Comparison of TRMM Rain-Rate Retrievals in Tropical Cyclones

Daniel J. CECIL and Matt WINGO

University of Alabama - Huntsville, Alabama, USA

(Manuscript received 10 July 2008, in final form 22 December 2008)

Abstract

Rain rates from four algorithms are examined in tropical cyclones (TCs). Old and new versions of the Remote Sensing Systems (RSS) rain estimates (RSS V03 and RSS V04) are compared with the standard version 6 TMI 2A12 and PR 2A25 algorithms, after averaging those down to the 0.25° scale used by RSS. RSS V03 produces more rain by a factor of two than the others, frequently assigning rain rates up to 25 mm h^{-1} (which is an internal limit for that product). Among the three current algorithms, PR 2A25 produces the most rain when averaged over a 0 to 100 km radius in hurricanes. This results from PR 2A25 assigning much higher grid-scale rain rates (up to 100 mm h^{-1}) in the small fraction of grid boxes having heaviest rain. TMI 2A12 has the least rain, assigning moderate rain rates (5 mm h^{-1}) to more grid boxes than the other products. The differences between algorithms are greatest for the inner regions of Category 3 to 5 hurricanes. In weaker TCs, or further away from the TC center, the three current algorithms tend to agree on mean rain rate. However, they arrive at these areal means from completely different distributions of grid-scale rain rates. PR 2A25 gets a greater fraction of its rain from grid boxes having high rain rates, with little contribution from the light and moderate rain rates. RSS V04 gets much of its rain from grid boxes with 10 mm h^{-1} . TMI 2A12 gets less rain around 10 mm h^{-1} , but balances that with greater contributions both from the occasional higher (15 mm h^{-1}) and more common lower (5 mm h^{-1}) rain rates. At the 0.25° scale, the TMI-based products are better correlated with each other than with PR 2A25. The RSS products are better correlated with PR 2A25 than TMI 2A12 is. All the correlations increase when more zero-rain or light-rain grid boxes are included (i.e., the weaker TCs or greater distances from the center).

1. Introduction

Several algorithms use the Tropical Rainfall Measuring Mission (TRMM) satellite to estimate rain rates. Different algorithms may use different measurements, retrieval footprints, and resolutions, with resulting rain estimates that have differing sensitivities and dynamic range. Even if algorithms agree on total large-scale precipitation, this agreement may be a result of offsetting biases in a variety of precipitation types. Comparisons between algorithms are often made on very large scales, with precipitation accu-

mulated over thousands of kilometers and months at a time. Alternatively, this paper assesses the retrieval characteristics specifically for tropical cyclones. Yokoyama and Takayabu (2008) estimate that 3.3% of the rain in the TRMM domain (35°S to 35°N) falls in tropical cyclones (TCs).

Rain-rate estimates are collected from four products – TRMM Microwave Imager (TMI) 2A12, TRMM Precipitation Radar (PR) 2A25, and two products of the Remote Sensing Systems (RSS). These are collected for all TCs seen by TRMM from 1998 to 2005. Comparisons are made only for those cases and locations where all four algorithms produced a valid retrieval (e.g., excluding land geolocations, because RSS does not produce retrievals there and 2A12 uses different retrieval physics for land than for ocean). The magnitude of rain rate and the frequency of rain oc-

Corresponding author: Daniel J. Cecil, University of Alabama – Huntsville, 320 Sparkman Dr NW, Huntsville, AL 35805, USA
E-mail: cecild@uah.edu
©2009, Meteorological Society of Japan

currence (i.e., non-zero estimates) are compared at a common 0.25° grid size.

The TMI 2A12 product is based on the Goddard Profiling (GPROF) algorithm (Kummerow et al. 2001). It uses a Bayesian approach, with several cloud model integrations providing the basis for pairings between surface rain rates and upwelling microwave brightness temperatures. The input brightness temperature measurements from TMI have footprint sizes ranging from 63×37 km (10.7 GHz) to 7×5 km (85.5 GHz). Rain rates are reported at the 12×5 km grid spacing of the highest frequency (85.5 GHz) channel. Version 6 of the 2A12 algorithm is used here; some of its features are noted by Olson et al. (2006) and Yang et al. (2006).

The PR 2A25 product uses a Z-R relationship to convert from radar reflectivity to rain rate. The parameters of the Z-R relationship depend on properties of the measured reflectivity profile, for example whether it is convective or stratiform (Iguchi et al. 2000). Before computing a rain rate, the measured reflectivity is corrected for attenuation following Iguchi and Meneghini (2004). Horizontal resolution for the PR measurements is approximately 4×4 km. Version 6 of the 2A25 algorithm is used here. Seto and Iguchi (2007) describe Version 6, and Shige et al. (2006) make some comparisons with TMI 2A12.

