The Impact of Outflow Environment on Tropical Cyclone
Intensification and Structure

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ABSTRACT

In this study, the impacts of regions of weak inertial stability on tropical cyclone intensification and peak
strength are examined. It is demonstrated that weak inertial stability in the outflow layer minimizes an energy
sink of the tropical cyclone secondary circulation and leads to more rapid intensification to the maximum
potential intensity. Using a full-physics, three-dimensional numerical weather prediction model, a symmetric
distribution of environmental inertial stability is generated using a variable Coriolis parameter. It is found that
the lower the value of the Coriolis parameter, the more rapid the strengthening. The lower-latitude simulation
is shown to have a significantly stronger secondary circulation with intense divergent outflow against a com-
paratively weak environmental resistance. However, the impacts of differences in the gradient wind balance
between the different latitudes on the core structure cannot be neglected. A second study is then conducted
using an asymmetric inertial stability distribution generated by the presence of a jet stream to the north of the
tropical cyclone. The initial intensification is similar, or even perhaps slower, in the presence of the jet as a
result of increased vertical wind shear. As the system evolves, convective outflow from the tropical cyclone
modifies the jet resulting in weaker shear and more rapid intensification of the tropical cyclone–jet couplet.
It is argued that the generation of an outflow channel as the tropical cyclone outflow expands into the region
of weak inertial stability on the anticyclonic shear side of the jet stream minimizes the energy expenditure of
forced subsidence by ventilating all outflow in one long narrow path, allowing radiational cooling to lessen the
work of subsidence. Furthermore, it is hypothesized that evolving conditions in the outflow layer modulate the
tropical cyclone core structure in such a way that tropical cyclone outflow can access weak inertial stability
in the environment.

1. Introduction

a. Background

Contrary to the results of many idealized numerical
simulations, tropical cyclones (TCs) in nature often fail
to reach their theoretically defined maximum potential
intensity (MPI), as defined by the sea surface tempera-
ture (SST) and the overlying thermodynamic profile
(Emanuel 1986; Holland 1997). In fact, a 31-yr clima-
tology of North Atlantic basin TCs by DeMaria and
Kaplan (1994) revealed that, on average, the storms
reached 55% of their MPI. Since idealized numerical
simulations of a “hurricane in a box” always produce
storms at their MPIs, it is likely that such simulations
neglect important processes that act to limit intensity
(Holland 1997). Advances in the understanding of in-
tensity change require knowledge of not only those
mechanisms that define MPI, but also those that limit
intensity (Persing et al. 2002) or that modify intensifi-
cation rates.

One ingredient neglected in such simplified idealized
experiments is an environmental flow field. Significant
lower- and midtropospheric interactions between TCs and
environmental flows are limited due to the strong inertial
stability of the storm core. The upper-troposphere–lower-
stratosphere however is susceptible to external forcing
due to the low inertial stability of the anticyclonic outflow
(Holland and Merrill 1984, hereafter HM84). Therefore,
asymmetries in the outflow layer exist as a response of the tropical cyclone outflow to external environmental features. A composite study by Merrill (1988) utilizing cloud model, rawinsonde, and aircraft winds, found that intensifying TCs exhibit asymmetric outflow patterns, with the outflow organized into one or more outflow channel(s) or jet(s).

Previous studies have speculated on the dynamical cause for asymmetric outflow (HM84; Shi et al. 1990; Rodgers et al. 1990). It was suggested that a coupling occurs between the outflow and an approaching mid- and upper-tropospheric trough. As the cold trough encroaches upon the warm outflow, a coupled jet forms in the steep gradient between the lowered tropopause associated with the trough and the elevated tropopause associated with the outflow. However, Ooyama (1987) was able to generate asymmetric outflow in a simple two-dimensional model of the outflow layer by superimposing various horizontal shear profiles. The Ooyama and HM84 results are not inconsistent as the TC is embedded or close to the anticyclonic shear side of the “coupled” jet.

Several mechanisms have been suggested as a means of quantifying the interaction of a tropical cyclone with cyclonic disturbances such as midlatitude waves or upper-tropospheric tropical troughs. These include 1) eddy flux convergence (EFC), 2) potential vorticity dynamics, and 3) enhanced divergence aloft. Pfeffer (1958) first suggested that cyclonic eddy angular momentum fluxes could be transported into the storm volume, resulting in a net cyclonic increase of the angular momentum budget. Alternatively, Molinari and Vollaro (1990) proposed that the inward transport of EFC leads to an enhanced outflow branch of the secondary circulation to restore balance to a perturbed upper troposphere. They employed the Eliassen (1952) balanced vortex model to explain the secondary intensification of Hurricane Elena (1985) in terms of inward-propagating vertical motions (eyewall replacement cycle) coincident with the inward transport of cyclonic momentum forcing. Numerous observational studies have been conducted utilizing EFC with varying results (Pfeffer and Challa 1981; McBride and Zehr 1981; Holland 1983; Molinari and Vollaro 1989, 1990; Challa and Pfeffer 1990; DeMaria et al. 1993; Merrill and Velden 1996; Bosart et al. 2000). Merrill (1988) suggested that there should be no clear relationship between EFC and increased storm intensity, as increased eddy fluxes are often accompanied by increased vertical shear. As discussed in a number of studies, including McBride and Zehr (1981), vertical shear is known to be detrimental to TC intensification.

