15A.5 STEADY-STATE HURRICANE INTENSITY IN THE WRF MODEL: COMPARISON TO MPI THEORY AND SENSITIVITY TO PBL AND SURFACE FLUX PARAMETERIZATION

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1. INTRODUCTION

The understanding of the physical processes controlling tropical cyclone intensity has been an area of ongoing debate in recent years. Emanuel (1986) suggested that the intensification and maintenance of tropical cyclones depends almost exclusively on self induced heat transfer from the ocean, and not on the release of preexisting instability (air-sea interaction theory). In addition to advancing the air-sea interaction theory, Emanuel (1986) also developed an analytical model relating the maximum intensity of a tropical cyclone (TC) to the sea surface temperature (SST) and the atmospheric temperature profile. The values calculated using this method agreed favorably with the observed strength of intense tropical cyclones, indicating a promising consistency.

Despite these advances in our understanding of TC dynamics, the intensity of *model-simulated* tropical cyclones often differs significantly from that observed, suggesting the presence of deficiencies in model design. The theory of Emanuel (1986) suggests that the energy source of tropical cyclones is strongly tied to fluxes of heat and moisture from the ocean; thus it is logical to examine the representation of these processes in numerical models as a starting point in an investigation of the source for model difficulty in TC intensity prediction. Specifically, the analytical model of Emanuel (1986) predicts that the maximum wind speed of a TC is directly dependent on the ratio of the exchange coefficients for enthalpy and momentum, C_k/C_d.

Observations at high wind speeds within the planetary boundary layer of hurricanes are difficult to obtain, and therefore the conditions found at high wind speeds over the ocean are not well understood. Lacking an observationally-based method of determining the proper values for the exchange coefficients, Emanuel (1995) attempted to estimate these values at high wind speeds by comparing the results of numerical model simulations with his analytical model. In this study, two numerical models containing a tropical vortex in an idealized testing environment were run for different values of the surface exchange coefficients. These idealized simulations were run until the vortex reached a quasi-steady intensity. The simulated storms' intensity most closely matched the results of Emanuel (1986) when the value of C_k/C_d was in the range 1.2 – 1.5. The method of comparing the results of an analytical model and a primitive equation model appears to have provided insight into the environment found within intense tropical cyclones.

Previous studies have found that model simulations of tropical systems are highly sensitive to the parameterization of surface and PBL processes. In particular, Davis and Bosart (2002) found that different choices of model physics and initial conditions could produce a very wide variety of intensities for simulations of Hurricane Diana (1984). The sensitivity to the SST analysis was also found to be significant; in fact, the use of a manual SST analysis instead of the operational analysis resulted in a storm that was about 27 hPa deeper after 60 h of integration. In this case, the sensitivity of the results to the initial conditions used in the model was larger than the sensitivity to the model physics. The evaluation of model physics by direct comparison with observational data is difficult in this case due to the fact that the choice of initial conditions could dictate which model-physics configuration produces the simulation closest to the observations.

Numerical simulations using *idealized* atmospheric and SST data are used in this study to investigate model sensitivity to physics choices without the added sensitivity of the result to initial condition data. Here, we employ a methodology similar to that used by Emanuel (1995), with the results of Emanuel's analytical model being compared to simulations using the

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Weather Research and Forecasting (WRF) model. Idealized WRF simulations were performed using a model environment that satisfied the fundamental assumptions of MPI theory, with the main goal being to investigate the sensitivity of the results to the choice of surface and boundary layer parameterizations. Both the minimum central pressure and maximum winds found in the idealized simulations were compared with values predicted by MPI theory as one step in the process of assessing the model's ability to simulate tropical cyclone intensity. In addition to the comparison with MPI theory, the sensitivity of the physical structure of the simulated storms to PBL and surface parameterizations was investigated through comparisons with both previous modeling studies and observations.

2. INITIAL DATA

In order justify comparison of WRF TC intensity with the theoretical MPI, a dataset consistent with the assumptions of MPI theory was created. Specifically, the assumptions made when calculating MPI include: (i) a time-independent, horizontally uniform SST, (ii) no vertical wind shear, (iii) sufficient time for the vortex to reach a quasi-steady maximum intensity, and (iv) no interaction between the vortex and land. Two distinct issues needed to be addressed when creating the idealized model atmosphere: (i) the characteristics of the ambient environment, and (ii) specification of the initial vortex.

