What is the Key Feature of Convection Leading up to Tropical Cyclone Formation?

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ABSTRACT

Infrared brightness temperature data are used to investigate convective evolution during tropical cyclone (TC) formation in a quasi-Lagrangian framework. More than 150 named Atlantic storms during 1989–2010 were examined. It is found that both convective intensity and convective frequency increase with time in the inner pouch region but change little, or even weaken slightly, in the outer pouch region. Convection thus appears to concentrate toward the circulation center as genesis is approached. However, large variability is found from storm to storm in convective intensity, area, and duration, and the convective evolution of individual storms does not resemble the composite mean. Further analysis suggests that the composite mean or the median represents the probability of occurrence of convection instead of a recurrent pattern. Three distinct spatial patterns of convection are identified using cluster analysis. Substantial differences in convection intensity and area are found among the clusters and can be attributed to the impacts of environmental conditions. These differences suggest that convection intensity or area is not a key feature of convection for tropical cyclogenesis. In particular, a small and weak convective system is not necessarily associated with a weak vortex. A simple proxy of the radial gradient of convection is found to be similar among the clusters. Furthermore, convection is most effective in strengthening the TC protovortex when its maximum occurs near the pouch center. These findings suggest that organized convection near the pouch center is a key feature of convection for tropical cyclogenesis and that emphasizing convective intensity or frequency without considering the spatial pattern may be misleading.

1. Introduction

Tropical cyclogenesis is one of the most fascinating and challenging issues in tropical meteorology. Our understanding of tropical cyclogenesis has improved significantly in the past few decades owing to advances in computational technology and the increasing availability of observational data. Intensive observations during field campaigns have provided valuable information on the dynamics and thermodynamics of storm evolution (e.g., Elsberry and Harr 2008; Houze et al. 2009; Montgomery et al. 2012; Braun et al. 2013). However, since tropical cyclones often form over the open ocean, in situ observations of genesis are unavailable for most storms, and satellite imagery is the major data source for qualitative

and quantitative monitoring or evaluation of tropical cyclogenesis. Microwave sensors, whose signals can penetrate through clouds, provide useful information on surface wind, temperature, and moisture, even in regions of convection (e.g., Wentz 2013; Gentemann et al. 2004; Ruf et al. 2016). Visible and infrared (IR) imagery, with relatively high spatial and temporal resolution, depicts the vivid animation of cloud evolution throughout the life cycle of a tropical cyclone (TC), and cloud motion also provides information on the wind field. Although cloud-tracked wind vectors in the mid- and lower troposphere are often obscured by high clouds, there is no question that convection is strongly coupled to the wind field in a tropical cyclone, and experienced forecasters can estimate the minimum sea level pressure and the maximum surface wind speed based on cloud patterns in infrared measurements using the Dvorak technique (Dvorak 1984; Velden et al. 2006). However, the Dvorak technique is mainly used to estimate the intensity of a tropical cyclone, and a similar technique is not widely used for genesis (Cossuth et al. 2013). In fact, it remains

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elusive what is the key feature of convection leading up to tropical cyclogenesis, and this hinders the effective use of satellite data in predicting tropical cyclogenesis.

Zehr (1992) carried out one of the earliest analyses of IR brightness temperature (Tb) data on tropical cyclone formation. He examined 50 typhoons over the western North Pacific during 1983–84 and proposed a two-stage conceptual model for tropical cyclone formation. The first stage is characterized by a convective maximum that is followed by a period of reduced convection and the formation of a distinct low-level circulation. The second stage is marked by the onset of increasing deep convection associated with the low-level circulation and ends with the formation of a tropical storm. It is worth noting that TC genesis in Zehr (1992) is defined as the formation of a tropical storm. In addition, the time interval between the early convective maximum in the first stage and the genesis of a tropical storm in the second stage varies from less than 1 day to more than 8 days among storms, and a tropical depression may form in the first stage or the second stage.

Lee et al. (2008) examined convective evolution during tropical cyclone formation in different types of synoptic-scale environments over the western North Pacific. They focused on the 2-day time window prior to genesis¹ and revealed different characteristic temporal evolutions of deep convection. In addition to storms with two convective peaks that fit the conceptual model by Zehr (1992), they identified other scenarios, including storms with one convective peak, with three convective peaks, with gradually deepening convection, and with highly fluctuating convection. The various convective evolution scenarios reflect the complex nature of tropical cyclogenesis.

More recently, Leppert et al. (2013) analyzed IR Tb along with Tropical Rainfall Measuring Mission (TRMM) Lightning Imaging Sensor (LIS), Precipitation Radar (PR), and Microwave Imager (TMI) data and showed that convective area increases but convective intensity decreases as tropical cyclogenesis is approached. Using passive microwave satellite data in combination with the TRMM 3B42 rain rate, Zawislak and Zipser (2014) tracked vorticity maxima and showed that developing disturbances have a larger raining area than nondeveloping disturbances within 3° of the center, but a clear trend in raining area was not found prior to genesis. In addition, they did not find any unique features of

intense convection in terms of intensity, area, or proximity to the disturbance center within 24 h prior to genesis.

The emphasis of convective area or frequency over convective intensity by Leppert et al. (2013) and Zawislak and Zipser (2014) is thought provoking. It implies that the collective effect of convection is more important to tropical cyclogenesis than a few intense convective cells, and the thinking is in line with Fritz et al. (2016), who suggested that tropical cyclogenesis is the outcome of the collective contribution by different types of precipitation. However, the lack of an increasing trend in convective intensity is counterintuitive and also contradicts case studies based on numerical model simulations (e.g., Nolan et al. 2007; Wang et al. 2010a) or composite analysis of satellite data (Fritz et al. 2016; Wang and Hanks 2016). In particular, Wang and Hanks (2016) examined the coevolution of moisture and precipitation during tropical cyclogenesis using the SSM/I and SSMIS passive microwave data. In contrast to the aforementioned studies, they found a sharp increase in precipitation within 24 h prior to genesis, and the increase in precipitation was preceded by an increase in column water vapor near the pouch center. However, Wang and Hanks's (2016) finding was solely based on composite analysis due to the long revisit time of the near-polar-orbiting satellites. Given the sporadic nature of convection prior to genesis, it is possible that convective peaks, which were emphasized by Zehr (1992), were smoothed out in composite means.

