14.2 THE EFFECTS OF SMALL-SCALE TURBULENCE ON MAXIMUM HURRICANE INTENSITY

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1. INTRODUCTION

In a recent article, Bryan and Rotunno (2009b) (hereafter BR09) studied the maximum possible intensity of tropical cyclone (TCs) using an axisymmetric numerical model. They found the maximum azimuthal velocity ($v_{\max}$) to be sensitive to several parameters in the numerical model that have uncertain values, including: the terminal fall velocity of liquid water; the ratio of the surface exchange coefficients for enthalpy and momentum; and settings in the turbulence parameterization. BR09 found their results to be *most sensitive* to the horizontal turbulence length scale (l_h). As shown in Fig. 1, $v_{\max}$ can be changed by more than a factor of 3.

In this axisymmetric model, the intensity of radial diffusion (mixing) is directly proportional to l_h. Consequently, the radial gradients in scalars and velocity are reduced as l_h is increased. Weaker radial gradients are consistent with weaker intensity by consideration of thermal-wind balance; that is, weaker radial temperature gradients are consistent with weaker vertical wind shear (and, thus, weaker azimuthal velocity). Bryan and Rotunno (2009a) also showed that supergradient flow in axisymmetric models is reduced as l_h increases.

The most appropriate value of l_h is unclear. There is no quantitative theoretical guidance to help set the value of l_h in axisymmetric models. In previous studies, values between 3000 m (Rotunno and Emanuel 1987) and 0 m (Hausman et al. 2006) have been used. By comparing their model output against observational analyses of TCs, BR09 argued that $l_h \approx$ 1500 m is probably the most reasonable value.

So the question remains: what value of l_h is most appropriate for axisymmetric numerical models? It is important to provide reasonable bounds on this parameter because axisymmetric models continue to be used for research and operational forecasting (e.g., Emanuel et al. 2004). As we show later (in Section 3), l_h is also needed in a radial turbulence parameterization for three-dimensional models with horizontal grid spacing of order 1 km (i.e., for high-resolution NWP models).

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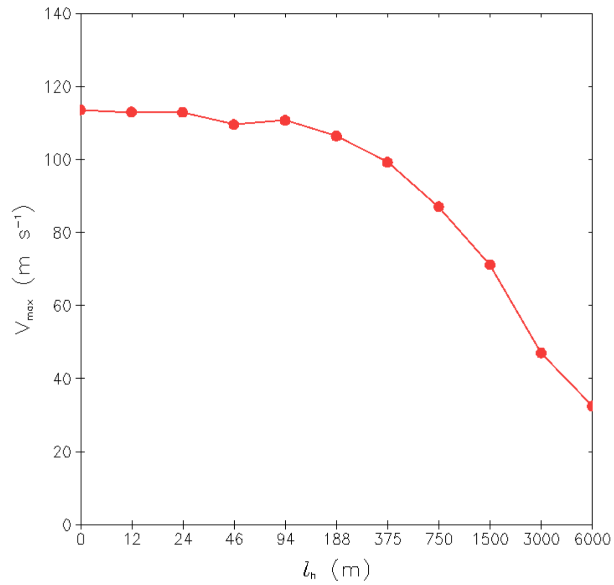

FIG. 1: Maximum azimuthal velocity ($v_{\max}$) from axisymmetric model simulations with different values for l_h. [Adapted from Bryan and Rotunno (2009b).]

Determination of l_h using observations within TCs will require special field observations. In the meantime, it might be possible to obtain reasonable estimates of l_h from simulations that directly resolve the turbulent processes in TCs. Obviously, three-dimensional simulations are required for this purpose, as turbulent processes are inherently three-dimensional. Additionally, very high resolution (grid spacing $<$ 100 m) is required to simulate turbulence in hurricanes, as shown recently by Rotunno et al. (2009).

Herein, we present the first attempt to determine l_h from a turbulence-resolving numerical simulation.

2. METHODOLOGY

We use the numerical model of Bryan and Rotunno (2009b), except the code used here is a three-dimensional version using a Cartesian grid. The initial conditions are identical to those in Bryan and Rotunno (2009b) except small-amplitude random temperature perturbations are placed into the initial state to encourage development of three-dimensional motions.

