6.2 VARIABILITY OF ICE AND LIQUID PRECIPITATION CONTENTS AND SHAPE OF RADAR REFLECTIVITY PROFILES IN TROPICAL CYCLONES

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

1. INTRODUCTION

It is very important to obtain a better understanding of ice water content (IWC) and liquid water content (LWC) to improve our knowledge of cloud and precipitation processes and to validate microphysical schemes in numerical simulation models. IWC and LWC have implications on tropical cyclone intensity. High correlations were found between future tropical cyclone intensity and satellite-based 85-GHz ice-scattering signature within 1^0 radius of the cyclone center (Cecil and Zipser, 1999) and rainfall rates within the 2^0 radius of the center of typhoons (Rao and MacArthur, 1994). Therefore, some of the questions motivating this study are: "*Is there any correlation between the tropical cyclone intensity and the ratio of total ice mass and total liquid water mass? If it exists, is it positive or negative? What kind of physical processes cause it?*"

By quantitatively intercomparing minimum Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI) 85- and 37-GHz brightness temperatures with maximum TRMM Precipitation Radar (PR) reflectivity at each vertical level and total Lightning Imaging Sensor (LIS) lightning flash count in each precipitation feature in a 1-year TRMM tropical cyclone database, Cecil and Zipser (2002) examined the microphysical characteristics of clouds and precipitation in hurricane eyewalls and rainbands, and also in other tropical oceanic regions and tropical continental regions. They found that the outer rainband region contains relatively more lightning than the eyewall and inner rainband regions, but less lightning than tropical continental storms for a given ice scattering signature. It was hypothesized that tropical continental precipitation features contain abundant supercooled liquid water above the freezing level, coexisting with hail and large graupel; that tropical oceanic precipitation features have a much shallower layer of supercooled water and large graupel; that outer rainband region precipitation features contain more supercooled water and large graupel than general tropical oceanic features, but less than tropical continental storms; that eyewall region precipitation features have a strong convective characteristic but hydrometeors associated with them are spread out over a greater horizontal area because of the extreme horizontal wind speeds. However, due to obvious limitations of instrumentation and logistics, the whole distributions of IWC and LWC in clouds and precipitation can not be measured directly. Cecil and Zipser's (2002) study used only satellite-observed parameters such as radar reflectivity and brightness temperatures as indirect indicators of ice amount. The ice and liquid precipitation profiles derived from space observations, if sufficiently accurate, can be used for improved estimates of microphysical properties, quantitative precipitation estimation, and latent heating profiles.

Zipser and Lutz (1994) proposed that rapid decreases of radar reflectivity with height in convective cells are characteristics of tropical oceanic regions. This is consistent with the observations of weak vertical velocities of oceanic cumulonimbus cells within mesoscale convective systems (MCSs) (Lucas et al. 1994) and hurricanes (Jorgensen et al. 1985). The slope of radar reflectivity profiles above freezing level is also very helpful to investigate the fractions of ice particles and supercooled liquid water in upper portions of clouds (Yuter and Houze 1995b). An important issue now under study is the slope of the reflectivity profiles in the rain region. This has clear implications for both radar and radiometer retrievals of surface rain rate. In this context, a detailed examination of vertical profiles of the radar reflectivity can provide an indicator of the vertical distribution of microphysical properties.

This paper comprises two main objectives: 1) to quantitatively describe of the range of variability of IWC and LWC calculated by using some existing algorithms in eyewalls and rainbands of tropical cyclones; 2) to quantitatively investigate the shape of the radar reflectivity profile in eyewalls and rainbands of tropical cyclones and compare with that in other tropical precipitation systems.

2. DATABASES

There are two kinds of databases to be used: 1) a 1-year tropical cyclone database that contains all tropical cyclones viewed by TRMM for its first year in orbit (Dec. 1997 -- Dec. 1998), sorted by eyewall, inner rain band, and outer rain band; 2) a subset of the cooperative NASA/NOAA aircraft-based field programs into tropical cyclones (CAMEX-3, 4) in 1998 and 2001. The combination of radar (Precipitation Radar (PR) on TRMM satellite or Doppler radar on the NASA ER-2 airplane (EDOP) during CAMEX) and passive microwave (TRMM Microwave Imager (TMI) or Advanced Microwave Precipitation Radiometer (AMPR) on the ER-2) data are extremely powerful and may provide several ways to estimate ice water content (IWC) and liquid water content (LWC). By using the statistical results from TRMM database, a few case studies during CAMEX could be placed in a large statistical context.

