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Differences in the vertical velocity characteristicspopulations associated with various cloud populations are evaluated for two simulated cases of tropical cyclone (TC) rapid intensification (RI) under varying wind shear. Within the radius of maximum wind (RMW), preceding RI in the low shear TC (Hurricane Ike of 2008) increased updraft magnitudes for the top 1% of the distribution at 7 km occur, while in the high shear scenario (Hurricane Earl of 2010) RI is led by increased updraft magnitudes of the top 1% of the distribution at 12 km. Three-dimensional analyses of individual updrafts relative to their peak altitude enables direct quantification of processes associated with shallow cumuli, cumulus congestus, deep convection failing to penetrate the tropopause, and convective bursts (CBs). Mean profiles for each convective regime reveal positive contributions in certain variables of each updraft variety towards RI with positive diabatic heating, absolute vorticity, and moisture convergence roles.

Within the RMW, CBs are shown to be the primary diabatic heating and vertical mass and vapor flux contributors in both simulations, while Ike includes secondary contributions from deep convection and congestus in addition to noteworthy diabatic heating from apparent stratiform processes that act to spin-up the mid-level vortex. Inner-core moisture convergence has divided contributions from shallow cumuli, cumulus congestus, and CBs. CBs act to enhance potential vorticity to the greatest amount and over the deepest vertical layer at low-levels. The simulation results overwhelmingly support the aggregate importance of vertically-developed deep convection and its associated ice processes with initiation and maintenance of RI.

tropical cyclone, hurricane, typhoon, rapid intensification, convective processes, mesoscale processes, precipitation, vertical motion

Varied pathways for simulated tropical cyclone rapid intensification. Part II: Vertical motion and cloud populations

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Wed Mar 02 19:02:06 2016

1 Introduction

Prediction of tropical cyclone (TC) intensity change at timescales on the order of a day remains problematic for forecasting agencies. [DeMaria ~al.(2014)DeMaria, Sampson, Knaff and Musgrave] details improved intensity predictions as seeing statistically significant improvement in some products over the past 25 years, but with gains only being on the order of 1% for time periods of 24-48 hours. The most problematic of intensity change events from a predictability standpoint are those occurring within the tails of the distribution that may fall outside traditional statistical forecasting approaches that are focused on better characterizing the bulk of the tropical cyclone intensity change distribution rather than extreme events. Of great interest within the upper tail are TCs undergoing rapid intensification (RI), defined as a 30 kt wind increase over 24 h by [Kaplan and DeMaria(2003)].

Multiple perspectives have been put forth about identifying RI causes in terms of large scale environmental versus internal processes. [Kaplan ~al.(2010)Kaplan, DeMaria and Knaff] showed mean environmental differences between RI episodes and TCs not undergoing RI for the North Atlantic and East Pacific oceanic basins, finding statistical significance at the 99.9th percentile for 850-200 hPa shear magnitude, 200 hPa divergence, 850-700 hPa relative humidity, and oceanic heat content. They also note such statistical significance for inner-core parameters of infrared brightness temperature areal coverage $\leq$-30°C and their standard deviation. [Hendricks ~al.(2010)Hendricks, Peng, Fu and Li] however found no such significant differences between environmental parameters of TCs undergoing RI versus those intensifying but at a lesser rate for a global dataset. This supports the perspective that environmental conditions alone are insufficient to dictate whether a TC will merely intensify or rather undergo RI.

In terms of inner-core processes driving RI episodes one frequently investigated subject is that of so-called convective bursts (CBs), or episodes of extremely intense convection. [Black ~al.(1994)Black, Bluestein and Black] highlighted CBs during the RI of Hurricane Emily (1987) with vertical velocities reaching up to 24 m s^{-1} within the eyewall. [Molinari and Vollaro(2010)] detailed an abrupt intensification episode in Tropical Storm Gabrielle (2001) linked with an exceptionally strong CB rotating cyclonically inward. [Tao and Jiang(2013)] used the Tropical Rainfall Measuring Mission (TRMM) Precipitation Radar (PR) to note a positive correlation between the area of convection penetrating the tropopause and subsequent intensity change, in line with [Kelley ~al.(2004)Kelley, Stout and Halverson] who previously showed an intensification preference for TCs with at least one CB within their eyewall. [Heymsfield ~al.(2001)Heymsfield, Halverson, Simpson, Tian and Bui] followed a different perspective in attributing the subsidence along the inner-edge of a CB in Hurricane Bonnie (1998) for several degrees of eye warming. [Chen and Zhang(2013)] similarly attributed RI in their simulation of Hurricane Wilma (2005) to this process. Not all studies point to the importance of CBs in RI however, as [Rogers(2010)] in his simulation of Dennis (2005) found no clear trend in CB number or location relative to RI. Similarly, [McFarquhar ~al.(2012)McFarquhar, Jewett, Gilmore, Nesbitt and Hsieh] in another Dennis simulation noted CB areal coverage increasing only after RI had begun, however they did show a contracting trend in preferred CB location. Both [Rogers(2010)] and [McFarquhar ~al.(2012)McFarquhar, Jewett, Gilmore, Nesbitt and Hsieh] attributed RI to weaker updrafts driving the low-level mass flux and latent heating respectively. [Nguyen and Molinari(2012)] also observed extremely deep convective cells occurring late in the RI cycle for Hurricane Irene (1999), further muddling potential causal roles of RI via CBs.

Lesser attention has been given to inner-core precipitation outside the CB classification however. [Johnson ~al.(1999)Johnson, Rickenbach, Rutledge, Ciesielski and Schubert] and [Takayabu

~al.(2010)Takayabu, Shige, Tao and Hirota] described the full spectrum of clouds and precipitation in the tropics, highlighting the importance of non-CB cloud modes such as cumulus congestus. [Rogers(2010)] and [McFarquhar ~al.(2012)McFarquhar, Jewett, Gilmore, Nesbitt and Hsieh] included a statiform-convective distinction, while such delineation is rare in other RI simulation studies. [Harnos and Nesbitt(2011)] used 20+ years of passive microwave ice scattering signals to suggest two shear-delineated structures associated with TCs undergoing RI: widespread modest convection with a relatively symmetric ring-like presence under low wind shear and asymmetric intense convection preferentially downshear and downshear-left under high shear. [Kieper and Jiang(2012)] linked observations of TCs undergoing RI with a ring-like feature attributed to shallow clouds associated with warm rain. Recently, [Wang(2014)] evaluated the role of inner-core congestus in the simulated genesis of Tropical Storm Fay (2008), noting its important role in moistening the low to mid-levels while spinning up the near-surface circulation. [Terwey and Rozoff(2014)] introduced a metric to track individual updrafts in four dimensions and provided general statistics on updraft character for multiple convective modes. [Harnos and Nesbitt(2015)] showed an increased presence of clouds associated with frozen hydrometeors within the TC core of an order of magnitude for RI episodes relative to other intensity changes. To date no study has explicitly quantified varying inner-core convective cloud populations or their potential roles in RI. [Tao and Jiang(2016)] attempted to quantify convective cloud population presence relative to the onset of RI using the TRMM PR using the 20 dBZ height as a proxy for vertical development to draw attention to the prevalence of what they deemed shallow precipitation and convection (20 dBZ height ≤ 6 km) in order to argue for the warm rain importance as put forth by [Kieper and Jiang(2012)]. [Tao and Jiang(2016)] do not however differentiate stratiform precipitation presence, which typically exhibits a 20 dBZ height between 5-8 km altitude [?, e.g.]]black1994,black1996,black2002,hence2011,didlake2013,reinhart2014 which would substantially alter their conclusions regarding the importance of “shallow convection”.

