Analysis of Idealized Tropical Cyclone Simulations Using the Weather Research and Forecasting Model: Sensitivity to Turbulence Parameterization and Grid Spacing

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ABSTRACT

The Weather Research and Forecasting Advanced Research Model (WRF-ARW) was used to perform idealized tropical cyclone (TC) simulations, with domains of 36-, 12-, and 4-km horizontal grid spacing. Tests were conducted to determine the sensitivity of TC intensity to the available surface layer (SL) and planetary boundary layer (PBL) parameterizations, including the Yonsei University (YSU) and Mellor–Yamada–Janjic (MYJ) schemes, and to horizontal grid spacing. Simulations were run until a quasi-steady TC intensity was attained. Differences in minimum central pressure ($P_{\text{min}}$) of up to 35 hPa and maximum 10-m wind ($V_{10\text{max}}$) differences of up to 30 m s$^{-1}$ were present between a convection-resolving nested domain with 4-km grid spacing and a parent domain with cumulus parameterization and 36-km grid spacing. Simulations using 4-km grid spacing are the most intense, with the maximum intensity falling close to empirical estimates of maximum TC intensity. Sensitivity to SL and PBL parameterization also exists, most notably in simulations with 4-km grid spacing, where the maximum intensity varied by up to $\pm 10$ m s$^{-1}$ ($V_{10\text{max}}$) or $\pm 13$ hPa ($P_{\text{min}}$). Values of surface latent heat flux (LHFLX) are larger in MYJ than in YSU at the same wind speeds, and the differences increase with wind speed, approaching 1000 W m$^{-2}$ at wind speeds in excess of 55 m s$^{-1}$. This difference was traced to a larger exchange coefficient for moisture, $C_Q$, in the MYJ scheme. The exchange coefficients for sensible heat ($C_u$) and momentum ($C_D$) varied by $\pm 7\%$ between the SL schemes at the same wind speeds. The ratio $C_u/C_D$ varied by $\pm 5\%$ between the schemes, whereas $C_Q/C_D$ was up to 100% larger in MYJ, and the latter is theorized to contribute to the differences in simulated maximum intensity. Differences in PBL scheme mixing also likely played a role in the model sensitivity. Observations of the exchange coefficients, published elsewhere and limited to wind speeds $\leq 30$ m s$^{-1}$, suggest that $C_Q$ is too large in the MYJ SL scheme, whereas YSU incorporates values more consistent with observations. The exchange coefficient for momentum increases linearly with wind speed in both schemes, whereas observations suggest that the value of $C_D$ becomes quasi-steady beyond some critical wind speed ($\sim 30$ m s$^{-1}$).

1. Introduction

It has been shown that improvements in the accuracy of tropical cyclone (TC) intensity predictions continue to lag improvements in track prediction (e.g., Knaff et al. 2003; DeMaria et al. 2005; Rogers et al. 2006). This discrepancy is in part due to the fact that numerical models are able to provide reliable track guidance even when the intensity forecast from the same model is inaccurate, provided that the synoptic-scale steering flow is reasonably well depicted. The lack of accuracy in numerical intensity forecasts from operational dynamical models is attributable to several factors, including but not limited to (i) poor representation of TCs in model initial conditions (e.g., Kurihara et al. 1995, 1998; Xiao et al. 2000; Zou and Xiao 2000; Aberson 2003), (ii) inaccuracies in model representation of processes taking place near the air–sea interface (e.g., Emanuel 1995; Andreas and Emanuel 2001; Braun and Tao 2000; Persire et al. 2005), and (iii) model resolution (e.g., Braun and Tao 2000; Davis and Bosart 2002; Persing and Montgomery 2003). The resolution sensitivity is linked to a growing body of evidence that small-scale vortices in and near the eyewall can alter TC thermodynamics sufficiently to change intensity (e.g., Persing and Montgomery 2003; Braun et al. 2006; Gentry 2007; Cram et al. 2007; Yang et al. 2007). In this study, we will use the Weather Research and Forecasting Advanced Research Model (WRF-ARW) to examine factors ii and iii above,
while eliminating consideration of i by utilizing idealized simulations of long duration.

Tropical cyclones intensify and maintain themselves against dissipation by extracting energy from the ocean (e.g., Byers 1944; Emanuel 1986; therefore numerical model simulations of TCs are highly sensitive to the parameterization of energy transfer processes at the air–sea interface (e.g., Ooyama 1969). Numerical models calculate the air–sea exchange of heat, moisture, and momentum using a surface layer (SL) parameterization scheme, and estimate turbulence-induced tendencies of momentum and thermodynamic quantities using a planetary boundary layer (PBL) scheme. The validity of current model SL parameterizations in TC environments is questionable, owing to their empirical nature and the lack of observational data taken at high wind speeds over water (e.g., Large and Pond 1981; Emanuel 1995; Braun and Tao 2000; Powell et al. 2003; Perrie et al. 2005). Recent field observations, such as those taken during the Coupled Boundary Layers/Air–Sea Transfer (CBLAST) experiment (Black 2004; Black et al. 2007), suggest that linear extrapolation of exchange coefficients from those based on low wind speed measurements, as done in current SL schemes, is incorrect. PBL parameterization schemes also impact simulated TC intensity, but typically to a lesser extent than SL schemes (Braun and Tao 2000). To assess simulated TC sensitivity to these parameterizations, several previous studies have performed numerical simulations of real-case TCs and compared the results with observations (e.g., Braun and Tao 2000; Davis and Bosart 2002). Through this comparison, the model’s ability to accurately represent a TC can be assessed, and, indirectly the validity of model design assumptions can be investigated.

