Cloud-fraction-dependent bias in satellite liquid water path retrievals of shallow, non-precipitating marine clouds

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Received 17 May 2007; revised 20 September 2007; accepted 5 October 2007; published 20 November 2007.

[1] This study compares Wentz microwave liquid water path retrievals with MODIS and MISR optical estimates in shallow, non-precipitating marine clouds. In overcast conditions, the microwave and optical estimates are comparable; however, as cloud fraction decreases microwave retrievals strongly and increasingly overestimate optical ones. This positive microwave bias cannot be explained neither by the elimination of negative values in the operational Wentz dataset, nor by the somewhat reduced sensitivity of MODIS cloud detection to small clouds.
Citation: Horváth, Á., and C. Gentemann (2007), Cloud-fraction-dependent bias in satellite liquid water path retrievals of shallow, non-precipitating marine clouds, *Geophys. Res. Lett.*, *34*, L22806, doi:10.1029/2007GL030625.

1. Introduction

[2] Shallow oceanic clouds, such as marine stratocumulus and trade wind cumulus, have a strong impact upon the global radiative energy balance due to their ubiquitous nature. They represent the major source of uncertainty in simulated tropical cloud feedbacks because Global Climate Models underestimate the interannual variability of their albedo [*Bony and Dufresne*, 2005], which is mostly determined by their liquid water path (LWP).

[3] Currently, cloud LWPs can be either retrieved from passive satellite microwave brightness temperature measurements or deduced from visible/near-infrared solar reflectances. Low-level marine clouds offer the least challenging cases to both retrieval techniques. These clouds consist entirely of liquid drops; hence, there is no ice scattering contribution to the measured brightness temperature, allowing the use of simple emission-based microwave algorithms. Visible/near-infrared sensors, which infer cloud LWP from optical thickness and droplet effective radius, also benefit from the absence of complicated ice scattering. Furthermore, these clouds are thought to be the best candidates for 1D plane-parallel radiative transfer used exclusively in operational optical retrievals.

[4] However, the Clouds with Low Optical (Water) Depth (CLOWD) project has recently found that large discrepancies exist among the various ground-based and satellite LWP retrieval techniques even for the simplest single-layer overcast stratocumulus case [*Turner et al.*, 2007]. This is particularly worrisome because CLOWD has also shown that longwave and shortwave radiative fluxes are very sensitive to LWP in thin water clouds.

[5] Motivated by these challenges, in this paper we follow up on our recent comparison of microwave water path retrievals from the Tropical Rainfall Measurement Mission (TRMM) Microwave Imager (TMI) and optical water path retrievals from the Moderate Resolution Imaging Spectroradiometer (MODIS) and Multiangle Imaging SpectroRadiometer (MISR) instruments [*Horváth and Davies*, 2007; hereafter HD07]. In HD07 microwave and optical cloud water path estimates had good overall consistency for warm, non-precipitating clouds, although microwave LWP retrievals increasingly overestimated optical ones at lower cloud amounts. This study further investigates the cloud-fraction-dependent microwave-optical bias, which is most likely due to errors in both techniques. In optical retrievals the plane-parallel assumption is often a poor one and 3D effects (side leakage, shadowing, and illumination) can be significant error sources [*Horváth and Davies*, 2004]. In broken Cu and Sc clouds, however, 3D effects partly cancel out when calculating LWP, because overestimation of effective radius tends to go in pair with underestimation of optical thickness, and vice versa [*Marshak et al.*, 2006]. Quantifying 3D optical effects also requires very high resolution imagery and in-situ cloud microphysical data as inputs, which is beyond the limitations of the satellite data considered here. Therefore, we leave the topic of 3D optical effects to a later study and focus instead on two particular issues within reach of our current dataset. Specifically, we investigate to what degree the microwave-optical bias observed in warm clouds can be explained by (i) the elimination of negative microwave LWP retrievals, or (ii) cloud detection errors in 1D optical retrievals.

