COMBINED RADAR-RADIOMETER RETRIEVAL OF HYDROMETEOR PROFILES IN TROPICAL CYCLONES: A TRMM CASE STUDY

Haiyan Jiang and Edward J. Zipser*
Department of Meteorology, University of Utah, Salt Lake City, UT

1. INTRODUCTION

A retrieval algorithm was developed by Jiang and Zipser (2004) to estimate vertical profiles of precipitation ice water content (IWC) and liquid water content (LWC) in tropical cyclones and convection over ocean from combined spaceborne radar and radiometer measurements. The algorithm has some new features compared with existing Tropical Rainfall Measurement Mission (TRMM)-related precipitation algorithms. It is a fully physical technique that is designed to retrieve the different N_0's for rain, snow, and graupel and to provide physically meaningful estimates for both IWC and LWC profiles. It uses the vertical radar reflectivity profile to constrain the vertical shape of the retrieved hydrometeor profiles and uses the radiometer brightness temperatures (T_b) to determine the vertically integrated ice and liquid water content, making the retrieval consistent with both radar and radiometer observations. The validation of the IWC retrieval by using the aircraft *in situ* microphysical measurements indicates that the algorithm can provide reliable IWC estimates, especially in stratiform regions. In convective regions, the large variability of the microphysical characteristics causes a large uncertainty in the retrieval, although the *mean* difference between the retrieved IWC and aircraft derived IWC is very small. The IWC estimated by the radar-only algorithm is higher than those retrieved by the combined algorithm and derived by the aircraft *in situ* observations, which suggests that information useful for improving the radar-only estimates is contained in the T_b measurements.

Both TRMM radar-only 2A25 (Iguchi et al. 2000) and radiometer-only 2A12 (Kummerow et al. 1996) products are available for comparison with the combined retrieval. The first objective of this paper is to apply this combined algorithm to a TRMM tropical cyclone case, and to compare the retrieved hydrometeor profiles with radar-only and radiometer-only retrievals.

One difficulty in retrieving rain rate and hydrometeor content from space-based platforms is correcting for the so-called beamfilling effect (Chiu et al. 1990; Short and North 1990). For spaced-based microwave instruments, the footprint size or field of view (FOV) is usually larger than the typical size of rain cells. This implies that the rainfall within the FOV may not be uniformly spread, especially when observing convective rainfall. A beamfilling problem comes about because the radiometer or radar measures a FOV area average microwave T_b or radar reflectivity factor Z, while the observer desires an estimate of the FOV area average rain rate R or water content M. The problem is that the formula relating the point value of T_b or Z and the point value of R or M is nonlinear. Hence, straightforward insertion of the measured FOV T_b or Z into the formula does not lead to the FOV average R or M because of the heterogeneity of rainfall within the FOV. The magnitude of beamfilling error for a specific instrument is dependent on its footprint size. An aircraft radiometer would have less beamfilling error than a satellite radiometer because the footprint size of an The aircraft radiometer is typically much smaller than that of a satellite radiometer. Radiometers at low frequencies would have more severe beamfilling problems than radiometers at high frequencies because of the much larger footprint size of low-frequency radiometers.

For applying the combined radar-radiometer algorithm to TRMM observations, the beamfilling error cannot be neglected and the nonuniform beamfilling would have different effects for stratiform and convective precipitation regions and for LWC and IWC retrievals. Therefore, the second objective of this paper is to answer the following questions, *"Would the magnitude of the beamfilling bias from the combined radar-radiometer LWC retrieval be the same as that from the radiometer-only LWC retrieval given that the PR footprint is much smaller than those of the low frequency channels of TMI? How would the beamfilling errors of LWC retrievals be different for different rain type regions?"* We are not attempting to find the absolute beamfilling error, but instead we compare the different beamfilling bias for the combined and radiometer-only algorithm relative to the radar-only algorithm.

