Intensity and Structure Changes during Hurricane Eyewall Replacement Cycles

MATTHEW SITKOWSKI
Department of Atmospheric and Oceanic Sciences and Cooperative Institute for Meteorological Satellite Studies, University of Wisconsin—Madison, Madison, Wisconsin

JAMES P. KOSSIN
NOAA/National Climatic Data Center, Asheville, North Carolina, and Cooperative Institute for Meteorological Satellite Studies, University of Wisconsin—Madison, Madison, Wisconsin

CHRISTOPHER M. ROZOFF
Cooperative Institute for Meteorological Satellite Studies, University of Wisconsin—Madison, Madison, Wisconsin

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ABSTRACT
A flight-level aircraft dataset consisting of 79 Atlantic basin hurricanes from 1977 to 2007 was used to develop an unprecedented climatology of inner-core intensity and structure changes associated with eyewall replacement cycles (ERCs). During an ERC, the inner-core structure was found to undergo dramatic changes that result in an intensity oscillation and rapid broadening of the wind field. Concentrated temporal sampling by reconnaissance aircraft in 14 of the 79 hurricanes captured virtually the entire evolution of 24 ERC events. The analysis of this large dataset extends the phenomenological paradigm of ERCs described in previous observational case studies by identifying and exploring three distinct phases of ERCs: intensification, weakening, and reintensification. In general, hurricanes intensify, sometimes rapidly, when outer wind maxima are first encountered by aircraft. The mean locations of the inner and outer wind maximum at the start of an ERC are 35 and 106 km from storm center, respectively. The intensification rate of the inner wind maximum begins to slow and the storm ultimately weakens as the inner-core structure begins to organize into concentric rings. On average, the inner wind maximum weakens 10 m s\(^{-1}\) before the outer wind maximum surpasses the inner wind maximum as it continues to intensify. This reintensification can be quite dramatic and often brings the storm to its maximum lifetime intensity. The entire ERC lasts 36 h on average.

Comparison of flight-level data and microwave imagery reveals that the first appearance of an outer wind maximum, often associated with a spiral rainband, typically precedes the weakening of the storm by roughly 9 h, but the weakening is already well under way by the time a secondary convective ring with a well-defined moat appears in microwave imagery. The data also show that winds beyond the outer wind maximum remain elevated even after the outer wind maximum contracts inward. Additionally, the contraction of the outer wind maximum usually ceases at a radius larger than the location of the inner wind maximum at the start of the ERC. The combination of a larger primary eyewall and expanded outer wind field increase the integrated kinetic energy by an average of 28% over the course of a complete ERC despite little change in the maximum intensity between the times of onset and completion of the event.

1. Introduction
The seminal work of Willoughby et al. (1982) formally presented the axisymmetric phenomenology of hurricane eyewall replacement cycles (ERCs). The work detailed the now well-established paradigm of intensity changes associated with many, but not all ERCs. Typically, as a secondary outer eyewall forms at a distant radius from an existing primary inner eyewall, the intensification rate of the inner eyewall slows and usually reverses, causing the storm to weaken. This weakening trend of the inner eyewall continues as the developing outer eyewall contracts and intensifies. Eventually the inner eyewall is replaced by the more intense outer eyewall leaving a larger hurricane with...
a single primary eyewall. This process can take on the order of a day or two.

The motivation to understand and forecast ERCs is high, as they can have very serious consequences arising from dramatic intensity and structure changes. While the formation of an outer eyewall can cause the most intense winds to weaken temporarily, the outer wind maximum tends to broaden the hurricane wind field thereby increasing integrated kinetic energy (Maclay et al. 2008). This has profound impacts both near and far from coastal regions. A sudden expansion of hurricane force winds near landfall can impact a larger coastal area while reducing preparation time. When a hurricane is farther from shore, an increased hurricane wind field is likely to lead to a greater storm surge (Irish et al. 2008). Additionally, the contraction of an outer eyewall near the end of an ERC can sometimes lead to rapid intensification resulting in a more intense hurricane than when the ERC began. This was the case for Hurricane Andrew (1992), which intensified to a category 5 hurricane as it approached the southeast coast of Florida during the end of an ERC (Willoughby and Black 1996; Landsea et al. 2004).

Improved tropical cyclone monitoring, especially since microwave instrumentation on low earth-orbiting satellites became available in the late 1990s, has resulted in more frequent views of the cloud-scale structure of a tropical cyclone’s inner core. The ability to view precipitation structures beneath the upper-level cirrus shield revealed that ERCs occur frequently for intense tropical cyclones (Hawkins and Helveston 2004; Hawkins et al. 2006; Kossin and Sitkowski 2009; Kuo et al. 2009).

With a growing archive of microwave data, recent work has aimed at documenting the behavior of ERCs. Hawkins and Helveston (2008) outlined a variety of common inner-core structure changes that can occur with ERCs in intense (>62 m s$^{-1}$) tropical cyclones, including the “classic” ERC evolution laid out by Willoughby et al. (1982), the possibility for multiple ERCs for a single storm, the existence of a double eyewall configuration that lasts for days, and the transitioning of the storm to an annular eyewall configuration (Knaff et al. 2003). Kuo et al. (2009) used microwave data and best-track data to examine the intensity changes associated with ERCs and characteristics of the moat of low-echo reflectivity between concentric eyewalls. Like many previous observational studies (Willoughby et al. 1982; Willoughby 1988, 1990; Hawkins et al. 2006; Black and Willoughby 1992; Houze et al. 2006, 2007; Dodge et al. 1999), they found that concentric eyewalls can have a profound impact on a tropical cyclone’s intensity and that there is large variability associated with the intensity changes. Kossin and Sitkowski (2009) developed a climatology of secondary eyewall formation (SEF) events in the Atlantic and eastern and central Pacific Ocean basins. Hurricane intensity and large-scale environmental conditions near the time of SEF were examined to develop a Bayesian probability model that alerts forecasters when SEF and an ensuing ERC may be imminent.