2. Data and Methodology

[6] Our microwave retrievals were produced by the Wentz algorithm, which simultaneously finds cloud LWP, water vapor path (WVP), rain rate, and near-surface wind speed by fitting TMI brightness temperatures [*Wentz*, 1997]. These parameters are available as daily 0.25° gridded maps; however, one should note that actual TMI footprints are elliptical, varying in size from 16×9 km^2 at 37 GHz to 63×37 km^2 at 10.65 GHz. The Wentz algorithm resamples channels to a common footprint, calculates atmospheric parameters, and then averages them on a uniform 0.25°-resolution grid. Due to resampling and channel side lobes a portion of the microwave signal comes from outside the $0.25° \times 0.25°$ grid cell. In order to rule out possible biases caused by the footprint-to-grid conversion or side lobes, we have made calculations for actual 10.65-GHz footprints as well. These computations have not changed our conclu-

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0094-8276/07/2007GL030625$05.00

sions, thus we only present results for the nominal 0.25°-grid.

[7] Since HD07 the TMI dataset has been upgraded from Version 3 to Version 4 (www.ssmi.com/support/2006_09_update_to_RSS_Climate_Data_Records.html). Because the effect of these changes on LWP estimates and LWP-WVP error correlations is negligible, only the latest V4 Wentz product is considered here. A more important caveat to note is the truncation of LWP estimates at zero. For clouds with small liquid water amounts microwave LWP retrievals can yield negative values, which are eliminated from the dataset. Since setting all negative values to zero would cause an obvious bias, untruncated V4u retrievals are converted to operational V4 values by a smoothly varying function plotted in Figure 1a. This transformation leaves data above 70 g m^{-2} unchanged, sets negative values essentially to zero, but also reduces smaller positive LWPs. Because retrievals are additionally quantized to the nearest multiple of 10 g m^{-2}, LWPs originally in the 10–40 g m^{-2} range are typically reduced by 10–20 g m^{-2} in the operational V4 product.

[8] Our first optical dataset comprised 1–km resolution MODIS-Terra retrievals of cloud LWP, optical thickness, droplet effective radius, cloud phase, and cloud mask from the MOD06 and MOD35 products [*Platnick et al.*, 2003]. The Collection 4 data used in HD07 have recently been upgraded to Collection 5 (http://modis-atmos.gsfc.nasa.gov/products_C005update.html). Unlike the Wentz update, the MODIS upgrade does cause significant changes in our analysis; therefore, we present results for both Collection 4 and Collection 5 data.

[9] The second optical dataset contained 1.1-km resolution cloud optical thickness and cloud mask estimated from MISR nadir (AN) camera reflectances [*Diner et al.*, 1999]. Lacking a water-absorbing channel, MISR optical thickness is interpolated or extrapolated from visible channel reflectances computed for fixed effective radii of 5, 8, and 15 μm. Both optical thickness interpolation and then conversion to LWP requires MODIS or some other effective radius as ancillary data. Our objective here is to test what effect the MISR Radiometric Camera-by-camera Cloud Mask (RCCM) has on the microwave-optical bias compared to the MODIS cloud mask.

[10] As in HD07, TRMM-Terra coincidences no more than 15 minutes apart are selected. Areas where TMI indicates the presence of rain or MODIS the presence of ice or mixed-phase droplets are excluded. The resulting scenes are mainly of low-level marine boundary layer clouds with tops typically below 800 mb. Consequently, uncertainty in cloud temperature, which can otherwise be an error source in microwave retrievals, has little impact on our results. We note, however, that our optical LWP estimates assume vertically homogeneous effective radius and show ~20% overestimation compared to an adiabatic stratification which would be a more suitable model for boundary layer clouds [*Bennartz*, 2007].