The RSS rain-rate products are based on the algorithm by Wentz and Spencer (1998), with a modification by Hilburn and Wentz (2008). These are referred to in this paper as RSS V03 (Wentz and Spencer 1998) and RSS V04 (Hilburn and Wentz 2008). RSS uses the same algorithms but with version numbers 05 and 06 for the Special Sensor Microwave Imager (SSM/I) and versions 04 and 05 for the Advanced Microwave Scanning Radiometer – EOS (AMSR-E). The rain-rate retrievals are preceded by retrieval of several other geophysical parameters (sea-surface temperature, surface wind speed, total column water vapor, etc.) from the microwave brightness temperatures. These other parameters are then used as constraints when retrieving a total column liquid water. This column total water is then converted to a constant mean rain rate below the melting level. Treatment of the melting level height is one of the key improvements in RSS V04 compared to V03. The other major difference is the treatment of non uniform beam-filling (Hilburn and Wentz 2008). Although retrievals are made at the TMI pixel locations, RSS releases its rain rate estimates on a $0.25^\circ \times 0.25^\circ$ grid.

As an example, the rain rates are plotted on the

0.25° grid for Hurricane Ivan (2004) in Fig. 1. Ivan was a Category 4 hurricane in the Gulf of Mexico at this time. Even after averaging to the 0.25° grid, PR 2A25 presents much more detail in the horizontal structure than the others. The TMI-based algorithms all use frequencies with footprint sizes exceeding the 0.25° grid, so they are not truly capable of resolving this spatial scale. PR 2A25 has a greater dynamic range, resolving a contrast between low rain rates of a few millimeters per hour and high rain rates well over 25 mm h^{-1} . In comparison, the others paint a broad swath of moderate or high rain rates. Other than PR 2A25, each product tends to have a “favored” range of rain rates. These will be noted in Section 4.

All of these algorithms (or their previous versions) have been used for studying TCs. Lonfat et al. (2004) and Chen et al. (2006) used earlier versions of TMI 2A12 and PR 2A25, Yokoyama and Takayabu (2008) used PR 2A25 Version 5 and TMI 2A12 Version 5, Cecil (2007) used RSS V03, and Wingo and Cecil (2008) used RSS V04. Yokoyama and Takayabu (2008) presented compelling evidence that PR 2A25 Version 5 more effectively distinguishes between convective and stratiform rain than Version 6, with very high stratiform rain rates ($> 10 \text{ mm h}^{-1}$) occurring much more often in Version 6 than in Version 5. This paper only considers Version 6 of both 2A12 and 2A25 because those are the current versions of the standard TRMM algorithms and the older versions are not readily available. However, the “old” (V03) version of the RSS products are used simply because they were on hand from the study by Cecil (2007). The goal of this paper is not to determine which rain rate retrieval product is “best” but instead to understand the characteristics of each one when dealing with TCs.

2. Data and methods

The rain-rate estimates are collected for each TRMM pass over a TC (Tropical Depression, Tropical Storm, or Hurricane stage, in any ocean basin) from 1998 to 2005. The TMI 2A12 and PR 2A25 rain rates are averaged from their original spacing (5×12 km for 2A12 and 4×4 km for 2A25) to the fixed $0.25^\circ \times 0.25^\circ$ latitude – longitude grid used for the RSS estimates. Only those grid boxes that have rain estimates from all algorithms are retained for analysis. These homogeneous $0.25^\circ \times 0.25^\circ$ grid boxes are the focus of Sections 4 to 6. This excludes grid boxes with contamination by land (no RSS rain estimates available) or boxes located outside the radar swath (no PR 2A25

Fig. 1. 0.25° grid scale rain rates for Hurricane Ivan, 0511 UTC 15 Sep 2004. Contours are at 0, 3, 7, 10, 15, 20, and 25 mm h⁻¹. (a) RSS V03. (b) RSS V04. (c) TMI 2A12. (d) PR 2A25. Latitude – longitude lines are plotted with 1° intervals.

rain estimates available).

The remaining homogeneous set of rain estimates is grouped by distance from the TC center and

also by TC intensity (using the best track data from the National Hurricane Center and Joint Typhoon Warning Center). The resulting sample sizes are list-

Table 1. Sample size. Number of grid points (top) and number of TCs (bottom). Note that the TC counts are not exclusive – e.g., the same storm is counted during both tropical storm and hurricane stages.

