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# ISOLATING SURFACE FLUX INFLUENCES ON SIMULATED HURRICANE INTENSITY

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## 1. INTRODUCTION

The basic structure of the hurricane is for there to be a cloudy, stormy ring called an eyewall surrounding a relatively quiescent central region called an eye. Surrounding these structures is a region where convection, sometime organized in curved, banded structures, becomes relatively less prevalent with increasing distance from the center until at some limit the weather is indistinguishable from standard tropical conditions in the absence of any hurricane. Despite the obvious importance in details such as banded structures of convection, overall the hurricane is suited for a description in a cylindrical framework, and naturally for a description of the axisymmetric hurricane (symmetry about a central axis) and its resulting asymmetries.

The axisymmetric theory for maximum possible intensity of hurricanes of Emanuel (various references, but 1995 will be chiefly referred to herein as E-MPI) has provided an important point for comparison for many of the theories, observations, and simulations developed to describe very intense hurricanes. Among the many approximations of E-MPI are axisymmetry, rain-only physics, and a bulk aerodynamic formulation of surface interaction. These three approximations are shared by the numerical model of Rotunno and Emanuel (1987; hereafter RE87), formulated on an $r,z$-grid mesh. Persing and Montgomery (2003; hereafter PM03) showed that simulations of the RE87 numerical model at higher resolution (namely, $\Delta r$=3.75 km; $\Delta z$=625 m) than that published in RE87 leads to a stronger intensity for the simulated hurricanes than that originally published and stronger than that predicted by E-MPI. E-MPI theory, particularly the 1995 derivation, is derived based on a local WISHE-like effect (wind-induced surface heat exchange), namely the air-to-ocean entropy difference at the eyewall chiefly determines the intensity found at the eyewall.

To test the relative importance of the eye and eyewall to determining the intensity of the hurricane, a series of experiments are presented below using the RE87 hurricane model. To test the "superintensity" mechanism presented in PM03, an eye region is identified and surface fluxes of heat and moisture between the atmosphere and the ocean in the eye region are suppressed ("E" experiments). To test the WISHE mechanism, an eyewall region is identified where surface fluxes of heat and moisture are suppressed ("W" experiments). These are compared to unaffected controls ("C" experiments) and experiments where neither eye nor eyewall fluxes are permitted ("N" experiments) which could be hypothesized to be severely affected by the rather extreme reduction in the source of energy for the hurricane.

## 2. EXPERIMENTAL FRAMEWORK

Experiments are performed using the RE87 hurricane model using the resolution and settings published by PM03. Three different initial soundings are used: 1) the 4x sounding of PM03 ("P"), 2) the sounding of RE87 interpolated to the resolution of this study ("R"), and 3) the sounding of Jordan (1958) ("J"). A fixed sea surface temperature (SST) is used, with 26.13 C for the P and R soundings and 28.0 C for the J sounding.

Surface fluxes of potential temperature and vapor mixing ratio are suppressed by first identifying the radial grid point at lowest vertical grid level at each time step with the strongest wind speed, $i=I$. In the E experiments, the surface fluxes are suppressed for grid points $i=\{0, 1, ..., I-1\}$. In the W experiments, the surface fluxes are suppressed for grid points $i=\{I-2, I-1, ..., I+9\}$, namely, -9 to +36 km from the radius of maximum surface wind speed. In separate experiments, fluxes are suppressed starting at either 0, 2, 3.5, or 6.5 days after initialization.

## 3. BASIC RESULTS

Control simulations for each sounding (RC for the RE87 sounding, PC for the PM03 sounding, JC for the Jordan sounding) each intensify[†] from the specified starting intensity of 17 m $s^{-1}$ to a quasi-steady

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[†] The peak value of tangential winds is used here as the measure of intensity, which is typically found at the $z$=1 km level in the eyewall.

intensity after 4 days. Statistics extracted from between day 8 and 15 of each simulation is summarized in the following table:

| **sim** | **avg $v_{max}$** | **stddev $v_{max}$** |
|---|---|---|
| RC | 84.17 | 2.41 |
| RE | 75.87 | 3.06 |
| RW | 70.33 | 2.27 |
| RN | 62.90 | 4.96 |
| PC | 89.21 | 5.09 |
| PE | 71.23 | 8.08 |
| PW | 63.18 | 4.66 |
| PN | 20.54 | 4.96 |
| JC | 102.13 | 4.70 |
| JE | 75.90 | 7.68 |
| JW | 77.14 | 3.03 |
| JN | 36.45 | 4.17 |