[11] The 1D optical retrievals are first averaged within the large microwave grid cells, then each optical mean is renormalized by the corresponding subgrid cloud fraction in order to account for the fact that optical LWPs are computed for cloudy areas only, while microwave LWPs are averages over the total (clear plus cloudy) area of a grid cell. (However, no beam-filling correction is applied to our microwave LWPs as beam-filling is only considered in the Wentz algorithm under raining conditions.) The final dataset consists of ~16,000 coincident, 0.25°-resolution microwave-optical LWP pairs predominantly from August 2003 and February 2004, representing an order of magnitude increase in sample size compared to HD07.

3. Microwave LWPs in Cloud-Free Areas

[12] First, we investigate Wentz microwave LWPs for possible biases in clear areas, where one would expect a distribution centered on zero and having both small negative and positive values. Cloud-free microwave grid cells are identified using our optical cloud masks. The MODIS cloud mask (MOD35) classifies each 1-km pixel as confident clear, probably clear, uncertain/probably cloudy, and cloudy/not clear. Similarly, the MISR RCCM classifies a 1.1-km pixel as high-confidence cloudy, low-confidence cloudy, low-confidence clear, and high-confidence clear. In this section, we only treat confident clear MODIS and high-confidence clear MISR pixels as clear while everything else is considered cloudy in order to be as clear-conservative as possible. A recent comparison of MODIS and MISR products with 15-m-resolution imagery from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) has shown that the MISR cloud mask is much more clear-conservative than the MODIS cloud mask. The average agreement rate with the perfect ASTER clear-conservative cloud mask has been 62% for MODIS and 83% for MISR [*Zhao and Di Girolamo*, 2006]. Therefore, we expect the MISR RCCM to be more accurate than MODIS at filtering out cloud contaminated domains. However, even the MISR cloud mask is imperfect, thus there might be scenes identified as 'clear' that still contain some undetected small clouds. We will attempt to address this limitation of MODIS/MISR-type moderate resolution cloud masks in a future study by examining coincident TMI and very high-resolution ASTER observations.

[13] With the caveats noted above, we plot microwave LWP histograms in clear areas for the operational truncated V4 data (Figure 1b), and the raw, untruncated V4u data (Figure 1c) with red, green, and black corresponding to the MODIS Collection 4, MODIS Collection 5, and MISR RCCM cloud mask, respectively. As shown, results are very similar for all three cloud masks. The only difference is in the number of clear samples due to the varying sensitivity to (small) clouds, with MODIS Collection 4 apparently being the least clear-conservative, MISR RCCM being the most clear-conservative, and MODIS Collection 5 being in between. Conversely, histograms for V4 and V4u microwave data are very different. The untruncated V4u dataset contains a few (~1%) negative values; however, it also contains many more LWPs at 20–30 g m^{-2} and much fewer LWPs at 10 g m^{-2} compared to the truncated V4 dataset. (This is explained by the particular transformation between V4 and V4u data shown in Figure 1a.) In both cases microwave LWP retrievals have an overall positive bias: 15 g m^{-2} for untruncated V4u data and 12 g m^{-2} for truncated V4 data. The bias also depends on column water vapor, with LWP histograms shifting to larger values for higher WVPs. As shown in Figure 1d, the V4u bias

