COMPARISON OF MICROWAVE AND OPTICAL CLOUD WATER PATH ESTIMATES FROM TMI, MODIS, AND MISR

Ákos Horváth and Roger Davies

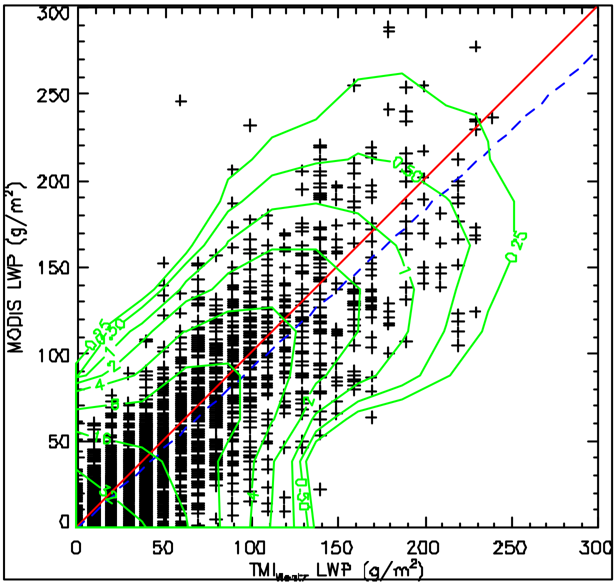
Jet Propulsion Laboratory, California Institute of Technology
Pasadena, California, 91109, USA

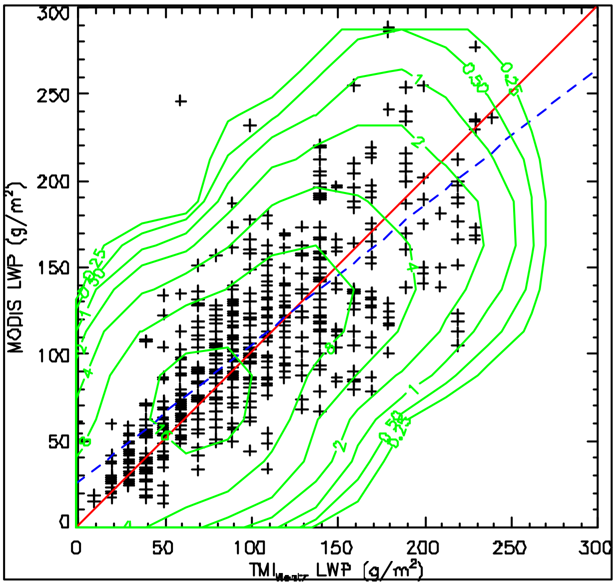
1. Objectives

In this study, we compared water path retrievals of oceanic clouds obtained by current state-of-the-art microwave and optical methods in order to investigate the error characteristics of the two techniques. Here, optical estimates from Terra were compared against microwave estimates from coincident passes of the TRRM satellite. Optical estimates were parameterized from cloud optical thickness and particle effective radius obtained by MODIS, and evaluated with the help of multiangle MISR data. The TMI microwave data set consisted of cloud liquid water path (LWP) from the Wentz algorithm and cloud liquid water path, cloud ice water path (IWP), and cloud total water path (TWP) from the standard 2A12 profiling algorithm. We performed our analysis at a domain scale of 25 km, separately for warm non-precipitating clouds and cold precipitating clouds.

2. Warm Non-Precipitating Clouds

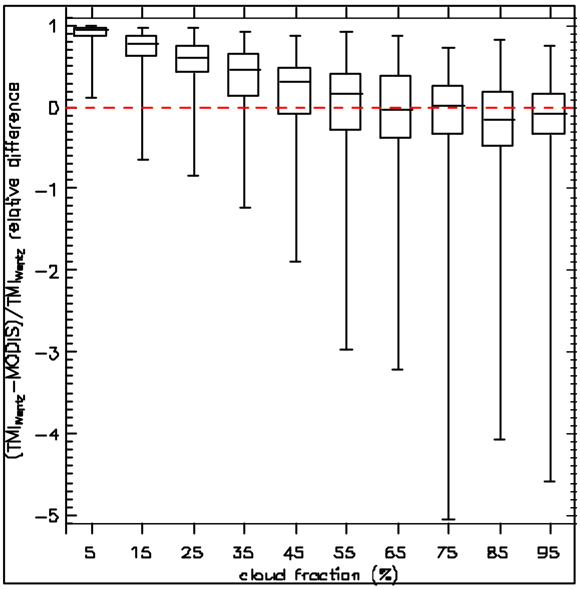
For these clouds only Wentz retrievals were available, which were scaled by the sub-domain cloud fraction before the comparison with optical retrievals. Scatter plots of MODIS LWP versus Wentz LWP for all and overcast domains are shown below.