Molinari et al. (1998) and Bosart et al. (2000) suggested that the vertical shear problem is minimized in certain “good trough” conditions. Convective ridging above the tropical cyclone can lead to equatorward wave breaking as described by Thorncroft et al. (1993), which leads to a scale reduction or fracturing of high environmental potential vorticity (PV) such that vertical shear is diminished. Molinari et al. (1995, 1998) utilized PV thinking to suggest that PV associated with upper-level cyclonic systems may superpose with the low- and midlevel PV of the hurricane. The primary circulation would be enhanced at the expense of the mean wind that brought the two systems together. With diabatically generated low PV continuously being pumped into the outflow layer above the tropical cyclone, it may be difficult for a significant superposition to occur, so this mechanism may only be important for early development. The above authors also suggested that upper-level PV associated with environmental systems may utilize the relatively weak static stability of the subtropics to excite the wind-induced surface heat exchange instability (Emanuel 1989), leading to intensification through an eyewall replacement cycle as was later investigated by Nong and Emanuel (2003).

Enhanced divergence ahead of an approaching trough has also been considered in understanding external interactions. Divergence in the secondary circulation of the jet-entrance region may enhance tropical cyclone outflow (and the downstream jet through geostrophic adjustment). Using European Centre for Medium-Range Weather Forecasts (ECMWF) and National Centers for Environmental Prediction (NCEP) gridded datasets, Bosart et al. (2000) found that enhanced divergence ahead of an approaching midlatitude wave was partly responsible for the intensification of Hurricane Opal (1995). However, Persing et al. (2002), using output from the fifth-generation Pennsylvania State University–National Center for Atmospheric Research Mesoscale Model (MM5), concluded that the approaching trough had little impact on Opal’s intensification. Finally, Rodgers et al. (1991) and Shi et al. (1997) speculated that intensification may result from large scale ascent near the storm core in association with the ascent branch of an approaching midlatitude trough’s jet-entrance region’s secondary circulation. In fact, M88 speculated that the TC itself acts as the ascending branch of the secondary circulation associated with the coupled jet.

b. Motivation

Tropical cyclone intensity is largely controlled by the strength and spatial scale of the secondary circulation. Emanuel (1986, 1988) succinctly described the four branches of a steady-state hurricane secondary circulation as an idealized, reversible Carnot engine. In Emanuel’s (1986) treatment of the Carnot energy cycle, he assumed that the outflow-layer environment (typically at levels between 100 and 300 hPa) would support a steady-state
hurricane. Emanuel speculated that by reducing the work needed to restore the outflow’s angular momentum to its environmental value (spinup of the outflow anticyclone) more energy would be available to overcome frictional dissipation in the inflow. Within the context of his analytical model, the outflow work term was negligible so that the choice of radius at which the outflow angular momentum is equivalent to the ambient value has little impact on the overall intensity. The study here hypothesizes that by reducing the angular momentum of the environment around numerically simulated tropical cyclones to a value close to that of typical outflow values, the tropical cyclone will undergo symmetric intensification more quickly and reach maximum intensity sooner. A reduction in the amount of work done by the hurricane to expand its outflow does not necessarily lead to a more intense storm (in the absence of asymmetric environmental flow) but one which reaches its maximum intensity more rapidly.

Environmental inertial stability is a useful measure of the resistance to convective outflow. Inertial stability implies a balance between Coriolis and pressure gradient forces so that divergent outflow is reduced in favor of rotation and restrained to the near-storm environment. Conversely, inertial instability implies an imbalance of the Coriolis and pressure gradient forces so that outflow will accelerate away from the near-storm environment. The relatively larger areal extent of the outflow in cases of weak inertial stability means the work done by the tropical cyclone in forcing subsidence against buoyancy forces is reduced by additional radiative cooling.

The concept of minimizing the work done by a convective system to expedite rapid intensification is not new. Mecikalski and Tripoli (2003) showed how the outflow environment of tropical cloud clusters influences the structural characteristics of individual clouds through the evolutionary selection of cloud structures that resonate with the environmental weaknesses. Utilizing the diagnostic parameter inertial available kinetic energy (IAKE, which is to inertial instability as CAPE is to gravitational stability), a quantity that is near zero (minimal outflow energy drain) when the difference between the outflow potential vorticity and the environmental potential vorticity is small, Mecikalski and Tripoli (2003) found that the convective structures in a tropical plume region are modulated so as to produce convective plumes that access the least environmental inertial stability. Furthermore, they found that intertropical convergence zone (ITCZ) convective outflow, normally directed equatorward toward a lower Coriolis parameter, can be redirected northward as low-valued potential vorticity from the equator is advected northward by a downstream ridge. In the calculations of IAKE, it was found that a certain type of convective momentum transport reproduced the poleward tropical plume formation, implying that the convection and its internal structure are governed by the environmental inertial stability.

Blanchard et al. (1998) studied the impacts of upper-level inertial stability on the circulation strength of mesoscale convective systems. They showed that lowered environmental inertial stability, in a two-dimensional numerical study, produced by the anticyclonic shear side of a jet resulted in a stronger, divergent outflow (and secondary circulation in general) and the more rapid onset of convective-symmetric instability. Increasing the latitude of the numerical experiment offset the reduced inertial stability by increasing the Coriolis parameter.

One of the first numerical studies to display the channel-like nature of TC outflow, though quite inadvertently, was Kurihara and Tuleya (1974). In their Fig. 12, four outflow channels are visible. The paths of these outflow channels yield the most direct access to artificially imposed outflow-layer convergence and subsidence induced by the no-flux boundary conditions. Today’s simulations, with open boundary conditions and large domain sizes, do not have to contend with containing the outflow. However, minimization of the outflow-layer energy expenditure in TCs by development of asymmetric outflow channels is realized in theoretical (Handel 1993) and observational studies (M88).

It is suggested in this study that TCs may undergo rapid intensification if they have effectively plugged into a region of weak inertial stability such that the energy expense of forced subsidence is lessened in the expansive outflow channel. In the absence of weak inertial stability in the environment, outflow will expand against the ambient environment out to the Rossby radius of deformation, where subsidence is forced while consuming energy as divergence gives way to rotation.