a. The 1-year TRMM tropical cyclone database

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

A 1-year (Dec. 1997- Dec. 1998) tropical cyclone database of collocated TRMM PR, TMI, and Lightning Imaging Sensor (LIS) observations was created and analyzed by Cecil et al. (2002). It consists of *648 TRMM overpasses of 79 tropical cyclones*, i.e., each cyclone was observed on an average of 8 overpasses. The tropical cyclone was subdivided into three separate regions: eyewall, inner rainband, and outer rainband. The categorizations were made subjectively, based on the horizontal fields of PR reflectivity and 85-GHz ice scattering. In this database, the mean radii for eyewall region, inner rainband region, and outer rainband region are 50, 135, and 350 km, respectively. Inside above regions, precipitation features were identified based on the criteria by Nesbitt et al. (2000): at least four contiguous pixels (~75 km^2) on the PR grid having at least 20 dBZ near surface reflectivity or TMI 85-GHz polarization corrected temperatures (PCTs, Spencer et al. 1989) of 250 K or less. Inside any precipitation feature, stratiform, convective, and "others" are separated by TRMM PR algorithm 2A23.

b. The CAMEX tropical cyclone database

CAMEX-3 and CAMEX-4 were based on Florida Aug. 06 - Sep. 27, 1998 and Aug. 16 - Sep. 24, 2001, respectively. These cooperative NASA-NOAA experiments focused on the study of tropical cyclone development, tracking, intensification, and landfalling impacts using aircraft and surface remote sensing instrumentation. During these field campaigns, a large volume of data was collected from in-situ microphysical instruments, and passive and active remote sensing instruments. The aircraft data have higher spatial and temporal resolution than observations from TRMM PR and TMI. The combination of radar reflectivity profiles measured by the ER-2 Doppler radar (EDOP) and passive microwave brightness temperatures measured by the Advanced Microwave Precipitation Radiometer (AMPR; also on the ER-2) is potentially very powerful, especially for some specific case studies. Since EDOP has higher horizontal and vertical resolution, higher sensitivity, and longer wavelength (therefore less attenuation problem) than the TRMM PR, the shape of the radar reflectivity profile described by EDOP is more realistic than by the PR (Heymsfield et al, 2000). During CAMEX, reflectivity data from several other radars are available, including a precipitation Doppler radar on the DC-8, and several ground-based Doppler radars.

3. METHODS

Four methods are used or implemented to estimate IWC and LWC profiles from TRMM database. Generated from the two main instruments, PR and TMI, on the TRMM satellite, the single-instrument algorithms 2A12 (TMI only, Kummerow et al. 1996) and 2A25 (PR only, Iguchi et al. 1998) provide the hydrometeor profiles and attenuation corrected radar reflectivity and rainfall rate profiles. As a supplement to Cecil's 1-year TRMM tropical cyclone database, we have added 2A12 hydrometeor profile parameters (precipitation ice water, precipitation liquid water, cloud ice water, and cloud liquid water contents). Also 3 other methods have been developed to calculate IWC and LWC from 2A25 radar reflectivity and rain rate profiles. The first one is by using the empirical Ze-IWC (Black 1990) and Ze-LWC (Gamache et al. 1993) relationships (therefore Z-M method); the second (called 2A25 method) and third (called 2A25_iguchi method) methods are to calculate LWC and IWC from 2A25 rain rate and fall speed, the latter is obtained by using the empirical reflectivity-fall speed relationship in Marks and Houze (1987). In the above 3 methods, the classification of rain type and the brightband height (or the freezing level) are determined by TRMM algorithm 2A23. The top and bottom of the mixed phase region are defined at 500 m above or below the brightband height for stratiform region, at 750 m above or below the freezing level for convective or "others" region (Iguchi et al. 1998). In Z-M method and 2A25 method, it is assumed that all particles above the top of the mixed phase region are in ice phase and all particles below the bottom of mixed phase region are liquid. But in 2A25_iguchi method, the 2A25 water content fraction profile assumption (Iguchi et al. 1998) is used for above the top of mixed phase region. For these 3 methods, inside the mixed phase region, the values of IWC and LWC are interpolated from those at the top and bottom of the mixed phase region.

For CAMEX case studies, two methods are used to estimate IWC and LWC profiles from EDOP and AMPR observations. The first method is Z-M method as described above; the second one is a combined radar-radiometer algorithm developed by Jiang and Zipser (2003).