As ERC research progresses, especially with successful modeling experiments (e.g., Zhang et al. 2005; Terwey and Montgomery 2008; Wang 2008a,b, 2009; Hill and Lackmann 2009; Hogsett and Zhang 2009; Zhou and Wang 2009; Qiu et al. 2010; Judt and Chen 2010; Fang and Zhang 2011, manuscript submitted to Mon. Wea. Rev.; Martinez et al. 2011; Abarca and Corbosiero 2011), detailed documentation of in situ measured intensity and structure changes associated with ERCs is highly desirable. Previous studies are primarily limited to case studies for a few individual storms. This work aims to document typical intensity and structures changes, and their variance, associated with Atlantic basin ERCs using a large newly constructed flight-level aircraft dataset. This unprecedented climatology may benefit researchers as well as forecasters. Intensity changes are quantitatively described and the amount of time to complete these changes is also documented. Presently, forecasters at the National Hurricane Center use intensity forecast guidance techniques that largely fail to capture intensity fluctuations associated with ERCs (Elsberry et al. 2007). Additionally, there is no obvious expectation that diagnostic satellite-based intensity estimation would recognize intensity departures due to eyewall replacement. This work may provide the basis for the development of statistical/empirical intensity forecast tools when an ERC is imminent. As part of an ongoing National Oceanic and Atmospheric Administration (NOAA) Joint Hurricane Testbed project, the authors will further exploit the newly created dataset to provide forecasters with information that may enhance forecast accuracy.

Discussion of flight-level observations in conjunction with the convective appearance in microwave imagery, the most frequent method of observing ERCs, is also detailed.

This paper is organized as follows: Section 2 summarizes the flight-level datasets used in constructing a climatology of Atlantic ERCs. The methodology to objectively document ERC phenomenology is described in section 3. The results of this climatological analysis are summarized in section 4. Finally, conclusions are provided in section 5.

2. Data

The recorded intensity of past Atlantic basin hurricanes is maintained by the best-track dataset (HURDAT;
Jarvinen et al. (1984). It is a smoothed, discrete (every 6 h) estimate of hurricane location and maximum intensity (resolved within 2.5 m s$^{-1}$ intervals) during the entire lifetime of a tropical cyclone. Often, the official intensity of a storm is a fusion of various intensity estimates. Forecasters have the option to weight these various estimates based on the reliability of the measuring platform. For this reason and the inherently smoothed nature of this dataset, intensity changes associated with ERCs are often washed out or underrepresented. To largely mitigate this issue, this study utilizes flight-level aircraft reconnaissance data to better capture inner-core intensity and structure changes. While there are differences between best-track intensities and aircraft data, the use of a single, consistent raw data source allows for a better depiction of intensity and inner-core wind structure changes associated with ERCs.

Flight-level aircraft data provide critical in situ measurements of the inner-core intensity and wind structure over the data sparse ocean. In this study, NOAA’s Hurricane Research Division (HRD) archive of Atlantic flight-level aircraft observations processed from 1977 to 2001 is utilized. Details of the dataset are discussed in Kossin and Eastin (2001) and Mallen et al. (2005). The dataset consists of kinematic and thermodynamic measurements at various isobaric levels collected from both NOAA WP-3D and U.S. Air Force WC-130 aircraft. The aircraft typically fly radial legs through the storm center out to at least 150 km and they alternate their angle of approach toward storm center to sample all four quadrants of the storm. For each radial leg, storm-centered, storm-relative data are smoothed and interpolated to a radial grid with 0.5-km grid spacing from storm center out to 150 km. The HRD database is only available from 1971 to 2001, so 2002–07 flight-level data are processed in a nearly identical manner as the HRD dataset. The updated portion of the dataset utilizes the HRD “.trak” files, which contain an estimated center fix every 2 min and is based on the center-finding methodology of Willoughby and Chelmow (1982). In addition, linear interpolation is used to fill gaps of missing flight-level data that cover a distance of less than 10 km.

Storms that never achieved hurricane intensity are excluded in this study and limitations were encountered during data-gathering that prevented every storm flown by aircraft from being included in the dataset. Nonetheless, our full dataset consists of over 6000 radial legs in 79 hurricanes between 1977 and 2007. While many hurricanes were sampled by reconnaissance aircraft while undergoing an ERC, inclusion in the dataset used to develop the ERC climatology requires that hurricanes remain over water during the entire ERC and that temporal sampling must be concentrated so virtually the entire ERC is captured by reconnaissance aircraft. This resulted in 24 ERCs, consisting of nearly 1700 radial legs of aircraft data, from 14 of the 79 hurricanes. Because of the discontinuous nature of aircraft sampling, there is implicit uncertainty in measures such as start and end times of these 24 ERC events, and it is understood that this may introduce error into our analyses. Additionally, error can be introduced by data gaps during an individual ERC, but this is likely to be small as aircraft observations occurred, on average, nearly every hour and timespans between sorties averaged less than 4 h. Some well-known hurricanes that contained ERCs (e.g., Allen in 1980 and Gilbert in 1988) unfortunately did not meet the rigorous temporal sampling requirements of the study. Table 1 lists the observed start and end times of the 24 ERCs used to develop the climatology.

Since flight-level data are taken at various pressure surfaces, all tangential winds are adjusted to a common reference level of 700 mb following Franklin et al. (2003), who documented mean vertical wind profiles of the eyewall and outer vortex region for numerous hurricanes using GPS dropwinds. Here, we average the eyewall and outer vortex vertical wind profiles from

<table>
<thead>
<tr>
<th>ERC event</th>
<th>Start time</th>
<th>End time</th>
<th>ERC event</th>
<th>Start time</th>
<th>End time</th>
</tr>
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<tbody>
<tr>
<td>1984 Diana</td>
<td>1323 UTC</td>
<td>1916 UTC</td>
<td>2004 Frances</td>
<td>0540 UTC</td>
<td>1729 UTC</td>
</tr>
<tr>
<td>1995 Luis</td>
<td>2216 UTC</td>
<td>2054 UTC</td>
<td>2004 Frances</td>
<td>1636 UTC</td>
<td>1901 UTC</td>
</tr>
<tr>
<td>2002 Isidore</td>
<td>1754 UTC</td>
<td>2310 UTC</td>
<td>2005 Katrina</td>
<td>1103 UTC</td>
<td>1721 UTC</td>
</tr>
<tr>
<td>2003 Fabian</td>
<td>1728 UTC</td>
<td>1122 UTC</td>
<td>2005 Rita</td>
<td>1753 UTC</td>
<td>1020 UTC</td>
</tr>
<tr>
<td>2003 Isabel</td>
<td>1936 UTC</td>
<td>1654 UTC</td>
<td>2005 Wilma</td>
<td>1953 UTC</td>
<td>1020 UTC</td>
</tr>
<tr>
<td>2004 Frances</td>
<td>0547 UTC</td>
<td>2116 UTC</td>
<td>2007 Dean</td>
<td>0500 UTC</td>
<td>0511 UTC</td>
</tr>
<tr>
<td>2004 Frances</td>
<td>1812 UTC</td>
<td>1105 UTC</td>
<td>2007 Dean</td>
<td>0105 UTC</td>
<td>0516 UTC</td>
</tr>
</tbody>
</table>
Franklin et al. (2003) and apply a single pressure-dependent correction to the entire length of the radial leg. Winds observed at lower (higher) pressure surfaces than 700 mb will have their winds increased (reduced) when adjusted to 700 mb. Roughly 67% of the flight-level observations from the 14 hurricanes used to develop the ERC climatology were obtained near 700 mb. The majority of the remaining observations were taken at higher pressure (lower altitude) levels. This necessary adjustment is motivated solely to add consistency to wind magnitudes for subsequent composite analyses, and should not be interpreted to imply that the radial wind structure is maintained vertically.

