

Is Environmental CAPE Important in the Determination of Maximum Possible Hurricane Intensity?

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ABSTRACT

In numerical simulations using an axisymmetric, cloud-resolving hurricane model, hurricane intensity shows quasi-steady-state behavior. This quasi-steady intensity is interpreted as the maximum possible intensity (MPI) of the model.

Within the literature, numerical demonstrations have confirmed theoretically anticipated influences on hurricane intensity such as sea surface temperature, outflow temperature, and surface exchange coefficients of momentum and enthalpy. Here these investigations are extended by considering the role of environmental convective available potential energy (CAPE) on hurricane intensity. It is found that environmental CAPE (independent of changes to the outflow level) has no significant influence on numerically simulated maximum hurricane intensity. Within this framework, MPI theories that are sensitive to environmental CAPE should be discarded.

1. Introduction

A hurricane is without doubt one of the most vivid examples of a long-lived intense coherent structure in the atmosphere. Among the many questions that concern the dynamics of hurricanes, recent work has suggested that even such a basic question—How strong can a hurricane become?—is still open (Persing and Montgomery 2003, hereafter PM03). Here we continue our examination of this problem by exploring the influence of environmental convective available potential energy (CAPE) on hurricane intensity.

For given environmental conditions, maximum possible intensity (MPI) is a conceptualized upper limit on the intensity of a hurricane. Camp and Montgomery (2001) gives a review of MPI theories current in the literature. Of particular interest here are the formulations of Emanuel (1986; updated in Emanuel 1995b) and Holland (1997). Emanuel's theory assumes simplified balances of momentum and entropy at the base of the eyewall and approximates the character of convection in the eyewall by moist-neutral reversible ascent. Neglecting ocean feedback when these balances are asserted (with some additional assumptions such as thermal and gradient wind balance, bulk aerodynamic formulation of exchange of heat and moisture with the ocean surface, complete mixing of the eye with moist

entropy properties of the eyewall, and relative humidity in the boundary layer being constant from the eyewall to the environment), an "optimal" solution for maximum tangential velocity at the top of the boundary layer¹ can be found along with a corresponding minimum sea level pressure. Holland's theory, by contrast, builds on earlier work of Miller (1958) and considers parcels of air as they ascend in the eyewall then recirculate down in the eye with some mixing from the eyewall. From this idealized trajectory and the corresponding column warming in the eye, a central surface pressure deviation is inferred after comparison with the environmental profile of temperature. Maximum tangential winds are not predicted in Holland's theory, and this theory does not depend explicitly on either the momentum or enthalpy exchange coefficients (Camp and Montgomery 2001).

The underlying premise of the Emanuel (1995b, 1986) theories is that the energy source for the mature hurricane is the air-sea disequilibrium and not the energy initially available in the moist tropical atmosphere. This would suggest that the ultimate intensity and structure of the vortex (one which achieves an optimal degree of disequilibrium with the underlying ocean) should be independent of any available energy that may be present in the initial atmosphere. We will demonstrate here that this is indeed the case.

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¹ By assumption, the top of the boundary layer in Emanuel's theory is the same as the top of the subcloud layer and the top of the inflow layer.

Every extant MPI theory (not just the theories under scrutiny here) is constructed under the assumption of axisymmetry. Strictly speaking, then, these theories should be referred to as axisymmetric MPIs. Three-dimensional, coupled climate-regional model simulations (Knutson and Tuleya 1999; Shen et al. 2000) using parameterized moist convection and a coarse 15-km resolution sacrifice one aspect of realism for another in comparison with high-resolution axisymmetric simulation, but since our objective is to test axisymmetric MPIs within the milieu of their construction, we will apply an axisymmetric model to our test. Noting that the axisymmetric system is an approximation of reality, the confidence placed by a researcher or forecaster in these axisymmetric MPIs in real-world applications should increase if these theories are successful in predicting hurricane intensity in an axisymmetric numerical model.

Rotunno and Emanuel (1987, hereafter referred to as RE87) and PM03 have demonstrated that the RE87 axisymmetric hurricane model is an appropriate framework for testing axisymmetric MPI theories. PM03 showed that modeled hurricanes can reach a quasi-steady-state intensity that is maintained for a period of weeks. PM03's results suggest that these solutions are optimal to the physics of the model (in the sense that the storm is as intense as possible, creating and dissipating as much kinetic energy as possible) and that vortex intensity converges to a "model MPI." We will assume that this model MPI responds to the physics of a hypothetical, well-constructed, axisymmetric MPI theory.

By pointing to specific violations of Emanuel's MPI, PM03 demonstrated the importance of physics unanticipated by theory for producing extremely intense hurricanes in axisymmetric simulations. The phenomena associated with these superintense hurricanes (hurricanes stronger than Emanuel's MPI) are nonetheless consistent with features observed in real hurricanes. Entrainment into the eyewall of high-entropy air from the low-level eye was found by PM03 to greatly enhance (by 63%) hurricane maximum tangential winds over the prediction of Emanuel's MPI. The warmer eyewall that results permits a larger thermal wind at the top of the boundary layer at the base the eyewall.

