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Recent advances in research on tropical cyclogenesis

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Abstract

This review article summarizes recent (2014−2019) advances in our understanding of tropical cyclogenesis, stemming from activities at the ninth International Workshop on Tropical Cyclones. Tropical cyclogenesis involves the interaction of dynamic and thermodynamic processes at multiple spatio-temporal scales. Studies have furthered our understanding of how tropical cyclogenesis may be affected by external processes, such as intraseasonal oscillations, monsoon circulations, the intertropical convergence zone, and midlatitude troughs and cutoff lows. Additionally, studies have furthered our understanding of how tropical cyclogenesis may be affected by internal processes, such as the organization of deep convection; the evolution of the "pouch" structure; the role of friction; the development of the moist, warm core; the importance of surface fluxes; and the role of the mid-level vortex. A relatively recent class of idealized, numerical simulations of tropical cyclogenesis in radiative-convective equilibrium have highlighted the potential importance of radiative feedbacks on tropical cyclogenesis. We also offer some recommendations to the community on future directions for tropical cyclogenesis research.

Keywords: Tropical cyclone; Tropical cyclogenesis; Tropical cyclone formation; Tropical disturbance

1. Introduction

Continued progress has been made in understanding a number of aspects of tropical cyclogenesis (hereafter called "genesis"). Fundamental questions, however, remain concerning both external and internal processes, and the interactions of processes, in bringing about genesis. The purpose of this review article is to summarize the recent progress and offer future directions for genesis research. The focus of this article is on physical processes occurring between the microscale and synoptic scale. We will not focus on forecasting and predictability of genesis, and longer timescales (seasonal to climate), although the topics discussed have applicability to these foci.

From definitions in the World Meteorological Organization (2017) Global Guide to Tropical Cyclone Forecasting, genesis may be described as the development from a tropical

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disturbance − "a discrete tropical (or subtropical) weather system of apparently organized convection" − to a tropical depression or tropical storm − "a warm-core, non-frontal, synoptic-scale cyclone with organized deep convection and a closed surface wind circulation about a well-defined center". There is no lower bound on maximum sustained wind speed for a tropical depression. Tropical storms have a maximum, 1-min sustained wind speed of at least 17 m s^{-1}. While there are operationally driven definitions of genesis, i.e., the first appearance of a tropical depression or storm in best-track records, it is difficult to come up with a single definition of genesis that fits all needs. Rather, from a research standpoint, it is important to recognize that genesis is a continuous and complex, multiscale process that occurs over a period of time.

The review is divided up into external (environmental) processes (Section 2) and internal processes (Section 3) that affect genesis. We then discuss how radiative processes and feedbacks may influence genesis (Section 4). The review ends with a summary and overarching recommendations (Section 5).

2. Environmental influences on genesis

2.1. Intraseasonal oscillation interactions

The role of intraseasonal oscillations, including tropical waves and the Madden-Julian Oscillation (MJO), on genesis continues to be an area of active research (e.g., Bian et al., 2018; Chen et al., 2018; Hsieh et al., 2017; Wu and Takahashi, 2018; Xu et al., 2013; Yoshida et al., 2014; Yuan et al., 2015; Zhao and Li, 2019). Schreck (2015, 2016) showed that Kelvin-wave-induced wind anomalies favor genesis days after the Kevin wave convection has passed. The westward tilting wind anomalies persist longer than the Kevin wave period. Westerly anomalies can reach up to 500 hPa days after the convection has moved away (Fig. 1), which can help close the circulation of a disturbance. Zhao and Wu (2018) showed equatorial Rossby waves modulate the mid-level moisture and low-level vorticity, enhancing genesis rates during the convectively active phase. In addition to the direct effects mentioned above, intraseasonal oscillations may also exert indirect effects on genesis by affecting synoptic-scale wave trains (Xu et al., 2014; Zhao et al., 2018, 2019).

Genesis may be simultaneously influenced by more than one type of intraseasonal oscillation (e.g., Park et al., 2015), particularly over the western North Pacific (Cao et al., 2019). The MJO, equatorial Rossby waves, and/or mixed Rossby−gravity waves can cooperatively act to modulate the vertical wind shear and mid-level moisture, and intensify the local circulation by increasing upward motion, deep convection, and low-level vorticity at the genesis location (Chen and Chou, 2014; Ching et al., 2015; Fang and Zhang, 2016; Landu et al., 2020; Shu and Zhang, 2015; Yang and Wang, 2018).

Numerical model simulations have been widely used to quantify the role of intraseasonal oscillations in genesis, which has subseasonal forecasting implications. Extended-range forecasts that have skill in predicting intraseasonal oscillations show skill in predicting genesis events up to two weeks prior to genesis (Nakano et al., 2015; Xiang et al., 2015). A research extension would be to identify the role of intraseasonal oscillations in modulating predictability and skill in subseasonal forecasting of tropical cyclone activity.

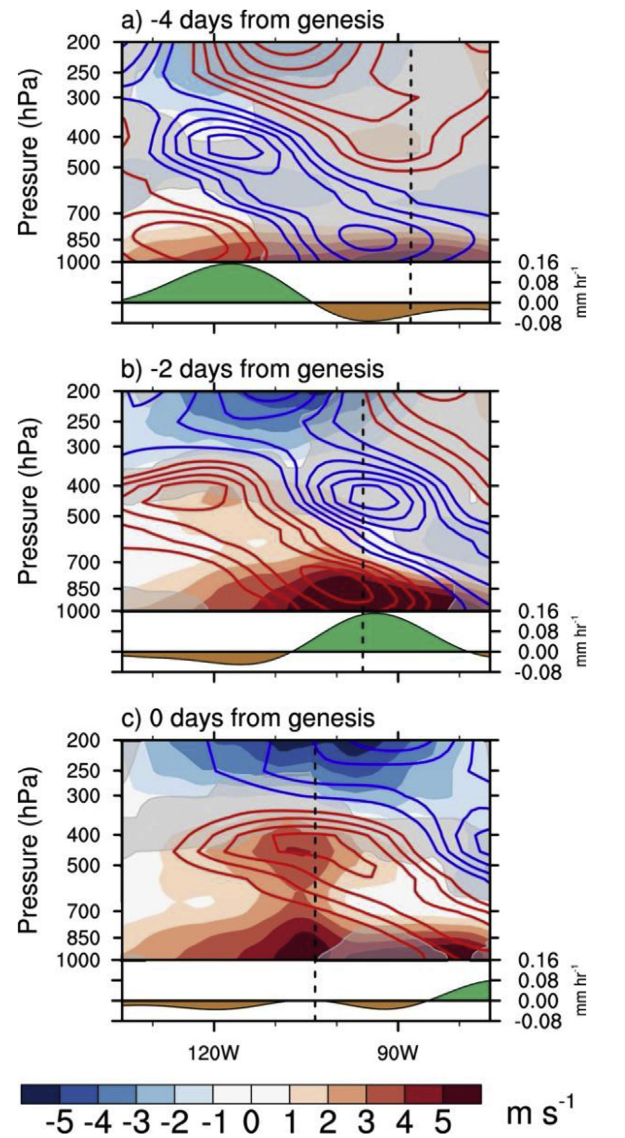

Fig. 1. Composite longitude−height cross sections of semi-Lagrangian total zonal wind (shading) and Kelvin−filtered zonal wind anomalies (contours) averaged 0°−10°N for (a) four, (b) two, and (c) zero days before genesis. Values that are not 95% statistically significantly different from climatology are grayed out. Contours are drawn every 0.2 m s^{-1} with westerlies in red and easterlies in blue. Line graphs show the associated Kelvin-filtered rainfall anomalies averaged 0°−10°N. Longitudes are relative to genesis and are shown for reference only. Vertical dashed line identifies the estimated easterly wave trough. Reproduced from Schreck (2016). © American Meteorological Society. Used with permission.

Multiple tropical cyclogenesis events (MTCEs) are series of tropical cyclones forming in the presence of at least one preexisting tropical cyclone in the same basin. Schenkel (2016, 2017) and Shi et al. (2017) found that Rossby wave radiation contributes to a substantial fraction of MTCEs.

MTCEs occur most frequently in the western and eastern North Pacific (Fig. 2; Schenkel, 2017). In the eastern North Pacific, strong intraseasonal anomalies favor MTCEs (Schenkel, 2016). MTCEs in the western North Pacific occur more frequently when the monsoon trough extends eastward (Guo and Ge, 2018). Hu et al. (2018) found that a Rossby wave packet interacting with a long-lasting monsoon trough resulted in an MTCE. Future research should continue to examine MTCEs across basins, including the role of preexisting tropical cyclones and large-scale flows in favoring MTCEs, together with predictability and forecasting challenges of MTCEs.

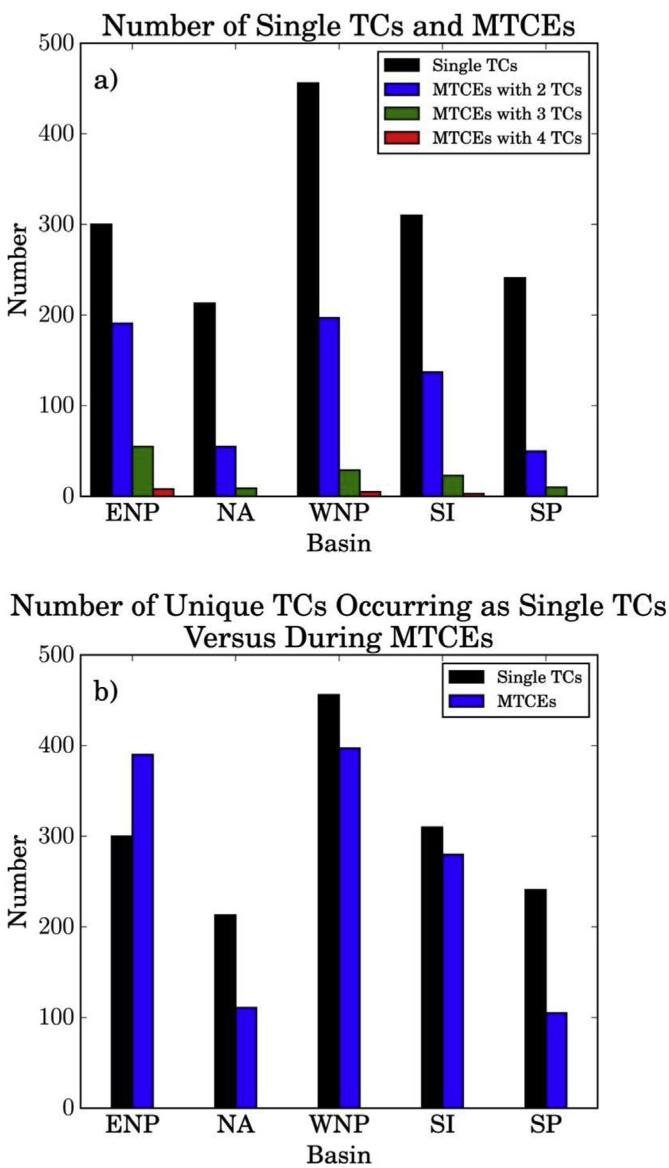

Fig. 2. Number of (a) single tropical cyclones and MTCEs with two, three, and four tropical cyclones and (b) uniquely named tropical cyclones occurring as single tropical cyclones vs. during MTCEs at any point during their lifetime within the eastern North Pacific (ENP), North Atlantic (NA), western North Pacific (WNP), South Indian (SI), and South Pacific (SP). Reproduced from Schenkel (2017). © American Meteorological Society. Used with permission.

