aClimate Prediction Center, NOAA/NWS/NCEP, College Park, Maryland, USA
bDepartment of Atmospheric Sciences, University of Illinois at Urbana-Champaign, Urbana, Illinois, USA
Dr. Daniel S. Harnos, Climate Prediction Center, National Center for Weather and Climate Prediction, 5830 University Research Court, Room 3113, College Park, Maryland, USA 20740. E-mail: daniel.harnos@noaa.gov

Two 1-km Weather Research and Forecasting model simulations of the rapid intensification (RI) periods of Hurricanes Ike (2008) and Earl (2010), under low and high wind shear respectively, are performed to evaluate mechanisms linked to the initiation and maintenance of RI. Despite similar simulated intensification time series, the exhibited hydrometeor characteristics are disparate between the two cases as Ike possesses lesser asymmetry and a reduced presence of vigorous convection relative to Earl.

An objective method to quantitatively estimate the the radius of maximum wind (RMW) with respect to height is introduced for quantifying the primary circulation character of each storm, permitting analysis of where heating is most efficient for driving warm core growth and subsequent intensification. Following eye development in each, diabatic heating remains embedded within the RMW. Earl's RI onset coincides with an absolute maximum in diabatic heating occurring within the RMW, while Ike possesses relatively less diabatic heating inside the RMW throughout and lacks an absolute peak associated with RI. The majority of diabatic heating within the RMW of both cases occurs at subfreezing temperatures, indicative of the importance of clouds associated with ice processes in these RI simulations. Earl's diabatic heating peak is tied to a maximum in convective burst activity residing within the RMW. Earl's preference for more sparse but intense convection is associated with increased sea surface temperatures, surface heat fluxes, moisture convergence, and near-surface equivalent potential temperature relative to the broader, weaker convective character in Ike.

tropical cyclone, hurricane, typhoon, rapid intensification, radius of maximum wind, convective processes, mesoscale processes

Varied pathways for simulated tropical cyclone rapid intensification. Part I: Precipitation and environment

Daniel S. Harnosa and Stephen W. Nesbittb
Thu Mar 03 06:49:11 2016

1 Introduction

Landfalling tropical cyclones (TCs) have vast potential societal impacts in terms of economic harm and loss of life [Rappaport(2000)]. TC impacts are largely coupled to intensity, driven by oceanic

This is the author manuscript accepted for publication and has undergone full peer review but has not been through the copyediting, typesetting, pagination and proofreading process, which may lead to differences between this version and the Version of Record. Please cite this article as doi: 10.1002/qj.2780

and atmospheric processes, that act to alter the resulting storm surge, rain, and wind distributions. These impacts are compounded by continued population shifts to coastal areas and increased coastal vulnerability [?, e.g.]]pielke2008,willoughby2012. Accordingly, TC intensification is considered a key problem facing tropical meteorologists.

Intensity prediction difficulties are well documented over recent years. [DeMaria ~al.(2014)DeMaria, Sampson, Knaff and Musgrave] revealed improved intensity prediction from dynamical and statistical models and forecasting offices as seeing statistically significant improvement in some products over the past 25 years, but with gains only being on the order of 1% for 24-48 h leads. The most problematic of intensity change events from a predictability standpoint are those occurring within the tails of the intensity change distribution, with those residing within the upper tail of the distribution referred to as undergoing rapid intensification (RI). The typically cited RI threshold is a wind increase of 30 kt over 24 h, the top 5% of the 24 h intensity change distribution, realized at least once by 31% of Atlantic TCs from 1989-2000 [Kaplan and DeMaria(2003)]. The aforementioned lack of intensity prediction improvement on short time scales is troubling considering the increased availability and breadth of observations from satellite platforms and improvements to in-situ instrumentation available to characterize the diabatic heating (H_D) distribution and its influences on the primary and secondary circulations. In addition, greater computing power available for numerical simulations that assimilate these observations may lead to improved forecasts as data assimilation techniques continue to improve incrementally.yields further puzzlement regarding the slow intensity forecasting gains. One potential key reason for this lack of improvement is due to intensity changes being caused by processes occurring across a breadth of spatial scales over the synoptic, vortex, convective, turbulent, and microscales [Marks and Shay(1998)]. The sum of these issues have resulted in the National Hurricane Center (NHC) declaring: “the slow rate of improvement in intensity forecast accuracy and skill, and the particularly large errors that can occur in episodes of rapid intensification, have prompted NHC to elevate this deficiency to its top priority for the tropical meteorology research community” [Rappaport ~al.(2009)Rappaport, Franklin, Avila, Baig, II, Blake, Burr, Jiing, Juckins, Knabb, Landsea, Mainelli, M.~Mayfield, Sisko, Stewart and Tribble]. The societal implications of missed intensification forecasts and particularly RI episodes are clear, in that underestimated intensity can increase loss of life and property.

Among influences on TC intensification, one focus has been the relative role of environment versus internal TC processes. [Hendricks ~al.(2010)Hendricks, Peng, Fu and Li] used reanalysis data of TCs along with Tropical Rainfall Measuring Mission (TRMM) Microwave Imager brightness temperature composites to evaluate the differences among environmental and inner-core distributions for TCs relative to their subsequent intensity changes. The differences between the distributions of environmental variables for populations of TCs undergoing RI versus those intensifying but at a lesser rate revealed minimal differences, suggesting that large-scale environmental processes alone are insufficient to yield RI. In a similar fashion, [Jiang and Ramirez(2013)] used TRMM to evaluate minimum criteria for TCs undergoing RI, determining baseline values of reflectivity, brightness temperatures, and total volumetric rainfall necessary for RI to occur. The two aforementioned studies assume environmental considerations are sufficient for most TCs, and rather the precipitative characteristics of the TC inner-core delineate potential RI. [Harnos and Nesbitt(2011)] put forth two prevailing hydrometeor structural modes for impending RI episodes from over two decades of passive microwave observations, with RI under low wind shear associated with modest convective signatures surrounding the TC inner-core while high shear RI cases exhibit more intense, asymmetric convection preferentially downshear and downshear-left of the shear vector. Further evaluation of inner-core cloud and precipitation character associated with RI is undertaken by [Harnos and Nesbitt(2015)], revealing RI episodes saw an order of magnitude more clouds associated with frozen hydrometeors than solely warm hydrometeors relative to lesser intensity changes.

Inner-core cloud and precipitation character alone is an insufficient driver of TC intensification however, as the associated H_D spatial distribution alters the response of the primary and secondary circulations. Inertial stability governs the radial response extent to heat and momentum forcings [Shapiro and Willoughby(1982)], and is an important consideration whether H_D or adiabatic heating via subsidence will be able to accumulate to enhance the TC warm core and induce sea level pressure decreases. In cylindrical coordinates the inertial stability parameter I^2 is defined by:

$$I^2 = \left(f + \frac{1}{r}\frac{\partial rv}{\partial r} \right)\left(f + 2\frac{v}{r} \right) \tag{1}$$

where f is Coriolis parameter, r radius, and v the tangential wind. The first term within Equation ?? represents absolute vorticity, while the second is the Coriolis parameter plus twice the solid body rotation. From Equation ??, I can be maximized through a combination of: high absolute vorticity, strong tangential winds, and close proximity to the TC center. [Holland and Merrill(1984)] depicts a composite profile of I^2 gathered from in-situ data (their Figure 6A) showing I^2 maximized near the TC inner-core (small r, large v, large absolute vorticity) and I^2 decaying with height as v and cyclonic vorticity wane. The radius of maximum wind (RMW) location is a key consideration for the distribution of I^2. Via the second term in Equation ??, at radii within (outside) the RMW the radial gradient of v is positive (negative), thus the radial gradient of I is maximized at the RMW with greatest values of I lying at or within the RMW [Schubert and Hack(1982)]. As such, within the RMW, heating responses are radially constrained to permit warm core enhancement, while outside the RMW heating is more easily dissipated away from the TC center and thus less efficient to drive intensification.