On the basis of the findings from PM03, we believe a fresh evaluation of the factors important for MPI is warranted. Eastin (2003) infers a role for low-level eye entropy in the observed equivalent potential temperature of the most intense eyewall convection. Eastin (2003) identifies this intense eyewall convection as "buoyant convection" and from the buoyancy standpoint suggests alternate mechanisms for enhancing intensity. The distinctions between these explanations and that for superintensity (PM03) must wait for examination of three-dimensional, near-cloud-resolving simulations, which is beyond the scope of this paper.

Of the environmental factors hypothesized to influence MPI, many have been verified to varying degrees in numerical models (RE87; Emanuel 1995a; PM03; Y. Wang, 2003, personal communication), with an exception being the sensitivity to environmental CAPE anticipated by some MPI theories.

This paper evaluates the sensitivity of modeled hurricane intensity to changes in environmental CAPE that are independent of changes to surface and outflow temperatures. We shall call this concept ECAPE. Under ideal circumstances, a vertical profile of thermodynamic quantities can be specified with vanishing ECAPE and prescribed equilibrium level. The initial profiles of temperature and moisture of RE87 were designed to produce a state of near-vanishing CAPE. Given the surface temperature and equilibrium level, assuming moist adiabatic ascent, the equilibrium level temperature can be computed. In numerical practice, a small amount of CAPE is needed to provide the modeler with some degree of control over the equilibrium level (EL) and thus the outflow height,² which is what RE87 simulated. RE87 showed that a tropical depression-strength surface vortex can intensify to hurricane strength in the presence of minimal CAPE [with similar experiments performed by Emanuel (1989, 1995a) and in three dimensions by Dengler and Reeder (1997) and Zhu et al. (2001)]. We could propose to cool this sounding in midlevels without changing the outflow levels—the CAPE would change greatly but the equilibrium level and outflow temperature would not change. The distinction between these two profiles highlights the differences we express in the term ECAPE. ECAPE appears nowhere in Emanuel's MPI formulation, but it is a factor in Miller's MPI model and to a lesser extent in Holland's MPI model, since the complete environmental sounding (not just the equilibrium or outflow level) is needed to compute the surface pressure deviation. We will demonstrate that model MPI is completely insensitive to ECAPE as defined above.

The outline of this paper is as follows. Section 2 reviews the RE87 numerical model. The method for computing CAPE is discussed in section 3. Section 4 presents the main results. The results are discussed in section 5 and summarized in section 6.

2. The RE87 model

The RE87 hurricane model is an axisymmetric (radius versus height coordinates), nonhydrostatic, cloud-resolving version of the Klemp and Wilhelmson (1978) numerical model. The Klemp and Wilhelmson model

² For a perfectly neutral CAPE sounding, the cloud-top height of initial convection is uncertain, and we have found that a stable layer will evolve at some initial cloud-top height. This is because not only does the model environment affect the model storm, but the model storm affects the model environment.

was developed originally for the study of cumulus clouds and supercell storms (see RE87 for model equations and numerical details). The RE87 numerical model is integrated on a staggered Arakawa C-grid using fixed radial and vertical grid spacings. There is no ice in the model. The representation of explicit convection assumes a fixed precipitation fall speed of 7 m s^{-1} . Subgrid-scale turbulence is parameterized using a standard Smagorinsky (1963) formulation modified to allow a variable mixing length. This mixing length is a function of the local static stability using a gradient Richardson number formulation following Lilly (1962). Longwave radiation is represented crudely by a standard Newtonian cooling parameterization that tends to restore the local potential temperature to that found initially in the environment; the initial vortex is a spatially limited perturbation upon this environment with maximum winds near the surface. In the numerical experiments presented here the radiative heating/cooling rate is capped at 2 K day^{-1} (as in experiment J of RE87). A standard sponge-layer damping occurs above the model tropopause ($z > 19.4 \text{ km}$). The outer boundary at $r = 1500 \text{ km}$ is open. The results presented here are found to be insensitive to a doubling of either the outer or upper boundary. Surface interaction is accomplished via a standard bulk aerodynamic parameterization. The surface drag coefficient C_D is represented by a linear function of wind speed using Deacon's formula (Roll 1965). For simplicity, the surface enthalpy exchange coefficient C_k is set equal to the drag coefficient ($C_k/C_D = 1$). The u and w fields are computed using a "fast" time step to handle sound waves. All of the above processes are unchanged from that described in RE87. Like RE87, and for simplicity, the effects of dissipational heating are not included. Bister and Emanuel (1998) and Zhang and Altshuler (1999) suggest that dissipative heating can boost intensity by roughly $10\text{--}12 \text{ m s}^{-1}$.