Based on previous observational, numerical, and theoretical studies, it is the aim of this work to provide an alternative top-down path to the study of TC structure, intensity, and environmental interactions based on the availability of outflow-layer channels to the developing storm system. The experimental setup along with simulations with a symmetric environmental inertial stability distribution are investigated in section 2. Section 3 looks at the impacts of an asymmetric distribution of inertial stability on TC structure and intensity. A concluding discussion follows in section 4.

2. Symmetric environment
   a. Model description and experimental setup

The model used for this study is the time-split, quasi-compressible, nonhydrostatic, University of Wisconsin-Nonhydrostatic Modeling System (UW-NMS), as described
in Tripoli (1992). The model uses a two-way interactive, movable grid-nesting scheme that permits the simultaneous resolution of both the synoptic-scale environment and the hurricane core. The dynamical core predicts momentum by utilizing a vorticity- and enstrophy-conserving form of the equations of motion. Ice–liquid water potential temperature is the predicted thermodynamic quantity with temperature, potential temperature, and cloud water diagnosed. A six category grid-scaled bulk microphysical scheme represents liquid- and ice-phase processes while a radiative parameterization with long- and shortwave transfer is employed. In addition to a Smagorinsky-type deformation-based eddy diffusion scheme, fourth- and sixth-order explicit diffusion schemes are applied in the horizontal and vertical, respectively.

The simulations use square grids of 48-, 12-, and 3-km resolution with dimensions of 6240, 2100, and 300 km, respectively. The outermost grid employs a modified form of the Emanuel cumulus parameterization (Emanuel 1991) with radiative boundary conditions on the lateral boundaries (Klemp and Wilhelmson 1978). The inner grids employ two-way nesting and are centered on the minimum in surface pressure. Forty-two levels were used on a stretched vertical grid with a resolution as small as 150 m in the boundary layer and as large as 600 m in the lower stratosphere. The Jordan (1958) sounding was used as base state. Finally, the sea surface temperature was fixed at 28°C. Output was converted to cylindrical coordinates by using two-dimensional bicubic interpolation at each model level.

In the absence of a basic-state wind profile, the environmental inertial stability is defined as

\[ I = (f + \zeta)\left(f + \frac{2\nu}{r}\right). \]

In the case of no environmental flow, this reduces to \( f^2 \), where \( f \) is the Coriolis parameter, \( r \) the radius, \( \nu \) the azimuthal wind, and \( \zeta \) the relative vorticity. An easy way to modify a symmetric distribution of inertial stability in three dimensions is to vary \( f \). Since this will affect the inertial stability at all heights uniformly, it is an uncomplicated way to vary the inertial stability of the outflow-layer environment. Two experiments were conducted. The first, hereafter referred to as \( f10 \), was performed on an \( f \) plane at 10°N. The second, \( f30 \), was performed at 30°N. Each vortex was initialized using the Rotunno and Emanuel (1987) symmetric vortex structure:

\[
\nu(r, z) = \frac{z_{top} - z}{z_{top}} \left\{ \left( \frac{r}{r_m} \right)^2 \left[ \left( \frac{2r_m}{r + r_m} \right)^3 - \left( \frac{2r_m}{r_0 + r_m} \right)^3 \right] \right. \\
\left. + \frac{f^2 r^2}{4} \right\}^{1/2} - \frac{f r}{2},
\]

where \( \nu \) is the tangential velocity, \( z_{top} \) is the height where \( \nu = 0 \) m s\(^{-1} \), \( r_m \) is the radius of maximum wind (RMW), \( f \) is the Coriolis parameter, and \( \nu_m \) is the maximum tangential wind. Values of \( f, r_m, \) and \( \nu_m \) are taken to be \( 5 \times 10^{-5} \) s\(^{-1} \), 100 km, and 15 m s\(^{-1} \), respectively, for both simulations. Only the outer two grids were run for the first 10 h of the simulation as the model tropical cyclone developed a divergent boundary layer flow. The innermost grid was then turned on and run for the remainder of the simulation.

### b. Structure

The azimuthally averaged tangential winds at the lowest model level are displayed in Fig. 1. The \( f10 \) simulation reaches its maximum equilibrium value near 35 h while \( f30 \) does not reach its maximum value until 55 h. The minimum surface pressure trace (not shown) reveals that by hour 80 the two simulations have reached an equal intensity. The similar rates of rapid intensification and equilibrium intensity suggest that the primary difference between the two simulations is the time to rapid intensification.

Figure 2 shows the azimuthally averaged circulations of the two simulations at times corresponding to the maximum intensity for the respective case. It is clear that the secondary circulation—as given by the radial flow (Figs. 2a and 2b), vertical motion (Figs. 2e and 2f), and mass flux (not shown)—is significantly more intense for the low-latitude simulation. The results seen here are quite similar to those found for mesoscale convective systems in Blanchard et al. (1998). The weak resistance to convective outflow allows for a more intense outflow, which through mass continuity implies more vigorous vertical motion. While the magnitude of the tangential wind is similar for the two simulations, the \( f30 \) vortex has a larger RMW and is significantly broader than the \( f10 \) vortex (Figs. 2c and 2d). As the environmental rotation increases, the deflection of the inflow increases and the radius at which the pressure gradient balances the Coriolis and centrifugal forces increases, hence the larger RMW and broader vortex for the \( f30 \) case.

The structure aloft is not nearly as complex as the low-level structure. As air exits the eyewall in the upper troposphere–lower stratosphere, it rises slowly and expands anticyclonically outward as it approaches the level of neutral buoyancy. As the simulations conducted in this section are performed on an \( f \) plane in a quiescent environment, the outward expansion is symmetric (Fig. 3). After a day of model integration, differences between \( f10 \) and \( f30 \) are apparent (cf. Figs. 3a and 3b). The outflow in \( f10 \) is characterized by a stronger divergent flow relative to \( f30 \). Indeed, the outflow of \( f30 \) shows significant

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rotation throughout the simulation (Figs. 3b, 3d, and 3f), whereas \( f_{10} \) develops a small anticyclonic component to the outflow at later times. As the value of \( f \) increases, the deformation radius decreases, leading to the formation of an intense, symmetric, anticyclonic outflow jet as seen in \( f_{30} \). It will be shown that the formation of a strong symmetric outflow jet is an energetic drain on the TC system as the large inertial stability provides resistance against continued expansion.