Averaged Global Forecast System (GFS) 1° analyses were used to create the ambient atmospheric conditions around the vortex. Height and temperature data were spatially averaged in a region of the tropical Atlantic Ocean found between 10 and 30°N latitude, and 60 and 40°W longitude. Initial tests were performed using a constant SST of 29°C. In order to replicate atmospheric conditions found at this SST, atmospheric variables were averaged when the average SST in this region was close to 29°C. For the initial vortex, data from Hurricane Ivan at September 11, 2004 at 00 UTC were used. The vortex was characterized by a minimum central pressure of 995 hPa and maximum 10-m winds of ~30 m s^{-1}. Outside of the vortex, relative humidity was set at a constant 80% and wind speeds were set to zero.

3. MODEL CONFIGURATION

Version 2.1.1 of the WRF model was used for the simulations presented here. The WRF model is a fully compressible, nonhydrostatic model with a terrain-following hydrostatic pressure coordinate (see Skamarock et al. 2005 for more information). Table 1 provides information on physical parameterizations used in each simulation, while the next section describes the model physics sensitivity tests. All model simulations thus far were run with 20-km grid spacing and 31 vertical levels.

Physical Process:	Parameterization:
Microphysics	Lin et al.
Longwave Radiation	RRTM Scheme
Shortwave Radiation	Dudhia Scheme
Land Surface	NOAH LSM
Cumulus	Kain-Fritsch

Table 1. Physics options used in WRF simulations.

The MPI of a cyclone, as theorized by Emanuel, is independent of the strength of the initial vortex (Emanuel 1986). Ultimately, the upper bound on the intensity of the vortex should depend only on the sea-surface temperature and the upper-atmospheric outflow temperature. In order to test this hypothesis while examining sensitivity to the choice of initial vortex, model simulations were performed with several different choices of initial vortex. A gridded Ivan vortex from 9/12/04 at 00 UTC was radially-averaged and then inserted into the idealized ambient atmosphere. This vortex was characterized by a minimum sea-level-pressure of 979 hPa.

4. SENSITIVITY EXPERIMENTS

Sensitivity tests were performed using the Yonsei-University (YSU) and Mellor-Yamada-Janjic (MYJ) PBL schemes. Currently in WRF, each PBL scheme is only compatible with a specific surface layer parameterization scheme. Both surface layer schemes are based on Monin-Obukhov similarity theory, although slight differences exist between the two. For the purposes of this study, the PBL and surface layer parameterization schemes will be viewed as a package; i.e. model simulations referred to as "MYJ" are those runs performed with the MYJ PBL parameterization accompanied by its matching surface layer scheme.

a. Intensity

Based on a time series of the minimum sea level pressure (SLP) displayed in Fig. 1, it is evident that the results of the idealized simulations are not highly sensitive to the initial vortex choice. Simulations initialized using vortices of different strength but using the same PBL scheme (YSU represented by pink and yellow, MYJ light and dark blue) reached minimum central pressure values by day 20 that were within ~5 hPa of one another. This result suggests that the maximum intensity is determined by environmental conditions, and is fundamentally consistent with MPI theory. The results shown in the rest of this paper are from the simulations using the radially averaged initial vortex, although results found using the other vortex are very similar.

Using a subroutine (available at: ftp://texmex.mit.edu/pub/emanuel/TCMA), designed by Prof. Emanuel, the MPI of a vortex in the idealized testing environment was estimated. The theoretical MPI was calculated to be approximately 907 hPa using this subroutine; this value corresponds closely with the value found in Emanuel (1986, his Fig. 2), after estimating the near surface and outflow temperatures of the idealized testing environment.

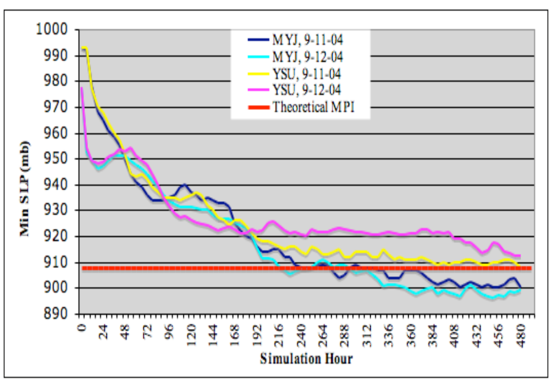

Figure 1. Minimum SLP time series for MYJ and YSU PBL schemes using both initial vortices. Theoretical minimum SLP predicted by MPI theory in red.