a. The model as a testing ground for theory

Many of the processes described above are very simplistic, but the objective here is to make use of a numerical setting that is both simple and appropriate for testing the underlying assumptions of MPI theories. The rain-only simulations are most appropriate for comparison with Emanuel's and Holland's theories, both of which neglect ice. Beyond the heating of condensation, both theories also ignore the effects of precipitation, so the assumption of a fixed fall speed is simply an expedient. Since radiation is only implicit in these theories through the maintenance of environmental characteristics, the crude radiation parameterization is justified, but will be insufficient to deal with changes in environmental moisture, for which there is no remedy in the numerical model. The subgrid-scale formulation used here 1) is a function of the local state of the modeled atmosphere, 2) is a crude substitute for the effects of mixing (particularly around the eye-eyewall

interface) hypothesized by both MPI theories, and 3) is not constrained by the assumptions of those theories. Emanuel chooses an eye closure in which radial mixing of angular momentum and entropy forces the eye to be in solid body rotation with the radius of maximum winds. Holland, following Miller (1958), asserts a closure of partial mixing of eyewall properties from the eyewall to the eye such that the eye maintains a constant moist entropy through the vertical. The use of standard bulk aerodynamic parameterization of surface interactions best models the assumptions on drag used in Emanuel's theory. According to Emanuel's theory, the ultimate storm intensity is a function of the ratio C_k/C_D , so some liberty might be taken with the surface parameterization as far as testing theory is concerned as long as a ratio of effective exchange coefficients can be identified. Miller's theory does not explicitly consider surface drag, and hence would anticipate insensitivity of modeled storms to the surface formulation so long as they were close to reasonable, but this experiment is outside the scope of the present paper.

The hurricane will exist in an modeled environment that will be free to evolve (constrained partially by the Newtonian relaxation as described above). Several MPI parameters will be sensitive to these changes in the environment (e.g., vertical profiles of temperature and moisture in Miller's and Holland's theories and the outflow level and temperature in Emanuel's theory). Our approach will be to diagnose these characteristics as the model evolves, since the maintenance of the environment through a parameterized "radiation," parameterized surface interaction, and a resolved, yet axisymmetric, interaction between the modeled boundary layer and the free troposphere is likely to be unrealistic. An ideal circumstance, which we have not yet succeeded to simulate, is a quasi-steady hurricane in equilibrium with an quasi-steady environment.

b. Simulations presented here

Our baseline simulation is that described in PM03³ as the "default run" and is summarized in Table 1. The default run is similar to experiment J of RE87. The high CAPE, mid CAPE, and low CAPE simulations (described below) are simulated at the same spatial and temporal resolution as the "4x run" of PM03, which is the default run with one-quarter the grid spacing in both the radial and vertical direction as well as one-quarter the time step as experiment J of RE87.

3. Model CAPE

CAPE is a measure of the energy that can be released in the presence of free convection. CAPE measures are normally analyzed for undilute parcel ascent,

³ This simulation is also reported in Persing (2002, chapter 5).

TABLE 1. Default run settings. See RE87 and PM03 for details.

Model characteristic	Value
No. of radial v points	NR = 100
No. of vertical v points	NZ = 20
Outer boundary	$R_o = 1500$ km
Upper boundary	$z_{\text{top}} = 25 \times 10^3$ m
Radial grid spacing	$\Delta r = R_o/\text{NR} = 15$ km
Vertical grid spacing	$\Delta z = z_{\text{top}}/\text{NZ} = 1250$ m
First sponge layer grid level	$l_{\text{zspn}} = 16$
Simulation run time	$t_{\text{end}} = 30$ days
Time step (long)	$\Delta t = 20$ s
Time step (short)	$\Delta t_s = \Delta t/5 = 4$ s
Coriolis parameter	$f = 5 \times 10^{-5} \text{ s}^{-1}$
Drag coefficient at $V = 0$	$C_{D0} = 1.1 \times 10^{-3}$
Ratio exchange coefficients	$C_k/C_D = 1.00$
“Total” mixing length	$l = 200$ m
“Horizontal” mixing length	$l_h = 0.2 \times \Delta r = 3$ km
Initial V_{max}	15.0 m s^{-1}
Initial radius of max winds	$\text{RMW}_i = 82.5$ km
Initial outer radius of vortex	$r_{oi} = 412.5$ km
Initial ocean potential temperature	$\theta_{si} = 298$ K
Ambient surface pressure	$p_{\text{amb}} = 1015.1$ mb
Ocean temperature	$T_s = 299.2$ K = 26.13°C

and we shall evaluate this using the approximate physics of the numerical model, that is, a model CAPE (MCAPE). The relevant equations from the model code that govern condensation and latent heating are copied to a separate piece of computer code. This computer code can be used diagnostically on any arbitrary parcel of air to model forced ascent until saturation and to model saturated ascent above that height until there is very little water vapor left. The potential temperature that results from this diagnostic is an exact equivalent potential temperature for the model physics. If the arbitrary parcel that is input to the code has values derived from a model grid point, then that resulting potential temperature is the model equivalent potential temperature (model θ_e) for the original model grid point. This form of θ_e closely follows that of Bolton (1980):