In [Harnos and Nesbitt(2015)], hereafter referred to as Part I, the authors describe simulated RI phases of Hurricanes Ike (2008) and Earl (2010) with the Weather Research and Forecasting (WRF) model at cloud-resolving resolution (1 km). Motivation for simulating two RI episodes stems from each case existing under varying magnitudes of environmental wind shear at RI onset (Ike and Earl under low and high wind shear respectively) such that the inner-core cloud and precipitation character varies in terms of both intensity and coverage following [Harnos and Nesbitt(2011)]. Each simulation produces a 24 hour period leading up to the onset of RI, which then continues for 24+ hours. The RI phases match closely to observed in terms of both timing (accelerated 6 hours from observations) and inner-core precipitation structures near RI initiation (Ike possessing widespread weak convection whereas Earl exhibits pronounced wavenumber-1 asymmetry with intense convection existing downshear and downshear-left). In Part I the authors introduce an objective method to objectively quantify the TC center and axisymmetric RMW position with respect to height to investigate the primary circulation structure of each TC. This RMW framework is then used as an objective analysis region to quantify where thermodynamic impacts on TC intensification are greatest following the inertial stability arguments of [Schubert and Hack(1982)], [Vigh and Schubert(2009)], and [Pendergrass and Willoughby(2009)] and observational work such as [Rogers ~al.(2013)Rogers, Reasor and Lorsolo]. Within the RMW diabatic heating (H_D) peaks at subfreezing temperatures, with Earl exhibiting an absolute maximum in aggregate H_D within the RMW over the 6 hours immediately preceding and following RI onset whereas Ike exhibits a weak relative peak. Earl's H_D peak is linked to a peak in CB coverage within the RMW and strong vertical velocity (w) values, while Ike exhibits lesser CB activity but more widespread, relatively axisymmetric precipitation and weaker w. Earl's RI has been previously linked to CB activity through the observational studies of [Stevenson ~al.(2014)Stevenson, Corbosiero and Molinari], [Susca-Lopata ~al.(2015)Susca-Lopata, Zawislak, Zipser and Rogers], and [Rogers ~al.(2015)Rogers, Reasor and Zhang].

Given the results of sometimes contradictory results of previous studies (e.g cold clouds importance in harnos2011 as opposed to warm clouds in kieper2012) and the general lack of attention that cloud populations outside of CBs e.g. shallow cumuli, cumulus congestus, deep convection that fails to penetrate the tropopause, and stratiform clouds have received in TC intensification, some clarification is sought on the relative cloud roles in RI. Further, these aforementioned remote sensing studies can quantify the relative presence of clouds relative to RI, but cannot quantify a causal physical mechanism for RI to take place. Here an objective quantification metric for updrafts in three dimensions is introduced and used to enable analysis at the individual updraft scale. The updraft analysis enables delineation and quantification of processes associated with convection in approximated regimes, i.e.: shallow cumulus (SC), cumulus congestus (CC), deep convection that fails to penetrate the tropopause (DC), and CBs. Objectives for this article are to: (i) characterize the typical profiles of each convective regime relative to RI and (ii) demonstrate convective regime contributions towards TC intensification from perspectives of H_D, moistening of the TC inner-core, and primary circulation spin-up. The article is structured as follows: section two quantifies the full spectrum of vertical motions within the RMW, section three introduces the updraft feature methodology, section four provides typical profiles of each convective regime and quantifies the roles of updraft features towards TC intensification, while sectionchapter five summarizes and concludes the work. For more background on the simulations used in this article the reader is referred to Part I. All times within this article are given relative to the times of simulated RI onset (18 UTC 2 September 2008 in Ike and 18 UTC 28 August 2010 in Earl), with positive (negative) times following (preceding) RI onset. All results within this article are exclusively from the 1 km domain.

2 Vertical Motion Spectrum within the RMW

With Part I linking CB presence in Earl to enhanced H_D in the vicinity of RI onset, it is worthwhile to investigate how the entire w distributions evolve within the height-varying RMW that is allowed to vary with respect to height relative to RI. To do so, cumulative contoured frequency by time diagrams [?, CCFTDs;]]mcfarquhar2012 of w are constructed at fixed heights for Ike (Figure 2A,C,E) and Earl (Figure 2B,D,F). Within the 2 km CCFTDs (Fig. 2A,B) for Ike no distinct signals exist relative to RI timing, while for Earl there is only a slight increase in $\geq$99% updraft magnitudes for 12 h preceding onset. The area covered by both up- and downdrafts at 2 km increases gradually for each simulation. At 7 km (Fig. 2C,D) there is a relative maxima near RI onset seen in Ike's updraft magnitudes at percentiles $\geq$99% whereas no distinctive signals exist for Earl. Up- and downdraft areas at 7 km again increase gradually for each TC, with the greatest fractional coverage increases seen in Ike following +18 h. At 12 km (Fig. 2E,F) Ike exhibits a relative maximum of updraft magnitudes $\geq$95% over $\pm$3 h, yet the strongest vertical motions are not seen until +18 h onward, while Earl shows an absolute maxima in the magnitudes of updraft populations $\geq$99% from -12 h through RI onset. The 12 km Earl w distributions are similar to those of [McFarquhar ~al.(2012)McFarquhar, Jewett, Gilmore, Nesbitt and Hsieh] at 14 km, however Earl exhibits no increase in mid-level (7 km) updraft magnitudes after RI onset as witnessed therein. Both up- and downdraft areas at 12 km tend to increase slowly throughout for Ike, while Earl exhibits the greatest updraft coverage within the RMW from -6 through +3 h. All altitudes lack a clear signal in the downdraft populations relative to RI timing, suggesting the dominant role of diabatic processes towards each RI. It is also interesting to note the area covered by downdrafts within Ike's RMW are $<$2% through +10 h at 2 and 7 km. For the low shear case (Ike) the greatest signal within the vertical motion distributions relative to impending RI is for mid-levels updraft magnitudes $\geq$99%, while in the high shear case the strongest discriminant is increased magnitudes of updrafts $\geq$99% at upper-levels and updraft areal coverage. No signals are apparent near the median w distribution at any altitude or at 2 km, pointing towards the importance of vertically-developed, relatively intense, inner-core convection associated with ice processes in RI.