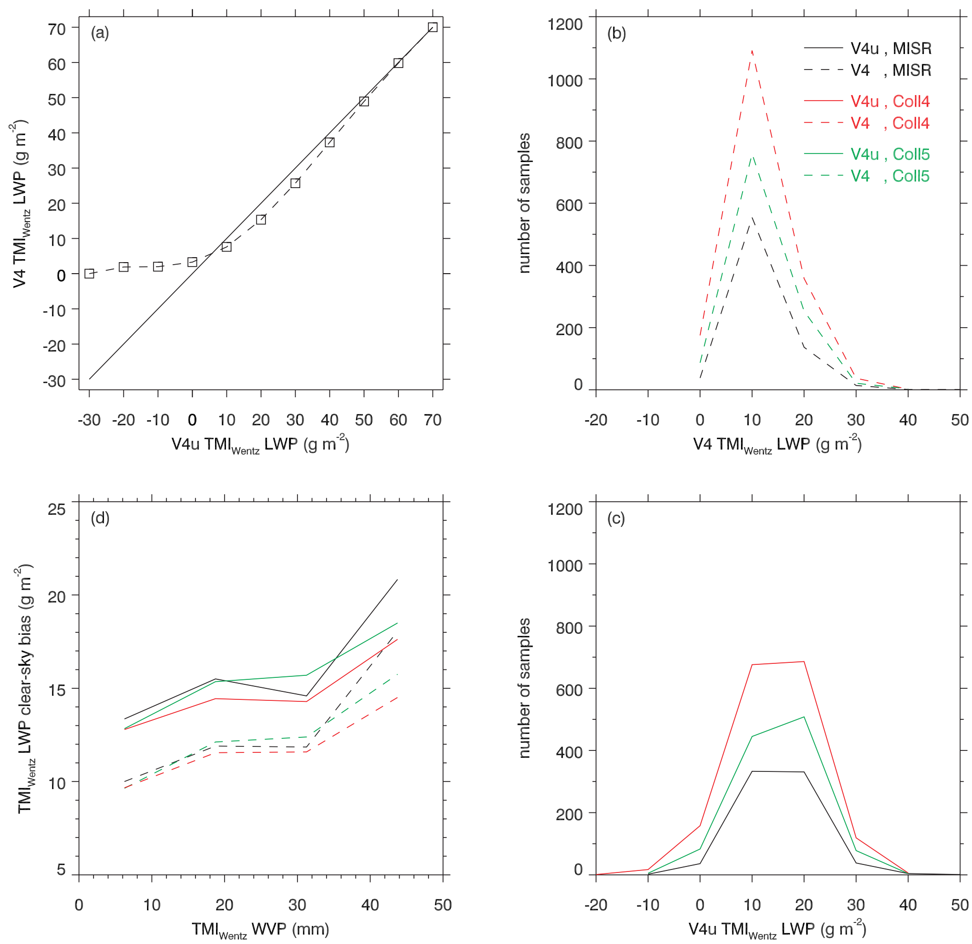

Figure 1. (a) Truncated V4 versus untruncated V4u Wentz LWP values. The solid line represents a 1:1 relationship. (b) Truncated V4 and (c) untruncated V4u Wentz LWP histograms for clear grid cells identified by the MODIS Collection 4, MODIS Collection 5, and MISR AN RCCM cloud masks, and (d) the corresponding clear-sky LWP bias as a function of water vapor path.

increases from 13 g m^{-2} in the driest scenes to 18–19 g m^{-2} in the wettest scenes, while the V4 bias is consistently smaller by ~3 g m^{-2}.

4. Microwave-Optical Bias Versus Cloud Fraction

[14] In this section, we investigate the dependence of microwave-optical bias on subdomain cloud fraction determined from the optical cloud masks. Here, both cloudy and probably cloudy (MODIS), and high-confidence and low-confidence cloudy (MISR) pixels are treated as clouds. As MISR LWP calculations require ancillary effective radius information, we use MODIS effective radii where available. However, MISR is more sensitive to small clouds than MODIS, resulting in large numbers of cloudy MISR pixels with no MODIS cloud property retrievals. For such MISR pixels we assume a constant effective radius of 15 μm, which is a typical cloud-top value obtained from in-situ Fast-Forward Scattering Spectrometer Probe (FFSSP) measurements during the Rain in Cumulus over the Ocean (RICO) campaign [*Rauber et al.*, 2007], and it is also the modal value of MODIS effective radii in our dataset.

