Tropical Cyclogenesis From Self-Aggregated Convection in Numerical Simulations of Rotating Radiative-Convective Equilibrium

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Abstract In a modeled environment of rotating radiative-convective equilibrium (RCE), convective self-aggregation may take the form of spontaneous tropical cyclogenesis. We investigate the processes leading to tropical cyclogenesis in idealized simulations with a three-dimensional cloud-permitting model configured in rotating RCE, in which the background planetary vorticity is varied across \( f \)-plane cases to represent a range of deep tropical and near-equatorial environments. Convection is initialized randomly in an otherwise homogeneous environment, with no background wind, precursor disturbance, or other synoptic-scale forcing. We examine the dynamic and thermodynamic evolution of cyclogenesis in these experiments and compare the physical mechanisms to current theories. All simulations with planetary vorticity corresponding to latitudes from 10\( ^\circ \) to 20\( ^\circ \) generate intense tropical cyclones, with maximum wind speeds of 80 m s\(^{-1}\) or above. Time to genesis varies widely, even within a five-member ensemble of 20\( ^\circ \) simulations, indicating large stochastic variability. Shared across the 10\( ^\circ \)–20\( ^\circ \) group is the emergence of a midlevel vortex in the days leading to genesis, which has dynamic and thermodynamic implications on its environment that facilitate the spin-up of a low-level vortex. Tropical cyclogenesis is possible in this model at values of Coriolis parameter as low as that representative of 1\( ^\circ \). In these experiments, convection self-aggregates into a quasicircular cluster, which then begins to rotate and gradually strengthens into a tropical storm, aided by strong near-surface inflow that is already established days prior. Other experiments at these lower Coriolis parameters instead self-aggregate into a nonrotating elongated band and fail to undergo cyclogenesis over the 100-day simulation.

Plain Language Summary Despite decades of research on tropical cyclones, we still do not have a universal agreement on how they form. Current theories agree that some sort of disturbance must exist beforehand, but our knowledge of the processes leading to a surface-based cyclone remains limited. To address this, we examine idealized numerical simulations in which convection is allowed to spontaneously cluster together on its own due to interactions between clouds, moisture, and radiation. Using this framework, we obtain a complete view of the tropical cyclone formation process, including the formation of the precursor disturbance. New to this study is the use of lower values of background rotation to simulate the formation of hurricanes at lower latitudes. Overall, simulations are run to represent latitudes from 0.1\( ^\circ \) to 20\( ^\circ \). Every simulation corresponding to latitudes between 10\( ^\circ \) and 20\( ^\circ \) produces a major hurricane, a few days after a vortex emerges a few kilometers aloft and affects its surrounding environment. Some simulations at 1\( ^\circ \) and 2\( ^\circ \) lead to formation of a weaker tropical cyclone, after clouds have first organized into one circular cluster. In other low-latitude cases, this cluster of storms is instead a long band and fails to form a tropical cyclone. We offer detailed analysis of the tropical cyclone formation process in each case by considering both dynamic and thermodynamic factors.

1. Introduction

Organized systems of tropical convection have garnered an increasing amount of attention in recent decades, in both observational studies and idealized numerical simulations. These range in scale from mesoscale convective systems (Houze, 2004) to tropical cyclones (TCs) (Emanuel, 2003), to planetary-scale features such as the Madden-Julian oscillation (Madden & Julian, 1971; Zhang, 2005). Despite comprising a small percentage of total rain-bearing systems in the tropics, organized convection has significant implications, with mesoscale convective systems producing a majority of tropical rainfall (Nesbitt et al., 2006).
Recent studies making use of idealized numerical simulations of radiative-convective equilibrium (RCE) have identified feedbacks directly contributing to the organization of otherwise random tropical convection. Many of these simulations were performed with three-dimensional cloud-resolving models configured on square domains (Abbot, 2014; Hohenegger & Stevens, 2016; Holloway & Woolnough, 2016; Bretherton et al., 2005; Jeevanjee & Romps, 2013; Muller & Bony, 2015; Muller & Held, 2012; Tompkins & Craig, 1998; Wing & Emanuel, 2014) and brought further attention to the “self-aggregation” phenomenon. Convective self-aggregation is defined as a spontaneous transition from randomly distributed to organized convection in an otherwise homogeneous environment without external forcing (Bretherton et al., 2005; Wing et al., 2017). The feedbacks contributing to convective self-aggregation generally involve clouds, water vapor, radiation, and mesoscale circulations, serving to transport frozen moist static energy (FMSE) from dry to moist regions. The end result is one or several isolated regions of persistent moisture and deep convection, surrounded by dry, subsiding air across a broader portion of the model domain. Connections between idealized self-aggregation and real convective organization in the tropics are now being made (Bretherton & Khairoutdinov, 2015; Holloway et al., 2017), serving as a catalyst for further research into the topic, particularly in the realm of its connection to climate sensitivity (Bony et al., 2015; Mauritzen & Stevens, 2015; Wing et al., 2018; Wing, 2019).

TCs are among the most dangerous manifestations of organized convection, with several impacts including wind damage, storm surge, and potentially extreme rainfall. Studies of rotating RCE have shown that self-aggregation can take the form of spontaneous tropical cyclogenesis (Bretherton et al., 2005; Boos et al., 2016; Davis, 2015; Held & Zhao, 2008; Khairoutdinov & Emanuel, 2013; Merlis et al., 2016; Muller & Romps, 2018; Nolan et al., 2007; Reed & Chavas, 2015; Shi & Bretherton, 2014; Wang et al., 2019; Wing et al., 2016; Zhou et al., 2014, 2017). Idealized simulations in these studies led to TC formation from both a prescribed moist bubble or vortex and white noise random convection. However, little correlation was found by Nolan et al. (2007) between time to genesis and parameters such as the Coriolis parameter, midlevel relative humidity, and convective instability. Wing et al. (2016) examined spontaneous TC genesis from a homogeneous environment using the budget equation for the spatial variance of column-integrated FMSE developed by Wing and Emanuel (2014). They found significant contributions to the cyclogenesis process from radiative feedbacks in addition to surface fluxes, results which were supported by similar experiments performed by Muller and Romps (2018). In addition, their results suggested the potential for self-aggregation feedbacks to accelerate the cyclogenesis process by as much as a factor of two. A vorticity-based analysis of TC genesis in rotating RCE was recently performed by Wang et al. (2019), who examined the evolution of lower-tropospheric vorticity in sensitivity tests where wind shear and surface cold pools were altered.