2.2. Monsoon and intertropical convergence zone interactions

The monsoon trough is an important synoptic-scale system that influences genesis. Using a modified definition of the monsoon trough, Zong and Wu (2015a) found the percentage of genesis events within the monsoon trough (43.1%) is much smaller than that in previous studies (cf. 73% in Molinari and Vollaro, 2013). In addition, more tropical cyclones form in the monsoon shear region, compared to the confluence zone. In both the monsoon shear region and confluence zone, genesis is associated with baroclinic energy conversion that increases the eddy kinetic energy (Feng et al., 2014).

The contributions of low-frequency variability, associated with the monsoon trough, and high-frequency (synoptic) variability to genesis have been investigated. Wu and Duan (2015) compared simulations − using unfiltered, full winds and filtered, low-frequency winds − of genesis events developing from a synoptic-scale wave train within the monsoon trough. They found that simulations initialized with only low-frequency winds were able to still simulate genesis events successfully. Nonetheless, synoptic disturbances embedded in the monsoon trough provide a rotation-dominant area where positive vorticity mergers can readily occur, and where there is more efficient conversion of diabatic heating to kinetic energy (Fig. 3; Zong and Wu, 2015b). Hsieh et al. (2017) found in their model experiments that genesis events were better simulated in background environments with large low-frequency vorticity, associated with a stronger monsoon trough. A stronger monsoon trough provides greater low-level vorticity, convergence, and moisture for development (Cao et al., 2014, 2016).

Several studies have focused on genesis mechanisms within the monsoon gyre in the western North Pacific. Most tropical cyclones tend to form in the center and eastern part of the monsoon gyre, with the genesis location depending on the size of the monsoon gyre (Liang et al., 2014; Wu et al., 2013). Liang et al. (2014), running idealized simulations of genesis within monsoon gyres, found Rossby wave energy dispersion to the southeast of the monsoon gyre may play an important role in genesis.

The intertropical convergence zone (ITCZ) is also important for genesis in certain circumstances. Cao et al. (2013) documented how a synoptic-scale wave train could trigger ITCZ breakdown, and subsequently lead to genesis in the western North Pacific. Yokota et al. (2015) found that barotropic instability of the ITCZ low-level flow is responsible for the formation of precursor vortices, which agrees with previous studies. Thereafter, buoyancy production on the system scale is important for continued development.

Future research should continue to investigate multiscale influences on genesis in different environments and background flows to build our understanding of the global diversity of genesis pathways.

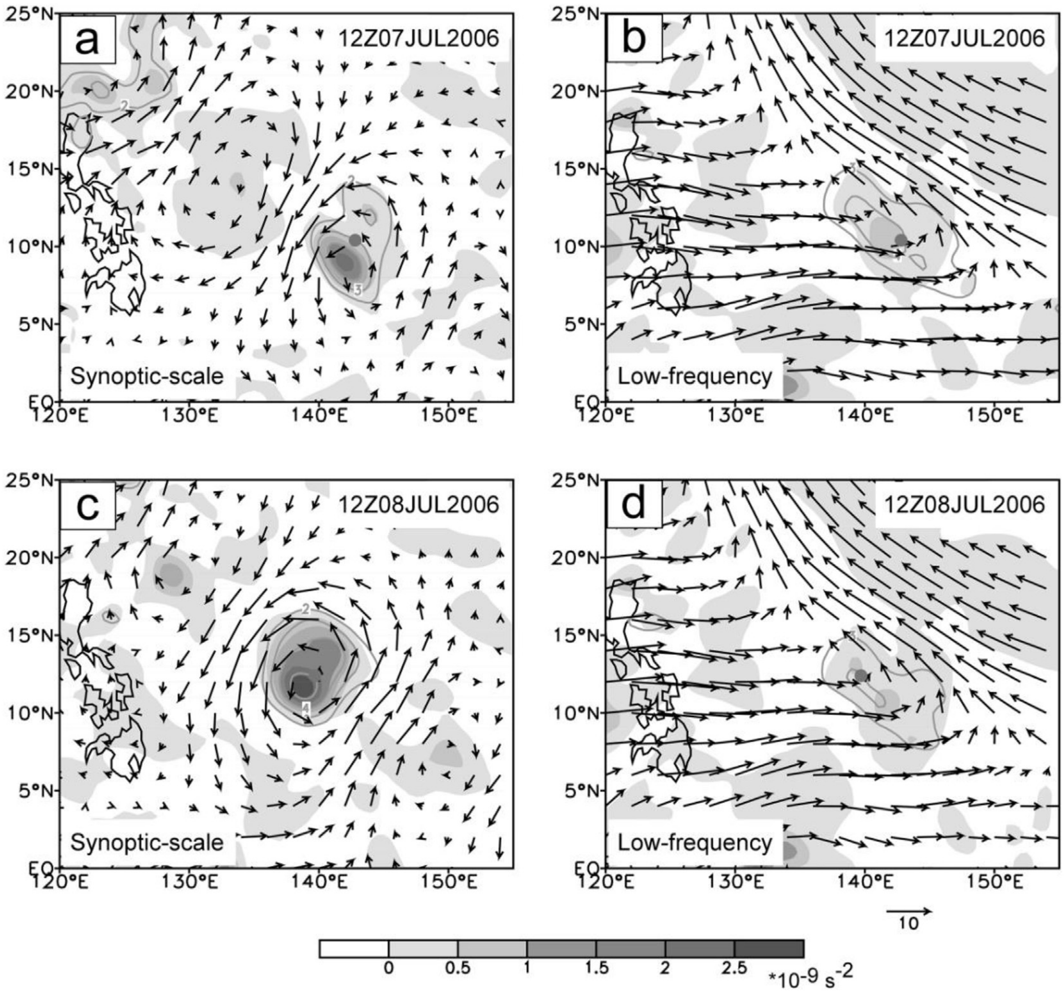

Fig. 3. (a),(c) The 850-hPa synoptic-scale and (b),(d) low-frequency relative vorticity (contours, 10^{-5} s^{-1}), Okubo−Weiss parameter (shaded, 10^{-9} s^{-2}), and winds (vectors, m s^{-1}) at (a),(b) 1200 UTC 7 July and (c),(d) 1200 UTC 8 July 2006, with dots indicating the tropical disturbance center associated with Typhoon Bilis. Reproduced from Zong and Wu (2015b). © American Meteorological Society. Used with permission.

2.3. Midlatitude interactions and tropical transition

Although many tropical cyclones form in the deep tropics (far removed from the influence of midlatitude systems), about 16% of global genesis events from 1948 to 2010 formed via tropical transition, during which a cold-core cyclone of baroclinic origin transitions into a warm-core tropical cyclone (Davis and Bosart, 2003; McTaggart-Cowan et al., 2013). Recent case studies have identified tropical cyclones forming via tropical transition in a variety of basins, including the South Atlantic (Pinto et al., 2013), eastern North Pacific (Bentley and Metz, 2016), western North Pacific (Chang et al., 2019; Yuan and Wang, 2014), and Mediterranean Sea (Mazza et al., 2017).

Tropical transition genesis events typically develop poleward of 25° latitude, and their frequency of formation varies between and across individual ocean basins (McTaggart-Cowan et al., 2013). These events can occur over sea surface temperatures colder than 26.5 °C (e.g, Tory and Dare, 2015), particularly in the North Atlantic (Defforge and Merlis, 2017), due to the reduction of bulk tropospheric stability beneath the upper-tropospheric disturbance that steepens lapse rates and facilitates the development of deep convection. A better metric of the potential for a tropical cyclone to form via tropical transition is the coupling index, a measure of bulk tropospheric stability (Bosart and Lackmann, 1995). McTaggart-Cowan et al. (2015) suggested that a coupling index $\leq$ 22.5 °C is necessary for tropical transition to occur.

According to Galarneau et al. (2015), genesis occurring in the vicinity of an upper-tropospheric disturbance may result from either favorable interaction of a preexisting low-level cyclonic vorticity anomaly with an upper-tropospheric trough or the tropical transition of a subtropical cyclone (e.g., Bentley et al., 2016). González-Alemán et al. (2015) and Bentley et al. (2017) examined upper-tropospheric features associated with North Atlantic subtropical cyclone formation. The structure of these upper-tropospheric features vary − often identified as cutoff lows, meridional troughs, or zonal troughs (Fig. 4) − and typically form as a result of anticyclonic wave breaking (Galarneau et al., 2015; McTaggart-Cowan et al., 2013). After anticyclonic wave breaking, as in the case of Hurricane Chris