This study revisits the convective evolution of tropical waves leading up to Atlantic tropical cyclone formation. We will take advantage of the relatively high temporal resolution and spatial coverage of IR Tb data and investigate the key feature(s) of convection for tropical cyclogenesis. A key feature of convection should be a common feature among developing disturbances and can help to distinguish developing disturbances from nondeveloping disturbances.² The analysis will be carried out in a quasi-Lagrangian framework based on the marsupial paradigm (i.e., Dunkerton et al. 2009). The marsupial paradigm suggested that the wave “pouch,” a quasi-closed Lagrangian circulation (i.e., the cat's eye) within the critical layer of a synoptic-scale wave, provides favorable conditions for tropical cyclone formation. The marsupial paradigm is adopted here because it

¹ Genesis in Lee et al. (2008) is defined as the time that a TC reaches 25 kt, which is usually after the release of a tropical cyclone formation alert by the Joint Typhoon Warning Center, but before the formation of a tropical storm (i.e., TC reaches 34 kt).

² Nondeveloping waves were not examined in this study. However, given the typical development time scale of a tropical cyclone, a developing wave at 72 h prior to genesis is likely not distinguishable from a nondeveloping wave (Peng et al. 2012; Fu et al. 2012; Hopsch et al. 2010), and it thus provides a useful reference state.

has been proven to be a useful framework to study the dynamic and thermodynamic evolution of precursor disturbances before tropical cyclogenesis (e.g., Wang 2009; Montgomery et al. 2010; Wang 2012). Since tropical cyclogenesis is involved with strong coupling between the dynamics (primary and secondary circulations), thermodynamics, and convection, convective evolution will be interpreted in the context of dynamic and thermodynamic evolution. The remainder of the paper is organized as follows. Data and methodology are described in section 2. The temporal evolution and spatial pattern of convection are examined in sections 3 and 4, respectively, followed by a summary in section 5. The differences between the present findings and previous studies are also discussed in section 5.

2. Data and methodology

Infrared brightness temperature data from GridSat-B1 (Knapp et al. 2011; <https://www.ncdc.noaa.gov/gridsat/>) are used to examine convective evolution. The dataset is a combination of multiple geostationary satellite observations. The high temporal (3 h) and spatial (0.07°) resolution of the data allows nearly continuous observations of clouds. A weakness of the dataset is that precipitation features may be obscured by high clouds. To address this limitation, the CPC morphing technique (CMORPH) precipitation (Joyce et al. 2004) is examined to assist the interpretation of IR Tb data. The CMORPH precipitation is derived from passive microwave retrievals, and IR data are used only to advect precipitation features. The gridded precipitation data at 0.25° horizontal resolution are analyzed for the time period from 2003 to 2010.

In contrast to many previous studies that tracked cloud clusters or vorticity maxima, we track wave pouches and examine the convective evolution in a pouch-centric frame of reference. The physical and dynamical basis is that the quasi-closed Lagrangian circulation (i.e., the wave pouch) associated with a synoptic-scale wave provides a favorable mesoscale environment for convective organization and vorticity aggregation, and that the pouch center is the preferred location for genesis (Dunkerton et al. 2009; Wang et al. 2009; Montgomery et al. 2010; Wang et al. 2010a,b; Wang 2012). A wave pouch track dataset for 164 named storms over the Atlantic during 1989–2010 (Wang and Hanks 2014) is used, and we focus on the time window from 72 h before genesis (-72 h) to genesis (0 h). Although the analysis time period is the same as that in Wang and Hanks (2016), the effective sample size in this study is much larger because the IR data provide high-frequency sampling of individual storms.

The 6-hourly data from the ERA-Interim (Simmons et al. 2006) are used to examine the dynamic and thermodynamic conditions associated with the convective evolution of precursor disturbances. With the spatial resolution of $\sim 0.7^\circ$, the reanalysis data can represent the dynamic and thermodynamic differences between the meso- β scale TC protovortex and the meso- α scale wave pouch (Wang and Hanks 2014). In addition, the National Hurricane Center (NHC) best track data are used to determine the genesis time and location (Landsea et al. 2004). The beginning of a storm track in the best track data is defined as the genesis point, which is the designation of a tropical depression in most cases. In addition, the extended best track dataset (Demuth et al. 2006) is used to provide additional storm information.

3. Temporal evolution

a. Composite analysis of IR Tb and precipitation

The temporal evolution of IR Tb is examined in this section. Figure 1a shows the time–radius plot of composite mean IR Tb from -72 to 0 h. Prior to -66 h, the azimuthal mean IR Tb is above -10°C at all radii, and there is no clear sign of convective organization in the radial direction. Over the 3-day period prior to genesis, the composite mean IR Tb remains above -10°C and does not change much at radii $\geq 3^\circ$ (approximately the outer pouch region) but decreases with time at radii $\leq 2^\circ$ (approximately the inner pouch region³). In particular, a sharp decrease in Tb occurs within 1 day prior to genesis. The different evolution in the inner versus outer pouch regions leads to a strong radial gradient of IR Tb prior to genesis.

The sequence of the two-dimensional composite mean IR Tb from -60 to 0 h is shown in Figs. 1b–g, along with 700-hPa streamlines in the wave co-moving frame of reference. The wave pouch is indicated by the quasi-closed wave-relative streamlines. Composite mean IR Tb $\leq 0^\circ\text{C}$ is largely confined within the wave pouch but suppressed in the northwest quadrant. A weak contrast in IR Tb between the inner and outer pouch regions is discernible from -60 h onward, although the pattern of low IR Tb around the pouch center is diffuse before -36 h. Convection intensifies (IR Tb decreases) and becomes more symmetric about the pouch center as genesis is approached, especially within

³ The inner pouch region refers to a meso- β -scale region (within a radius of ~ 200 km) around the pouch center, while the wave pouch is a meso- α -scale structure. Wang (2012) showed that the midlevel equivalent potential temperature increases by 4 – 6 K in the inner pouch region 1–2 days prior to genesis but changes little in the outer pouch region. The different dynamic structures of the inner versus outer pouch regions were examined in Wang (2014).

FIG. 1. (a) Time–radius evolution of composite mean IR Tb ($^{\circ}\text{C}$) from -72 to 0 h (genesis). (b)–(g) The sequence of composite mean IR Tb from -60 to 0 h with a time interval of 12 h. Composites are constructed with respect to the pouch center [the domain center in (b)–(g)], and superimposed on IR Tb are the composite mean 700 -hPa wave-relative streamlines.

24 h prior to genesis. Meanwhile, convection weakens slightly in the outer pouch region, resulting in a contracted convective core.

To facilitate the interpretation of IR Tb composites, the composite means of the CMORPH precipitation are constructed. The composites have a smaller sample size (88 named storms) because the CMORPH precipitation is not available before 2003. The region of cold IR Tb shows a good agreement with strong precipitation rate (Fig. 2), although the latter is noisier due to the nature of precipitation and the smaller sample size. The overall convective evolution, including the sharp increase in precipitation after -24 h and the lateral contraction of the precipitating region, is consistent with the evolution of IR Tb. Overall, the comparison between Figs. 1 and 2 suggests that IR Tb can be used as a good proxy for precipitation, with cold IR Tb indicating strong precipitation. In the following sections, we will also refer to cold IR Tb as strong convection, although precipitation can be contributed by both convective and stratiform types of precipitation (Fritz et al. 2016).