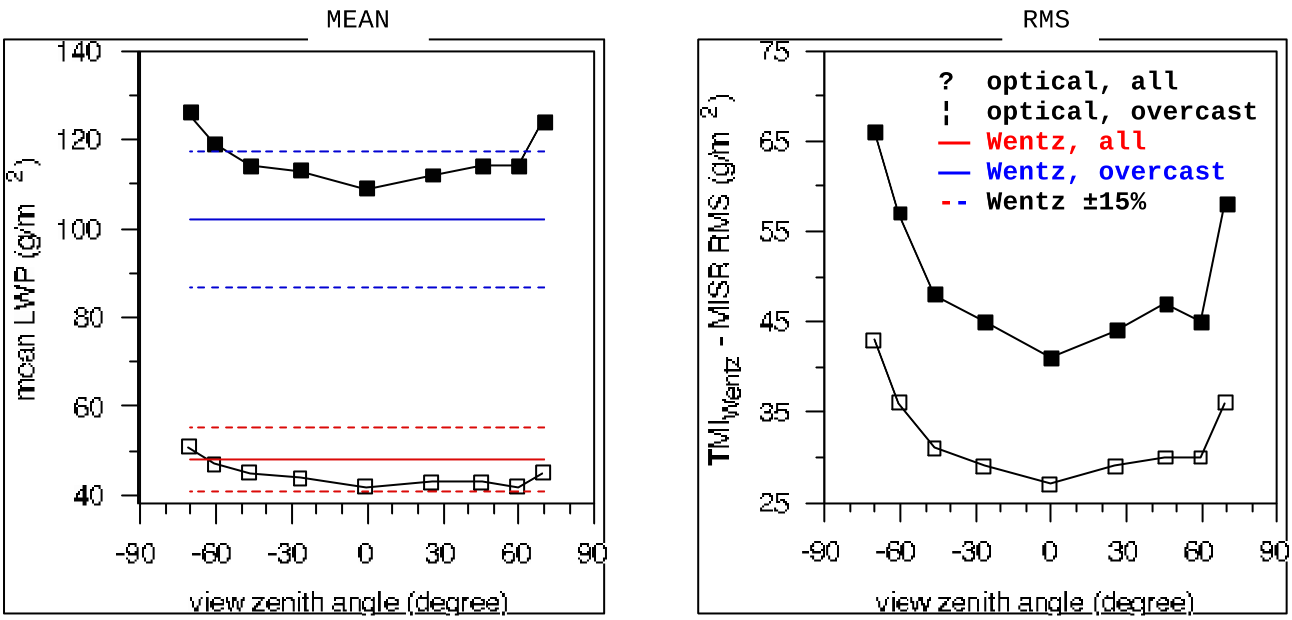
In this and similar figures the blue dash line is a linear fit to the data, and green curves are relative density contours in arbitrary units. When all domains were considered, the mean Wentz LWP of 47 g m^{-2} was slightly higher than the mean MODIS LWP of 42 g m^{-2}, and the rms difference between the data sets was 25 g m^{-2}

with a correlation coefficient of 0.85. For overcast domains, on the other hand, the mean Wentz LWP of 102 g m^{-2} was slightly lower than the mean MODIS LWP of 106 g m^{-2}, and the rms difference was 36 g m^{-2} with a correlation of 0.78. These results indicated that the Wentz-MODIS relative LWP difference was a function of cloud fraction, which is depicted in the following box-whisker plot.