Although the data contain additional kinematic and thermodynamic information, the climatology presented in this paper is limited to flight-level tangential winds in order to concentrate on the climatological evolution of hurricane wind field size and intensity during ERCs. A forthcoming paper will present climatology of accompanying flight-level thermodynamic variables during ERCs and the dynamical relationships between kinematic and thermodynamic variables.

The analysis of aircraft data is supplemented by 85-GHz radiances from low earth-orbiting satellites with passive microwave sensors. These data have been obtained from the NOAA/National Climatic Data Center (NCDC) Hurricane Satellite (HURSAT)-microwave (MW) data set [Special Sensor Microwave Imager (SSMI); Knapp 2008] and National Aeronautics and Space Administration (NASA) Advanced Microwave Scanning Radiometer for Earth Observing System (AMSR-E) and Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI; Ashcroft and Wentz 2006). An overlying cirrus canopy associated with tropical cyclone outflow typically obscures inner-core structure in infrared and visible satellite imagery, but this cloud layer is largely transparent in the 85-GHz channel. Scattering of large precipitation particles provides a snapshot of the inner-core precipitation structure in the 85-GHz channel (Hawkins and Helveston 2004). Figure 1 is an example of microwave imagery of an inner and outer convective eyewall. Although microwave observations of any tropical cyclone can be occasionally limited to time increments exceeding 12 h because of the finite global coverage of the satellites, these data have proven essential in identifying outer eyewalls over the open ocean. Hawkins and Helveston (2008), Kossin and Sitkowski (2009), and Kuo et al. (2009) developed criteria for SEF based on subjective determination of how complete and thick an outer convective ring appears on microwave imagery. In these studies, however, there was no discussion of whether or not a wind maximum was associated with convection, and no study to date has assembled a large enough sample of ERCs to determine the average time required to complete an ERC and its associated variance.

3. Methodology

Hurricane tangential wind profiles along radial flight legs are often noisy and determination of the maximum intensity, radius of maximum wind (RMW), and outer wind maximum can be difficult to ascertain. For these reasons, tangential wind profiles are often smoothed or approximated by continuous analytic functions with adjustable parameters that represent physically meaningful aspects of the profile. The Holland (1980) model, dual-exponential profiles (Willoughby et al. 2006), and the modified Rankine vortex (Mallen et al. 2005) all capture the essence of the tangential wind profile under the assumption that there is a single primary wind maximum located at the RMW. More recently, complex equations have been developed to account for tangential wind profiles with dual wind maxima (Holland et al. 2010; Wood et al. 2010). This study utilizes a simpler and more objective method in order to capture the most relevant features of the radial profiles and facilitate analyses and comparison while keeping the number of adjustable parameters tractable.

Each pressure-adjusted tangential wind profile is fit with a modified Rankine vortex and double modified Rankine vortex (defined below). Hereafter, “modified Rankine vortex” will be referred to as “single modified Rankine vortex” to explicitly distinguish between the two fits. Examples of these fits can be seen in Fig. 2. The single modified Rankine vortex is described by the equation:
The function is zero at the vortex center and increases to a maximum tangential wind value of $v_1$ at radius $r_1$. The function then decreases gradually away from the storm center according to the decay parameter $\alpha_1$. When $\alpha_1$ equals 0, the outer wind field is constant and equal to the maximum intensity $v_1$. As $\alpha_1$ increases, the outer wind field quickly decays and the maximum intensity becomes more peaked in structure. The combination of $r_1$, $v_1$, and $\alpha_1$ that results in the smallest root-mean-squared error between the parameterized fit and the observations is obtained for each flight leg. Here, $r_1$ and $\alpha_1$ are of the resolution 1 km and 0.025, respectively.

As a potentially useful aside, fitting observed wind profiles in this manner offers an effective objective method for identifying the radius of maximum slope change defined by Corbosiero et al. (2005). This radius can be argued to be more physically relevant than the RMW in cases where the tangential wind beyond the eyewall is relatively constant and the RMW becomes highly sensitive to small wind changes in that region.

The same procedure is followed for the double modified Rankine vortex, but five new parameters are introduced (Fig. 2a). The inclusion of $r_{\text{moat}}$, $v_{\text{moat}}$, $r_2$, $v_2$, and $\alpha_2$ allows for the identification of an outer wind maximum. The $\alpha_1$ portion of the fit in the double modified Rankine vortex ceases at a pivot location between the two wind maxima. This position is labeled ($r_{\text{moat}}$, $v_{\text{moat}}$), but there is no thermodynamic reasoning for the naming convention. Rather, the moat simply refers to a position between the inner and outer wind maxima. The position ($r_{\text{moat}}$, $v_{\text{moat}}$) is analogous to the vortex center in the single modified Rankine vortex. From this position the fit is allowed to continue away from the storm center to identify an outer wind maximum. Again, the smallest root-mean-squared error between the parameterized fit and the observations is obtained for each flight leg. The double modified Rankine vortex is represented by the equation:

$$V_r = \begin{cases} v_1 \left( \frac{r}{r_1} \right), & (r \leq r_1) \\ v_1 \left( \frac{r}{r_{\text{moat}}} \right)^{\alpha_1}, & (r_1 < r \leq 150 \text{ km}) \end{cases}$$

$$V_r = \begin{cases} v_1 \left( \frac{r}{r_1} \right), & (r \leq r_1) \\ v_1 \left( \frac{r_{\text{moat}}}{r} \right)^{\alpha_1}, & (r_1 < r \leq r_{\text{moat}}) \\ v_2 \left( \frac{r_2}{r} \right)^{\alpha_2}, & (r_{\text{moat}} < r \leq r_2) \\ v_2 \left( \frac{r_{\text{moat}}}{r} \right)^{\alpha_2}, & (r_2 < r \leq 150 \text{ km}) \end{cases}$$