In addition to turbulence parameterization, it is recognized that TC simulations are sensitive to other parameterizations as well, such as precipitation microphysics (e.g., Rogers et al. 2007), and subgrid-scale cumulus convection (e.g., Ooyama 1982; Karymampudi et al. 1998). While we recognize these sensitivities, our emphasis here is upon the turbulence parameterization, and in particular the surface flux parameterization. In addition to these parameterization issues, TC simulations are also sensitive to horizontal and vertical resolution (e.g., Braun and Tao 2000; Davis and Bosart 2002; Persing and Montgomery 2003; Zhang and Wang 2003; Kimball and Dougherty 2006), since altering the grid spacing influences how well different physical processes are resolved, and impacts the behavior of parameterization schemes. Braun and Tao (2000) found that smaller horizontal grid spacing led to more intense modeled TCs. However, Davis and Bosart (2002) found that simulations of Hurricane Diana (1984) were more intense on a 9-km grid than on a 3-km grid because of a distribution of vertical motion on the 9-km grid that was skewed toward updrafts, increasing vorticity generation through stretching. Higher-resolution simulations have also been shown to resolve mixing between the low-level eye and the eyewall, which provides extra buoyancy to eyewall updrafts, leading to more intense simulated TCs (e.g., Persing and Montgomery 2003; Wu et al. 2006; Montgomery et al. 2006; Cram et al. 2007).

This study aims to quantify the sensitivity of simulated TCs to SL and PBL representation and model grid spacing through the use of idealized simulations. In contrast to many previous studies, we will utilize idealized simulations of long duration. The use of idealized conditions conducive to intense TC development allows for model results to be viewed in the absence of case-specific conditions. A comparison between model results and observationally based empirical estimates of maximum potential intensity (MPI) is presented and is used as a benchmark for model performance in the place of observations. This comparison is a necessary prerequisite to a more complete implementation of high wind speed exchange coefficients in NWP models. Flux and exchange coefficient values are compared for two widely used SL schemes, and the results are discussed in light of recent observational measurements.

In section 2, the numerical experiments are described, including the idealized initial and boundary condition dataset, the methods used to estimate MPI, and other model configurations. Section 3 provides a description of the TC intensity found in each simulation, and a comparison of the results to the empirically estimated maximum intensity. Section 4 describes the sensitivity of model surface fluxes to the SL parameterization scheme, and conclusions are presented in section 5.

2. Simulation description

a. Model

Version 2.1.21 of the WRF-ARW model (Skamarock et al. 2005) was used to conduct two separate sets of model experiments designed to test the sensitivity to model physics and grid spacing (Table 1), with each set utilizing either the Yonsei University (YSU) or the Mellor–Yamada–Janjic (MYJ) suite of PBL and SL parameterizations. WRF version 2.1.2 must be run with PBL and SL schemes as a matching pair, precluding the ability to test SL or PBL schemes individually. Higher-

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1 Results obtained from version 2.2 are consistent with those presented here.
resolution simulations were performed using one-way interactive nests between the coarse grid (36-km grid spacing) and two finer grids (12 and 4 km). Both the 12- and 4-km grids were moved using an automatic vortex-tracking algorithm to keep the storm nearly centered in the nested domains; despite a lack of environmental flow in the idealized model environment, beta drift generates a west-northwest movement of the simulated TCs. The model simulations utilized 31 vertical layers, with a higher concentration located in the boundary layer.

The Kain–Fritsch cumulus parameterization scheme (Kain and Fritsch 1993; Kain 2004) was used to estimate the effects of subgrid-scale convection on the 12- and 36-km grids, while cumulus convection was not parameterized on the 4-km grids. The top of the model atmosphere was set at the 50-hPa pressure level, with a Rayleigh damping layer used near the model top in order to prevent the reflection of wave energy back into the model domain. The Purdue–Lin scheme was used for the parameterization of microphysical processes (Lin et al. 1983; Hong et al. 2004). The Rapid Radiative Transfer Model (RRTM) scheme, based on Mlawer et al. (1997) and adapted from the fifth-generation Pennsylvania State University–National Center for Atmospheric Research (PSU–NCAR) Mesoscale Model (MM5), was used to estimate the effects of longwave radiation. Shortwave radiation was represented using the scheme described by Dudhia (1989).

The SL schemes compute roughness length, friction velocities, exchange coefficients, and surface fluxes. The SL parameterization scheme compatible with the YSU PBL scheme is based on Monin–Obukhov similarity theory (Monin and Obukhov 1954), with several modifications. Surface exchange coefficients for heat, moisture, and momentum are estimated using stability functions from Paulson (1970), Dyer and Hicks (1970), and Webb (1970). The YSU SL scheme classifies the surface layer as being representative of one of four stability regimes as discussed by Zhang and Anthes (1982), which are determined by the Bulk Richardson number (BR). The MYJ SL scheme (Janjić 1996, 2002; Z. I. Janjić 1998, personal communication) is also based on Monin–Obukhov similarity theory. Using an iterative approach, first-guess momentum and heat flux values are used to estimate the Obukhov length. The iterative procedure typically converges after three or less iterations (Z. I. Janjić 1998, personal communication).