For the lowest cloud fractions Wentz LWPs were biased high by ~15 g m^{-2} in comparison with MODIS LWPs. For larger cloud fractions, however, this high bias disappeared. Possible explanations for the bias included exclusion of negative retrievals in the Wentz data set, use of older (pre-1995) gaseous and liquid absorption models in the Wentz algorithm, or the MODIS cloud mask missing some popcorn Cu clouds and hence underestimating the sub-domain cloud fraction.

We also evaluated the validity of the above plane-parallel optical LWP retrievals by combining MISR angular optical thicknesses with MODIS effective radii and analyzing the view angle dependence of the results.

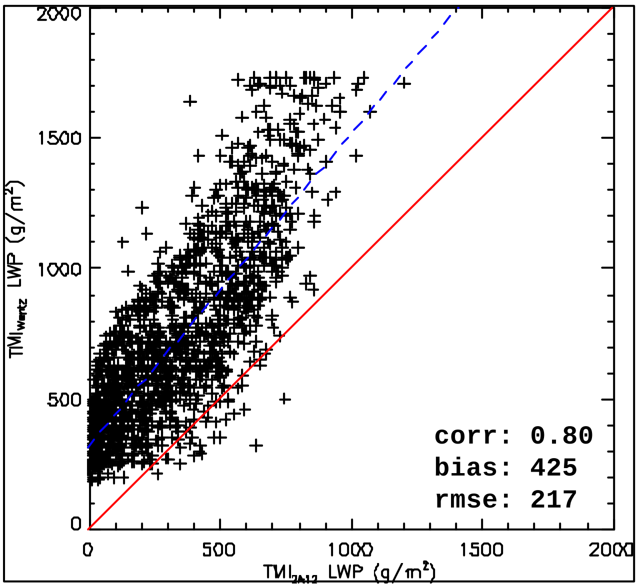


As shown, the mean optical LWP showed a small increase with view zenith angle, but generally remained within ±15% of the microwave mean. However, the microwave-optical comparison also became noisier as the view zenith angle increased. Nevertheless, the relatively weak view angle dependence of the results indicated some confidence in the optical LWP retrievals. These coarse resolution results can be contrasted with the high resolution multiangle analysis of Horváth and Davies (2004). Our angular consistency test applied to simultaneous pixel-level (275-m) radiances suggested that only ~20% of maritime liquid water clouds fit a 1D model within ±5%. Here, the good consistency of mean angular optical LWP values suggested that heterogeneity errors mostly canceled out when calculating large scale averages. This was not surprising for thin boundary layer clouds because the relationship between reflectance and optical thickness was close to linear.

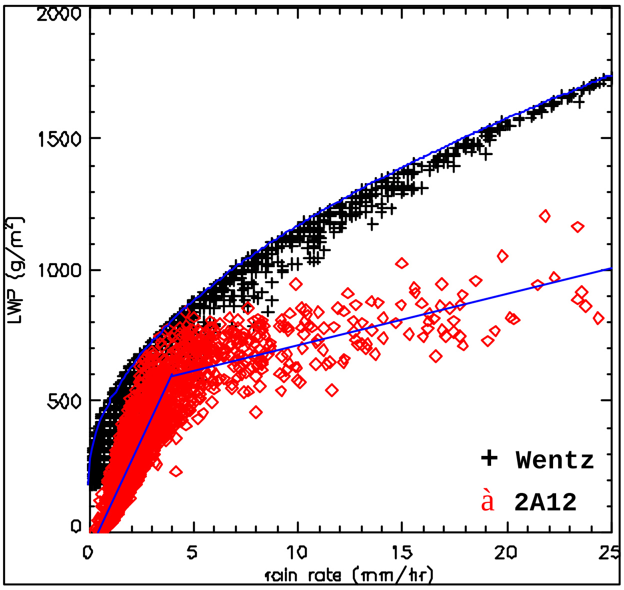
3. Cold Precipitating Clouds

Before analyzing microwave and optical estimates for cold precipitating clouds, we compared the corresponding Wentz and 2A12 cloud LWP retrievals and investigated their rain rate dependence.