2. APPROACHES

For applying the algorithm to TRMM observations, TRMM PR 2A25 attenuation corrected reflectivity profiles and TMI 1B11 brightness temperatures are used as input to the algorithm. PR and TMI observations are matched by a nearest-neighbor technique (Nesbitt et al. 2000). At 10 and 19 GHz, the *normalized polarization difference* (P, 1994a) is used instead of the brightness temperature to single out precipitation (liquid water) emission by decoupling it from the impact of scattering and variations in atmospheric temperature, column water vapor, and surface emissivity. At 37 and 85 GHz, the Polarization Corrected Temperature (PCT, Spencer et al. 1989) is used instead of the brightness temperature to minimize the effect of the radiometrically cold sea surface. Notice that P and PCT have different magnitudes. In the retrieval, a weighting factor is added

* *Corresponding author address*: Edward J. Zipser, Dept. of Meteorology, Univ. of Utah, Salt Lake City, UT 84112; e-mail: ezipser@met.utah.edu

for each frequency to keep the contribution approximately equivalent from each channel.

Besides 2A25 and 2A12 algorithms, a so-called Z-M algorithm is also used to compare with the combined retrievals. The Z-M algorithm uses the empirical Z-IWC (Black 1990) and Z-LWC (Willis and Jorgensen 1981) relationships for first-guess IWC and LWC profiles from 2A25 radar reflectivity profiles.

The nonuniform beamfilling would have different magnitudes for stratiform and convective precipitation regions and for LWC and IWC retrievals. For nearly uniform stratiform regions, the beamfilling problem would not be very large because the inhomogeneity of rainfall is minimized. But for convective regions, even the PR footprint size of 4.3 km (5.0 km after TRMM boost) is larger than the typical size of convective rain cells. This implies that the rainfall within PR and TMI footprints may often be highly variable when observing convective rainfall. Therefore the beamfilling error in convective rainfall retrievals would be large. Consider the difference for IWC and LWC retrievals. The IWC retrievals are mainly obtained from the radar and high frequency radiometer observations. Among the TMI high frequency channels, 85 GHz would dominate the IWC estimation. The footprint sizes of PR, and the TMI 85 GHz channel are not larger than 4-8 km. According to Chiu et al. (1990), the rain rate bias is about 25% for a footprint size of 8 km. The error of IWC retrievals would be small. In the rain region, the LWC retrieval might be largely biased by the beamfilling problem considering the large 10 and 19 GHz FOV (60 km and 30 km) and the inhomogeneity of precipitation in hurricanes.

Based on the above hypothesis, we carefully choose a hurricane case with widespread stratiform regions around rainbands and strong convective regions in the eyewall to test the algorithm performance in IWC and LWC retrievals. The case selected is the TRMM orbit on Sept. 08, 2003 for Hurricane Isabel (2003) over the North Atlantic Ocean (orbit number 33151). The retrieval results will be compared with TRMM 2A12 (radiometer-only) and Z-M (radar-only) algorithms. Retrieval results from 2A25 are also considered but not shown here because the original algorithm developer Dr. Iguchi (personal communication) has confirmed that the particle size distribution (PSD) assumption of 2A25 in the ice region is very crude and will not be improved until version 7. [Ice water content retrieved from 2A25 for this Isabel orbit is indeed about 1 order of magnitude less, while the liquid water content retrieved from 2A25 is similar to that from our Z-M (Willis and Jorgensen).

3. RESULTS

In the TRMM Isabel orbit, three boxes are chosen to represent the nearly uniform stratiform rain region (box 1 and 2 in Fig. 1) and the eyewall convective region (box 3 in Fig. 1). Fig. 1 shows the retrieval results of ice water path (IWP) in box 1, 2, and 3. The 85 GHz PCT and PR 2A25 7 km reflectivity are presented in panel (a) and (b) respectively, which are the two main inputs for the combined radar-radiometer IWC retrieval. Inside box 1 and 2, the relatively high reflectivity values (about 30 dBZ) at 7 km correspond to the 85 GHz ice scattering signature (PCT less than 220 K). Panels (c) – (f) are the retrieved IWP by the combined algorithm, version 5 (V5, current version of TRMM standard