Tendencies of basic variables due to turbulent eddies are computed by the model PBL scheme. Using values of surface fluxes calculated by the SL scheme, the PBL scheme estimates flux distributions within the boundary layer, providing tendencies of temperature, moisture, and horizontal momentum. The YSU PBL scheme (Noh et al. 2003; Hong et al. 2006) is a successor to the MRF PBL scheme (Hong and Pan 1996), and estimates fluxes due to nonlocal gradients using countergradient terms. New to the YSU scheme is an explicit treatment of the entrainment at the PBL top, which was found to significantly improve model results (Noh et al. 2003; Hong et al. 2006). The PBL top is defined using a critical BR number of zero, and is generally lower than in the MRF scheme. The MYJ PBL parameterization is based on Mellor–Yamada 2.5-level turbulence closure. The PBL height in this scheme is defined based on turbulent kinetic energy (TKE). The vertical limit over which mixing can occur in this scheme is proportional to the TKE and a function of large-scale buoyancy and shear parameters (Janjić 2002).

b. Environment and initial conditions

Model runs were initialized with an idealized tropical environment designed to allow for the development of strong TCs. The idealized initial conditions were used to initialize the full-physics WRF Model on an actual geophysical domain, but with the domain set to include only water. Tropical cyclones in the real atmosphere rarely attain their MPI, often because of the limiting effects of wind shear and upwelling (e.g., DeMaria and Kaplan 1994, hereinafter DK94; Tonkin et al. 2000), interactions with land, and dry environmental air. To provide atmospheric conditions within which a TC should reach its MPI, a model domain consisting of all water was constructed with (i) a horizontally uniform, time-independent SST of 29°C, (ii) no environmental wind shear, and (iii) a constant environmental relative hu-

<table>
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<th>Simulation name</th>
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<th>Cumulus parameterization</th>
<th>Grid spacing (km)</th>
<th>Grid dimension</th>
<th>Vertical levels</th>
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<td>MYJ</td>
<td>Kain–Fritsch</td>
<td>36</td>
<td>99 × 104</td>
<td>31</td>
</tr>
<tr>
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<td>31</td>
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<tr>
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<td>Kain–Fritsch</td>
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midity of 80%. The ambient temperature profile (and lateral boundary condition for the outermost domain) was specified by the mean tropical sounding of Jordan (1958), within which a weak initial vortex (i.e., maximum near-surface wind speeds of \(-22\) m s\(^{-1}\) and minimum central pressure of \(-990\) hPa) in hydrostatic and gradient wind balance was inserted. Model simulations were performed with a wide variety of idealized vortices, ranging from an unbalanced warm bubble to fully balanced vortices. The most important difference between these runs was the amount of time required for the system to reach maximum intensity; an initial vortex strength of 22 m s\(^{-1}\) was used in order to reduce the amount of time needed to reach the maximum intensity, while not overprescribing the system structure. These findings, which are consistent with previous idealized modeling studies (e.g., Ooyama 1969; Rosenthal 1971), are not presented here in the interest of brevity. In this case, an integration length of 10 days allowed for the simulated TCs to attain a quasi-steady maximum intensity and then begin weakening. Experiments with varying run length confirm that 10 days is adequate for the purposes of this study.

c. MPI comparisons

DK94, utilizing a 31-yr sample of tropical cyclones in the North Atlantic basin, developed an empirical relationship between climatological sea surface temperature (SST) and TC maximum intensity. The results were shown to agree with the theoretical MPI formulation of Emanuel (1988). The observationally based empirical formulation for MPI of DK94 will provide the basis for a comparison to the model runs; a SST of 29\(^\circ\)C predicts maximum sustained 10-m winds (\(V_{10\text{max}}\)) of \(-75\) m s\(^{-1}\). DK94 do not provide an estimate of minimum central pressure (\(P_{\text{min}}\)), but a \(V_{10\text{max}}\) of 75 m s\(^{-1}\) corresponds to a \(P_{\text{min}}\) value of 910 hPa using the pressure–wind relationship of Brown et al. (2006), or 891 using the relation of Atkinson and Holliday (1977). The difference in the relationship between \(P_{\text{min}}\) and \(V_{10\text{max}}\) in these two studies is likely due to the observational datasets used to determine the relationship; the Atkinson and Holliday (1977) study utilized a dataset consisting of Pacific TCs, while Brown et al. (2006) utilized data from Atlantic TCs. Since the idealized initial vortex is not necessarily intended to represent either ocean basin, simulated MSLP values will be compared to both estimates.

3. Intensity

To determine a 10-m wind speed value from the model output, an assumption regarding the wind speed profile in the boundary layer is required, since the lowest model layer is above 10 m. For consistency with the observationally determined estimates of maximum 10-m wind speed used in DK94, 10-m wind speed was obtained by multiplying the model wind speed at the 700-hPa level by 0.90 [based upon the recommendation of Franklin et al. (2000) and used in DK94]. Sampling issues exist when comparing model results to observations, since the maximum intensity of an observed TC may not always be sampled sufficiently. This issue must be taken into account when comparing the results of the model simulations with the observationally based MPI estimates of DK94.

