Large-Eddy Simulation of an Idealized Tropical Cyclone

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Advances in computing have allowed present-day numerical weather-prediction models to forecast and/or simulate tropical cyclones (TCs) with high resolution (horizontal grid spacing ~1 km). While these numerical models of TCs can capture many of their important structural features (eyewall, rainbands, etc.), the effects of small-scale [~O (100 m)], three-dimensional turbulence must still be parameterized. No objective basis has yet been found for such parameterizations, yet the maximum wind speeds in axisymmetric numerical TC models have been shown to be highly sensitive to the radial turbulent transfer and diffusion at these scales. As there is little observational guidance on the nature of radial turbulent diffusion in a TC, the present study was conceived to indicate the impact of these effects through computation of the small-scale scale turbulence (i.e., a large-eddy simulation, or LES) using a numerical weather prediction model applied to an idealized tropical cyclone.

The numerical experiments reported on herein were carried out with the Advanced Research Weather research and forecasting (ARW) model, version 2.2, using six nested grids centered on the TC. As the ARW model is nonhydrostatic, it can and has been used as an LES model,[1] and therefore one can expect the numerical solutions to capture turbulent eddies, given sufficient resolution. Here we show that using a horizontal grid size < 100 m in a TC simulation produces three-dimensional turbulent eddies, which have the effect of decreasing the maximum sustained (1-min average) wind and the maximum predicted azimuthally averaged wind.

TURBULENCE EFFECTS IN TROPICAL-CYCLONE MODELS. Existing tropical-cyclone models need to simulate circulations reaching outward to a distance of ~O (1,000 km) from the TC center. Modern-day computers have allowed real-time numerical forecasts and sensitivity studies of the TC with horizontal grid spacing as small as 1 km. We note that TC models fall into the general category of mesoscale model wherein, according to a 2004 *Journal of the Atmospheric Sciences* essay by J. Wyngaard, the grid scale Δ is much greater than the length scale *l* of three-dimensional turbulent eddies that may be O (100 m) and smaller, and consequently, all three-dimensional turbulence effects must be parameterized. The parameterization of horizontal diffusion in most mesoscale models is such that the horizontal diffusion coefficient is proportional to Δ so as to arrest frontal collapse; in the typical case, the front is long and straight and the horizontal diffusion serves its purpose without significantly changing the forecast wind intensity. However, in a TC, the eyewall, which is a type of front (as discussed by K. Emanuel in a 1997 *Journal of the Atmospheric Sciences* article), is circular, and diffusion exerts great control over the radius of the eyewall (i.e., the radius to which fluid parcels will converge), and hence the magnitude of the maximum tangential velocity. A recent numerical study in *Monthly Weather Review* by G. H. Bryan and R. Rotunno systematically varies the horizontal mixing length in an idealized TC model and finds the maximum wind speed to be very strongly dependent on it.

In the absence of any information on horizontal diffusion in natural TCs, the present study attempts to carry out a large-eddy simulation (LES) of the inner

[1] Examples using ARW as an LES model to simulate the idealized convective planetary boundary layer and the sea breeze are listed in the bibliography.

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core of a tropical cyclone. Again, following the 2004 essay by J. Wyngaard, an LES model is one in which $\Delta \ll l$—consequently, the effects of the largest turbulent eddies can be explicitly computed, and the effects of the smaller subgrid-scale eddies can be parameterized according to the statistical theory of turbulence. In the LES subgrid-scale parameterization, the diffusion coefficient is also proportional to Δ; reducing Δ permits a larger range of eddies to be computed and correspondingly less of a range to be parameterized. Therefore, in an LES model, reducing the grid size allows more of the three-dimensional turbulence to be explicitly computed, while in a mesoscale model, reducing the grid size simply reduces the horizontal diffusion coefficient. The present study shows in vivid detail how this latter distinction is vital in simulations of TCs. Although the LES technique is a great advance, there is, however, the strong caveat that the subgrid-scale parameterization must be modified near solid boundaries, as the key assumptions of homogeneity and isotropy do not hold there. In the present study, no attempt is made to change the subgrid-scale parameterization near the sea surface, as very little is known about turbulence in a TC boundary layer.

Table 1. Description of domain size, grid resolution, time step, and start time for each of the domains used in the present integration.