The efficiency of heating sources relative to vortex intensification response has been frequently studied previously. [Schubert and Hack(1982)] used an idealized vortex model to note that heating efficiency on the wind field was maximized when the heating occurred within a region of increased I^2 residing within the RMW, therein attributing RI to increased heating efficiency rather than increased convective vigor. [Nolan ~al.(2007)Nolan, Moon and Stern] extended this work, developing a metric for kinetic energy efficiency within idealized vortex simulations, noting efficiency doubled when specified heating r was halved. [Nolan(2007)] continued the use of kinetic energy efficiency in idealized vortices, with efficiency values tripling over the 24 h prior to RI onset and maximized near the warm core altitude. [Vigh and Schubert(2009)] showed via an idealized model that sensitivity of the heating source location relative to the RMW position can yield a temperature tendency two orders of magnitude greater for a heat source residing within, rather than outside, the RMW. [Pendergrass and Willoughby(2009)] solved a modified version of the Sawyer-Eliassen equation and used a simplified model to show that a small RMW and heat source lying within this region results in the strongest vortex intensification, while vortex shape and slope of the heat source with respect to the vertical are of lesser importance. Studies noted in this paragraph are highly idealized, and may lack applicability to realistic TCs. Observations have begun to reveal similar results, with the radar composites of [Rogers ~al.(2013)Rogers, Reasor and Lorsolo] showing intensifying TCs to possess a preference for an increased number of episodes of extremely intense convection, referred to as a convective burst (CB), activity within a more vortical environment inside the RMW than for steady state TCs.

It is hypothesized that RI episodes are fundamentally similar regarding the growth of heat accumulation within the RMW, but the cloud and precipitation populations responsible for the H_D associated with this heating fundamentally varies dependent upon the broader environment. The intent of this article is to simulate RI in two TCs under low (Hurricane Ike of 2008) and high wind shear (Hurricane Earl of 2010), and evaluate the RMW along with cloud and precipitation character before, during, and after RI. An accompanying paper investigates the influence of inner-core vertical motions and cloud populations on RI. Objectives for this article include to: (i) introduce an objective metric to approximate the RMW with respect to height and time, (ii) characterize the distribution of hydrometeors with respect to azimuth and RMW position, and (iii) assess environmental influences on the observed hydrometeor distributions. The paper is structured as follows: section 2 describes the numerical model and provides synoptic overviews of both TCs, section 3 introduces an objective TC centering and axisymmetric RMW determination method, section 4 overviews the simulated hydrometeor distributions, section 5 examines simulated warm core character, section 6 investigates environmental influences, while section 7 provides summary and overarching conclusions.

2 Simulation Background

2.1 Numerical model setup

Simulations are performed with version 3.3 of the Weather Research and Forecasting (WRF) model - Advanced Research WRF [?, ARW;]]skamarock2005. The ARW is a fully compressible, Eulerian, nonhydrostatic mesoscale model. Four two-way domains are utilized for each simulation, with horizontal resolutions of 27, 9, 3, and 1 km. The 27 km domains encompass the majority of the Atlantic, while the 1 km domain is sized to adequately cover the entire TC inner-core and majority of rainbands. For the Ike simulation the innermost domain covers 777 by 777 km while in the Earl simulation it encompasses 786 by 780 km. The 1 km domains incorporate user-specified preset moves to shift their position every 3 minutes, ensuring the TC remains approximately centered within that domain. All results presented here are from the 1 km domain with the exception of the wind shear evaluations.

Vertical resolution has been shown to be important in achieving proper treatment of processes within the boundary layer, freezing level vicinity, and outflow layer by [Kimball and Dougherty(2006)], [Fierro ~al.(2009)Fierro, Rogers, Marks and Nolan], and [McFarquhar ~al.(2012)McFarquhar, Jewett, Gilmore, Nesbitt and Hsieh]. As such, 55 vertical levels are used with common values for each simulation, similar to those of [McFarquhar ~al.(2012)McFarquhar, Jewett, Gilmore, Nesbitt and Hsieh]. The outermost domain uses European Centre for Medium Range Weather Forecasts' (ECMWF) Re-Analysis Interim product [?, ERA-Interim;]]dee2011 as lateral boundary conditions and initialization. Parameterization choices are outlined in Table 0 and utilized on all domains, except the Kain-Fritsch cumulus parameterization used only at 27 km. No vortex is prescribed within the model, and the initial 24 h of each simulation (beginning 18 UTC 31 August for Ike and 18 UTC 26 August for Earl) are ignored from analyses as the model spins up.

Process modules utilized in WRF simulations. Parameterizations used on each domain, except the Kain-Fritsch scheme for only the 27 km domain.

Process module	Parameterization	Reference

Cumulus	Kain-Fritsch (d01 only)	[Kain and Fritsch(1993)]
Planetary boundary layer	Yonsei University	[Hong ~al.(2006)Hong, Noh and Dudhia]
Microphysics	WRF Single-moment, 6-class	[Hong and Lim(2006)]
Longwave radiation	Rapid Radiative Transfer Model	[Mlawer ~al.(1997)Mlawer, Taubman, Brown, Iacono and Clough]
Shortwave radiation	Rapid Radiative Transfer Model	[Mlawer and Clough(1997)]

2.2 Synoptic Overviews

2.2.1 Hurricane Ike

Ike developed from an African easterly wave moving off the African coastline on 28 August, 2008 [Berg(2010)]. The wave passed south of Cape Verde over the next two days, failing to organize further. At 06 UTC 1 September the NHC declared the wave a tropical depression, with an upgrade to tropical storm status 6 h later. Ike intensified minimally as it continued west-northwest for the next 48 h. Abrupt intensification of 7.7 m s^{-1} (15 kt) over the next 6 h began at 12 UTC 3 September, reaching hurricane strength at 18 UTC. Intensification doubled over the next 6 h, with winds increasing from 38.6 to 54.0 m s^{-1} (75-105 kt), thus meeting the RI threshold over a mere 6 h period. Peak intensity of 64.3 m s^{-1} (125 kt; category 4 hurricane status) was achieved at 06 UTC 4 September before slow weakening over the following days. A more thorough overview of Ike's history is available in [Berg(2010)].

Figure 1A depicts a time series of Ike's intensity. It is stressed that during this period Ike's intensity was satellite estimated, rather than directly sampled, due to the location over the Central Atlantic [Berg(2010)]. Ike began undergoing RI following the 15.4 m s^{-1}/24 h definition of [Kaplan and DeMaria(2003)] while at 28.3 m s^{-1} (55 kt) intensity on 00 UTC 3 September, concluding at 18 UTC 4 September and 59.2 m s^{-1} (115 kt) winds for a RI period spanning 42 h with a total intensity change of 30.9 m s^{-1} (60 kt). It is noted that the observed RI in Ike occurred predominantly following between 18 UTC 3 September and 00 UTC 4 September with 15.9 m s^{-1} of intensification, whereas the simulation intensified only 7.2 m s^{-1} over this same 6 h period. Adjusting the [Kaplan and DeMaria(2003)] integration time for RI calculations to 6 or 12 h (7.7 m s^{-1}/12 h) as in [Rogers ~al.(2013)Rogers, Reasor and Lorsolo] would minimally alters the results of each simulationresult in the observed RI occurring 6 h later (06 UTC verus 00 UTC on 3 September). It is noted however, that [McFarquhar and Silver(2014)] showed shorter time integrationssuch methods permit $>5\%$ of the intensity change distribution to be characterized as RI.

Simulated intensity trends (Fig. 1A) closely follow observations through 4 September. In particular, errors between observed and simulated winds on 3 September are negligible. Simulated sea level pressure (SLP) values are generally within 5 hPa of observed through 4 September. Simulated RI begins at 17:40 UTC 2 September (hereafter approximated to 18 UTC), 6 h before observed. This 6 h offset is possibly linked to the simulated track being faster than observed and passing the observed locations by approximately 6 h earlier (not shown). The greatest simulated 24-h intensity change of 25.3 m s^{-1} occurs following 21:20 UTC 2 September. RI initiation occurs on 18 UTC 2 September while concluding at 08 UTC 4 September. Subsequent times are given relative to RI onset, with negative (positive) times preceding (following) onset. Simulated RI using the aforementioned 12 h definition would yield RI essentially from 6 UTC on 1 September through the end of the simulation (onset 12 h earlier than the 24 h definition), with the intensity change hovering around the 7.7 m s^{-1} threshold from 06 UTC 1 September through 00 UTC 2 September.

Figure 1: Comparison of simulated (solid line) to observed (dash-dotted line) intensity for Ike (A) and Earl (B). Maximum 10 m winds in black while minimum SLP is in gray.

Simulated ambient wind shear variation impacting Ike is depicted in Figure 2A; where shear is taken as 850 and 200 hPa wind difference averaged between r of 200-800 km. The shear vector magnitude is ≤ 3 m s^{-1} through +24 h before steadily increasing. Observed NASA Modern Era Retrospective-Analysis for Research and Applications [?, MERRA;]]rienecker2011 shear is qualitatively comparable in direction and magnitude to simulated values (not shown).

Figure 2: Time series of wind shear for the Ike (A) and Earl (B) simulations with magnitude in black and direction in gray. No direction is plotted for magnitudes below 2.5 m s^{-1}.