Results indicate that both simulations using the MYJ PBL scheme exceeded the theoretical MPI, reaching a minimum sea level pressure of approximately 900 hPa. Neither simulation performed using the YSU PBL scheme reached the MPI, deepening to a minimum SLP of approximately 910 hPa. Overall, the minimum SLP values obtained during the idealized simulations and the theoretical minimum value predicted by MPI theory were in good agreement. The sensitivity of the minimum SLP to the PBL scheme choice was found to be ~10 hPa at the end of the simulation period.

A time series of maximum 10-m wind speeds was constructed (Fig 2.) and compared to values predicted using MPI theory. Although the simulated storms reached minimum SLP values that were close to the MPI, the wind speeds were much slower than the theoretically determined maximum. The maximum wind speeds were fairly similar between the different PBL schemes, generally differing by ~5 ms^{-1} during the quasi-steady state intensity attained near the end of the simulations.

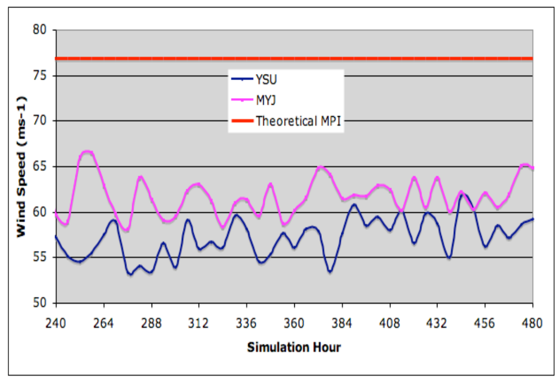

Figure 2. Maximum 10-m wind speed ($m\ s^{-1}$) time series for simulation hours 240-480. YSU (blue), MYJ (pink) and theoretical maximum winds (red).

b. Vertical Wind Distribution

The average vertical wind profile produced in simulations using each PBL scheme was analyzed and compared with previous studies. In order to facilitate comparisons with observational studies, vertical wind profiles were normalized by the 700-hPa wind speed. Profiles taken at individual grid points were found to vary greatly; in order to obtain wind profiles that could be compared, spatially and temporally-averaged profiles were calculated. In order to construct a representative wind profile for the strongest portion of the storm, grid profiles were averaged for the 25 points with the highest 10-m wind speed values at each output time. Temporal averaging was performed by averaging the previously found profiles at 5 different output times during the period when the simulations had reached a quasi-steady intensity.

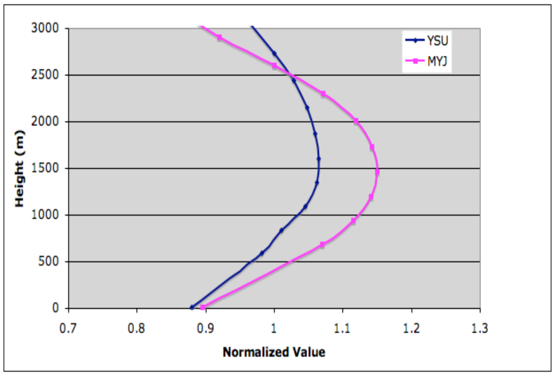

Figure 3. Average vertical wind profiles from idealized simulations. Values normalized by the wind speed at 700-hPa. YSU (blue) and MYJ (pink).

Large differences in the vertical wind profile exist between both PBL schemes and observational data. Both PBL schemes produced maximum wind speeds at approximately 1500-m altitude. The MYJ simulation exhibited a more pronounced maximum wind speed at this level, with wind speeds being approximately 20% greater than those found at the 700-hPa level. At the 10-m level, both PBL schemes produced winds that were approximately 90% as fast as the wind speed at 700-hPa.

c. *Simulated Radar Reflectivity Structure*

Figures 4 and 5 display simulated radar reflectivity for the MYJ and YSU simulations, respectively. Simulated radar reflectivity is not exactly equivalent to actual radar reflectivity, representing the overall distribution of hydrometeors produced by the model microphysics and not directly accounting for precipitation produced by cumulus parameterization. Simulated radar images are useful, however, in assessing the horizontal precipitation structure of the simulated storms. The images included here are of the respective storms at their peak intensity (at the model output time where the storms reached their minimum SLP). Based upon model simulated radar reflectivity, model runs using both PBL schemes produced well organized TCs, with a clearly defined eye surrounded by rings of precipitation. MYJ simulations produced a TC with a larger overall precipitation area and a larger eye.

