8B.1 STRUCTURE AND INTENSITY CHANGES DURING HURRICANE EYE FORMATION[†]

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1. INTRODUCTION

The formation of an eye has long been viewed as the hallmark of a storm that has reached hurricane intensity. In addition to the observation that storms readily form eyes as they approach the hurricane threshold, several researchers have associated the formation of an eye with a period of rapid intensification. Malkus (1958) brought forward the idea that a storm's intensity is limited to moderate tropical storm strength *until* the storm forms an eye. Mundell (1990, p. 26, 31) studied 119 rapidly intensifying typhoons in the western North Pacific from 1956–1987 and found that most (87.4%) of these rapid intensifiers commenced their rapid rate of intensity change when the central pressure was in the range of 987 to 962 mb. Mundell states that "this range of initial intensities is significant because it closely approximates the point at which a tropical cyclone develops a central eye which is apparent on radar and satellite imagery (Weatherford and Gray 1988).' Yet, the presence of an eye is not a guarantee that the storm will achieve a high intensity. Malkus (1958) points out that many storms repeatedly attempt to form eyes, but do not succeed.

While much qualitative association has been made concerning the importance of the eye/eyewall structure to the underlying evolution of the storm's intensity and structure, quantitative information has mostly been lacking thusfar. The purpose of this study is to quantitatively characterize the kinematic and thermodynamic changes that occurred before, during, and after the initial eye formations of a broad set of Atlantic tropical cyclones.

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2. DATA AND METHODS

To obtain the requisite structure and intensity parameters, a new data set[1] has been synthesized from the Vortex Data Messages (VDMs) transmitted by routine aircraft reconnaissance from 1989-2008. Over 5500 VDMs have been compiled into a comprehensive *in situ* data set of structure and intensity observations at a relatively high frequency (fixes taken every 1.5 to 3 h when a plane was on station, with gaps between planes typically of 4 to 12 h). The data set provides not only the typical intensity parameters such as the flight level maximum wind speed (FL v_{max}) and the minimum central pressure (p_{min}), but also the dynamically-important radius of maximum winds (r_{max}) and thermodynamic quantities such as the maximum eye temperature at flight level (T_{eye}), the minimum dew point temperature ($T_{d,eye}$) and associated dew point temperature depression at that location ($T_{DEP,eye}$), and the horizontal temperature difference between the eye and just outside the eyewall ($\Delta T_{eyewall}$) which serves as a measure for the integrated baroclinity across the eyewall. To compare these data to the Best Track, flight level wind speeds were reduced to surface equivalent values using standard reduction factors following Franklin et al. (2003). Eye temperature data were also adjusted to 700 hPa to deconvolve the effect of changing flight levels from fix to fix. $T_{DEP,eye}$ and $\Delta T_{eyewall}$ did not need any adjustment since they offer a measure of the subsidence and baroclinity, respectively, without regard to the specific flight level.

The keystone of this study is the use of reconnaissance aircraft to establish whether an eye was present or not for all time periods. This aircraft-only approach is important because reconnaissance aircraft have used a consistent and reliable method for determining eye presence over the entire 20-y period (1989-2008) studied here. *An eye is only reported if a circular, precipitating, inner-cloud feature is observed to subtend at least half of the candidate eye region* (Weatherford and Gray

[1]The author plans to release the VDM structure and intensity data set to the research community later this summer. Please check the following location for updates: http://euler.atmos.colostate.edu/~vigh/eyeformation/. Detailed graphical presentations of the VDM and Best Track data for each storm are already available at: http://euler.atmos.colostate.edu/~vigh/hurricanes/structure/formation/.

1988) on the aircraft's forward-pointing 3-cm (X-band) weather avoidance radar or is otherwise judged visually by the flight meteorologist. If the eyewall feature completely encircles the eye region, a *closed eye* is reported. If the eyewall subtends at least 180° of the eye with no breaks, an *open eye* is reported. If the eyewall feature does not encircle at least half the central region, no eye is reported, but the flight meteorologist[2] may put a mention of *partial eyewall* in the remarks. As also described by Weatherford and Gray (1988), to be considered an eyewall, the circular convective feature must also be distinct from the adjacent spiraling bands. If the convection is not separate from these bands, the descriptor *spiral banding* (or simply *banding*) is often given. The time of first IR satellite eye is reported when a closed warm spot near or at the center first exceeds −50 °C or is at least 15 °C warmer than the surrounding convection.