The decreasing composite mean IR Tb (Fig. 1) can be due to increasing convective frequency, or increasing convective intensity, or both. Leppert et al. (2013) and Zawislak and Zipser (2014) emphasized the increasing convective frequency (or area) without convection intensification, and here we revisit this issue in wave-centric analyses. To represent convective frequency, the

probability of occurrence of $\text{Tb} < -25^{\circ}\text{C}$ is calculated at each grid point in the pouch-centric framework, defined as the ratio of the number of storms with $\text{Tb} < -25^{\circ}\text{C}$ at a grid point to the total number of storms. The threshold of -25°C is chosen to represent cold cloudiness, and reasonable variations of the threshold do not change the results below qualitatively. To represent convective intensity, the 5th percentile of IR Tb is calculated among all storms at each grid point.

The evolution of cold cloudiness occurrence (Fig. 3) resembles the composite mean IR Tb (Fig. 1). The time–radius plot shows the increasing frequency of occurrence of cold cloudiness in the inner pouch region, and the maximum occurs at the pouch center after -30 h. As shown by the contour of 30% frequency of occurrence in Figs. 3b–g, cold cloudiness initially has a low frequency of occurrence and scatters within the wave pouch. It occurs more frequently with time near the pouch center, and the azimuthal distribution becomes more symmetric around the pouch center. In addition, the 15% contour shows a lateral contraction, consistent with the slightly increasing IR Tb in the outer pouch region (Fig. 1). The time sequence of the 5th-percentile IR Tb (Fig. 4) shows that convective intensity also increases with time near the pouch center but does not show an appreciable increase in the outer pouch region. This leads to the appearance of strong convection moving closer to the pouch center as genesis is approached.

FIG. 2. Composite mean precipitation (mm day^{-1}) from -60 to 0 h with a time interval of 12 h. Composites are constructed with respect to the pouch center (the domain center).

Overall, Figs. 3 and 4 show that convective frequency and convective intensity both increase with time and that strong convection occurs closer to the pouch center as genesis is approached. This is in contrast to the findings by Zawislak and Zipser (2014) and Leppert et al. (2013). The discrepancies likely result from methodology differences as discussed in section 5.

b. Stochastic nature of convection

Although composite analysis is a useful diagnostic tool, averaging over a large number of storms smooths out storm-to-storm variability. To examine how representative the composite means are of individual storms, we show the fractional coverage of cold IR Tb within a $4^\circ \times 4^\circ$ box (approximately the inner pouch region) for 11 tropical cyclones in 2010 in Fig. 5. The fractional coverage of cold Tb, instead of the areal averaged Tb, is shown to facilitate the comparison with Zehr (1992). The threshold of -65°C is chosen following Zehr (1992), and a second threshold of -45°C is also shown because convection over the Atlantic is overall not as deep as that in the western North Pacific (Jiang et al. 2011; Gettelman et al. 2002).

A striking feature of Fig. 5 is the large storm-to-storm variability. The fractional coverage of $\text{Tb} \leq -65^\circ\text{C}$ peaks above 30% in some storms but remains below 5% in some other storms. The storms also exhibit different evolution patterns. For example, pre-Bonnie, pre-Julia, and pre-Karl are characterized by three convective bursts; pre-Igor and pre-Fiona have two convective bursts prior to genesis; and pre-Gaston has a low fractional coverage of deep convection with strong fluctuations and does not show a prominent peak. The various evolution scenarios of the individual storms illustrated in Fig. 5 are consistent with Lee et al. (2008), although the storms in the present study all developed from tropical easterly waves. The different temporal evolutions of IR Tb suggest that not all storms fit the two-stage conceptual model proposed by Zehr (1992).

The time series of 5th percentile of IR Tb is also shown in Fig. 5. Here the 5th percentile is calculated within a $4^\circ \times 4^\circ$ box (with more than 3000 grid points) for each storm at each time step. Again, large variability in convective intensity and duration is found from storm to storm. For example, pre-Earl and pre-Igor are characterized by prolonged periods of intense convection with

FIG. 3. As in Fig. 1, but showing the frequency of occurrence (%) of $\text{IR Tb} \leq -25^{\circ}\text{C}$. The magenta curves in (b)–(g) are the 30% contour.

IR Tb down to -70°C , pre-Gaston has only short bursts of $\text{IR Tb} < -60^{\circ}\text{C}$, and the convective episodes in pre-Karl and pre-Fiona are strongly modulated by the diurnal cycle. In addition, convection intensification is often concomitant with increasing convective frequency, consistent with Figs. 3 and 4.

The bottom-right panel of Fig. 5 shows the composite mean (blue curve), the median (green curve), and the 10th–90th percentiles of the fractional coverage of $\text{Tb} \leq -45^{\circ}\text{C}$ based on all the storms during 1989–2010. The composite mean and the median have a steady increase from -72 to 0 h, consistent with the steady

FIG. 4. As in Fig. 1, but for the 5th-percentile IR Tb ($^{\circ}\text{C}$).

FIG. 5. Time series of the fractional coverage of cold cloudiness within a $4^{\circ} \times 4^{\circ}$ box centered at the pouch center for 11 named storms in 2010. Green curves and red curves represent the fractional coverage of $T_b \leq -45^{\circ}\text{C}$ and $T_b \leq -65^{\circ}\text{C}$, respectively. The abscissa shows time (from -72 to 0 h) and the left ordinate shows the fractional coverage (%). Shaded bars are the time series of the 5th-percentile IR T_b ($^{\circ}\text{C}$) within a $4^{\circ} \times 4^{\circ}$ box centered at the pouch center (the ordinate is shown on the right and is flipped to facilitate comparison with the cold IR T_b coverages). (bottom right) The mean (blue curve), the median (green curve), and the 10th–90th-percentile range (gray shading) of the fractional coverage of $T_b \leq -45^{\circ}\text{C}$ for all the storms during 1989–2010.

decrease in the composite mean T_b (Fig. 1). However, none of the individual storm evolutions shown in Fig. 5 resemble the mean or the median. Also worth noting is the wide range between the 10th and 90th percentiles, which indicates the large storm-to-storm variability and is consistent with the stochastic nature of convection. The results suggest that the mean or the median does not represent a typical or recurrent pattern of convective evolution. Instead, the composite mean or median represents the probability of occurrence of strong convection.