Figure 1 shows a time series of the model-simulated \(V_{10\text{max}}\) for the duration of the 240-h simulations. In each simulation, the storm undergoes a period of rapid intensification during the first 24 h of model integration, reaching hurricane strength (\(-33\) m s\(^{-1}\)) within 12 h. Simulations using 4- or 12-km grid spacing intensify at nearly the same rate through 24 h, but after this time maximum winds level off in the 12-km simulations, while continuing to increase in the 4-km simulations. After hour 72, \(V_{10\text{max}}\) is quasi-steady (\(\pm 10\) m s\(^{-1}\)) in all simulations except YSU4, where an increase in the TC size after simulation hour 120 led to a weaker pressure gradient (not shown) and weaker \(V_{10\text{max}}\) (Fig. 1b). Simulations with higher resolution produce stronger winds, and the MYJ4 and YSU4 simulations both exceed the estimated MPI of 75 m s\(^{-1}\); however, the difference of \(-5\) m s\(^{-1}\) in the YSU4 run is quite small, given the assumptions used in our 10-m wind computation and uncertainty in the observations that were used to derive this empirical MPI. Simulations with 12-km grid spacing produce peak \(V_{10\text{max}}\) values that are near (\(<5\) m s\(^{-1}\) difference) the MPI, while the 36-km grid spacing simulations are 5–10 m s\(^{-1}\) below the MPI.\(^2\)

Figure 2 shows a time series of the model-simulated \(V_{\text{min}}\). The evolution of \(P_{\text{min}}\) is similar to that of \(V_{10\text{max}}\) with rapid deepening in the first 24 h of each simulation, varying amounts of intensification between 24 and 144 h depending upon the specific simulation, and then quasi-steady \(P_{\text{min}}\) after hour 144. The 4-km simulations produce TCs with the lowest \(P_{\text{min}}\) values, yielding pressures slightly lower than those provided by either of the pressure–wind relationships described above. The TC in simulation YSU12 attains a minimum central

\(^2\) We acknowledge that the comparison between maximum wind speed values between model domains with different grid spacings is not direct, as smaller grid boxes more easily attain a given maximum speed than larger grid boxes. However, the result of higher intensity in the higher-resolution runs was also evident with all data interpolated to a 36-km grid (not shown).
pressure of 900 hPa, a value that falls between the $P_{\text{min}}$ estimates discussed above. Simulations MYJ12, YSU36, and MYJ36 all reach a similar $P_{\text{min}}$ of $\sim 910–915$, within $\sim 5$ hPa of the estimate based on Brown et al. (2006). The sensitivity of $P_{\text{min}}$ to parameterization choice varies with grid spacing, with simulations utilizing the MYJ parameterizations and 4 (12) km grid spacing being more (less) intense than those with YSU. Simulations with 36-km grid spacing were of comparable intensity with the two schemes. We speculate that the use of a convective parameterization (CP) scheme in the 12- and 36-km simulations could contribute to this discrepancy; CP scheme activity in the eyewall reduces the TC secondary circulation, and the interplay between shallow mixing in the CP scheme and parameterized moist entrainment in the YSU scheme may explain the differences between runs with explicit and parameterized convection. Additional simulations would be required to determine whether TCs in MYJ simulations would be consistently stronger than for the YSU scheme, but this was the case for all of the explicit convection runs that we performed.

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**Fig. 1.** Time series of model maximum 10-m wind speed (m s$^{-1}$; model run indicated in legend) for the (a) MYJ and (b) YSU simulations.
The fact that in the simulations using 4-km grid spacing $P_{\text{min}}$ values showed little sensitivity to parameterization choice, while $V_{10\text{max}}$ values did, is likely due to differences in the simulated TC size. After simulation hour 120, the simulated TC in YSU4 grew to be much larger than in MYJ4. Therefore, despite a continued deepening of the vortex, the maximum $V_{10\text{max}}$ values in YSU4 are found before simulation hour 120, while the lowest $P_{\text{min}}$ occurs close to simulation hour 200. The sensitivity of model-simulated TC size to the surface layer and planetary boundary layer parameterization schemes is the topic of ongoing research.

4. Sensitivity of fluxes and exchange coefficients to SL parameterization

Since theory and previous modeling studies have indicated a relationship between hurricane intensity and the model turbulent exchange coefficients (Ooyama 1969; Rosenthal 1971; Emanuel 1995; Braun and Tao 2000), it is anticipated that different exchange coeffi-
coefficients (and fluxes) computed by the WRF SL parameterization schemes tested here will contribute substantially to the differences in simulated TC intensity. Because the SL characteristics may vary in each simulation because of factors other than the SL parameterization (such as the different PBL schemes being used), it can be difficult to evaluate the SL schemes unless identical winds, temperatures, and vapor mixing ratios are used in the calculations. To alleviate this difficulty, the values of different SL parameters from the 4-km grid spacing simulations will be presented as a function of the 10-m wind speed. The model output 10-m wind speed is much less than the 10-m wind speed we estimate utilizing from multiplying the 700-hPa wind speed by 0.9, but it is used for analyzing the surface layer parameters because it is the wind speed used by the schemes for the calculations. Output from simulation hour 102 will be shown, since the TCs exhibited similar near-surface wind speeds at this time (Fig. 3). Examination of other times demonstrates that the results are not sensitive to this choice. To examine the average conditions near the TC center, 280-km area-averaged (hereafter AA) fields will be discussed. The 280-km distance was chosen because it allows for the core of strong winds to be covered, although the results are not highly sensitive to this choice. The AA 10-m wind speed ($V_{10}$) is nearly identical between the two 4-km runs at this simulation hour, allowing for a consistent comparison between area-averaged SL parameters (Table 2).