To compare simulated storm structure with observations, Figure 3 shows a comparison of column-integrated ice (graupel, snow, and cloud ice) mass (ice water path; IWP) at -1:40 h (Fig. 3A) to 89 GHz polarization corrected temperature (PCT) from the Advanced Microwave Scanning Radiometer-Earth Observing System (AMSR-E) at -1:38 h (Fig. 3B). The 89 GHz datapassive microwave sensor depicts reduced brightness temperatures associated with scattering of upwelling radiation by increased IWP [Vivekanandan ~al.(1991)Vivekanandan, Turk and Bringi]. Both panels show disorganized convectiondiffuse hydrometeors surrounding the circulation center with relatively modest IWP values and brightness temperature depressions respectively. The simulation is biased towards more convectionconvective structure to the south-southwest of the circulation, where observations here lack depressed brightness temperatures. Still, the prevailing structure of each is of widespread hydrometeors with inner-core characteristics qualitatively following the low shear RI composites of [Harnos and Nesbitt(2011)].

Figure 3: Comparison of simulated IWP for Hurricanes Ike at -1:40 h (A) and Earl at -1:20 h (C) and AMSR-E 89 GHz PCT for Ike at -1:38 h (B) and Earl at -1:21 h (D). Black X's indicate surface centers in panels A and C. AMSR-E swaths courtesy of the United States Naval Research Laboratory (www.nrlmry.navy.mil/sat_products.html).

2.2.2 Hurricane Earl

Earl developed from an African easterly wave entering the Atlantic on 23 August, 2010 [Cangialosi(2011)]. A closed circulation developed on 24 August in conjunction with increased convection as the system passed south of Cape Verde. The NHC declared the system a tropical depression at 06 UTC 25 August and a tropical storm 6 h later. Earl maintained tropical storm strength on its westward path, before steady intensification from 00 UTC 29 through 18 UTC 30 August. Earl became a hurricane at 12 UTC 29 August, passing near the Leeward Islands on 30 August and Puerto Rico the following day. Earl's peak intensity over this period was 59.2 m s^{-1} (115 kt) at 18 UTC 30 August. Following the simulated period Earl paralleled eastern North America. A more thorough overview of Earl's synoptic history is available in [Cangialosi(2011)].

Figure 1B shows Earl undergoing RI at 00 UTC 29 August with 28.3 m s^{-1} (55 kt) winds and continuing for 48 h, concluding at 00 UTC 31 August with 59.2 m s^{-1} (115 kt) winds (RI onset occurring at 18 UTC 28 August, 00, 06, 12, 18 UTC 29 August and 00 UTC 30 August) for a total intensity change during RI of 30.9 m s^{-1} (60 kt). Earl was regularly penetrated by reconnaissance and research aircraft, thus observed intensity values are more confident than in Ike. Using a 12 h RI definition would shift the RI onset back by 6 h relative to the 24 h definition (06 UTC versus 00 UTC 29 August), as in Ike.

Earl's simulation closely follows observed intensification trends (Fig. 1B). Simulated RI onset occurs at 1750 UTC 28 August (approximated to 18 UTC), 6 h before observed, with the greatest 24-h intensity change occurring following 1810 UTC 28 August of 22.7 m s^{-1}. The simulation goes through prolonged RI as observed, with onset occurring at 18 UTC 28 August and RI conclusion on 01 UTC 30 August. Again, subsequent times are given relative to the initial simulated RI onset time. SLP trends are similar to wind, with the simulation again deepening slightly faster. [Rogers(2010)] and [Chen ~al.(2011)Chen, Zhang, Carton and Atlas] have noted similar accelerated intensification in their simulations, with the intensity discrepancies herein less than [Rogers(2010)] and slightly worse than [Chen ~al.(2011)Chen, Zhang, Carton and Atlas]. Were a 12 h RI definition utilized for Earl there would have been three distinct RI periods with the criteria met for approximately 12 h periods in each (beginning 20 UTC 27 August, 17 UTC 28 August, and 20 UTC 29 August). This shorter analysis window for characterizing RI muddies results relative to the 24 h RI definition of [Kaplan and DeMaria(2003)], supporting the perspective of [McFarquhar and Silver(2014)] that the shorter integration period may be too lenient.

Simulated wind shear for Earl is depicted in Figure 2B. The shear vector generally has a northerly component, with a shift from a more easterly to a westerly component around +42 h. Note the shear magnitude increases from near zero at -18 h to 7-8 m s^{-1} 24 h later. MERRA shear values closely follow simulated trends in both magnitude and direction (not shown).

Figure 3C depicts a comparison of IWP at -1:20 h to observed AMSR-E 89 GHz PCT 1 minute prior (Fig. 3D). Each panel depicts an asymmetric system with frozen hydrometeors prominent south of the circulation, with the southeastern portion curving cyclonically inward. Embedded deeper convection is evident in each, associated with increased IWP and reduced brightness temperatures respectively. Earl's convection is more asymmetric but more vigorousstronger than in Ike (Fig. 3A,B), again in line with the composites of [Harnos and Nesbitt(2011)] with asymmetric, intense convection preferentially occurring downshear and downshear-left.

3 TC centering and RMW quantification

In describing vortex structure of each TC, RMW quantification is desirable. In developing an objective RMW estimate, the initial challenge is decomposing zonal and meridional winds into radial and tangential components. In doing so, a valid center approximation is necessitated at all altitudes should the vortex be tilted, otherwise error is introduced into the wind components. Vertical tilt is a near certainty in both reality and these simulations, particularly in Earl considering the typical wind shear of ≥ 5 m s^{-1} (Fig. 2B). A novel centering and RMW generation algorithm has been developed, allowing for objective storm center estimation as a function of height and subsequent quantification of the RMW and its variation in the vertical. Various steps of the algorithm are shown in Figure 3. The numerous steps involved throughout RMW determination underscore the resultant RMW acting as a best approximation, however methodsMethods such as those used here and by [Hazelton ~al.(2015)Hazelton, Rogers and Hart] and [Rogers ~al.(2015)Rogers, Reasor and Zhang] are an improvement upon arbitrary inner-core definitions [?, e.g.]]rogers2010,mcfarquhar2012 or axisymmetric RMW estimates at only selected altitudes [?, e.g.]]nguyen2012,chen2013,rogers2013. Furthermore, the RMW region can be used as an objective analysis region to evaluate where heating influences maximize TC intensification.

To address tilt in TC center location determination, the authors have developed a center tracking method following the precipitation feature framework [Nesbitt ~al.(2000)Nesbitt, Zipser and Cecil], where here horizontally contiguous pressure regions below a threshold value are treated as a singular entity which is designated a low pressure feature. First, the vortex center is approximated through the use of low pressure features introduced at each output time and 250 m altitude increments. Initially, the entire 1 km domain SLP field is smoothed with a 5x5 Gaussian filter 20[1] times. The 0.1 percentile value is then taken of the smoothed SLP, with regions below the threshold isolated and the largest contiguous (4-sided) region being deemed associated with the mesoscale circulation, such that its centroid is assumed as the TC center. This procedure is repeated upward through 16 km altitude on each constant height surface, with the exception that after the surface evaluation the preceding altitude's center is used to constrain the search of pressure values on the subsequent surface (e.g. surface center used at 250 m, 250 m center used at 500-m), with the 10th percentile value over a 1° radius circle about the below layer's storm center (Figure 3A). The regions and percentiles used for the center calculations are not evaluated quantitatively, but rather utilized for subjectively producing substantial vertical consistency for the center's location through several various combinations of values (not shown). [Nguyen ~al.(2014)Nguyen, Molinari and Thomas] has shown that a method using the pressure field centroid, as done here, for TC center diagnoses yields the most coherent vertical structure relative to other center-defining methods. It is noted that the contiguous qualifier with the center finding algorithm here means that the area of the contiguous regioncenter taken with respect to height varies, while [Nguyen ~al.(2014)Nguyen, Molinari and Thomas]

[1] The smoothing iteration was tested at 0, 1, 5, and 20 times. Through use of several test output times and altitudes, particularly early in the simulation where a limited mesoscale circulation existed with significant convective influences, the 20timesx filter consistently characterized the TC center location with the least vertical variation while producing v that were the most symmetric in appearance.

and [Ryglicki and Hart(2014)] have demonstrated sensitivity of theto center location evaluation based upon the areal extent with which it is calculated.