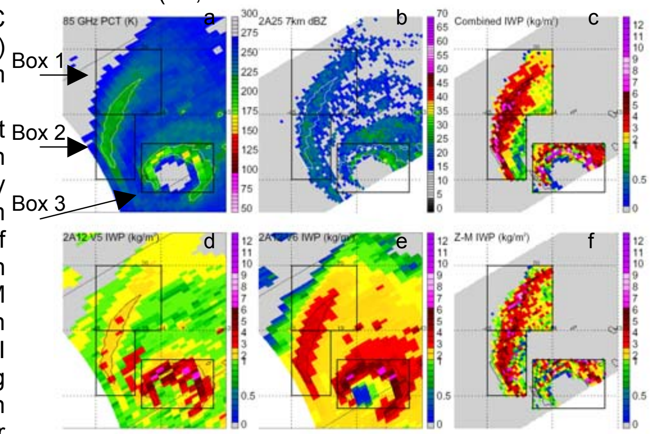

Figure 1. Retrieval results of ice water path (IWP) in box1, 2, and 3 of the Hurricane Isabel overpass on Sept. 8, 2003. Each panel shows (a) TMI 85 GHz PCT (shaded, K,), (b) PR 2A25 7 km reflectivity (shaded, dBZ), (c) IWP retrieved by the combined radar-radiometer algorithm (shaded, kg/m^2), d) IWP retrieved by the version 5 of 2A12 algorithm (shaded, kg/m^2), (e) IWP retrieved by the version 6 of 2A12 algorithm (shaded, kg/m^2), (f) IWP retrieved by the Z-M algorithm (shaded, kg/m^2). The contour of 220 K 85 GHz PCT is overplotted in each panel.

product) of 2A12, version 6 (V6, future version of TRMM standard product, will be available in late 2004) of 2A12, and Z-M algorithm.

Let us first look at the stratiform region (box 1 and 2). There is a general agreement in the spatial pattern of the combined, Z-M, and 2A12 V6 IWP fields. They are consistent with the TMI 85 GHz PCT and PR reflectivity observations. The large 2A12 V6 IWP values are related to the low 85 GHz PCT area, which is also a high reflectivity area at 7 km altitude. A similar pattern is shown in combined IWP field, but in higher resolution because of the combined use of TMI and PR. A significant result of the combined IWP field is that *all IWP values greater than 10 kg/m^2 are inside the 220 K 85 GHz PCT contour.* The Z-M IWP field has a similar pattern, but it is noisy, with several large IWP pixels outside the 85 GHz ice scattering contour. Version 5 of 2A12 IWP has a quite different pattern that is consistent with neither the TMI 85 GHz PCT nor the PR reflectivity observations. An area with large IWP values (about 7 kg/m^2) at the east edge of box 2 is artificial. Version 6 of 2A12 has been improved by removing this artifact. The reason could be that version 6 of 2A12 uses more cloud model profiles than version 5.

For the convective region (box 3), the combined IWP field (c) has a similar pattern to the 2A12 V5 (d) and V6 (e) and Z-M (f) retrievals and 85 GHz PCT (a) and PR 7 km reflectivity (b), except that the Z-M IWP field appears to be noisy. For the eye region, the combined and radar-only algorithm can easily identify the no-echo region from the PR observations, but there are non-zero values of IWP from the 2A12 V5 and V6, showing that the radiometer-only algorithm has trouble identifying this kind of feature.

Fig. 2 shows the pixel-by-pixel comparisons of IWP between the combined, Z-M, and 2A12 V6 retrievals in box 1&2, and box 3. In general, the plots are very scattered and the correlation coefficients are low. One of the main reasons is the mismatch between the TMI and PR observations. The PR beam looks at nadir, while the TMI scans conically with an incident angle of 52.8°. In this study, a very simple parallax correction is done by moving TMI observations one scan number ahead or behind. Since the distance between adjacent scan lines is about 16 km, an over-correction is very possible. So the pixel-by-pixel comparison might not be fair, but it can at least tell the range of the retrieved parameters and the mean differences between two retrievals.

