A Statistical Analysis of Steady Eyewall Sizes Associated with Rapidly Intensifying Hurricanes

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ABSTRACT

It is well known that hurricane intensification is often accompanied by continuous contraction of the radius of maximum wind (RMW) and eyewall size. However, a few recent studies have shown rapid and then slow contraction of the RMW/eyewall size prior to the onset and during the early stages of rapid intensification (RI) of hurricanes, respectively, but a steady state in the RMW (S-RMW) and eyewall size during the later stages of RI. In this study, a statistical analysis of S-RMWs associated with rapidly intensifying hurricanes is performed using the extended best-track dataset during 1990–2014 in order to examine how frequently, and at what intensity and size, the S-RMW structure tends to occur. Results show that about 53% of the 139 RI events of 24-h duration associated with 55 rapidly intensifying hurricanes exhibit S-RMWs, and that the percentage of the S-RMW events increases to 69% when RI events are evaluated at 12-h intervals, based on a new RI rate definition of $10\,m\,s^{-1}\,(12\,h)^{-1}$; both results satisfy the Student's *t* tests with confidence levels of over 95%. In general, S-RMWs tend to appear more frequently in more intense storms and when their RMWs are contracted to less than 50 km. This work suggests a new fruitful research area in studying the RI of hurricanes with S-RMWs.

1. Introduction

Despite considerable progress in tropical cyclone (TC) research, our understanding of TC structural and intensity changes is very limited, especially during its rapid intensification (RI) phase, where RI is defined by Kaplan and DeMaria (2003, hereafter KD) as an intensification rate of more than $15\,m\,s^{-1}$ per day in the maximum sustained surface wind V_{MAX}. It has long been well known that intensifying TCs are often accompanied by continuous contraction of the radius of maximum wind (RMW) or eyewall size with intensifying radial inflows in the planetary boundary layer (PBL) (Shapiro and Willoughby 1982; Willoughby et al. 1982; Schubert and Hack 1982; Willoughby 1990; Liu et al. 1999; Yau et al. 2004; Rogers 2010). Ooyama (1982) demonstrated theoretically that radial inflows, induced by diabatic heating in the eyewall, play an important role in spinning up tangential flows by advecting higher absolute angular momentum (AAM) inward. Zhang et al. (2001) showed, through AAM budgets using modeled Hurricane Andrew (1992) data, that the AAM is materially conserved above the PBL. Even in the PBL where the AAM is not conserved because of friction, its inward advection still accounts for the amplification of tangential flows (Zhang et al. 2001; Yau et al. 2004; Montgomery and Smith 2011).

Apparently, the intensity changes of TCs are negatively correlated with the RMW changes, as shown statistically by Carrasco et al. (2014) and Xu and Wang (2015, hereafter XW), and rapid contraction of the RMW could precede the RI of TCs (Liu et al. 1999;

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Sitkowski and Barnes 2009; Chen et al. 2011). However, some recent studies show that intensifying TCs are not always accompanied by contracting RMWs. For example, Vigh (2010) and Stern et al. (2015) mentioned a few major hurricanes (e.g., Andrew in 1992, Lili in 2002, and Emily in 2005) exhibiting rapid contraction of the RMWs during intensification, but contraction was halted long before they reached their peak intensities, that is, showing nearly a steady state in RMWs (hereafter referred to as S-RMWs). A numerical prediction of Hurricane Wilma (2005) by Chen et al. (2011) presented a slowly contracting RMW, followed by an S-RMW, during the RI stage, and even an increased RMW as Wilma was reaching its maximum intensity. Kieu (2012) documented the abrupt slowdown of the RMW contraction in the middle of hurricane intensification and, then, the appearance of an S-RMW during RI from a series of ensemble simulations of Hurricane Katrina (2005). Wang and Wang (2014) showed an S-RMW occurring even during a 60-h RI period of the simulated Typhoon Megi (2010). Stern et al. (2015) have shown similar scenarios in their idealized simulations of intensifying TCs. However, few observational studies have been performed to systematically confirm how frequently and significantly the S-RMW structure occurs in rapidly intensifying TCs.