CCTFDs of w within the RMW at altitudes of 2 (A,B), 7 (C,D), and 12 (E,F) km for Ike (A,C,E) and Earl (B,D,F) simulations. The area within the RMW covered by updrafts (w $\geq$1 m s^{-1} and downdrafts (w $\leq$-1 m s^{-1}) at each corresponding altitude is seen in the right of each panel.

Figure 2 shows contoured frequency by altitude diagrams [?, CFADs;]]yuter1995 of w averaged within the RMW over the 9 hours immediately preceding and following RI onset. Readily apparent for both TCs is the shrinking of the w distribution after RI has begun at subfreezing temperatures ($\geq$5 km), while below these heights the w distributions are relatively static aside from some reduced values between 1-4 km in Earl's percentiles $\geq$99.9%. This highlights the importance of ice processes in spurring RI, with the additional latent heat of fusion [Zipser(2003)] providing for the observed stronger values of w aloft preceding RI. Updrafts in Ike possess a bimodal distribution in percentiles $\geq$95% with peaks near 5 and 12 km (Figs. 2A,B), while Earl's vertical motion distribution is more top heavy with a peak near 11 km preceding RI (Fig. 2C) and near 8 km following onset (Fig. 2D). As noted in Part I, Earl possesses more vigorous convection within the RMW than Ike, leading to a greater range of w values at all altitudes for both up- and downdrafts. This is most apparent in Earl's subfreezing temperature updraft percentiles $\geq$90%, which typically are twice the magnitudes of Ike. Simulation character aloft is difficult to rectify with observational studies above approximately 12 km due to observational sample size limitations [?, e.g.]]rogers2013. These results reinforce the w character preceding RI of more vigorous convection existing within the RMW to drive subsequent warm core development. The CFADs for Ike are comparable in magnitude to those of the simulations by [Rogers ~al.(2007)Rogers, Black, Chen and Black], while all CFADs are broader than those of [McFarquhar ~al.(2012)McFarquhar, Jewett, Gilmore, Nesbitt and Hsieh] with discrepancies possibly attributed towards microphysical treatment or the RMW-centric framework undertaken here. Earl's CFAD preceding RI (Fig. 2C) does appear qualitatively similar to Figure 10A of [McFarquhar ~al.(2012)McFarquhar, Jewett, Gilmore, Nesbitt and Hsieh] aside from aforementioned magnitude differences.

CFADs of w where simulated radar reflectivity is $\geq$-5 dBZ within the RMW averaged over the 9 h preceding RI onset for Ike (A) and Earl (B) and the 9 hours following RI onset for Ike (C) and Earl (D) simulations.

3 Updraft Features

Part I incorporated CB approximations following [Rogers(2010)], where mean w between 700-300 hPa $\geq$5 m s^{-1} denotes a CB. The Rogers CB definition, and two similar definitions by [Montgomery ~al.(2006)Montgomery, Nicholls, Cram and Saunders] and [Reasor ~al.(2009)Reasor, Eastin and Gamache] that are popular within recent literature, are for upright columns that neglect vertical slope. CBs typically possess horizontal scales on the order of 10 km [Montgomery ~al.(2006)Montgomery, Nicholls, Cram and Saunders], while air parcels closely follow surfaces of absolute angular momentum that slope outward with height within the TC inner-core. Further tilting can be caused by vertical wind shear with [Black ~al.(1994)Black, Bluestein and Black] and [Black ~al.(1996)Black, Burpee and Marks Jr.] both depicting observations of sloping inner-core updrafts for TCs. Figure 3 displays a hypothetical example of this scenario where use of upright definitions to approximate vertically sloping features yields potential representativeness issues, with frameworks neglecting vertical variation yielding chronic underestimation of CB presence. Furthermore, CB definitions are only one variety of the convective cloud spectrum while less vertically developed clouds and their associated updrafts are neglected. An improved method for quantifying convective roles is desirable relative to these aforementioned CB options.

Example of columnar definitions failing to account for a slope in CB analyses. R and H indicate non dimensional radius and height respectively, with H indicating the vertical threshold for CB distinction and R being the RMW position.

To overcome the CB definition shortcomings a different approach is required, and here *updraft features* similar to those of [Wang(2014)] are utilized in a three-dimensional adaptation of the precipitation feature framework as introduced by [Nesbitt ~al.(2000)Nesbitt, Zipser and Cecil]. At each WRF output time the three-dimensional w field is analyzed, with contiguous (6-sided) regions of w $\geq$1 m s^{-1} treated as single entities (i.e. evaluating regions lying within the 1 m s^{-1} isosurface as a single entity where that isosurface extends 3 grid cells in both horizontal directions and vertical). Resulting *updraft features* of $\geq$1 km depth are classified via their maximum altitude into approximated convective regimes following the observational studies of [Houze and Cheng(1977)] and [Johnson ~al.(1999)Johnson, Rickenbach, Rutledge, Ciesielski and Schubert], where features with peak updraft altitudes' (i.e. peak altitude of the contiguous 1 m s^{-1} isosurface) of: $<$5 km are associated with shallow cumuli (SC), $\geq$5-8 km cumulus congestus (CC), $\geq$8-14 km deep convection that fails to penetrate the tropopause (DC), and $>$14 km CBs. No distinction is made for stratiform clouds. No constraints are imposed on the *updraft features* regarding association with hydrometeor presence.

An example of the updraft classification is shown over a 20 minute period during the Ike simulation in Figure 3. At 1 km for these times all four convective modes are apparent (Fig. 3A-C), while updraft growth, decay, and mergers occur during these 20 minutes. A region is isolated in the marked boxes in Figure 3A-C, with Fig. 3D-F zooming in on this area while Fig. 3G-I provide a vertical cross-section. The initial updraft of interest is a SC at -1:30 h (Fig. 3A). Closer analysis reveals the updraft to be vortical, with 1 km absolute vorticity in excess of $4\text{x}10^{-3}$ s^{-1} (Fig. 3D). Also, while the updraft core reaches below 4 km altitude it still possesses $w \geq 3$ m s^{-1} (Fig. 3G). This reinforces a key oversight by [Rogers(2010)], where association of weak (strong) vertical velocities with shallow (vertically-developed) convection is not always valid, as pointed out by [Wang(2014)], which can lead to inappropriate attribution of the causal processes taking place. Ten minutes later the SC has grown into a CC (Fig. 3B). Here the focal updraft has strengthened with $w \geq 11$ m s^{-1}. 10 minutes later the updraft has grown into a CB (Fig. 3C), with the updraft core exhibiting stronger rotation (Fig. 3F), w (Fig. 3I), and peak w exceeding 11 m s^{-1} between 5 and 7 km (Fig. 3I). Throughout the simulations a preference for simulated updrafts to be broader than observations [?, e.g]]black1994,black1996,heymsfield2001 is noted. It is beyond this article's scope to evaluate the reasons for this bias, however potential contributors include model turbulence [Bryan ~al.(2003)Bryan, Wyngaard and Fritsch, Waite and Khoudier(2010)] or microphysical treatment [Varble ~al.(2011)Varble, Frindlind, Zipser, Ackerman, Chaboureau, Fan, Hill, McFarlane, Pinty and Shipway]. In spite of the bias towards broader features, sensitivity tests of increased w thresholds necessary for *updraft feature* consideration had negligible results on subsequent analyses (not shown).