Out of the 310 Atlantic tropical cyclones (including all named systems, tropical depressions, and designated subtropical depressions and storms) which occurred from 1989 to 2008, 180 had sufficient data to be included in the VDM data set. The CIRA IR satellite imagery archive covers a shorter period from 1995 to 2008, during which 204 storms occurred. Only 193 of these storms had usable satellite data however, because significant gaps in imagery occurred during key periods of some early storms.

Intensity ranges were then determined for the times when the eye/eyewall structure first appears in aircraft radar and infrared satellite imagery. Changes about the time of eye formation have been examined for intensity, the radius of maximum winds, the minimum Rossby radius of deformation, and the maximum temperature and dew point temperature depression in the eye. Finally, cases were stratified based on the persistence of the initial eye formation. The cases are (a) complete failure (an eye forms and then dissipates shortly afterwards with no reformation attempt), (b) intermittant failure (an eye forms, dissipates, reforms, but never persists for longe than 24 h), (c) delayed success (an eye forms initially and dissipates, then reforms and persits for at least 24 h *within* 72 h of the initial formation), (d) complete success (an eye forms and persists for at least 24 h without any observed gaps). The full methods are described in chapter 4 of Vigh (2010) and will be submitted shortly for publication in *Monthly Weather Review* as Vigh et al. (2010a).

[2]On the AFRES aircraft, the flight meteorologist duties are conducted by the Aerial Reconnaissance Weather Officer.

3. MAIN RESULTS

The full results are reported in chapters 5 and 6 of Vigh (2010). These chapters will also be submitted shortly for publication in *Monthly Weather Review* as Vigh et al. (2010b) and Vigh et al. (2010c). The main results are summarized below.

Banding found to be a precursor to eye formation: Banding was often noted by aircraft before an aircraft eye appeared and was observed in 43% of all storms. Of the storms which displayed banding, 79% went on to form an aircraft eye. Clearly, banding is a strong precursor to eye formation, but since it is only reported some of the time, its usefulness to a forecaster may be somewhat limited.

Eyes are more frequently seen in satellites than by aircraft: 59% of reconnoittorred storms reported an aircraft eye. Closed aircraft eyes (A2, 47%) were less commonly observed than open aircraft eyes (A1, 58%), as expected. 61% of all storms reported an eye in IR satellite imagery (IR3), but only 43% developed an IR eye which lasted longer than 6 h, and just 21% displayed a strong eye (IR5). Out of the storms which were well observed by both aircraft and satellite, eyes were more frequently observed by satellite (IR3, 67%) than by aircraft (A, 58%). This result was unexpected since it has been generally thought that the convective ring of the developing eyewall should be apparent before the eye is observed by satellite. It is unclear whether this statistic is simply due to the less frequent observations of aircraft, or whether perhaps the indications of a forming eye are more apparent than previously thought.

Storms which form aircraft eyes tend do so quickly after reaching tropical storm threshold: The temporal distribution of the observed eye formation baselines shows that most of the storms which form eyes (whether successful or not), tend to do so with 24 h of reaching tropical storm strength (35 kt). This is somewhat quicker than the Dvorak model and seems to suggest that there is about a 1 d window during which a storm which has recently undergone genesis can quickly form an eye. If the environmental conditions are not favorable so that the initial attempt fails, the storm may take days and days to form an eye. But the failure of the initial eye is not necessarily detrimental — a sizable subset of storms form an eye which does not persist, but upon reforming an eye within a day or so, continue on a rapid development. This suggests that environmental conditions may play a key role in the success or failure of the eye. If adverse conditions improve, the storm development can be rapid.