Two numerical simulations are reported herein. Both use a domain of 3000 km $\times$ 3000 km $\times$ 25 km. The two simulations differ in their horizontal grid spacing. Horizontal grid stretching is used to reduce computational cost, but both simulations have a fine-mesh grid with constant grid spacing ($\Delta \equiv \Delta x = \Delta y$) in the center of the domain, as explained below.

One simulation has a fine-mesh grid of size 142 km $\times$ 142 km that has constant horizontal grid spacing of 1 km. Vertical grid spacing (Δz) is 250 m at all levels in this simulation. Because the turbulent boundary layer cannot be reproduced with this resolution (Rotunno et al. 2009), this simulation imposes a constant vertical length scale l_v of 200 m in the subgrid turbulence scheme. This simulation, hereafter referred to as the Δ = 1 km simulation, is run for 12 days. Consistent with the axisymmetric model simulations by BR09, $v_{\max}$ increases over the first 6 days, and then a steady intensity is maintained thereafter.

The second simulation has a fine-mesh grid of size 49 km $\times$ 49 km, which is large enough to contain the entire eye and eyewall of the simulated TC. Horizontal grid spacing is constant at 62.5 m. The vertical grid spacing is constant at 62.5 m from the surface to z = 5 km, and then Δz increases gradually to 250 m at z = 25 km. A subgrid turbulence model appropriate for large eddy simulation (LES) is used for this simulation. We choose a Smagorinsky-type model, which is analogous to the turbulence scheme used in the axisymmetric model except the settings are determined from theory for homogeneous isotropic turbulence (Lilly 1967). Because this simulation would be prohibitively expensive to run for 12 simulated days, we instead use the output from the Δ = 1 km simulation at 10 days to initialize this simulation. This simulation is then integrated for 12 hours. This simulation is hereafter referred to as the Δ = 62.5 m simulation.

3. RESULTS

Consistent with Rotunno et al. (2009), these simulations produce laminar flow for grid spacing of order 1 km (Fig. 2) and turbulent flow for grid spacing less than 100 m (Fig 3). The scale and magnitude of the vertical velocity structures in Fig 3 are comparable to those observed in Hurricane Hugo (Marks et al. 2008); that is, updrafts are $\sim$2 km across, and magnitudes can exceed 20 m s^{-1}.

In terms of intensity, the Δ = 62.5 m simulation produces stronger wind gusts (not shown) but has weaker azimuthally averaged tangential velocity $\langle v \rangle$ [as in Rotunno et al. (2009)]. The Maximum value of $\langle v \rangle$ is 91.1 m s^{-1} for the Δ = 1 km simulation and is 84.7 m s^{-1} for the Δ = 62.5 m simulation.

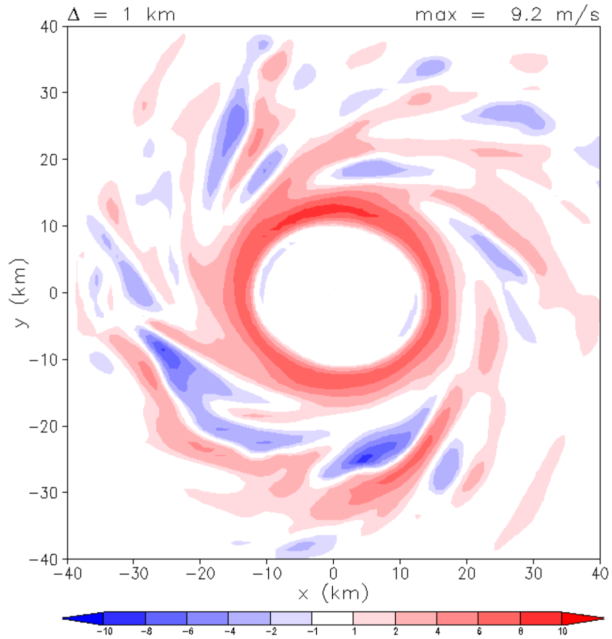

FIG. 2: Vertical velocity at z = 1 km for Δ = 1 km.