	0-100km	100-200km	200-300km	300-400km	400-500km
Tropical Depression	21532 508	63568 593	103815 636	135400 649	140289 647
Tropical Storm	19882 444	58700 509	95052 549	124730 552	129587 555
Cat 1-2 Hurricane	10455 232	30928 273	52238 295	70095 302	73371 301
Cat 3-5 Hurricane	6162 136	18913 153	31563 160	41995 162	44509 163

ed in Table 1. Rain-rate histograms are generated for each radial grouping (100 km increments from the center) and intensity range (tropical depression < 18 m s⁻¹, tropical storm 18 to 32 m s⁻¹, category 1 or 2 hurricane 33 to 49 m s⁻¹, category 3 to 5 hurricane ≥ 50 m s⁻¹). This gives the fractional occurrence of any particular rain rate (in 1 mm h⁻¹ increments) according to each algorithm. The total rain contributed by each rain-rate interval is also considered. For example, if 90% of the grid boxes are raining at 1 mm h⁻¹, they contribute 0.9 mm h⁻¹ per unit area to the total mean rain rate. If the other 10% of grid boxes are raining at 20 mm h⁻¹, they contribute an additional 2 mm h⁻¹ per unit area to the total mean rain rate.

3. Mean rain rates

First we consider the mean rain rate for each algo-

rithm (Fig. 2). All four algorithms agree that the mean rain rate decreases with distance from the TC center, and decreases with decreasing TC intensity. However, RSS V03 estimates much more rain than the other algorithms. For Category 3 to 5 hurricanes (Fig. 2a), RSS V03 estimates 16.1 mm h⁻¹ in the innermost 100 km. Estimates from the other algorithms range from 6.6 mm h⁻¹ (TMI 2A12) to 9.5 mm h⁻¹ (PR 2A25). At greater distances from the center, RSS V04 estimates more rain than the other two current algorithms, but only around half as much as RSS V03. Beyond 200 km, PR 2A25 estimates the least rain of all algorithms.

The comparison of mean rates is similar for Category 1 or 2 hurricanes (Fig. 2b). In the inner core, where the heaviest small-scale rains occur, PR 2A25 estimates greater total rain than TMI 2A12 or

Fig. 2. Areal mean rain rate versus distance from the center for the four products. (a) Category 3 to 5 hurricanes. (b) Category 1 and 2 hurricanes. (c) Tropical storms. (d) Tropical depressions. Note that the range of rain rates on the y-axis increases with increasing TC intensity.

RSS V04. At greater distances, RSS V04 estimates more rain than these other two current algorithms, but RSS V03 estimates twice as much rain as even RSS V04. The inner core high bias for PR 2A25 is not seen in the tropical storm (Fig. 2c) and tropical depression (Fig. 2d) mean rain rates. The three current algorithms closely agree on mean inner core rain rates for tropical storms (2.6 mm h^{-1}) and tropical depressions (1.5 mm h^{-1}). At greater distances from the center, RSS V04 consistently estimates slightly more rain and PR 2A25 estimates slightly less rain than TMI 2A12. However, these are small differences between total rain coming from the current algorithms, while RSS V03 estimates twice as much rain.

This general agreement on mean rain rates from the current algorithms contrasts with the previous version 5 of TMI 2A12 and PR 2A25. Yokoyama and Takayabu (2008) demonstrated that TMI 2A12 substantially over-estimated the mean rain rates, compared to PR 2A25. The differences were greater than a factor of two in the 110 to 240 km region of major hurricanes, and greater than a factor of 1.5 for weaker TCs. Yokoyama and Takayabu (2008) also mention that mean PR 2A25 rain is significantly greater than mean TMI 2A12 rain in version 6, but we see in Fig. 2 that that is only the case in the hurricane inner core, not at greater distances from the center or in weaker TCs.

4. Rain-rate histograms on 0.25° grid

Rain-rate histograms are presented for the innermost 100 km from the TC center (Fig. 3). At greater distances, more of the grid points are rain-free and few have heavy rain rates. Under these conditions, the algorithms generally approach better agreement. Given the general agreement on inner core areal mean rain rates from the three current algorithms, it is surprising to see how different their underlying rain rates are on the 0.25° grid.

The histograms from RSS V04 and TMI 2A12 have similar shapes, but they peak at different rain rates. This is easily seen for category 3 to 5 hurricanes (Fig. 3a); 9 to 11 mm h^{-1} are the most common rain rates for RSS V04, while 4 to 7 mm h^{-1} rain rates are most common for TMI 2A12. TMI 2A12 has more grid boxes with rain rates of 3 to 7 mm h^{-1} than any other product; RSS V04 has more with values of 7 to 15 mm h^{-1} than any other product. For both of these algorithms, it is rare to have rain rates greater than 15 mm h^{-1} on the 0.25° grid scale. The maximum values are 17 mm h^{-1} for RSS V04 and 27 mm h^{-1} for TMI 2A12.