The statistics of vertical radar reflectivity profiles are produced for eyewall, rainbands, convective, and stratiform regions respectively from the 1-year TRMM tropical cyclone database and compared with those from CAMEX database. For CAMEX case studies, the vertical profile of maximum radar reflectivity in convective cells in hurricanes is compared with that in tropical convection storms.

4. RESULTS

As an example using the LWC and IWC profiles in this 1-year database, Fig. 1 gives the composite averaged LWC and IWC vertical profiles estimated by the above 4 methods in all regions of cyclones, and in eyewall, inner rainband, and outer rainband regions. From the figure, large variable range of LWC and IWC can be seen among the 4 methods, although 2A12 profiles are close to Z-M profiles except for the lowest 2-3 km. 2A12 retrieval has well-know problem in that region (C. Kummerow, Colorado State Univ., personal communication). The average liquid water path (LWP) and ice water path (IWP) in table 1 are vertical integrals of IWC and LWC calculated from figure 1. Notice in both figure 1 and table 1, the precipitation LWC and IWC from 2A12 is compared with the total LWC and IWC derived from 3 other methods, since unlike

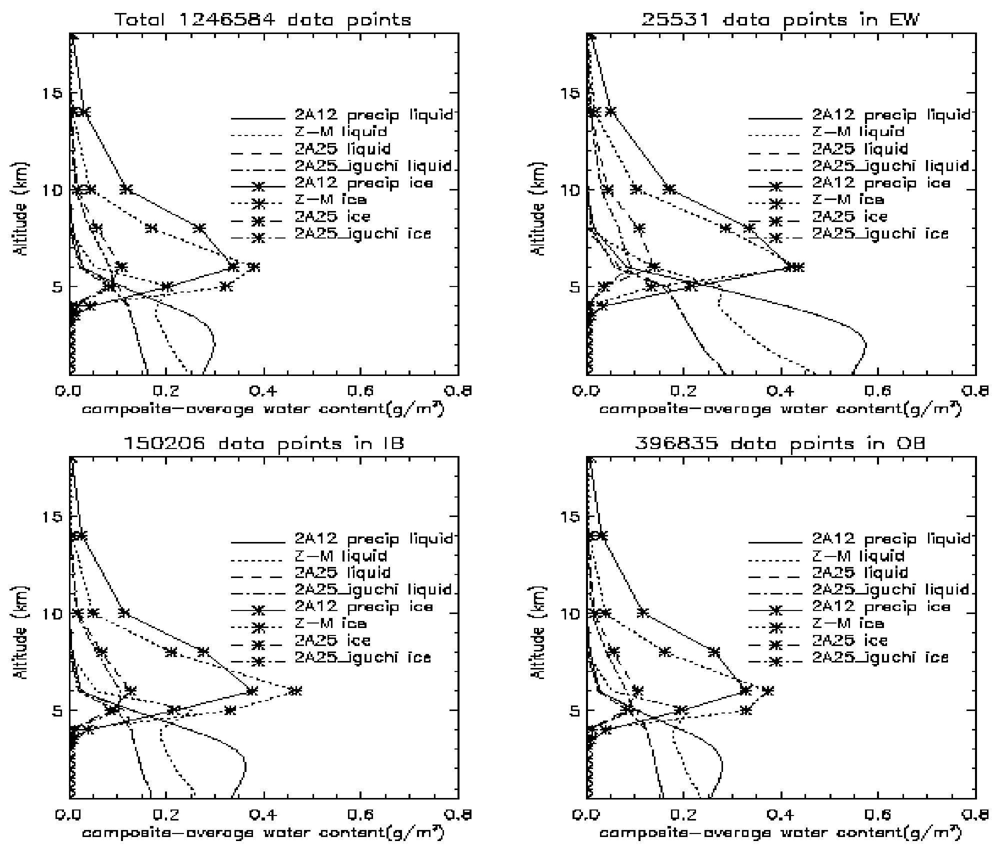

Fig. 1. Hydrometeor vertical profile composites estimated by 2A12, Z-M, 2A25, and 2A25_iguchi methods for (upper left) all regions in tropical cyclones, (upper right) eyewall regions, (lower left) inner rainband regions, and (lower right) outer rainband regions from the 1-year TRMM tropical cyclone database.