$$\theta_e = \theta \exp \left[1000 q_v (1 + 0.81 q_v) \left(\frac{3.376}{T_L} - 0.00254 \right) \right], \quad (1)$$

but errors in using (1) to calculate model θ_e increase as q_v increases. Here, $\theta = T(p_0/p)^{R/c_p}$ is the potential temperature, and T_L is the temperature (T) of a parcel lifted dry adiabatically to saturation. The specific heat of dry air and the gas law constant for dry air are c_p and R , respectively. A standard pressure of $p_0 = 1000$ mb is used here. Model θ_e differs from Bolton in that the modeled saturation relation is approximate, thus low-level (moist air) θ_e values bias a little warm relative to Bolton. This is the physics of the model, however, so the model θ_e is used throughout this paper. The method for computing a surface-based MCAPE follows that

from Holton (1992, 292–294), using model θ_e where such a variable is required.

We begin our calculation of MCAPE by identifying those grid levels in the vertical profile where saturated equivalent potential temperature (θ_e^* ; solid in Fig. 1) is less than $\theta_e = \theta_{e,0}$, the value at the lowest grid level ($z = \Delta z/2$; dotted in Fig. 1). The EL is defined as the highest z level of instability, that is, $\max\{z: \theta_e^* < \theta_{e,0}\}$. Let EL' denote the highest z -grid level of instability. The level of free convection (LFC) is the level in the profile below the EL where θ_e^* is once again equal to $\theta_{e,0}$. Let LFC' denote the z -grid level just above the LFC where there is instability.⁴ The method used here shows good temporal continuity. At each height, the pressure (p) of the original sounding is applied to the lifted parcel, which is standard practice in parcel theory. The temperature is then found that matches the value $\theta_{e,0}$ at saturation at the given pressure. Knowing temperature and the saturated mixing ratio q_v^* , the virtual temperature $T_v = T(1 + 0.61q_v^*)$ of the parcel can be found. MCAPE is then computed using a discretized form of Eq. (3.4.38) from Bluestein (1993):

$$\text{MCAPE} = g \sum_{i=\text{EL}'}^{\text{LFC}'} \left(\frac{T_v^{\text{parcel}} - T_v^{\text{env}}}{T_v^{\text{env}}} \right) \Delta z. \quad (2)$$

MCAPE strongly tracks traditionally computed CAPE, but it is also consistent with the physics of the numerical model for hypothetical undilute parcel ascent.

4. Simulation results

PM03 showed that vortex intensities in the RE87 model can be quasi-steady for a long period (up to several weeks), whether at low or high model resolution. For their cases, the quasi-steady-state intensity has variability on a variety of time scales (from minutes to days) but has little overall trend. We have encountered some simulations though with a downward trend in intensity when differing combinations of radial and vertical resolutions or different vertical profiles of thermodynamic variables are employed. Quasi-steady-state intensity nevertheless occurs for at least a moderate amount of time (several days) for each of our experiments here. We thus interpret this quasi-steady-state intensity as the model MPI.

PM03 showed further that at high model resolution, azimuthal vortices at the eye–eyewall interface can be resolved and that these eddies transport high-entropy air from the low-level eye to the eyewall. PM03 implicates this transport in the observed superintensity at high model resolution, where storm maximum winds ($V_{\text{max}} \approx 90 \text{ m s}^{-1}$) greatly exceed Emanuel's MPI

⁴ Evaluation in the other direction, that is, first to find the LFC then the EL, frequently encountered short-lived low-level inversion layers that resulted in very small MCAPEs.