At times indicated in title rom Ike simulation: example of updraft feature algorithm at 1 km altitude (A-C), 1 km absolute vorticity (filled contours) and maximum column vertical motion below 8 km altitude for indicated boxes centered on updraft of interest in panels A-C (D-F), and vertical cross-section of absolute vorticity (filled contours) and w at 2 m s^{-1} intervals and a base value of 1 m s^{-1} with dashed lines indicating negative values (G-I). Panels G-I are taken along dashed gray line in Panels D-F.

4 Convective Contributions to RI

4.1 Typical Convective Regime Updraft Profiles

Analysis at the individual updraft scale begins with characterizing the mean vertical profiles of each convective regime. Figures 4.1 and 4.1 depict averages for Ike and Earl respectively of: w, H_D, updraft absolute vorticity relative to the background mean, and moisture convergence within the RMW for the 24 h preceding and following RI.

In Ike all convective regimes exhibit stronger mean w profiles (Fig. 4.1A) preceding RI except CBs between 8-15 km. For all Ike profiles the w profile magnitudes decrease in reverse order of vertical development (CBs have the strongest w at all altitudes while SC have the lowest w). Ike's CB profile preceding RI exhibits a bimodal structure, with the first peak near 5 km associated closely with strong H_D (Fig. 4.1A), and a secondary peak near 12 km associated with reduced hydrometeor loading apparent from the reduced H_D at these levels. Ike's DC and CB profiles preceding RI are similar below 7 km altitude, aside from a difference of <0.25 m s^{-1} near the freezing level (5 km), while differences further aloft exceed 1 m s^{-1}. Ike's mean SC and CC profiles following RI are slightly weaker than preceding it, with greatest differences of near 0.5 m s^{-1}. The w profiles in Ike are stronger than those seen in [Wang(2014)]'s Figure 3a, while their cumulus congestus (here corresponding to combined SC and CC) and deep convection (here corresponding to combined DC and CBs) exhibit similar behavior with a single peak at subfreezing temperatures for SC and CC while two peaks occur in the DC and CB profiles with the secondary maxima aloft likely associated with latent heating from fusion [Zipser(2003)]. Altitudes associated with peak w are also higher for the Ike simulation than comparable classifications from [Wang(2014)].

Earl's mean w profiles (Fig. 4.1A) are comparable to those of Ike (Fig. 4.1A). Mean w profiles in Earl are greater preceding RI for all regimes except CBs between 1.5-3 km. SC and CC exhibit differences of ≤ 1 and 0.5 m s^{-1} at common altitudes preceding and following RI respectively. DC differences approach 0.75 m s^{-1} relative to RI timing near the freezing level. CBs are within 0.25 m s^{-1} magnitudes for each time below the freezing level, with differences typically twice that at subfreezing temperatures. Earl lacks the secondary peak at subfreezing temperatures near 12 km altitude in DC and CB profiles seen in Ike (Fig. 4.1A) or Figure 3a of [Wang(2014)], except for CBs preceding RI onset. As with Ike, the peak altitudes of combined SC, CC and DC, CB profiles exist further aloft than those in [Wang(2014)]. Ike generally exhibits stronger w associated with SC, CC, and DC whereas above the freezing level, Earl exhibits greater w associated with increased latent heat of fusion from more vigorous convection (Figs. 2 and 2).

Mean vertical profiles for Ike simulation convective regimes averaged within the axisymmetric RMW over -24 h (solid lines) and +24 h (dashed lines) for w (A), H_D (B), perturbation absolute vorticity relative to the average vertical profile within the RMW for the corresponding periods (C), and moisture convergence (D).

As in Figure 4.1 but for Earl simulation.

Ike's average H_D by convective regime (Fig. 4.1B) is greater preceding RI for all regimes except CBs below 2 km or above 8 km, with these differences on the order of 1x10^{-3} K s^{-1}. For Earl (Fig. 4.1B), H_D is stronger preceding RI across all regimes except marginally for CBs $<$ 3 km or $>$ 11.5 km. In both TCs H_D increases at common altitudes are commensurate with convective regime vertical development (i.e. SC the smallest H_D with CBs being the greatest). Peak H_D for all regimes preceding RI occurs near 6 km altitude in Ike (except for SC, due to limited vertical extent), while all peaks except CBs are near 2 km in Earl. Mean H_D profile magnitudes tend to be greater in Ike than for Earl, with the exception of CBs which are comparable.

Finally of note from Figures 4.1B and 4.1B is that at the lowest levels the steepest vertical gradients of H_D in both TCs are associated with CBs while the weakest are with SC. Assuming common pressures across convective regime heights (mean profiles of pressure similar to Figure 4.1 and 4.1 that are not shown confirm this assumption), these H_D vertical distributions have implications if one were to attempt to relate H_D to TC spin-up using the assumption of a weak temperature gradient along with the continuity (Equation 1), thermodynamic (Equation 2), and barotropic vorticity (Equation ??) equations:

$$\nabla \vec{V}_h = \frac{\partial \omega}{\partial p} \tag{1}$$

$$-S_p \omega = \frac{H_D}{c_p} \tag{2}$$

$$\frac{\partial \zeta}{\partial t} = -\vec{V}_h \cdot \nabla \zeta - \beta m - (\zeta + f) \nabla \cdot \vec{V}_h \tag{3}$$

where $\vec{V}_h$ is the horizontal wind, ω the vertical velocity in pressure coordinates, p pressure, $S_p = -T \partial \ln(\partial \theta / \partial p)$ with T temperature and θ potential temperature (this term varies minimally throughout the troposphere where $\partial \theta / \partial p$ is small), c_p specific heat at constant pressure, t time, ζ relative vorticity, β Rossby parameter, m meridional component of the wind, and f Coriolis parameter. The thermodynamic equation (Eq. 2) can be inserted into the continuity equation (Eq. 1) yielding Equation 4:

$$\nabla \vec{V}_h = \left(\frac{1}{c_p S_p} \right) \left(\frac{\partial H_D}{\partial p} \right) \tag{4}$$

with S_p assumed to be relatively constant as p varies in the troposphere and thus brought outside the partial derivative. Equation 4 can then be substituted into the barotropic vorticity equation (Eq. ??) yielding Equation ??:

$$\frac{\partial \zeta}{\partial t} = -\vec{V}_h \cdot \nabla \zeta - \beta m - (\zeta + f) \left(\frac{1}{c_p S_p} \right) \left(\frac{\partial H_D}{\partial p} \right) \tag{5}$$

It can be seen from the third term of Equation ?? that the vertical gradient of H_D contributes to TC spin-up, with sharper vertical gradients of H_D yielding a greater circulation response. The idealized H_D profiles of [Schumacher ~al.(2004)Schumacher, Houze Jr. and Kraucunas]'s Figure 3 depict a steeper vertical gradient of H_D associated with shallow relative to deep convection, which would imply stronger spin-up for less vertically-developed convection. However, Figures 4.1B and 4.1B portray a different perspective where the vertical gradient of H_D is in fact the smallest of each convective regime, with the vertical gradient of SC H_D apparently increasing with vertical development over the lowest 5-6 km. Over the lowest 2 km in Ike over -24 h (+24 h) the vertical gradient of H_D for CBs is 124% (103%) that of SC, with corresponding values in Earl of 144% (322%). It remains to be seen whether these results are applicable for TCs beyond these two case studies, yet further investigation is supported. Nevertheless, using this perspective CBs appear to drive the strongest spin-up at low-levels, with this effect also acting to enhance the vortex over a greater depth than less vertically-developed convective modes given the higher altitudes of peak H_D.