Many storms which form an eye begin doing so at intensities substantially lower than hurricane intensity: Eye formation often occurs at a significantly lower

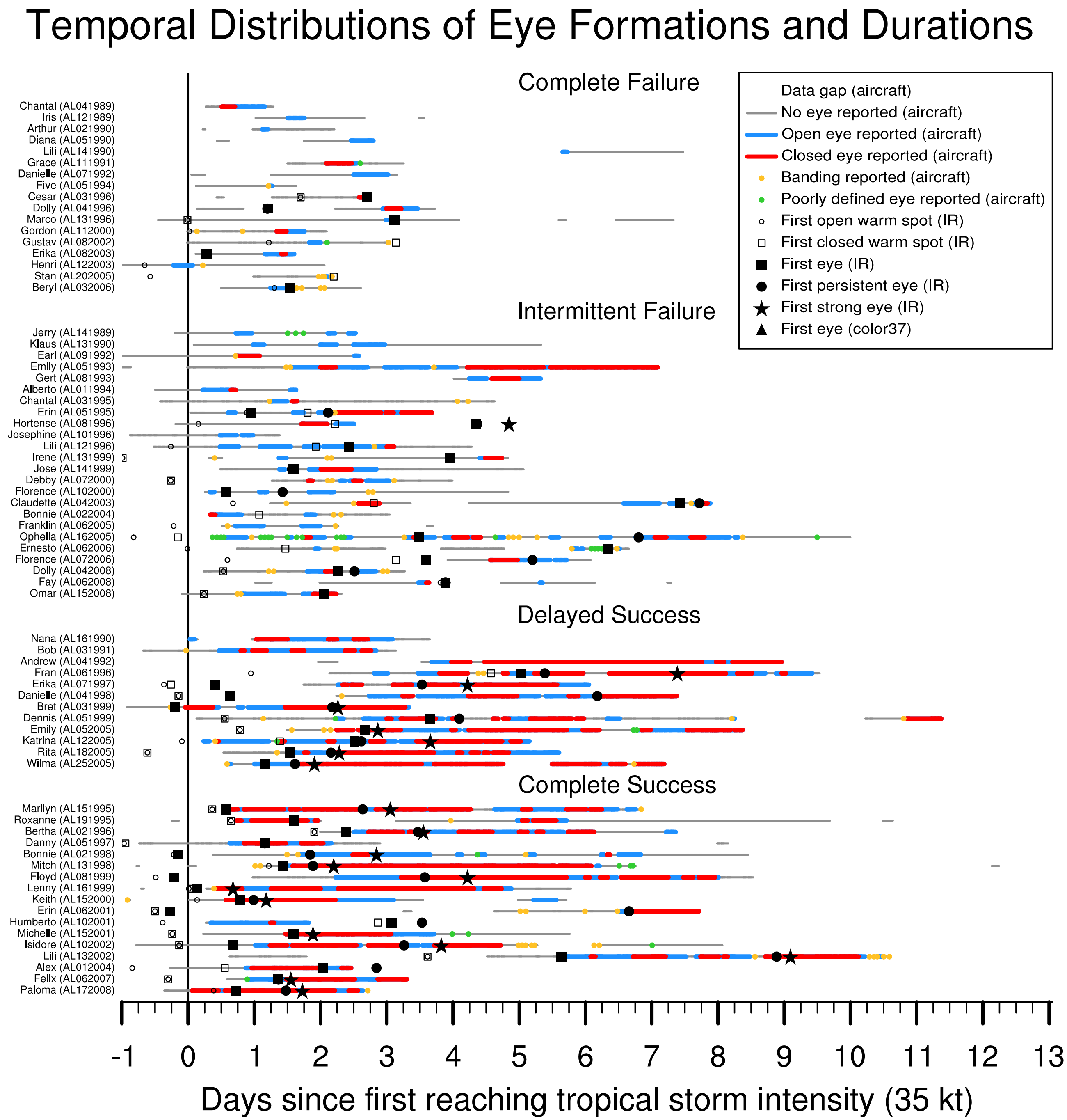

Figure 1: Temporal distribution of all Atlantic storms which formed eyes during the period of aircraft reconnaissance. See text for full description.

intensity threshold than some of the mythological values that appear in the literature. For our 70-storm sample, both the 'A' eye and the IR3 eye appear at a mean BT intensity of 58 kt. This is considerably below some values which have been reported, such as the oft-cited 68 kt from Shapiro and Willoughby (1982) or the 65 to 77 kt given by the Dvorak model (Dvorak 1984).