Despite extensive research, there still exists no general consensus for how TCs form. A concept applied particularly to genesis from easterly waves is the “marsupial pouch” paradigm (Dunkerton et al., 2009). In this framework, a layer emerges where a prototype vortex is protected from dry air intrusion, able to concentrate vorticity and convective heating, and eventually split from its parent wave and grow into a mature TC. Several theories focus on the role of a preceding midlevel vortex in facilitating development of vorticity at lower levels, including ideas presented by Bister and Emanuel (1997), Ritchie and Holland (1997), Raymond et al. (2011), and Gjorgjievsk and Raymond (2014). These studies differ on the dominant mechanisms by which a midlevel vortex leads to spin-up at lower levels, differences as fundamental as whether dynamic or thermodynamic factors play a leading order role. Other theories place less emphasis on the presence of a midlevel vortex. An example is the “vortical hot towers” concept from Hendricks et al. (2004) and Montgomery et al. (2006), in which the primary coherent vortices that emerge are those from individual deep convective towers. Given this lack of consensus, the rotating RCE modeling framework may be valuable for examining TC genesis across a wide range of atmospheric conditions. In this setup, the TC is allowed to form however it so chooses, free from bias from how it is initialized or how it is forced by the large-scale environment. This provides a more holistic view of genesis, allowing us to examine the processes that lead to the formation of the precursor disturbance which later facilitates development of the TC.

Many prior studies of rotating RCE were conducted on an $f$-plane with a constant Coriolis parameter of $5 \times 10^{-5}$ s$^{-1}$, corresponding to a latitude of 20°. However, while TCs are prevalent near 20°, they are also common equatorward, particularly in the Northwest Pacific basin. Notably, 14 known storms of tropical storm or hurricane intensity have been identified equatorward of 3° (according to the IBTrACS global data set, based on data from the National Hurricane Center and Joint Typhoon Warning Center). TCs have been
observed as equatorward as 1.4°N, in the case of Typhoon Vamei (2001) in the Northwest Pacific. The examination of rotating RCE on lower $f$-planes also allows for comprehensive study of the potential transition between the classic nonrotating and rotating self-aggregation regimes studied over the past two decades. To our knowledge, this is the first study that has analyzed self-aggregation with the low values of the Coriolis parameter that we employ.

This study considers a set of idealized numerical simulations of rotating RCE across different values of the Coriolis parameter, each initialized from a spatially uniform environment. We identify and analyze the processes leading to TC genesis in these simulations by addressing the following questions:

1. How does a TC form in rotating RCE, and does the evolution of cyclogenesis relate to preexisting theory from past observational and modeling studies?
2. Is it possible for a TC to form from random convection at values of the Coriolis parameter corresponding to latitudes equatorward of 10°?
3. If so, does the evolution of cyclogenesis in “low-$f$” simulations differ from that at the more traditional choice of 20°?

The remainder of this paper is organized as follows: section 2 entitled “Simulation Design” describes the characteristics of the model used for simulations, including domain geometry and resolution, radiation and physics schemes, along with other features common to all simulations. In addition, this section will outline the design of experiments with different values of Coriolis parameter. The next four sections after this are presented as a comparison of results between the “high-$f$” and “low-$f$” groups. Section 3 entitled “Evolution of Self-Aggregation and TC Characteristics” presents a view of the self-aggregation process and basic statistics on simulations, which either generate a TC or fail to do so. It also outlines the structural characteristics of modeled TCs at peak intensity and points to some key differences between the two groups. Dynamic and thermodynamic evolution and mechanisms leading to TC genesis are considered in sections 4 and 5. Included in the analysis is vorticity evolution, along with azimuthally averaged fields of several dynamic and thermodynamic parameters. Section 6, “Simulations at 7.5°,” analyzes the runs on the 7.5° $f$-plane that exhibit notable differences in convective behavior compared to the primary groups highlighted in sections 3 through 5. Finally, section 7 entitled “Conclusions” summarizes key results, implications, and future plans.

2. Simulation Design

Simulations of rotating RCE are performed using the System for Atmospheric Modeling (SAM) Version 6.8.2 (Khairoutdinov & Randall, 2003), which has been used in numerous prior studies of rotating RCE, including that by Wing et al. (2016), which our model setup is based on. SAM is a three-dimensional cloud-resolving model that employs the anelastic equations of motion. The prognostic thermodynamic variables are total nonprecipitating water, total precipitating water, and the liquid water/ice static energy, which are exactly conserved in this model. A square domain is employed with doubly periodic boundary conditions, spanning 1,536 km in the zonal and meridional directions. Prior studies have shown this domain size to be able to facilitate self-aggregation for a wide range of imposed sea surface temperatures in this model (Muller & Held, 2012; Wing & Emanuel, 2014; Wing et al., 2016). In addition, this domain size is comparable to others used to simulate TCs on doubly periodic $f$-planes (Boos et al., 2016; Davis, 2015; Khairoutdinov & Emanuel, 2013; Muller & Romps, 2018; Nolan et al., 2007; Wang et al., 2019; Wing et al., 2016). The model operates on an Arakawa-C grid, with a horizontal grid spacing of 3 km and 64 vertical levels to permit the explicit simulation of clouds. The lowest model level is at 37 m, with 75-m grid spacing near the surface increasing gradually to 500 m above 3.5 km, and a rigid lid at 28 km. Newtonian damping is applied in a sponge layer spanning the upper third of the domain to reduce gravity wave reflection and buildup.