FIG. 2. (a) A double modified Rankine vortex with all eight parameters labeled. The radius is from storm center. (b) A complete profile (inbound and outbound radial legs) of tangential wind (gray line) for Hurricane Gilbert (1988). The inbound pass is fit with a double modified Rankine vortex, capturing both wind maxima. The outbound pass is fit with a single modified Rankine vortex, which only allows for the detection of a single wind maximum.
To offset the vastly increased computational expense of determining eight parameters for the double Rankine fit, the parameters $r_1$, $r_{moat}$, and $r_2$ are of the resolution 3 km and $a_1$ and $a_2$ are resolved in increments of 0.08. This coarser resolution still provides adequate profile fits to the data.

Once both fits are applied to each radial leg, a subjective determination is made as to which profile more accurately parameterizes the radial wind structure. Therefore, every radial leg used in the study contains an $(r_1, v_1)$ pair. If there is only a single wind maximum, this pair is determined from the single modified Rankine vortex. If an outer wind maximum is present, then the $(r_1, v_1)$ pair is determined from the double modified Rankine vortex, along with a $(r_2, v_2)$ pair. An example of both single and double modified Rankine vortex fits for a complete pass (two radial legs) through the center of Hurricane Gilbert (1988) is presented in Fig. 2b. Because Gilbert contained double eyewalls, the double modified Rankine fit provides a superior fit to the data in this example. Similar good agreement is found between the single modified Rankine vortex fits and the flight-level data in storms containing only a single wind maximum.

In the event that an outer wind maximum is clearly evident in the radial wind profile, but the fitting procedure fails to correctly identify the correct wind maxima, a manual correction is applied. Corrected parameters account for roughly 15% of all the single and double modified Rankine parameters. Associated with each set of $(r_1, v_1)$ and $(r_2, v_2)$ pairs is a timestamp from when the aircraft is very near the storm center. This information can be used to examine the evolution of both the inner and outer (when one is observed) wind maxima during the entire time a hurricane is being investigated by reconnaissance aircraft.

Triple wind maxima (e.g., McNoldy 2004) were occasionally present in the radial wind profiles. Figure 3 provides an example from Hurricane Frances (2004), a hurricane with multiple ERCs. In this example, the innermost wind maximum is associated with a decaying inner eyewall and the middle wind maximum is intensifying as an ERC nears its completion. The outermost wind maxima are from spiral rainbands that eventually organize into an outer eyewall where an additional ERC ensues. Calculating a triple modified Rankine vortex, which contains 13 parameters, for every profile is computationally unfeasible, so for the few profiles that displayed three wind maxima, the Rankine parameters were subjectively determined and manually entered into the dataset.

### 4. Results

This section presents the climatology of intensity and structure changes during an ERC. Hurricane Diana (1984) is presented first to introduce the reader to the process involved in developing the climatology. Because of the extensive use of microwave imagery in diagnosing ERCs and its familiarity among forecasters, comparison of the imagery with the intensity and structure change is presented. Finally, cases of multiple ERCs in individual hurricanes and the ability of ERCs to greatly expand the hurricane wind field are briefly examined.
decides have never been formally established. This
may be due to the short-lived, stochastic nature of
convection during the developmental stages of a tropical
storm, which can cause the primary wind maximum to be
transient, resulting in variability in $r_1$ (Simpson et al.
1997). When the aircraft began sampling on 11 Sep-
tember, the tropical cyclone was stronger and intensify-
ing. A more robust inner core with sustained convection
(see Willoughby 1990, Fig. 18) was established and the
$r_1$ variance is reduced; however, some spread remains.
Some small variance is expected as a result of the accu-
cracy of the least squares Rankine fits correctly iden-
tifying the location of the primary wind maximum. More
importantly, variance exists because hurricanes are not
perfectly axisymmetric. For example, an elliptical eye-
wall will result in a larger $r_1$ parameter if the aircraft flies
along the major axis instead of the minor axis. Piech and
Hart (2008) found that aircraft observations routinely
report elliptical eye structures prior to the formation of
concentric eyewalls.

As seen in Fig. 4, the aircraft encountered an outer
wind maximum in Diana (1984) shortly before 1200 UTC
9 September. Outer wind maxima are not always col-
located with a developing convective outer eyewall feature
(Samasury and Zipser 1995) and the lack of additional
outer wind maximum observations suggests this local
maximum was likely from isolated cellular convection or
a rainband. Near 1200 UTC 11 September, the aircraft
again encountered outer wind maxima at roughly the
same distance (75 km) from storm center. Unlike the
outer wind maximum from two days prior, this outer
wind maximum was the first of many measurements that
formed a coherent evolution of a contracting outer wind
maximum.

Just before Diana’s landfall on 13 September (Fig. 4),
an outer wind maximum roughly 140 km from storm
center was observed. Although only a single data point,
it is possible that it signals the initiation of another ERC.
The timing and location of the observation are in
agreement with many ERCs examined in the study that
underwent multiple ERCs, which are discussed later in
this section. Some storms even formed an outer wind
maximum while a previous ERC was concluding; these
storms exhibited triple wind maxima.

Criteria for determining when an ERC initiates and
concludes have never been formally established. This
decision is subjective and is heavily influenced by the
medium being used to investigate the inner core of
a hurricane. An added level of complexity is that re-
gardless of which observing platform is being operated,
the formation of an outer eyewall and decay of inner
eyewall are not instantaneous events, rather they can
occur over several hours. This study defines the length
of an ERC based solely on flight-level aircraft data. The
start of ERC begins when the first of a coherent cluster
of outer wind maximum, in space and time, is detected.
The cycle concludes when the outer wind maximum
transitions to the primary eyewall and the remnant inner
wind maximum can no longer be detected.