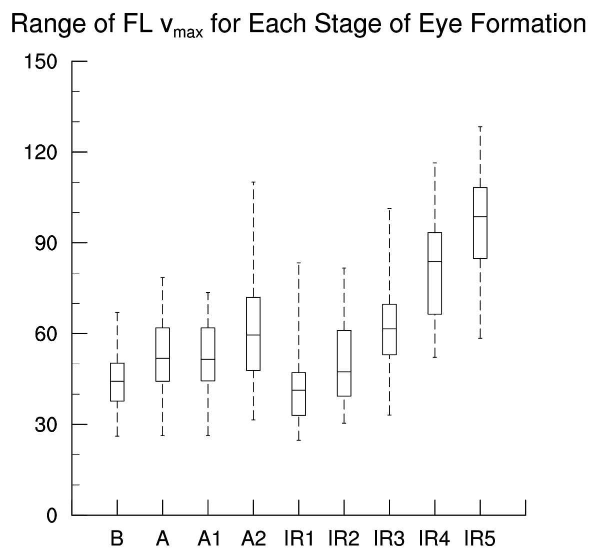

Figure 2: Intensity ranges are obtained by interpolating the reduced FL v_{max} winds to the observational baseline times.

An increasing intensity trend is seen with improving structural organization: Storms intensify as they progress from the baselines associated with less structural organization [such as open warm spots (IR1, 38 kt), closed warm spots (IR2, 45 kt, and the first aircraft observation of banding (B, 50 kt)], to baselines associated with more defined eye structure: the open aircraft eye (A1, 56 kt), the first satellite eye (IR3, 58 kt, the first closed aircraft eye (A2, 68 kt), the first persistent satellite eye (IR4, 77 kt), and finally, the first strong satellite eye (IR5, 101 kt).

The lower bound intensity for eye formation is near minimal tropical storm strength: The least intense tropical cyclones to sport a bona fide eye was TD5 (1994) and Henri (2003), both of which were close to minimal tropical storm strength with maximum sustained surface wind speeds of 30 to 35 kt.

The upper bound intensity for eye formation is at least 80 to 85 kt: The most intense tropical cyclone in the data set to not form an eye was Hurricane Earl (1998), which was being disrupted by high shear and about to undergo extratropical transition. Storms which do not form eyes at high intensity often display some of the commonly-observed precursors to eye formation, such as a distinct 'curl' of a deep convective 'blob' as it rotates and rolls over the north side of the center. Some storms will even display cold rings in the IR imagery, but it seems that these are local mesoscale features associated with the deep convection that do not persist or have a strong dynamical influence on the resulting storm evolution.

Storms which form eyes successfully and maintain them intensify the most rapidly *once a persistent eye has formed*: These successful cases intensify the longest and reach the highest overall intensity. An interesting subset of success cases experience very rapid intensifications. These are storms in which an eye forms, but then is stymied until a persistent eye can form later (usually about a day or so). Many of these rapid intensifiers seem to be late season tropical cyclones in the Caribbean which were held back by unfavorable environmental conditions. Once the conditions improved, development and intensification occurred rapidly.

Vertical wind shear is highly disruptive to eye formation: Preliminary analysis suggests that eyes generally do not form if the vertical wind shear is above 25 kt. Most eyes form when the vertical shear is between 10 and 20 kt. This results suggests that environmental influences to play an important role, so the possibility that eye formation is a dynamical attractor of the system is not precluded, although more analysis is needed.

BT $r_{max}$is found to have an erroneous and substantial high bias: The r_{max} values contained in the best track 'bdecks' and the extended best track data set are not actually 'best tracked' radius values — that is, they have not undergone the scrutiny and vetting that the intensity values undergo in the post season. Rather, the BT r_{max} values are simply what was given by the operational forecaster, who is tasked with choosing a value of the storm's radius of maximum winds to initialize the numerical models with. Since those best of those models has had a relatively low resolution of 40 n mi until recently, it seems likely that this may be why forecasters were reluctant to assign smaller values of r_{max} to a given storm. If the FL r_{max} values are taken as "truth" and no tilt of the vortex is assumed, the BT r_{max} values are biased high by 30 to 90%.

About half of the storms studied undergo a substantial and rapid contraction in FL r_{max} starting during the 24-h period before the eye forms: In these eye-forming systems, FL r_{max} contracts from 40 n mi or greater to between 5 and 20 n mi by the time an aircraft eye is observed. The mean r_{max} at that time is 15 n mi.