Domain	Side length (km)	Grid interval (km)	Time step (s)	Start time (d)
D1	6,075	15.0	60.0	0
D2	1,500	5.0	20.0	0
D3	1,000	1.67	6.7	0
D4	333	0.556	2.2	6.0
D5	111	0.185	1.1	8.0
D6	37	0.062	0.37	9.5

DESIGN OF THE NUMERICAL EXPERIMENT.

The practical numerical approach for our problem is to refine the model grid spacing locally, so that adequate resolution is placed in the core of the storm without having to cover an excessive area in which little is happening. In this case we use nested grids, all with the same origin, in which the grid increment decreases by a factor of three with each new nest (Table 1), yielding a microscoping effect. Each nest "feeds back" the solution to its parent domain; thus, upscale transfer of information is possible all the way to the coarsest model domain. The coarse domain (D1) is bounded by impermeable walls. The first nest is D2 and so on to D6, the nest with a 62-m grid increment. On all domains, 50 model levels are used with the model top at 15 hPa. The finest vertical resolution is found in the boundary layer.[2]

The model version of the tropical atmosphere is in an equilibrium state in which the thermodynamic field is moist-neutral according to the ARW-model thermodynamic and saturation-vapor-pressure equations. This means that a hypothetical parcel lifted from the undisturbed boundary layer experiences zero buoyancy at all altitudes in the troposphere. The relative humidity is initially specified as 85% at the lowest grid level and then decreases linearly with pressure in the troposphere.

The model thermodynamic state is maintained by inclusion of a relaxation term in the thermodynamic equation with a time constant of 36 h. Through trial and error, this value was found to be large enough not to interfere with the fast processes of convection and TC-vortex dynamics, but small enough to achieve the desired constancy in the modeled TC environment. As atmospheric radiation is one of the effects represented in the relaxation term, no other parameterization of it was used. Other necessary parameterizations include those for clouds and for turbulence in the planetary boundary layer (PBL). All cloud processes are modeled explicitly using a relatively simple scheme that predicts cloud water, rain, snow, and cloud ice, assuming a simple distribution of particle sizes. For horizontal grid increments greater than 1 km, turbulence is represented by a scheme that relates the amount of vertical mixing to the stability of the PBL and surface buoyancy flux,[3] and horizontal mixing is related to the local

[2] The grid levels are at z = 62, 152, 268, 413, 597, 831, and 1,109 m; above the boundary layer, the vertical grid spacing varies from 510 to 750 m at z = 20 km, with somewhat larger spacing above.

[3] The cloud physics scheme is the ARW Single-Moment Class 3 scheme (WSM3) and the PBL mixing is handled by the Yonsei University (YSU) scheme.

horizontal wind deformation. This separation of vertical and horizontal turbulence processes is typical in mesoscale models. The level of turbulence in D3 is therefore diagnosed, not predicted. For domains D4–D6, effects of horizontal and vertical turbulence processes are unified and parameterized using a grid-spacing-dependent eddy viscosity based on a three-dimensional turbulence–kinetic-energy equation appropriate for LES. Air–sea exchange uses a bulk aerodynamic formulation for heat and momentum. Hurricane intensity is known to depend strongly on the ratio of the enthalpy coefficient to the drag coefficient. Below a wind speed of about 30 m s^{-1}, this varies from about 1.8 at low wind speeds down to about 0.65 on the verge of hurricane strength. At higher wind speeds, little is known about these coefficients. In our simulation, the ratio asymptotes to 0.6 for extreme winds. In all experiments, the sea surface temperature SST = 26.3°C is held fixed.

The initial velocity field represents an incipient TC-like axisymmetric vortex with maximum lowest-level winds of 20 m s^{-1}, radius of maximum wind of 82.5 km, and radius of zero wind of 412.5 km. The vortex decays in the vertical as log *p*. The Coriolis parameter is spatially uniform with its value at 20° latitude (5×10^{-5} s^{-1}).