Steps taken to evaluate the TC center, v distribution, and RMW for the of Earl at RI onset. (A) depicts the smoothed pressure field at 2 km over the innermost 1° relative to 1.75 km, with the largest pressure feature outlined and the x indicating its centroid. (B) depicts the x- (thin blue) and y- (thin red) centers throughout the column used for the vertical regression to determine the TC center (thick lines). Dashed lines are values of pressure feature centroids deemed irrepresentative of the TC center. Horizontal thin black line indicates maximum altitude used in center regression. (C) depicts 2 km v (contoured) and initial RMW (black line) every 1° of azimuth. (D) depicts the same as (C) but for the final smoothed asymmetric RMW (thin line) and axisymmetric RMW (thick line) estimates. Colorbar valid for v in panels C,D.

The centroids of these pressure features (thin lines in Fig. 3B) are generally representative of the TC circulation center, however some issues can reduce algorithm accuracy. The warm core is slow to manifest itself aloft due to the analyses preceding Ike and Earl becoming tropical storms, and conjointly there is a transition to anticyclonic behavior aloft. To combat these issues, a least squares linear regression is introduced to ensure the most vertically consistent region of the center fixes is used to characterize the TC. Values where the net horizontal distance over 250 m in altitude varied >10 km are discarded. This threshold was tested for various horizontal magnitudes and also the net distance versus individual x- and y-variability, in addition to a no regression scheme option, with the chosen threshold subjectively producing the most symmetric v field while consistently providing a sufficiently deep layer for the regression. Using this approach, a linear polynomial is fit to both x- and y-centroids with the resulting functions taken to represent the TC center at all vertical levels (thick lines in Fig. 3B). While the tilt of the TC is almost certainly nonlinear [?, e.g.]]rogers2013,reasor2013 due to variation in the wind shear profile or baroclinicity [?, e.g.]]jones2000,reasor2012, the least-squares fit is a compromise solution between fixing the center for a single altitude and using the pressure feature analysis but permitting potentially questionable centers aloft. As far as the authors are aware, this study is the first to evaluate heating relative to the RMW using a vortex that is allowed to tilt in the vertical. While the physical implications for this are not entirely clear given the realistic nature of the simulations the efficiency arguments regarding the increased I within the RMW should generally hold with the possible exception of when the absolute angular momentum surfaces fail to lie within the RMW across consecutive vertical levelsat the RMW boundary is misaligned with height.

With unique centers for all times and altitudes in the simulation, v and the resultant RMW are calculated. First, hourly averaged storm motion is removed from the model winds, with the wind field then decomposed into tangential (Figure 3C) and radial components. The RMW is assumed to reside a minimum of 5 km and maximum of 1° (111 km) from the center. At each altitude v is evaluated along 111 km radii at each degree of azimuth, where along the radial v is smoothed with a 1-3-1 filter to limit small-scale variability, with maximum v along the radial deemed the initial RMW. At times, particularly early in the simulation due to the weak TC intensities, scattered convection results in strong azimuthal RMW variation as the convective flow is superimposed on the mesoscale vortex (e.g. southwest in of Fig. 3C). To restrict any such large shifts, and to best insure the RMW represents the mesoscale circulation with limited convective influence, for each azimuth an average of the RMW is taken along $\pm 4^\circ$ of azimuth and should the central RMW vary more than ± 2 standard deviations from the subset mean, the mean then replaces the central RMW value. This method does not remove all such strong azimuth-to-azimuth RMW variability early in the simulation, and to further correct the x- and y-coordinates of the RMW are twice smoothed with a Gaussian filter across $\pm 3^\circ$ of azimuth. The resulting values are then averaged across 360° of azimuth, with this taken as the final axisymmetric RMW estimate (Figure 3D). The azimuthally varying RMW values are not utilized here due to uncertainty for the implications of these asymmetries, however substantial azimuthal variation is expected (as seen in Figure 3C,D) for TCs undergoing RI due to the typically weak v of the vortex [?, e.g.]]kaplan2003,harnos2011 that can be readily impacted by convective flows of comparable magnitudes early in RI. [Croxford and Barnes(2002)] previously used aircraft data to depict the increasing symmetry of v during intensification. Hereafter RMW references denote the axisymmetric mean RMW.

4 Hydrometeor Overview

First, a qualitative perspective of the evolution of both the hydrometeor distributions and RMW is given in Figures 4 and 4 for Ike and Earl respectively. These portray horizontal cross-sections of simulated equivalent radar reflectivity (Z) and RMW position at 2 km from 24 h preceding RI onset through 18 h after RI begins. Also indicated are convective burst (CB) locations, following [Rogers(2010)], where vertical velocity averaged over 700-300 hPa is ≥ 5 m s^{-1}.

At -24 h (Figs. 4A, 4A) each TC lacks coherent inner-core structure despite widespread convection, while the RMW extends beyond 75 km. 6 h later (Fig. 4B, 4B) precipitation continues to lack coherence, however Earl exhibits more convective vigor with higher Z and numerous CBs 50 km north of the center. By -12 h (Figs. 4C, 4) precipitation exhibits increased organization with curvature and banding apparent, while Earl remains more convectively active with CB activity near its center. Here Earl's RMW has contracted to near 50 km, while Ike's RMW remains near 80 km. 6 h before RI onset (Figs. 4D, 4D) each TC's precipitation is relatively asymmetric with convection preferentially located to the south and west, as Earl still possesses more CBs and has evidence of an eye attempting to form.

Simulated 2 km reflectivity (contoured), RMW position (black line) and CB locations following [Rogers(2010)] (black x's) at 6 h intervals from 24 h preceding RI onset through 18 h following RI onset for Ike simulation.

As in Figure 4 but for Earl simulation.

As RI begins (Figs. 4E, 4E) each storm still lacks an eye, with Earl possessing strong wavenumber-1 asymmetry with convection and embedded CBs preferentially-oriented downshear and downshear-left (recalling shear is out of the northeast, per Figure 2B) in line with the high-shear composite of [Harnos and Nesbitt(2011)]. CB activity is predominantly occurring just outside the RMW at 2 km at RI onset, however the perspective of Figure 4 provides no information regarding positioning of CB activity or the RMW aloft where the bulk of the diabatic heating occurstakes place. At onset Ike lacks a clear ring-like feature in 2 km Z as suggested by [Harnos and Nesbitt(2011)] or [Kieper and Jiang(2012)], but the convection surrounding the circulation center may appear somewhat ring-like if coarsened to passive microwave resolution. At +6 h (Figs. 4F, 4F) each simulated TC has formed an eye, with Earl's RMW contracting to near 30 km while Ike exhibits some RMW contraction as well. At this point there is a lack of CB presence within the RMW aside from isolated regions 50 km west and north of Ike's center. Over the following 12 h (Figs. 4G,H, 4G,H) the RMWs continue to contract while a shift is apparent with the area inside the RMW characterized by Z associated with fewer hydrometeors, indicating the transition from H_D maintaining the warm core towards subsidence warming instead.

Quantifying asymmetry of the precipitation field is desirable over the qualitative descriptions of the preceding two paragraphs. From Figures 4 and 4, the majority of the variability within the precipitation field lies over r of 15-70 km, with the RMW residing within this range throughout for both storms. To evaluate asymmetry, the mean liquid water path (LWP; column-integrated cloud liquid water and rain) and IWP at each output time are taken across an annulus of 15-70 km, with this axisymmetric mean for each time removed from the azimuthal values across the same range, with the results shown in Figure 4. Muted (vivid) colors represent greater axisymmetry (asymmetry), with Ike (Fig. 4A,B) exhibiting greater axisymmetry than Earl (Fig. 4C,D), which possesses wavenumber-1 asymmetry throughout. Ike's LWP asymmetries (Fig. 4A) are generally $\leq$ 5 kg m^{-2} while Earl's LWP asymmetries (Fig. 4C) approach 10 kg m^{-2} through +6 h (downshear and downshear-left recalling Figure 2B), before decreasing for the remainder of the simulation. IWP asymmetries (Figs. 4B,D) are generally greater than those seen in LWP. Ike (Fig. 4B) exhibits some of its weakest IWP asymmetries near RI onset from -3 through +3 h, supportive of the ring-like feature associated with precipitation-sized ice noted by [Harnos and Nesbitt(2011)]. As with LWP, Earl possesses greaterstronger IWP asymmetries (Fig. 4D) than Ike and increased IWP to the south and southeast of center in the vicinity of RI onset. These enhanced IWP values occur downshear and downshear-left (Fig. 2B), similar to the perspective presented in Figure 3 of [Harnos and Nesbitt(2011)] for RI under high wind shear.

Radius-time perspective for Ike (A,B) and Earl (C,D) of LWP (A,C) and IWP (B,D) with respect to azimuth and time between 15-70 km radius relative to axisymmetric mean across the same radial range. Center used is at 2 km altitude. Azimuth of 0° is north, 90° east, and so on.