Using azimuthally averaged plots of the horizontal wind field and PV, the symmetric development of the upper-level outflow is examined in Fig. 4. There is a marked contrast in the radial wind evolution of the two simulations. The \( f_{10} \) simulation exhibits a strongly divergent outflow initially (Fig. 4a), which subsequently weakens, while \( f_{30} \) displays a slow, near-linear increase of divergent outflow in time (Fig. 4b). The cyclonic core development aloft (Figs. 4c and 4d) mimics the evolution at low levels (not shown). The smaller Rossby radius of deformation of \( f_{30} \) leads to rotational flow closer to the storm core than in \( f_{10} \) and the development of an intense, symmetric, anticyclonic jet. As the outflow expands, there is a loss of the divergent (i.e., radial) wind at the expense of rotational (i.e., tangential) wind.

Differences in the ambient PV field are determined by the Coriolis parameter as the ambient stratification is determined by the initial sounding shared by both simulations (neglecting the impacts of transient gravity waves on stratification). Figures 4e and 4f show that the environmental PV of \( f_{10} \) is much closer in value to the outflow PV than in \( f_{30} \), yielding a smaller radial PV gradient at the outflow–environment interface. Also note that the outflow of \( f_{10} \) expands outside of the second grid’s domain by hour 60 while the expansion of outflow in \( f_{30} \) slowly decreases with increasing time and increasing distance from the storm core.

c. Interpretation

As stated in the introduction, Emanuel (1986) utilized a Carnot-type theory for steady-state hurricanes to develop a theory of MPI. Since the work done in the outflow was small compared to the net heat input, its impact on MPI was neglected and a fully developed outflow anticyclone was assumed at steady state. It is possible however that during the evolution of a hurricane, the work done in the outflow may have an impact on intensification rates or affect its ability to achieve MPI. The term “work done” in Carnot theory refers to energy expended by the hurricane to spin up and expand the outflow anticyclone. Given enough time, and the absence of shear, TC outflow will dominate the environment by pushing away the initial environmental air. With weak inertial stability, the environment provides little resistance to being pushed aside, leading to more rapid intensification.

Carnot theory states that the net heat into a system is equal to the net work available to that system:

\[
\Delta Q = \Delta Q_{in} + \Delta Q_{out} = W_{in} + W_{out}.
\]

Following Emanuel’s idealized cycle [see Fig. 13 in Emanuel (1986)],

\[
\Delta Q_{in} = \int_a^c \Delta Q = \int_{\theta_{ea}}^{\theta_{ec}} c_p T_{in} d\ln\theta_e = c_p T_{in} \ln \frac{\theta_e}{\theta_{ea}}
\]

and

\[
\Delta Q_{out} = \int_c^{\theta_{ec}} \Delta Q = \int_{\theta_{ea}}^{\theta_{ec}} c_p T_{out} d\ln\theta_e = -c_p T_{out} \ln \frac{\theta_e}{\theta_{ea}}.
\]

where \( \theta_e \) is the equivalent potential temperature, \( a \) is a characteristic radius of the ambient environment, and \( c \) represents the radial position of the eyewall. Combining the two above equations yields

\[
\Delta Q = \Delta Q_{in} + \Delta Q_{out} = c_p T_{in} \epsilon \ln \frac{\theta_e}{\theta_{ea}}.
\]

where \( \epsilon = (T_{in} - T_{out})/T_{in} \) is the Carnot efficiency. Here, \( T_{in} \) is taken as the sea surface temperature while \( T_{out} \) is calculated by averaging the temperature at the tropopause, which was defined here as the 1.5 PVU surface, where 1 PV unit (PVU) = 10^{-6} m^2 s^{-1} K kg^{-1}.

The work done in the outflow was calculated by Emanuel to be the energy needed to restore the angular
momentum of the outflow back to its ambient value [Eq. (61) in Emanuel (1986)]:

$$W_{\text{out}} = \frac{1}{2} \Delta V^2 = \frac{1}{2} \left[ \left( \frac{M}{r_1} - \frac{1}{2} fr_1 \right)^2 - \left( \frac{M_a}{r_1} - \frac{1}{2} fr_1 \right)^2 \right],$$

where the definition of the angular momentum is $M = rV + \frac{1}{2}fr^2$ and $r_1$ is the radius at which the angular momentum along the tropopause becomes equal to the ambient value.

In the eyewall, angular momentum and entropy surfaces are mostly congruent with the entropy gradient pointing upward and toward the storm center and the angular momentum gradient directed toward the environment. With this knowledge, the radius $c$ was calculated by determining the radial position that satisfied

$$\min(\nabla M \cdot \nabla \theta_c).$$

The eyewall entropy and angular momentum were taken to be their respective values at the first model level above the surface. The ambient environment radius, $r_a$, is the radius at which air begins to flow inward near the surface. Numerous values between 200 and 800 km were tested and the solution did not change appreciably so a value of 500 km was chosen. As at the eyewall, the ambient angular momentum and entropy values were taken at the first grid level above the surface at radius $r_a$. Finally, $r_1$ was determined by finding the radius at which the angular momentum along the tropopause first exceeds the ambient value.