Radiative fluxes are calculated via the RRTM radiation scheme (Clough et al., 2005; Iacono et al., 2008; Mlawer et al., 1997), with constant solar insolation of 413 W m$^{-2}$ (corresponding to the tropical annual mean with a solar constant of 650.83 W m$^{-2}$ and a zenith angle of 50.5°). The sea surface temperature (SST) is set to a constant value of 305 K for all simulations. While nonrotating self-aggregation is often sensitive to SST in limited area square domains (e.g., Wing & Emanuel, 2014), Wing et al. (2016) noted that spontaneous TC genesis occurred in their rotating RCE simulations across a wide range of SST values, so the choice of SST here is not expected to significantly impact our results. Subgrid-scale fluxes are accounted for and calculated using a Smagorinsky-type parameterization, and the default SAM one-moment microphysics package is used. The simulation is run for 100 days, and the initial sounding is developed from the domain mean of the
The Coriolis parameter is the only parameter altered across the set of simulations, allowing for the simplest possible view of the dependence of TC genesis on background rotation. Most prior studies of TC genesis in rotating RCE, including Wing et al. (2016), used a Coriolis parameter of $5 \times 10^{-5}$ s$^{-1}$, representing an $f$-plane at a latitude of $20^\circ$. A total of 27 simulations is run for $f$-planes representing latitudes from $0.1^\circ$–$20^\circ$. Multimember ensembles are run for most $f$-planes utilized in this study. To generate ensembles on a singular $f$-plane, the initial distribution of temperature perturbations is altered with different, but statistically equivalent, white noise. A three-member ensemble is performed for each simulation in the $1^\circ$–$15^\circ$ range. Simulations are split into two primary groups for analysis: a “low-$f$” group that includes simulations from $0.1^\circ$–$5^\circ$ and a “high-$f$” group more representative of rotating RCE simulations performed in past studies, from $10^\circ$–$20^\circ$. We make a brief note about the set of $7.5^\circ$ simulations later. This range of Coriolis parameters includes those at which we expect TCs to form ($10^\circ$–$20^\circ$) and a range in which the expected behavior is unknown ($0.1^\circ$–$7.5^\circ$). We note that the five simulations on the $20^\circ$ $f$-plane are the same as those analyzed by Wing et al. (2016). The full list of simulations can be found in Table 1.

Much of the analysis performed in this study is performed relative to the TC center. Initial identification of the TC center used the grid point of minimum surface pressure. However, this proved sensitive to areas of deep convection away from the future TC prior to genesis. Thus, the center location failed to correctly stabilize in some cases until a day before genesis took place, which is insufficient for our purposes. As such, we instead follow the center finding technique of Wang et al. (2019). In this strategy, vorticity is averaged in a $150 \times 150$-km box around each grid point to produce a smoothed field of relative vorticity. The center is identified as the grid point of maximum midtropospheric vorticity in the smoothed field. A difference from the approach of Wang et al. (2019) is that the vertical level that the center is identified at varies between simulations, rather than being fixed across the full set. We tested the sensitivity of our results to the choice of levels by repeating our analysis using fixed vertical levels of 1, 4, and 6 km to identify the center across all simulations. This test revealed our pregensis dynamic and thermodynamic results to be robust to the choice of level, but in some simulations, those specific levels precluded an early identification of the incipient cyclone. Therefore, the results we present use a vertical level for center finding that is between 1.66 and 4.46 km but is optimized for each simulation. This facilitates the earliest possible identification of the convective region that becomes a TC. This is particularly important in the “high-$f$” group where deep convection may still be occurring in other parts of the domain as the cyclone forms.

Once the center is identified, data are then interpolated to radial coordinates, including horizontal wind, anomalies of virtual temperature (taken from the spatial mean at each vertical level), relative humidity, radiative heating rate, vertical velocity, and mixing ratios for both precipitating and nonprecipitating cloud
condensate. The radius-height cross-sectional analyses and Hovmuller diagrams in the “Dynamic Perspectives” and “Thermodynamic Perspectives” sections are the result of this technique, which is applied to one-hourly instantaneous output (six-hourly for four simulations in the 20° ensemble).

3. Evolution of Self-Aggregation and TC Characteristics

3.1. Overview

Of the 27 simulations of rotating RCE examined in this study, 14 produced TCs as summarized in Table 1. Genesis time is defined as the first time at which the maximum hourly averaged wind speed anywhere in the domain persists at a value of at least 18 m s⁻¹ for at least 6 hr. This effectively separates tropical storm winds associated with a coherent circulation from general convective gustiness that operates on shorter time scales. Several other definitions of TC genesis are possible, but this method robustly separates the period of surface vortex development from the intensification stage across all TC-producing cases. All 11 simulations with a Coriolis parameter corresponding to latitudes of 10° and poleward develop intense TCs whose peak wind speeds exceed 80 m s⁻¹. There is a 36-day range in genesis time within the 20° ensemble (Figure 1), suggesting substantial stochastic variability associated with the distribution of initial random convection.

Figure 2 shows the hourly averaged precipitable water (PWAT) at four stages of a “high-f” 15° simulation. During the first 10 days, convection occurs randomly through the domain, though several small dry anomalies emerge rather quickly (Figure 2a). With time in this simulation and others in the high-f group, moisture anomalies form and amplify concurrently with the development of a broad circulation covering roughly a third of the domain. The circulation persists and gradually contracts, in concert with drying away from the primary convective region (Figures 2b and 2c); 10–20 days after initial development of a broad circulation, TC genesis is achieved, and rapid intensification then occurs robustly across all high-f simulations. It maintains major hurricane intensity (at least 50 m s⁻¹ as in the Saffir-Simpson Hurricane Wind Scale) for about 25 days, after which a weaker vortex persists through the end of the 100-day run.

The low-f group consists of 13 simulations from the 0.1°–5° range of Coriolis parameters. A three-member suite of simulations is run for each of the 1°, 2°, 3°, and 5° groups, and one simulation is performed for the 0.1° f-plane. There is a significantly lower occurrence of TC formation in this group. Three of the 13 simulations exhibit TC genesis, and all three TCs remain below hurricane intensity, less than half the peak

Figure 1. Time series of maximum hourly averaged surface wind speed for all simulations in this study. Multiple lines of the same color indicate different ensemble members of a single f-plane. Horizontal dashed lines are the 18 and 33 m s⁻¹ thresholds.
Figure 2. Hourly averaged precipitable water in a 15° simulation, showing (a) random convection prior to self-aggregation taking full effect, (b, c) amplification of dry patches and initial development of a broad circulation, and (d) a major hurricane after self-aggregation has progressed.