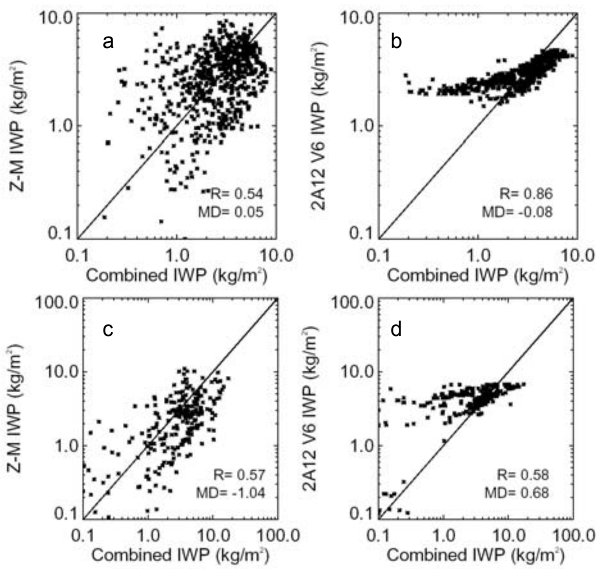

Figure 2. The scatter plot of (a) Z-M ice water path (IWP) versus radar-radiometer combined algorithm retrieved IWP in box 1&2; (b) Version 6 of 2A12 IWP versus radar-radiometer combined algorithm retrieved IWP in box 1&2; (c) Z-M IWP versus radar-radiometer combined algorithm retrieved IWP in box 3; (d) Version 6 of 2A12 IWP versus radar-radiometer combined algorithm retrieved IWP in box 3 of the Hurricane Isabel overpass on Sept. 8, 2003. The correlation coefficient (R) and mean difference (MD) are indicated.

In stratiform regions, for Z-M IWP versus combined IWP in Fig. 2a, the correlation is low, but the mean difference is very small, indicating the agreement on average between combined and radar-only algorithm. The agreement between combined and 2A12 V6 IWP (Fig. 2b) is better, with a lower absolute mean difference and higher correlation coefficient. But it is interesting to note that the 2A12 V6 has no IWP values less than 1 kg/m^2 and greater than 5 kg/m^2 comparing the IWP range of 0.1 to 10 kg/m^2 in the combined and Z-M estimates, showing an insensitivity of 2A12 V6 relative to the combined and Z-M estimates. As discussed above, the beamfilling problem is not substantial for the IWC retrieval in stratiform regions for both radar-only, radiometer-only, and the combined algorithms. That is why the mean IWP differences among those retrievals are very small. But because the footprint difference between TMI 85 GHz and PR is about 2-3 km, this very likely causes the 2A12 insensitivity problem. The combined algorithm doesn't show this problem because of the use of PR observations.

In convective regions, comparing with the radar-only algorithm (Fig. 2c), the combined algorithm doesn't show the beamfilling-caused insensitivity problem that is shown for 2A12 V6 comparing with the combined algorithm (Fig. 2d). This fact indicates that even in the eyewall convective region with a strong rain inhomogeneity, the combined algorithm performs more like a radar-only algorithm and avoids the beamfilling problem of the radiometer-only algorithm.

Fig. 3 shows the retrieval results of liquid water path (LWP) in box 1, 2, and 3. The 19 GHz vertical polarization brightness temperature and PR 2A25 near surface reflectivity are presented in panel (a) and (b). The 220 K contour of 85 GHz PCT is over-plotted in each panel of Fig. 3 for comparisons. The similar patterns in the whole box 1, 2, and 3 among (a), (b), (c), and (f), indicates that the combined and Z-M retrievals are consistent with the PR and TMI observations. The spatial patterns of the 2A12 V5 (d) and V6 (e) LWPs are quite different from the above two retrievals as well as from the observations. They appear to be consistent with the 85 GHz ice scattering instead of the low frequency rain emission and PR low-level reflectivity observations. This strange performance demonstrates that in this case the 2A12 overemphasizes the high frequency information, but neglects the information from low frequencies, which sometimes are very important although they have very coarse resolution. In box 1 and 2 (stratiform regions), the overestimate of 2A12 V5 LWP inside the ice-scattering contour is about a factor of 2 relative to the combined and Z-M estimates. A significant change of the 2A12 V6 LWP magnitude is found, especially inside the ice-scattering contour, which makes it very close to the radar-radiometer and radar-only retrievals. This change results from the inclusion of the melting layer emission in 2A12 V6 (C. Kummerow, personal communication). But the pattern of 2A12 V6 LWP field is still similar to that of 2A12 V5, showing that the large footprint of the low frequency channels remains problematic. In box 3 (eyewall convective regions), because of the beamfilling problem, no clear eye can be seen in the 2A12 V5 LWP field, while the 2A12 V6 makes an improvement by showing about 1/3 clear eye in its LWP retrieval.