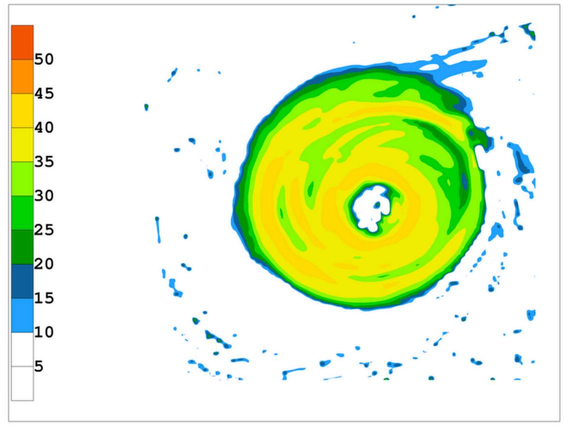

Figure 4. Simulated radar reflectivity at time of peak intensity for MYJ (simulation hour 462).

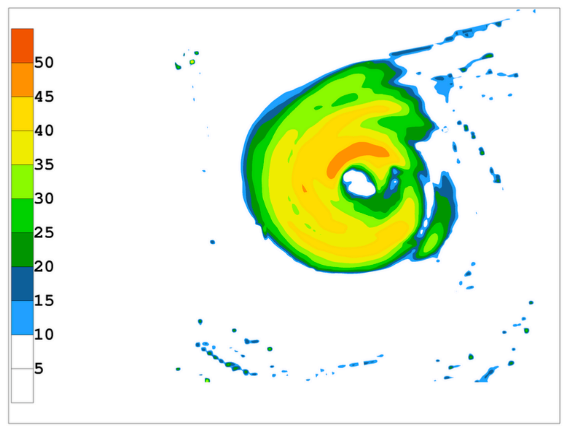

Figure 5. Simulated radar reflectivity at time of peak intensity for YSU (simulation hour 480).

c. *Latent Heat Flux*

Braun and Tao (2000) suggested that the simulated intensity of tropical systems is more sensitive to surface flux parameterization than to vertical mixing in the PBL. The latent heat flux (LHFLX) produced during the idealized simulations was analyzed by computing radially averaged values in 100-km “slices” surrounding the eye of the simulated storms. These radial averages were then time averaged over a 30-h period near the end of the simulations when the vortices had reached a quasi-steady state intensity.

	MYJ	YSU
Maximum	2425.0	1830.5
0-100 km	370.3	491.5
100-200 km	1217.9	1113.4
200-300 km	1615.6	940.4
300-400 km	1075.5	582.6
400-500 km	609.4	365.6
0-500 km	1328.9	969.6

Table 2. Maximum and area-averaged values of Latent Heat Flux (WM-2).

The MYJ simulations produced much larger values of latent heat flux than simulations using the YSU package (Table 2). The greater average flux in the 0-100 km portion of the simulated storm can be attributed to the large eye structure found in simulations using MYJ, which led to a larger area of weaker wind speed and in turn weaker fluxes concentrated near the vortex center (not shown).

d. Roughness Length

Braun and Tao (2000) demonstrated that even for identical values of the exchange coefficients for enthalpy and momentum, TC intensity is also sensitive to the wind speed dependence of the surface roughness parameter. Figure 6 displays the values of model-computed roughness length for wind speeds of 20–70 ms^{-1}. Both PBL schemes vary the surface roughness parameter proportional to the square of the wind speed, although the roughness parameter is slightly larger in YSU than in MYJ.

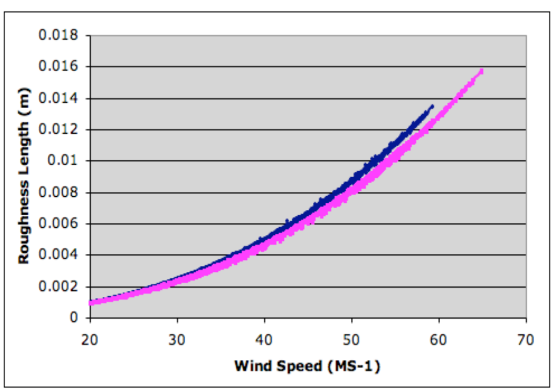

Figure 6. Roughness length (m) dependence on wind speed (ms^{-1}) during simulation hour 480. MYJ (pink) and YSU (blue).