Given the successful reproduction of many inner-core structures and the patterns of evolution of TCs by today's numerical models, we may hypothesize that S-RMWs tend to occur often in rapidly intensifying TCs, especially after reaching category-3 stage in which the inertial resistance to radial motion is large. Thus, one of the major objectives of this study is to test the above hypothesis by examining to what extent it is statistically valid from a 25-yr observation-based dataset. In this study, we focus only on intense TCs (i.e., hurricanes with a V_{MAX} of at least $33\,m\,s^{-1}$), because we believe that weaker TCs may have poorly defined RMWs/eyewalls and intensify simultaneously with the contraction of the RMWs/eyewall.

The next section describes the observational dataset used to test the above hypothesis and data processing. Section 3 examines statistically how frequently rapidly intensifying hurricanes exhibit an S-RMW, and at what intensity and radius S-RMWs frequently occur at 24-h intervals. Section 4 repeats the procedures from section 3, but at 12-h intervals after a revised RI criterion is developed and applied. A summary and concluding remarks are given in the final section.

2. Data description and processing

In this study, the extended best-track (EBT) dataset at 6-h intervals for North Atlantic TCs, which has been the main data source employed to examine some climatology of TC intensity and size (e.g., Kimball and Mulekar 2004; Demuth et al. 2006; Carrasco et al. 2014; XW), is used to investigate the relationship between the S-RMW and rapidly intensifying hurricanes during the 25-yr period of 1990–2014. This dataset was constructed using aircraft reconnaissance data, ship and other surface reports, and satellite imagery (Sampson and Schrader 2000; Kimball and Mulekar 2004). The variables of our interest from the EBT dataset include V_{MAX}, discretized at 5 kt (or $2.57\,m\,s^{-1}$) intervals, and the RMW, discretized at 5 n mi (or 9.26 km) intervals.

It is necessary to mention that TCs change their intensities and RMWs at 6-h intervals by amounts that are not the same as the above discretization intervals. In addition, certain observation errors could further limit the extent to which accurate estimates of V_{MAX} and the RMW can be obtained (Uhlhorn and Nolan 2012; Torn and Snyder 2012; Landsea and Franklin 2013). Since the RMWs change slowly or remain nearly constant during RI as a result of the presence of large inertial stability, which has also been shown by the above-mentioned modeling studies, we believe that the associated observational errors should be smaller than the discretization intervals of 5 n mi. On the other hand, it is quite possible that the RMWs in some slowly contracting hurricanes were treated as S-RMWs with the 5 n mi discretization intervals.

To minimize the effects of data discretization, the unit of nautical miles recorded for the RMW will not be converted to the unit of kilometers, and any interpolation or smoothing is avoided. Since our hypothesis involves only hurricanes, any 6-h events, in which V_{MAX} is weaker than $33\,m\,s^{-1}$ (category-1 hurricane), and any landfalling storm, are excluded from our analysis. Some records are also discarded because of missing RMW information. As a result, a total of 175 hurricanes occurring during the 25 yr are identified for the present study.

3. S-RMW and RI evaluated at 24-h intervals

a. Statistical results

As a first step, we attempt to determine whether or not there exists a statistically significant relationship between S-RMWs and rapidly intensifying hurricanes that satisfies KD's RI criterion. By calculating the 24-h rates of V_{MAX} changes, we find that 1) 139 events of 24-h duration associated with 55 hurricanes meet KD's RI criterion and 2) 53% of them (i.e., 73 events) exhibit S-RMWs, hereafter referred to as the S-RMW RI events. Note that RMWs may increase slightly during RI (see Fig. 11 in Chen et al. 2011). So these events, albeit only a few, have been included in the analysis. A Student's *t*