Minimum FL r_{max} is reached at or soon after the eye forms, supporting Kuo's idea of a limiting radius: Storms which continue to rapidly intensify may contract slowly for some time after eye formation, but in many storms r_{max} is steady after eye formation until peak intensity is reached. r_{max} experiences a substantial expan-

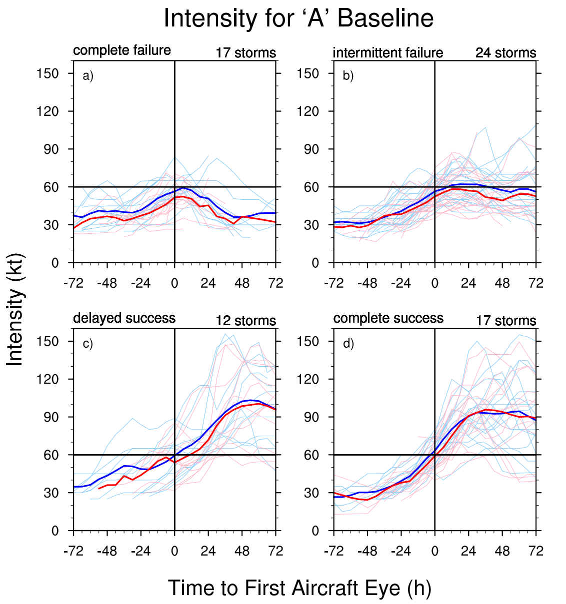

Figure 3: BT v_{max} and rFL v_{max} interpolated to various times before and after the first report of an open or closed aircraft eye (A). Each panel shows the individual intensity curves of storms in the designated eye formation case type and the mean composite intensity of those cases. Individual intensities of storms for that particular baseline for both the BT v_{max} (thin light blue lines) and the rFL v_{max} (thin light pink lines). The mean intensities computed from the individual storms are also shown for both the BT v_{max}(thick blue line) and the rFL v_{max}(thick red line). Data from periods when a storm was over land are not included for the BT v_{max}. For the reader's convenience, a vertical reference line has been added at zero on the time coordinate to indicate the time when aircraft first reported an eye. Similarly, a horizontal baseline has been added at v_{max} = 60 kt. Data from periods when a storm was over land are not included for the BT v_{max}. Results are paneled for the following case types: a) complete failure, b) intermittent failure, c) delayed success, d) complete success.

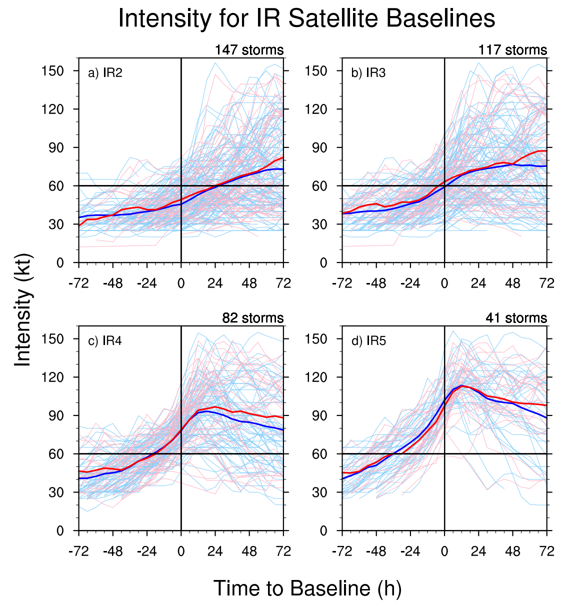

Figure 4: Intensity curves for IR satellite baselines: IR2, IR3, IR4, and IR5.

sion in storms in which the eye formation failed.

There is no absolute value of $\lambda_{R,min}$ that triggers eye formation, but many storms undergo a sharp contraction in $\lambda_{R,min}$ in the 24 h before the eye forms: The average $\lambda_{R,min}$ at the time of eye formation is just 26 n mi, but a few storms form eyes at considerably higher values (30 to 45 n mi). $\lambda_{R,min}$ continues to contract for storms that continue intensifying after forming eyes, but increases rapidly for storms in which eye formation fails. Storms that form a strong (IR5) eye $\lambda_{R,min}$ averages 10 n mi.