Figure 4 displays latent heat flux (LHFLX) as a function of 10-m wind speed. Values of LHFLX are larger in MYJ4 than in YSU4 at wind speeds stronger than ~17 m s$^{-1}$, with the largest differences, up to 1000 W m$^{-2}$, found at wind speeds above 55 m s$^{-1}$. The AA 10-m wind speeds vary by ~1 m s$^{-1}$ between the runs, yet the AA LHFLX is 178 W m$^{-2}$ (~22%) larger in the MYJ4 simulation (Table 2). The large disparity in the LHFLX values could be due to different vertical moisture gradients near the ocean surface in the simulations, or due to other differences within the SL schemes. To investigate these possibilities, the difference in specific humidity between the surface and 10 m was calculated (hereinafter referred to as $\Delta q_{0-10}$). All else being equal, the moisture flux should be larger in a simulation in which the vertical water vapor gradient near the ocean surface is larger. However, Fig. 5 reveals that the near-surface vertical moisture gradient is larger in the YSU4 simulation relative to MYJ4 at all wind speeds shown. At high wind speeds, where LHFLX values are ~50% larger in MYJ4, $\Delta q_{0-10}$ remains larger in the YSU4 simulation. These results suggest that the significant differences in the LHFLX between the schemes is related to the moisture exchange coefficient, $C_Q$ (see the Appendix for the computational method), which is shown in Fig. 6 as a function of wind speed. In MYJ4, $C_Q$ linearly increases with wind speed, while in YSU4 $C_Q$ is nearly constant with wind speed. At wind speeds of 50 m s$^{-1}$ and above, the $C_Q$ value in the MYJ4 simulation is more than twice as large as in YSU4, and over all the AA $C_Q$ value is ~50% larger in MYJ4 (Table 2). To summarize, AA LHFLX values are 22% larger in the MYJ4 simulation despite having a smaller gradient of moisture near the surface, because of a larger exchange coefficient for moisture.

While there are large differences in LHFLX values produced in the simulations, the values of sensible heat flux (HFLX) are more similar (Fig. 7). Values of HFLX differ by up to ~50 W m$^{-2}$. The AA HFLX values are ~30% larger in the MYJ4 simulation (Table 2), but this difference can be mainly attributed to the distribution of potential temperature ($\theta$) in the SL. The near-surface vertical $\theta$ gradient is larger in the MYJ4 simulation at almost all wind speeds (Fig. 8), leading to an AA vertical $\theta$ gradient that is ~27% larger (Table 2). The values of the exchange coefficient for sensible heat, $C_{\theta}$, used in the schemes are within 5% of one another at all wind speeds shown (Fig. 9) and AA values vary by ~3% (Table 2), supporting the fact that the calculation of HFLX is nearly identical in the MYJ and YSU SL schemes. Examination of Table 2 reveals that the exchange coefficients for moisture and heat are identical in the MYJ4 simulation, but are not in YSU4.

Figure 10 is a plot of the momentum exchange coefficient, $C_D$, as a function of 10-m wind speed. Throughout the range of winds speeds shown, $C_D$ is nearly identical in the two model simulations, indicating that differences in this parameter likely did not play a role in the sensitivity to the surface layer parameterization.

Emanuel (1995), utilizing an idealized hurricane model, investigated the sensitivity of simulated TC intensity to the ratio $C_k$ (the exchange coefficient for enthalpy) to $C_D$. The results suggested that the value in real hurricanes is likely between 0.75 and 1.5. As previously shown, the exchange coefficients for heat and water vapor are equal in the MYJ SL scheme, but not in the YSU scheme. Therefore, the ratios $C_{\theta}/C_D$ and $C_Q/C_D$ will each be examined separately. At almost all wind speeds, $C_{\theta}/C_D$ is larger in the MYJ4 simulation (Fig. 11), although the largest difference is ~3%, and AA values are within 1% of one another (Table 2). Values at all wind speeds fall within the range suggested by Emanuel (1995). The <1% difference in the AA $C_{\theta}/C_D$ value is not likely to fully explain the observed difference in intensity. Figure 12 displays the value of the ratio $C_Q/C_D$. Owing to the fact that $C_Q$
increases more slowly with wind speed than $C_D$ in the YSU4 simulation, the ratio $C_Q/C_D$ decreases with increasing wind speed. The largest difference in $C_Q/C_D$ is at wind speeds greater than 50 m s$^{-1}$, where $C_Q/C_D$ is approximately twice as large in the MYJ4 simulation. The AA values of the ratio are $\sim$55% larger than the MYJ4 simulation. At wind speeds above $\sim$35 m s$^{-1}$, the ratio in the YSU4 simulation is less than the minimum value suggested by Emanuel (1995), although it is difficult to assess the realism of this behavior due to a lack of flux observations at high wind speeds over water. We speculate that the large difference in this ratio is most likely responsible for the differences in simulated TC intensity seen in the MYJ4 and YSU4 simulations.