Figure 3. Same as Figure 2 but for the TC-producing 2° simulation. (a, b) Early stage of self-aggregation process, with initial emergence of dry patches; (c) convection aggregated as a nonrotating elongated band surrounded by dry, subsiding air; and (d) the TC after the convective band has collapsed into a quasicircular cluster.
Figure 4. Time series of daily averaged spatial variance of column-integrated frozen moist static energy, with lines representing the ensemble mean of each $f$-plane in this study. Shaded are the ranges of daily averaged FMSE variance within each ensemble.

The degree of self-aggregation can be approximately quantified using the spatial variance of column-integrated FMSE (Wing & Emanuel, 2014). Through each simulation, this quantity increases by roughly two orders of magnitude as dry regions dry further and grow to consolidate clusters of deep convection (Figure 4).

In the early stages, ensemble-mean FMSE spatial variance is systematically lower at higher values of Coriolis parameter, and a clear separation between the “low-$f$” and “high-$f$” groups is apparent until after Day 60. Acknowledging the TC as a form of self-aggregated convection here, this implied difference in aggregation timescales also hints at the fundamentally different pathways to genesis highlighted in the remainder of the article. However, the magnitude of FMSE variance at the end of a simulation does not directly indicate the existence of a TC, as it does not take into account the geometry of the aggregated cluster (e.g., the $3^\circ$ simulations). The $7.5^\circ$ group is a notable outlier in Figure 4 and will be examined in greater detail in section 6. Analyses of PWAT and other variables to be examined later in the manuscript can be found for the remaining TC-producing simulations in the supporting information.

3.2. Axisymmetric Structure

Before examining the mechanisms facilitating TC genesis in the high-$f$ group, we outline several elements of their structure using the azimuthal averaging technique described in section 2. Radius-height cross sections of the $15^\circ$ hurricane at the time of its peak intensity are displayed in Figure 5. Azimuthal-mean tangential winds of tropical storm force extend vertically to 16 km, and hurricane-force winds are even seen above 10 km (Figure 5a). This TC and other high-$f$ cases are compact radially, as seen here by the 20-km radius of maximum winds and 50-km extent of hurricane-force tangential winds. Radial inflow is notably confined to the lowest 500 m, with inflow speeds in excess of 15 m s$^{-1}$ near the surface in the inner core (Figure 5b).

Upper-tropospheric outflow extends well over 200 km radially from the center, at a comparable speed to the low-level inflow region.

At the peak intensity of the $2^\circ$ TC and the other low-$f$ cases, a cyclonic circulation is clearly evident but notably weaker and shallower compared to those seen in the high-$f$ group (Figure 6a). This may be in part because the background vorticity is insufficient to facilitate significant large-scale vortex intensification. Despite the relative weakness of the TC, classical characteristics and circulation features are still evident. For example, a persistent band of strong low-level inflow extends beyond 400 km radially. This exists well before TC genesis occurs, as self-aggregation into a circular convective cluster has already taken place. Outside of the inner core, radial flow seems to fluctuate between regions of inflow and outflow. For example, at the time intensity of any high-$f$ TC. These tend to be more short lived and reach their peak intensity shortly after they form. Surprisingly, those three TCs form in select simulations on the $1^\circ$ and $2^\circ f$-planes, while the six simulations in the $3^\circ–5^\circ$ group self-aggregate into a nonrotating, elongated band. Two of the $1^\circ$ simulations produce TCs along with one ensemble member of the $2^\circ$ set, and the range of genesis times is from Days 64.5–80.42. Genesis occurs faster in two of these cases than in one of the $10^\circ$ runs, providing further evidence that the Coriolis parameter is not the leading factor that determines the time to genesis in these simulations.

For comparison, we use a $2^\circ$ simulation as a representative example of “low-$f$" cyclogenesis. The convective pattern remains quasirandom early in the simulation (Figure 3a). Over time, dry regions amplify and expand such that by Day 50, dry and cloud-free air covers nearly half of the domain, while convection is confined to a nearly continuous band in the middle portion of the domain (Figure 3c). Most simulations in the low-$f$ group end in this aggregated state, as periodic bursts of convection occur within a band that narrows to a width under 500 km along its minor axis. In the simulation shown in Figure 3, however, convection then collapses into a quasicircular cluster, similar to what is seen in nonrotating RCE (Wing & Emanuel, 2014). This starts to take place near Day 60, and within the next 5 days, the quasicircular cluster spins up to form a tropical storm with a genesis time in this simulation of Day 64.50 (Figure 3d). This indicates that the geometry of the aggregated convection (i.e., banded vs. circular) is significant in determining whether a TC subsequently spins up, a distinction that robustly applies to the entire low-$f$ simulation set.
Figure 5. Structure of the 15° TC at Day 60.04, its time of peak intensity. Azimuthally averaged snapshots of (a) tangential wind/primary circulation, (b) radial wind/secondary circulation, (c) virtual temperature anomaly, (d) relative humidity, (e) vertical velocity, (f) radiative heating rate from combined effects of shortwave and longwave radiation, (g) nonprecipitating condensate, and (h) precipitating condensate. Contours of 18 and 33 m s\(^{-1}\) tangential wind are overlaid in (a).

of this snapshot, there is a layer of weak outflow above the boundary layer as well as a strong inflow region at 10–12 km vertically (Figure 6b). The low-level outflow above the boundary layer inflow is reminiscent of the shallow overturning circulation that has been emphasized as an important factor in driving nonrotating self-aggregation (Muller & Held, 2012; Muller & Bony, 2015; Coppin & Bony, 2015). Similar features are found in the other TC-producing low-\(f\) simulations but are relatively weak across the high-\(f\) group.

The mature high-\(f\) hurricane exhibits a pronounced warm core (Figure 5c), which extends from the surface to the tropopause near 18 km, with the strongest warm anomalies located in the upper troposphere. Analysis of relative humidity shows a moist low troposphere, coincident with the area of peak radial inflow, that proves particularly favorable for inner core deep convection. Figure 5d also indicates a consistently moist eyewall through the depth of the troposphere and a moist outflow region including an extensive cirrus
canopy. Strong azimuthally averaged ascent up to 3 m s$^{-1}$ is found within 40 km of the storm center radially, along with a small descending eye. The condensate fields (Figures 5g and 5h) show a dense cloud layer coincident with strong ascent (Figure 5e) in the upper-tropospheric eyewall region. This confirms that, as expected, the majority of deep convection is occurring inside the eyewall of the TC.