The calculation of the net heat input and outflow work was performed at each azimuth and then azimuthally...
averaged. The azimuthal average is useful in these simulations as the symmetric environmental inertial stability is associated with symmetric outflow expansion. The results are shown in Fig. 5. The net heat input for $f_{10}$ (Fig. 5a) jumps out to a large value ($2500$ J kg$^{-1}$) as the rapid spinup of the primary circulation leads to a strong wind-induced surface heat exchange (WISHE) mechanism and concomitant rapid rise in the boundary layer entropy. After the initial strengthening, the net heat input fluctuates about an equilibrium value of $1500$ J kg$^{-1}$. The $f_{30}$ simulation shows a steady increase until about hour 40 where it reaches a steady equilibrium of $2100$ J kg$^{-1}$. The larger value in the net heat input for $f_{30}$ is the result of a larger ratio of $\theta_e$ to $\theta_{eq}$.

The work done in expanding the outflow is small and constant ($10$ J kg$^{-1}$) in $f_{10}$ (Fig. 5b). The low inertial stability of the environment provides little resistance to outflow expansion. Conversely, there is strong resistance to outflow early ($150$ J kg$^{-1}$) in the high-latitude simulation and this resistance grows larger with time, nearly doubling after $100$ h. As the outflow expands in area, the physical size of the environment that needs to be replaced increases, requiring an increasing amount of energy to be expended by the tropical cyclone. A result of the growing energy sink is the significant slowdown of

Fig. 3. The $f_{10}$ and $f_{30}$ isotachs (m s$^{-1}$, grayscale) and streamlines at 13 km: (a) $f_{10}$ at 25 h, (b) $f_{30}$ at 25 h, (c) $f_{10}$ at 55 h, (d) $f_{30}$ at 55 h, (e) $f_{10}$ at 80 h, and (f) $f_{30}$ at 80 h.
the outflow expansion (as measured by PV; see Fig. 4f). The ratio of the work done in the outflow layer to the net heat input (Fig. 5c) shows that despite the significantly larger net heat input of f30, the work done against the outflow environment grows as large as 13% of the net heat input. The small amount of energy expended to expand the anticyclone in f10 yields a storm that reaches MPI much more rapidly than in f30. This result is consistent with the results found by Emanuel (1989) in which doubling the physical size of the original vortex of the experiment produced a storm of the same intensity but took a longer period of time to attain that intensity. By quadrupling the size of the original vortex, the storm failed to develop. Emanuel attributed the failure to develop the surface cyclone to the large amount of energy used to spin up an outflow anticyclone at the expense of the WISHE feedback.

3. Asymmetric environment

a. Experimental design and model setup

Unlike the idealized tropical cyclones modeled in the preceding section, real tropical cyclones, particularly those in the subtropics, interact with the momentum, moisture, and thermal fields of their environment. The large inertial stability of the primary tropical cyclone vortex negates any possible lateral interaction in the lower troposphere. Therefore, these external interactions are restricted to the outflow layer where the inertial stability is small.

To produce an asymmetric distribution of environmental inertial stability on an f plane, a zonally uniform jet, generated with exponential functions similar to those in Blanchard et al. (1998), is placed to the north of a hurricane vortex. The absence of along-jet variations

FIG. 4. The f10 and f30 Hovmöller diagrams at z = 13 km for the (a) f10 radial wind (m s$^{-1}$), (b) f30 radial wind (m s$^{-1}$), (c) f10 tangential wind (m s$^{-1}$), (d) f30 tangential wind (m s$^{-1}$), (e) f10 PV (10$^6$ m$^2$ s$^{-1}$ K kg$^{-1}$), and (f) f30 PV (10$^6$ m$^2$ s$^{-1}$ K kg$^{-1}$).
guarantees that there are no initial secondary circulations. A view from the east of this initial condition is shown in Fig. 6. A few changes to the experimental setup with respect to the previous section were made. The number of levels in the vertical was increased to 50. Periodic boundary conditions were employed in the zonal direction. Finally, the domain size was nearly doubled to ensure that the impacts of the TC-induced, downshear, wave train would not propagate across the domain and have an appreciable upstream impact on the tropical cyclone (Fig. 7).

Due to the placement of the jet and the vortex, a region of anticyclonic shear is established between the jet maximum and the tropical cyclone core. By varying the intensity and/or structure of the jet, the magnitude of the inertial stability can be controlled. Significant care was taken in determining the separation distance between the tropical cyclone and the jet. If the separation is too large (greater than a Rossby radius), the systems will evolve independently of one another. If the separation distance is too small, vertical shear will dominate any influence of the asymmetric environmental inertial stability in the dynamic evolution of the storm. A separation of 900 km was chosen so that a significant interaction with the jet occurred while the vertical shear over the vortex was kept small. No additional mean flow was added to the simulations in order to minimize the shear and to restrict the focus to changing the environmental inertial stability. All simulations were set up with the outer grid centered at 31°N and the inner two grids centered on the minimum in surface pressure. The tropical cyclone was placed at 27°N with a 45 m s\(^{-1}\) jet centered at 35°N in experiment JET and the jet removed in experiment NOJET. Additionally, simulations using 15 (JET15), 30 (JET30), and 60 (JET60) m s\(^{-1}\) jets were performed.

An initial Rotunno and Emanuel (1987) vortex of 12 m s\(^{-1}\) was first tested in the tropical cyclone–jet simulations. At this speed, the slow development of the boundary layer convergent flow allowed the small vertical shear introduced by the presence of the jet (Fig. 6) to develop a wavenumber 1 asymmetry in the vertical motion field prior to rapid deepening (not shown). With the vertical motion confined to the storm quadrant downshear

**FIG. 5.** Energy sources and sinks to the idealized Carnot cycle: (a) \(f_{10}\) and \(f_{30}\) net heat inputs (J kg\(^{-1}\)), (b) \(f_{10}\) and \(f_{30}\) work done in the outflow layer (J kg\(^{-1}\)), and (c) the ratio of the two terms for \(f_{10}\) and \(f_{30}\).