The IR evolution sheds new light on the two-stage conceptual model proposed by Wang (2014) for tropical cyclone formation. The first stage of the conceptual model is characterized by gradual moistening and low-level spinup by cumulus congestus, and the second stage is marked by the rapid development of deep convection near the pouch center after the inner pouch region is moistened sufficiently. The two-stage conceptual model

is supported by the analysis of numerical model simulations (Wang 2012, 2014) and the composite analysis of satellite data (Wang and Hanks 2016; Fritz et al. 2016). In particular, Wang and Hanks (2016) showed that precipitation increases exponentially with saturation fraction above the same threshold (i.e., a critical point) as in general tropical convection (Raymond 2000; Neelin et al. 2009; Peters et al. 2009), corresponding to the onset of deep convection. An important difference is that convection occurs more frequently near and above criticality in an incipient tropical cyclone than in general tropical convective systems, likely due to the strong positive feedback between convection and low-level moisture convergence. However, Fig. 5 shows that genesis is not concurrent with a convective peak in every storm. In addition to the modulation by the diurnal cycle, the lack of concurrency can be attributed to the stochastic nature of convection (e.g., Wang 2014; Van Sang et al. 2008;

Stechmann and Neelin 2011) and the loose definition of tropical cyclogenesis.⁴ In light of the statistical analyses here, the conceptual model should be interpreted from a probabilistic perspective: the probability of occurrence of deep convection in the inner pouch region increases sharply (stage II) after a gradual process of moisture preconditioning and low-level spinup by cumulus congestus (stage I). Studies also suggested that the tropical cyclogenesis is an outcome of the collective, cumulative contribution by cumulus congestus, stratiform precipitation, and transient deep convection (Wang 2012, 2014; Fritz et al. 2016).

c. Inner versus outer pouch regions

The different convective evolutions in the inner and outer pouch regions in Figs. 1–4 are noteworthy: convection intensifies and occurs more frequently with time around the pouch center, whereas it does not change much, or even weakens slightly, in the outer pouch region. To better demonstrate the differences, we construct the contoured cumulative frequency by time diagrams (CCFTD) for the inner and outer pouch regions (Figs. 6a,b). Here the inner pouch is referred to as the region with radii $\leq 2^\circ$, and the outer pouch region is represented by an annulus between 3° and 5° radii. A 1° gap is chosen to better illustrate the differences. The CCFTD shows the cumulative distribution function (CDF) of Tb at different times from -72 to 0 h. The CDF of Tb in the outer pouch region remains about the same throughout the 3-day time period, while the sloping contours of the CDF for the inner pouch region indicate that the frequency of occurrence of cold cloudiness (e.g., $T_b < -15^\circ\text{C}$) and convective intensity (e.g., 5th-percentile Tb) both increase with time. The differences between the inner and outer pouch regions are shown in Fig. 6c. The blue curve in Fig. 6c indicates the value of IR Tb at which the CDF difference peaks at a given time, and IR Tb less than this value occurs more frequently in the inner pouch region than in the outer pouch region. To better interpret the CCFTD plots, we construct the contoured frequency by time diagrams (CFTD) for the inner and outer pouch regions,

which illustrate the probability distribution function (PDF) of IR Tb at different times. As shown in Figs. 6d and 6e, the frequency of occurrence of $T_b \leq -60^\circ\text{C}$ is very low ($\leq 2\%$) in both regions prior to -60 h. Consistent with Fig. 6b, the frequency of occurrence of $T_b < -15^\circ\text{C}$ increases in the inner pouch region but does not change much in the outer region. Figure 6f shows that the largest differences between the inner and outer regions occur after -36 h for $T_b < -30^\circ\text{C}$.

4. Spatial patterns of convection

a. Distinct convective patterns identified by cluster analysis

The previous section focuses on the temporal evolutions of convection. In this section, we will examine the spatial pattern of convection. Cluster analysis is adopted to identify different spatial patterns of convection within a wave pouch. Euclidean distance (i.e., the geometric distance in the multidimensional space) is used to measure the dissimilarities in IR Tb among storms. The dissimilarities can also be measured by spatial correlation, but Euclidean distance can extract information on both the spatial distribution and intensity of convection and is found to be a better measure for our analysis. To suppress high-frequency fluctuations, IR Tb is first averaged from -12 to 0 h for each storm in a pouch-centric coordinate system, and the k -means cluster analysis is then applied to the 12-h averaged IR Tb. The mean silhouette value (Rousseeuw 1987) is used to determine into how many clusters the storms should be grouped. The silhouette value measures how similar a storm is to the other storms in its own cluster (cohesion) when compared to the storms in the other clusters (separation), and a high value indicates that a storm is well matched to its own cluster and poorly matched to neighboring clusters. We experimented with two, three, and four clusters. Three clusters produced the maximum mean silhouette value and were optimal to represent the spatial distribution and intensity of convection.

The composite mean IR Tb for each cluster at the genesis time is shown in Figs. 7a–c. Also shown is the composite mean 700-hPa streamlines in the wave-relative frame of reference for each cluster. Cluster 1 is characterized by a large cloud system with the center displaced $\sim 4^\circ$ east of the pouch center. Cluster 2 is characterized by a much smaller and weaker but more symmetric cloud system than that in cluster 1. Cluster 3 has a cloud system of similar size and intensity to cluster 1, and the overall pattern is less asymmetric than cluster 1, with the convective center displaced by $\sim 1.5^\circ$ south of the pouch center. Also shown are the cluster mean genesis locations (white dots). The genesis location is very close to the

⁴ Tropical cyclogenesis is often defined as the formation of a tropical depression. Since most tropical depressions intensify into a tropical cyclone, the formation of a tropical depression likely indicates that the disturbance has become self-sustaining. On the other hand, a tropical depression is defined based on the development of “a closed surface wind circulation about a well-defined center” by the NHC (<http://www.nhc.noaa.gov/aboutgloss.shtml>), which depends on the mean flow. In addition, the declaration of a tropical depression, without a wind speed threshold, is relatively subjective compared to the declaration of a tropical storm.

FIG. 6. CCFTDs of IR Tb in (a) the inner pouch region, (b) the outer pouch region, and (c) their difference. (d)–(f) As in (a)–(c), but for the CFTDs. The blue curve in (c) shows the IR Tb at which the CCFTD difference peaks, which roughly corresponds to the zero contour in the CFTD difference shown in (f).

pouch center in clusters 2 and 3 but displaced slightly east of the pouch center in cluster 1, consistent with the eastward displacement of convection.