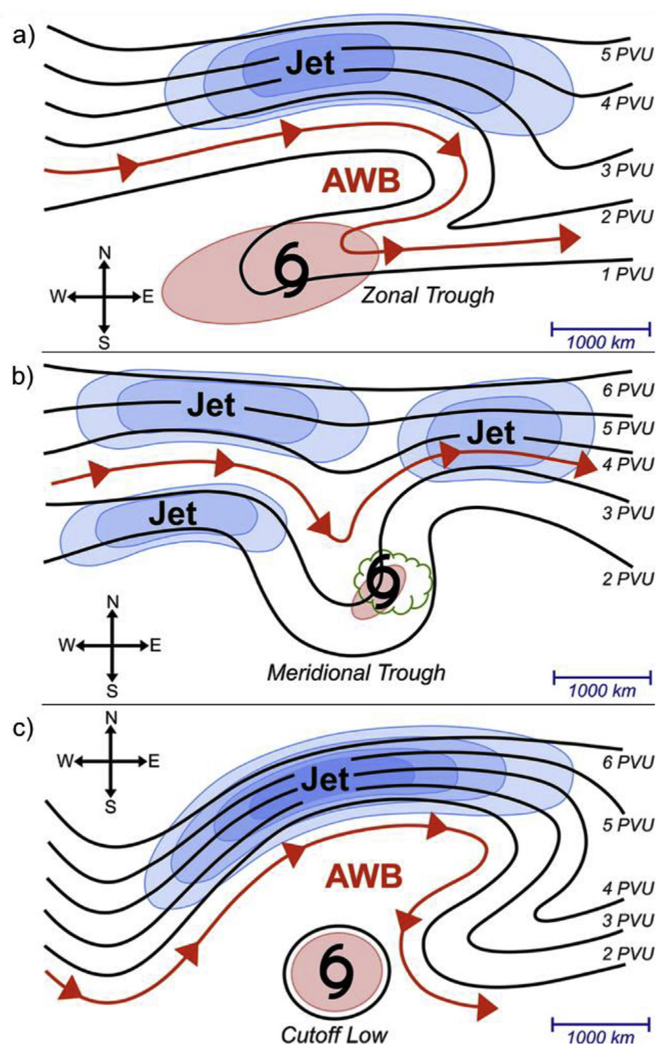

Fig. 4. Schematic representation of a subtropical cyclone forming in association with an (a) cutoff low, (b) meridional trough, and (c) zonal trough. Black contours depict upper-tropospheric potential vorticity (PVU). Red arrows depict an upper-tropospheric streamline. The blue-shaded region indicates the location of the upper-tropospheric jet. The pink-shaded region indicates the location of coupling index values of $\leq 22.5\,^{\circ}C$. The "AWB" label denotes a region where anticyclonic wave breaking is occurring. In (b), the green-scalloped contour surrounds a region of mid-level quasi-geostrophic forcing for ascent. Adapted from Bentley et al. (2017). © American Meteorological Society. Used with permission.

(2012), the merger of potential vorticity anomalies and cyclonic roll-up of the potential vorticity streamer contributed to genesis (Maier-Gerber et al., 2019).

An area of future research is to examine the predictability of tropical cyclones forming via the tropical transition process through ensemble prediction systems, and to further explore features and processes associated with tropical transition.

2.4. Vertical wind shear

There is increased understanding of how vertical wind shear affects genesis, particularly the sensitivity in different environments. The alignment of the low- and mid-level vortices is associated with genesis and subsequent intensification (Fig. 5; Tao and Zhang, 2014; Yoshida et al., 2017). Failed genesis in high shear occurs when convection is advected farther away from the low-level center, leading to reduced secondary circulation strength and weakening vortex precession (Tao and Zhang, 2014). Tropical cyclones at higher latitudes (Zhou, 2015) and at higher sea surface temperatures (Tao and Zhang, 2014) are able to better resist shear and align.

Vertical wind shear can also enhance the flux of environmental dry air into the Lagrangian recirculation region of a tropical disturbance, particularly if the mid-level vortex is weak or misaligned from the low-level vortex (Brammer et al., 2018; Fowler and Galarneau, 2017; Freismuth et al., 2016; Fritz and Wang, 2013; Gjorgjievska and Raymond, 2014; Penny et al., 2015; Rajasree et al., 2016b; Rutherford et al., 2017). A drier mid-troposphere implies a greater entropy deficit, which reduces the upward mass flux and inhibits the spinup of the low-level vortex (Tang et al., 2016; Wang et al., 2018; 2019; Zhou, 2015). This spinup inhibition could be caused by downdrafts flushing of the boundary layer with low-entropy air (Penny et al., 2015; Tao and Zhang, 2014); a feedback, whereby an initial dry-air intrusion weakens convection and the mid-level vortex, leading to greater susceptibility to more dry-air intrusions (Freismuth et al., 2016; Gjorgjievska and Raymond, 2014); and concurrent subsidence occurring with drying (Fritz and Wang, 2013).

Future research should continue to understand how nonlinear interactions of environmental factors (e.g., vertical wind shear, tropospheric moisture, sea surface temperature, etc.) affect genesis, particularly how these factors influence convective evolution and vortex development. In particular, it would be beneficial to better understand the mechanisms responsible for aligning a weak, tropical-disturbance strength vortex in the presence of moderate vertical wind shear.

3. Internal processes during genesis

3.1. Convective evolution

The convective evolution ahead of and during genesis, and how it differs from nondeveloping disturbances, has been an important focus. Leppert et al. (2013a, 2013b) found that the coverage of low infrared brightness temperatures ($\leq$240 K) provides the best distinction between developing and nondeveloping African easterly waves (AEWs). The convective intensity, measured by the lightning flash rate, decreases as genesis approaches (Leppert et al., 2013a). Additionally, passive microwave data also indicates that convective intensity is not a good differentiator between developing and nondeveloping disturbances (Zawislak and Zipser, 2014a). These studies suggest that updraft intensity is less important than the areal coverage of persistent convection near the circulation center.

More recently, Wang (2018) investigated the convective evolution of more than 150 genesis events over the North Atlantic. There are three distinct clusters (Fig. 6), which differ in convective intensity, area, and asymmetry. In contrast to the abovementioned studies, the convective intensity and

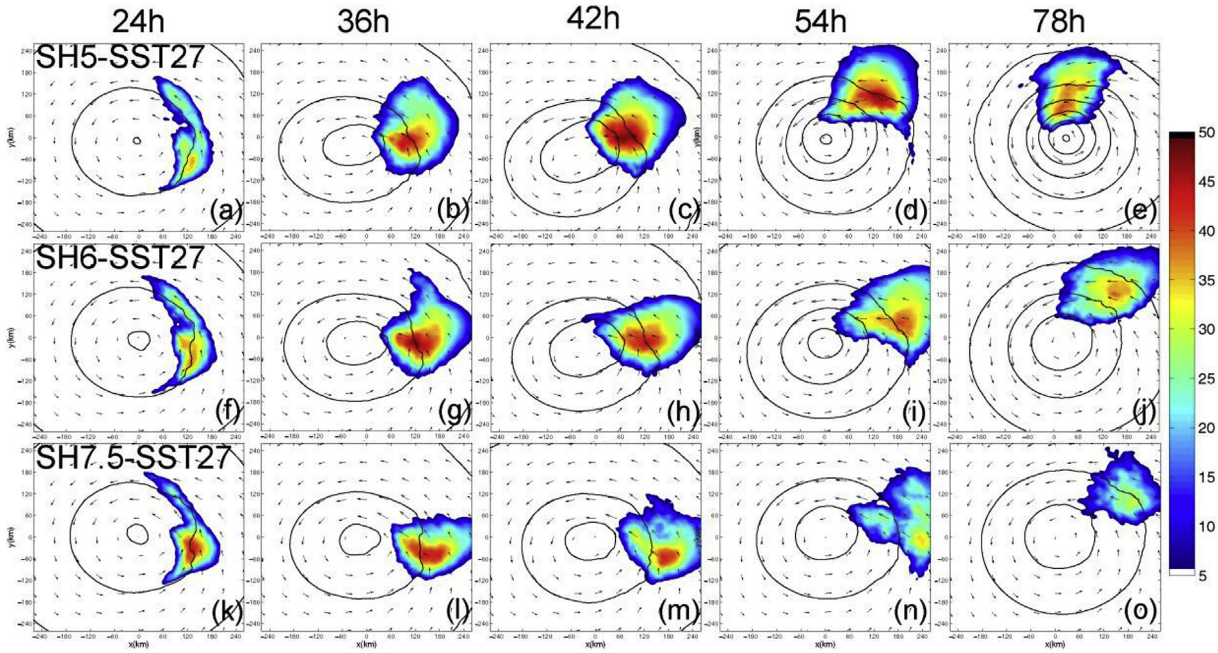

Fig. 5. Sea-level pressure (contour), surface wind (vector), and maximum reflectivity (shading) at 24, 36, 42, 54, and 78 h for simulations with (top row) 5 m s^{-1}, (middle row) 6 m s^{-1}, and (bottom row) 7.5 m s^{-1} of westerly shear. All simulations have a sea surface temperature of 27 °C. Reproduced from Tao and Zhang (2014).

frequency in developing disturbances both increase with time in the inner-circulation region, while changing little, or even weakening slightly, in the outer-circulation region. Wang (2018) emphasized that the spatial pattern of convection is important to consider, particularly the presence of organized convection near the circulation center, not just convective intensity or area alone. Since different studies employ different tracking and composite methods, it would be valuable to reproduce results from contrasting studies using consistent tracking, areal averaging, and compositing methods in order to reevaluate differing conclusions regarding the observed convective evolution leading up to genesis.

The distributions of convective and stratiform clouds/precipitation have been compared in developing and nondeveloping disturbances. Deep convective towers within diurnally evolving mesoscale convective systems have been observed in a number of genesis events (e.g., Akter, 2015; Park et al., 2015, 2017). Park and Elsberry (2013) found a sharp latent heating maximum in the strong updraft region of the pre-Nuri (2008) disturbance during the Tropical Cyclone Structure 2008 (TCS08) field campaign. In contrast, nondeveloping tropical disturbances had deeper layers of more vertically uniform heating and cooling rates, and some evidence of more shallow cloud tops, which distinguished nondeveloping cases from the developing cases. When viewing precipitation on the system scale using passive microwave data, Zawislak and Zipser (2014a) found developing disturbances have a larger precipitating area than nondeveloping disturbances, but there is no clear trend in precipitating area prior to genesis. Fritz et al. (2016) found that precipitation rate increases substantially within 36 h of genesis in the inner-circulation region, and suggested that genesis is the outcome of the collective contribution of different types of precipitation, including stratiform precipitation. Data from the latest and next generation of satellites will be helpful for improving our understanding of cloud and precipitation structure evolution in both developing and nondeveloping tropical disturbances.

The roles of convective bursts and the persistence of convection have been studied in developing and nondeveloping disturbances. Chang et al. (2017) found that multiday convective bursts are observed in 67.5% of developing disturbances and in 13.8% of nondeveloping disturbances in the western North Pacific. Multiday convective bursts lead to increases in low-level vorticity and circulation (Bell and Montgomery, 2019), particularly in favorable environments, although there are many nondeveloping disturbances that also exist in favorable environments (Kerns and Chen, 2013). Further investigation of nondeveloping disturbances in favorable environments would be useful in assessing why vigorous convective bursts do not lead to genesis in certain cases.