Table 1. Mean microphysical properties estimated by 2A12, Z-M, 2A25, and 2A25_iguchi methods from the 1-year TRMM tropical cyclone database (IWP and LWP in g/m^2)

	All regions	Eyewall	Inner rainband	Outer rainband
2A12 IWP	1486.19	1902.59	1520.05	1453.56
Z-M IWP	1386.38	1757.84	1598.47	1343.82
2A25 IWP	430.556	648.285	471.947	416.951
2A25_iguchi IWP	353.815	430.828	421.992	340.664
2A12 LWP	1253.10	2491.25	1498.25	1174.25
Z-M LWP	1159.34	1978.96	1262.03	1143.90
2A25 LWP	748.588	1253.27	786.427	747.382
2A25_iguchi LWP	744.758	1279.25	772.602	744.235
2A12 (IWP/LWP)	1.18601	0.76371	1.01455	1.23787
Z-M (IWP/LWP)	1.19584	0.888264	1.26658	1.17477
2A25 (IWP/LWP)	0.575157	0.517274	0.600116	0.557882
2A25_iguchi (IWP/LWP)	0.475074	0.336780	0.546196	0.457738

radiometers that respond to both precipitation and cloud particles, EDOP and the TRMM radar can only detect precipitation hydrometeors. In general, eyewall regions have much more precipitation ice and liquid water mass than inner rainband and outer rainband region; inner band regions have more than outer band regions. In eyewall regions, precipitation liquid water mass is larger than precipitation ice mass. In inner and outer rainband regions, the reverse is true according to some methods, but not all, an issue needing further study. These types of analyses as well as relating the IWC and LWC estimates to the current or future intensity of hurricanes will allow a characterization of difference between eyewalls and rainbands and their interaction with hurricane intensity.

The shape of radar reflectivity profiles is investigated for both the CAMEX-4 hurricane cases and the 1-year TRMM tropical cyclone database. Fig. 2 shows the

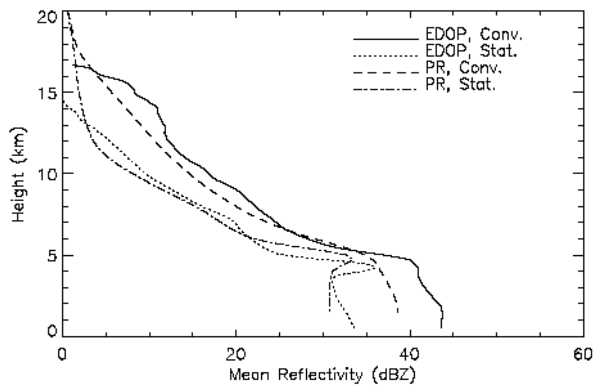

Fig. 2. Mean vertical profiles of radar reflectivity in convective and stratiform regions for 7 EDOP tropical cyclone passes during CAMEX-4 and for 648 TRMM PR overpasses during Dec. 1997-Dec. 1998.

comparison of the mean vertical profiles of radar reflectivity in convective and stratiform regions between 7 EDOP tropical cyclone passes (e.g. Chantal, Erin, and Humberto 2001) during CAMEX-4 and 648 TRMM PR overpasses during Dec. 1997-Dec. 1998. EDOP is an X-band vertical scanning radar and may suffer an attenuation problem especially in strong convective precipitation. An attenuation correction has been applied for these 7 passes data. Attenuation correction for TRMM PR data has been done by TRMM standard algorithm 2A25. From Fig. 2 we note that the reflectivity in convection rain continues to increase downward toward the surface below freezing level for both EDOP and TRMM PR measurements. But in stratiform rain, the EDOP reflectivity increases downward but the PR reflectivity remains constant from 3 km down to 1.5 km. This is consistent with Ferreira et al. (2001) results. They showed a 0~1 (1~3) dB increase downward from 3 km to 1.5 km in stratiform (convective) region for two hurricane cases by using TRMM PR and P3 radar data.

5. CONCLUSIONS AND FUTURE WORK

By investigating hydrometeor content profiles in tropical cyclones estimated by 4 different methods from a 1-year TRMM database, the big variability can be seen among different estimations. From Table 1, 2A12 tends to overestimate all IWPs and LWPs compared with 3 other methods except for IWP in inner rainband regions. The two 2A25 methods tend to underestimate all IWPs and LWPs, especially IWPs. More detailed examination is needed to find out the microphysical limitations of those methods.

The downward increasing (or being constant) of radar reflectivity below 3 km in both convective and stratiform region in hurricanes has important implications for both radar and radiometer surface rainfall retrievals. Future work will focus on comparing the shape of radar reflectivity profiles in hurricanes with that in other tropical oceanic systems.

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