[15] In general, microwave and optical LWP estimates become more consistent with increasing cloud fraction. As an example, Figure 2 shows histograms of Wentz V4u minus MODIS Collection 5 LWP differences for low, medium, and high cloud fraction bins. Clearly, the LWP difference distribution shows less and less positive shift as cloud fraction increases, and for overcast cases it is correctly centered on zero. As a result, the bias between microwave and optical retrievals sharply decreases with increasing cloud fraction: 27 g m^{-2}, 18 g m^{-2}, and −3 g m^{-2}, respectively, for the three bins shown. This is accompanied by an increase in correlation (0.45, 0.63, and 0.70, respectively) and also in root-mean-square difference (18 g m^{-2}, 32 g m^{-2}, and 45 g m^{-2}, respectively). Note that there are some domains with rather large (≥100 g m^{-2}) instantaneous LWP differences. Visual inspection finds these cases representing temporal and spatial mismatches. For example, cloud development can be a significant factor when the TRMM-Terra time difference is relatively large (10–15 minutes). Additionally, "leakage" from neighboring grid cells might affect the gridded and averaged microwave signal due to side lobes and the elliptical nature of actual footprints, and can result in a sharp microwave-optical contrast at cloud edges.

[16] The dependence of the microwave-optical LWP bias on cloud amount is plotted in more detail in Figure 3a for all

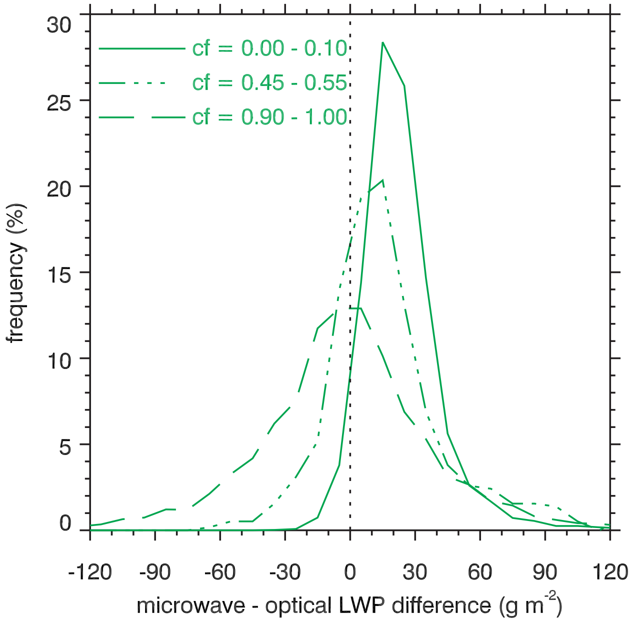

Figure 2. Histograms of the difference between Wentz V4u and MODIS Collection 5 LWPs for cloud fraction (cf) bins of 0–10%, 45–55%, and 90–100%.

possible data combinations. The most striking feature is the general decrease of the bias with cloud fraction in all cases. Domains with the lowest cloud amounts show a microwave LWP overestimation of 20–30 g m^{-2}, exceeding the clear LWP bias of ~15 g m^{-2}. For overcast domains, however, the bias is within ±5 g m^{-2}. (This range of absolute biases corresponds to relative biases in microwave LWPs between 100% and ±5%.) Similarly to clear cases in section 3, the bias is slightly reduced for the operational truncated V4 data. This is caused by a 1–3 g m^{-2} decrease in bin-average microwave LWPs due to the smoothed truncation function shown in Figure 1a. At lower cloud fractions (<40%) MISR shows the best agreement with microwave values probably due to its increased sensitivity to small clouds. At higher cloud fractions (>50%), the microwave-optical bias is smallest for the latest MODIS Collection 5 data. These results indicate that the somewhat reduced sensitivity of the MODIS cloud mask to small clouds might be a factor at lower cloud fractions, but it can only explain a relatively small portion (5–7 g m^{-2}) of the microwave-optical bias and cannot explain the cloud-fraction dependence.