FIG. 3. Model 10-m wind speed (shaded; m s$^{-1}$) at simulation hour 102 for the (a) MYJ and (b) YSU simulations. The black contour indicates the 280-km distance from the TC centers.
5. PBL tendencies

The impact of PBL parameterization on the vertical structure of the simulated TCs was assessed by examining vertical cross sections of temporally and azimuthally averaged potential temperature and mixing ratio, along with tendencies of temperature and moisture due to PBL parameterization. Hourly model output from the 4-km grid spacing simulations during the period from 72 to 84 h was used. In cases where negative and positive tendencies were both present, the tendencies were averaged separately, to avoid cancellation.

Figure 13 displays the average potential temperature from the 4-km simulations for this 12-h interval. A realistic warm-core structure is evident in both simulations (Figs. 13a,b), although the TC core is generally warmer in the MYJ4 simulation than in YSU4 (Fig. 13c). The largest difference (~8 K) is found between 4- and 6-km altitude within ~35 km of the TC center. The difference in potential temperature in this area can be partially attributed to PBL scheme tendencies of heat (Fig. 14). The YSU PBL scheme produced strong (~10 K h$^{-1}$) cooling in this area (Fig. 14b), while the MYJ PBL scheme produced no tendency (Fig. 14a).

Outside of the eye, large differences in the magnitude and location of PBL scheme potential temperature tendency exist as well. Azimuthally and temporally averaged positive (warming) tendencies are up to ~8 K in both schemes, while the maximum cooling is approximately one order of magnitude larger in the YSU scheme. The YSU scheme produces appreciable tendencies up to ~8-km altitude, while the MYJ scheme produces.
generally produces a shallower layer of heating and cooling, up to \( \sim 5\)-km altitude.

Figure 15 displays the average mixing ratio from the 4-km simulations, with an outward-sloping eyewall seen in both simulations (Figs. 15a,b). The largest difference in mixing ratio is found in the TC center, where the MYJ4 simulation is dryer than in YSU4 by up to \( \sim 4 \) g kg\(^{-1}\) (Fig. 15c). The difference in mixing ratio in the aforementioned area can be partially attributed to PBL scheme tendencies of moisture (Fig. 16). The YSU PBL scheme produced strong (\( > 4.5 \) g kg\(^{-1}\)) moistening in this area (Fig. 16b), while the MYJ PBL scheme pro-

![Figure 5](image1.png)

**Fig. 5.** The difference in mixing ratio (g kg\(^{-1}\)) between the surface and the 10-m level, as a function of 10-m wind speed (simulation indicated in legend).

![Figure 6](image2.png)

**Fig. 6.** The exchange coefficient for moisture, \( C_Q \times 10^{-3} \), as a function of 10-m wind speed (simulation indicated in legend).
duced no tendency (Fig. 16a). Outside of the eye, the PBL schemes in general produce a similar pattern of mixing. The YSU scheme produces negative (drying) tendencies that are up to 10 times larger than in MYJ.

6. Discussion and conclusions

The WRF model has been used to produce idealized TC simulations within an environment that allows for intensification to the environmental MPI of the model atmosphere. The empirical relationship between SST and maximum intensity of DK94 provides a comparison that is useful in determining the overall consistency of the model with observations, although it is important to emphasize that numerous complexities exist when comparing observations to model output and the intensity comparison is more qualitative than quantitative in na-
More specifically, the sensitivity to model resolution and SL and PBL physics was investigated by performing two separate experiments, where the horizontal grid spacing was varied on three domains. Much of the model sensitivity is attributed to the SL physics, although large differences in PBL scheme–induced mixing have been shown to exist, and could impact the simulated TC intensity as well. Additional sensitivity of the results to microphysics parameterization, the use of convective parameterization on the outer grids, or other aspects of the model have not been systematically addressed here.
a. Maximum TC intensity

The maximum intensity reached in the simulations exhibited strong sensitivity to horizontal grid spacing, and to a lesser extent to the choice of SL and PBL parameterization. Simulations using 4-km grid spacing produced TCs that were of comparable intensity to empirical MPI estimates for the idealized environment, while simulations using coarser (12 or 36 km) grid spacing were weaker. The greater intensity seen in the higher-resolution domains is likely due to either (i) the omission of convective parameterization on the 4-km grid, and/or (ii) the ability of the higher-resolution domain being able to at least partially resolve mixing by
FIG. 13. Temporally and azimuthally averaged potential temperature (K) for the (a) MYJ4, (b) YSU4, and (c) MYJ4 – YSU4 simulations.
eyewall vortices between the low-level eye and the eye-wall; these findings are thus consistent to those of Persing and Montgomery (2003), Braun et al. (2006), and Cram et al. (2007). Simulations utilizing sub 4 km have not been tested here, but we speculate that simulations with even higher resolution would be more intense (Montgomery et al. 2006; Gentry 2007).

b. Fluxes and exchange coefficients in the YSU and MYJ schemes

Large differences are shown to exist between LHFLX computations between the two available surface layer parameterization schemes in WRF. The MYJ scheme produces values of LHFLX that are up to 1000

