large area. To clearly distinguish differences in AMSR-E and MWR retrieval results due to LWP spatial variability from actual retrieval errors would require additional instrumentation (e.g., multiple ground-based radiometers deployed within a single AMSR-E grid cell) to characterize the LWP over an extended region. The lack of such measurements currently prevents true validation of the AMSR-E based method in cloudy conditions (Wentz and Meissner 2000). Nevertheless, there exists a clear correlation between AMSR-E and MWR LWP values. The calculated correlation coefficient (excluding the observations indicating strong scattering) is approximately 0.4. However, as indicated by the least-squares fit slope values, AMSR-E based LWP retrievals are typically 40 to 50% less than corresponding MWR values. Possible sources for this apparent "scaling bias" include (1) errors in the forward radiative transfer model underlying the PDP, (2) parameterization errors associated with the PDP, (3) possible nonlinearity in the retrieval algorithm (coupled with LWP spatial variability) and (4) systematic errors in the MWR retrieval algorithm.

For one overpass of the SGP region on 3 December, 2003, LWP retrievals based on AMSR-E observations were compared with corresponding retrievals derived from the MODIS (the Moderate Resolution Imaging Spectrometer) instrument (King et al. 2000) on Aqua (the same platform as AMSR-E). Although MODIS-based LWP retrievals have not yet been extensively validated, the use of MODIS observations for evaluating AMSR-E LWP retrievals effectively eliminates problems related to sampling time and area. For each AMSR-E retrieval grid cell, the mean MODIS LWP value was obtained by averaging MODIS LWP retrievals for simultaneous observations geolocated in the same cell. Corresponding maps of LWP retrieved by AMSR-E and MODIS for the Aqua overpass occurring at approximately 1936 UTC on 3 December, 2003 are shown in Fig. 3. A scatterplot of the same data is presented in Fig. 4. At the time of the overpass, archived NEXRAD imagery do not indicate any precipitation in the region.

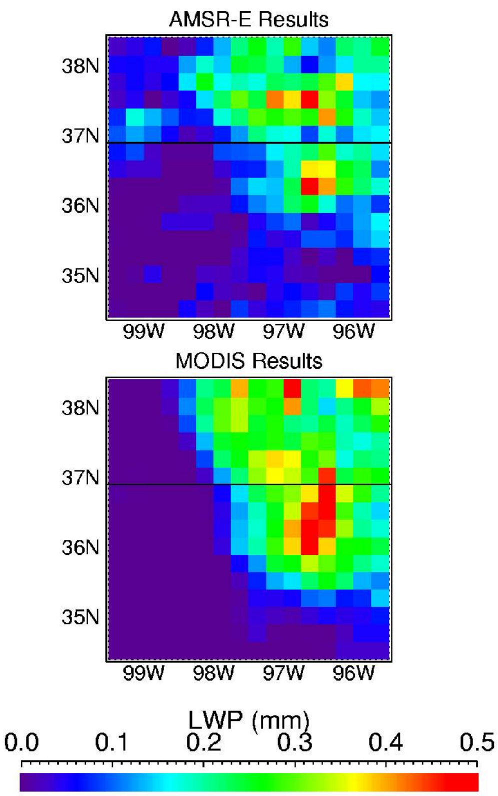

Figure 3. Comparison of AMSR-E and MODIS LWP retrieval results (commonly gridded) for overpass of SGP region at 1936 UTC on 3 December, 2003.

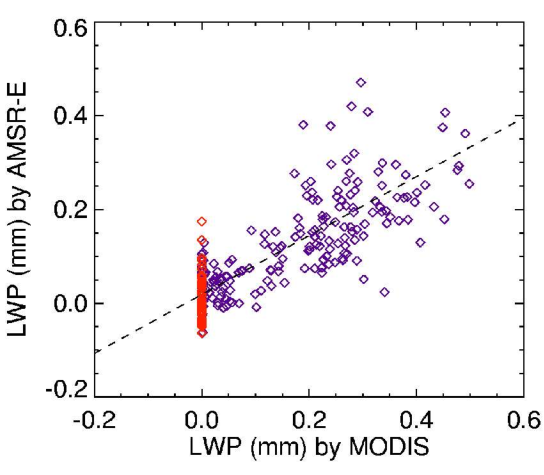

Figure 4. Scatterplot of AMSR-E and MODIS LWP retrieval results shown in Fig. 3. Comparisons plotted in red indicate clear sky conditions, as determined by MODIS.

Results of AMSR-E and corresponding MODIS LWP retrievals are generally consistent with AMSR-E/MWR comparisons. AMSR-E and cell-averaged MODIS LWP retrievals are well correlated with a correlation coefficient of 0.64. AMSR-E clear-sky bias (0.012 mm) and RMS error (0.044 mm) results are within the uncertainty estimated by propagation of errors analysis. Also like the AMSR-E/MWR comparisons, the AMSR-E/MODIS least-squares fit slope value (0.63) suggests a possible “scaling bias” of the AMSR-E LWP values.