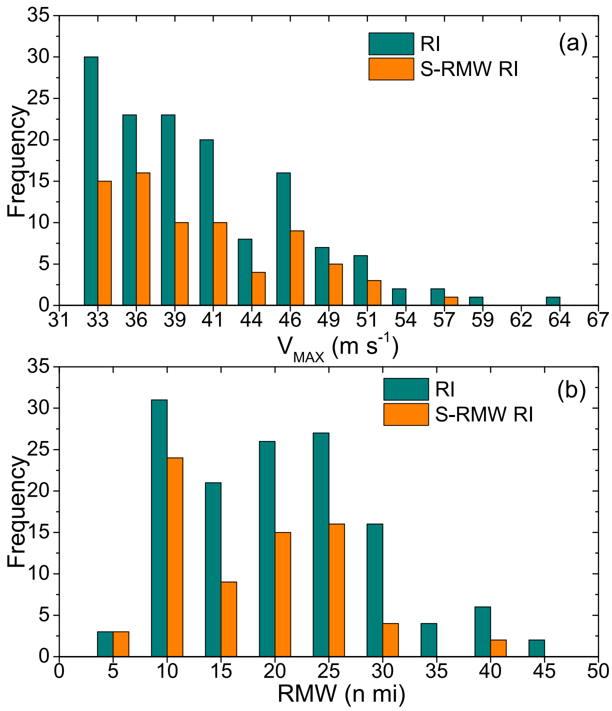

FIG. 1. The frequency (number) distribution of the 24-h S-RMW RI events (orange columns, summed to 73) and the corresponding total RI events (green columns, summed to 139) as a function of (a) V_{MAX} (m s^{-1}) and (b) RMW (n mi). Note that the RI events shown here are calculated, following KD, without considering any intensity change occurring within the 24-h interval of interest. There are 73 S-RMW RI events of 24-h duration out of a total of 139 RI events of 24-h duration associated with 55 rapidly intensifying hurricanes.

test examining the RI and S-RMW RI events indicates that the latter are significantly different at over a 95% confidence level from the former with contracting RMWs for all 175 of the storms selected.

After ensuring the statistical significance of the above results, Fig. 1a shows the frequency distribution of the RI and the S-RMW RI events as a function of V_{MAX}. We see that both frequencies decrease as a hurricane intensifies from category 1 to 4 (i.e., 33, 44, 51, and 59 m s^{-1}, respectively), as expected. That is, about 70% of both the RI and the S-RMW RI events are confined to category-1 storms. This result is in agreement with that of XW, who showed that the peak intensification of TCs tends to occur for those storms whose V_{MAX} ranges between 36 and 41 m s^{-1}.

The frequency distribution of the RI and S-RMW RI events as a function of the RMW is given in Fig. 1b, showing that the 24-h RI events take place mostly when the RMWs range between 10 and 30 n mi (1 n mi = 1.852 km), similar to the results for the S-RMW RI events. The RI and RMW relationship agrees with that of Carrasco et al. (2014) and XW, who showed that TCs with RMWs of 20–60 km are more easily intensified. A further examination of the frequency distribution indicates that rapidly intensifying hurricanes with smaller RMWs tend to more likely exhibit S-RMWs, especially for those with a RMW less than 15 n mi.

b. *Limitations*

The above results indicate that KD's criterion tends to skew toward the RI of category-1 hurricanes, partly because it was obtained by considering TCs at all intensities and with all intensity changes, even weakening ones. As Ventham and Wang (2007) pointed out, the intensification rates of TCs should be a function of their initial intensities. That is, very intense TCs are less likely to intensify at the rates that are higher than weak TCs. So Fig. 2a shows the cumulative percentage of the 24-h intensification rates from different hurricane intensity categories. Considering only hurricane categories, the 85th–90th percentile range, corresponding to the RI rate of 15 m s^{-1} (24 h)$^{-1}$, should be used to obtain an RI criterion that is equivalent to KD's taken at the 95th percentile. It is evident that the 24-h intensification rate at the 90th–95th percentile decreases as a storm intensifies from initial category 3 to category 5. That is, stronger storms tend to intensify at slower rates, which may be attributed partly to the evaluation of RI at the 24-h interval, which is too long to resolve the RI of hurricanes. Moreover, the S-RMW structure in some rapidly intensifying TCs may not be sustainable for 24 h. In this regard, it is highly desirable to obtain high temporal resolution data in order to capture the S-RMW structure during the RI of hurricanes. On the other hand, the 6-h data discretization time is too short to reveal realistically the nature of the S-RMWs. Thus, the duration issue of the RI and S-RMW events has to be considered prior to the evaluation of the RI and S-RMW events at shorter durations.