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**FIG. 14.** Temporally and azimuthally averaged PBL potential temperature tendency (K h\(^{-1}\)). Positive (negative) values are shaded (contoured) for the (a) MYJ4 and (b) YSU4 simulations. Note that positive and negative tendencies are contoured at different intervals, and the negative tendencies are contoured at different intervals between the schemes.
FIG. 15. Temporally and azimuthally averaged mixing ratio (g kg$^{-1}$) for the (a) MYJ4, (b) YSU4, and (c) YSU4 – MYJ4 simulations.
This was traced to a larger exchange coefficient for moisture ($C_Q$) in the MYJ scheme. The $C_Q$ in the YSU scheme is nearly independent of wind speed (varying between 1.4 and 1.8), while in the MYJ scheme $C_Q$ linearly increases with wind speed, reaching a value of $\sim 3.8 \times 10^{-2}$ at a wind speed of $\sim 55$ m s$^{-1}$. The difference in the LHFLX values calculated by the schemes increases with increasing wind speed, suggesting that the sensitivity of TC intensity to the parameterization scheme may be largest for intense systems. The large values of LHFLX at high wind speeds may have been the factor that allowed the MYJ4 simulation to exceed...
the intensity of YSU4. Values of HFLX and the exchange coefficients for momentum and heat are nearly identical in the MYJ and YSU schemes.

c. Comparison with observations

Assessing which scheme is more realistic is complicated by the lack of observations at high wind speeds over oceans. Numerous studies have attempted to estimate the turbulent exchange coefficients over water in high wind speed conditions (e.g., Smith 1980; Large and Pond 1981; Smith et al. 1992; Yelland et al. 1998; Powell et al. 2003) utilizing a wide range of measurement platforms and analysis techniques. Measurements during the 2002–04 Coupled Boundary Layers Air–Sea Transfer (CBLAST) field program were made at wind speeds up to \( \sim28 \text{ m s}^{-1} \), allowing for the exchange coefficients to be estimated based on measurements at higher wind speeds than was previously possible. Model-simulated wind speeds greatly exceeded these values, but nevertheless, CBLAST observations provide the best metric for assessing the surface layer parameterization schemes over the widest range of wind speeds possible. CBLAST observations indicate that \( C_D \) is quasi-steady at wind speeds within the range of \( \sim18–28 \text{ m s}^{-1} \) (Black et al. 2007, their Fig. 5), with a value of 1.5–2.0. At wind speeds in this range, \( C_D \) is nearly identical in the MYJ and YSU SL schemes, with a value of \( \sim2.1–2.6 \times 10^{-3} \), exceeding the upper bound of the observations. At wind speeds \( >30 \text{ m s}^{-1} \), \( C_D \) increases with wind speed in both model SL schemes, reaching a value of \( \sim4.6 \times 10^{-3} \) at a wind speed of \( \sim55 \text{ m s}^{-1} \). Based on the available observations, it is evident that the momentum exchange coefficient may be too large in both the YSU and MYJ schemes.

CBLAST observations indicate that the exchange coefficient for moisture is quasi-steady with increasing wind speed for wind speeds \( <28 \text{ m s}^{-1} \). The \( C_Q \) increases slowly with wind speed in the YSU scheme, while in MYJ it increases more rapidly with increasing wind speed. At wind speeds \( <28 \text{ m s}^{-1} \), \( C_Q \) in the YSU scheme more closely matches the observations. At a wind speed of \( \sim28 \text{ m s}^{-1} \), the \( C_Q \) value from the MYJ scheme exceeding the upper bound of the observations, suggesting that the scheme overestimates \( C_Q \), and consequently LHFLX. The wind speed dependence of \( C_Q \) in higher wind speed conditions \( (\geq30 \text{ m s}^{-1}) \) is difficult to assess given the limited range of observational data, although it is clear that the MYJ scheme produces much larger values than YSU.

Previous modeling studies and theoretical work suggest that the ratio of the exchange coefficient for enthalpy to the exchange coefficient for momentum strongly influences simulated TC intensity. Here it is suggested that when \( C_o \neq C_Q \), the ratios \( C_o/C_D \) and \( C_Q/C_D \) can both impact simulated TC intensity, and, given the fact that latent heat fluxes are much larger than sensible, \( C_Q/C_D \) may ultimately be more important. Theory suggests that increasing (decreasing) these ratios should lead to a more (less) intense simulated TC, and that the ratio should be between 0.75 and 1.5 (e.g., Emanuel 1995). Observations, although limited to wind speeds \( <30 \text{ m s}^{-1} \), indicate that the ratio may be toward the lower end of that spectrum, with a value of \( \sim0.75 \) (Black et al. 2007, their Fig. 7). Recent modeling studies suggest that full-physics numerical models can produce TCs of realistic intensity while utilizing values of this ratio of \(<0.75 \) (Cram et al. 2007). The ratio \( C_Q/C_D \) is similar in the MYJ4 and YSU4 simulations, with values between 0.8 and 0.95, in good agreement with Emanuel (1995) and slightly larger than that indicated by CBLAST observations (but within the range of uncertainty in the measurements). The small differences in this ratio likely do not contribute to differences in model TC intensity.