**FIG. 6.** Limited-domain \(y-z\) cross section of the zonal wind (m s\(^{-1}\)) initial conditions for JET simulation.

**FIG. 7.** Full-domain \(x-y\) plan view of the zonal winds (m s\(^{-1}\)) for JET at 70 h.
and to the left of the mean shear vector (Frank and Ritchie 2001), that is to the north with westerly shear, the parent vortex failed to develop, becoming only as intense as the minimum pressure of the most intense shear-confined convective cells. An initial vortex strength of 20 m s\(^{-1}\) at the RMW was selected for the tropical cyclone–jet simulations, as the cyclonic circulation and the boundary layer convergence are strong enough to overcome the shear.

b. Evolution

The maximum azimuthally averaged tangential wind at the lowest model level is shown in Fig. 8. Despite the presence of weak inertial stability over the vortex core, the intensification in JET is nearly identical (slightly lagging if intensity is measured as the minimum in surface pressure; see Fig. 9) to that in NOJET. This is in stark contrast to the results of the previous section in which weaker environmental inertial stability allowed more rapid intensification. There are a couple of plausible explanations for the observed behavior. First, it is reasonable to suspect that the short times to rapid intensification seen previously could be the result of a smaller Coriolis parameter and are therefore not manifested in the simulations discussed in this section. In other words, the decreased low-level inertial stability and the associated development of a relatively more compact core at low levels drive the timing to rapid intensification. Second, the presence of the jet increases the vertical shear of the horizontal wind over the storm core. Asymmetrical convection in the core can significantly delay or even halt symmetric intensification as noted above. Asymmetric distributions of inertial instability also lead to asymmetries in the core, as will be discussed shortly.

To determine the impacts of vertical shear on the evolution of the simulations presented in this section, the shear was calculated by taking the difference in azimuthally averaged winds in an annulus between 200 and 500 km from the storm center at the 200- and 850-hPa pressure levels. Figure 10 shows that the presence of the jet adds 3 ms\(^{-1}\) to the vertical shear early in the evolution. During the rapid intensification between 20 and 30 h, the shear in JET increases dramatically, peaking near 6 ms\(^{-1}\). While this shear is not strong enough to be detrimental to the storm (McBride and Zehr 1981), the enhanced shear due to the presence of the jet is strong enough to slow the rapid deepening phase. Shear generated by convective asymmetries in NOJET levels off at 3 ms\(^{-1}\) at hour 30. At the same time, outflow-layer anticyclonic forcing has deformed JET, lifting the jet core farther to the north, and rapidly diminishing the wind shear over the storm core so that by 40 h both simulations have a nearly identical vertical shear value. Beyond about 35 h, the weaker the inertial stability, the more rapid the intensification, as seen in Fig. 9.

c. Vortex structure

An important aspect of adding the asymmetry aloft and the associated weak shear is the generation of a significant wavenumber 1 symmetry near the surface. As can be seen in the surface entropy field (Figs. 11a and 11b) 20 h into both the NOJET and JET simulations, the vertical motion field at 1.5 km is largely composed of isolated, growing and decaying convective cells that form in the boundary layer convergence regions of the
parent vortex. At 20 h, a classic eyewall has not formed in either simulation. While the vertical motion field is symmetrically distributed in NOJET, the vertical motion field in JET is organized on the northern flank of the developing warm core, downshear and left of the west-to-southwesterly vertical shear. Despite being weaker in both intensity measures, JET appears to be closer to rapid intensification from a structural standpoint as there is a nucleus of high $u_e$ values that is absent in NOJET. The minimum pressure displayed in Fig. 12a (NOJET) is associated with a vigorous convective cell embedded within the parent vortex. Given the low pressure levels of the initial conditions, it appears that the structure must be considered to be in a relative state rather than an absolute one. In JET, the minimum pressure is associated with the parent vortex, as evidenced by the entropy maximum and lack of vertical motion near the center. Development of the TC core and primary band appear to be well under way by hour 20 of the JET simulation.

Thirty hours into the simulations (Figs. 11c and 11d), a well-defined, low-level warm core has developed in the eye of both simulations. JET displays a classical circular eye surrounded by a robust eyewall while NOJET is more elliptical. Banding is beginning to develop, as seen by the inner bands. Significant convection is still occurring in the periphery of the storm as evidenced by the significant entropy minima associated with convective downdrafts. A wavenumber-1 asymmetry has developed in the low-level entropy field of JET with warm, moist air wrapping around the eastern periphery of the storm and low entropy values wrapping around the western periphery of the storm. By 70 h into the simulation (Figs. 11e and 11f), the wavenumber-1 asymmetry in JET is well pronounced and wound up tightly about the core. The orientation of the asymmetry remains fixed in time with the primary inner band wrapping around the northwestern flank of the storm. NOJET displays the characteristics of a symmetric tropical cyclone.

The outflow isotach and streamline evolution patterns of NOJET and JET are given in Fig. 13. Not surprisingly, NOJET (Figs. 13a, 13c, and 13e) shows an upper evolution pattern that is similar to that in f30 of the previous section. The outflow expands symmetrically about the storm center with a strong anticyclonic jet forming where rotation dominates divergence. After rapid intensification, roughly 40 h into the simulation, the outflow has expanded to the Rossby radius of deformation such that the expansion of outflow slows considerably. The only way to expand further is to generate a stronger anticyclonic jet to spin down and expand against the environment. From a Carnot cycle perspective, a large fraction of the mechanical energy available to the storm goes toward strengthening the outflow anticyclone as opposed to frictional dissipation at the surface (Emanuel 1988).