Despite these differences in grid-scale rain rates, their areal mean values are close (7.6 mm h^{-1} for RSS V04 versus 6.6 mm h^{-1} for TMI 2A12).

The histograms from RSS V04 and TMI 2A12 have similar shapes, but they peak at different rain rates. This is easily seen for category 3 to 5 hurricanes (Fig. 3a); 9 to 11 mm h^{-1} are the most common rain rates for RSS V04, while 4 to 7 mm h^{-1} rain rates are most common for TMI 2A12. TMI 2A12 has more grid boxes with rain rates of 3 to 7 mm h^{-1} than any other product; RSS V04 has more with values of 7 to 15 mm h^{-1} than any other product. For both of these algorithms, it is rare to have rain rates greater than 15 mm h^{-1} on the 0.25° grid scale. The maximum values are 17 mm h^{-1} for RSS V04 and 27 mm h^{-1} for TMI 2A12. Despite these differences in grid-scale rain rates, their areal mean values are close (7.6 mm h^{-1} for RSS V04 versus 6.6 mm h^{-1} for TMI 2A12).

The PR 2A25 histogram has a completely different shape. It peaks at the lowest rain rates (0 to 1 mm h^{-1}) and decreases steadily from there. Unlike the RSS V04 and TMI 2A12 products, 21% of the grid points have PR 2A25 rain greater than 15 mm h^{-1} . The maximum PR 2A25 rain rate at this scale is 103 mm h^{-1} . The RSS V03 product has an inordinate number of rain rates assigned 25 mm h^{-1} values (32% of all grid points), and 58% exceed 15 mm h^{-1} . This preference for high rain rates, especially the 25 mm h^{-1} value, causes RSS V03 to produce much more total rain than the other algorithms. The anomalously high RSS V03 rain rates could possibly be due to an excessive beam-filling correction for some situations, while the new treatment of saturation in the RSS V04 beam-filling correction may create a preferred intermediate rain rate, at the expense of heavy rain rates (Hilburn 2008, personal communication).

All four products assign zero rain rates to only a tiny fraction (1 to 4%) of the grid boxes in the inner core of major hurricanes. If concentrated in a rain-free eye, this would equate to a 10 to 20 km radius. These products should substantially underestimate the rain-free area, though, because the fixed 0.25° grid is not aligned with the hurricane's center. The TMI-based products also include channels with large footprints, not necessarily aligned with the fixed 0.25° grid themselves. This smooths out the eye-eyewall gradient.

Category 1 or 2 hurricanes (Fig. 3b) have similar shapes for the histograms as those described above, although RSS V04 and TMI 2A12 both have peaks at the lowest rain rates (0 to 1 mm h^{-1}). TMI 2A12 again has more of the moderate (3 to 7 mm h^{-1}) rain rates

Fig. 3. Histograms of rain rate for each product, 0 to 100 km radius from TC center. (a) Category 3 to 5 hurricanes. (b) Category 1 and 2 hurricanes. (c) Tropical storms. (d) Tropical depressions. Histograms are computed with 1 mm h^{-1} bin size, with values plotted at the high end of that bin (the plotted value at 1 mm h^{-1} corresponds to the > 0 to 1 mm h^{-1} range). Only PR 2A25 has rain rates above 30 mm h^{-1} ; those higher rain rates are included in the 30 mm h^{-1} bin for plotting purposes.

than the other products; RSS V04 has the most in the 8 to 14 mm h^{-1} range. PR 2A25 again has the most rain-free (12%) or light-rain (29% below 1 mm h^{-1}) grid boxes and has a long tail to very high rain rates. eleven percent of the grid boxes have PR 2A25 rain rates over 15 mm h^{-1} , while less than 3% exceed this value for TMI 2A12 and less than 1% for RSS V04. For intermediate rain rates (4 to 12 mm h^{-1}), PR 2A25 has many fewer values than either RSS V04 or TMI 2A12. RSS V03 again has a disproportionate number of high rain rates; 37% of the RSS V03 rain rates exceed 15 mm h^{-1} , again with a spike (18%) at 25 mm h^{-1} .