While some qualitative inferences about CB activity can be drawn from Figures 4 and 4, Figure 4 quantifies the percentage ofrelative area within the RMW covered by CBs following the criteria of [Rogers(2010)] for Ike (Fig. 4A) and Earl (Fig. 4B). Minimal CB activity occurs in Ike for 6 h preceding RI, with areas <1% due to few CBs and the broad RMW (e.g. Fig. 4A-F). Earl generally possesses markedly greater CB coverage than Ike, particularly over ± 6 h and 5-12 km altitude with periodic coverage between 5-15%. Earl's CB activity declines abruptly after +6 h, not again approaching 10% coverage for another 18 h. The primary peak in Earl's CB activity preceding RI with a secondary peak immediately after follows the lightning observations over the innermost 100 km of [Stevenson ~al.(2014)Stevenson, Corbosiero and Molinari]., while [Rogers ~al.(2015)Rogers, Reasor and Zhang] similarly shows enhanced CB activity within the RMW preceding Earl's RI in airborne radar swaths. Also apparent in Figure 4 is the vertical variability of CB coverage within the RMW, such that use of a single altitude to approximate CB contributions may provide inaccurate estimates as others have noted [?, e.g.]]hazelton2015,rogers2015,susca-lopata2015., as for For example between +42 and +48 h there is often no CB coverage within either TC's near-surface RMW, yet values above 12 km often exceed 10%. The reader is directed to this manuscript's companion article for a thorough evaluation of vertical motion distributions and their contributions towards intensification.

Figure 4: Percentage of area within the unique RMW at each altitude covered by CBs with respect to time and height following the criteria of [Rogers(2010)] for Ike (A) and Earl (B) simulations.

5 Warm core influences

While the previous section provides some perspective on hydrometeor character relative to the RMW, no direct information is given about I^2 or H_D. To that end, axisymmetric mean plots of I^2, H_D and RMW position with respect to time are shown in Figure 5. Apparent first, is the small-scale variability seen in the RMW position of Ike through -18 h and in Earl at 7 km through RI onset with this variability decreasing as v grows. I^2 is maximized within the RMW, particularly at small r and over approximately 20 km immediately within the RMW. Through +6 h in both storms at 2 and 7 km altitude, H_D pulses at r <40 km, well within the RMW. After this point, where eyes have developed in both TCs (Figs. 4F and 4F), peak average H_D becomes spatially coincident just inside the RMW, particularly in Earl (Figs. 5C,D). This peak H_D is associated with the eyewall, and is around 10 km wide. Examination of the trends in RMW position and H_D reveal the two to be closely linked in their spatial behavior, as evidenced between +30 through +36 h at 2 km in Earl (Fig. 5C), where the RMW expands nearly 5 km and the H_D distribution shifts outward by a comparable distance. There is some evidence for the RMW excluding H_D from high I^2 in Ike at 7 km (Fig. 5B) between +24 and +39 h as the RMW contracts from 40 to 25 km while the H_D location remains stagnant at 20-30 km while Ike's deepening concurrently slows. However, this period at 7 km in Ike appears to be the only period supporting H_D exclusion from the high I^2 by eye development to limit intensification as put forth by [Schubert and Hack(1982)], while both TCs at 2 km and Earl at 7 km see substantial H_D remaining within the RMW even as intensification slows for the last 12 h of each simulation. Exclusion of some of the strongest H_D within Earl's RMW at low-levels, but not aloft, matches the observations for this TC by [Susca-Lopata ~al.(2015)Susca-Lopata, Zawislak, Zipser and Rogers]. A perspective similar to Fig. 5 but for coverage of CBs again using the definition of [Rogers(2010)] reveals comparable trends for CB location relative to that of the H_D contours in Fig. 5.

Radius-time perspective for Ike (A,B) and Earl (C,D) at 2 (A,C) and 7 (B,D) km altitude of I^2 (filled contours; s^{-1}), H_D (grey contours; 2.5×10^{-3} K s^{-1} km^{-2} at 2 km and 5×10^{-3} K s^{-1} km^{-2} at 7 km), and RMW position (black line). Note differing scales for I^2 in each TC.

The objectively defined RMW can also be used to quantify aggregate and average H_D occurring within this region of highest I^2, with a time-height perspective presented in Figure 5. Differences between the aggregate and average perspectives are implicitly tied to variations in the area encompassed by the RMW with respect to time. Peak total H_D in Ike (Fig. 5A) and Earl (Fig. 5B) are comparable between the two cases at most times, with the exception of surges at subfreezing temperatures (≥ 5 km altitude) over ± 6 h in Earl of above 40 K s^{-1} and +18 through +21 h in Ike exceeding 30 K s^{-1}. Largest H_D values are consistently at subfreezing temperatures between 5-12 km for both simulations, implying the presence and importance of clouds containing frozen hydrometeors in each simulated TC's intensification. Ike lacks a clear aggregate H_D signal relative to RI onset aside from a weak maxima near 25 K s^{-1} between 5-11 km over ± 3 h, whereas the aforementioned peak in Earl spanning ± 6 h is an absolute maximum. Earl's peak aggregate H_D coincides well with the period of enhanced CB activity over the same timeframe (Figure 4B). In terms of average H_D within the RMW, for Ike (Fig. 4C) there is little consistency between these peaks and those in aggregate H_D, with the slight exception of the absolute maximum in aggregate H_D near +18 h. Earl's average H_D within the RMW (Fig. 4D) is more consistent with the corresponding aggregate H_D time series, including peak average values around -3 h in both at subfreezing altitudes. Both TCs exhibit a slow increasing trend in their average H_D within the RMW, with the exception of Earl's surge of values around 10 K s^{-1} km^{-2} preceding RI onset. Both aggregate and average perspectives place the majority of the H_D at subfreezing temperatures before and during RI. A similar analysis to Fig. 5 but for the area lying within the innermost 1° but not within the RMW reveals no distinctive H_D behavior in an aggregate or average sense relative to the vicinity of RI onset (not shown).

Aggregate (A, B) and average (C, D) H_D occurring within the unique RMW at each altitude with respect to time and height for the Ike (A, C) and Earl (B, D) simulations.

Lastly, average potential temperature (θ) within the RMW is shown in Figure 5. Here downward (upward) sloping surfaces indicate warming (cooling) associated with the warm core. In Ike (Fig. 5A) and Earl (Fig. 5B) θ surfaces ≤ 340 K gradually descend over time beginning approximately 6 h prior to RI onset. More pronounced descent is apparent at 350 K for both TCs, with the surface shifting from near 13 km at RI onset for Ike to near 9 km by simulation conclusion, while for Earl this surface descends throughout the entire simulation over the same height range. For warmer θ surfaces (i.e. ≥ 360 K), likely associated with the stratosphere, no clear signals are seen. Ike's 360 K surface lacks variability, while in Earl this surface descends sharply from +30 h onward, yet RI concludes at +31 h. Accordingly, attribution of either TC's RI to stratospheric descent, as by [Zhang and Chen(2012)], appears inappropriate at the scale analyzed here.

Figure 5: Average θ occurring within the unique RMW at each altitude with respect to time and height for the Ike (A) and Earl (B) simulations. Black lines are at 10 K intervals.

6 Environmental influences

With the precipitation character and warm core discussed, potential links between these and the inner-core environment are sought. First evaluated are instability-related parameters, with the temporal evolution of surface fluxes and convective available potential energy (CAPE) shown in Figure 6. Relative to Ike (Fig. 6A), Earl (Fig. 6B) experiences greater surface sensible and latent heating fluxes, increasing at a rate approximately 2-4 times that of Ike. Peak sensible and latent heating occurs between +42 and +48 h with values of 250 W m^{-2} and 1050 W m^{-2} respectively. At RI onset Earl's sensible and latent heating are approximately 2 and 1.5 times greater respectively than Ike at this same point. The reason for the strong fluxes in Earl are likely due to the asymmetric convection downshear (Fig. 4)A-E due to the increased convergence associated with the vortex tilt [Reasor ~al.(2013)Reasor, Rogers and Lorsolo], aswith cool, dry downdrafts increase the thermodynamic disequilibrium between the ocean and atmosphere which is subsequentlybeing replenished by surface fluxes before convective maturationfeeding into the convection once more on the downshear side [?, e.g.]]molinari2013,zhang2013. Surface fluxes in Earl appear better correlated with intensity than seen in Ike, with the increasing trend in flux magnitudes through around +40 h being just prior to the peak intensity (Fig. 1B), followed by a plateau and slight weakening apparent in both the fluxes and wind speeds. No discernible trend in surface fluxes is apparent relative to RI despite the general increasing trend through +42 h in both TCs corresponding to approximately the same time period of increase in the maximum 10 m winds (Fig. 1). In line with the largerstronger surface fluxes experienced by Earl, CAPE is typically greaterstronger than that seen in Ike through +15 h. Earl's CAPE decreases over time across the innermost degree, beginning around 1950 J kg^{-1} and ending <700 J kg^{-1}. The decline in Earl's CAPE is attributed to increased equivalent potential temperature (θ_e) abovewithin the boundary layer at 2 km over this time acting to stabilize the lower atmosphere, while SST and 250 m θ_e within the boundary layer are relatively constant (not shown). Given the strong CAPE values seen through RI onset in Earl, the prevalence of CBs for Earl (Figure 4A-E) relative to Ike (Figure 4A-E) is unsurprising. The high CAPE values in Earl are also associated with warmer SSTs beneath the TCfor this region of approximately 2 K (not shown), with [Chen and Zhang(2013)] previously establishing a link between SST and CB presence. The θ_e is also warmer at 250 m by 2-3 K through +6 h for Earl relative to Ike, indicative of greater heat and moisture presence within the boundary layer to support convective development.