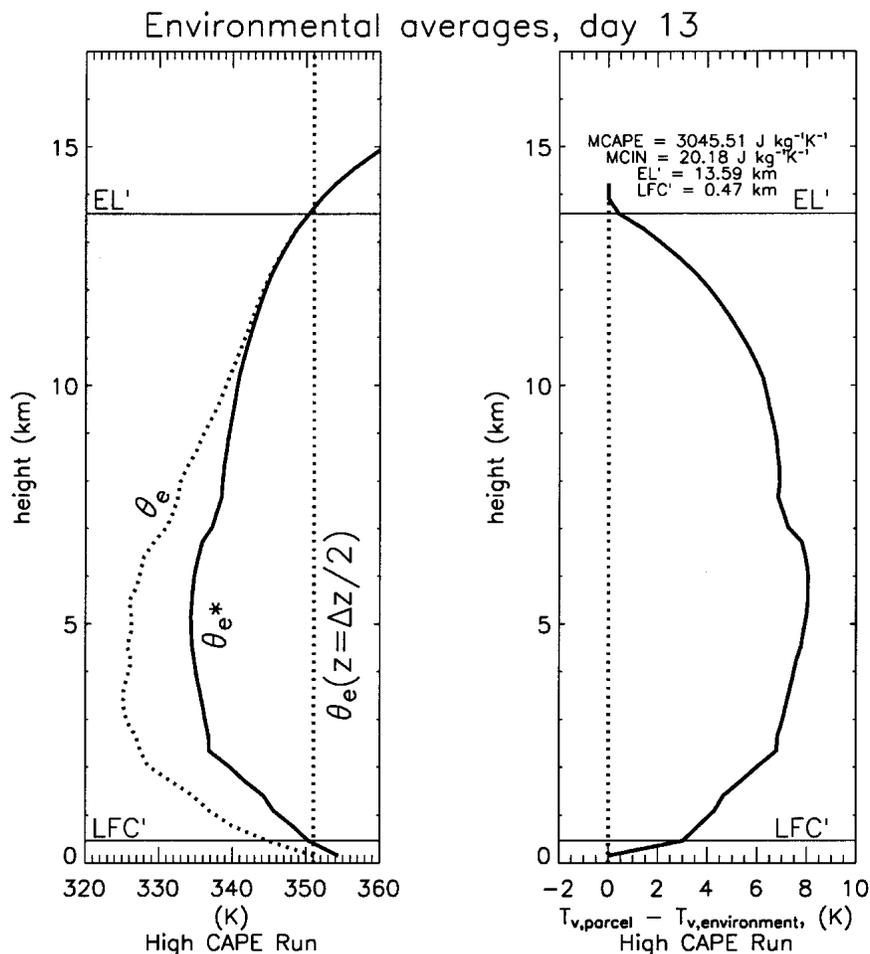


FIG. 1. Illustration of the computation of MCAPE. Model convective inhibition (MCIN) is shown here.

($V_{EMPI} \approx 55 \text{ m s}^{-1}$). In principle, the increase in resolution in PM03 from the default run to the 4x run could introduce a source of “effective CAPE,” perhaps as a result of discretization of the sounding. While beyond the scope of PM03, the much stronger intensities shown

in the 4x run ($V_{max} \approx 90 \text{ m s}^{-1}$) versus the default run ($V_{max} \approx 66 \text{ m s}^{-1}$) could hypothetically result from the increase of effective CAPE at higher resolution. Table 2 shows that, by design (see RE87), the initial soundings have very small MCAPEs, yet at the 4x resolution

TABLE 2. Summary of simulation characteristics. Angle brackets denote averages over the periods listed on the sixth line.

Run	Default		4x	High CAPE	Mid CAPE	Low CAPE
	(early)	(late)				
SST	26.13				28.13	
Horizontal grid spacing (km)	15				3.75	
Vertical grid spacing (m)	1250				312.5	
Initial MCAPE (J kg^{-1})	268		848	2761	2409	1013
Initial CAPE (J kg^{-1})	103		661	2249	1898	638
Period of steady state (day)	10–16	24–30	8–30	5–17	5–30	5–12
$\langle T_{out}^{EL} \rangle$ (K)	229.5	235.2	214.6	214.4	214.0	214.4
$\langle V_{max} \rangle$ (m s^{-1})	56.4	66.5	90.3	102.5	102.5	103.3
$\langle E\text{-MPI} \rangle$ (m s^{-1})	49.9	47.9	55.4	59.4	59.6	59.4
$\langle \text{RMW} \rangle$ (km)	33.8	37.5	23.9	24.1	23.4	26.8
$\langle \text{MCAPE} \rangle$ (J kg^{-1})	1865	1655	1490	3234	3158	1670
$\langle \text{CAPE} \rangle$ (J kg^{-1})	1223	1049	1019	2618	2516	1129

MCAPE is somewhat increased. Evaluations of MCAPE from the averaged environment⁵ as the storm evolves (Fig. 2) show that there is somewhat less MCAPE in the 4x run than in the default run. Thus changes in environmental CAPE cannot explain the superintensity phenomenon, and the conclusions of PM03 hold true.

Returning to the main focus of this paper, whether environmental CAPE has any impact on storm intensity, we now compare similar simulations with varying levels of initial MCAPE. Recall that the simple Newtonian cooling (a surrogate for the effects of longwave radiation to space) will nudge the vertical sounding back toward the initial profile of θ . The rate of cooling is capped at 2 K day^{-1} , thus “radiative” cooling is uniform in the eye–eyewall region where the θ perturbation over initial values are very large. In the environment of the storm, however, the radiative cooling will attempt to restore any CAPE (at least as far as temperature is concerned) in the initial profile. Thus, one simulation with more initial environmental CAPE than another will generally have more environmental CAPE throughout the period of the simulation as well. The surface heat and moisture fluxes are active in the environment, but are not constrained specifically toward initial ambient values.