Similar comparisons can be made in the tropical storm (Fig. 3c) and tropical depression (Fig. 3d) histograms. PR 2A25 has the most rain-free or very-light-rain grid boxes and has the longest tail to high rain

rates. TMI 2A12 has the most grid boxes with moderate rain rates near 4 mm h^{-1} , and RSS V04 has the most with rain rates near 9 mm h^{-1} . RSS V03 has the most with high rain rates, with its peak at 25 mm h^{-1} . All four products agree on identifying around 40% (25%) of the tropical depression (tropical storm) grid boxes as rain-free (Table 2). They mostly agree on how many of the grid boxes are either rain-free or very-light-rain, with 70% for tropical depressions and 50% of the tropical storms. PR 2A25, however, identifies substantially more (66%) of the tropical storm grid boxes as being rain-free or very-light-rain boxes.

The differences noted for tropical depressions and tropical storms are much smaller in magnitude than those for hurricanes. The products basically agree on so many rain-free / light-rain grid boxes, there is less room for disagreement on the higher rain rates. The

Table 2. Fraction of grid points with zero rain rate (top) and with rain rates less than or equal to 1 mm h⁻¹ (bottom). Only grid points 0 to 100 km from TC center.

	RSS V03	RSS V04	TMI 2A12	PR 2A25
Tropical Depression	42.4% 64.4%	44.5% 69.5%	37.9% 70.1%	41.8% 75.9%
Tropical Storm	26.7% 48.8%	28.3% 54.8%	22.8% 55.2%	31.6% 66.2%
Cat 1-2 Hurricane	6.7% 17.8%	7.1% 22.3%	5.3% 25.7%	12.2% 41.5%
Cat 3-5 Hurricane	1.6% 4.6%	1.7% 6.5%	1.3% 10.1%	3.9% 22.9%

same is true at greater distances from the TC center (not shown). Just as the mean rain rates for 100 to 200 km in Category 3 to 5 hurricanes are more comparable to those from 0 to 100 km in Category 1 to 2 hurricanes in Fig. 2, the rain-rate histograms for 100 to 200 km in Category 3 to 5 hurricanes are somewhat similar to those shown in Fig. 3b for 0 to 100 km in Category 1 and 2 hurricanes. Likewise, other rain-rate histograms at great distances from the TC center look similar to the tropical storm and tropical depression inner-core histograms in Figs. 3c to d. As in Lonfat et al. (2004) analysis using an earlier version of TMI 2A12, light rain rates dominate all storm intensity categories at great distances from the center.

5. Contributions to total areal-mean rain rates

Whereas the previous section examined the frequency of occurrence for each rain rate, this section examines the rainfall contribution from each rain rate. Even when low rain rates cover most of the area in a storm, that large area does not necessarily contribute most of the rainfall. The lines in Fig. 4, when summed over all 1 mm h⁻¹ increments of rain rate, add up to the areal-mean rain rates in Fig. 2. Note the logarithmic axes in Fig. 4. Contributions from the ranges of 3 to 7 mm h⁻¹ (most often favored by TMI 2A12), 7 to 15 mm h⁻¹ (more favored by RSS V04), and > 15 mm h⁻¹ (favored by PR 2A25 and RSS V03) are listed in Table 3, along with the total areal-mean rain rates. These are all for the inner 0 to 100 km from the TC center.

Comparing Fig. 4a with Fig. 2a, virtually the entire difference between RSS V03 areal-mean rain rate and those from the other algorithms can be accounted for by the frequent 25 mm h⁻¹ grid boxes in the RSS V03 product. They alone account for half (8.0 mm h⁻¹) of

the RSS V03 rain in the inner core of Category 3 to 5 hurricanes. Rain rates over 15 mm h⁻¹ account for over 80% of the RSS V03 total, and virtually none of the newer RSS V04 total (Table 3a).

In Section 4, it was noted that RSS V04 identifies 7 to 15 mm h⁻¹ rain rates more often than the other products in the inner core of category 3 to 5 hurricanes. This range accounts for 5.9 of the 7.6 mm h⁻¹ total for RSS V04 (Table 3a). The same range contributes only 3.4 mm h⁻¹ to the total for TMI 2A12 and 1.9 mm h⁻¹ for PR 2A25. The 3 to 7 mm h⁻¹ range was noted as occurring more often in TMI 2A12 than in the others, but it only contributes 1.9 mm h⁻¹ to the total (1.4 mm h⁻¹ for RSS V04, 0.9 mm h⁻¹ for PR 2A25). These moderate rain rates do not amount to much difference in total rainfall.