The effects of convectively generated downdrafts and cold pools on genesis have been more closely examined. Numerical simulations have found that downdrafts become more widespread and stronger prior to genesis (Davis, 2015; Wang, 2014a), contrary to the hypothesis that downdrafts must weaken prior to genesis (e.g., Bister and Emanuel, 1997). The resulting cold pools help to organize new convective updrafts and increase the low-level vorticity, albeit cold pools may modulate the timing of genesis and may not be essential for genesis itself (Wang et al., 2019). Moreover, low-level convectively induced vorticity anomalies at the edge of cold pools, and subsequent mergers of these anomalies, can form the positive vorticity nucleus of a developing disturbance

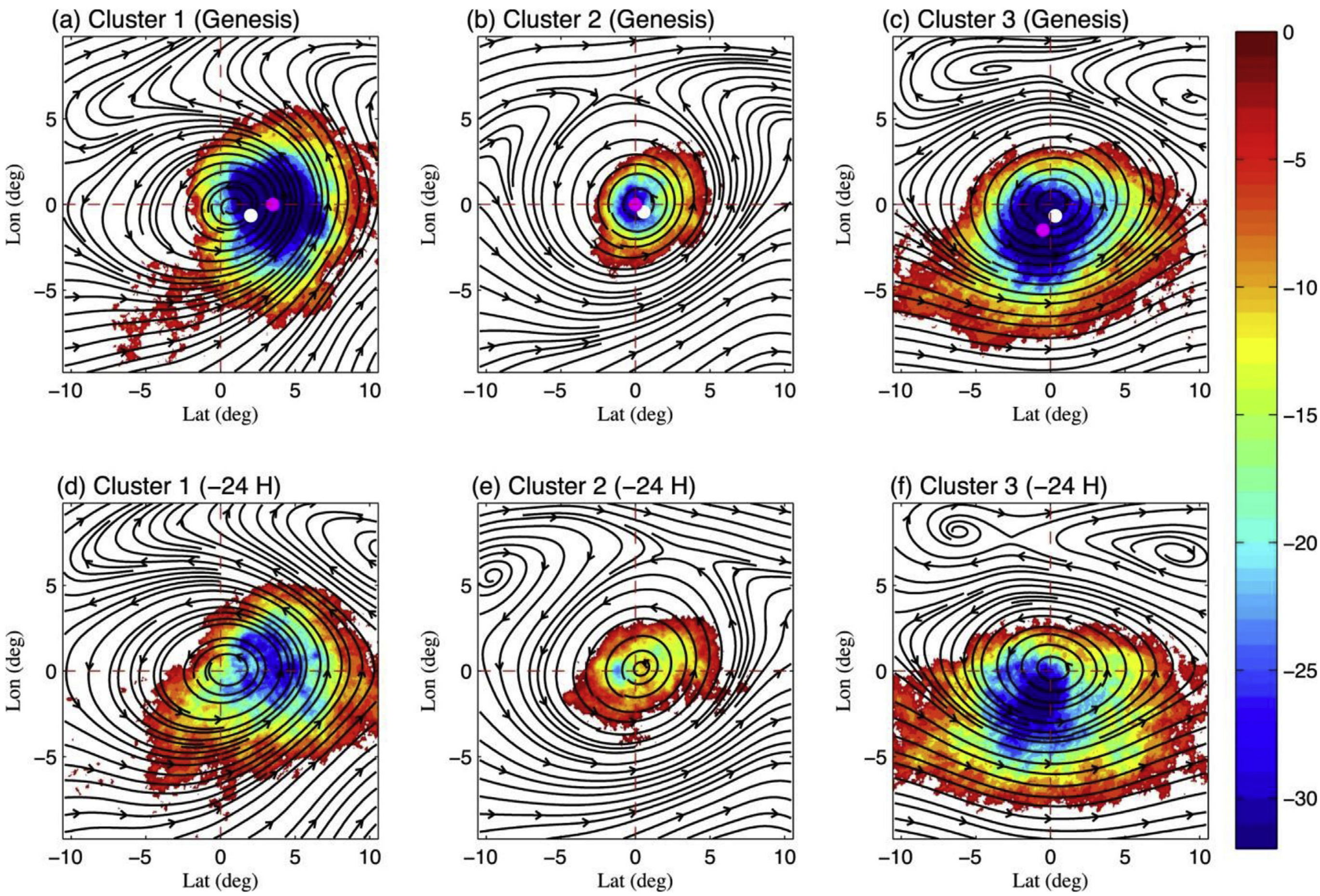

Fig. 6. Composite mean of infrared brightness temperature (°C) superimposed on 700-hPa wave-relative streamlines for three distinct convective clusters embedded in different environments at (a)−(c) the time of genesis and (d)−(f) 24 h prior to genesis. The white dots in (a)−(c) represent the composite mean genesis location for each cluster, and the magenta dots are the convection centers. Reproduced from Wang (2018). © American Meteorological Society. Used with permission.

(Fig. 7; Smith and Nicholls, 2019). Future research should continue to clarify the role of convectively generated cold pools on genesis, and whether certain flavors of downdrafts are harmful or helpful to genesis.

The rotating convection framework (Kilroy and Smith, 2013, 2016; Montgomery and Smith, 2017) was applied to genesis by Kilroy et al. (2017b). They found that cyclonic vorticity, generated by deep convection, can gradually organize into a monopole at relatively low wind speeds (Fig. 8) and, in a different study, at low latitudes (Steenkamp et al., 2019). Kilroy et al. (2017b) hypothesized that the processes involved in genesis are not fundamentally different from those involved in intensification, and that genesis does not require the prior existence of a mid-level vortex. Wu and Fang (2019), in their simulation of the genesis of Super Typhoon Nepartak (2016), found that the low-level vortex weakened as the mid-level vortex strengthened, suggesting that the mid-level vortex may not be directly helpful for genesis. Additionally, the interaction of identical mid-level vortices that are close to one another can inhibit or delay genesis under certain circumstances in an idealized framework (Schecter, 2016). Future research should continue to investigate the role of the mid-level vortex leading up to genesis.

3.2. Marsupial paradigm

The “marsupial paradigm” (Dunkerton et al., 2009) continues to be used to study genesis in different ocean basins. Lussier III et al. (2014) applied the ideas of the marsupial paradigm in the genesis of Typhoon Nuri (2008) during the TCS08 field campaign, concluding that the Kelvin cat's eye (or “pouch”) region is favorable for mesoscale vorticity organization by convection and low-level spinup. Rajasree et al. (2016a, 2016b) investigated the genesis of Cyclone Madi (2013) in the North Indian Ocean, particularly the upscale cascade of vorticity within the pouch and the inhibition of entrainment of environmental dry air into the pouch. Asaadi et al. (2016a, 2016b, 2017) used a potential vorticity framework to study the formation of the Kelvin cat's eye in AEWs, reiterating the importance of the wave critical layer for genesis.

In the North Atlantic, AEWs are a primary source of tropical cyclones. Russell et al. (2017) estimated that about 70% of Atlantic tropical cyclones directly or indirectly originate from AEWs. Compared to nondeveloping AEWs, developing waves have larger lower-to-middle tropospheric moisture (Fig. 9), associated with a more dominant, moist

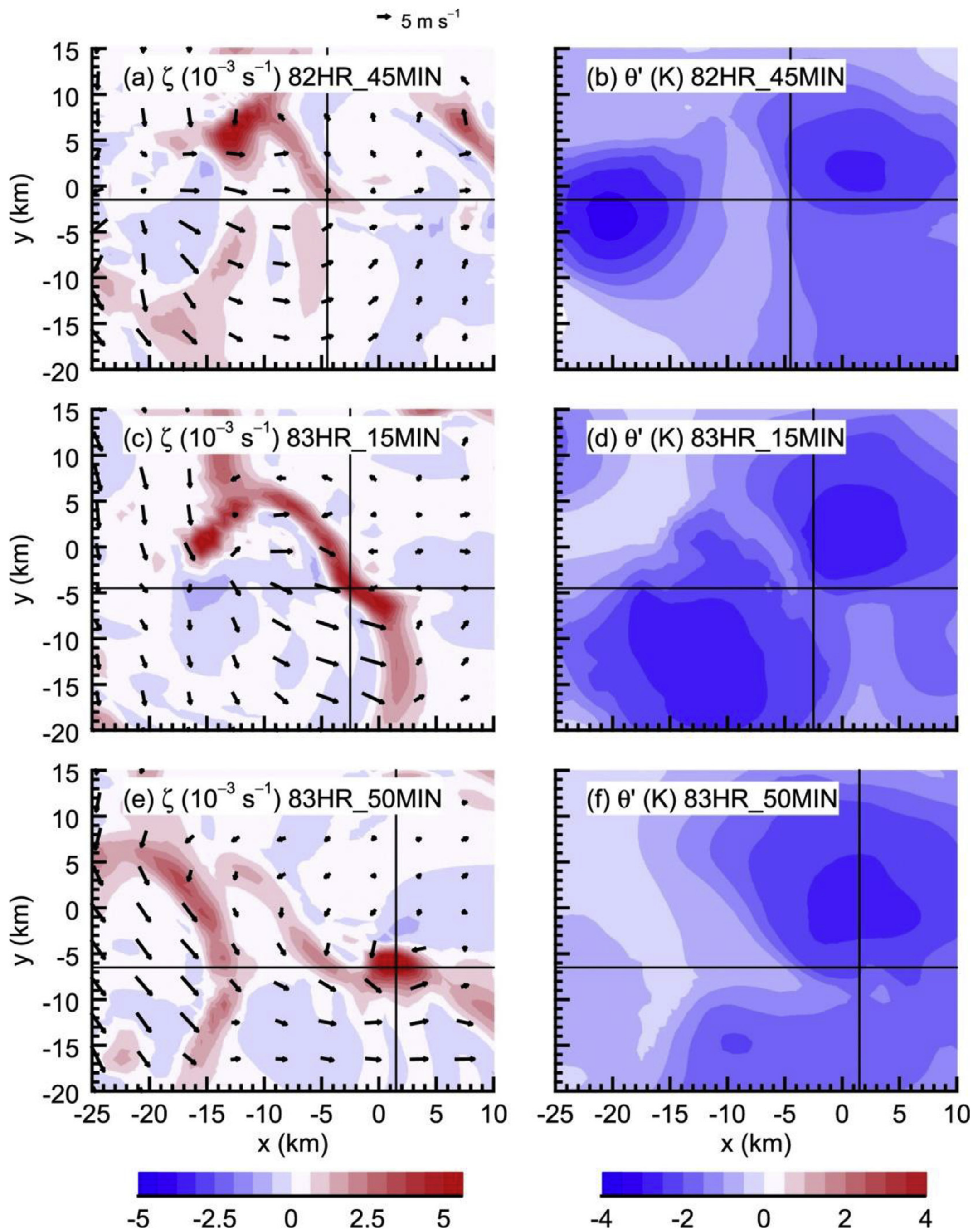

Fig. 7. Horizontal cross sections of (left) vertical vorticity with horizontal wind vectors and (right) perturbation potential temperature taken at the lowest model level (z = 29.5 m) at (a),(b) 82 h 40 min, (c),(d) 83 h 15 min, and (e),(f) 83 h 50 min into a simulation. The crosshairs in each plot mark the genesis low-level convectively induced vorticity anomaly. Reproduced from Smith and Nicholls (2019). © American Meteorological Society. Used with permission.

southern vortex (Chen and Liu, 2014) and less ingestion of environmental dry air into the wave (Brammer and Thorncroft, 2015; Hankes et al., 2015) from sources over the eastern Atlantic (Brammer and Thorncroft, 2017). The more favorable, moist environment promotes convective bursts, resulting in upper-level warming and contributing to storm-scale surface pressure falls (Cecelski and Zhang, 2013; Cecelski et al., 2014). Thereafter, the coalescing of positive low-level vorticity anomalies in the pouch, along with the vertical alignment of the low- and mid-level vortices, can lead to genesis (Zhu et al., 2015).