The Jordan (1958) mean profile with a SST of 28.13°C is used as a sounding that provides an appreciable amount of CAPE [1898 J kg^{-1} using traditional thermodynamic variables; 2409 J kg^{-1} using Eq. (2)]. The simulation using Jordan’s temperature and moisture profiles as an initial sounding will be referred to as the “mid CAPE run”. Cooling this sounding by up to 2 K in midlevels provides a sounding for a second simulation with more MCAPE (2761 J kg^{-1} ; 2249 J kg^{-1} by traditional techniques), referred to as the “high CAPE run”. Finally, a profile for a “low CAPE run” is produced by the technique described in RE87 (where profiles with little MCAPE were tested). That is, we initialize the model without a vortex and without radiational cooling and use the averaged, convectively modified tropospheric profiles of temperature and moisture that emerge after 12 h.

Figure 3 and Table 2 summarize the evolution of the runs described above, each using a 28.13°C SST. MCAPE in the environment of the storm generally exceeds the initial amount of MCAPE, although at a later time, stable layers can develop in the environmental profile that prevent convection from exceeding a certain height. Simulations with larger initial MCAPE reach quasi-steady-state intensity with larger amounts of environmental MCAPE. Of the two methods used to estimate T_{out} in the figure, direct evaluation of the en-

vironmental temperature at the level of environmental EL ($T_{\text{out}}^{\text{EL}}$) is more indicative of the broadscale measure of outflow temperature (since it is evaluated at radii $700 < r < 1500 \text{ km}$). Also, $T_{\text{out}}^{\text{EL}}$ can change quite quickly with changes in the EL when near-neutral stability occurs. The outflow-weighted outflow temperature at a smaller radius $r = 150 \text{ km}$ [using the technique of Eq. (11) of PM03; $T_{\text{out}}^{\text{PM03}}$] is also shown and measures the near-storm changes in outflow temperature, which often take some time to respond to changes in the environment. The high CAPE and low CAPE runs exhibit a quasi-steady state for some period (at least 5 days) before a gradual weakening ensues. The weakening is associated with a lowering of the equilibrium level and is indicative of a stabilization of the upper troposphere. Associated with the lower EL is a warmer outflow temperature (computed by either technique described above) and a weakening of MCAPE. Nonetheless, multiday periods of quasi-steady-state intensity can still readily be identified for these simulations. The high, mid, and low CAPE runs all obtain nearly the same intensity ($102\text{--}3 \text{ m s}^{-1}$) by the fifth simulation day. As discussed above, these three runs are specifically designed to change ECAPE without changes to the surface or equilibrium level temperature. These results provide no quantitative evidence of a benefit to either storm maximum intensity or intensification rate by the presence of ECAPE.

5. Discussion

We present evidence that the RE87 axisymmetric hurricane model is largely insensitive to the initial and time-evolving amounts of CAPE in the environment of the storm. Obviously, certain environmental configurations (such as a lower tropopause) that negatively influence hurricanes can have signatures in CAPE also. In a variety of situations, however, *in simulations with approximately the same SST and outflow temperature, the modeled storms reach much the same intensity independent of the value of environmental CAPE.*

Comparison with the three-dimensional, coupled climate-regional modeling of Knutson and Tuleya (1999) and Shen et al. (2000) provides at first glance a contrary evaluation to our results. The equilibrium level is changed within these three-dimensional studies due to changes in their temperature perturbations, and thus it is not clear to what degree ECAPE, as we have defined it here, has changed. Second, high spatial resolution is needed to resolve the pressure gradients found near the radius of maximum winds, thus these “low-resolution” storms tend to be weaker than they possibly can be. Parameterized convection also can respond to environmental forcing differently from explicit convection.

We assume that the simulated intensities approximate a model MPI, that is, the model cannot sustain a stronger intensity for any length of time. The RE87

⁵ For calculations of CAPE and MCAPE, an average between $700 < r < 1500 \text{ km}$ is used to define the environment considered throughout this paper.