Figure 6: Time series of average CAPE (gray line), surface latent heating (solid black line), and surface sensible heating (dashed black line) occurring within the innermost 1° at the surface for the Ike (A) and Earl (B) simulations. Positive values indicate heat transfer from the ocean to the atmosphere. Center used is at 250 m altitude.

For further investigation of the moisture's presence in the simulations, average moisture convergence across the innermost 1° with respect to time and height are shown in Figure 7. Preceding RI, Ike (Fig. 7A) exhibits net moisture convergence typically extending through 3-4 km altitude, whereas Earl (Fig. 7B) has shallower moisture convergence typically extending through 2.5 km with periodic surges extending to 6-8 km. Despite the typically shallower layers of positive moisture convergence, Earl exhibits increasedstronger moisture convergence values within the lowest 1 km, often 2-3 times that of Ike. Moisture convergence magnitudes increase over time for each simulation at the lowest-levels as the storms intensify and low-level convergence grows. Despite the greaterstronger moisture convergence, Ike typically has higher precipitable water values across the innermost 1° preceding RI by 2-4 kg m^{-2} (not shown). The difference is somewhat misleading however, as Ike has widespread precipitable water near 60 kg m^{-2}, whereas Earl possesses a dipole-like structure with values >70 kg m^{-2} associated with the convectively active regions (e.g. south and west of the center in Figure 4C-E) while convectively inactive regions (e.g. north and east of the center in Figure 4C-E) are at times <50 kg m^{-2}. Such azimuthal variation in the low-level moisture is previously noted observationally by [Molinari ~al.(2013)Molinari, Frank and Vollaro] and [Zhang ~al.(2013)Zhang, Rogers, Reasor, Uhlhorn and Marks Jr.], and is associated with the development of convection oriented right ofcyclonically relative tothe shear vector that maturesdecays downshear yielding downdrafts with low θ_e left ofanticylonically to the shear vector acting to stabilize the boundary layer before subsequent replenishment of heat and moisture by surface fluxes, as noted earlier for Fig. 6. This asymmetry is also likely a source of the greater sensible and latent heat fluxes off the sea surface preceding RI in the Earl simulation relative to Ike (Fig. 6) as the low θ_e associated with the downdrafts recharges before subsequently fueling convection on the cyclonic side of the shear vector.

Figure 7: Average moisture convergence with positive (negative) values indicating convergence (divergence) occurring within the innermost 1° with respect to time and height for the Ike (A) and Earl (B) simulations. Center used is at 250 m altitude. Vertical scaling for lowest 1 km (below dashed black line) is elongated.

7 Conclusions

Hurricanes Ike of 2008 and Earl of 2010, observed to undergo RI while within low and high ambient wind shear respectively, have had their RI periods simulated with the WRF model. Simulated intensification was accelerated approximately 6 h from observations for both storms, with similar biases noted by [Rogers(2010)] and [Chen and Zhang(2013)]. Precipitation structures associated with RI qualitatively mirror the shear-dependent archetypes introduced by [Harnos and Nesbitt(2011)], with the low shear case (Ike) possessing widespread weak convection with associated stratiform precipitation surrounding the TC center while the high shear case (Earl) exhibits pronounced wavenumber-1 asymmetry with intense convection downshear and downshear-left.

An objective method to quantify the TC center and axisymmetric RMW with respect to height is introduced to characterize the primary circulation. Low pressure features, or regions of contiguous pressure values below a specified quantile, are used to characterize the TC center with respect to height and allow decomposition of the v field from model output winds. The resulting RMW allows for an objective analysis region in realistic TCs for evaluating the heating distribution where it is shown to be most efficient for subsequent TC intensification following the work of [Schubert and Hack(1982)], [Vigh and Schubert(2009)], and [Pendergrass and Willoughby(2009)].

Each storm possesses a CB presence within the RMW preceding RI, however Earl's is far greater in both CB areal coverage and overall convective vigor while leading up to, and in the early stages of RI. Earl exhibits a peak in the aggregate H_D at subfreezing temperatures within the RMW over ± 6 h, associated with a surge in CB numbers within the RMW. Ike exhibits no such peak in aggregate H_D within the RMW and these values are more muted relative to Earl. The strongest H_D presence within the RMW for each simulation occurs at subfreezing temperatures, implying the presence and importance of clouds associated with frozen hydrometeors through RI. Such importance has been previously implied in observations of w within the RMW by [Rogers ~al.(2013)Rogers, Reasor and Lorsolo] for intensifying TCs. This would seemingly support the perspective of [Harnos and Nesbitt(2011)] on the utility of passive microwave ice scattering signatures as an RI predictor. Potential roles for less vertically-developed cloud populations remain unclear, and are addressed in the companion article. Both simulations provide little evidence for H_D being fully excluded from within the RMW, even following eye development. The RMW appears proximate to the eyewall position late in the simulations, with each shifting in unison such that adiabatic processes fail to exclusively drive warm core development. Furthermore, there is no evidence in θ surfaces associated with the stratosphere descending relative to RI, unlike the simulation of [Zhang and Chen(2012)].

Taken together, environmental influences on inner-core cloud and precipitation character through RI onset confirm the hypothesized disparities between cloud and precipitation character for different RI episodes. For Earl, present to help drive and sustain convection are: high wind shear, factors promoting high CAPE (warm SST, high near-surface θ_e, and strong surface sensible and latent heat fluxes), and strong moisture convergence within the boundary layer. This convection, containing numerous CBs, is oriented preferentially downshear and downshear-left as put forth by [Molinari ~al.(2013)Molinari, Frank and Vollaro] and [Zhang ~al.(2013)Zhang, Rogers, Reasor, Uhlhorn and Marks Jr.]. In Ike, reduced wind shear is present in an environment marginally favorable for convective development with instability and moisture parameters that slowly grow that results in a less conducive environment for CBs. The updrafts, and associated cloud populations, of each TC are evaluated more in depth in the companion article. Pathways for future investigation regarding influences on inner-core cloud and precipitation character could involve radial and azimuthal dependencies of surface fluxes, convergence, and θ_e relative to the RMW positioning, RI timing, and environmental wind shear magnitude.

It would be helpful to extend the study of hydrometeor presence relative to the RMW further with observational data. Ideally dual-Doppler measurements could be utilized to characterize the wind field and precipitation character over a sufficiently broad region while also providing vertical profiles. The best opportunity to do so is likely with a radar based on an aircraft with a substantial time on site over the TC inner-core, such as the NASA Global Hawks. A broad swath would also be desirable for allowing the wind field characterization to be sufficiently categorized spatially, such as available from the High-Altitude Imaging Wind and Rain Airborne Profiler (HIWRAP; [Heymsfield ~al.(2007)Heymsfield, Carswell, Li, Schaubert and Creticos]). A legacy instrument to the Electra Doppler Radar [?, ELDORA;]]hildebrand1996, such as the proposed Airborne Phased Array Radar for the National Center for Atmospheric Research C-130, would also prove capable of providing such information without the need for multiple aircrafts flying coincidentally. Further work investigating the potential for asymmetry within v and its influences on the RMW position and intensification are also necessitated considering the modest intensity that TCs typically begin to undergo RI and the findings of [Croxford and Barnes(2002)]. Lastly, it is noted that the work described herein assumes that H_D evaluated within a vertically-slopingtilted vortex (e.g. RMW, angular momentum surfaces, vertical velocity, and so on) behaves as theoretical and idealized work has shown to be valid in a vertically-aligned vortex. While [Pendergrass and Willoughby(2009)] found weak influences of tilting of the heat source on vortex evolution, examination of the impacts of heating in a vertically-slopingtilted RMW framework as described herein may require further study that appears best suited for idealized TC simulations.