PR 2A25 has many more light-rain grid boxes than the other algorithms (Fig. 3a), but these account for only a tiny fraction of the total rainfall (about 4% of the PR 2A25 rainfall comes from rain rates less than 3 mm h⁻¹ on the 0.25° grid scale). Instead, the long tail of high rain rates produces most of the total rain. Grid boxes with over 15 mm h⁻¹ contribute 6.2 of the total 9.5 mm h⁻¹ areal-mean rain rate (Table 3a). Yokoyama and Takayabu (2008) show that these high PR 2A25 rain rates include both convective and stratiform pixels (their Fig. A1), which draws the Version 6 PR 2A25 convective-stratiform classification into question. The previous Version 5 of PR 2A25 had greater separation between convective and stratiform rain rates, but also had lower values for both (comparing Yokoyama and Takayabu's Fig. 3 and Fig. A1). Shige et al. (2006) use 10.7 GHz brightness temperatures to suggest that high rain rates are handled better by PR 2A25's Version 6 than Version 5. Although there re-

Fig. 4. As in Fig. 3, but contribution to areal-mean rain rate from each individual rain-rate value.

main some problems in the convective-stratiform rain separation, we select version 6 for our analysis since we compare only the total rain in this work.

These differences between the products in Fig. 4a and Table 3a seem to explain much of the difference in mean rain rates. RSS V03 produces much more rain than the others because of its strong contributions from 25 mm h^{-1} grid boxes in particular, and more generally from its many grid boxes with over 15 mm h^{-1} rain rates. PR 2A25 has the next highest mean rain rate because of its long tail of very heavy rain rate grid boxes. RSS V04 assigns rain rates over 15 mm h^{-1} less often than any of the others, but does assign many rain rates near 10 mm h^{-1} . TMI 2A12 produces the least rain of these algorithms because it tends to assign so many moderate (5 mm h^{-1}) rain rates instead, while only rarely exceeding 10 mm h^{-1} on this grid scale.

Similar comparisons apply for Category 1 and 2 hurricanes in Fig. 4b and Table 3b. For tropical

storms, though, the three current algorithms all produce essentially the same 0 to 100 km mean rain rate (Fig. 2c and Table 3c): 2.6 mm h^{-1} . The high rain-rate tail of the PR 2A25 distribution drops off more sharply in tropical storms than it does in hurricanes. Rain rates exceeding 15 mm h^{-1} account for less than half of the PR 2A25 tropical storm rain, compared to almost two-thirds for the Category 3 to 5 hurricane rain. Rain rates in the 7 to 15 mm h^{-1} range still account for more rain in RSS V04 than in TMI 2A12, but only by a small amount. They are balanced by the higher rain rates that are occasionally produced by TMI 2A12, but practically never produced by RSS V04.

6. Correlations on 0.25° grid scale

One question raised by the previous analysis is whether the grid-scale rain rates are basically shifted toward moderate values for TMI 2A12 and high values for RSS V03 and PR 2A25 in a somewhat uniform manner. In other words, is there a straightfor-

Table 3. Contribution to total 0 to 100 km areal-mean rain rate from particular ranges of 0.25° grid rain rate values. (a) Category 3 to 5 hurricanes. (b) Category 1 and 2 hurricanes. (c) Tropical storms. (d) Tropical depressions.

a)

Category 3-5 hurricanes	RSS V03	RSS V04	TMI 2A12	PR 2A25
3-7 mm h ⁻¹	0.5	1.4	1.9	0.9
7-15 mm h ⁻¹	2.2	5.9	3.4	1.9
> 15 mm h ⁻¹	13.3	0.1	1.0	6.2
Areal - mean	16.1	7.6	6.6	9.5

b)

Category 1-2 hurricanes	RSS V03	RSS V04	TMI 2A12	PR 2A25
3-7 mm h ⁻¹	0.7	1.3	1.6	0.8
7-15 mm h ⁻¹	2.0	3.6	2.2	1.4
> 15 mm h ⁻¹	8.3	0.1	0.5	3.0
Areal - mean	11.2	5.4	4.7	5.6

c)

Tropical storms	RSS V03	RSS V04	TMI 2A12	PR 2A25
3-7 mm h ⁻¹	0.5	0.8	0.8	0.5
7-15 mm h ⁻¹	1.1	1.4	1.1	0.6
> 15 mm h ⁻¹	3.3	0.0	0.4	1.2
Areal - mean	5.3	2.6	2.6	2.6

d)

Tropical depressions	RSS V03	RSS V04	TMI 2A12	PR 2A25
3-7 mm h ⁻¹	0.4	0.5	0.5	0.3
7-15 mm h ⁻¹	0.8	0.7	0.6	0.4
> 15 mm h ⁻¹	1.7	0.0	0.2	0.4
Areal - mean	3.2	1.6	1.6	1.5

ward transformation from one product to another, or is there substantial scatter in the relationships?