Each low-$f$ TC has a warm core, which is much weaker than that of the high-$f$ cases (Figure 6c). Another difference from the high-$f$ TCs is that the strongest warm anomalies are in the lowest 2 km, rather than the upper troposphere. Anomalous warmth extends beyond 300 km radially, coinciding with a steady band of low-level relative humidity above 80%. The inner core of the low-$f$ TC is more humid than the high-$f$ case, but the dry region away from the center is both drier and more expansive (Figure 6d). Azimuthal-mean ascent approaches a maximum of 3 m s$^{-1}$ near the center similar to the high-$f$ case but occurs over a broader area. This suggests that the low-$f$ TCs, though substantially weaker, are larger than their high-$f$ counterparts,

Figure 6. Same as Figure 5 but for the 2° TC at Day 64.71, its time of peak intensity.
in agreement with the notion that a lower Coriolis parameter would theoretically correspond to a larger TC as derived by Emanuel (1986) and examined by Chavas and Emanuel (2014). This raised the question of whether the lack of TC formation in some low- \( f \) simulations was linked to a restricted domain size. To address this issue, we performed an additional simulation on the 1° and 2° \( f \)-planes with a domain twice the length in each dimension. Convection failed to fully self-aggregate in the large 2° simulation. However, a TC formed by similar mechanisms on a similar time scale in the 1° simulation, suggesting that the lack of TC formation in some low- \( f \) simulations is not due to a restrictive domain size.

In addition, there is no evidence of a clear, dry, subsiding eye in the low- \( f \) simulation (Figure 6e) though the traditional secondary circulation still takes place. Precipitation is largely confined to the innermost 200 km, with only shallow precipitating clouds located radially outward from there, though the region of maximum precipitating condensate extends quite far from the center (about 50 km; Figure 6h).

In summary, the high- \( f \) TCs are substantially more intense and feature structural characteristics of a radially compact mature hurricane. Low- \( f \) TCs have deep convection occurring over a broader area, but their circulations are weaker and shallower while appearing to be aided by anomalous low-level humidity, warmth, and inflow at the time of peak intensity. Complete self-aggregation into one nonrotating circular cluster precedes TC genesis in all TC-producing low- \( f \) cases, unlike the high- \( f \) simulations in which a broad circulation develops concurrently with self-aggregation feedbacks.

4. Dynamic Perspectives

4.1. Tangential Wind

We now shift focus from a general view of the TC structure at peak intensity to analysis of the cyclogenesis process, beginning with the dynamical evolution. Figure 7 shows radius-height cross sections of azimuthal-mean tangential wind for the 15° simulation. Similar snapshots for other TC-producing simulations, as well as animations showing the evolution leading up to and beyond genesis, can be found in the supporting information. The predominant feature 36 hr before TC genesis (Figure 7a) is a maximum of tangential wind in the middle troposphere, centered at 4 km vertically and 150 km radially from the center. The strength of the tangential circulation at this time is weaker at lower levels. Over the next 24 hr, vortex development takes place at lower levels, coincident with a contraction of the strongest tangential winds toward the center (Figures 7c, 7e, and 7g). As the vortex develops at lower levels and contracts, radial inflow in the lowest kilometer increases substantially, increasing mass and vorticity convergence at the lowest levels in the simulation and adding to a net tendency for spin-up. These processes occur concurrently with a significant rise in surface heat fluxes (not shown). Upon strengthening of a surface vortex, rapid intensification into a major hurricane occurs. All high- \( f \) simulations feature a similar midlevel vortex emergence prior to significant surface cyclone intensification, which will be examined in closer detail in section 4.3.

In addition to differences in structure and intensity, the evolution of the wind field prior to TC genesis is markedly different in the low- \( f \) group. Employing the same 2° simulation from section 3 as a representative low- \( f \) case, a very weak low-level circulation is apparent 36 hr before cyclogenesis (Figure 7b). Weak cyclonic winds are apparent through the lower and middle troposphere 36 hr before cyclogenesis, but the peak is in the lowest 2 km. This is a stark contrast to the clear midlevel circulation seen in most of the high- \( f \) simulations. Twenty-four hours later, the circulation has strengthened at all vertical levels but remains strongest near the surface (Figure 7f). Eventually, intensification of the vortex to tropical storm strength at the lower levels takes place. Upon reaching tropical storm intensity, azimuthally averaged tangential winds of at least 10 m \( \text{s}^{-1} \) extend less than 100 km radially and 6 km vertically (Figure 7h). In the 6–12 hr after reaching tropical storm strength, intensification continues and the TC deepens vertically. Beyond this time, however, intensity oscillates near the tropical storm threshold, in contrast to a high- \( f \) TC that generally maintains hurricane intensity for tens of days. Overall, the low- \( f \) TCs have a weaker, shallower, and more transient circulation than the high- \( f \) TCs. The pathway to genesis starting with a low-level circulation in this 2° case (and other low- \( f \) examples) is consistent with recent analysis of observed near-equatorial TCs performed by Steenkamp et al. (2019). In this study, TCs form within a similar environment of broadscale, marginally positive vorticity, amplified by vortex stretching by persistent deep convection.