Although the cluster analysis is carried out over IR Tb averaged from -12 to 0 h, the composite means of the clusters at -18 h (not shown), -24 h (Figs. 7d–f), and -48 h (not shown) are similar to those in Figs. 7a–c, except with weaker and less concentrated convection. The robustness of the clusters through time and the distribution of the genesis time in UTC hours (not shown) suggest that the pattern differences are not an artifact due to the diurnal cycle. Convective intensity is also examined for each cluster (Fig. S1 in the online

supplemental material). The 5th-percentile IR Tb has similar patterns as the composite mean IR Tb: convective intensity is overall weaker in cluster 2 than the other two clusters, and intense convection in cluster 1 is displaced eastward of the pouch center.

b. Causes of the distinct convective patterns

Given the distinct patterns of IR Tb, it is natural to ask the following questions: 1) What causes the different convective patterns? 2) How do the differences in convective area, intensity, and asymmetry affect tropical cyclone formation and storm characteristics? Since vertical shear often induces convective asymmetries, we

FIG. 7. Composite mean of IR Tb ($^{\circ}\text{C}$) for the three clusters (a)–(c) at the genesis time and (d)–(f) 24 h prior to genesis. Superimposed on IR Tb are the composite mean 700-hPa wave-relative streamlines. The white dots in (a)–(c) represent the composite mean genesis location for each cluster, and the magenta dots highlight the convection centers.

first address question 1 by examining vertical wind shear. We focus on the zonal wind here as the vertical shear of the meridional wind is much weaker than that of the zonal wind. The vertical shear of the zonal wind is calculated with respect to the 700-hPa level [i.e., $u(p) - u(700 \text{ hPa})$] and averaged over a 10° square box moving with the propagating wave pouch. Since the 700-hPa zonal flow averaged over a 10° box is close to the wave propagation speed, $u(p) - u(700 \text{ hPa})$ can be interpreted as the relative flow with respect to the wave pouch. As shown in Fig. 8, cluster 1 has stronger westerly relative flow in the upper troposphere than the other two clusters, and the westerly relative flow increases with time and exceeds 5 m s^{-1} by genesis. Westerly relative flow is also present in the boundary layer in cluster 1 but weakens with time. Cluster 2 shows moderate westerly relative flow ($\sim 3 \text{ m s}^{-1}$) in both the boundary layer and the upper troposphere. Cluster 3 has easterly relative flow in the upper troposphere and westerly flow in the boundary layer and both weaken with time. The strong upper-level westerly relative flow in cluster 1 indicates a stronger westerly vertical shear than in the other two

clusters, and it is consistent with the eastward displacement of convection off the pouch center. The downshear preference of convection in an incipient tropical cyclone is different from the downshear-left preference of convection in a hurricane, which is probably due to the relatively weak rotation of an incipient tropical cyclone. This is consistent with Corbosiero and Molinari's (2002) finding that lightning maxima tend to occur downshear in tropical depressions/storms and downshear-left in hurricanes. Further analysis shows that the three clusters have similar mean wave propagation speeds (Table 1), and that the composite mean 700-hPa zonal wind differs by 1 m s^{-1} or less among the three clusters (not shown). The stronger westerly relative flow in cluster 1 is mainly due to the weaker upper-level easterlies. The southward displaced convection in cluster 3, however, cannot be attributed to the vertical shear of the meridional wind, which is less than 1 m s^{-1} at the genesis time (not shown).

Since convection is strongly modulated by humidity, we next examine the humidity field for the three clusters. Figure 9 shows the composite mean 600-hPa relative humidity for each cluster. A striking feature is the small

FIG. 8. Time–height cross section of the zonal flow (m s^{-1}) relative to the 700-hPa zonal flow [i.e., $u(p) - u(700 \text{ hPa})$] for the three clusters.

moist core in cluster 2 surrounded by dry air, and the air in the northwest quadrant is particularly dry (Fig. 9b). It is worth noting that the wave pouch is not exactly a closed circulation because of the nonzero divergent component of the horizontal flow. A saddle point of streamlines in the northwest quadrant represents an opening of the wave pouch and allows an influx of environmental dry air (Wang et al. 2010a; Brammer and Thorncroft 2017). In addition, the upper troposphere may be a weak spot of a precursor disturbance, where a wave pouch is often absent at the early stage of tropical cyclone formation (Wang et al. 2012; Fritz and Wang 2013; Hanks et al. 2015; Riemer and Montgomery 2011). The longitude–height cross section of relative humidity (Figs. 11b,e) reveals a thick layer of dry air in the middle to upper troposphere west of the wave pouch, which, along with the upper-level westerly relative flow (Fig. 8b), indicates a possible pathway of dry air from the upper troposphere. Despite the surrounding

dry air, the inner pouch region remains moist, which allows the development of a tropical cyclone.

Dry air is also present north of the wave pouch for cluster 1 (Fig. 9a), but it contains a large moist core. The moist core is displaced about 4° eastward off the pouch center, consistent with the displaced convection. A moisture tongue extends southwestward from the pouch, reminiscent of a wave detached from the ITCZ (often seen in the total precipitable water animation: <http://tropic.ssec.wisc.edu/real-time/mtpw2/>).

The wave pouch in cluster 3 is associated with a relatively moist environment (Fig. 9c). Dry air with $\text{RH} < 44\%$ is absent in the vicinity of the wave pouch. The moist core is displaced a couple of degrees south of the pouch center and is embedded in an east–west elongated moist zone, which resembles the ITCZ.

Similar differences in relative humidity among the three clusters are also found at 700 and 500 hPa (not shown). Since dry-air entrainment into clouds can induce evaporative cooling and reduce parcel buoyancy (Molinari et al. 2012), the small convective system in cluster 2 is likely due to the relatively dry ambient environment. On the other hand, the southward-displaced convection in cluster 3 is consistent with the abundant moisture south of the wave pouch and may be tied to the enhanced large-scale, low-level convergence associated with the ITCZ (Fig. 9c).

c. Key feature of convection for tropical cyclogenesis

The next question is whether the differences in convective area, intensity, and asymmetry affect tropical cyclone formation or storm characteristics. In particular, is a smaller and weaker cloud system, such as that in cluster 2, associated with a smaller and weaker TC protovortex? Figure 10 shows 600-hPa relative vorticity

TABLE 1. The frequency of occurrence, mean phase speed, and storm size for the three clusters. The storm size is measured by the radius of 34-kt wind in nautical miles ($1 \text{ n mi} = 1.852 \text{ km}$). The last row shows the storm distribution in different intensity categories within 24–72 h after the declaration of a tropical storm: tropical depression intensity or less, tropical storm intensity, and hurricane intensity.

Cluster	1	2	3
Occurrence (%)	31	38	31
Phase speed (m s^{-1})	−6.9	−6.4	−7.1
Mean AR34 (n mi)	72	59	66
Median AR34 (n mi)	72	53	62
Intensity distribution (%)	26/31/43	26/43/31	18/34/48

FIG. 9. Composite mean of 600-hPa relative humidity (%) and wave-relative streamlines at the genesis time for the three clusters. Stipples highlight regions where 950-hPa convergence exceeds $3 \times 10^{-6} \text{ s}^{-1}$.

superimposed on the wave-relative streamlines. Compared to the humidity or convection field, the vorticity distribution within the wave pouch is more symmetric about the pouch center. A zonally elongated vorticity strip is associated with the wave pouch in cluster 3, indicating its close connection to the ITCZ. Another noticeable and probably counterintuitive feature is that the relative vorticity in cluster 2, despite the much weaker and less extensive convection, has a similar intensity to that in cluster 3, and both are stronger than that in cluster 1. It suggests that the surrounding dry air may not affect the intensity of an incipient tropical cyclone if the inner pouch region remains moist.