JET displays an entirely different evolutionary pattern (Figs. 13b, 13d, and 13f) as the asymmetric environmental inertial stability has an almost immediate impact on the outflow structure. In JET the tropical cyclone utilizes the weak resistance to outflow in the northern section of the storm environment. The low inertial stability of this region provides an outflow channel in which the storm may ventilate to large radial distances (well outside the domain of grid 2) with very little resistance and little rotation. While the outflow is not limited to the northern sector, the ventilation into the other regions is similar to that at NOJET in which rotation forms an anticyclonic jet that curves around the storm periphery until it asymptotically merges with the southwest–northeast-oriented midlatitude jet. Even after the symmetric expansion to the deformation radius, JET continues to intensify, with respect to NOJET, as outflow can expand in a narrow channel that provides little resistance to continuous expansion.

An important consequence of the outflow channel that forms in the presence of the jet is the generation of a downstream anticyclone, as seen in Figs. 13d and 13f. Convective mass rearrangement within the eyewall produces a cyclonic PV anomaly at low levels and an anticyclonic PV anomaly aloft. With outflow venting to the north and then to the northeast, the anticyclonic PV anomaly is advected downstream, leading to the formation of the anticyclone to the northeast. The anticyclonic circulation produces easterly flow on the eastern side of the hurricane, cutting off all outflow in this region and forcing the outflow to expand to the west against...
a resistant environment. Additionally, the strengthening of the anticyclone and the easterly flow over the hurricane pinches off the outflow channel’s access to the weak inertial stability to the north. It is for this reason that JET60 fills toward the end of the simulation (Fig. 9).

The TC of the JET simulation is embedded in an environment with weak inertial stability (instability) to the north and northeast of the storm center. Ventilation of outflow in these directions minimizes the energy expenditure of the hurricane as the environmental angular momentum to the north and northeast closely matches that of the hurricane outflow. Verification is made by calculating the work done in expanding the outflow, as was done for \( f_{10} \) and \( f_{30} \) of the last section. In this case, it is the azimuthal variations of the outflow work that is of most interest. The outflow work results, as a function of azimuth (rotating cyclonically beginning to the east) at 30, 50, and 70 h, are plotted in Fig. 14. The energy required to expand the symmetric outflow increases with time as was shown previously from the results of \( f_{30} \) in the previous section. The outflow work term in JET shows that after rapid intensification, ventilation to the northeast requires less and less energy. By ventilating a large percentage of the outflow toward the northeast,
a large asymmetry is generated. As discussed in the introduction, Handel (1993) suggested that the development of asymmetries minimizes the energy expenditure of tropical cyclones as development and expansion of anticyclonic flow is an energetic drain on the system (Emanuel 1989). Symmetric expansion led to large energy expenditures as manifested by the continuously strengthening symmetric anticyclonic jet.

Perhaps the simplest way to generate an inertial stability asymmetry, without the need for environmental flow, is to run a $\beta$-plane simulation. To investigate further, a simulation identical to $f_{10}$, except for the variation in the Coriolis parameter, was conducted. The low value and rapid latitudinal variation of the Coriolis parameter of the tropical and subtropical atmospheres suggest that tropical cyclone outflow should be more favorably directed equatorward. Indeed, this is verified in a plot of the outflow-layer streamlines displayed in Figs. 15 and 16, where the outflow work term is minimized in the southern azimuthal angles. It is evident from Fig. 15 that there is a reduction in the Carnot cycle outflow work term in the presence of asymmetric outflow channels.

With the generation of $\beta$ gyres, the $\beta$ shear generates a sustained core asymmetry (Fig. 16f) that leads to a slower intensification than its $f$-plane counterpart (not shown). Therefore, there are competing effects on TC intensification in the presence of asymmetric environmental inertial stability. While organized outflow in asymmetric channels may minimize an energetic drain, the core asymmetries driven by such an inertial stability distribution may reduce symmetric intensification, especially early in the TC life cycle. In the simulations presented here, shear-driven asymmetries are not strong enough to prevent symmetric intensification.

Figure 16 displays the impacts of the outflow environment on the TC core structure. On the left of Fig. 16 the outflow layer streamlines and the logarithm of the ratio of the divergence to rotational flow are displayed. The images on the right show 5-h accumulated precipitation patterns for the NOJET, JET, and $\beta$ simulations corresponding to the images on the left of the figure. Note the changes in domain size for the different image types. While convection is present in all quadrants of the core, regions of convective growth and decay can be inferred from the asymmetric precipitation patterns of JET and $\beta$. As noted above, the precipitation in $\beta$ is consistent with the $\beta$-shear interpretation. JET displays an asymmetric precipitation pattern despite the vertical shear having been reduced to a magnitude comparable to the $f$-plane simulation.

An interesting pattern is evident when a comparison is made between the precipitation and outflow-layer flow patterns. Regions with the most persistent convective activity, be it in the storm core or rainband activity, are located radially inward from regions where the strongest rotation feeds most directly into the paths that expand outward toward environments dominated by divergence and low inertial stability (the darker colors). Conversely, minima in the precipitation patterns are located radially inward from where inner divergent maxima lead directly into outflow paths that wrap anticyclonically around the storm core. This suggests that TC convective activity organizes in such a way as to have the most direct access to regions of weak inertial stability in the far environment.

Although the JET simulations presented here are highly idealized, their outflow structures (Fig. 13d) are remarkably similar to those of real tropical cyclones. Figure 17 shows a mid-/upper-level water vapor and satellite-derived wind image, courtesy of the tropical cyclone research group at the Cooperative Institute for Meteorological Satellite Studies (CIMSS) at the University of Wisconsin—Madison (UWM), of Typhoon Ma-on at 0600 UTC 7 October 2004. At this time,
Ma-on has just begun to undergo rapid intensification and displays a radially elongated outflow jet expanding into the region of weak environmental inertial stability found on the anticyclonic shear side of the jet to its northeast.