4.2. Radial Wind

The evolution of the secondary circulation is displayed for the same time frame in Figure 8 for the 15° case. One day before cyclogenesis, an upper-tropospheric outflow region is coupled with weak low-level inflow
Figure 7. Radius-height cross sections of azimuthal-mean tangential wind (hourly snapshot) in the 15° (left) and 2° (right) simulations: (a, b) 36 hr prior to genesis; (c, d) 24 hr prior to genesis; (e, f) 12 hr prior to genesis; and (g, h) genesis time, Days 53.38 and 64.5 respectively for the two simulations. Contoured is the region of maximum tangential wind at each snapshot.

near the center. However, there also exists an interesting region of low-level outflow at outer radii with a broad inflow region above (Figure 8c). Closer to the center, inflow is colocated vertically with the midlevel vortex that precedes the TC. Twelve hours later (Figure 8e), inflow in the lower troposphere has strengthened and spans over 400 km radially. This trend continues until the genesis time, as the strongest near-surface inflow occurs within 60 km of the center, and upper-tropospheric outflow strengthens (Figure 8g). Another upper-tropospheric local inflow maximum emerges in the hours shortly before genesis at far radii, with
Convection has already self-aggregated into a quasicircular cluster several days before cyclogenesis takes place in each of the TC-producing low-f simulations. As such, low-level inflow is well established and much stronger compared with the high-f simulations near the time of genesis (Figure 8). This inflow helps to converge mass and vorticity near the center of the cluster, aiding the low-level spin-up process. This process is thought to operate along with low-level convergence from latent heat release and precipitation as hypothesized by Raymond et al. (2007). Twelve hours before genesis, there is a notable region of strong upper-tropospheric inflow that is coupled with a local maximum in the tangential wind near 9 km vertically.
(Figure 8f). By the genesis time, peak inflow exists within the boundary layer, from 100–300 km radially (Figure 8h). Beyond this time, elevated regions of inflow and outflow continue to develop and propagate upward, more prominently than in the high-$f$ case. Regions of inflow aloft are often colocated with transient maxima in near-center tangential wind above the persistent low-level circulation that precedes the TC.

### 4.3. Vorticity

Figure 9 displays the relative vorticity averaged (from the smoothed vorticity field) in a $150 \times 150$-km box around the center near the genesis time for a representative simulation from all $f$-planes with a TC-producing simulation. Consistent with the results of Wang et al. (2019), a clear midlevel vorticity maximum appears 3 days before genesis in the $15^\circ$ case, varying in strength over the following 36 hr. One day prior to genesis, a stronger midlevel maximum begins to emerge, after which vorticity is increasingly generated in the lower troposphere, consistent with the evolution of azimuthal-mean tangential wind displayed in Figure 10. A vortex that is strongest at low levels, but extends through most of the troposphere, becomes clearly evident in the next day after the genesis time. A somewhat similar evolution occurs in the simulations at 10 and $20^\circ$ (Figures 9a and 9c), though the $20^\circ$ case in particular has heightened low-level vorticity several days before cyclogenesis. It is in the final 1.5 days that a relative maximum emerges at middle levels, helping to further amplify the vortex at lower levels to tropical storm strength. Notably, this midlevel circulation emerges prior to significant intensification of the low-level winds near the inner core, leading to an overall contraction and strengthening of the circulation. This pathway is observed in a subset of the $20^\circ$ simulations, but midlevel vortex emergence robustly precedes an intense surface cyclone in all high-$f$ simulations. Further evidence of this can be found in animations of tangential wind available in the supporting information.

The general preference of a midlevel vortex preceding cyclogenesis in the high-$f$ group (Figures 9a–9c) is sharply contrasted by the lack of a strong midlevel circulation in low-$f$ simulations that produce a TC (Figures 9d and 9e). For the $1^\circ$ and $2^\circ$ runs shown here, vorticity is weak (only half the magnitude of the high-$f$ cases) through the lower and middle troposphere. In the day leading to TC genesis, a vorticity maximum emerges in the lowest levels consistent with the tangential wind maximum seen in Figure 7. While positive vorticity exists through the majority of the troposphere in the low-$f$ runs from persistent deep convection, a facilitating midlevel vorticity maximum is unnecessary. This is because strong low-level inflow is already well established several days before genesis, which by the continuity principle corresponds to strong mass and vorticity convergence. This represents fundamentally different dynamical pathways to cyclogenesis between the two groups, which occur at different stages of the self-aggregation process.

### 5. Thermodynamic Perspectives

#### 5.1. Temperature

To develop a more complete description of the tropical cyclogenesis process, a consideration of thermodynamic mechanisms and their connection to dynamic factors is appropriate. Figure 10 shows the evolution of azimuthally averaged virtual temperature anomaly (from the horizontal mean) through the 36 hr leading to TC genesis in the $15^\circ$ simulation examined in prior sections. Cold pools initially persist near the surface as a consequence of evaporatively driven downdrafts, though low-level inflow and convergence keep ascent and deep convection active. Before genesis, a clear midlevel tangential wind and vorticity maximum exists at about 4 km, as shown in Figure 7. The balanced thermodynamic response to this is apparent with a shallow cold core beneath and warm core above the midlevel vortex (Figure 10a). In agreement with the theory posed by Gjorgjievska and Raymond (2014), this corresponds to an increase in low-level static stability, favoring a moist-neutral convective pattern that shifts the distribution of vertical mass flux toward a more bottom-heavy profile. The shift of the mass flux profile is robust in the 5 days leading to TC genesis across the high-$f$ group, leading to increased mass convergence below the midlevel vortex, and vorticity convergence increasing particularly in the lowest 1.5 km (Figures S16–S18).

The shift toward a more bottom-heavy convective mass flux profile (not shown) must be associated with an increase in low-level mass convergence as a consequence of mass continuity, which therefore increases vorticity convergence below the midlevel vortex. The increase in low-level vorticity corresponds to a downward shift in the cold core (Figures 10c and 10e). This positive feedback process continues at increasingly lower levels over the 12 hr leading to cyclogenesis. By genesis time, a warm core extends into the lowest 2 km within the inner core of the TC (Figure 10g). Warm anomalies strengthen through the troposphere over the next few days and eventually maximize in the upper troposphere as a descending eye forms in the rapidly
intensifying TC. This process occurs across the high-\(f\) cases, which develop a pronounced midlevel vorticity maximum well before significant near-surface intensification. A smaller subset of 20° simulations lacks a persistent dynamically induced cold core. In these cases, it only appears transiently, though six-hourly output (rather than hourly in other simulations) makes this feature difficult to assess robustly. These are the simulations with a preexisting low-level circulation that intensifies upon development of a near-center midlevel maximum shortly before the genesis time.