Results from the corresponding E, W, and N experiments for each sounding are also shown. The reductions of intensity for the E experiments are comparable to their corresponding W experiments for the same sounding, but the reductions of intensity from the controls are much less for the RE87 sounding (8-14 m s$^{-1}$) versus the PM03 sounding (18-26 m s$^{-1}$) and the Jordan sounding (25-27 m s$^{-1}$). Also the N experiments for the PM03 and Jordan soundings show marked reductions in intensity (23% and 36% of the control intensity) compared to the RE87 sounding (75%). One chief difference of the RE87 sounding that it has very low CAPE (103 J kg$^{-1}$ K$^{-1}$) compared to the moderate CAPE of the PM03 sounding (661 J kg$^{-1}$ K$^{-1}$) and the Jordan sounding (1898 J kg$^{-1}$ K$^{-1}$). For this numerical model, changes in CAPE between this moderate level of CAPE and very large CAPE have been shown to have near-negligible impact on intensity (Persing and Montgomery 2005).

E-MPI for the PM03 and RE87 soundings is 55 m s$^{-1}$. The RC control is a proper evaluation of the RE87 model simulation at four times the published resolution of RE87 (an interpolation error lead to an imperfect comparison in PM03), which remains much more intense than E-MPI (53% stronger). The experiment E of RE87 at the original, coarse resolution matches very closely E-MPI, thus some aspect of the change in resolution (in contrast to changes in environmental sounding, e.g.) must lead to this stronger intensity. The rough correspondence in intensity between the RE and RW simulations, between the PE and PW simulations, and between the JE and JW simulations suggests that the effect of WISHE and of the eye/eyewall interaction of PM03 must be roughly the same upon hurricane intensity.

## 4. PM03 AND JORDAN SOUNDING EXPERIMENTS

Since the experiments using the PM03 and Jordan soundings are broadly similar, these results can be summarized together. The PN and JN experiments show a rapid collapse (half original intensity in less than a day) upon onset of reduced surface fluxes. The RMW expands to greater than 100 km in each case. Overall, these behaviors match our expectations following the concepts of WISHE plus whatever positive contribution might be found from the eye. The drop in intensity in the PE and JE experiments (as well as the PW and JW experiments) still leaves these simulations somewhat stronger than E-MPI (59.6 m s$^{-1}$), thus the superintensity mechanism identified by PM03 does not completely explain the problem. The PC simulation is 34 m s$^{-1}$ superintense and the PE simulation is 16 m s$^{-1}$ superintense, so half the difference is illustrated with these simulations. The PW simulation remains 8 m s$^{-1}$ superintense, so while WISHE cannot be thought of as an unimportant processes in hurricane maintenance, this simulation shows that a simulated hurricane is also eager to find other mechanisms to sustain itself when WISHE is unavailable.

## 5. RE87 SOUNDING EXPERIMENTS

The simulations using the RE87 sounding present some interesting departures from the above experiments. The RN experiment shows only a 22 m s$^{-1}$ weakening from the RC control and still remains stronger than E-MPI. The control retains much of the structure anticipated by PM03 for a superintense hurricane (Fig. 1). A third mechanism must help to sustain the RN experiment. For the sake of argument, begin with the vortex of the RC experiment. Consider an inflowing parcel of air, traveling close to the ocean surface ($z$ < 500 m) with decreasing radius from the environment toward the eyewall. At some point in its trajectory, 36 km exterior to the RMW, the parcel passes a point where in the RC experiment that parcel will continue to benefit thermodynamically from a surface interaction and in the RN experiment it will not. (We have separately confirmed that the outer vortices in both simulations are roughly the same.) In the RN experiment, the equivalent potential temperature $\theta_e$ bubble in the low-level eye is quickly eradicated, thus for the rest of the traverse of the parcel through the secondary circulation the parcel cannot gain any $\theta_e$ in addition to what it has at this moment (except if it detains into the stratosphere, but that is not of importance here). In the RN experiment, $\theta_e$ is not significantly reduced in approach to the eyewall and ascent to the outflow (Fig. 2). This is in marked contrast to the PN and JN experiments where detrainment from the middle-level troposphere causes a marked reduction in $\theta_e$. Upon reaching the RMW, the PN and JN experiments are no longer warm enough to sustain the eyewall convection, in contrast to the RN experiment. The very low CAPE situation appears to be rather special in this regard. Other aspects of a very-low CAPE are the lower standard deviations of intensity (table above) and a much lower standard deviation of w exterior to 5*RMW (0.08 m $s^{-1}$ in the RC experiment versus 0.26 m $s^{-1}$ in the PC experiment and 0.52 m $s^{-1}$ in the JC experiment.) By itself this is probably not enough to sustain the hurricane vortex, but what also appears important is the advection of low $\theta_e$ air in the inflow jet that appears below the outflow (Fig 2) that also helps sustain the radial $\theta_e$ gradient at the $z$=7 km level of the eyewall.