Lesser differences are seen between the two TCs in perturbation absolute vorticity (Figs. 4.1C and 4.1C) and moisture convergence (Figs. 4.1D and 4.1D). Perturbation absoluteAbsolute vorticity profiles reveal the vortical nature of all convective modes, supporting the need for inclusion of less vertically developed convective modes in the vortical hot tower paradigm [?, e.g.]]hendricks2004,montgomery2006. Updrafts are more vortical for Earl relative to Ike, likely due to the stronger coincident intensities of Earl relative to Ike over these periods and Earl's smaller RMW providing enhanced background vorticity for the CBs to converge and stretchbe embedded within and drive subsequent convergence and stretching in the vertical. Absolute vorticity decreasesincreases for each convective regime following RI onset in each TC, associated with RMW contraction (Figure 9 of Part I). Moisture convergence is similar for both TCs, with SC being a net positive at ≤ 1 km at all times, whereas the other convective regimes contribute positively below 4 km preceding RI in Earl and throughout in Ike. It should also be noted that the profiles of Figures 4.1 and 4.1 are comparable for an analysis framework utilizing the RMW region or the innermost 1° (not shown).

4.2 Aggregate Influences of Convective Regimes

In addition to the mean profiles of convective updraft populations, determining the net contributions of each convective regime towards TC intensification related parameters is desirable. First, the percentage of area covered by each regime within the axisymmetric RMW is shown in Figure 1 and 2 for Ike and Earl respectively. In Ike, coverage for each convective mode is $<$10% through RI onset aside from periodic surges of greater CB coverage between 8-15 km where values approach 30%. In Ike, non-CB convection remains sparse within the RMW throughout the remainder of the simulation, while CB coverage steadily increases from +6 h onward throughout the vertical. Earl contains little non-CB convection within the RMW throughout the simulation. CBs in Earl (Fig. 2D) typically have the greatest coverage between 6-15 km altitude, with a surge to $\geq$60% coverage in the 6 h preceding RI onset at these altitudes, while later times have typical coverage of 30-50% here. Clearly the extensive coverage of CBs in both simulations will have implications for their aggregate contributions towards the intensification of each TC relative to the less prevalent shallower convective varieties. Also noteworthy in both simulations is at 2 km the CB coverage never exceeds 40% coverage despite greater values aloft, indicative of the need to account for vertical variation in both the RMW and presence of convection.

Figure 1: Percentage of area within the RMW with respect to time and height covered by shallow cumuli (A), cumulus congestus (B), deep convection (C), and CBs (D) for Ike simulation.

Figure 2: As in Fig. 1 but for Earl simulation.

Next, the relative contributions of each regime towards vertically integrated mass and vapor fluxes within the RMW is given in Figure 3. Given the vertically integrated nature of these figures, CBs are expected to have the greatest values due to their greatest vertical extent, if coverage among all regimes were equivalent. In Ike (Figs. 3A,B) through -18 h these fluxes are primarily from CC and DC at magnitudes around 30% each with a secondary contribution from CBs (generally $\leq$20%) while SC contribute around 10% or less. CB contributions steadily increase at the expense of other regimes such that by -12 h the percentages are approximately evenly divided between CC, DC, and CBs. Afterward in Ike the roles of non-CB convection show a tendency for reduced roles with the exception of +2 through +9 h where CC and DC contributions briefly spike, before a return to the increasing CB trend, with CB contributions $\geq$95% by +15 h. Enhanced vertically integrated flux activity by non-CB convection in Ike (e.g. preceding -12 h, +2 through +9 h) is associated with limited CB coverage during these periods (Fig. 1D). Earl (Figs. 3C,D) similarly displays minimal CB fluxes initially, however CBs quickly dominate within the RMW, as by -18 h they account for $\geq$80% of mass and vapor fluxes. As with Ike, minimal CB coverage within the RMW (e.g. prior to -18 h; Fig. 2D) is associated with enhanced vertically integrated flux contributions by non-CB convection. In summary for Ike the vertical flux contributions in the vicinity of RI onset are primarily from CBs with secondary contributions from CC and DC, while Earl is overwhelmingly CB driven from -18 h through simulation completion. These results seemingly contrast with those of [Rogers(2010)] who attributed RI not to CB roles, but instead to increased vertical mass flux preceding RI by updrafts of 1-2 m s^{-1} over the lowest 1.5 km. The approach of [Rogers(2010)] however is unable to explicitly disassociate CBs from w of 1-2 m s^{-1} at these altitudes, thus not permitting categorization of updraft vertical extent. Further, w $\geq$2 m s^{-1} below 1.5 km can be associated with developing SC or CC (e.g. Figure 3 and the appendix of wang2014). Definitive interpretations of the differing results of [Rogers(2010)] and those herein regarding updraft character cannot be made without an objective convective regime classification method being utilized on their simulation.

Figure 3: Cumulative relative contributions of *updraft features* within the RMW with respect to time towards integrated vertical mass flux (A,B) and vapor flux (C,D) for Ike (A,C) and Earl (B,D) simulations.

In Part I, aggregate H_D within the RMW for each TC was shown (their Figure 10) with elevated H_D over $\pm$6 h of RI in Earl correlated with increased CB activity, yet no quantification of how much H_D CBs produced is made. Furthermore, questions remain regarding H_D roles of less vertically developed convection and how Ike's H_D distribution is partitioned. Figure 4 depicts the aggregate contribution of each convective regime towards H_D within Ike's RMW with respect to time and altitude. Despite Ike's apparent lack of CB activity relative to Earl (Figure 7 of Part I), CBs (Fig. 4D) comprise the greatest H_D contributions within the RMW throughout the majority of the simulation, reaching $\geq$25 K s^{-1} from +18 through +22 h. The second greatest H_D contributions are from CC (Fig. 4B), slightly peaking between 10-15 K s^{-1} from RI onset through +6 h near the freezing level. SC (Fig. 4A) and DC (Fig. 4C) are generally confined to $<$10 K s^{-1} in Ike for all times and altitudes, with DC generally contributing more H_D than SC.

Figure 4: Aggregate H_D within the RMW with respect to time and height due to shallow cumuli (A), cumulus congestus (B), deep convection (C), and CBs (D) for Ike simulation.