In addition to the dynamical differences highlighted in the prior section, the low-\(f\) group exhibits significant thermodynamic departures from the high-\(f\) simulations. There is anomalous warmth in the lowest 1.5 km, spanning the width of the convective region radially 36 hr prior to genesis time for the TC-producing 2° case (Figure 10b). The combination of strong low-level convergence and low-level instability in the anomalously warm boundary layer provides a favorable environment for bottom-heavy vertical mass flux. Not surprisingly, a low-level maximum in mass flux begins to emerge around this time (not shown). Strong latent heating within the aggregated region begins to provide anomalous warmth at this stage. Along with this, the lack of a strong dynamically induced cold core (midtropospheric cold pools in the inner core are weak and transient features) or persistent midlevel vortex are key contrasts with the high-\(f\) group.

The thermal structure of the low-\(f\) TC is similar 24 hr later (12 hr before genesis), except the weak anomalous warmth in the upper troposphere becomes more persistent near the center (Figure 10f). Convective available potential energy (CAPE; lifted from the lowest vertical level at 37 m, not shown) often approaches 2,000 J kg\(^{-1}\) when convection begins to self-aggregate into an elongated band, but decreases substantially as this
Figure 10. Same as Figure 7 but for azimuthal-mean virtual temperature anomaly (hourly snapshot) in the 15° (left) and 2° (right) simulations.

collapses into a quasicircular cluster. After another 12 hr, a warm core has developed through the majority of the troposphere. At the time of genesis, the strongest warm anomalies are still in the lowest 2 km, but upper-tropospheric warm anomalies have strengthened considerably (Figure 10h). The upper-level warm core extends out to a radius of 100 km. Above this, there are cold anomalies indicative of both overshooting convective tops and lifting of the tropopause due to persistent deep convection over several days.

5.2. Humidity

Another ingredient commonly cited as a prerequisite for TC formation is moistening, particularly in the middle troposphere. For example, Nolan (2007) showed in simulations that development of a midlevel vortex
was preceded by relative humidity near the inner core exceeding 80% through a large depth of the troposphere. To examine this, Figures 11a–11c show the relative humidity (calculated from hourly output of water vapor and condensate quantities, along with other relevant thermodynamic variables computed directly in SAM) averaged in the same 150 × 150-km box around the center as Figure 9. Modest moistening of the lower and middle levels is achieved prior to genesis in each of the 10°–20° cases, with periodic fluctuations due to bursts of deep convection near the center of the incipient cyclone. The midlevel vortex established days prior to cyclogenesis in these cases aids in this process by mixing, which is in agreement with the emergence of a shallow cold core beneath the initial vortex. Substantial moistening of the upper troposphere is more readily apparent. Relative humidity values as low as 20% are seen above 7 km more than 2 days prior to cyclogenesis, particularly in the 20° case (Figure 11c). In time, relative humidity through the full tropospheric column increases to at least 60% while low levels approach saturation. Though this sometimes lies below the 80% threshold suggested by Nolan (2007), the result is qualitatively similar in the sense that progressive moistening is a predecessor to vortex formation and development across this set of high-\textit{f} simulations.

Since self-aggregation has already taken place prior to TC genesis in the low-\textit{f} group, convection has consistently occurred and moistened the column within the cluster well before the TC forms. Indeed, the low-\textit{f} TCs are characterized by a nearly saturated lower and middle troposphere days prior to cyclogenesis, as shown by Figures 11d and 11e. The full column around the center of the incipient TC is substantially more humid in this group than in the high-\textit{f} group. In addition, the upper-tropospheric dry anomalies preceding genesis...
are not seen in the low-$f$ group, as periodic bursts of deep convection are well concentrated within the aggregated cluster. The lowest 2 km is nearly saturated over 3 days before genesis, a feature that is particularly amplified in the $1^\circ$ simulation (Figure 11d) and common across all low-$f$ cases.

The robust existence of a low-level cold core prior to genesis in the high-$f$ simulations, and lack thereof in the low-$f$ simulations, provides thermodynamic evidence of fundamentally different pathways to TC genesis between the two groups. The completion of the self-aggregation process in the low-$f$ group amplifies humidity in the convective cluster and assists in cyclogenesis by preventing the tendency of evaporatively driven downdrafts from spinning down the incipient low-level vortex.

6. Simulations at 7.5°

The ensemble of simulations on the 7.5° $f$-plane does not fall into either the “low-$f$” or “high-$f$” categories. A TC does not form like in most low-$f$ simulations, but unlike the other simulations, the self-aggregation of convection is weak and incomplete. Figure 12 displays the hourly averaged PWAT (Figure 12a) and OLR (Figure 12b) fields at the end of a 7.5° run. Only one small dry patch is apparent at the end of the simulation, which initially emerges near Day 55. In addition, the maximum PWAT throughout the 100-day simulation is 80 mm, about 30 mm less than any of the other simulations that complete self-aggregation. Deep convection still occurs across the majority of the domain, in contrast to other simulations in which convection takes the form of an isolated band or circular cluster prior to Day 65.

Using the spatial variance of column-integrated FMSE as a proxy for self-aggregation, we revisit Figure 4. While there is some increase in the spatial variance of FMSE in the 7.5° cases, after Day 65, it is an order of magnitude lower than that of any of the surrounding cases. This indicates that the 7.5° simulations are much more weakly self-aggregated. It appears as though the self-aggregation process reverses course, as small dry patches that emerge in the middle of the run moisten, such that by Day 100, only one predominant dry patch persists surrounded by regularly convecting, moist air. This is in contrast to the other simulations, where once dry patches emerge, they continually amplify and grow until convection is confined to an isolated band or cluster.

The set of simulations at 7.5° fall in a “gray area” between the low-$f$ and high-$f$ groups, which either fully self-aggregate or form a TC. One hypothesis is that there is too much planetary vorticity for convection to follow the nonrotating pathway to self-aggregation, as it does in the low-$f$ group where aggregation is achieved similarly to a simulation with no rotation. At the same time, there may not be enough planetary vorticity to generate a circulation concurrently with aggregation as in the high-$f$ group. Another hypothesis is a shift in the magnitude of surface flux feedbacks due to changes in surface winds as planetary vorticity varies. Also, there is an anomalous vertical distribution of clouds in the 7.5° simulations, which may affect radiatively induced circulations near convective clusters. These hypotheses and other possible explanations will be investigated in future work. This work may identify a critical Coriolis parameter for the transition...
between the nonrotating/low-rotation and high-rotation self-aggregation regimes and explain the failure of the 7.5° simulations to fully self-aggregate.