There is a straightforward (but not quite uniform) transformation with little scatter between RSS V03

and RSS V04 (Fig. 5a). Rain rates of 10 mm h⁻¹ in RSS V03, for example, are shifted down to 4 to 6 mm h⁻¹ in RSS V04. For hurricane strength cases in the inner 0 to 100 km, the linear correlation coefficient is

0.97. This is not surprising, since the two algorithms are based on the same measurements and the same basic retrieval physics.

The TMI-based products have higher correlations with each other than with the radar-based PR 2A25. Correlation coefficients between both RSS products and TMI 2A12 are 0.77, with substantial scatter. The new RSS V04 does correlate better with PR 2A25 ($r^2=0.70$) than did the old RSS V03 ($r^2=0.62$). An alarming number of the grid boxes with 15 to 25 mm h⁻¹ RSS V03 rain rates had PR 2A25 rain rates of only a few millimeters per hour (or less!). The scatter is notably reduced in the plot of RSS V04 versus PR 2A25 (comparing Figs. 5d to e). The correlation coefficients are lowest (0.61) when comparing TMI 2A12 to PR 2A25. For any of the TMI versus PR scatter plots, however, low PR rain rates tend to be shifted

up to moderate values for TMI, and high PR rain rates are shifted down to values usually limited to 10 to 15 mm h⁻¹ for TMI.

Correlation coefficients are higher for all combinations of products at greater distance from the TC center and for weaker TC intensities. In those circumstances, a greater percentage of grid points have either no rain or only light rain. These grid points make it relatively easy for all products to converge on the same answer. While developing a new TMI-based rain rate retrieval algorithm, Prabhakara et al. (2008) compared TMI 2A12 and PR 2A25 for twenty tropical oceanic cases, after averaging to a 20 km x 20 km grid. Linear correlation coefficients ranged from 0.51 to 0.83 for the individual cases, generally consistent with the correlations in this study. Two TC cases were presented. One had a 0.51 correlation and little

Fig. 5. Scatter plots of (a) RSS V03 vs. RSS V04, (b) RSS V03 vs. TMI 2A12, (c) RSS V04 vs. TMI 2A12, (d) RSS V03 vs. PR 2A25, (e) RSS V04 vs. PR 2A25, and (f) TMI 2A12 vs. PR 2A25 for 0 to 100 km from the TC center.

rain-free area; the other had a 0.77 correlation and a broader rain-free area.

7. Summary and conclusions

This paper compares tropical cyclone (TC) rain rates from four algorithms, all using a uniform 0.25° grid. The old RSS V03 algorithm produces a factor of two more rain than the current RSS V04, TMI 2A12, and PR 2A25 algorithms. RSS V03 assigns many more high rain-rate values to grid boxes than the others, often reaching the algorithm's limit of 25 mm h^{-1} . The current algorithms generally agree on the mean rain rates at great distances from the TC center and for weak TCs. Those conditions include a larger fraction of rain-free or light-rain areas than the hurricane inner core, and the algorithms basically agree on identifying grid boxes as rain-free or light-rain.

For hurricanes (using the term generically, regardless of ocean basin), there are notable differences between the algorithms for the mean inner-core rain rate. PR 2A25 produces the most 0 to 100 km rain, due largely to a small fraction of grid boxes that have very high localized rain rates. On the 0.25° grid scale, the PR 2A25 distribution has a long tail extending to rain rates as high as 100 mm h^{-1} . The current TMI-based products are limited to around 15 mm h^{-1} on this scale. RSS V04 assigns 10 mm h^{-1} rain rates to more grid boxes than the other products. TMI 2A12 assigns more moderate (3 to 7 mm h^{-1}) rain rates than the others, yielding the lowest 0 to 100 km mean.

Even when the three current algorithms agree on total areal-mean rain, they arrive at these rain totals from completely different distributions of grid-scale rain rates. PR 2A25 gets a greater fraction of its rain from grid boxes having high rain rates, with little contribution from the light and moderate rain rates. RSS V04 gets much of its rain from grid boxes with 10 mm h^{-1} . TMI 2A12 gets less rain around 10 mm h^{-1} , but balances that with greater contributions both from the occasional higher (15 mm h^{-1}) and more common lower (5 mm h^{-1}) rain rates.

Correlations of the 0.25° grid-scale rain rates are highest when intercomparing the TMI-based products. RSS V03 and RSS V04 have a correlation near one, with rain rates shifted down substantially from the older to the newer version. Both RSS products have 0.77 correlation coefficients with TMI 2A12 in the hurricane inner core. PR 2A25 correlates better with RSS V04 (0.70) than with TMI 2A12 (0.61). These correlation coefficients increase for weaker TCs or greater distances from the center, where there

are more rain-free or light-rain areas and subsequently better agreement between the products.