Based on this criterion, the complete ERC of Diana
(1984) is shown in Fig. 5. The $r_1, v_1, r_2, v_2$ parameters are
fit with a third-order polynomial best fit line to make use
of all the data and capture the essence of the structure
and intensity evolutions. The initial $r_2$ measurements
contain considerable spread since outer wind maxima
are prone to be associated with rainbands that are lo-
cated at various distances from storm center. At the start
of the ERC the best fit suggests the outer wind maxi-
num is near 70 km with an intensity around 25 m s$^{-1}$.
The inner wind intensity is roughly 48 m s$^{-1}$ and is lo-
cated about 18 km from storm center. The inner wind
maximum intensifies at the start of the ERC during an
intensification phase, but eventually reaches a maximum
intensity near 1800 UTC 11 September before beginning
to weaken for the remainder of the ERC. As the primary
intensity weakens during the weakening phase, the outer
wind maximum contracts and intensifies, eventually
surpassing the intensity of the inner wind maximum
around 1500 UTC 12 September. After 0600 UTC 12
September, the $r_2$ estimates are tightly clustered and a
well-defined outer eyewall and moat between eyewalls is
visible from aircraft radar (see Willoughby 1990, Fig.
18c). The outer wind maximum continues to intensify
during the reintensification phase until the aircraft de-
parts the hurricane. When an aircraft returns, less than
6 h later, the first pass detects a single wind maximum
with an $r_1$ value of 28 km. The hurricane returns to
a single wind maximum structure.

Even in the case of Diana (1984), where confidence is
very high that virtually the entire ERC is captured by
aircraft, it is not known exactly when concentric eye-
walls, rather than organizing spiral rainbands, first ap-
ppear by simply analyzing the Rankine parameters. The
first few $r_2$ observations are more scattered than those
toward the end of the ERC. This behavior is found in
several of the ERCs investigated in the study. At what
point are the outer wind maxima being encountered by
aircraft associated with concentric rings, rather than spi-
cral rainbands? To gain an appreciation of the convective
structure of the hurricane inner core at the onset of an ERC, microwave imagery was examined for many of the ERCs.

b. Flight-level data and microwave imagery comparison

Extensive examination and comparison of microwave imagery and flight-level data for 20 out of the 24 ERCs is carried out to clarify the inner-core precipitation structure during the evolution of an outer wind maximum. The hurricanes not included in this portion of the study occurred before the advent of microwave imagery or they lack sufficient imagery. Diagnosing when a double eyewall structure first appears in microwave imagery is challenging given the irregularity of the temporal sampling, and there is inherent uncertainty in our estimates of these times.

The analysis reveals that for all 20 ERCs, aircraft detect outer wind maxima several hours before a pronounced double eyewall configuration appears in microwave imagery. Microwave imagery usually shows rainbands spiraling from the eyewall when an outer wind maximum is first detected by aircraft. These data reveal that the outer wind maximum associated with the spiral rainbands contracts and intensifies during the transition to an outer eyewall. It appears the outer wind maximum associated with concentric eyewalls has been contracting before the concentric eyewall first appeared in microwave imagery. The physical relevance of this observed behavior is an interesting and open question.

On average, the concentric eyewall configuration is estimated to appear in microwave imagery nearly 18 h after the first detection of an outer wind maximum as defined in the aircraft flight-level data. In addition, 17 out of the 20, or 85% of ERCs with adequate microwave imagery contained a more intense inner eyewall than outer wind maximum when concentric eyewalls first appear in microwave imagery, but the inner eyewall is typically halfway through its weakening phase at this time. The inner eyewall typically weakens for almost 8 h prior to the double eyewall structure first appearing in microwave imagery and continues weakening for several more hours before it is overtaken by the contracting outer wind maximum.

Figure 6 illustrates an example from Hurricane Floyd (1999) of spiral rainbands containing local wind maxima transitioning to a concentric eyewall structure. The spiral rainbands in Floyd are visible in the microwave imagery and contain local wind maxima that range over various radii, depending on the approach of the aircraft. The rainbands do not completely wrap around the center initially (Fig. 6, bottom left), but eventually develop and organize into a concentric ring with a well-defined
moat between the inner and outer eyewalls (Fig. 6, bottom middle). In this example, the primary eyewall intensifies prior to the development of the concentric eyewalls in microwave imagery. At some critical point, shortly before the time concentric eyewalls appear in microwave imagery, the storm’s intensity begins to decrease. These results suggest the developing outer eyewall begins its detrimental effects on the inner eyewall before a complete outer ring structure is established. The weakening is consistent with previous work that indicates rainbands alone can introduce low-entropy air into the low-level inner eyewall inflow, as well as act as a barrier to the eyewall (e.g., Barnes et al. 1983; Barnes and Powell 1995; Powell 1990a,b; Hausman 2001). As the inner eyewall’s latent heating begins to weaken, the ability of the storm to maintain an intense, localized warm core decreases (Rozoff et al. 2008).

Aircraft leave Floyd just as the decaying inner eyewall diminishes and microwave imagery depicts a single, larger eye and eyewall than what was observed at the start of the ERC. This newly established primary eyewall continues to contract and the storm intensifies. The entire ERC takes just over 2 days.

c. Climatology of intensity and structure changes

The ERC intensity evolutions of Hurricanes Diana (1984) and Floyd (1999) are fairly representative of the 24 ERCs examined in this study. Both ERCs contain an...
intensification, weakening, and reintensification phase. To quantify the intensity changes during an ERC and the amount of time required for those changes, a third-order polynomial best fit of the Rankine parameters $r_1$, $r_2$, $y_1$, and $y_2$ is applied to all 24 ERCs. This results in a smooth, continuous evolution of radii, intensity, and time, and allows for determination of several key properties of ERCs. Each ERC is then divided into the previously mentioned phases (e.g., Fig. 5). The documentation of the three phases expands upon the known paradigm first established by Willoughby et al. (1982).

The composite analysis of the polynomial fit data along with the distribution of that data for all the three phases of the ERC is displayed in Fig. 7. Associated with each ERC phase are vertical box plots that display the range of intensity changes ($\text{m s}^{-1}$) of $v_1$ and $v_2$ and horizontal box plots that display the range of time (h) required to complete that particular portion of the ERC (Fig. 7a). Figure 7b follows the same arrangement, but displays the radii changes. Details of each phase are as follows:

1) **Intensification:** This phase begins at the start of an ERC and concludes when the inner wind maximum reaches peak intensity. In general, this portion of the ERC is characterized by both inner and outer wind maxima undergoing contraction and intensification even though the outer wind maximum is unlikely to be associated with a well-developed convective ring during this phase. Often, the inner wind maximum concludes a period of rapid intensification. Ten storms contained an inner wind maximum intensification rate that exceeded 0.5 m s$^{-1}$ h$^{-1}$ during this phase, which is comparable to the 90th percentile of 24 h over-water intensification rates for tropical cyclones examined by Kaplan et al. (2010). Seven of the twenty-four ERCs did not contain an intensification phase because the inner eyewall was at peak intensity at the start of the ERC.