The vorticity fields shown in Fig. 10 are associated with both the wave precursors and TC protovortices. The Okubo–Weiss parameter (OW) is calculated to better illustrate the protovortices. OW is defined as vorticity squared minus strain rate squared. Positive values of OW highlight flow of strong rotation and weak deformation (Dunkerton et al. 2009; Rozoff et al. 2006⁵) and have been used, in combination with other variables, to detect

⁵ Please note that Rozoff et al. (2006) used a different sign convention and defined OW as strain rate squared minus vorticity squared.

FIG. 10. As in Fig. 9, but for 600-hPa relative vorticity (10^{-5} s^{-1}) and streamlines.

tropical cyclones in coarse-resolution reanalysis or global model simulations (Tory et al. 2013). The east–west vertical cross sections of OW and relative humidity at the genesis time are shown in Figs. 11a–c. To take into account the southward displacement of convection in cluster 3, OW and RH are both averaged within $\pm 2^\circ$ of the pouch center latitude for all clusters. Consistent with the westerly vertical shear, the protovortex (roughly represented by $\text{OW} \geq 5 \times 10^{-10} \text{ s}^{-2}$) in cluster 1 has an eastward vertical tilt, suggesting that a TC protovortex is less resilient to vertical shear than a hurricane-strength vortex. The latter may remain upright even in the presence of strong vertical shear (e.g., Frank and Ritchie 2001). Cluster 2 has an upright protovortex surrounded by dry air on both sides. The protovortex in cluster 3 is also upright, but different from cluster 2, it is embedded in a deep layer of high moisture. A closer look at the OW

field shows that OW in cluster 2 has a magnitude similar to cluster 3 and stronger than cluster 1. The vertical cross section of OW is also examined 24 h prior to genesis (Figs. 11d–f), and cluster 2 has the strongest OW among the three clusters. The analysis suggests that a smaller and weaker cloud system does not mean a weaker vortex and that convective area or intensity is not a key factor for tropical cyclogenesis.

To take another look at the convective evolution, we calculate the areal mean IR Tb over a 10° square box and a 4° square box, centered at the minimum IR Tb of the cluster composite means (magenta dots in Fig. 7). The median of the areal averaged Tb for each cluster from -72 to 0 h is shown in Figs. 12a and 12b. Cluster 2 has much higher IR Tb than the other two clusters in both plots. The 10° box averaged IR Tb in cluster 2 does not show a clear trend, and the differences in the 10° box

RH and OW

FIG. 11. Vertical cross section of the composite mean relative humidity (shading; %) and OW (contours; 10^{-10} s^{-2} ; contours start at $5 \times 10^{-10} \text{ s}^{-2}$ with an interval of $5 \times 10^{-10} \text{ s}^{-2}$) for the three clusters (a)–(c) at the genesis time and (d)–(f) 24 h prior to genesis.

averaged Tb between cluster 2 and the other two clusters even increase with time. This result again suggests that the intensity or area of convection is not a key feature for tropical cyclone formation. In particular, the relatively high IR Tb in cluster 2 suggests that tropical cyclogenesis can occur with relatively weak convection in a small cloud system.

As a simple metric of the radial gradient of IR Tb, or a measure of convection organization, we take the differences between the two box averages (the small-box average minus the large-box average). As shown in Fig. 12c, the median curves for the three clusters collapse together and have a downward trend. The good agreement among the clusters suggests that the radial gradient of IR Tb is an important feature of convection for tropical cyclogenesis, which can be understood by recalling the Sawyer–Eliassen equation in pseudo-height coordinates (e.g., Schubert and Hack 1982):

$$\frac{\partial}{\partial r} \left(A \frac{\partial r \psi}{\partial r} + B \frac{\partial \psi}{\partial z} \right) + \frac{\partial}{\partial z} \left(B \frac{\partial r \psi}{\partial r} + C \frac{\partial \psi}{\partial z} \right) = \frac{g}{\theta_0} \frac{\partial Q}{\partial r}, \quad (1)$$

where ψ is the mass streamfunction, satisfying

$$u = -\frac{\partial \psi}{\partial z}, \quad w = \frac{\partial r \psi}{\partial r}; \quad (2)$$

A , B , and C denote static stability, baroclinicity, and inertial stability, respectively:

$$A = \frac{g}{\theta_0} \frac{\partial \theta}{\partial z}, \quad B = -\frac{g}{\theta_0} \frac{\partial \theta}{\partial r}, \quad \text{and} \quad C = (f + \xi) \left(f + \frac{2v}{r} \right); \quad (3)$$

r is the radius with respect to the pouch center; v and w are the tangential and vertical wind components, respectively; $\xi = (1/r) \partial(rv)/\partial r$ is the vertical component of relative vorticity; θ is potential temperature; θ_0 is a constant surface value; and Q is the diabatic heating rate, which can be derived as the residual term of the thermodynamic equation. Wang (2012) examined the balanced flow at the pregenesis stage of Tropical Storm Fay (2008) and showed that the balanced response is broadly consistent with the WRF Model simulation except within the boundary layer.

FIG. 12. (a) The median of IR Tb (°C) averaged over a $10^\circ \times 10^\circ$ box from -72 to 0 h for each cluster. (b) As in (a), but for a $4^\circ \times 4^\circ$ box. (c) The median of the small-box average minus the large-box average (note that the median of the differences is not equal to the difference of the medians). Black, red, and blue colors represent the first, second, and third clusters, respectively.

The term on the right-hand side of Eq. (1) suggests that what drives the transverse circulation is not diabatic heating itself, but the radial gradient of heating. Therefore, heating associated with tightly, circularly organized convection can still effectively drive the transverse circulation even if convection is only moderately strong (Fig. S2). This explains why tropical cyclogenesis can occur in cluster 2 with much weaker and less extensive but well-organized convection.

Furthermore, previous studies have shown that the response of a vortex to heating is dependent on the intensity and structure of the vortex and the radial location of the heat source. The energy efficiency theory based on an axisymmetric, balanced vortex (Hack and Schubert 1986; Schubert and Hack 1982) suggests that a specified heat source can most effectively increase the potential energy of the vortex and intensify the balanced rotational motion when located in a region of strong inertial stability. The maximum inertial stability occurs near the pouch center in all three clusters (not shown). If we use IR Tb as a proxy for convective heating (as indicated by Fig. 2), the maximum heating and the maximum inertial stability are collocated in cluster 2 and nearly collocated in cluster 3, but are displaced off each other by 4° – 5° in cluster 1, which explains the slightly weaker vortex in cluster 1 despite the strong convection.