There have been refinements of diagnostics and methods to monitor and study pouches. Tory et al. (2013) introduced the Okubo−Weiss−Zeta parameter, a Galilean-invariant metric that is the product of the absolute vorticity and normalized Okubo-Weiss parameter, to highlight the importance of low-deformation vorticity in genesis. Rutherford et al. (2017) developed Lagrangian frame-independent variables to

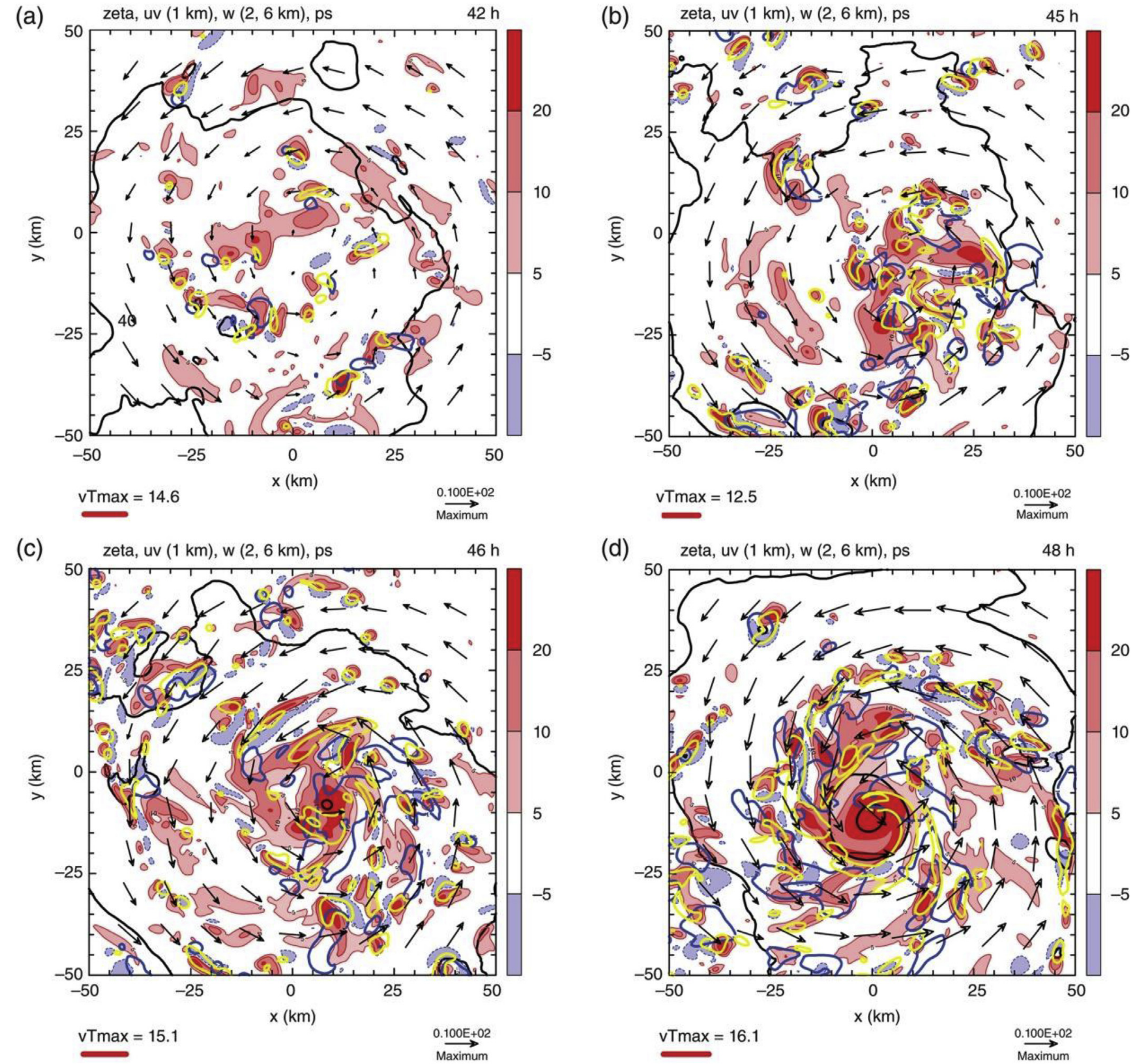

Fig. 8. Horizontal cross-sections of relative vertical vorticity ($\times 10^{-4}$ s^{-1}, color shading) and wind vectors at a height of 1 km for a genesis simulation, with 1 m s^{-1} contour of vertical velocity at heights of 2 km (blue) and 6 km (yellow). Also shown are surface pressure (black contours every 2 hPa). The wind vectors are in relation to the maximum reference vector at the bottom right, while on the bottom left the maximum total wind speed in the domain plotted is given in m s^{-1}. The times shown are: (a) 42 h, (b) 45 h, (c) 46 h, (d) 48 h. Reproduced from Kilroy et al. (2017b).

analyze vorticity and moisture transport in relation to Lagrangian boundaries, and applied this framework to study the genesis of Hurricane Nate (2011). Additionally, Rutherford et al. (2018) showed that Lagrangian Okubo-Weiss parameter and the Lagrangian vorticity field, along with threshold values for each, are useful for tracking pouches and their development (Fig. 10). Further application of novel ways to track and analyze the flow structure of disturbances that can be applied broadly to all disturbances would be of benefit to the research and forecast communities.

3.3. Friction

The role of friction in genesis had been thought to be relatively unimportant at low wind speeds (e.g., Ooyama, 1982). Kilroy et al. (2017a) and Wang et al. (2019) performed idealized numerical simulations that showed boundary-layer convergence produced by friction plays a crucial role in organizing deep convection near the circulation center, even with a weak initial vortex. The role may be through decreasing the convective inhibition (Raymond and

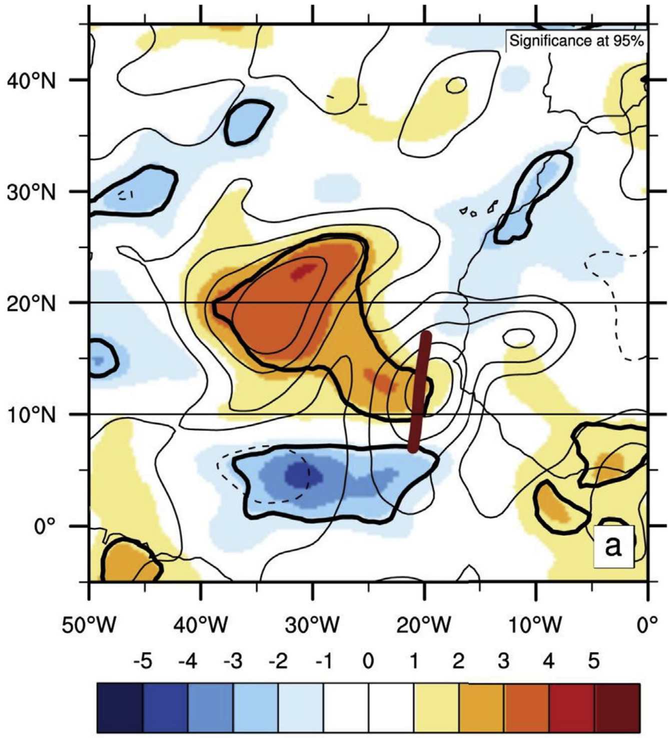

Fig. 9. Mean composite total precipitable water (mm) differences for favorable developing waves vs. favorable nondeveloping waves (shading). Contours represent the composite favorable developing waves. The shading and contour intervals are equivalent. The thick red line depicts the mean trough line of all included waves. The thick black contour encompasses the regions that are statistically significant at greater than 95%. Adapted from Brammer and Thorncroft (2015). © American Meteorological Society. Used with permission.

Kilroy, 2019). The strength of the frictional boundary-layer convergence and the location where the air exits the boundary layer are dependent on the size of the initial vortex. Kilroy and Smith (2017) showed that the smaller the initial vortex, the sooner genesis occurs in their numerical simulations.

3.4. Thermodynamic evolution

3.4.1. Warm-core development

The evolution of the thermal structure before and during genesis was examined by a number of studies using recent field campaign data. Using dropsonde data from The Pre-depression Investigation of Cloud-systems in the Tropics (PREDICT) field campaign, Komaromi (2013) found that developing disturbances had warmer temperature anomalies from 500 to 200 hPa ahead of genesis. Using microwave temperature profiler data from PREDICT, Davis et al. (2014) showed developing disturbances had a more negative radial gradient of temperature in the upper troposphere, attributed to organized convection near the circulation center.

The development of the warm-core structure in the lower troposphere was examined by Kerns and Chen (2015). They focused on the role of stratiform precipitation, and suggested that the lower tropospheric subsidence associated with stratiform precipitation may induce net warming in regions of light precipitation, where adiabatic warming exceeds evaporative cooling (Fig. 11). They also hypothesized that the vertical alignment of the lower tropospheric subsidence warming with the middle-to-upper tropospheric warming, which induces larger surface pressure falls, is a critical step for genesis. A research extension would be to develop a more coherent picture linking the roles of convective and stratiform precipitation in developing the warm-core structure during the genesis period.