2) **Weakening:** This phase is bounded by the peak intensity of the inner wind maximum to when the outer wind maximum intensity surpasses the intensity of the inner wind maximum. During this phase, the inner wind maximum steadily weakens as the outer wind maximum continues to contract and intensify. All but two ERCs contained an intersection of intensities. Georges (1998) had an outer wind maximum that was weakening in tandem with the inner wind maximum and aircraft departed Isidore (2002) just before the intensities were preparing to intersect. As was the case with the inner wind maxima in the intensification phase, many of the secondary wind maxima in the weakening phase rapidly intensified. At this point in the ERC the outer wind maximum, if it has not already, organizes into a circular ring. Although determination of the exact

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1 The inner wind maximum was able to intensify in tandem with the outer eyewall even after the intensities intersected during Hurricane Dean (2007). Since the inner wind maximum reached peak intensity after the intersection of intensities a negative time appears for the weakening phase of the composite analysis.
SEF time is unrealistic, the average estimated time when a double eyewall configuration first appears on microwave imagery occurs during this phase, or almost 18 h after the start of the ERC. While the secondary wind maximum becomes better defined and arranges into a convective ring, it is also contracting. During the weakening phase the average contraction rate of $r_2$ is 1.75 km h$^{-1}$.

3) **Reintensification**: The reintensification portion of the ERC refers to the period when the outer wind maximum intensity surpasses the inner wind maximum intensity and continues to intensify. As this occurs, the inner wind maximum decays and eventually dwindles away in the eye. Once the inner wind maximum can no longer be detected, the ERC is considered complete and the storm returns back to a single eyewall structure. Although the ERC has concluded and the intensity is no longer tracked once the inner eyewall has decayed, the hurricane often will continue to intensify. In some cases this occurs rapidly, resulting in the hurricane’s maximum lifetime intensity (e.g., Hurricane Katrina in 2005).

A schematic diagram summarizing the evolution of an ERC appears in Fig. 8. The average amount of time to complete each phase, along with the average values of the Rankine parameters, as determined from the third-order polynomial fits, are listed for the start and end of the ERC, as well as the transition of phases.

### Table 2. Mean and standard deviations for $r_1$, $r_2$, $y_1$, and $y_2$ changes during each ERC phase. The mean and standard deviation are also given for the time required to complete each phase, the time to complete an entire ERC, and the amount of time until concentric eyewalls first appear on microwave imagery.

<table>
<thead>
<tr>
<th>Phase</th>
<th>Intensification</th>
<th>Weakening</th>
<th>Reintensification</th>
</tr>
</thead>
<tbody>
<tr>
<td>$r_1$ (km)</td>
<td>7.0</td>
<td>11.5</td>
<td>1.4</td>
</tr>
<tr>
<td>$r_2$ (km)</td>
<td>14.8</td>
<td>18.8</td>
<td>28.8</td>
</tr>
<tr>
<td>$y_1$ (m s$^{-1}$)</td>
<td>7.0</td>
<td>9.3</td>
<td>10.2</td>
</tr>
<tr>
<td>$y_2$ (m s$^{-1}$)</td>
<td>4.7</td>
<td>5.6</td>
<td>9.2</td>
</tr>
<tr>
<td>Time (h)</td>
<td>9.4</td>
<td>9.1</td>
<td>16.6</td>
</tr>
</tbody>
</table>

Length of ERC and Microwave appearance

<table>
<thead>
<tr>
<th>Phase</th>
<th>Intensification</th>
<th>Weakening</th>
<th>Reintensification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time (h)</td>
<td>36.3</td>
<td>13.4</td>
<td>17.5</td>
</tr>
</tbody>
</table>

Figure 9 compares the climatological ERC intensity, radii, and time changes with those observed from an Ivan (2004) ERC. The most anomalous phase for this ERC is the intensification phase, where the intensity increase, contraction of the inner wind maximum, and length of time to complete this phase are more than double the climatological values. The weakening phase is more in line with climatology, but the outer wind maximum has an extraordinary intensification rate resulting in a much greater increase in intensity after the inner and outer intensities intersect. Although the final values of $r_1$ and $r_2$ were similar to the climatological ERC values, the final flight-level $y_2$ intensity at the end...
of the ERC is almost 70 m s\(^{-1}\), or just over 25 m s\(^{-1}\) greater than at the start of the ERC. Further work with this newly developed dataset will explore methods to detect systematic conditions that can help better quantify inner-core structure and intensity changes to assist forecasters.

The composite analysis for the ERC phases only examines key times of the ERC, so a phase diagram of the ratio of wind maxima \(v_1/v_2\) versus the ratio of their respective locations \(r_1/r_2\) was developed to make use of the entire polynomial fits for each of the 24 ERC events (Fig. 10). It is important to note that time and intensity are not captured in Fig. 10. Some lines in the phase diagram can occur over a period of 18 h, while others exceed 48 h and hurricanes from all categories are included.

The slight arc shape of the phase diagram in Fig. 10 begins with many of the ERCs containing an average inner wind maximum around 1.5 times the intensity of the outer wind maximum located 3 times the distance of the inner eyewall. This is one region in the phase space where data are more tightly clustered. Roughly 25% of all the ERCs passed very near this region. As the secondary wind maximum contracts inward, the \(r_1/r_2\) ratio increases as \(r_1\) changes little and \(r_2\) is reduced. The \(v_1/v_2\) ratio usually decreases as a result of \(v_2\) increasing, \(v_1\) decreasing, or some combination of the two. When \(v_1/v_2\) equals 1, the intensities of the inner and outer eyewalls are equal. This usually occurs when \(r_1/r_2\) is near 0.5, or when \(r_2\) has reached twice the distance of \(r_1\). Roughly one in four ERCs pass near this region at some point during the ERC. The final \(v_1/v_2\) ratio is less than 1, indicating the outer eyewall has transitioned into a primary eyewall.