WENTZ LWP *vs.* 2A12 LWP



LWP *vs.* RAIN RATE

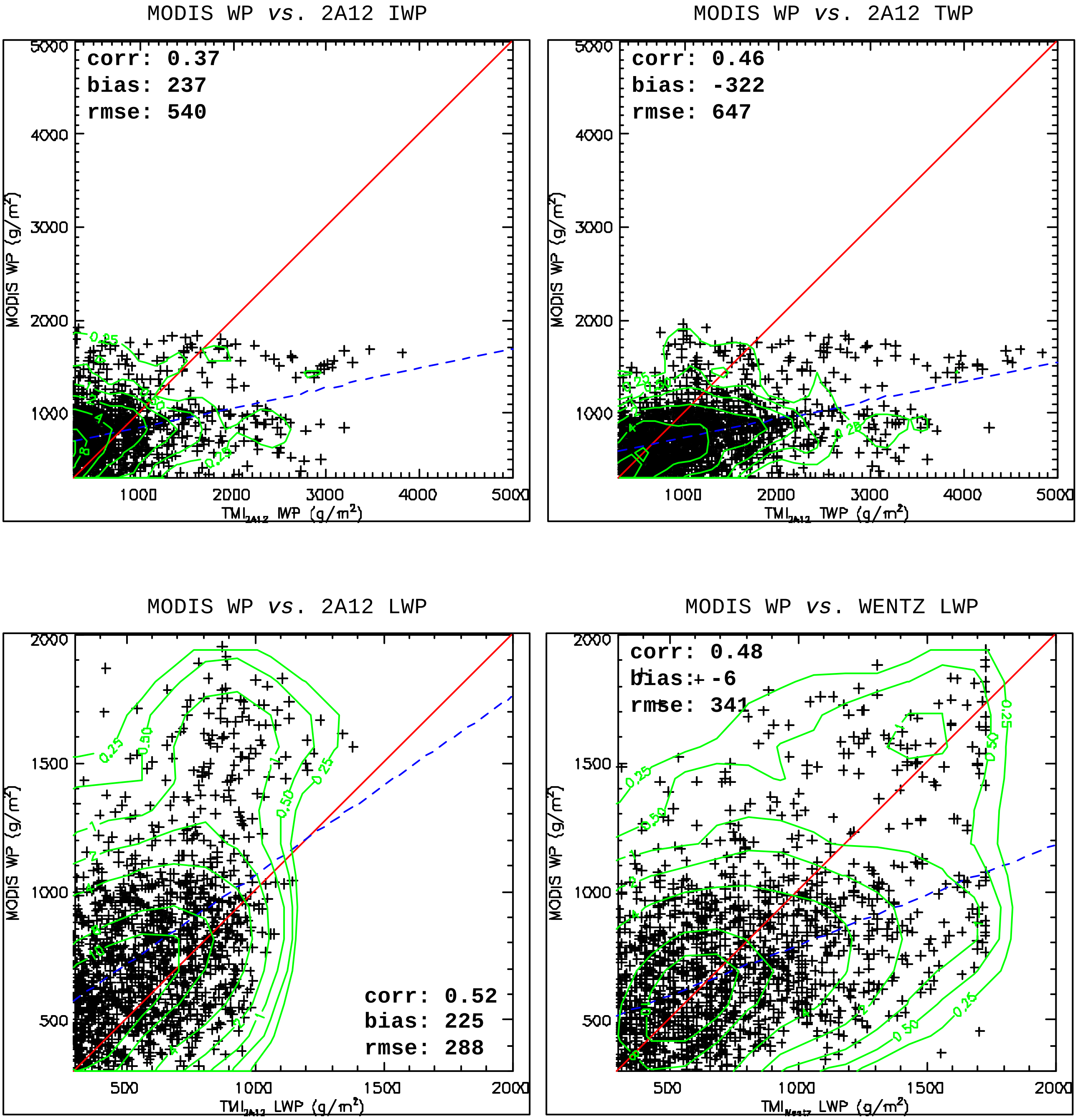


As shown, the two microwave cloud LWP estimates were highly correlated with correlation coefficient 0.80; however, 2A12 retrievals were biased low by ~400 g m^{-2}. This low bias could partly be explained by analyzing the rain rate dependence of the retrievals. Cloud LWP showed a strong increase with rain rate in both data sets with a correlation coefficient of 0.96 and 0.77 for the Wentz[1] and 2A12[2] algorithm, respectively. The 2A12 algorithm, however, produced physically inconsistent results in as much as it assigned zero cloud LWP to a zero rain rate. This result was obviously incorrect because light rain should start at some finite threshold cloud LWP (~180 g m^{-2} in Wentz data). This behavior was surprising because 2A12 retrievals, which were based on cloud-resolving model simulations, were expected to be more accurate than the Wentz retrievals that incorporate only a simple empirical relationship between cloud LWP and rainfall. In order to reduce the apparent bias in profiling data we increased 2A12 cloud LWPs by a constant 180 g m^{-2} thereby making them more consistent