4. Concluding discussion

Energy acquired from the air–sea interaction during inflow is used to overcome processes such as 1) surface dissipation, 2) spinup of primary circulation, 3) eye development, and 4) expansion of the outflow anticyclone against the ambient rotation of the environment. By minimizing one of these energy sinks, more energy is available to overcome the other sinks, which may result in larger intensification rates or a stronger overall intensity. It was the aim of this work to demonstrate that regions of weak resistance to tropical cyclone outflow, characterized by weak environmental inertial stability, provide preferred outflow channels (i.e., outflow jets) so that the energy expended in developing and expanding the outflow is minimized.

A set of three-dimensional experiments was performed in which the inertial stability was symmetrically modified.
by varying the Coriolis parameter. While such a set of experiments produces varying inertial stability aloft and at the surface, it is a reasonable first step toward understanding the more complex three-dimensional asymmetric environment. From these studies it was found that tropical cyclones developing at lower latitudes intensified at a more rapid rate. This result was attributed to the significant decrease in the work done in expanding the outflow layer (as the environmental angular momentum more closely matched the tropical cyclone outflow angular momentum), which allowed for more intense divergent upper-tropospheric outflow, which, through mass continuity, was associated with more vigorous ascent in the eyewall. Of course, the lower inertial stability at low levels permitted the more rapid development of a relatively more compact core, which could also be vital to the rapid intensification. Tropical cyclones at higher latitudes were slower to develop as more kinetic energy was required to expand the outflow against the environment.

To explore the influence of asymmetric environmental distributions of inertial stability on a developing idealized tropical cyclone, a set of experiments in which a jet of varying intensity was placed to the north of the developing tropical cyclone. While the results of these experiments show that the outflow utilized the weak inertial stability south of the jet to produce a more rapid tropical cyclone deepening, this deepening was preceded by a period during which the deepening rate was slowed because of the imposed vertical shear associated with the jet. Toward the end of the simulation, the downstream advection of convectively generated low PV produces an anticyclone to the north and east of the tropical cyclone. The flow associated with this anticyclone restricted the outflow of the hurricane, eventually leading to weakening.

In a quiescent environment, outflow expands symmetrically against the ambient cyclonic rotation to the Rossby radius where divergence gives way to rotation, forcing subsidence, which acts as an energetic drain on the TC circulation. The presence of a jet and its locally depressed inertial stability associated with the horizontal anticyclonic shear provides a preferred outflow path. Again, outflow expands out to the Rossby radius, where the outflow “searches” for a weakness in the inertial wall. If one is found, and the work required for further expansion is less than that required to force subsidence at the Rossby radius, the outflow is ventilated through that weakness so that further radiational cooling reduces the energy drain of forced subsidence against buoyancy. As noted in previous studies, particularly HM84, conditions in the simulations presented here are often short lived. Regions of strong anticyclonic horizontal shear near a TC core are often followed by significant increases in vertical shear associated with an approaching trough. It is therefore possible to see rapid intensification as a hurricane accesses an outflow channel only to be followed by rapid decay as strong vertical shear disrupts the storm core.

Likewise, early in the life cycle, a tropical cyclone that is within a deformation radius of a region of weak inertial stability can ventilate preferentially and form an
outflow jet. With enhanced divergent outflow, mass continuity requires more intense vertical motion and therefore increased diabatic heating and pressure falls. If the interaction occurs before the development of a mostly symmetric secondary circulation, the interaction may actually be harmful in a similar fashion as vertical shear. It is suggested here that convection organizes itself in the core so as to access the preferential outflow path. Such a convective asymmetry, similar to one produced by vertical shear, would be detrimental to early growth.

Perhaps because the “culture” of atmospheric dynamics was originally built on earlier work toward understanding of the baroclinic cyclone, it has become conventional to expect that positive outflow-layer interactions of tropical cyclones with the environment suggest a “top down” energy transfer (environment to storm) be it through mechanisms such as the eddy importation of cyclonic angular momentum or enhanced divergence. In this study we have shown that environmental interactions of the tropical cyclone actually tend to flow in the opposite direction, that is, from the “bottom up.” Previous investigations have suggested that energy is supplied to the tropical cyclone by heat transfers and conversions to kinetic energy internal to the tropical cyclone. At the same time, the cyclone consumes energy primarily through surface friction and work performed against environmental resistance. This study has shown that the spatial and temporal variabilities of this environmental resistance modulate the amount of energy available not only for the normal maintenance of the

![FIG. 16. Logarithm of the divergent to rotational flow (color shading) and 13-km streamlines at 40 h for (a) NOJET, (c) JET, and (e) β. The accumulated precipitation (mm) between 35 and 40 h for (b) NOJET, (d) JET, and (f) β.](image-url)
The spatial pattern of environmental resistance helps determine which areas of the storm grow or weaken. Consequently, this strongly affects the evolution of the spatial structures of the storm such as size, bandedness and asymmetries.

Often times, the most intense tropical cyclones show two outflow jets in satellite imagery: one toward the north, where there is weak inertial stability associated with the anticyclonic shear side of a belt of westerlies, and another toward the south and the anticyclonic shear side of the easterlies or even outflow from the ITCZ. In such a setup, there is no external system providing energy. Rather the tropical cyclone has developed asymmetric outflow jets to minimize the energy expense of the outflow development and compensating subsidence.

One outstanding issue in the TC–environment interaction is how exactly the interaction is communicated to the storm core. Environmental flow patterns that promote outflow asymmetries lead to a more rapid intensification of a tropical cyclone through the minimization of an energetic drain on the secondary circulation. The asymmetries in the outflow are not intrinsic to the storm, but are rather controlled by the environmental flow pattern. Therefore, it is suggested here that the outflow acts as a medium to transmit evolving environmental conditions to the storm core. Convective elements within the storm core and rainbands organize in a manner such that the outflow has direct access to regions of weak inertial stability in the environment. The physical process by which this occurs remains to be explored.

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