Where the lines are not located is also of interest. It is rare to have an outer wind maximum be less than half the intensity of the inner wind maximum at the start of an ERC. Also, it is rare for the outer wind maximum to be first detected at a radius more than 6 times the radius of the inner wind maximum. The concave shape of the diagram suggests that there is not a linear relationship between the behaviors of the two wind maxima.
Occasionally, conditions are favorable for hurricanes to undergo multiple ERCs (Hawkins and Helveston 2008). These hurricanes are a great resource to examine the intensity and structure variations associated with ERCs. Figure 11 displays all of the radii parameters observed during Hurricane Ivan (2004). There are seven separate events of an intensifying and contracting outer wind maximum during Ivan’s lifetime. Toward the end of each of these events are jumps in eye sizes indicative of the replacement of the inner eyewall by an outer wind maximum. Ivan also exhibits three cases where triple wind maxima were observed in the storm. The triple wind maxima eventually transition to secondary wind maxima once the innermost wind maximum decays. Microwave imagery for Ivan and other storms with triple wind maxima supports the notion of rainbands and collocated wind maxima organizing around a double eyewall structure rather than a well-developed triple ring structure depicted in microwave imagery. However, convective triple ring configurations were observed in Hurricane Juliette in 2001 (McNoldy 2004).

Figure 12 displays the evolution of wind maxima during the ERCs in Ivan between 1200 UTC 10 and 0000 UTC 13 September 2004. A previous ERC is concluding when the outermost wind maxima are first detected near 1800 UTC 10 September (Fig. 12). A microwave image taken shortly before aircraft arrived near 1900 UTC 10 September shows a double eyewall configuration with the outer eyewall located between 50 and 100 km from storm center (Fig. 12, bottom left). Banded convection elements also appear at and beyond 100 km, but these spiral bands do not contain the same cold brightness temperatures found in the outer eyewall. However, aircraft do encounter local wind maxima associated with the bands (Fig. 12, blue dots), resulting in triple wind profiles. The green dots show the innermost wind maximum from the previous eyewall decaying in the soon to be larger, developing eye.

There is a clear intensification of the storm in the 18 h between 1800 UTC 10 and 1200 UTC 11 September. This is a result of the previous ERC concluding as the once secondary wind maximum continues to contract and takeover as the primary eyewall. Ivan reached 910 mb, its lowest lifetime minimum sea level pressure, near 0000 UTC 12 September (Franklin et al. 2006). Microwave imagery taken just after the remnant eyewall can no longer be detected show a well-defined single eye with warm brightness temperatures, indicative of warm, subsiding air (Fig. 12, bottom center). At this time, the secondary wind maxima near 100 km are associated with more cellular convection that have become more circular, but still lack cold brightness temperatures, usually indicative of strong convection (Fig. 12, bottom center). More intense cellular convection, located beyond 100 km, could contain local wind maxima, but were not yet detected by aircraft. Roughly 18 h after the microwave image, aircraft encountered local wind maxima beyond 100 km, observing yet another start to an ERC. To avoid congestion, these triple wind maxima are intentionally left off of Fig. 12, but they do appear in Fig. 11.

Ivan reached peak intensity in flight-level winds around 1800 UTC 11 September, 6 h before a minimum in sea level pressure was attained and weakened until the outer wind maximum surpasses the inner wind maximum. Just after the wind maxima intersected, a microwave image reveals that rainband features quickly organized in a circular fashion and have become more convective (Fig. 12, bottom right). There was a rapid intensification rate of the secondary wind maximum that
was nonlinear and increased as the ERC progressed. The development of the convective structure of the inner core in less than 24 h between 1348 UTC 11 and 1252 UTC 12 September is stunning, and the intensity changes are drastic. As a result of this ERC, Ivan again reached its lowest lifetime minimum sea level pressure of 910 mb near 2100 UTC 13 September (Franklin et al. 2006). The outer wind maximum intensified 25 m s⁻¹ from 1800 UTC 11 to 1800 UTC 12 September. This rapid intensification occurred in association with rapid strengthening since the outer wind field beyond the outer wind maximum remained elevated (Fig. 13).

The Hovmöller diagram (Fig. 13) of pressure adjusted flight-level winds for Hurricane Ivan (2004) depicts several ERCs. All of the tangential wind profiles over a period of several days were utilized to create the diagram and interpolation was used for periods when reconnaissance was absent from the storm. There are several interesting features captured by the Hovmöller diagram. A repetitive process occurs with each ERC. At some distance beyond the RMW a local maximum of wind is observed, usually near a time where wind speeds at the RMW are very intense. Over time, the outer wind maximum contracts inward toward the vortex center and intensifies. In doing so, the outer wind field expands and remains elevated. Eventually, the inner eyewall is replaced by this outer wind maximum. Typically, the outer wind maximum fails to contract beyond the original primary eyewall radius. Instead, shortly after the secondary eyewall has transitioned into the primary
eyewall, contraction halts and the storm is left with a larger eye.

Aircraft data and Hovmöller diagrams from other hurricanes depict similar behavior indicating that ERCs are a mechanism for storm growth. Our dataset contains 10 ERCs that occur after an ERC has occurred previously for the same hurricane. The initial $r_1$ parameter at the start of the repeat ERCs was larger than the initial $r_1$ at the start of the previous ERC for 90% of these events. In addition 80% of the repeat events took longer to complete than the previous ERC. A larger eyewall and more expansive wind field can result in larger rainfall amounts and an increase in storm strength. Additionally, a broader post-ERC wind profile can certainly result in greater storm surges as the results of Irish et al. (2008) suggest.

A composite analysis of tangential wind profiles for each of the three ERC phases from all 24 ERC events is shown in Fig. 14. Similar to Maclay et al. (2008), integrated kinetic energy (IKE) for each composite leg was computed using the following equation:

$$IKE = \frac{\rho_0 \Delta z}{2} \int_0^{2\pi} \int_0^R v^2 r dr d\theta,$$

where $v$ is the tangential wind, $\rho_0$ is the density (0.9 kg m$^{-3}$), and $\Delta z$ is a 1-km depth of the atmosphere. The IKE for the intensification, weakening, and re-intensification phases were $3.6 \times 10^{16}$ J, $4.2 \times 10^{16}$ J, and $4.6 \times 10^{16}$ J, respectively. The combination of a larger RMW and an increase in storm strength produces a 28% increase of IKE during the ERC, even though there is a small decrease of maximum intensity. This behavior has been previously documented by Maclay et al. (2008). In addition to the RMW increasing, the hurricane wind field expands from 94 km during the intensification phase to just beyond 150 km toward the end of the ERC. This is nearly a 70% increase in the hurricane wind field. To isolate structure changes associated specifically with ERCs, we compare these changes with a climatology of structure changes developed from random sampling of the full radial leg dataset (~6000 legs; not shown). The increased outer wind field, which is a product of an ERC, far exceeds those changes expected by natural expansion of the winds with age and increasing latitude (Weatherford and Gray 1988a; Kimball and Mulekar 2004; Kossin et al. 2007). These large increases can occur over a short time period requiring the storm to obtain energy resources effectively and to use the energy efficiently.