with Wentz data. It was likely that similar biases affected 2A12 cloud IWP values as well, however, in the absence of any clear hints on the magnitude of such possible biases we decided not to apply corrections to these values.

[1] The rain rate dependence of cloud LWP is explicitly incorporated in the Wentz algorithm.

[2] A similar analysis between 2A12 cloud IWP and rain rate revealed a much weaker correlation of 0.48.

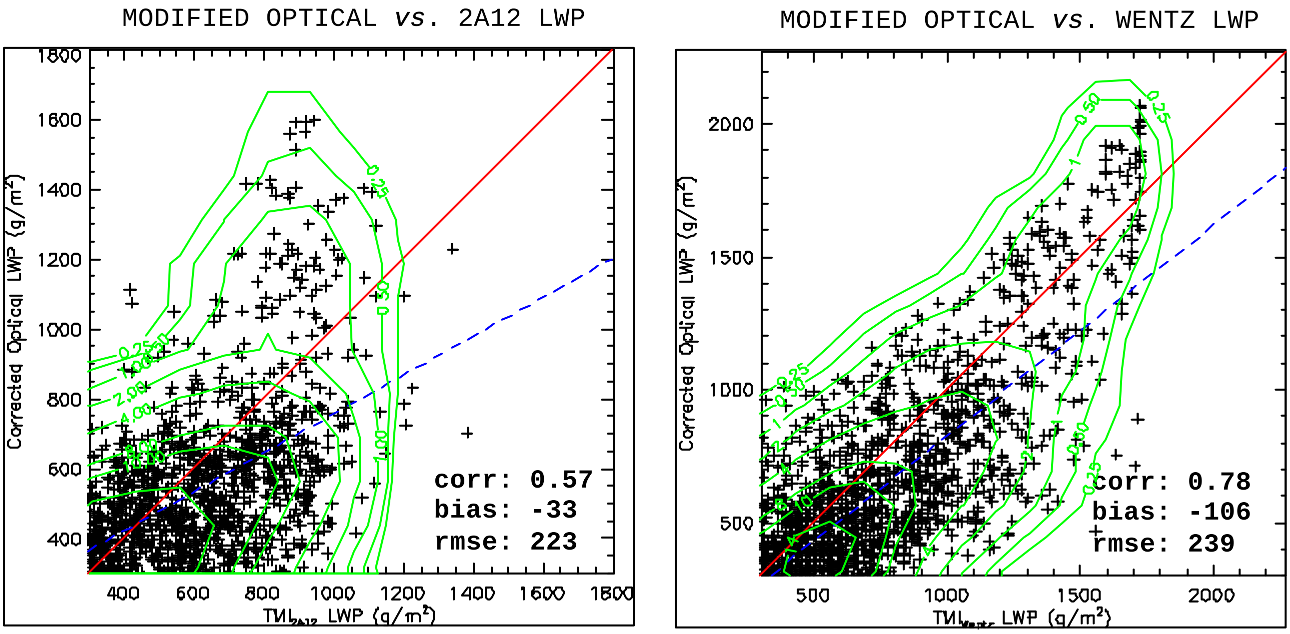
With these modifications in mind, we then compared MODIS water path (WP) values to the various microwave retrievals in order to investigate how to best interpret optical retrievals. The inherent problem with optical techniques in cold clouds is that the cloud top signal is some combination of the cloud liquid water and cloud ice signals, which cannot be unscrambled. These difficulties have resulted in ambiguous interpretations of optical retrievals in these clouds with some authors interpreting the results as ice water path (IWP), some as liquid water path (LWP), and still others as total water path (TWP), that is, the sum of the liquid and ice components. The results of our comparisons are summarized below.