3.4.2. Moistening

Another important aspect of the thermodynamic evolution during genesis is column moistening. Wang and Hankes (2016) showed that a nonlinear relationship between saturation fraction and precipitation rate exists in tropical disturbances, like it generally does for convection over tropical oceans (e.g., Bretherton et al., 2004). Therefore, saturation fraction can serve as a switch for sustained deep convection. Several recent observational studies showed moistening of the inner-circulation region two or three days prior to genesis (Fig. 12; Helms and Hart, 2015; Komaromi, 2013; Wang, 2012; Zawislak and Zipser, 2014b), which precedes a sharp increase in precipitation and low-level vorticity (Wang and Hankes, 2016).

Using numerical model simulations, Wang (2014a) proposed a two-stage conceptual model for genesis. In the first stage, cumulus congestus moistens the lower-to-middle troposphere and effectively spins up the low-level vortex, owing to its bottom-heavy heating profile (Wang, 2014b). In the second stage, deep convection, forming in the moistened inner-pouch region, moistens the upper troposphere and spins up the circulation over a deeper layer. Since column moistening occurs preferentially in the inner-core region (Wang, 2012; Wang and Hankes, 2016), upward motions and cyclonic vorticity preferentially increase in the inner-pouch region (Wang, 2014a). In addition to saturation fraction, the moist convective instability, convective inhibition, and surface heat fluxes are important for controlling the lower troposphere vertical mass flux (Raymond and Kilroy, 2019).

3.4.3. Surface fluxes

The structure and evolution of surface enthalpy fluxes, and their importance for genesis, has been more closely examined. Using an idealized model simulation, Murthy and Boos (2018) tested the hypothesis that a negative radial gradient of surface enthalpy flux is necessary for genesis. It was shown that sustained spinup does not occur if the surface enthalpy flux is homogenous, even when the surface enthalpy flux is set to a large value. A larger surface enthalpy flux near the circulation center can be realized via two mechanisms: 1) increased winds and the wind dependence of the surface enthalpy flux; or 2) enhanced air-sea enthalpy disequilibrium if the surface wind speed is capped to a constant value. Murthy and Boos (2018) suggested that a negative radial gradient in the surface enthalpy flux fosters greater convective instability near the circulation center and is a necessary condition for genesis, a finding corroborated by Gao et al. (2019). In contrast, Fritz

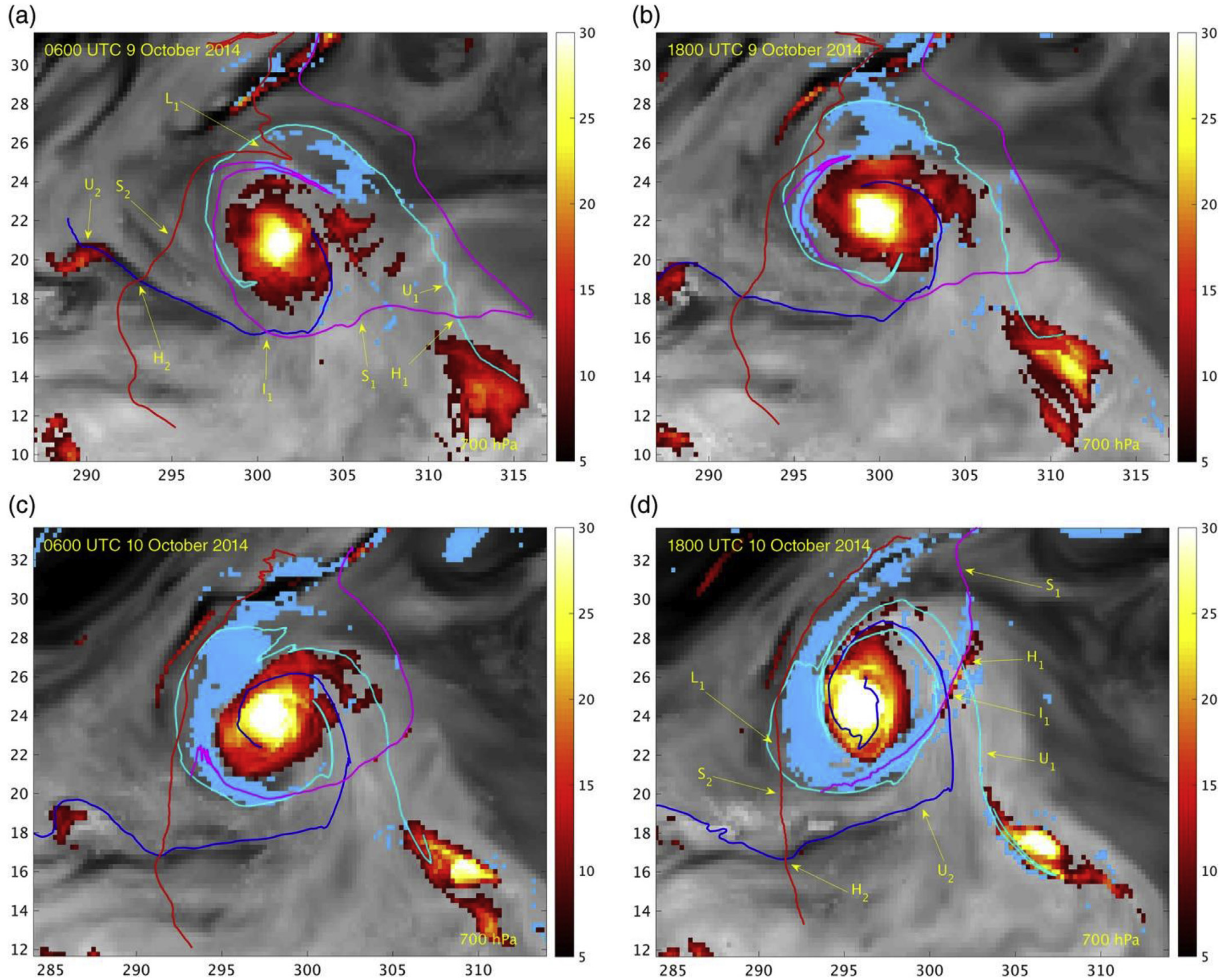

Fig. 10. Lagrangian flow topology (stable manifolds: magenta and red outlines, unstable manifolds: cyan and blue outlines), Lagrangian vorticity field (hot colors; dimensionless), the shearing regions of the Lagrangian Okubo-Weiss field (cool colors), and the equivalent potential temperature field (gray shading) at 700 hPa for Hurricane Fay during the development period at (a) 0600 UTC and (b) 1800 UTC on 9 October, and (c) 0600 UTC and (d) 1800 UTC on 10 October 2014. Reproduced from Rutherford et al. (2018).

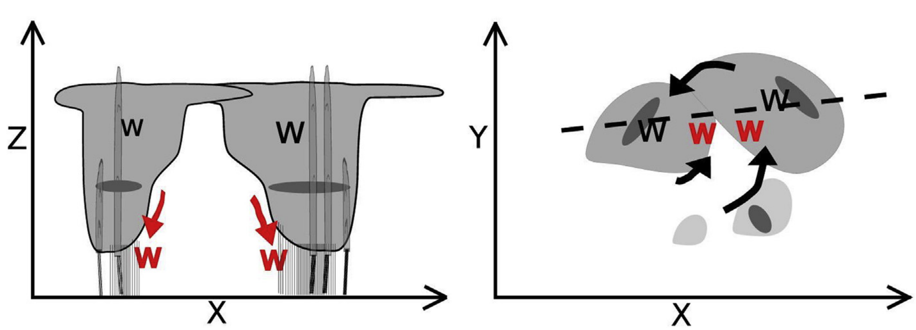

Fig. 11. Schematic of warm-core development in genesis. (left) Vertical cross sections: the dark horizontal shading represents the melting level within mesoscale convective systems. (right) Plan views with the cross-section location marked with the dashed line; dark shading represents heavy convective rainfall. Areas of mesoscale subsidence are indicated with red arrows, and associated warming by the red "W"s. Upper-level warming in the anvil is indicated by the black "W"s. Adapted from Kerns and Chen (2015). © American Meteorological Society. Used with permission.

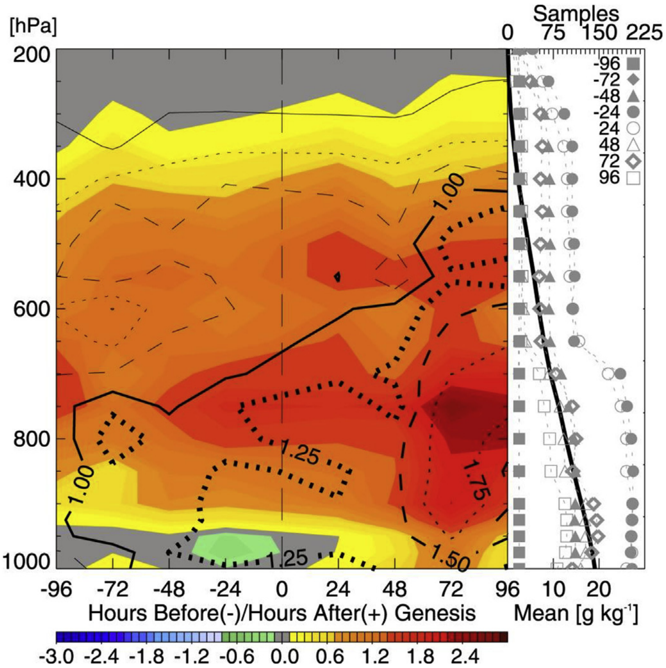

Fig. 12. Composite water vapor mixing ratio anomaly (color shaded) of all dropsondes within 3° of the 850-hPa vorticity maximum center for all genesis cases; black contours are standard deviation. Number of samples (gray) at each time and the mean profile (black) are indicated on the right. Reproduced from Zawislak and Zipser (2014b). © American Meteorological Society. Used with permission.

and Wang (2014) used a numerical simulation to show that the inward moisture flux from large radii, not local surface moisture fluxes, is a more important contribution to the negative radial gradient in enthalpy and total precipitation. Future research should continue to evaluate the sensitivity of genesis to the spatial structure and time evolution of surface and moisture fluxes, connecting these results to those in Section 3.4.2 concerning the saturation fraction and other moisture-related variables in controlling genesis.