The authors thank Zhuo Wang, Greg McFarquhar, Ryan Sriver, and Brian Jewett for discussions in developing this research. Constructive reviews from Dr. Robert Rogers and another anonymous reviewer are appreciated for further refining the manuscript. DH and SN were supported by Ramesh Kakar under NASA Hurricane Science Research Project grant NNX09AB82G; DH was supported by NASA ESS Fellowship NNX10AP50H. Computing resources were provided by the NASA Center for Climate Simulation. ERA-Interim and MERRA reanalyses were provided by ECMWF and NASA respectively.

References urlstyle

[Berg(2010)] Berg R. 2010. Tropical cyclone report: Hurricane Ike. [Available online at http://www.nhc.noaa.gov/pdf/TCR-AL092008_Ike_3May10.pdf].

[Cangialosi(2011)] Cangialosi JP. 2011. Tropical cyclone report: Hurricane Earl. Available online at [http://www.nhc.noaa.gov/pdf/TCR-AL072010_Earl.pdf].

[Chen and Zhang(2013)] Chen H, Zhang DL. 2013. On the rapid intensification of Hurricane Wilma (2005). Part II: Convective bursts and the upper-level warm core. *J. Atmos. Sci.* **70**: 146–162.

[Chen ~al.(2011)Chen, Zhang, Carton and Atlas] Chen H, Zhang DL, Carton J, Atlas R. 2011. On the rapid intensification of Hurricane Wilma (2005). Part I: Model prediction and structural changes. *Wea. Forecasting* **26**: 885–901.

[Croxford and Barnes(2002)] Croxford M, Barnes GM. 2002. Inner core strength of Atlantic tropical cyclones. *Mon. Wea. Rev.* **130**: 127–139.

[Dee ~al.(2011)Dee, Uppala, Simmons, Berrisford, Poli, Kobayashi, Andrae, Balmaseda, Balsamo, Bauer, Bechtold, Beljaars, van~de Berg, Bidlot, Bormann, Delsol, Dragani, Fuentes, Geer, Haimberger, Healy, Hersbach, Hólm, Isaksen, Kållberg, Köhler, Matricardi, McNally, Monge-Sanz, Morcrette, Park, Peubey, de~Rosnay, Tavolato, Thépaut and Vitart] Dee DP, Uppala SM, Simmons AJ, Berrisford P, Poli P, Kobayashi S, Andrae U, Balmaseda MA, Balsamo G, Bauer P, Bechtold P, Beljaars ACM, van de Berg L, Bidlot J, Bormann N, Delsol C, Dragani R, Fuentes M, Geer AJ, Haimberger L, Healy SB, Hersbach H, Hólm EV, Isaksen L, Kållberg P, Köhler M, Matricardi M, McNally AP, Monge-Sanz BM, Morcrette JJ, Park BK, Peubey C, de Rosnay P, Tavolato C, Thépaut JN, Vitart F. 2011. The ERA-Interim reanalysis: Configuration and performance of the data assimilation system. *Quart. J. R. Meteorol. Soc.* **137**: 553–597.

[DeMaria ~al.(2014)DeMaria, Sampson, Knaff and Musgrave] DeMaria M, Sampson CR, Knaff JA, Musgrave KD. 2014. Is tropical cyclone intensity guidance improving? *Bull. Amer. Meteor. Soc.* **95**: 387–398.

[Fierro ~al.(2009)Fierro, Rogers, Marks and Nolan] Fierro AO, Rogers RF, Marks FD, Nolan DS. 2009. The impact of horizontal grid spacing on the microphysical and kinematic structures of strong tropical cyclones simulated with the WRF-ARW model. *Mon. Wea. Rev.* **137**: 3717–3743.

[Harnos and Nesbitt(2011)] Harnos DS, Nesbitt SW. 2011. Convective structure in rapidly intensifying tropical cyclones as depicted by passive microwave measurements. *Geophys. Res. Lett* **38**: L07805.

[Harnos and Nesbitt(2015)] Harnos DS, Nesbitt SW. 2015. Passive microwave quantification of tropical cyclone inner-core cloud populations relative to subsequent intensity change. Revised.

[Hazelton ~al.(2015)Hazelton, Rogers and Hart] Hazelton AT, Rogers R, Hart RE. 2015. Shear-relative asymmetries in tropical cyclone eyewall slope. *Mon. Wea. Rev.* **143**: 883–903.

[Hendricks ~al.(2010)Hendricks, Peng, Fu and Li] Hendricks EA, Peng MS, Fu B, Li T. 2010. Quantifying environmental control on tropical cyclone intensity change. *Mon. Wea. Rev.* **138**: 3243–3271.

[Heymsfield ~al.(2007)Heymsfield, Carswell, Li, Schaubert and Creticos] Heymsfield G, Carswell J, Li L, Schaubert D, Creticos J. 2007. Development of the High-Altitude Imaging Wind and Rain Airborne Profiler (HIWRAP). [Available online at http://esto.nasa.gov/conferences/nstc2007/papers/Carswell_James_B5P2_NSTC-07-0085.pdf].

[Hildebrand ~al.(1996)Hildebrand, Lee, Walther, Frush, Randall, Loew, Neitzel and Parsons] Hildebrand PH, Lee WC, Walther CA, Frush C, Randall M, Loew E, Neitzel R, Parsons R. 1996. The ELDORA/ASTRAIA airborne Doppler weather radar: High-resolution observations from TOGA

COARE. *Bull. Amer. Meteor. Soc.* **77**: 213–232.

[Holland and Merrill(1984)] Holland GJ, Merrill RT. 1984. On the dynamics of tropical cyclone structural changes. *Quart. J. R. Meteor. Soc.* **110**: 723–745.

[Hong and Lim(2006)] Hong SY, Lim JOJ. 2006. The WRF Single-Moment 6-Class Microphysics scheme. *J. Kor. Meteor. Soc.* **42**: 129–151.

[Hong ~al.(2006)Hong, Noh and Dudhia] Hong SY, Noh Y, Dudhia J. 2006. A new vertical diffusion package with an explicit treatment of entrainment processes. *Mon. Wea. Rev.* **134**: 2318–2341.

[Jiang and Ramirez(2013)] Jiang H, Ramirez EM. 2013. Necessary conditions for tropical cyclone rapid intensification as derived from 11 years of TRMM data. *J. Climate* **26**: 6459–6470.

[Jones(2000)] Jones SC. 2000. The evolution of vortices in vertical shear. Part III: Baroclinic vortices. *Quart. J. R. Meteorol. Soc.* **126**: 3161–3185.

[Kain and Fritsch(1993)] Kain JS, Fritsch JM. 1993. Convective parameterization for mesoscale models: The Kain-Fritsch scheme. *Meteor. Monogr.* **23**: 165–170.

[Kaplan and DeMaria(2003)] Kaplan J, DeMaria M. 2003. Large-scale characteristics of rapidly intensifying tropical cyclones in the North Atlantic basin. *Wea. Forecasting* **18**: 1093–1108.

[Kieper and Jiang(2012)] Kieper M, Jiang H. 2012. Predicting tropical cyclone rapid intensification using the 37 GHz ring pattern identified from passive microwave measurements. *Geophys Res. Lett.* **39**: L13804.

[Kimball and Dougherty(2006)] Kimball SK, Dougherty FC. 2006. The sensitivity of idealized hurricane structure and development to the distribution of vertical levels in MM5. *Mon. Wea. Rev.* **134**: 1987–2008.

[Marks and Shay(1998)] Marks FD, Shay LK. 1998. Landfalling tropical cyclones: Forecast problems and associated research opportunities. *Bull. Amer. Meteor. Soc.* **79**: 305–323.

[McFarquhar ~al.(2012)McFarquhar, Jewett, Gilmore, Nesbitt and Hsieh] McFarquhar GM, Jewett BF, Gilmore MS, Nesbitt SW, Hsieh TL. 2012. Vertical velocity and microphysical distributions related to the rapid intensification in a simulation of Hurricane Dennis (2005). *J. Atmos. Sci.* **69**: 3515–3534.

[McFarquhar and Silver(2014)] McFarquhar GM, Silver AJ. 2014. Shorter time scale definitions for the rapid intensification of tropical cyclones. In: Proc., *31st Conf. on Hurricanes and Trop. Meteor.* Amer. Meteor. Soc.: San Diego, CA, p. 115.