Fig. 4 presents the pixel-by-pixel comparisons for LWP retrievals from different algorithms in box 1&2, and box 3. Again the plots are very scattered because of the matching problem between the PR and TMI due to the different incident angle of the two instruments. The best correlation is found between the Z-M and combined LWP (a) in the stratiform regions, with a correlation coefficient of 0.79. Although the mean difference between the 2A12 V6 and combined (b) is lower than that between the Z-M and combined, the insensitivity

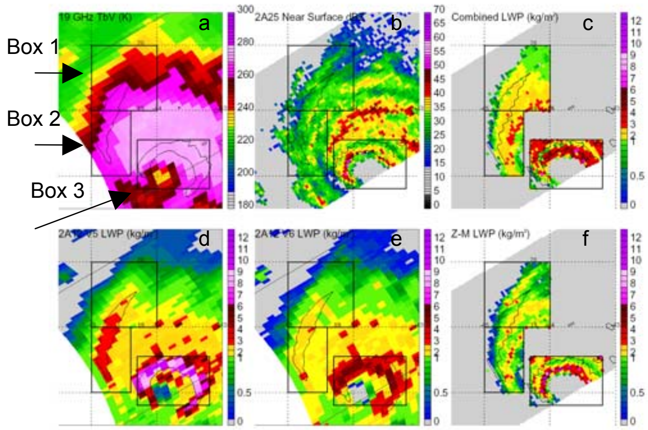

Figure 3. Retrieval results of liquid water path (LWP) in box 1, 2, and 3 of the Hurricane Isabel overpass on Sept. 8, 2003. Each panel shows (a) TMI 19 GHz vertical polarization T_b (shaded, K), (b) PR 2A25 near surface reflectivity (shaded, dBZ), (c) LWP retrieved by the combined radar-radiometer algorithm (shaded, kg/m^2), (d) LWP retrieved by the version 5 of 2A12 algorithm (shaded, kg/m^2), (e) IWP retrieved by the version 6 of 2A12 algorithm (shaded, kg/m^2), (f) LWP retrieved by the Z-M algorithm (shaded, kg/m^2). The contour of 220 K 85 GHz PCT is overplotted in each panel.

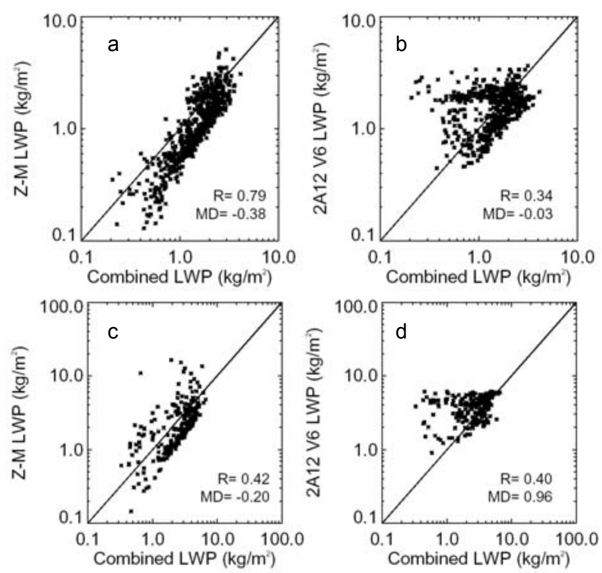

Figure 4. Same as Fig. 2, but for liquid water path (LWP).