3.5. Dynamic-thermodynamic interactions

The constructive interaction between dynamical and thermodynamical processes is critical to genesis. A bottom-heavy vertical mass flux profile, one that has a maximum vertical mass flux at lower-to-middle levels of the troposphere, is more conducive to an increase of near-surface vorticity (Gjorgjievska and Raymond, 2014). A mid-level vortex, and its associated balanced thermal structure, is associated with a smaller normalized gross moist stability and bottom-heavy vertical mass flux profiles, along with an increase in precipitation rates (Fig. 13; Raymond et al., 2014). A positive radial gradient of (normalized) gross moist stability may be important for creating a synergy between surface fluxes, advection by the developing secondary circulation, and the emerging inner-core vortex (Tang, 2017a; 2017b). A stronger mid-level vortex is also better able to preserve the heating and moistening by vortical hot towers, increasing the available potential energy, which can then be converted to the kinetic energy of the secondary and primary circulations (Wang et al., 2016; Xi, 2015). Bell and Montgomery (2019) hypothesize that the coupling of the vorticity and moisture fields, and episodic deep convection occurring in association with this coupling, are critical for building the low- and mid-level circulations during genesis. In this hypothesis, the mid-level vortex plays a supporting role, by containing moisture and protecting against dry-air intrusions, and deep convection plays the primary role (Bell and Montgomery, 2019; Wu and Fang, 2019). Additional understanding of the coupling of the vorticity and moisture fields during genesis, perhaps viewed from a spatially and temporally varying gross moist stability and circulation perspectives, would be helpful.

3.6. Microphysics

Genesis in numerical models is sensitive to the choice of microphysics scheme. Cecelski and Zhang (2016) conducted numerical model simulations of Hurricane Julia (2010) without the latent heat of fusion due to depositional growth. In these simulations, genesis did not occur. Penny et al. (2016) showed that vortex development in numerical models can be sensitive to the representation of graupel and diabatic heating profiles, and that larger heating rates lead to overdevelopment (Fig. 14). Moreover, more sophisticated microphysics schemes do not necessarily produce better genesis simulations.

Another effect of ice microphysics is to produce a mid-level vortex. Kilroy et al. (2018) showed that a mid-level vortex forms in the presence of ice, namely enhanced diabatic heating rates at mid-levels due to ice processes. In particular, cooling due to sublimation at the bottom of the stratiform ice region is an important factor (Nicholls et al., 2018). Kilroy et al. (2018) also argued that a mid-level vortex is not necessary for genesis to occur, and that a systematic lowering of the vertical mass flux maximum does not occur prior to genesis in their simulation, in contrast with the hypothesis offered by Raymond et al. (2014).

Aerosols may also affect the evolution of tropical disturbances. In the case of AEWs, Saharan mineral dust can have direct radiative effects, which can result in a generation of eddy available potential energy and a conversion to eddy kinetic energy (Bercos-Hickey et al., 2017; Grogan and Thorncroft, 2019), and may increase the growth rate of AEWs (Nathan et al., 2017). On the other hand, radiative heating may increase stability above the boundary layer, and lead to circulation changes that result in drying and increased wind shear, inhibiting genesis (Tao et al., 2018).

Future research should continue to clarify the role of microphysics and aerosol effects, and microphysics parameterizations in numerical models, in modulating genesis.

4. Radiative-convective equilibrium and radiative feedbacks

Radiative-convective equilibrium (RCE) is an idealization of the tropical atmosphere in which there is a balance between radiative heat loss of the atmosphere and heating by

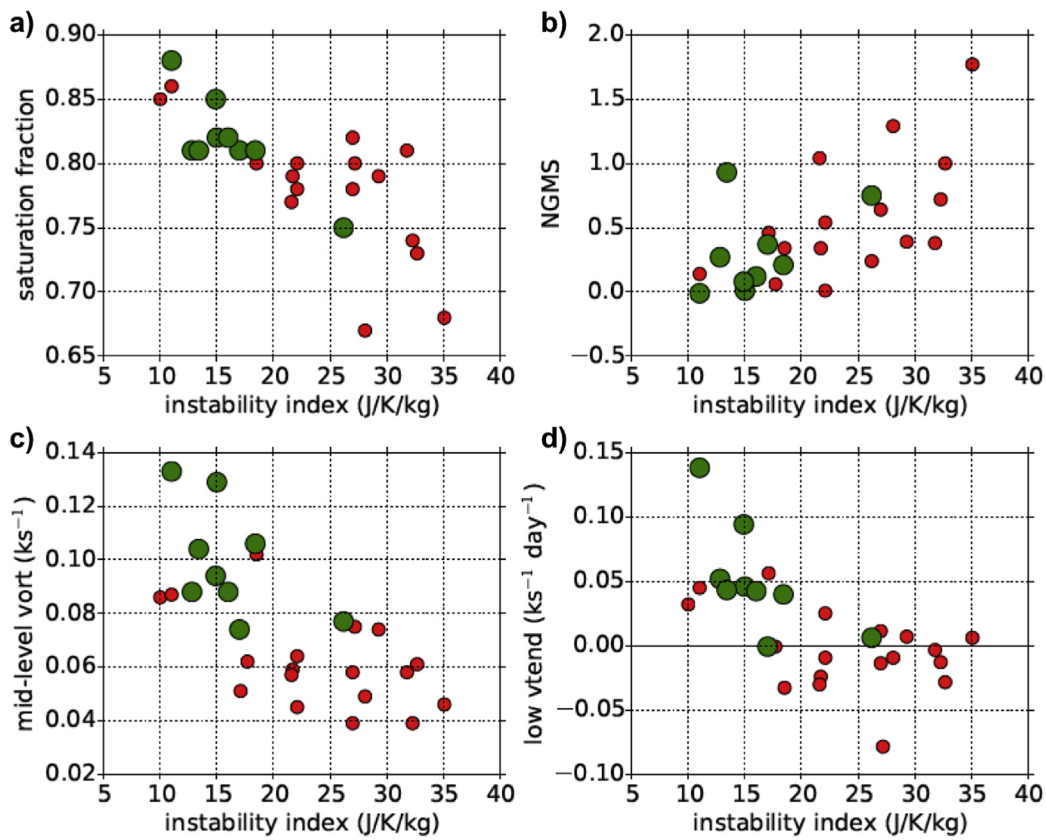

Fig. 13. (a) Saturation fraction, (b) normalized gross moist stability, (c) mid-level mean absolute vorticity, and (d) low-level mean absolute vorticity versus instability index (increasing values indicate greater moist convective instability between the lower and middle troposphere) for tropical disturbances observed by field campaigns in the western North Pacific (TCS08) and the North Atlantic (PREDICT). The cases represented by large green dots intensified into tropical storms within 48 h of the observations, while cases represented by small red dots did not. Adapted from Raymond et al. (2014).

convection. RCE has been used as a background state for tropical cyclone studies (Chavas and Emanuel, 2014; Chavas and Reed, 2019; Khairoutdinov and Emanuel, 2013; Nolan et al., 2007; Reed and Chavas, 2015). One phenomenon that has emerged from studies of RCE is convective self-aggregation, in which convection spontaneously organizes into one or several persistent clusters. Self-aggregation is the result of interactions between clouds, moisture, radiation, surface fluxes, and circulation (Bretherton et al., 2005; Wing and Emanuel, 2014), and when simulated on an f-plane, takes the form of spontaneous genesis (Nolan et al., 2007). In such RCE simulations, moist cyclonic vortices form, while other regions of the domain become drier, eventually forming a single dominant vortex that subsequently develops into a tropical cyclone (Davis, 2015; Wing et al., 2016). Consistent with other studies, Davis (2015) found that the approach to saturation within a mid-tropospheric vortex accelerates the genesis processes.

One result that has emerged is that radiative feedbacks, which are essential to self-aggregation, aid in the development of coherent rotating structures and accelerate genesis (Davis, 2015; Muller and Romps, 2018; Nicholls, 2015; Wing et al., 2016). Radiative feedbacks result not simply from the existence of radiative processes, but from interactions between spatially and temporally varying radiative heating/cooling and the developing tropical cyclone. Differential heating between deep convection and the surrounding cloud-free region favors rising motion and moistening in the region of deep convection, which promotes clustering of convection and continued moistening of the atmosphere (Wing et al., 2016). Differential heating also can generate a circulation response that favors genesis (Muller and Romps, 2018; Nicholls, 2015). Both mechanism denial experiments and column moist static energy variance budget diagnostics indicate that these radiative feedbacks, while not strictly necessary, significantly accelerate genesis, and are at least as important as surface flux feedbacks in the early stages of genesis (Fig. 15; Muller and Romps, 2018; Wing et al., 2016). These results from idealized simulations were also found in analysis of radiative feedbacks during genesis and intensification in historical high-resolution climate model simulations (Wing et al., 2019).

These recent results add to a growing body of evidence of the importance of radiation for tropical cyclones. Of particular relevance for the role of radiative feedbacks on genesis, the diurnal cycle has been found to accelerate genesis and intensification through a destabilization of the local and large-scale environment (promoting deep convection) due to strong nighttime longwave cooling (Fig. 16; Ge et al., 2014;