Although the concept of energy efficiency helps to explain some dynamic processes in tropical cyclone formation and intensification, there are some noteworthy limitations of the theory (Smith and Montgomery 2016). In particular, Schubert and Hack (1982) and Hack and Schubert (1986) assumed a constant heating rate. Under this assumption, stronger inertial stability impedes the transverse circulation, and the associated

weaker upward motion produces weaker adiabatic cooling and allows the specified heating to more effectively warm the vortex interior, which is associated with stronger balanced rotational motion. However, convection is closely coupled to the transverse circulation in real storms: stronger updrafts are generally associated with stronger diabatic heating, and stronger, better organized heating can more effectively drive the transverse circulation. Whether the transverse circulation intensifies or not depends on the competing effects of the increasing diabatic heating and the increasing inertial stability. High-resolution numerical model simulations (e.g., Fig. 5 in Wang et al. 2010b; Figs. 11 and 12 in Kilroy and Smith 2017) show that the radial extent and intensity of the transverse circulation increase with increasing storm intensity during tropical cyclone formation and intensification, suggesting that the effect of heating exceeds the effect of inertial stability.

It is generally accepted that the system-scale intensification associated with convectively driven low-level inflow is the essential dynamic process for tropical cyclone formation and intensification (e.g., Hendricks et al. 2004; Montgomery et al. 2006; Tory and Frank 2010; Wang et al. 2010a, b; Fang and Zhang 2011; Raymond and Carrillo 2011; Montgomery and Smith 2011, 2014; Kilroy et al. 2017). Convective evolution can be understood in this dynamic context. In addition to low-level inflow, the vortex stretching effect—the major process for the system-scale intensification—also depends on the vorticity field that the inflow acts on. The process is most effective when the maximum heating and the associated convergence are collocated with the maximum vorticity. This explains why convection displaced off the circulation center is not optimal for storm

FIG. 13. Cluster composite mean of the stretching term (10^{-11} s^{-2} ; contours start at $1 \times 10^{-11} \text{ s}^{-2}$ with an interval of $5 \times 10^{-11} \text{ s}^{-2}$) superimposed on IR Tb (shading; $^{\circ}\text{C}$). IR Tb is shown at the genesis time, and the stretching term is averaged over 975–500 hPa from -72 to 0 h.

intensification. Figure 13 shows the stretching term (relative vorticity times convergence) averaged from -72 to 0 h from 975 to 500 hPa. Despite the stronger convection, the stretching term in cluster 1 has a magnitude similar to that in cluster 2. Cluster 3, with strong and nearly symmetric convection, has the strongest stretching term.

d. Pregenesis convection and tropical cyclone size

Although the above analysis suggests that convective area is not a key feature for TC genesis, one may ponder whether it affects the storm size. The size of a tropical cyclone varies with the storm intensity, latitude, and the ambient environmental conditions along the storm track (Merrill 1984; Emanuel 1986; Liu and Chan 2002; Kimball 2006; Musgrave et al. 2012), and an initially small tropical cyclone tends to remain relatively small throughout its lifetime (e.g., Emanuel 1986). We evaluate tropical cyclone size using the radius of the 34-kt ($1 \text{ kt} = 0.51 \text{ m s}^{-1}$) winds from the Extended Best Track data. The radius of the 34-kt winds is averaged over the four quadrants and is denoted as AR34. We focus on the initial size of a tropical storm and average AR34 over 24 h following the declaration of a tropical storm. To reduce the influence of latitude on tropical cyclone size, we limit our calculation to tropical storms forming between 10° and 25°N . The median AR34 and mean AR34 (Table 1) show that cluster 2 is indeed associated with smaller tropical cyclones. The two-sided Student's t test and the Wilcoxon rank sum test show that the difference in AR34 between clusters 1 and 2 exceeds the 99% confidence level although the difference between clusters 2 and 3 is insignificant.

Previous studies suggested that convection in the outer circulation region can readily draw inflow from large radii (where inertial stability is weak) and increase the storm size (Xu and Wang 2010; Tsuji et al. 2016;

Kilroy and Smith 2017). The same mechanism may explain the link between the pregenesis convective area and the initial size of a tropical cyclone. Since convective area is affected by the environmental humidity (section 4b), the initial size of a tropical cyclone may be influenced by the pregenesis environmental humidity, just as hurricane size is influenced by the environmental humidity (Kimball 2006; Hill and Lackmann 2009; Braun et al. 2012; Wang 2009). Tropical cyclone size is an important factor for the storm damage potential, and the link between the pregenesis environmental humidity and the storm size merits further study.

The subsequent storm evolution after genesis is examined briefly by calculating the storm distribution in different intensity categories within 24–72 h after the declaration of a tropical storm (Table 1). Within the time window examined, storms in cluster 2 have a lower chance to reach hurricane intensity and a higher chance to maintain tropical storm intensity than the other two clusters. Given the negative correlation between tropical cyclone size and intensity change (Carrasco et al. 2014), the intensity differences among the clusters may be related to the environmental conditions rather than the different convective characteristics.

5. Summary and discussion

Geostationary IR brightness temperature data, with relatively high spatial and temporal resolution, are used to examine convective evolution during tropical cyclone formation. The IR Tb data are analyzed in a quasi-Lagrangian, wave pouch–centric framework, and 164 named Atlantic tropical cyclones during 1989–2010 are examined. It is found that convective intensity and convective frequency (or area) both increase with time in the inner pouch region and that strong convection

occurs closer to the pouch center as genesis is approached. In contrast, convection does not change much, or even weakens slightly, in the outer pouch region. Intense convection thus appears to “move” toward the pouch center as genesis is approached.

The convective evolution of individual storms, however, differs substantially from each other. Storms may undergo one, two, or three convective peaks, or do not show a prominent convective peak at all within three days prior to genesis. The various evolution sequences suggest that not all storms fit the conceptual model by Zehr (1992). In addition, convective intensity, area, and duration differ substantially among storms. The composite mean or the median of IR Tb does not represent a recurrent pattern of evolution. Instead, it represents the probability of occurrence of strong convection. In light of the analysis, the conceptual model for tropical cyclogenesis proposed by Wang (2014) is reinterpreted from a probabilistic perspective: the probability of occurrence of deep convection in the inner pouch region increases sharply (stage II) after a gradual process of moisture preconditioning and low-level spinup by cumulus congestus (stage I).