Many storms undergo a 'spike' in the 700 hPa-equivalent FL eye temperature which lasts between 18 and 36 h, but this period of strong eye warming is not well correlated with the time at which the *aircraft* eye is observed: A few storms have strong central warming *before* eye formation, while others experience it considerably later. Because of the varied times in relation to eye formation, the overall composite mean T_{eye} shows little change. The appearance of these spikes supports the findings of Jordan (1961); Kossin and Eastin (2001) and the idea that a storm's peak intensity is caused by a regime change in eye structure.

The appearance of a persistent (IR4) or strong (IR5) satellite eye *does* have a strong correlation to the timing of the peak eye column warming: T_{eye} rises an average of 2 to 4 °C for these baselines, but individual storms show much greater increases of 8 to 14 °C. The strongest warming of T_{eye} begin right at the time an IR5 eye is observed. These storms experience their peak eye temperatures between 12 and 36 h afterward. *Thus, the eye clearing and well-defined cold ring of eyewall cloud top temperature associated with the strong eye 'scene' is strongly associated with warming in the lower eye.*

A handful of storms exhibit substantial $T_{DEP,eye}$ of greater than 8 °C before forming an eye, suggesting that the subsidence may not necessarily just be a simple response to the establishment of an eyewall: In some cases, signs of central subsidence precede the actual eye formation by 12 to 24 h. Most storms experience their greatest $T_{DEP,eye}$ between 1 and 2 d after forming an eye.

The largest $T_{DEP,eye}$ are always found at the 700 hPa level in storms with moderate-sized eyes: This suggests that below this level, mixing with inflowing eyewall air or modification through contact with the ocean air moistens the air — or perhaps that total sub-

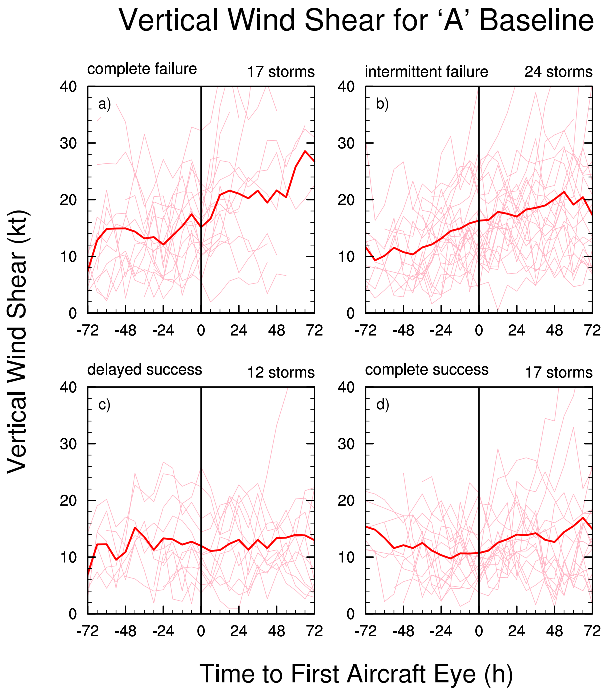

Figure 5: Vertical wind shear (SHDC) for the 'A' baseline, stratified by eye formation case type. The composite mean of the respective cases is indicated by the thick, solid line.