Hurricane Wilma (2005) has an extraordinary rate of intensification from 1200 UTC 18 to 1200 UTC 19 October. No other Atlantic storm has matched the 49 m s$^{-1}$ increase in a 24-h period (Beven et al. 2008). Additionally, Wilma also holds the record for the lowest estimated minimum pressure ever in the Atlantic, 882 mb, which occurred at the end of the rapid intensification (Beven et al. 2008). When this record low pressure was observed there was already a well-developed secondary wind maximum. As this maximum contracted and intensified, Hurricane Wilma had a dramatic increase in IKE (Fig. 15).

In general, the IKE mimics and lags the evolution of the maximum intensity, but the outer wind field is responsible for the large increase of IKE. Between
1800 UTC 19 and 0600 UTC 20 October, Wilma was an intense tropical cyclone with an extremely small (<4 km) eye, but maximum flight-level winds weakened within the inner eyewall (Fig. 15b). During this 12-h period, the Hovmöller diagram shows a large region of increasing winds in the outer wind field (Fig. 15a). Despite the storm weakening, the IKE increased roughly 35% during this period and eventually the storm reintensified as the outer eyewall became the dominant eyewall. Weatherford and Gray (1988a,b) identified this inverse relationship between intensity and the outer wind field for western Pacific typhoons and more recent studies observed this relationship during ERCs (Croxford and Barnes 2002; Maclay et al. 2008). To add some perspective for this specific case, the 24 h increase of IKE in Wilma from 0000 UTC 19 to 0000 UTC 20 October is similar to the IKE of Hurricane Dennis (2005) when it made landfall on the Florida panhandle as a category 3 hurricane.

Part of Wilma’s explosive intensification and concurrent IKE increases may be explained through efficiency arguments (Schubert and Hack 1982; Shapiro and Willoughby 1982; Nolan et al. 2007). Efficiency may have been high not only right near the vortex center, but also well beyond 50 km from storm center. The collocation of localized heating and vorticity allows for the storm to reduce the Rossby radius of deformation to focus energy, while the secondary wind maximum increases the inertial stability in a localized region. A forthcoming paper will use the Rankine parameters, along with thermodynamic flight-level data, to examine more closely the dynamics that occur within the inner core during an ERC.

5. Conclusions

Flight-level aircraft data were used to examine the inner-core structure and intensity changes associated with 24 eyewall replacement cycles for 14 Atlantic basin tropical cyclones. A single modified Rankine vortex and a double modified Rankine vortex (Fig. 2) were fit to pressure-adjusted (to 700 mb) radial legs to identify the location and intensity of double wind maxima. Triple wind maxima were occasionally identified and were also included in the dataset. The evolution of the fit parameters allowed for the determination of structure and intensity changes and the time required for these changes. Composite analysis was performed to document these changes and their variance. An ERC begins when the first of a coherent cluster of outer wind maxima is detected by the aircraft and concludes when the inner wind maximum can no longer be detected. The process of replacing an inner, primary eyewall with an outer, secondary eyewall lasts an average of 36 h.

Three distinct ERC phases were identified, expanding upon the intensity paradigm first established by Willoughby et al. (1982):

1) Intensification: This phase begins at the start of an ERC and ends when the inner wind maximum reaches peak intensity. In general, this portion of the ERC is characterized by both inner and outer wind maxima contracting and intensifying. The inner wind maximum was found to increase an average of 7 m s$^{-1}$ while contracting 7 km during this phase. The outer wind maximum increases some 4 m s$^{-1}$ while contracting 15 km. It is common for an inner
wind maximum to be rapidly intensifying as outer wind maxima begin to be detected.

2) Weakening: This phase is bounded by the peak intensity of the inner eyewall to when the outer wind maximum intensity surpasses the inner eyewall intensity. Generally during this phase, the outer wind maximum continues to intensify and contract an average of 10 m s\(^{-1}\) and 28 km, respectively. The inner wind maximum decreases an average of 10 m s\(^{-1}\) with very little contraction.

3) Reintensification: The reintensification portion of the ERC refers to the period when the outer wind maximum intensity surpasses the inner wind maximum intensity and continues to intensify. As this occurs, the inner wind maximum decays and eventually dwindles away in the eye. Once the inner wind maximum can no longer be detected, the ERC is considered complete and the storm returns back to a single eyewall structure. During this phase the outer wind maximum, now the maximum intensity of the storm, contracts an average of 12 km while intensifying a little over 2 m s\(^{-1}\).

Comparison of aircraft data and microwave imagery reveals that the double eyewall structure appears roughly 18 h after the first detection of an outer wind maximum, or about halfway through an ERC. The first outer wind maxima are commonly associated with spiral rainbands or convective elements that are not arranged in a concentric manner. Although contraction and intensification rates of the outer wind maximum are more impressive once concentric eyewalls appear on microwave imagery, it is worth noting that a well-established, circular outer wind maximum does not need to be present in order for the outer wind maximum to contract and intensify. Asymmetric convection beyond the RMW is capable of inducing intensity changes to the inner eyewall. On average, the inner wind maximum weakens for about 8 h prior to the double eyewall configuration appearing in microwave imagery. The detrimental effects to the inner wind maximum can occur prior to the outer wind maximum fully encompassing the inner wind maximum.

Examination of flight-level data during a hurricane lifespan reveals that the outer wind maximum typically contracts to a radius greater than that of the preexisting inner eyewall resulting in a larger eye and eyewall. Additionally, radial leg tangential wind profiles become less peaked with each subsequent ERC resulting in a broader outer wind field. The combination of a larger radius of maximum wind and elevated outer wind field resulted in rapid strengthening and dramatic increases of integrated kinetic energy, even if the maximum intensity of the storm was decreasing. The IKE was found to increase 28% during an ERC. These dramatic energy increases may be a result of efficient use of heating at both wind maxima. A forthcoming paper will use the Rankine parameters, along with thermodynamic flight-level data to examine more closely the dynamics that occur within the inner core during an ERC.

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