Acknowledgments

This work is supported by the National Aeronautics and Space Administration (NASA) Tropical Cloud Systems and Processes (TCSP) project, grant NNG05GR57G. Data were provided by the TRMM Science Data Information System (TSDIS) and Remote Sensing Systems (RSS). We also extend our appreciation to two anonymous reviewers and Kyle Hilburn for input that improved the manuscript.

References

- Cecil, D. J., 2007: Satellite-derived rain rates in vertically sheared tropical cyclones, *Geophys. Res. Lett.*, **34**, L02811, doi:10.1029/2006GL027942.
- Chen, S. S., J. A. Knaff, and F. D. Marks Jr., 2006: Effects of vertical wind shear and storm motion on tropical cyclone rainfall asymmetries deduced from TRMM. *Mon. Wea. Rev.*, **134**, 3190–3208.
- Hilburn, K. A., and F. J. Wentz, 2008: Intercalibrated passive microwave rain products from the Unified Microwave Ocean Retrieval Algorithm (UMORA). *J. Appl. Meteor. Climatol.*, **47**, 778–794.
- Iguchi, T., T. Kozu, R. Meneghini, J. Awaka, and K. Okamoto, 2000: Rain-profiling algorithm for the TRMM Precipitation Radar. *J. Appl. Meteor.*, **39**, 2038–2052.
- Kummerow, C., Y. Hong, W. S. Olson, S. Yang, R. F. Adler, J. McCollum, R. Ferraro, G. Petty, D.-B. Shin, and T. T. Wilheit, 2001: The evolution of the Goddard Profiling Algorithm (GPROF) for rainfall estimation from passive microwave sensors. *J. Appl. Meteor.*, **40**, 1801–1820.
- Lonfat, M., F. D. Marks Jr., and S. S. Chen, 2004: Precipitation distribution in tropical cyclones using the Tropical Rainfall Measuring Mission (TRMM) microwave imager: A global perspective. *Mon. Wea. Rev.*, **132**, 1645–1660.
- Meneghini, R., J. A. Jones, T. Iguchi, K. Okamoto, and J. Kwiatkowski, 2004: A hybrid surface reference technique and its application to the TRMM Precipitation Radar. *J. Atmos. Oceanic Technol.*, **21**, 1645–1658.
- Olson, W. S., C. D. Kummerow, S. Yang, G. W. Petty, W.-K. Tao, T. L. Bell, S. A. Braun, Y. Wang, S. E. Lang, D. E. Johnson, and C. Chiu, 2006: Precipitation and latent heating distributions

- from satellite passive microwave radiometry. Part I: Improved method and uncertainties. *J. Appl. Meteor. Climatol.*, **45**, 702–720.
- Prabhakara, C., R. Iacovazzi Jr., J.-M. Yoo, K.-M. Kim, and T. L. Bell, 2008: A method to estimate rain rate over tropical oceans with TRMM Microwave Imager radiometer. *J. Meteor. Soc. Japan*, **86**, 203–212.
- Seto, S., and T. Iguchi, 2007: Rainfall-induced changes in actual surface backscattering cross sections and effects on rain-rate estimates by spaceborne Precipitation Radar, *J. Atmos. Oceanic Technol.*, **24**, 1693–1709.
- Shige, S., H. Sasaki, K. Okamoto, and T. Iguchi, 2006: Validation of rainfall estimates from the TRMM Precipitation Radar and microwave imager using a radiative transfer model: 1. Comparison of the version-5 and -6 products, *Geophys. Res. Lett.*, **33**, L13803, doi:10.1029/2006GL026350.
- Wentz, F. J., and R. W. Spencer, 1998: SSM/I rain retrievals within a unified all-weather algorithm. *J. Atmos. Sci.*, **55**, 1613–1627.
- Wingo, M., and D. J. Cecil, 2008: Effects of vertical wind shear on tropical cyclone precipitation. *Mon. Wea. Rev.*, (submitted).
- Yang, S., W. S. Olson, J.-J. Wang, T. L. Bell, E. A. Smith, and C. D. Kummerow, 2006: Precipitation and latent heating distributions from satellite passive microwave radiometry. Part II: Evaluation of estimates using independent data. *J. Appl. Meteor. Climatol.*, **45**, 721–739.
- Yokoyama, C., and Y. N. Takayabu, 2008: A statistical study on rain characteristics of tropical cyclones using TRMM satellite data. *Mon. Wea. Rev.*, **136**, 3848–3862.