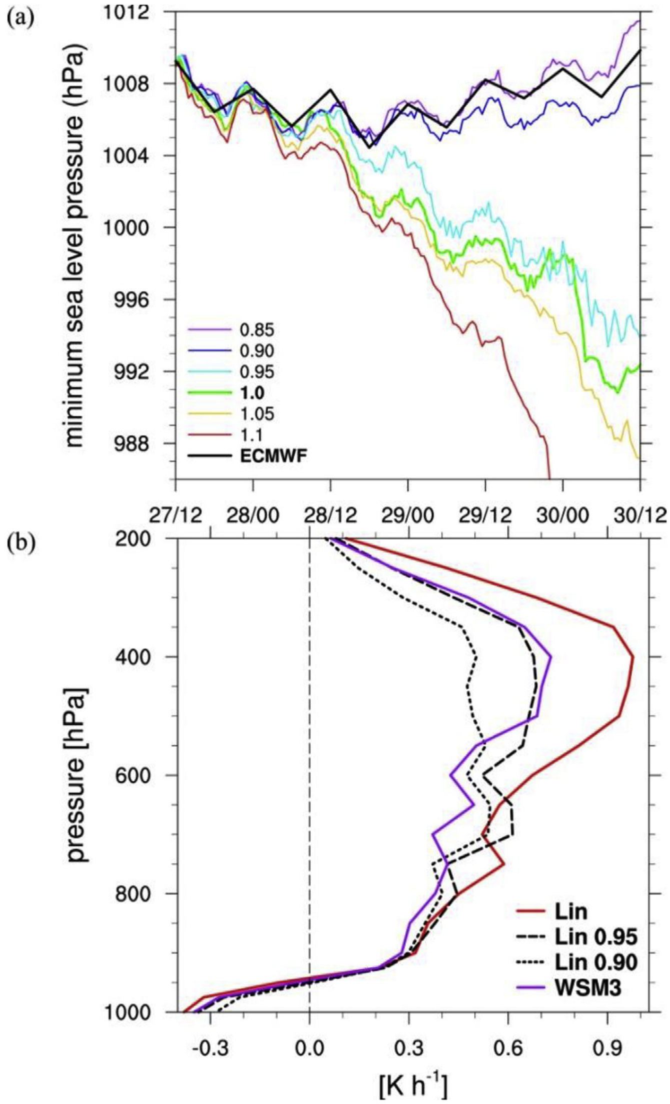

Fig. 14. (a) Minimum sea level pressure (hPa) for simulations that used the Purdue−Lin microphysics scheme in which the diabatic heating rate was multiplied by a factor ranging from 0.85 to 1.1. The minimum sea level pressure from the ECMWF analysis (black) is shown for reference. (b) Vertical profiles of the average diabatic heating rate (K h^{-1}) for the period 1800 UTC 27 August−0600 UTC 28 August for the Lin simulation (red line), the WSM3 simulation (purple line), and for simulations that used the Purdue−Lin microphysics scheme in which the diabatic heating rates were multiplied by a factor of 0.95 (long dashed line) and 0.90 (short dashed line). Reproduced from Penny et al. (2016). © American Meteorological Society. Used with permission.

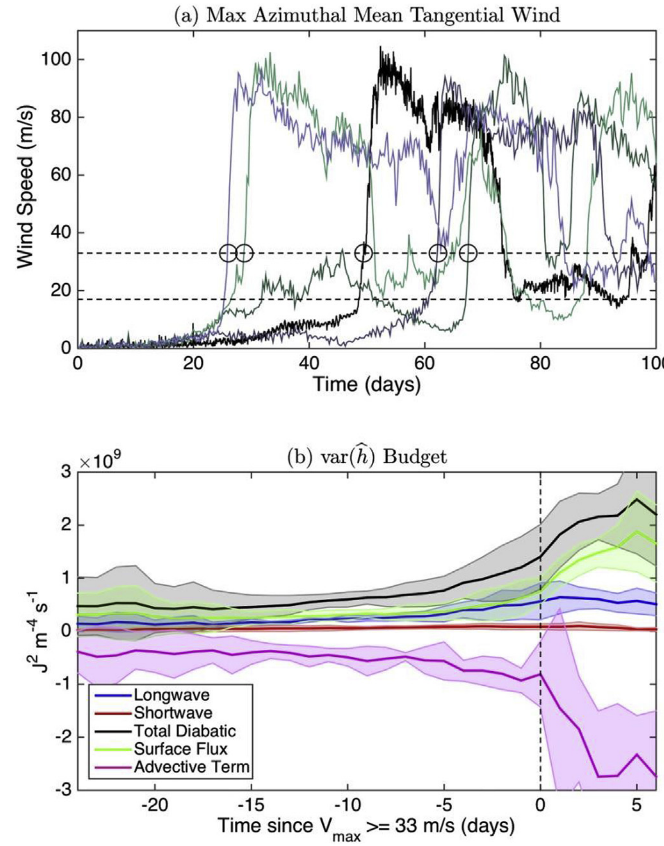

Fig. 15. Five-member ensemble of genesis in RCE simulations. (a) The evolution of the maximum azimuthal-mean tangential wind for each ensemble member. The dashed lines indicate wind speeds of 17 m s^{-1} and 33 m s^{-1}. The circles indicate the first time the wind speed reaches 33 m s^{-1}. (b) The contributions to the growth rate of column-integrated frozen moist static energy variance for the ensemble members shown in (a), where the solid line is the ensemble mean and the shading indicates the standard deviation. The ensemble members are aligned at the times indicated by the circles in (a), which is defined as time 0 on the time axis in (b). Reproduced from Wing et al. (2016). © American Meteorological Society. Used with permission.

Melhauser and Zhang, 2014; Tang and Zhang, 2016). In case studies of Hurricane Karl (2010) and Hurricane Edouard (2014), genesis was suppressed in the absence of nighttime cooling in numerical modeling experiments (Melhauser and Zhang, 2014; Tang and Zhang, 2016). Ruppert and O'Neill (2019), however, did not find that the diurnal cycle affected the timing of genesis in their RCE simulations.

Future research should continue to make use of RCE as an idealized framework for investigating the intrinsic properties of genesis. Future work should also further investigate the role of radiation in genesis. Observational analyses of radiative fluxes and feedbacks would be particularly valuable.

5. Summary and overarching recommendations

There have been numerous recent advances in our understanding of physical processes affecting genesis. A central theme has been to better understand how interactions between multiple external influences affect genesis, such as the interaction of intraseasonal and synoptic variability and the interaction of multiple environmental controls (e.g., vertical wind shear, tropospheric moisture, sea surface temperature, etc.). Understanding these interactions results in a more holistic understanding of the diversity of genesis pathways that occur in reality, including MTCEs and tropical transition events. Our overarching recommendation is to continue to investigate these multiscale interactions, particularly their influences on convective evolution and vortex structure (alignment) during the genesis process.

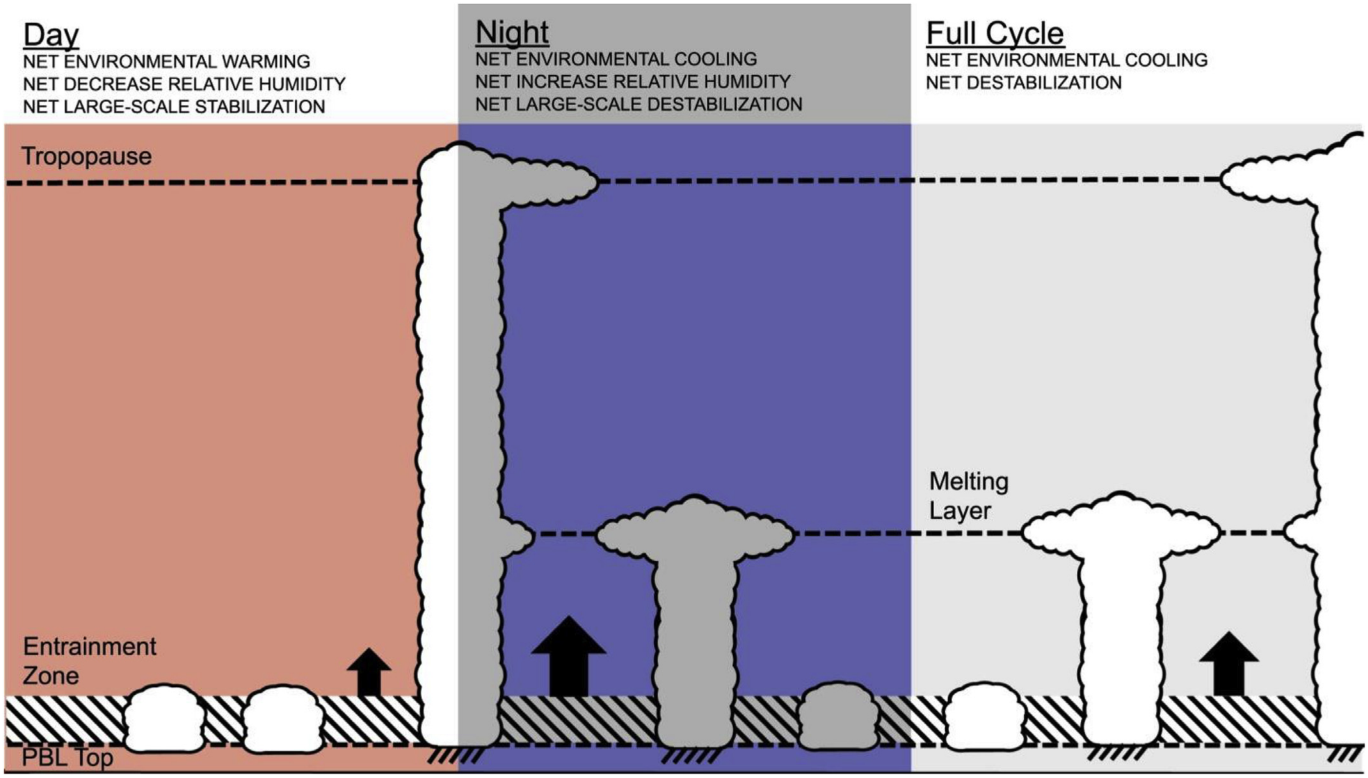

Fig. 16. Schematic depiction of the diurnal radiation cycle impact on the clear-air local and large-scale environment for the genesis of Hurricane Karl (2010) during the first 24 h of a simulation. The red (blue) background shading of day (night) indicates net clear-air large-scale environmental heating (cooling). Arrows indicate the relative magnitude of the local-environment clear-air net radiative cooling (solid) for the entrainment zone. Adapted from Melhauser and Zhang (2014). © American Meteorological Society. Used with permission.

Another central theme has been to better understand internal processes that are critical for genesis, and what nondeveloping disturbances lack. The spatial pattern (or circular organization) and multiday bursts of convection appear to be important differentiating factors between developing and nondeveloping disturbances. Convectively generated cold pools, through triggering of new convection and enhanced vorticity along their edges, may aid genesis. Stratiform precipitation, associated with mesoscale convective systems, is responsible for the development of the mid-level vortex. Cumulus congestus clouds contribute to the spinup of the low-level vortex and moisture preconditioning. There remain questions, however, as to whether the mid-level vortex plays a critical or supporting role in genesis. Additionally, there are new and refined hypotheses offered on how the spatial structure and temporal evolution of surface fluxes, column moistening, warm-core development, microphysical effects, and radiative feedbacks matter to genesis. Our overarching recommendation is to continue to investigate cloud, precipitation, and process-based differences between developing and nondeveloping disturbances, and apply the increased knowledge to improve models and forecast skill of genesis.

Future investigations will be aided by new and better observations from satellites and future field campaigns that address the hypotheses and uncertainties herein. The increased use of machine and deep learning approaches, combined with physical understanding and numerical modeling, may also be fruitful for untangling the complexities of genesis.

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