[17] Now, let us consider the sensitivity of these results to column water vapor. Inclusion of WVP in the analysis is supported by the fact that the older gaseous absorption

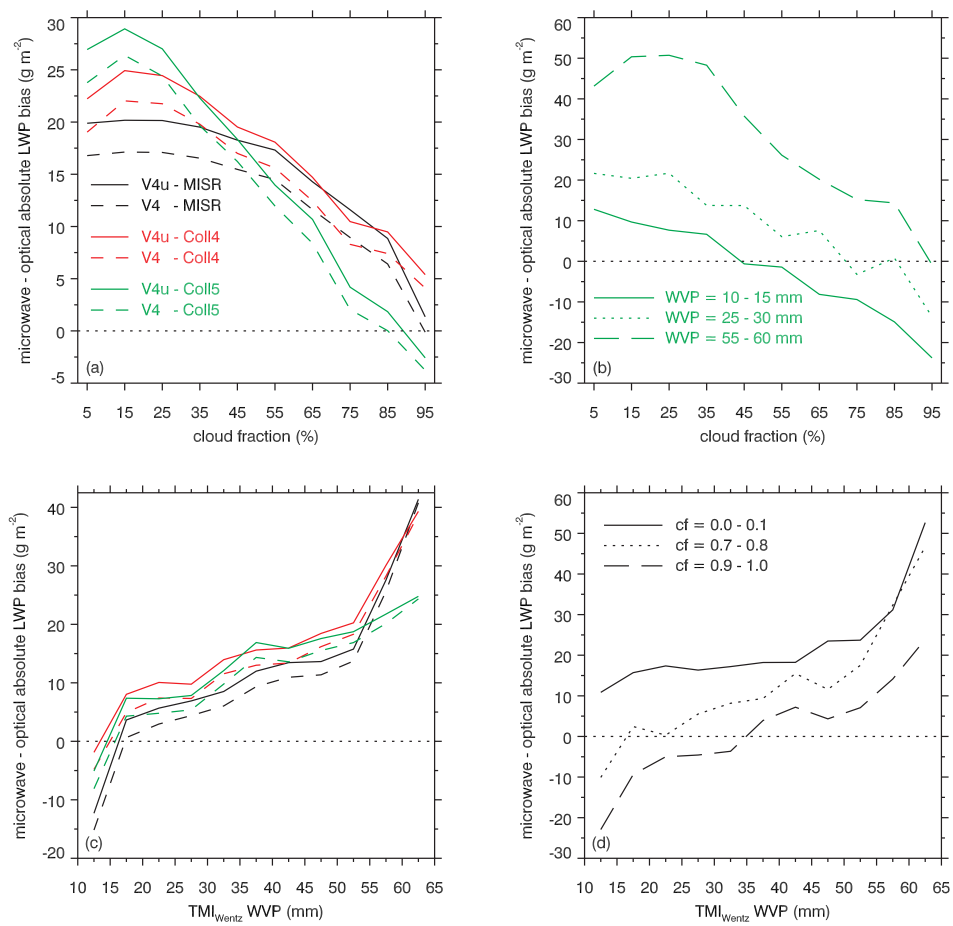

Figure 3. Microwave-optical absolute LWP bias versus (a and b) cloud fraction and (c and d) water vapor path. Figures 3a and 3c show all data for all possible microwave-optical combinations (same legend), while Figures 3b and 3d show results for Wentz V4u – MODIS Collection 5 data in three WVP bins and Wentz V4u – MISR data in three cloud fraction bins, respectively.

model used in the Wentz algorithm can result in LWP overestimations compared to the most recent models featuring an improved depiction of the water vapor continuum, as shown by *Zuidema et al.* [2005]. As an example, the (V4u – MODIS Collection 5) bias versus cloud fraction is given for separate WVP bins in Figure 3b (note that results in Figure 3a are averaged over all WVPs). The bias decreases with increasing cloud fraction in all cases, however, its sign and magnitude clearly depends on WVP. For a given cloud fraction the bias increases with WVP. In addition, the bias tends to be positive for larger WVPs, but in the driest cases it can be both positive and negative depending on cloud fraction, which can lead to cancellation of errors. The latter is clearly shown in Figure 3c plotting the bias versus WVP for all possible data combinations (and averaged over all cloud fractions). For the lowest WVPs (10–15 mm) the bias is close to zero due to cancellation of errors and then it is increasingly positive as the atmosphere moistens. Finally, we plot the WVP-dependence of the (V4u – MISR) bias for individual cloud fraction bins in Figure 3d. In general, the bias increases with increasing WVP and for a given WVP the bias increases with decreasing cloud fraction. For low to medium cloud fractions the bias is always positive, but for the highest cloud fractions it can be both positive and negative depending on WVP, which can, again, lead to cancellation of errors. In fact, this cancellation of errors seems mainly responsible for the small overall bias found previously in overcast cases. The above results suggest that the microwave-optical bias is a function of not only cloud fraction (or LWP since it is positively correlated with cloud fraction) but also WVP.