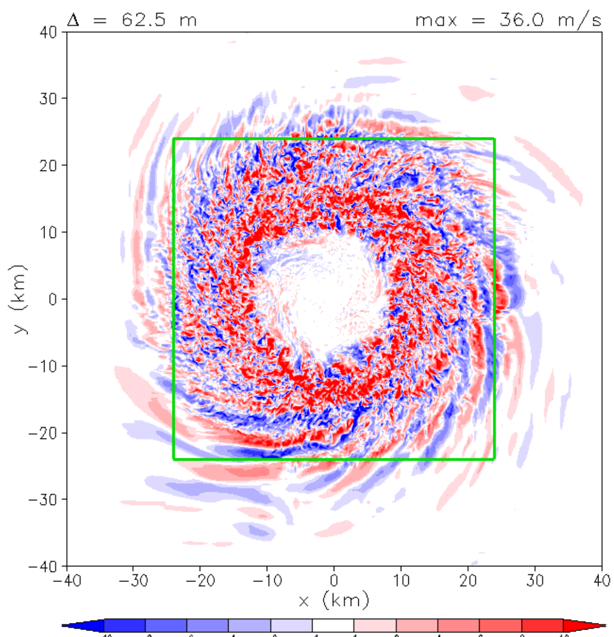

FIG. 3: The same as Fig. 2 but for Δ = 62.5 m after 6 hours of integration. The green box denotes the boundaries of the high-resolution grid.

Table 1: The radial gradient of azimuthally averaged entropy ($\partial \langle s \rangle / \partial r$) at the location of $v_{\max}$. The value for Hurricane Isabel is from Montgomery et al. (2006).

Case:	$\partial \langle s \rangle / \partial r$ (m s^{-2} K^{-1})
Δ = 1 km	-8.8×10^{-3}
Δ = 62.5 m	-4.3×10^{-3}
Isabel (2003)	-1.7×10^{-3}

Consistent with a weaker azimuthally averaged velocity, we find a weaker radial gradient of entropy (s) in the eyewall (Fig. 4). In fact, at the location of $v_{\max}$ the radial gradient of azimuthally averaged entropy ($\partial \langle s \rangle / \partial r$) is a factor of two lower in the Δ = 62.5 m simulation (Table 1). Montgomery et al. (2006) used a large number of dropsondes collected in Hurricane Isabel (2003) to estimate $\partial \langle s \rangle / \partial r$ (Table 1). The results from the Δ = 62.5 m simulation are closer to the value from Hurricane Isabel, indicating that small-scale turbulence *reduces radial gradients* towards more realistic values.

In principle, the Δ = 1 km simulation could reproduce the same azimuthally averaged results from the LES simulation if an appropriately formulated radial turbulence parameterization had been used. To this end, we obtain an estimate of l_h from the Δ = 62.5 m simulation as follows. We assume the traditional downgradient diffusion model

$$\langle u' s' \rangle = -K_s \frac{\partial \langle s \rangle}{\partial r}, \quad (1)$$

where brackets denote azimuthal averaging, primes indicate departures from an azimuthal average, u is radial velocity, and K_s is the eddy viscosity for entropy. The only unknown variable in (1) is K_s, which can be determined from a subgrid kinetic energy equation by assuming that subgrid turbulence is steady and isotropic (in the radial direction),

$$K_s = l_h^2 \left[2 \left(\frac{\partial \langle u \rangle}{\partial r} \right)^2 + 2 \left(\frac{\langle u \rangle}{r} \right)^2 + \left(\frac{\partial \langle v \rangle}{\partial r} - \frac{\langle v \rangle}{r} \right)^2 \right]^{1/2} . \quad (2)$$

These equations represent the simplest reasonable turbulence model. Some of the assumptions inherent in these equations may be relaxed in a future study. Nevertheless, we see from (1) and (2) that the only unknown parameter is l_h. Using output from the Δ = 62.5 m simulation, and averaging over three hours to produce a smoother result, we find that l_h is of order 1000 m in the eyewall (Fig. 5). This value is