Three distinct spatial patterns of convection within the wave pouch are identified using the *k*-means cluster analysis. The three clusters differ from each other in intensity and spatial distribution of convection. Cluster 1 is characterized by a large convective system displaced 4° – 5° east of the pouch center. The convective system in cluster 2 is much smaller and weaker than that in cluster 1 but is more symmetric about the pouch center. The convective system in cluster 3 has a similar size and intensity to that in cluster 1, but convection is displaced slightly south of the pouch center, and the overall pattern of convection is less asymmetric than cluster 1. The differences in convective patterns can be attributed to the impacts of the environmental humidity, vertical wind shear, and possibly large-scale, low-level convergence. The examination of the vorticity and Okubo–Weiss parameter fields suggest that a smaller and weaker convective system is not necessarily associated with a weaker vortex and that convective intensity or area is not a key feature for tropical cyclone formation.

Further analysis shows that the three clusters have a similar difference in IR Tb between the inner and outer pouch regions, which can be used as a proxy for the radial gradient of diabatic heating. The significance of this feature can be understood in a dynamic context: 1) the Sawyer–Eliassen equation suggests that the transverse circulation is driven by the radial gradient of heating, instead of heating itself, and 2) organized convection is most effective in strengthening the protovortex when its maximum is located near the pouch center (or collocated

with the vorticity maximum). The results suggest that convective organization near the pouch center is a key feature for tropical cyclone formation. Although intensifying convection and increasing convective area in the inner pouch region can contribute to a stronger radial gradient of heating, simply emphasizing convective intensity or area without considering the spatial distribution of convection may be misleading.

Although convective area is not a key feature of convection for tropical cyclogenesis, it may affect the initial size of a tropical cyclone. A smaller convective system, such as in cluster 2, tends to develop into a smaller tropical cyclone. Since convective area appears to be related to pregenesis environmental humidity, the pregenesis environmental humidity may influence the size of a tropical cyclone.

Our conclusion that convective intensity is not a key feature for tropical cyclogenesis is consistent with Leppert et al.’s (2013) and Zawislak and Zipser’s (2014) finding that convective intensity does not distinguish developing disturbances from nondeveloping disturbances. On the other hand, Leppert et al. (2013) and Zawislak and Zipser (2014) did not find a trend in convective intensity or proximity to the circulation center, which is in contrast to the intensifying convection near the pouch center illustrated in our analysis. The discrepancies are likely due to the different tracking and composite methods. Leppert et al. (2013) examined convective properties in different wave phases (northerly, trough, southerly, and ridge), which were defined based on daily mean meridional wind and vorticity averaged between 5° and 20° N using the $2.5^{\circ} \times 2.5^{\circ}$ resolution NCEP–NCAR reanalysis data, and the statistics of convection were also constructed within the latitude band 5° – 20° N. Such a large region may not capture the critical information of tropical cyclone formation within the meso- β -scale inner pouch region (Wang 2012). As shown in Fig. 14, the 5th percentile of IR Tb within a $4^{\circ} \times 4^{\circ}$ box shows a clear trend of intensifying convection. When a large domain ($15^{\circ} \times 15^{\circ}$) is used, the trend becomes much weaker (Fig. 14a) and is masked out by fluctuations when the sample size is reduced by half (Fig. 14b), just as the critical thermodynamic information on tropical cyclogenesis in the inner pouch region may be masked out if an average is taken over a large area (Wang 2012). In Zawislak and Zipser (2014), vorticity maxima were used to track disturbances. Although the vorticity maxima may be close to the pouch center near the genesis time, a good agreement may not exist at the early stage of tropical cyclone formation. In addition, only 12 developing disturbances were examined in Zawislak and Zipser (2014) because of the availability of the field data. Given the long revisit time

Time Series of 5th Percentile IR Tb

FIG. 14. The time series of the 5th percentile of IR Tb ($^{\circ}\text{C}$) within a $15^{\circ} \times 15^{\circ}$ box (black) and within a $4^{\circ} \times 4^{\circ}$ box centered on the pouch center (red). The percentiles are first calculated within a corresponding domain for each storm at each time step and then averaged over (a) 164 storms and (b) 82 storms, respectively.

of passive microwave satellites, stochastic nature of convection (especially the relatively low frequency of occurrence of intense convection), and the modulation of convection by the diurnal cycle, the sample size may be too small to identify a trend in convective intensity.

One may ponder what promotes convective organization in the inner pouch region. The preferred occurrence of deep convection near the pouch center is tied to the dynamic, kinematic, and thermodynamic structure of the wave pouch. Dropsonde data from the Pre-Depression Investigation of Cloud-Systems in the Tropics (PREDICT) field campaign (Montgomery et al. 2012) and high-resolution numerical model simulations both show that the inner pouch region is characterized by high moisture content (Wang 2012), which can reduce cloud-scale entrainment of dry air, maintain the effective buoyancy of air parcels, and thus promote deep convection (Wang 2014; Zipser 2003; Molinari et al. 2012). Moistening of the lower and middle troposphere is mainly realized by congestus convection, which has a lower precipitation efficiency than deep convection (Wang 2014). Moisture lofted by convection can be better retained in the inner pouch region owing to high rotation, weak deformation of the inner pouch flow, and the protection from dry-air intrusion by the outer pouch flow [see further discussions in Wang (2012, 2014) and Riemer and Montgomery (2011)]. The resultant radial differential distribution of moisture favors the development of deep convection near the pouch center. In addition, the boundary layer dynamics may also help to organize convection near the circulation center at the early stage

of tropical cyclone formation (Kilroy et al. 2017). Once organized convection has been established, the transverse circulation driven by convection and boundary layer dynamics concentrates vorticity and intensifies the storm. Meanwhile, the low-level inflow draws moisture from large radii and helps to sustain vigorous deep convection (Fritz and Wang 2014; Wang and Hanks 2016).

One limitation of the study is that we mainly relied on reanalysis data when investigating the dynamic features of incipient tropical cyclones. Reanalysis data, owing to the relatively coarse resolution, may not well represent the size and intensity of TC protovortices. Idealized high-resolution numerical model simulations will be helpful to address how environmental conditions affect the TC protovortex evolution and storm characteristics.

This study takes advantage of the relatively high temporal and spatial resolution of geostationary IR data, which provide nearly continuous monitoring of individual storms. Satellite data have played an important role in tropical cyclone research and operational forecasting in the past few decades, and they will remain an important resource in years to come. The availability of new satellites, such as the GOES-R series (<http://www.goes-r.gov>), the Cyclone Global Navigation Satellite System (CYGNSS; Ruf et al. 2016), and the Time-Resolved Observations of Precipitation Structure and Storm Intensity with a Constellation of Smallsats (TROPICS; <https://tropics.ll.mit.edu>), provides exciting opportunities for tropical cyclone monitoring and investigation. Proper analysis of satellite data can further advance our understanding of tropical

cyclones. Meanwhile, a better understanding of tropical cyclone dynamics and physics will aid in the more effective use of satellite data and contribute to improvements in tropical cyclone forecasting.

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