problem of 2A12 LWP makes the correlation coefficients in (b) quite low. From the Z-M LWP versus combined LWP (c) in the eyewall convective regions, the use of low frequency observations does produce an insensitivity problem on the combined retrieval relative to the radar-only retrieval. The large Z-M LWP values above 7 kg/m^2 are underestimated and the small Z-M LWP values below 0.2 kg/m^2 are overestimated by the combined algorithm. The insensitivity problem of the 2A12 V6 is more severe from the 2A12 V6 versus combined (d) comparison. The 2A12 V6 LWP is confined between 0.6 to 6 kg/m^2, all values beyond this range are either overestimated or underestimated. As noted above, the LWC retrieval in the strong convective region would be affected by the beamfilling problem to the largest extent. Comparing with three previous cases (IWC and LWC in the stratiform region, IWC in the convective region), this is the only case that the combined retrieval appears to be biased by the beamfilling problem relative to the radar-only algorithm. On the other hand, the 2A12 is biased for all four cases.

4. SUMMARY

This TRMM case study provides not only an intercomparison among the combined, radar-only (Z-M), and radiometer-only (2A12) algorithms, but also an investigation of the beamfilling problem of satellite-based remote sensing retrievals. It is shown that the 2A12 retrieval has an insensitivity problem caused by the beamfilling bias relative to the radar-only Z-M retrieval for both IWC and LWC in both nearly uniform stratiform and eyewall convective regions. However, an obvious improvement is seen from the combined retrieval. Since it is very complicated to deal with the beamfilling problem with a physical model, combining radar and radiometer observations provides a workable solution to reduce the beamfilling error from the radiometer-only retrieval.

Acknowledgements. We thank A. Heymsfield, A. Bansemer, G. Heymsfield, L. Tian, R. Hood, and F. LaFontaine for supplying processed data, C. Kummerow for providing the radiative transfer model and Ramesh Kakar for research support under NAG5-10682. This study is also supported by a NASA ESS Fellowship.

MAIN REFERENCES

Black, R. A., 1990: Radar reflectivity-ice water content relationships for use above the melting level in hurricanes. *J. Appl. Meteor.*, **29**, 955-961.

Chiu, L. S., G. R. North, D. A. Short, and A. McConnell, 1990: Rain estimates from satellite: Effect of the finite field of view. *J. Geophys. Res.*, **95**, 2177-2185.

Jiang, H., and E. J. Zipser, 2004: Retrieval of hydrometeor profiles in tropical cyclones and convection by a combined radar-radiometer algorithm. Preprints, *26th Conf. on Hurricanes and Tropical Meteorology*, Miami, FL, Amer. Meteor. Soc., 194-195.

Kummerow, C., W. S. Olson, and L. Giglio, 1996: A simplified scheme for obtaining precipitation and vertical hydometeor profiles from passive microwave sensors. *IEEE Trans. Geosci. Remote Sens.*, **34**, 1213-1232.

Nesbitt, S. W., E. J. Zipser, and D. J. Cecil, 2000: A census of precipitation features in the tropics using TRMM: Radar, ice scattering, and lightning observations. *J. Climate*, **13**, 4087-4106.

Petty, G. W., 1994a: Physical retrievals of over-ocean rain rate from multichannel microwave imagery. Part I: Theoretical characteristics of normalized polarization and scattering indices. *Meteor. Atmos. Phys.*, **54**, 79-99.

Spencer, R. W., H. M. Goodman, and R. E. Hood, 1989: Precipitation retrieval over land and ocean with the SSM/I: Identification and characteristics of the scattering signal. *J. Atmos. Oceanic Technol.,* **6,** 254-273.

Willis. P. L., and D. P. Jorgensen, 1981: Reflectivity relationships for hurricanes. Preprints, *20th Conf. on Radar Meteorology*, Boston, MA, Amer. Meteor. Soc., 199-200.