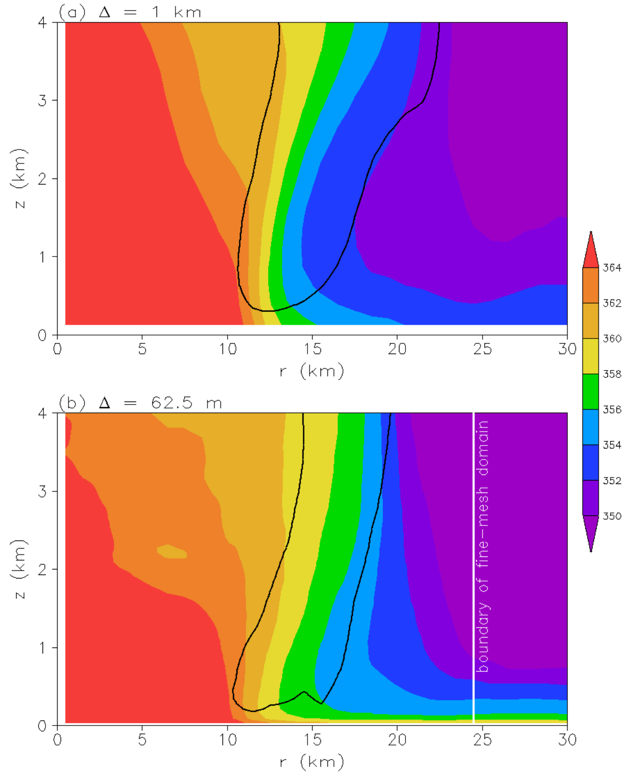

FIG. 4: Azimuthally averaged equivalent potential temperature (shading) from (a) Δ = 1 km and (b) Δ = 62.5 m. The black contour is $\langle w \rangle$ = 2 m s^{-1}, which denotes the approximate location of the eyewall.

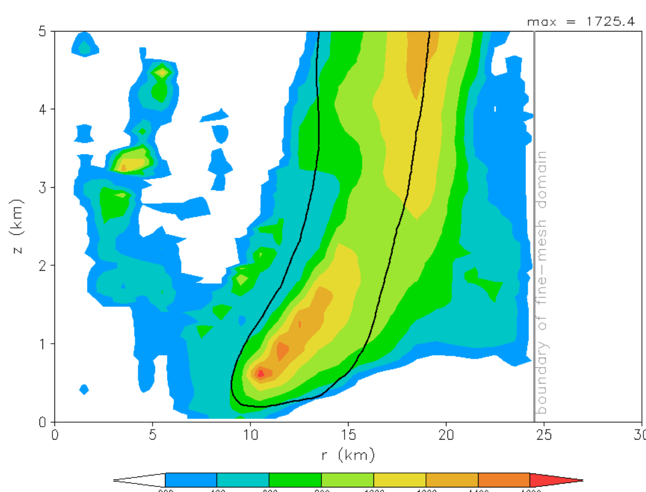

FIG. 5: Analysis of l_h (shaded) from the Δ = 62.5 m simulation. The black contour is $\langle w \rangle$ = 2 m s^{-1}, which denotes the approximate location of the eyewall.

encouragingly close to the value determined by trial-and-error using an axisymmetric model in Bryan and Rotunno (2009b).

4. SUMMARY

These preliminary results suggest that high-resolution (LES) simulations of TCs can be used to determine turbulence settings for lower-resolution simulations and for axisymmetric models. Further study is clearly warranted. One aspect of these solutions that we plan to explore next is whether even smaller grid spacing is required to obtain a statistically converged solution (i.e., a simulation in which the mean statistics are independent of grid spacing). It is possible that $\langle v \rangle$ and $\partial \langle s \rangle / \partial r$ will be reduced as Δ decreases.

These preliminary simulations also show that small-scale turbulence in the eye and eyewall primarily acts to *weaken* hurricanes (in terms of azimuthally averaged winds). These results also reaffirm the need to account for the effects of radial turbulence (i.e., mixing) in analytic models of maximum hurricane intensity, as argued by Bryan and Rotunno (2009a).

Acknowledgements

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