4. S-RMW and RI evaluated at 12-h intervals

a. *A 12-h RI criterion*

To determine an appropriate duration for our analysis, the cumulative percentage of the duration of S-RMWs events for all intensifying hurricanes is plotted in Fig. 2b, showing that the 24-h interval could only include less than 5% of the cases. In this regard, it may be mentioned that Hurricane Isaac (2000) has a 48-h sustained S-RMW of 15 n mi, and both Hurricanes Gert (1999) and Alberto (2000) had 42-h sustained S-RMWs of 25 n mi, as compared to a 60-h sustained S-RMW of 40 km in the simulation of Typhoon Megi (2010) by Wang and

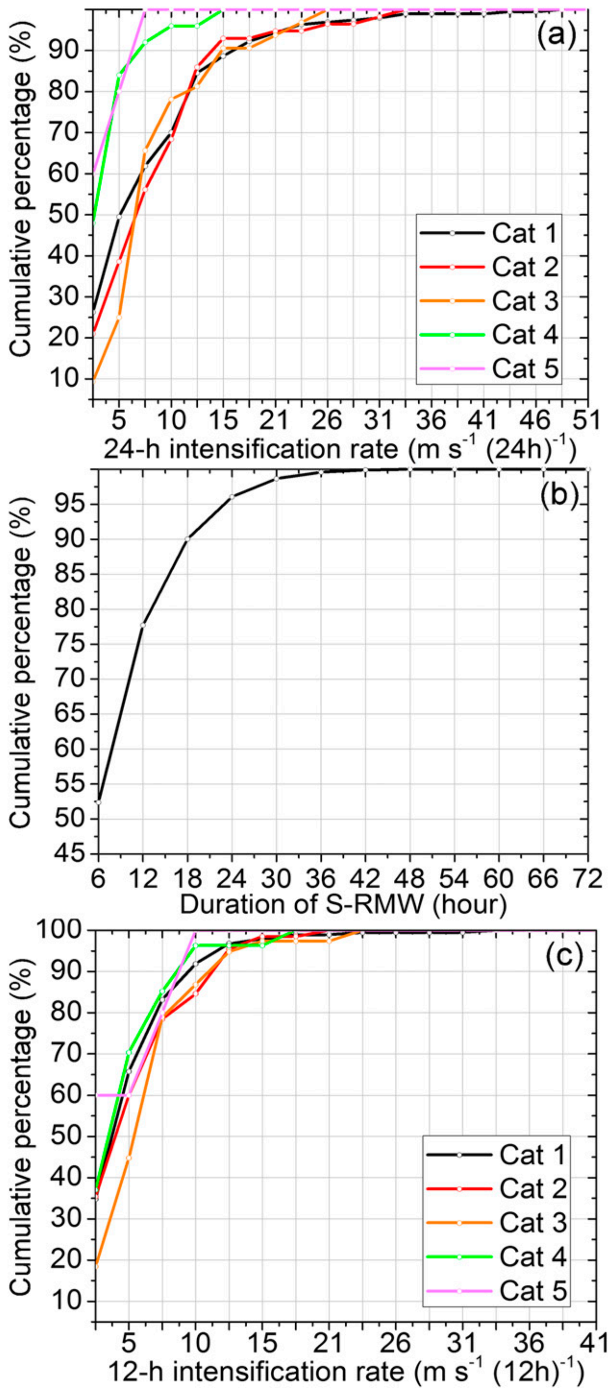

FIG. 2. Cumulative percentage distribution of (a) the 24-h intensification rates from the initial intensities of 33 m s^{-1} (category 1), 44 m s^{-1} (category 2), 51 m s^{-1} (category 3), 59 m s^{-1} (category 4), and 69 m s^{-1} (category 5). (b) The duration (h) of the S-RMWs events. (c) As in (a), but for the 12-h intensification rates, for the Atlantic hurricanes during the 25 yr of 1990–2014. The 24- and 12-h intensification rates in (a) and (c) are calculated without considering any intensity change within the 24- and 12-h intervals of interest.

Wang (2014). Again, it is possible that the above observed long durations of the S-RMWs might have included periods of slowly contracting RMWs during their RI stages because of the use of the 5 n mi discretization intervals, as mentioned in section 2.

Clearly, more cases would be included if a shorter time interval is used (Fig. 2b). We found 147 and 302 S-RMW events, respectively, when both V_{MAX} and RMW are evaluated at 18- and 12-h intervals. This indicates that it is appropriate to use a 12-h interval to identify S-RMW events, since its associated sample size is more than twice of that found when using an 18-h interval. Figure 2b indicates that the 12-h interval corresponds to about the 78th percentile, which is acceptable for our statistical analysis.