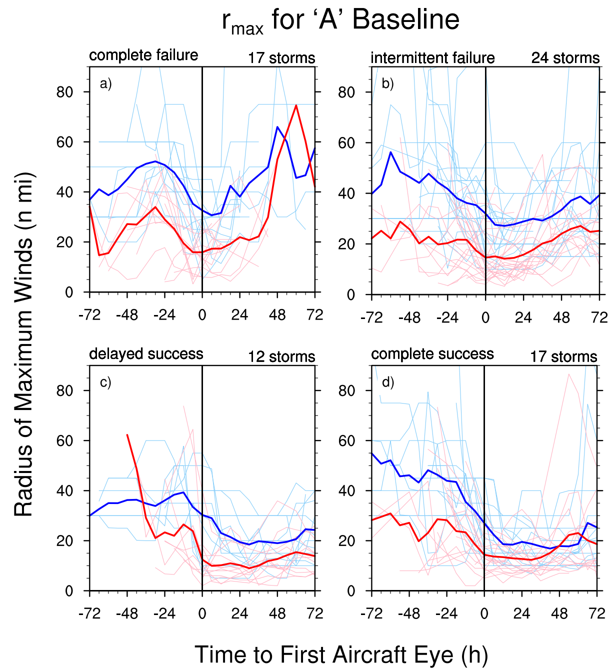

Figure 6: BT and FL $r_{\max}$ stratified by eye formation case type for the 'A' baseline: a) complete failure, b) intermittent failure, c) delayed success, d) complete success. The individual storm $r_{\max}$ are shown by thin lines for the BT (light blue) and FL (pink) values, while the composite mean is shown by thick lines for BT (blue) and FL (red).

sidence is just not as strong at this lower level due to air leaving the eye below 700 hPa. Such eyewall mixing undoubtedly occurs, so storms with smaller eyes (and therefore smaller eye volumes) are more strongly affected (and moistened). Storms with very large eyes also do not reach large $T_{\mathrm{DEP,eye}}$ values because the subsidence tends to be confined near the eyewall boundary by the low value of $\lambda_{\mathrm{R,min}}$.

While extraordinary dew point depressions of greater than 20 °C are in some storms, by no means is this a requirement for a storm to reach a high intensity — many storms reach high intensity without such signals of subsidence. It appears that only *some* storms experience strong warming in their lower eye regions, and that this is by no means required to have an intense storm. The greatest hydrostatic impact of warming occurs when the warming is at high levels, so of course all storms which reach high intensity possess a significant warm core aloft. But for whatever reason, strong warming is not always observed lower down. A possible cause is that the proposed 'momentum diffusion pump' (basically, the centrifugal effect) may only become substantial for the more intense storms. If so, then the mixing event which finally spins up the eye to solid body rotation would 'break' this pump, resulting in the peak of maximum intensity and subsequent weakening. Elements of this idea are discussed in more detail by Kossin and Eastin (2001) and Rozoff et al. (2009).

The temperature difference across the eyewall undergoes a strong increase on average only for the storms which are completely successful in their eye formations, supporting to some degree the idea that eye formation involves a frontogenetic collapse (Emanuel 1997). However, the strongest average $\Delta T_{\mathrm{eyewall}}$ increases occur later when the persistent (IR4) and strong (IR5) eyes are observed. Thus, as just noted above, it seems that the 'momentum diffusion pump' becomes most relevant for the latter stages of eye formation. In this view then, the so-called 'centrifugal effect' is the strongest mainly after the eye has already formed and contributes to storm intensification up until peak intensity. More analysis is needed however to verify or disprove this idea.

Observations of the storms which experienced complete success in their eye formations support the idea that the dynamic efficiency of the eyewall heating increases even as the physical scale of the efficient heating region shrinks: This effect is important in allowing a storm to continue intensifying, even as the diabatic heating becomes 'locked out' of the high inertial stability of the core. Efficiency gains in the eyewall appear to more than counteract the reduction in total diabatic heating that occurs as the eyewall contracts.

4. CONCLUSIONS

The mean intensity at which an eye is first observed in both aircraft or satellite imagery is found to be 58 kt, somewhat lower than reported in previous studies. Storms were found to intensify most rapidly near the time of eye formation, especially when a persistent eye is observed in infrared satellite imagery. Many storms which are forming eyes are found to undergo a substantial and rapid contraction in the radius of maximum winds during the 24-h period before the eye is observed; once the eye is present, this contraction slows or ceases. Strong warming at lower levels (850 or 700 hPa) of the eye is not observed to correlate well with the time in which the eye is first observed. Finally, observations suggest that the dynamical heating efficiency of the resulting eyewall increases even as the physical scale of the efficient heating region decreases. This allows a storm to continue intensifying even though its total inner core diabatic heating may be decreasing. Most eyes formed when the environmental vertical wind shear (850 to 200 hPa) was between 10 to 20 kt; very few eyes formed when the shear exceeded 25 kt. These results suggest that to a large degree, the formation of an eye is a manifold attractor of the system sometimes stymied by an unfavorable environment.

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