The ratio \( C_Q/C_D \) varies significantly between the schemes; in the MYJ4 simulation the value is between 0.8 and 0.95, while in YSU4 the ratio decreases from \( \sim0.75 \) to 0.40 as wind speed increases from 20 to 55 m s\(^{-1}\). This ratio is less than that suggested by Emanuel (1995), although this does not necessarily indicate a problem, as the model is still capable of producing realistic TC intensity. The value in YSU4 at a wind speed of 30 m s\(^{-1}\) falls within the 95% confidence interval of the CBLAST observations, but the decrease at higher wind speeds cannot be assessed using currently available observations. The smaller ratio at high wind speeds should lead to less intense TCs in YSU than in simulations with the MYJ SL scheme. Owing to the fact that the ratio becomes more dissimilar at higher wind speeds, it is anticipated that simulations of weaker TCs would exhibit less sensitivity to SL parameterization. The results presented here are consistent in this regard, as modeled TC intensity using 36-km grid spacing was similar \(<1 \text{ m s}^{-1} \) difference in peak \( V_{10max} \), whereas TC intensity using 4-km grid spacing varied considerably \(<10 \text{ m s}^{-1} \) difference in peak \( V_{10max} \).

d. Implications for TC modeling

Based upon the observational data it is evident that a linear extrapolation of measured exchange coefficient values at low wind speeds, as is done in the MYJ and YSU schemes, may not yield physically realistic exchange coefficient values in the high wind speed conditions of an intense TC. Despite this apparent incon-
sistency between the model values and observations, and even for an extremely intense TC, WRF-ARW is capable of producing simulated TC intensity that is comparable to empirical estimates of maximum intensity. It is unclear what effect modifying the model exchange coefficients in the model would produce, although theory suggests that if both $C_D$ and $C_Q$ (or $C_o$) were changed in the same sense then the simulated TC intensity should not change. Changes that lead to the ratio increasing (decreasing), however, should lead to more (less) intense simulated TCs. Although not undertaken in this project, a logical extension of this research would be to test the surface parameterization schemes on real and idealized cases while utilizing exchange coefficients that are more consistent with observations.

If future observational field programs are able to obtain flux measurements beneath the TC eyewall at wind speeds above 30 m s$^{-1}$, then corrections to model exchange coefficients will emerge. Comparisons of results from simulations with the revised SL schemes should be compared with observationally derived MPI values to best calibrate the models. With accurate model exchange coefficients at high wind speeds over water, improvements in TC intensity forecasting may be within reach. Coupled ocean–wave–atmosphere models, of the type discussed by Chen et al. (2007) perhaps offer the best hope for improvement of these important parameterization schemes, as the turbulent exchanges of heat, moisture, and momentum over water in the real atmosphere cannot be realistically parameterized as functions of wind speed alone.

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**APPENDIX**

Calculating Surface Layer Exchange Coefficients

The exchange coefficients $C_Q$, $C_\theta$, and $C_D$ are not output directly from the model, but are computed diagnostically using model-calculated fields. Both $C_Q$ and $C_\theta$ are calculated using the output variables FLQC and FLHC, respectively. FLQC and FLHC are the exchange coefficients for moisture and heat, respectively, but have the unit of meters per second. The surface layer schemes calculate moisture and heat fluxes using the following equations:

$$QFX = \text{FLQC}(QSFC - QX) \quad \text{and} \quad (A1)$$
$$HFX = \text{FLHC}(\text{THGB} - \text{THX}). \quad (A2)$$

where QFX and HFX are moisture and heat flux, QSFC and QX are mixing ratios at the surface and at the 10-m level, and THGB and THX are the potential temperature values at the surface and at the 10-m level. Rearranging (A1) and (A2), FLQC and FLHC become the following:

$$\text{FLQC} = \frac{QFX}{QSFC - QX} \quad \text{and} \quad (A3)$$
$$\text{FLHC} = \frac{HFX}{\text{THGB} - \text{THX}}. \quad (A4)$$

In a bulk formula framework, the fluxes are calculated as

$$QFX = \rho_a V_a C_Q(QSFC - QX), \quad (A5)$$
$$HFX = \rho_a c_p V_a C_\theta(\text{THGB} - \text{THX}), \quad (A6)$$

where $\rho_a$ is air density at the 10-m level, $c_p$ is the heat capacity of dry air at constant pressure, $V_a$ is the wind speed at the 10-m level, and $C_Q$ and $C_\theta$ are the exchange coefficients for moisture and heat, respectively. Rearranging (A5) and (A6), the exchange coefficients are

$$C_Q = \frac{QFX}{\rho_a V_a (QSFC - QX)} \quad \text{and} \quad (A7)$$
$$C_\theta = \frac{HFX}{\rho_a c_p V_a (\text{THGB} - \text{THX})}. \quad (A8)$$

After plugging in (A3) into (A7) and (A4) into (A8), we get expressions for the exchange coefficients:

$$C_Q = \frac{\text{FLQC}}{\rho_a V_a} \quad \text{and} \quad (A9)$$
$$C_\theta = \frac{\text{FLHC}}{\rho_a c_p V_a}. \quad (A10)$$

As previously stated, FLHC and FLQC are output from the model. The other variables in the equations were defined as follows:

- Air density $\rho_a$ at the 10-m level is not standard output from the WRF model, so this quantity was calculated using a linear interpolation for temperature (between the 2-m value and the value at the lowest model level) and for pressure (between the surface value and the value at the lowest model level).
- For this calculation of $V_a$, the model’s 10-m wind speed (which is standard output) was used.

To calculate the drag coefficient $C_D$, the following equation was used:
where $u_0$ is the friction velocity output by WRF and $V_a$ is defined as above.

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