All comparisons revealed a much weaker relationship between microwave and optical retrievals for cold clouds than for warm clouds. Correlation coefficients were generally no better then 0.5 and the rms difference between the techniques was at least an order of magnitude larger than for warm clouds. However, the weakest correlation (0.37) was obtained when MODIS retrievals were compared with 2A12 cloud ice water paths, even though this interpretation of optical estimates was the most straightforward as MODIS retrievals were based on an ice scattering phase function. A somewhat better agreement was achieved when optical retrievals were compared with 2A12 cloud total water path values. Surprisingly, however, the highest correlations (0.48-0.52) and smallest rms differences were obtained when optical results were interpreted as cloud liquid water path.

3.1. Correction of Optical Estimates

Now, the question arises whether optical estimates can be modified in a way that would improve their apparent relationship with microwave cloud LWP estimates? As we have found previously, in cold precipitating systems the fundamental correlation existed between cloud LWP and rain rate. This correlation, however, was captured by optical data to a much lesser degree. In particular, rain rate and MODIS effective radius (of cloud top ice crystals) were completely uncorrelated. From this it follows that the apparent relationship between microwave and optical cloud LWP estimates could be strengthened by combining optical thickness retrievals with effective radii (r_e) that contain some rain rate (r_r) dependence. As an example, we used the following effective radius parameterization derived by adding a typical raindrop size distribution to a cumulonimbus-type cloud droplet distribution: $r_e = 16 + 0.6r_r$ (Savijärvi *et al.*, 1997). The effect of these optical corrections is shown below.