5. CONCLUDING REMARKS

Idealized model simulations were performed in which the theoretical maximum intensity of a vortex in a highly idealized environment was used as one measure of the performance of PBL and surface layer parameterizations in the WRF model. The results were not found to be sensitive to the initial vortex choice, with initial vortices of different strength both reaching a similar maximum intensity (within ~5 hPa of one another near the end of the simulations). The results were somewhat sensitive to the choice of the PBL scheme, with the minimum SLP of simulations using MYJ being about 10 hPa less than in simulations using YSU. The sensitivity of model TC intensity to horizontal grid-spacing or model physics choices other than those displayed in table 1 is the focus of ongoing investigation.

The most significant result found thus far pertains to discrepancy between the simulated maximum wind and minimum pressure values and those predicted theoretically. The theoretical minimum SLP of ~907 hPa was in close agreement with the minimum values of ~900 hPa with MYJ, and ~910 hPa with YSU. Based strictly upon this measure of intensity, the results indicate a solid agreement between theory and model results. Upon further investigation, this result may have occurred for the wrong physical reasons, because model simulations did *not* produce 10-m wind speeds that were in as close agreement with the theoretically determined maximum. Specifically, the theoretically determined maximum wind speeds were approximately 15 (20) ms^{-1} stronger than the maximum values found in simulations using MYJ (YSU) towards the end of the simulation period. This discrepancy between minimum central pressure and maximum wind speed indicates a possible deficiency in MPI theory or, more likely, in the PBL and surface layer parameterizations currently available in WRF for TC conditions.

One possible explanation for the wind speeds being significantly slower than predicted by MPI theory concerns the amount of drag present over the ocean at high wind speeds. Observations taken at low wind speed suggest that the ratio of the exchange coefficients for enthalpy and momentum, C_k/C_d, decreases with increasing wind speed. Emanuel (1995), however, determined experimentally that in order for intense storms to possess observed wind speeds the ratio must increase at higher wind speeds. One physical process that may be responsible for this change at higher wind speeds is the effect of sea spray. Although beyond the scope of this research, previous studies have found that large amounts of sea spray and foam can both lead to an increase in the exchange coefficient for enthalpy and a decrease in the exchange coefficient for momentum. Andreas (2004), using basic mathematical principles, concluded that the 10-m drag coefficient reaches a peak in the wind speed range 30-40 m s^{-1}, and then decreases to about one-half the value it has in light winds by the time the wind speed reaches 60 m s^{-1}. This reduction in drag at high wind speeds is not represented in either of the surface layer parameterizations tested in WRF. Maximum wind speeds did reach 60 ms^{-1} in the simulations, and excessive surface drag at high wind speeds could be one of the reasons for the maximum wind speeds being significantly lower than predicted by theory.

Vertical wind profiles were highly sensitive to the parameterization of PBL and surface layer processes. Based upon the most recent observationally-based study of the vertical wind structure in hurricane eyewalls (Franklin et al. 2000) the WRF simulations produced maximum wind speeds which were higher in altitude than that indicated by dropwindsonde data. One possible cause for this discrepancy between the simulations and observation could again be the surface drag parameterization in the model. The wind profiles analyzed were taken at the grid points which had the largest 10-m wind speeds, and therefore were located at model grid points with large values of surface drag. The large value of surface drag may lead to a level of maximum winds that is higher than found in observed storms.

6. FUTURE WORK

The sensitivity of the results to the horizontal grid spacing will be investigated by running new simulations using grid spacing that is smaller and also larger than the current value of 20-km. The sensitivity of the present results to CP scheme choice should also be investigated by performing tests using the Betts-Miller-Janjic CP scheme. In addition, at a grid spacing where it is appropriate to turn off the CP-scheme, explicit model runs will be performed in order to address further study the sensitivity to the cumulus parameterization. So far, the idealized model environment has been characterized by a constant SST of 29°C. We will investigate a variety of SST values in order to see if the results are still qualitatively similar for environments with different MPI values.

Acknowledgements

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