7. Conclusions

This study examined the mechanisms leading to TC genesis in idealized $f$-plane simulations using nine different values of the Coriolis parameter, using the cloud-resolving System for Atmospheric Modeling. In total, 27 simulations were performed; 14 of these produce TCs, 11 of which intensify into major hurricanes. Notably, two simulations on the 1° $f$-plane and one on the 2° $f$-plane produce tropical storms with maximum wind speeds of 28–32 m s$^{-1}$. Analysis of these simulations and their genesis processes was divided into two primary groups: a high-$f$ group that includes the 10°–20° cases (11 simulations in total) and a low-$f$ group that includes the 0.1°–5° simulations (13 simulations in total). All simulations in the high-$f$ group produce TCs that intensify into major hurricanes, while the low-$f$ group only produces TCs in three of the 13 simulations. The 7.5° simulations (three in total) are revealed to be a “gray area” between the groups, in which self-aggregation does not occur to the same extent as in the other cases and no TC forms.

These groups represent different pathways of self-aggregation and TC genesis. In the high-$f$ group, a broad circulation develops as convection self-aggregates, as described by Wing et al. (2016). A pronounced midlevel vorticity maximum then develops in most cases. This facilitates development of vorticity toward the surface, in agreement with both recent modeling work (Wang et al., 2019) and prior theory that stresses the importance of a preceding midlevel vortex (Bister & Emanuel, 1997; Raymond et al., 2011; Ritchie & Holland, 1997). Consistent with thermal wind balance and facilitated by the mixing of low-entropy air from the midtroposphere into lower levels by convection, this midlevel vortex is generally associated with a shallow cold core beneath and warm core above, stabilizing the local atmosphere. This is more conducive to moist convection at lower levels, shifting the vertical mass flux profile to a more bottom-heavy pattern. This then increases mass and vorticity convergence near the surface, contributing to a positive low-level spin-up tendency (Gjorgjievska & Raymond, 2014). At this stage, vorticity develops near the surface, where surface flux feedbacks can intensify the incipient TC. Low-level cyclonic vorticity exists in some 20° simulations, but in these cases, strengthening of midlevel vorticity still precedes significant low-level vortex intensification close to the center of circulation.

The low-$f$ simulations that produce TCs complete the self-aggregation process prior to TC formation in a manner similar to nonrotating simulations (Wing & Emanuel, 2014; Wing et al., 2016), and the geometry of the aggregated cluster is critical in determining if subsequent TC spin-up occurs. All simulations that self-aggregate into a nonrotating elongated band and remain that way fail to produce TCs. In these cases (most of the low-$f$ simulations), convection remains in this state for tens of days and shows no signs of transition by the 100th day of the simulation. Those cases that then collapse convection into a quasicyclic cluster subsequently form a TC. Additional simulations on a larger domain suggest that our choice of a 1,536 km$^2$ domain is sufficient to contain the larger low-$f$ TC without interference across doubly periodic boundaries.

In the low-$f$ group, there is no emergence of a precursor midlevel vorticity maximum nor cold core; instead, a low-level cyclonic circulation first emerges days prior to cyclogenesis. This is consistent with recent analysis of observed near-equatorial TCs performed by Steenkamp et al. (2019). Since the convection is completely self-aggregated, there is already substantial low-level inflow and inward angular momentum flux, nearly saturated air in the lower and middle levels, and a bottom-heavy vertical mass flux profile prior to genesis. This facilitates the spin-up of a low-level vortex that then intensifies to TC strength. Between the near-surface inflow and tropopause outflow branching of the TC’s secondary circulation, radial flow fluctuates on a daily timescale, and midlevel to upper-level inflow regions contribute to transient intensification of cyclonic flow aloft.

A direct link between genesis time and Coriolis parameter is difficult to establish, similar to the results from the experiments conducted by Nolan et al. (2007). When considering the mean time to genesis across the $f$-planes in the high-$f$ group, genesis occurs faster on average for a higher value of Coriolis parameter; however, there exists a great deal of variability at a given value of $f$. For example, time to genesis across the five-member suite of 20° simulations ranges from Day 25.04 to Day 61.21, suggesting a large stochastic component to spontaneous TC genesis in this model framework. In addition, cyclogenesis occurs faster in
the TC-producing 2° simulation than in examples at both 10° and 15°, providing additional support for different pathways in these two cases.

This study examined TC genesis in the absence of any outside forcing or disturbances, allowing random convection to operate on its own accord and thus offer a simplified look into the processes governing cyclogenesis. For the first time, it has been shown that spontaneous TC genesis in rotating RCE is possible on f-planes equatorward of 10°. In addition, our results indicate that self-aggregation on near-equatorial f-planes strongly resembles the typical nonrotating regime seen in prior modeling studies. The high-f pathway to genesis resembles prior theories supported by observations that connect basic dynamic and thermodynamic principles. On f-planes corresponding to 10–20°, even when developing from random convection, a preceding midlevel vortex is generally the preferred pathway to genesis. In contrast, the low-f pathway suggests that the emergence of a midlevel vortex may not be necessary for formation but rather the preexisting presence of organized convection supported by strong low-level inflow and ample low-level moisture.

Acknowledgments

We would like to acknowledge high-performance computing support from Cheyenne (doi: 10.5065/D6RX9HX) provided by NCAR’s Computational and Information Systems Laboratory, sponsored by the National Science Foundation. Additional computing was performed on the High Performance Computing (HPC) cluster at the Research Computing Center at the Florida State University (FSU). A. A. W. acknowledges support from National Science Foundation Grant 1830724. We acknowledge Marat Khairoutdinov for providing and maintaining the System for Atmospheric Modeling (SAM) cloud-permitting model. We would like to thank Robert Hart and Jeffrey Chagnon for their feedback, commentary, and support while serving on the first author’s master’s degree committee. Finally, we thank three anonymous reviewers for their constructive feedback that substantially improved the manuscript.

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