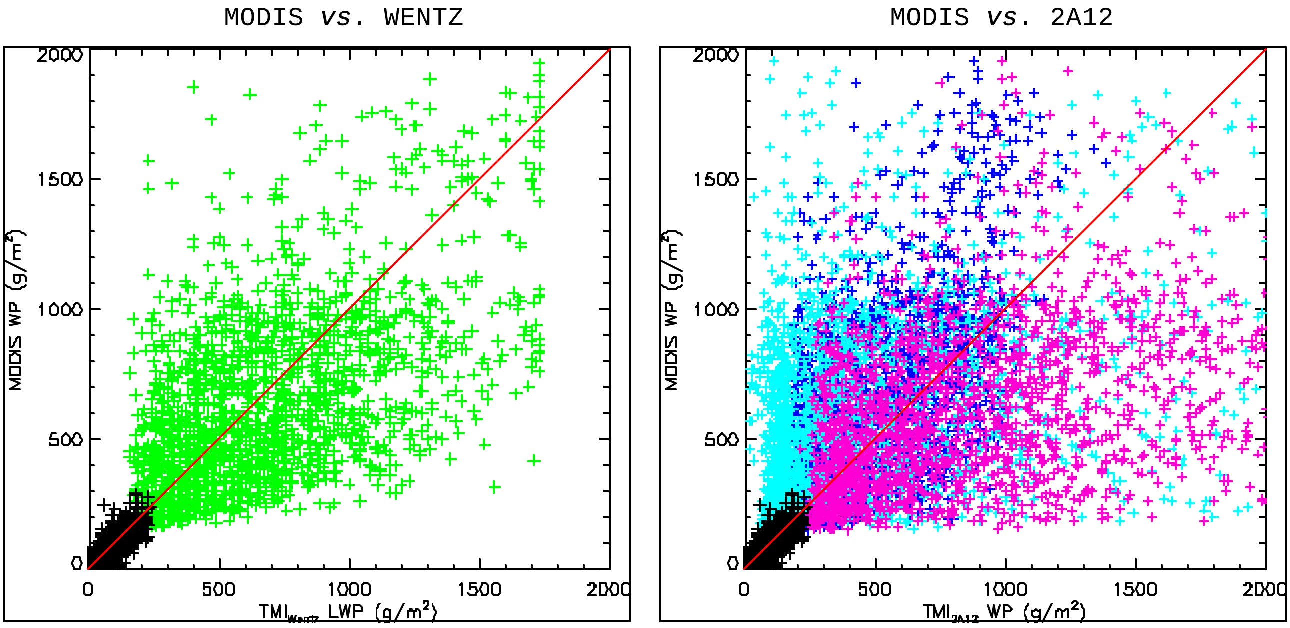


Overall, the relationship between microwave cloud LWPs and optical estimates improved in both cases. The improvement was only marginal for 2A12 data with a small increase in correlation from 0.52 to 0.57. For Wentz data, however, the improvement was significant with a correlation increase from 0.48 to 0.78, and an rms decrease from 341 g m^{-2} to 239 g m^{-2}. The corrections resulted in better agreement between optical and Wentz cloud LWP estimates because the Wentz data set had stronger rain rate dependence (correlation 0.96) than the 2A12 data set (correlation 0.77).

The practical applicability of the above optical corrections is limited by the fact that the effective radius parameterization requires rain rate estimates. Rain rate can be determined from microwave measurements. The availability of microwave measurements, however, would negate the need for corrected optical measurements, because microwave algorithms also yield cloud LWP. The outlined corrections, however, could still be useful to fix optical measurements in areas where no microwave data exist. In such areas, rain rate could be estimated from thermal infrared observations using, for example, a neural network based approach trained on microwave data, such as the PERSIANN (Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks) algorithm (Sorooshian *et al*., 2000). This approach has an adaptive training feature that facilitates updating of the network parameters whenever independent estimates of rainfall are available. It is particularly attractive because sensors that are used for optical thickness retrieval usually have thermal infrared channels as well.

4. Summary

Our comparisons between MODIS optical and TMI microwave water path retrievals at a resolution of 25 km are summarized below for all TRMM-Terra coincidences. Overall, it appears that water path retrievals show some skill for non-precipitating shallow clouds, but they remain a challenge for precipitating deep convective systems.



+ Wentz LWP warm non-raining
+ Wentz LWP cold raining

+ Wentz LWP warm non-raining
+ 2A12 LWP cold raining
+ 2A12 IWP cold raining
+ 2A12 TWP cold raining

Corroborating previous studies, we found that the microwave and optical methods agreed well for warm non-precipitating clouds characterized by typical water path values no more than 250-300 g m^{-2}. For such clouds, retrievals by both techniques could straightforwardly be interpreted as cloud liquid water path. In addition, the weak view zenith angle dependence of optical retrievals found in this study built further confidence in the results.

Conversely, for cold precipitating clouds microwave and optical estimates started to diverge significantly. In this regime, the comparison was complicated by the fact that MODIS retrievals could be interpreted (labeled) as cloud ice water path due to the presence of cloud top ice, while the Wentz microwave algorithm attempted to estimate cloud liquid water path. Therefore, comparing Wentz and MODIS retrievals for cold precipitating clouds (green) might have been misleading. Arguably, it would be more reasonable to compare optical retrievals with the standard TRMM profiling products, especially 2A12 cloud ice water path. However, MODIS-2A12 comparisons did not yield an agreement any better than the MODIS-Wentz comparison, regardless of whether MODIS estimates were compared with cloud liquid water path (blue), cloud ice water path (cyan), or cloud total water path (pink). If anything, optical estimates were best correlated with microwave cloud liquid water paths. We have also found that microwave cloud LWP tends to increase with rain rate. Consequently, a better apparent agreement between optical estimates and microwave cloud LWPs can be achieved by keeping optical thickness retrievals, which contain some information on cloud liquid water, but replacing effective radius retrievals with a parameterization that introduces rain rate dependence. These corrections only marginally improved the agreement between optical estimates and 2A12 cloud LWPs. On the other hand, an unbiased fit to Wentz cloud LWPs could be achieved with a correlation coefficient of 0.78, which was comparable to the one obtained for warm clouds (0.85). The rms difference between the techniques, however, still remained an order of magnitude larger than for warm clouds.

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