Figure 5 classifies aggregate H_D by convective regime within the RMW of the Earl simulation. As posited in Part I, CBs (Fig. 5D) are the primary contributor to the aggregate H_D peaks of $\geq$40 K s^{-1} over $\pm$6 h within the RMW (Figure 10 of Part I), with the CB contribution here approaching those values. CBs are seen to dominate the H_D distribution throughout Earl, with SC, CC, and DC (Figs. 5A-C) each contributing $\leq$10 K s^{-1} at all times, while CBs commonly provide $\geq$15 K s^{-1}, particularly at subfreezing temperatures. It is apparent throughout Earl that SC, CC, and DC often fail to exist whatsoever within the RMW at certain altitudes, particularly from -12 h onward and near the surface. The vertical variation of these convective populations emphasize the importance of using a RMW across multiple altitudes, as put forth in Part I.

Figure 5: As in Figure 4 but for Earl simulation.

It is necessary to highlight that the *updraft feature* framework neglects stratiform precipitation, excessively shallow features, and downdrafts. To evaluate the potential roles of these components in H_D contributions, the summed effect of Figures 4 and 5 can be subtracted from Figure 10 of Part I to calculate a residual term that characterizes areas within the RMW without w $\geq$1 m s^{-1} over a depth $\geq$1 km (Figure 6). In Ike (Fig. 6A) the residual H_D signature has a clear stratiform appearance through +12 h, with warming at subfreezing temperatures and evaporative cooling below the freezing level. Warming magnitudes above the freezing level approach 15 K s^{-1}, such that this heating is a secondary consideration to CBs, with comparable H_D magnitudes to CC and DC. Earl (Fig. 6B) lacks such a dipole-signature in residual H_D, generally possessing only the evaporative cooling signature below the freezing level through RI onset with sporadic weak warming at subfreezing temperatures. There is even some evidence of sublimation from -9 through -6 h in Earl with latent cooling through $\geq$8 km. Recalling Equation ??, the vertical gradient of H_D for the residual term in both storms would act to spin down the low-level circulation below the melting layer ($<$3-4 km), while acting to spin-up the mid-level circulation (approximately 4-8 km). From Figures 4-6 it is clear that Ike's RI is associated with H_D predominantly from CBs with additional contributions from CC, stratiform clouds, and DC whereas Earl's RI is near-exclusively associated with H_D from CBs. The CB dominance in terms of aggregate H_D are unsurprising considering they are the most extensive convective modemdoe within each TC's RMW (Figs. 1,2) along with possessing the greatest average H_D profile in the vertical (Figs. 4.1B, 4.1B).

Figure 6: H_D within the RMW with respect to time and height not accounted for by *updraft features* for Ike (A) and Earl (B) simulations.

Another key potential component of each convective regime is in regard to maintaining high moisture within the TC inner-core to promote convective growth, with [Wang(2014)] supporting CC role in moistening the lower and middle troposphere. Figure 7 portrays the aggregate horizontal moisture convergence within the innermost 1° by convective regime of Ike. Ike's SC (Fig. 7A) exhibits a clear tendency for net moisture inflow into the TC inner-core below 2 km through +8 h, while CC (Fig. 7B) exhibits slightly lesser moisture convergence magnitude but through 4 km across the same timeframe. Detrainment of moist air within SC (CC) is apparent above 2 (4) km altitude, as expected based upon the trade wind inversion (freezing level) height. DC moisture convergence is fairly negligible throughout (Fig. 7C), in contrast with CBs that consistently are the strongest contributors (Fig. 7D). CBs are associated with radial influx of vapor ≤ 4 km throughout and periodically ≥ 6 km, while between 4-6 km altitude CBs exhibit negative values. Greatest CB moisture convergence exists ≤ 1 km, with values rising after +6 h. In contrast, Earl (Fig. 8) shows comparable moisture convergence by SC (Fig. 8A) to Ike (Fig. 7A), however CC and DC contributions are extremely weak (Figs. 8B,C). As with Ike, Earl's CBs (Fig. 8D) are associated with the strongest moisture convergence, with large positive values below 4 km, and particularly ≤ 1 km, throughout the simulation. No clear links are apparent between the moisture convergence by each convective regime and RI, however Earl's CBs do exhibit a peak preceding RI over -9 to -4 h near 0.5 km altitude. Residual moisture convergence unaccounted for by the convective regimes (Figure 9) exhibits a stratiform-like appearance for both TCs with positive values typically between 46-8 km. The *updraft features* also fail to account for strong moisture convergence over the lowest 0.25-0.5 km altitude in each simulation, likely due to the weak w (Fig. 2) and strong low-level convergence (Fig. 13 of Part I) at these altitudes .

Figure 7: Aggregate moisture convergence within the innermost 1° with respect to time and height due to shallow cumuli (A), cumulus congestus (B), deep convection (C), and CBs (D) for Ike simulation. Values are normalized relative to the innermost 1°.

Figure 8: As in Figure 7 but for Earl simulation.

Figure 9: Aggregate moisture convergence within the innermost 1° with respect to time and height not accounted for by *updraft features* for Ike (A) and Earl (B) simulations. Values are normalized relative to the innermost 1°.

Lastly, the contributions of each convective regime towards potential vorticity (PV) production are investigated, using the methods outlined in [Wang(2014)], where:

$$\frac{dPV}{dt} = -g\left(\zeta + f\right)\left(\frac{\partial \dot{\theta}}{\partial p}\right) \tag{6}$$

with g the gravitational constant and $\dot{\theta}$ the time rate of change of potential temperature. Unlike in [Wang(2014)], f is not held constant in Equation 6, with actual values taken for each grid cell. In Ike (Fig. 10), SC and CC show persistent positive aggregate PV tendency below 1 km (Figs. 10A, B), while CC exhibit periodic net positive contributions through 4 km altitude, particularly from -6 through +12 h. Ike's DC (Fig. 10C) contribute intermittently to PV enhancement below 6 km, predominantly between -6 through +15 h, albeit at lesser magnitudes than SC or CC. CBs exhibit the largest positive PV tendency impacts in Ike (Fig. 10D), especially over the lowest kilometer following +9 h. It is also noteworthy that Ike's CBs exhibit the deepest layer of positive PV tendency, consistently to approximately 6 km with periodic surges to near 9 km from -6 through +18 h, allowing the vortex to spin-up over a greater depth and paralleling the findings of [Wang(2014)] for TC genesis.

Figure 10: Aggregate PV temporal tendency within the innermost 1° with respect to time and height due to shallow cumuli (A), cumulus congestus (B), deep convection (C), and CBs (D) for Ike simulation. Values are normalized relative to the innermost 1°.