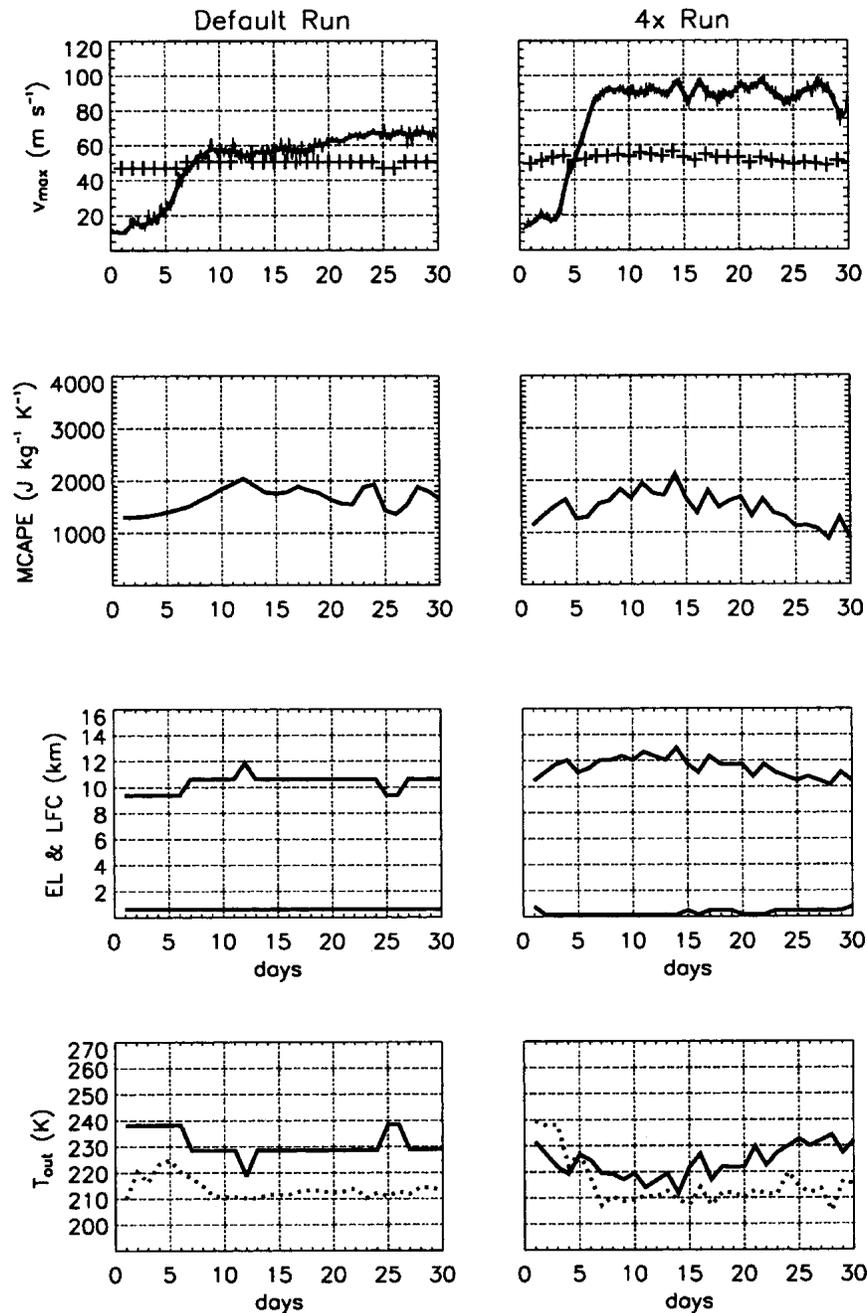


FIG. 2. Characteristics of the default and 4x run simulations from PM03. In the first row, maximum tangential winds at a 10-min output interval (thin line) is shown with daily running means of the same (thick line) and Emanuel's MPI(E-MPI) predictions of the maximum winds using SST = 26.13°C and RH = 80%. The second row shows the computed MCAPE in the environment from daily averaged data. The third row shows the levels EL' and LFC'. The fourth row shows T_{out}^{EL} (solid), which is also used in computing E-MPI shown above, and T_{out}^{PM03} (dotted) computed by Eq. (11) from PM03.

model is axisymmetric and contains many of the same simplifying assumptions (namely, rain-only physics and a constant SST) as Emanuel (1995b), Holland (1997), and other MPI theories. For these theories to be valid, they must be able to describe simulated maximum in-

tensity in the RE87 model. For this stringent test, the superintensity mechanism described by PM03 violates the assumptions of both Emanuel and Holland. A less-stringent test is to determine if the sensitivities of a given MPI theory are matched in the model. Here we