5. Summary and Conclusions

[18] Wentz microwave LWPs have been compared with MODIS and MISR optical retrievals in order to further evaluate an apparent cloud-fraction-dependent bias between the algorithms in warm, non-precipitating marine clouds. The techniques show good agreement in overcast regions; however, microwave retrievals increasingly overestimate optical ones as subdomain cloud fraction decreases. Although the operational Wentz algorithm eliminates negative LWP values, the results using untruncated LWP retrievals indicate that this is not the source of the observed positive microwave bias. On the contrary, the particular truncation employed in this dataset even decreases the bias by $\sim$3 g m^{-2} whereby setting negative values to zero is overcompensated by a reduction in smaller positive LWPs. Analysis of cloud-free areas suggests a growing clear-sky bias as WVP increases, with an average value of $\sim$15 g m^{-2} in untruncated Wentz LWPs.

[19] It is also found that the somewhat reduced sensitivity of the MODIS cloud mask to small cumulus cannot explain the cloud-fraction dependence of the bias. The MISR RCCM does indeed pick up quite a few more small clouds than MODIS; however, this only reduces the bias at lower cloud fractions without eliminating the marked overall dependence on cloud amount. A further stratification of cloudy results indicates sensitivity to column water vapor as well. In general, the bias tends to increase with WVP, but its sign and exact magnitude also depend on cloud fraction (or LWP). In addition, this analysis suggests that the small overall bias in overcast regions might be mainly due to cancellation of errors whereby microwave LWP is underestimated at lower WVPs and overestimated at higher WVPs.

[20] The above findings indicate that eliminating the clear-sky bias and WVP dependence from Wentz retrievals would significantly reduce microwave-optical LWP discrepancies. In addition, extending the beam-filling correction to non-raining microwave LWPs might also reduce the observed bias. We emphasize that while errors in 1D optical retrievals certainly influence the results, they are unlikely to explain the microwave overestimation in broken cloud fields. Overall, 3D effects tend to cause a strong positive bias of up to a factor of 2 in 1D effective radius [*Marshak et al.*, 2006], but only a moderate negative bias of $\sim$50% in 1D optical thickness [*McFarquhar et al.*, 2004; L. Di Girolamo, personal communication, 2007]. The likely net effect of these errors and the assumption of vertically homogeneous effective radius is an overestimation in our optical LWPs at low cloud fractions, suggesting a true microwave-optical bias even larger than what we have found in this study. Because quantification of 3D effects is beyond the limitation of the medium-resolution optical data considered here, such optical retrieval errors will be investigated in a future study combining high-resolution ASTER imagery with ground-based cloud radar and in-situ aircraft data collected during the RICO campaign.

[21] **Acknowledgments.** This research was partially supported by grant # ER64035 from the DOE/ARM program. TMI data were produced by Remote Sensing Systems and sponsored by the NASA Earth Science REASoN DISCOVER Project. Data are available at www.remss.com. MODIS data were provided by the NASA Goddard Space Flight Center Level 1 and Atmosphere Archive and Distribution System, while MISR data were supplied by the NASA Langley Research Center Atmospheric Science Data Center. J.-L. Brenguier provided the RICO FFSSP dataset. We thank Paquita Zuidema, Larry Di Girolamo, and two anonymous reviewers for useful suggestions.

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