Earl's PV tendency is shown in Figure 11, revealing a disparate picture for its convective spin-up contributions. As in Ike, Earl's SC (Fig. 11A) are a weak net positive contributor towards spin-up below 1 km throughout, however Earl's CC (Fig. 11B) only weakly impacts PV at magnitudes approximately half that of Ike (Fig. 10B). DC contributions in Earl (Fig. 11C) towards PV growth are again largely negligible as with H_D (Fig. 5C) and moisture convergence (Fig. 8C). Earl's CB contributions prominently enhance PV (Fig. 11D), throughout the simulation with positive values ≤ 4 km and particularly ≤ 1 km. Preceding Earl's RI there are periodic surges of positive PV tendency approaching 11 km altitude associated with CBs acting to enhance the vortex over a deeper layer. These results again align with those of [Wang(2014)], with roles of shallow convection (e.g. SC and CC) being weak contributors to low-level PV increases while the majority of positive PV contributions come from CBs that also act to spin-up the vortex over a greater depth. Finally, non-convective influences on PV tendency are shown in Figure 12. Positive PV tendencies are noted for both simulations between 4-8 km altitude and over the lowest half kilometer. The 4-8 km altitude PV growth tendencies are presumably associated with evaporative cooling from stratiform precipitation, while peak values at $\leq$0.5 km are likely due to typically weak w at these altitudes (Fig. 2) limiting the ability of the *updraft feature* methodology to properly categorize these updrafts. Taken together, despite the lesser areal coverage of updrafts in Earl relative to Ike (Fig. 2) and the varied mean convective regime attributes in each simulation (Fig. 4.1 and 4.1) the aggregate PV contributions across convective regimes are generally comparable for each TC in both time and extent.

Figure 11: As in Figure 10 but for Earl simulation.

Figure 12: Aggregate PV temporal tendency within the innermost 1° with respect to time and height not accounted for by *updraft features* for Ike (A) and Earl (B) simulations. Values are normalized relative to the innermost 1°.

5 Summary and Discussion

Two simulated TCs have had their vertical motion distributions investigated in order to isolate key commonalities and differences between RI episodes under varying magnitudes of environmental wind shear (Hurricane Ike of 2008 under low wind shear and Hurricane Earl of 2010 under high wind shear). This is accomplished via a pair of novel analysis frameworks: an objective quantification of the RMW (described in Part I) used to specify a subsequent analysis region and a three-dimensional analysis of updraft populations, here deemed *updraft features*, to directly quantify populations of varying convective regimes. The RMW algorithm permits isolation of the region where heating gains are maximized towards maintenance and enhancement of the TC warm core due to the increased inertial stability following [Schubert and Hack(1982)], [Vigh and Schubert(2009)], and [Pendergrass and Willoughby(2009)] and the observational composites of [Rogers ~al.(2013)Rogers, Reasor and Lorsolo]. The *updraft feature* framework overcomes past updraft analyses that could only crudely quantify CBs due to consistent underestimation of their presence due to upright constraints [?, e.g.]]montgomery2006,reasor2009,rogers2010, instead accounting for three-dimensional w variability while permitting quantification of all convective modes. Such analysis is also able to yield proper perspective on convective modes rather than using w magnitude as a proxy for vertical development which has been shown to misconstrue vertical development by [Wang(2014)].

Part I supported two different characters in terms of the clouds and precipitation existing within the RMW, with Ike associated with more widespread and modest convection and associated stratiform precipitation whereas Earl was highly asymmetric with intense convection. CCFTD and CFAD analyses of w reinforce these characteristics, however for each TC extreme updraft w values appear most closely linked to harbingers of RI (magnitudes $\geq$99% at 7 km in Ike and at 12 km in Earl). The elevations of both of these w trends occurring at subfreezing temperatures implicates the role of frozen hydrometeors in RI following the statistically significant differences observed in w magnitudes for intensifying versus steady state TCs above 6 km altitude by the composites of [Rogers ~al.(2013)Rogers, Reasor and Lorsolo]. Further implication of clouds associated with frozen hydrometeors being linked to initiation and maintenance of RI have been seen in the observational case-studies [Heymsfield ~al.(2001)Heymsfield, Halverson, Simpson, Tian and Bui], [Guimond ~al.(2010)Guimond, Heymsfield and Turk], and [Rogers ~al.(2015)Rogers, Reasor and Zhang] and simulations of [Miller ~al.(2015)Miller, Chen and Zhang]. Little signature is seen for inner-core downdraft coverage or magnitudes relative to RI, reinforcing instead the importance of updrafts and their associated H_D in these RI episodes.

Mean vertical profiles of each convective regime are given for w, H_D, absolute vorticity, and moisture convergence to underscore the presence and contributions of each type of convective cloud towards RI. Of note are the vertical gradients of H_D being steepest over the deepest layer for CBs in each simulation, implying the greatest contributions towards spin-up at low-levels from these updrafts. However, peak H_D magnitude differences across convective regimes approach only a factor of two, while all updrafts possess a vortical component. The vortical hot tower paradigm [Montgomery ~al.(2006)Montgomery, Nicholls, Cram and Saunders] assumes asymmetric H_D from CBs to be the forcing for the secondary circulation while the mergers of the updrafts allows for upscale vorticity growth, yet these simulations reinforce that less vertically-developed convection should not be neglected. Further, each convective regime is shown to act to moisten the lowest layers of the atmosphere, supporting subsequent convective growth and development to help drive and sustain RI as shown previouslyearlier by [Wang(2014)] for genesis.

In Part I it was shown that Earl's RI is closely tied to an absolute maxima in H_D that is correlated with increased CB activity. The *updraft feature* framework allows for quantification of H_D contributions by convective regimes, explicitly showing that CBs are in fact responsible for the overwhelming majority of Earl's H_D. The signatures seen in Ike's 7 km updraft $\geq$99% w values leading RI are closely linked with increased H_D and vertical mass and vapor fluxes by CBs, despite the columnar CB perspective of [Rogers(2010)] implying minimal CB presence at these times as seen in Part I. While Earl's RI is near-entirely CB driven, Ike's H_D appears driven in descending order by: CBs, CC, non-convective precipitation with a stratiform-like appearance, and DC. CBs in each TC also act to drive a substantial portion of the low-level moisture convergence for each RI episode, particularly in Earl. Low-level PV growth is most strongly-linked and occurs over the deepest vertical layer for CBs in each simulation, however weak positive contributions at lower-levels also occur from less vertically-developed convection. In addition to CB roles, substantial midlevel contribution to PV development at the mid-levels is accomplished via regions not covered by convective regimes, presumed to be largely stratiform precipitation, while non-CB convection plays a limited role.