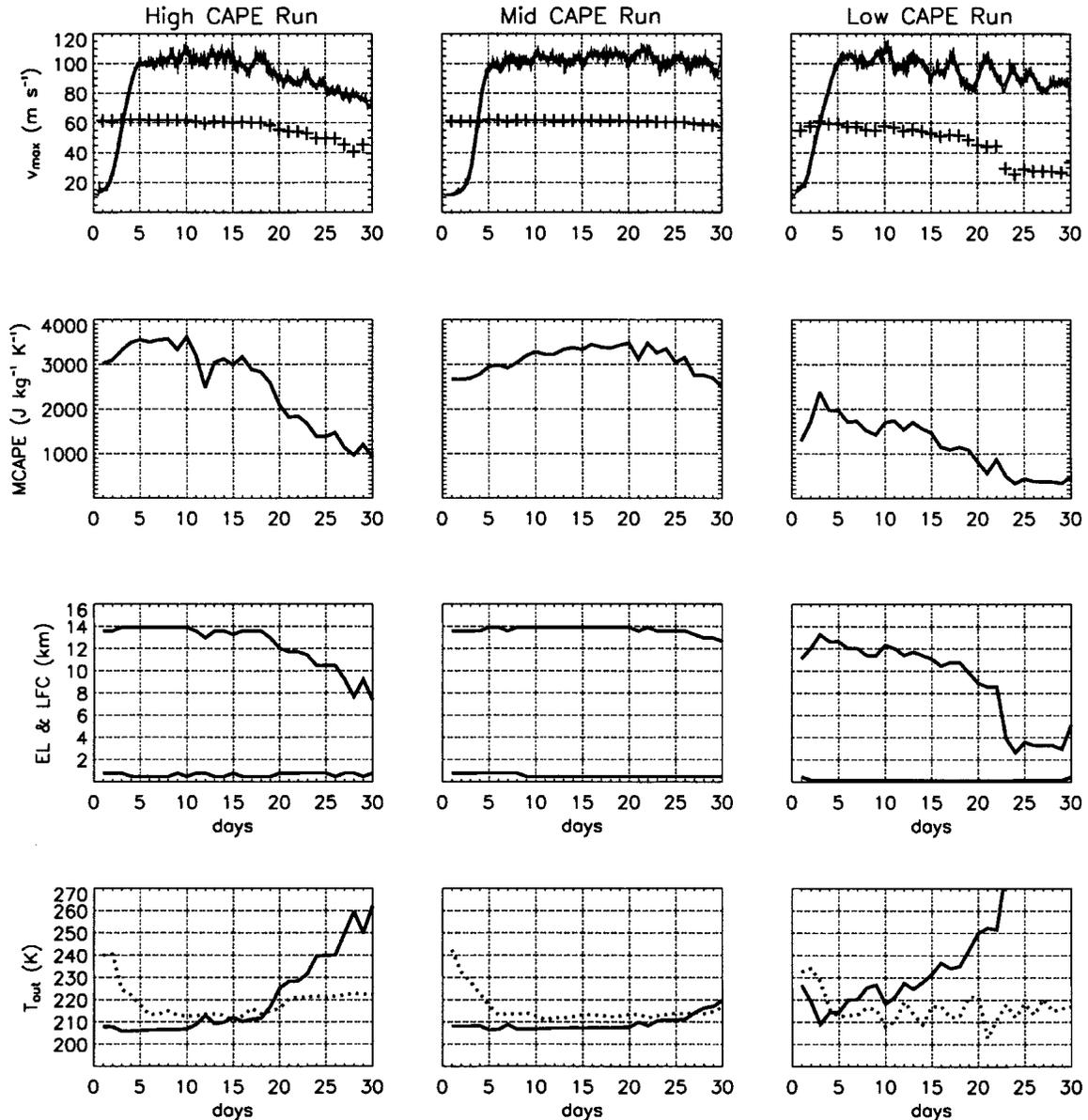


FIG. 3. Characteristics of the high CAPE, mid CAPE, and low CAPE simulations. In the first row, maximum tangential winds at a 10-min output interval (thin line) is shown with daily running means of the same (thick line) and E-MPI predictions of the maximum winds using SST = 28°C and RH = 80%. The second row shows the computed MCAPE in the environment from daily averaged data. The third row shows the levels EL' and LFC'. The fourth row shows T_{out}^{EL} (solid), which is also used in computing E-MPI shown above, and T_{out}^{PM03} (dotted) computed by Eq. (11) from PM03.

have tested the sensitivity of model MPI to ECAPE and have found no sensitivity.

Ultimately, a hurricane near hydrostatic balance will have a central pressure deficit relative to the environmental surface pressure that can be described through a hypsometric computation, given perfect knowledge of the eye and environmental soundings. We might assume that the environmental sounding is known. Miller (1958) and Holland (1997) assert closure assumptions for estimating the eye sounding, but retain a sensitivity

to the characteristics of the environmental sounding, namely ECAPE. The fact that modeled MPI here shows no sensitivity to environmental CAPE means that the closure assumptions used by Miller (1958) and Holland (1997) do not apply to an axisymmetric hurricane near maximum intensity.

While much work remains to formulate an axisymmetric MPI that is consistent with simulations, we suggest that Emanuel (1995b), Miller (1958), and Holland (1997) are inadequate for explaining model MPI. By

predicting many of the important sensitivities for model MPI (RE87; Emanuel 1995a; PM03), Emanuel (1995b) nonetheless provides more insight on the controlling physics of MPI. This confirms numerically the conclusion of Camp and Montgomery (2001).

6. Conclusions

We have presented results from an axisymmetric numerical model designed to test the underlying assumptions of MPI theories. Using specifically constructed experiments, it is found that numerically modeled hurricane intensity is insensitive to the amount of environmental CAPE, given equal sea surface and outflow temperatures. Among various MPI theories, those with a strong sensitivity to environmental CAPE are inconsistent with the results presented here and should be discarded.

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