[Mlawer and Clough(1997)] Mlawer EJ, Clough SA. 1997. On the extension of the rapid radiative transfer model to the shortwave region. proceedings of the 6th Atmospheric Radiation Measurement ARM Science Team Meeting, U.S. Department of Energy, CONF-9603149 .

[Mlawer ~al.(1997)Mlawer, Taubman, Brown, Iacono and Clough] Mlawer EJ, Taubman SJ, Brown PD, Iacono MJ, Clough SA. 1997. Radiative transfer for inhomogeneous atmospheres: RRTM, a validated correlated-k model for the long-wave. *J. Geophys. Res.* **102**: 16 663–16 682.

[Molinari ~al.(2013)Molinari, Frank and Vollaro] Molinari J, Frank J, Vollaro D. 2013. Convective bursts, downdraft cooling, and boundary layer recovery in a sheared tropical storm. *Mon. Wea. Rev.* **141**: 1048–1060.

[Nesbitt ~al.(2000)Nesbitt, Zipser and Cecil] Nesbitt SW, Zipser EJ, Cecil DJ. 2000. A census of precipitation features in the Tropics using TRMM: Radar, ice scattering, and lightning observations. *J. Climate* **13**: 4087–4106.

[Nguyen and Molinari(2012)] Nguyen LT, Molinari JE. 2012. Rapid intensification of a sheared, fast-moving hurricane over the Gulf Stream. *Mon. Wea. Rev.* **140**: 3361–3378.

[Nguyen ~al.(2014)Nguyen, Molinari and Thomas] Nguyen LT, Molinari JE, Thomas D. 2014. Evaluation of tropical cyclone center identification methods in numerical models. *Mon. Wea. Rev.* **142**: 4326–4339.

[Nolan(2007)] Nolan DS. 2007. What is the trigger for tropical cyclogenesis? *Aust. Meteor. Mag.* **56**: 241–266.

[Nolan ~al.(2007)Nolan, Moon and Stern] Nolan DS, Moon Y, Stern DP. 2007. Tropical cyclone intensification from asymmetric convection: Energetics and efficiency. *J. Atmos. Sci.* **64**: 3377–3405.

[Pendergrass and Willoughby(2009)] Pendergrass AG, Willoughby HE. 2009. Diabatically induced secondary flows in tropical cyclones. Part I: Quasi-steady forcing. *Mon. Wea. Rev.* **137**: 805–821.

[Pielke ~al.(2008)Pielke, Gratz, Landsea, Collins, Saunders and Musulin] Pielke Jr RA, Gratz J, Landsea CW, Collins D, Saunders MA, Musulin R. 2008. Normalized hurricane damage in the United States: 1900-2005. *Nat. Haz. Rev.* **9**: 29–42.

[Rappaport(2000)] Rappaport EN. 2000. Loss of life in the united states associated with recent Atlantic tropical cyclones. *Bull. Amer. Meteor. Soc.* **81**: 2065–2073.

[Rappaport ~al.(2009)Rappaport, Franklin, Avila, Baig, II, Blake, Burr, Jiing, Juckins, Knabb, Landsea, Mainelli, M.~Mayfield, Sisko, Stewart and Tribble] Rappaport EN, Franklin JL, Avila LA, Baig SR, II JLB, Blake ES, Burr CA, Jiing JG, Juckins CA, Knabb RD, Landsea CW, Mainelli M, M Mayfield C J McAdie RJP, Sisko C, Stewart SR, Tribble AN. 2009. Advances and challenges at the National Hurricane Center. *Wea. Forecasting* **24**: 395–419.

[Reasor and Eastin(2012)] Reasor PD, Eastin MD. 2012. Rapidly intensifying Hurricane Guillermo (1997). Part II: Resilience in shear. *Mon. Wea. Rev.* **140**: 425–444.

[Reasor ~al.(2013)Reasor, Rogers and Lorsolo] Reasor PD, Rogers R, Lorsolo S. 2013. Environmental flow impacts on tropical cyclone structure diagnosed from airborne Doppler radar composites. *Mon. Wea. Rev.* **141**: 2949–2969.

[Rienecker ~al.(2011)Rienecker, Suarez, Gelaro, Todling, Bacmeister, Liu, Bosilovich, Schubert, Takacs, Kim, Bloom, Chen, Collins, Conaty, daSilva, Gu, Joiner, Koster, Lucchesi, Molod, Owens, Pawson, Pegion, Redder, Reichle, Robertson, Ruddick, Sienkiewicz and Woollen] Rienecker MM, Suarez MJ, Gelaro R, Todling R, Bacmeister J, Liu E, Bosilovich MG, Schubert SD, Takacs L, Kim GK, Bloom S, Chen J, Collins D, Conaty A, daSilva A, Gu W, Joiner J, Koster RD, Lucchesi R, Molod A, Owens T, Pawson S, Pegion P, Redder CR, Reichle R, Robertson FR, Ruddick AG, Sienkiewicz M, Woollen J. 2011. MERRA: NASA's Modern Era Retrospective Reanalysis for Research and Applications. *J. Climate* **24**: 3624–3648.

[Rogers(2010)] Rogers R. 2010. Convective-scale structure and evolution during a high-resolution simulation of tropical cyclone rapid intensification. *J. Atmos. Sci.* **67**: 44–70.

[Rogers ~al.(2013)Rogers, Reasor and Lorsolo] Rogers R, Reasor P, Lorsolo S. 2013. Airborne Doppler observations of the inner-core structural differences between intensifying and steady-state tropical cyclones. *Mon. Wea. Rev.* **141**: 2970–2991.

[Rogers ~al.(2015)Rogers, Reasor and Zhang] Rogers RF, Reasor PD, Zhang JA. 2015. Multiscale structure and evolution of Hurricane Earl (2010) during rapid intensification. *Mon. Wea. Rev.* **143**: 536–562.

[Ryglicki and Hart(2014)] Ryglicki DR, Hart RE. 2014. An investigation of center-finding techniques for tropical cyclones in mesoscale models. *J. Appl. Meteor. Climatol.* **54**: 825–846.

[Schubert and Hack(1982)] Schubert WH, Hack JJ. 1982. Inertial stability and tropical cyclone development. *J. Atmos. Sci.* **39**: 1687–1697.

[Shapiro and Willoughby(1982)] Shapiro LJ, Willoughby HE. 1982. The response of balanced hurricanes to local sources of heat and momentum. *J. Atmos. Sci.* **39**: 378–394.

[Skamarock ~al.(2005)Skamarock, Klemp, Dudhia, Gill, Barker, Wang and Powers] Skamarock WC, Klemp JB, Dudhia J, Gill DO, Barker DM, Wang W, Powers JG. 2005. A description of the Advanced Research WRF, version 2. *NCAR Tech Note NCAR/TN-468+STR* : 88 pp.

[Stevenson ~al.(2014)Stevenson, Corbosiero and Molinari] Stevenson SN, Corbosiero KL, Molinari J. 2014. The convective evolution and rapid intensification of Hurricane Earl (2010). *Mon. Wea. Rev.* **142**: 4364–4380.

[Susca-Lopata ~al.(2015)Susca-Lopata, Zawislak, Zipser and Rogers] Susca-Lopata G, Zawislak J, Zipser EJ, Rogers RF. 2015. The role of observed environmental conditions and precipitation evolution in the rapid intensification of hurricane earl. *Mon. Wea. Rev.* **143**: 2207–2223.

[Vigh and Schubert(2009)] Vigh JL, Schubert WH. 2009. Rapid development of the tropical cyclone warm core. *J. Atmos. Sci.* **66**: 335–3350.

[Vivekanandan ~al.(1991)Vivekanandan, Turk and Bringi] Vivekanandan J, Turk J, Bringi VN. 1991. Ice water path estimation and characterization using passive microwave radiometry. *J. Appl. Meteor.* **30**: 1407–1421.

[Willoughby(2012)] Willoughby HE. 2012. Distributions and trends of death and destruction from hurricanes in the United States, 1900-2008. *Nat. Haz. Rev.* **13**: 57–64.

[Zhang and Chen(2012)] Zhang DL, Chen H. 2012. Importance of the upper-level warm core in the rapid intensification of a tropical cyclone. *Geophys. Res. Lett* **39**: L02806.

[Zhang ~al.(2013)Zhang, Rogers, Reasor, Uhlhorn and Marks Jr.] Zhang JA, Rogers RF, Reasor PD, Uhlhorn EW, Marks Jr FD. 2013. Asymmetric boundary layer structure from dropsonde composites in the presence of environmental wind shear. *Mon. Wea. Rev.* **141**: 3968–3984.