Updraft feature classifications also serve as proxies for the importance of convective clouds associated with solely liquid (SC and CC) versus those incorporating frozen hydrometeors (DC and CBs) in RI. The overwhelming importance of convection associated with ice in Earl and majority combined contributions from DC and CBs with a secondary contribution of stratiform precipitation in Ike points towards the critical role of clouds associated with ice in RI in line with the satellite work of [Harnos and Nesbitt(2011)] and [Harnos and Nesbitt(2015)]. There is no evidence of a dominant role and limited spatial coverage for organized precipitation with solely warm rain processes in these simulations, in opposition to the results of [Kieper and Jiang(2012)], however SC and CC appear to be partial contributors towards RI under low wind shear, particularly in terms of maintaining low-level moisture. One potential caveat to this finding is that the *updraft features* are static perspectives at a single point of updraft life, providing no information about subsequent growth or decay. Some of the congestus classified by the updraft feature methodology may in fact by developing convection of greater vertical extent, however such information is unavailable without an updraft tracking method such as that of [Terwey and Rozoff(2014)]. Failing that, a starting point for quantifying how many congestus may continue growing can be approximated from the CloudSat study of [Luo ~al.(2009)Luo, Liu, Stephens and Johnson] who estimated 31-56% of observed oceanic congestus subsequently continue vertical growth.

One limitation of this study is that it only uses two simulated case studies, where applicability is limited towards other simulations or observations. It is noted that the results herein are generally towards the higher end of prior results in terms of coverage of vigorous convection [?, e.g.]]braun2002,braun2006,rogers2010; methodology differences such as simulation resolution and analysis regions can contribute to the observed variability between studies. Further simulations are required to better evaluate the roles of different types of convection in TCs as this article, [Wang(2014)], and [Terwey and Rozoff(2014)] are some of the only investigations regarding these roles at present. As more studies evaluate the full scope of cloud and precipitation activity within the TC inner-core it is hoped the the classification techniques such as those used here and by [Wang(2014)] and [Terwey and Rozoff(2014)] can be further refined. The *updraft feature* methodology can also be applied to observational dual-Doppler analyses where the aircraft is flying at a sufficiently high altitude to capture the updraft top within a reasonably small range gate while the radar swath is sufficiently broad. The NASA Global Hawk would appear to be the optimal platform for such analyses, with the dual-Doppler retrieval methods of [Guimond ~al.(2014)Guimond, Tian, Heymsfield and Frasier] and [Didlake ~al.(2015)Didlake, Heymsfield, Tian and Guimond] for the High-Altitude Wind and Rain Airborne Profiler (HIWRAP) appearing ideal to enable extension of the observational composite analyses of the primary and secondary circulations by [Rogers ~al.(2013)Rogers, Reasor and Lorsolo] across all convective modes. Further modeling studies using the *updraft feature* framework should also consider higher horizontal resolutions, for both improved resolving of updrafts [?, e.g]]bryan2003,varble2011 and due to the 6-sided dependency resulting in the minimum horizontal updraft scale being a factor of 3 times the simulation's horizontal resolution. Adaptation of the updraft feature framework to account for downdraft contributions towards TC intensity change is also desirable given the importance of downdrafts specified in works such as [Riemer ~al.(2010)Riemer, Montgomery and Nicholls] and [Molinari ~al.(2013)Molinari, Frank and Vollaro], however methods to classify downdraft contributions remains unclear due to the lack of clearly-defined vertical boundaries that updrafts conform to.

Taking the results of this study in concert with those of Part I some overarching hypotheses regarding RI can be drawn. First, generalized processes from these simulations can be broadly applied to real TCs undergoing RI. In the low-shear scenario of Ike, broad environmental conditions (low wind shear, moderate convective instability, sufficient low-level moisture, modest surface fluxes) can all be considered generally favorable with limited variability throughout time across the TC inner-core. This permits slow development of multiple cloud modes occurring broadly in a quasi-axisymmetric sense around the TC center, whereafter RI ensues and a shift occurs toward CB dominance of the inner-core and maintenance of the RI period. Although their are the multiple cloud modes present in this low-shear mode, the dominant H_D and spin-up contributions are explicitly due to CBs despite their limited coverage. For the high shear simulation of Earl, instability and moisture are strongly favorable in preferential regions due to localized convergence effects, impacting the growth/decay cycle of convection. In Earl, strong surface fluxes act to further aid rapid convective development, apparent in the CB populations and stronger w magnitudes across the TC inner-core. In this case of RI, under high shear, CBs act to drive both the onset of RI, and its maintenance over the course of the intensification. These strong surface fluxes also act to replenish the boundary layer for subsequent convective development as cool, dry downdrafts circle the TC inner-core following [Molinari ~al.(2013)Molinari, Frank and Vollaro] and [Zhang ~al.(2013)Zhang, Rogers, Reasor, Uhlhorn and Marks Jr.]. While it appears there is no firm threshold in terms of H_D acting as a trigger for RI, a relative peak in H_D magnitude at subfreezing temperatures within the RMW appears to be closely associated with initiation of RI, following the w observations of [Rogers ~al.(2013)Rogers, Reasor and Lorsolo]. Interestingly, the high shear simulation experienced a greater magnitude associated with this aggregate H_D peak within the RMW, commensurate with the average H_D within the field being stronger for Earl near RI onset. From the Earl simulation however, it can be seen that RI can apparently happen both in spite of the strong shear altering the background environment to limit updraft coverage, and partially due to the strong shear acting to increase convective organization [?, e.g.]]frank2001, permitting development of CBs associated with intense H_D to supply sufficient H_D for RI to occur.

While the work here, by [Wang(2014)], and [Terwey and Rozoff(2014)] provide a foundation for quantification and investigation of roles across convective varieties within TC simulations, efforts should look to bridge this work into observational studies. Satellite-based remote sensing studies that can approach climatological scales are most desirable, with radar platforms being an obvious option for quantifying convection by its vertical extent once more via echo top height. Caution must be used with such studies however, given the minimum reflectivity sensitivity by radar platforms. For example, the TRMM Precipitation Radar may be unsuitable for such work due to its minimum detectable signal of approximately 18 dBZ [Kummerow ~al.(1998)Kummerow, Barnes, Kozu, Shiue and Simpson] which may not be representative of the true cloud top. Accordingly, the Cloudsat Profiling Radar [?, approximately -30 dBZ;]]marchand2007 and Global Precipitation Measurement Dual-Frequency Precipitation Radar [?, approximately 12 dBZ at Ka-band;]]hou2014 appear more appropriate for categorizing vertical convective development due to their increased sensitivities. The recent attempt by [Tao and Jiang(2016)] to quantify cloud populations relative to RI using the TRMM Precipitation Radar is likely to suffer from these issues in addition to the failure to differentiate stratiform precipitation from shallow convection. The results here do appear to mirror those of [Harnos and Nesbitt(2011)] and[Harnos and Nesbitt(2015)] for passive microwave work underscoring the importance of vertically-developed clouds associated with frozen hydrometeors in RI, however their use of the integrated perspective of passive microwave platforms does not permit explicit quantification of the variety of convection being sampled. It also remains important to note that while satellite-based studies of RI and relative cloud presence can provide information to help inform forecasters, they do not provide any direct information regarding relative dynamic or thermodynamic contributions by various cloud populations as can be accomplished via numerical modeling.

The authors thank Zhuo Wang, Greg McFarquhar, Ryan Sriver, and Brian Jewett for discussions that improved the quality of this work. Constructive reviews from Robert Rogers and another anonymous reviewer are appreciated for further improving this project. 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.

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