Now, a 12-h RI criterion needs to be defined to examine the relationship between RI and S-RMWs. Clearly, KD's 24-h RI criterion cannot be simply extended to 12 h, but their philosophy in developing the RI criterion can be followed. For this reason, Fig. 2c is plotted in the same manner as in Fig. 2a, but as a function of 12-h intensification rate. One can see significant shifts in the curves toward smaller intensification rates in the lower left with higher percentiles, as the time interval is reduced from 24 to 12 h (cf. Figs. 2c and 2a). Specifically, the percentile for all intensities decreases from about 90 at a 15 m s^{-1} $(24\,h)^{-1}$ rate to about 80 at a 7.5 m s^{-1} $(12\,h)^{-1}$ rate. An exception occurs for category-4 and -5 hurricanes at 24-h intervals, which should be excluded from examination because of their small sample sizes, but their curves converge with category-1 to -3 storms at 12-h intervals (Fig. 2c). Obviously, the 80th percentile appears to misrepresent KD's RI criterion. However, if 12-h RI is defined as the 85th–90th percentile of V_{MAX} changes, as indicated in section 3b, the 10 m s^{-1} $(12\,h)^{-1}$ RI rate would be statistically equivalent to the 15 m s^{-1} $(24\,h)^{-1}$ RI rate, and it will reflect well the cumulative percentages of category 1–3 hurricanes. Thus, the former rate is used in the next section to identify 12-h RI events in the same way as the 24-h RI events.

b. S-RMW events at 12-h intervals

By applying the procedures described above, a total of 164 RI events of 12-h duration associated with 71 hurricanes are identified, and about 69% of them (i.e., 113 events) possess S-RMWs. This result satisfies the significance *t* test at more than the 95% confidence level. Note that although the total RI events at 12-h intervals only increase 18%, the 12-h S-RMW events increase 55% compared with their 24-h counterparts. We may speculate that the S-RMW events may be seen more frequently if higher temporal resolution observations are available. In addition, we find that about 66% (of