4. CONCLUSION

All satellite-based methods for retrieving LWP suffer from fundamental limitations. No method based on any single instrument will likely ever be capable of retrieving LWP in all conceivable situations (with respect to solar illumination, surface type, and cloud structure) with high accuracy. Therefore, to support widely varying applications, new methods which complement the capabilities of current established techniques are highly desired. We have developed and demonstrated a new “stand-alone” satellite-based method for retrieving LWP in non-precipitating clouds over land using passive microwave observations from the AMSR-E instrument. Unlike existing methods based on visible/infrared radiances, the new method is applicable day and night and is insensitive to the presence of overlying cirrus clouds.

The new method is based on a new parameterization which simply relates AMSR-E polarization-difference signals to two surface parameters (temperature and $\Delta\epsilon$) and two atmospheric parameters (LWP and PWV). Fundamentally different methods for calculating the parameterization coefficients ultimately produce only weak variability in the LWP retrieval results. Thus, the parameterization seems valid over highly variable atmospheric conditions.

For the Southern Great Plains region in the United States, theoretical estimates and MWR-based validation results both indicate LWP root-mean-square errors close to 0.06 mm in clear-sky conditions. Results for cloudy conditions are more difficult to interpret, partly because of the large disparity between the sampling areas of the MWR instrument and the AMSR-E retrieval grid cell. Nevertheless, calculated correlation coefficients for AMSR-E and MWR-based retrieval results for both the SGP region and area around Montreal, Canada (to be presented elsewhere) are reasonable (in the range of 0.4 to 0.6).

Further validation will be required to demonstrate the applicability of the new method over surface types distinctly different from those found in the SGP and Montreal regions. The sparseness of operational ground-based MWR instruments (like those deployed at the ARM SGP site) favors other satellite-based methods (e.g., MODIS) for validating AMSR-E retrievals in other regions. Retrieval errors are expected to increase as surface emissivity values approach unity (where $\Delta\epsilon$ tends towards zero); densely forested regions may be the most difficult case. However, the similarity of $\Delta\epsilon$ values at 37 and 89 GHz, which the dual-frequency method described here assumes, appears valid over a wide variety of land surface types in North America (Ruston and Vonder Haar 2004).

5. REFERENCES

Combs, C. L., T. J. Greenwald, A. S. Jones, D. L. Randel, and T. H. Vonder Haar,1998: Satellite detection of cloud liquid water over land using polarization differences at 85.5 GHz, *Geophys. Res. Lett.*, **25**, 75-78.

Deeter, M. N., and J. Vivekanandan, 2005: AMSU-B observations of mixed-phase clouds over land, *J. Appl. Met.*, **44**, 72-85.

Greenwald, T. J., C. L. Combs, A. S. Jones, D. L. Randel, and T. H. Vonder Haar, 1997: Further developments in estimating cloud liquid water over land using microwave and infrared satellite measurements, *J. Appl. Met.,* **36**, 389-405.

Greenwald, T. J., C. L. Combs, A. S. Jones, D. L. Randel, and T. H. Vonder Haar, 1999: Error estimates of spaceborne passive microwave retrievals of cloud liquid water over land, *IEEE Trans. Geosci. Remote Sens.*, **37**, 796-804.

Gueldner, J., and D. Spaenkuch, 2001: Remote sensing of the thermodynamic state of the atmospheric boundary layer by ground-based microwave radiometry, *J. Atmos. Ocean. Techn.*, **18**, 925-933.

King, M. D., W. P. Menzel, Y. J. Kaufman, D. Tanre, B. C. Gao, S. Platnick, S. A. Ackerman, L. A. Remer, R. Pincus, and P. A. Hubanks, 2003: Cloud and aerosol properties, precipitable water, and profiles of temperature and humidity from MODIS, *IEEE Trans. Geosci. Remote Sens.*, **41**, 442-458.

Liljegren, J. C., E. E. Clothiaux, G. G. Mace, S. Kato, and X. Dong, 2001: A new retrieval for cloud liquid water path using a ground-based microwave radiometer and measurements of cloud temperature, *J. Geophys. Res.*, **106**, 14,485-14,500.

Ruston, B. C., and T. H. Vonder Haar, 2004: Characterization of summertime microwave emissivities from the Special Sensor Microwave Imager over the conterminous United States, *J. Geophys. Res.*, **109**, D19103, doi:10.1029/2004JD004890.

Wentz, F. J., and T. Meissner, 2000: AMSR Ocean Algorithm: Algorithm Theoretical Basis Document, Ver. 2, Remote Sensing Systems Technical Proposal RSS121599A-1 (*available at http://eospso.gsfc.nasa.gov/eos_homepage/for_scientists/atbd*)