## 6. SUMMARY

The $\theta_e$ structure of the RC eyewall shows this mid-level thermal gradient found in the RN experiment, but also shows a low-level $\theta_e$ gradient within the lowest 2 km altitude. It appears that sustaining both such $\theta_e$ structures leads to the stronger intensity of the RC experiment, and without the available surface fluxes, and radial gradient of saturated $\theta_e$ at the ocean surface (due largely to the radial pressure gradient), the low-level structure cannot be sustained. The mid-level structure can be sustained, but only so long as convection can persist at the RMW. Using the moderate CAPE and high CAPE soundings (PM03 and Jordan, respectively), detrainment of low $\theta_e$ air from the mid-troposphere cools the inflowing air too much in the absence of the offsetting surface fluxes.

## 7. ACKNOWLEDGEMENTS

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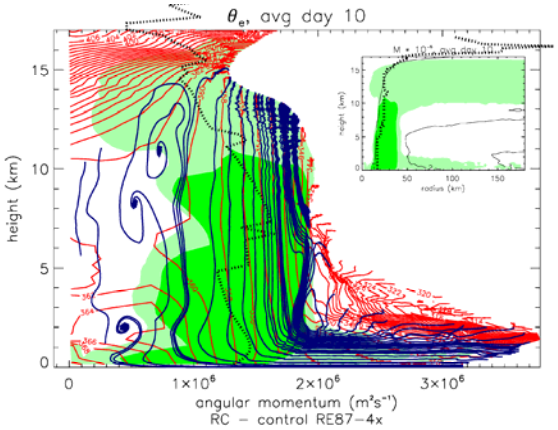

**Figure 1 - Model $\theta_e$ (red) as a function of absolute angular momentum *M* and height from the half-day averaged model output of the RC simulation. Streamlines (blue) and the radius of maximum tangential winds as a function of height (black dotted) are also shown. The inset figure provides reference in physical coordinates. Mixing ratio of liquid water $q_l$ is shown to depict the approximate eyewall cloud with light (dark) green exceeding 0.3 (1.0) g $kg^{-1}$.**

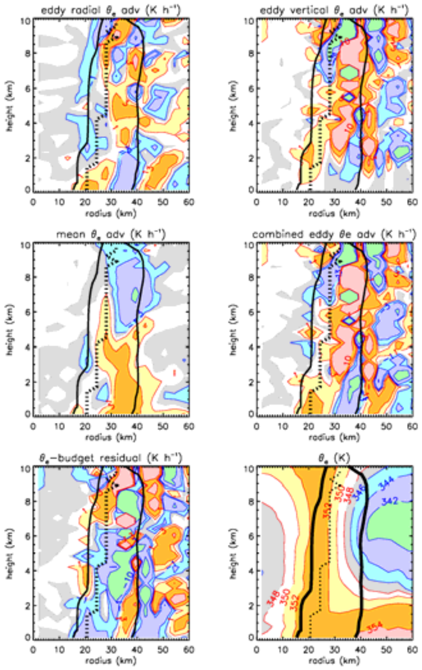

**Figure 2 - A budget of $\theta_e$ from the RN6.5 simulation between 12 to 12.25 days. Panels a-e show components of the budget with the colors white, yellow, orange, and pink indicating positive tendencies for $\theta_e$ while gray, blue, purple, and green indicate negative tendencies for $\theta_e$. Panel e shows a hypothetical term that would produce a zero tendency for $\theta_e$ , which indicates the combined effects of microphysics, diffusion, surface forcing, and tendency. Panel f shows the averaged $\theta_e$ field.**

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