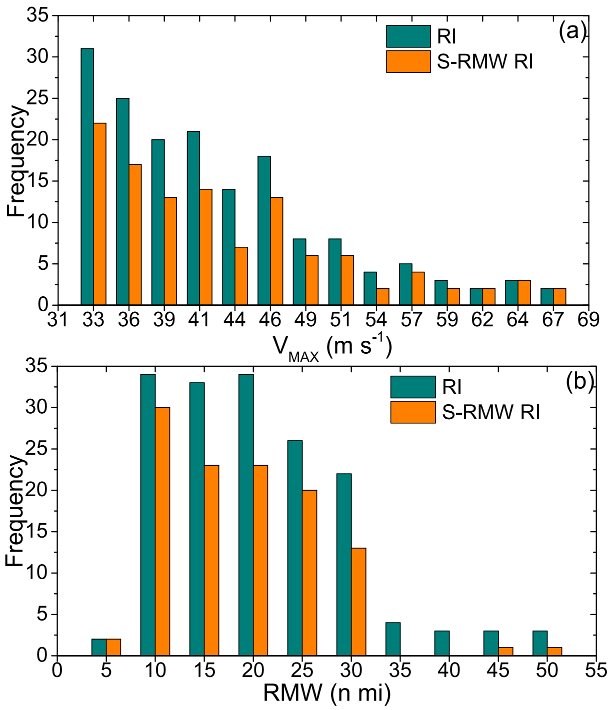

FIG. 3. As in Fig. 1, but for the 12-h S-RMW RI (orange columns, summed to 113) and the corresponding total RI events (green columns, summed to 164). There are 113 S-RMW RI events of 12-h duration out of a total of 164 RI events of 12-h duration associated with 71 rapidly intensifying hurricanes.

680) of the 12-h intensifying but non-RI events show the occurrences of S-RMWs, in which a sizeable portion of the S-RMW events are associated with the storms that have undergone RI but with slower intensification rates. The results suggest that some S-RMW events may not occur simultaneously as RI, but may lag behind it, as has also been shown by some modeling studies (e.g., see Fig. 11 in Chen et al. 2011, and Fig. 8a in Wang and Wang 2014).

Figure 3 presents the same diagrams as those in Fig. 1, but for the 12-h intervals, showing that like the 24-h counterparts, the frequency of the 12-h RI events decreases with increasing V_{MAX}, and similarly for the corresponding S-RMW RI events. Again, a large portion of these events is associated with category-1 hurricanes. However, the percentages of S-RMWs at individual intensity ranges show significant increases, with higher percentages for stronger hurricanes. In particular, 75% ~ 100% of category-3 and -4 hurricanes possess S-RMWs. Thus, we may state that the more intense a rapidly intensifying hurricane is, the easier it is for the storm to attain the S-RMW structure.

With the 12-h intervals, Fig. 3b shows more clearly that S-RMWs occur frequently in the range of 5–30 n mi, with higher percentages toward much smaller-sized storms (e.g., at 5 and 10 n mi). This is relatively easy to understand since larger-sized hurricanes experiencing RI may result more from rapid contraction of the larger RMWs under the relatively weak inertial constraint.

5. Concluding remarks

In this study, a statistical analysis of S-RMWs associated with rapidly intensifying hurricanes is performed using the EBT dataset during the 25 yr of 1990–2014. Results show that about 53% of 139 RI events of 24-h duration that are associated with 55 rapidly intensifying hurricanes exhibit S-RMWs. This percentage increases to 69% when RI events are evaluated at 12-h intervals, based on a new RI rate definition of $10\,\mathrm{m\,s^{-1}}\,(12\,\mathrm{h})^{-1}$. We may expect this percentage to increase further if higher temporal resolution data are available. Student's *t* tests confirm that the S-RMW structure is a significant feature of rapidly intensifying TCs, especially after they reach category-3 intensity. This significant feature could be attributed partly to the presence of large inertial stability in intense hurricanes. Thus, we may state that S-RMWs tend to appear more frequently in more intense storms during their RI stages and when the RMWs contract to less than 50 km. The S-RMW phenomenon could remain in very intense hurricanes long after reaching their maximum intensification. Finally, it should be mentioned that we have also examined RMW changes in intensifying but non-RI events, and found S-RMWs in about 52% of 663 and 66% of 680 intensifying events when they are evaluated at 24- and 12-h intervals, respectively. In a forthcoming study, diagnostic analyses will be performed to reveal how the S-RMW structure can be developed and maintained, and how RI can occur in the absence of the RMW contraction.

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