We start the simulation with only the first three domains—that is, with a finest grid spacing of 1.67 km. This grid spacing is comparable to what is used in many recent research simulations of hurricanes. The three-domain configuration develops a mature, statistically steady tropical cyclone by Day 6, and the integration is carried forward until Day 12 (Fig. 1). The effect of increasing resolution on the representation of the eye, eyewall, and surrounding features is examined by adding domains D4, D5, and D6 (Table 1) beginning at Days 6, 8, and 9.5, respectively. The staggered start times allow detail to develop on a given nest before the next nest is introduced and reduces the computational cost. Note that each parent domain is also run without a nest, so that each experiment is independent.

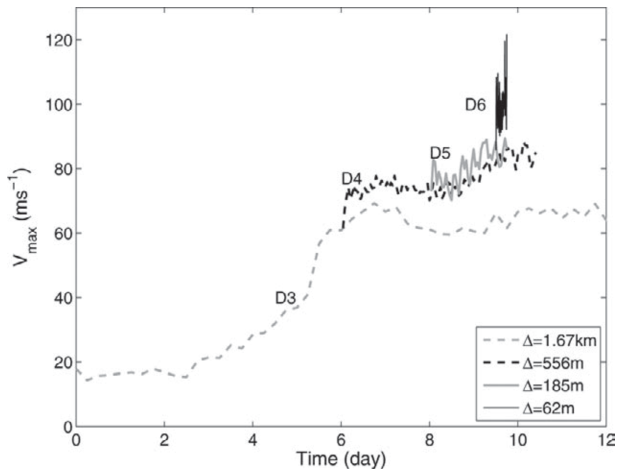

Fig. 1. Time series of the maximum wind speed V_{max} at the 10-m level for integrations with decreasing grid size in the inner core of the tropical cyclone.

RESULTS. Figure 1 shows time series of the instantaneous maximum horizontal wind speed V_{max} at the (standard) 10-m level for the D3–D6 experiments. For D3, the vortex develops over several days before reaching a statistically steady state. For D4 (nest started at Day 6), there is a rapid adjustment to a higher maximum wind before reaching a steadier state with a slow undulation similar to D3. Within nest D4, the boundary layer parameterization has been turned off in addition to the reduction in horizontal grid size; a test with the parameterization retained indicated a similar wind increase in maximum winds (not shown), and hence the increase in maximum wind speed can largely be attributed to the increased resolution.

Experiment D5 was initiated from the D4 simulation at 8 days and produced only marginal intensity changes (D5 in Fig. 1). However, the highest-resolution experiment, D6, initiated from D5 at 9 days and terminated at 9.75 days, produced highly variable maximum winds with instantaneous peak values > 120 m s^{-1}!

The 10-m wind speed at 9.75 days for experiments D3–D6 is shown in Fig. 2. In D3, the region of strongest winds in the inner core is rather broad (Fig. 2a) and V_{max} barely exceeds 60 m s^{-1} (Table 2). The vortex contains a modest asymmetry but is generally axisymmetric. With the addition of domains 4 and 5, the vortex strengthens markedly (Table 2) yet still retains its nearly axisymmetric character (Figs. 2b and 2c).[4] We note that both the maximum wind and the maximum of the azimuthally averaged tangential wind v_{max} vary similarly with increased resolution in D3–D5. Consistent with the increase in v_{max}, the radius of maximum winds is reduced with increasing resolution. However, at a grid spacing of 62 m (D6, Fig. 2d), a distinct change

[4] J. Persing and M. M. Montogomery, using an axisymmetric numerical model, noted an increase in simulated intensity with increasing resolution, and that the increased intensity exceeded the potential intensity given by Eq. (8) of Emaunel (1997) and shown here in Table 2.

occurs with the flow structure characterized by vigorous, small-scale eddies within the annulus of strong winds. Interestingly, the mean intensity V_{max} decreases to 67 m s^{-1}, though the maximum wind speed becomes, by any reasonable measure, extreme at 122 m s^{-1}.

The marked change between Figs. 2c and 2d suggests a transition to randomly distributed, small-scale turbulent eddies when the grid size is decreased from 185 to 62 m. The marked increase in maximum wind variability for D6 in Fig. 1 is indicative of the short lifetime of these turbulent eddies. This is confirmed by the 1-minute average wind speed for 9.75 days, shown in Fig. 2e, which almost completely removes the small-scale variations and reduces the maximum winds to 79 m s^{-1}. Clearly, a threshold has been crossed for a grid increment somewhere near 100 m.

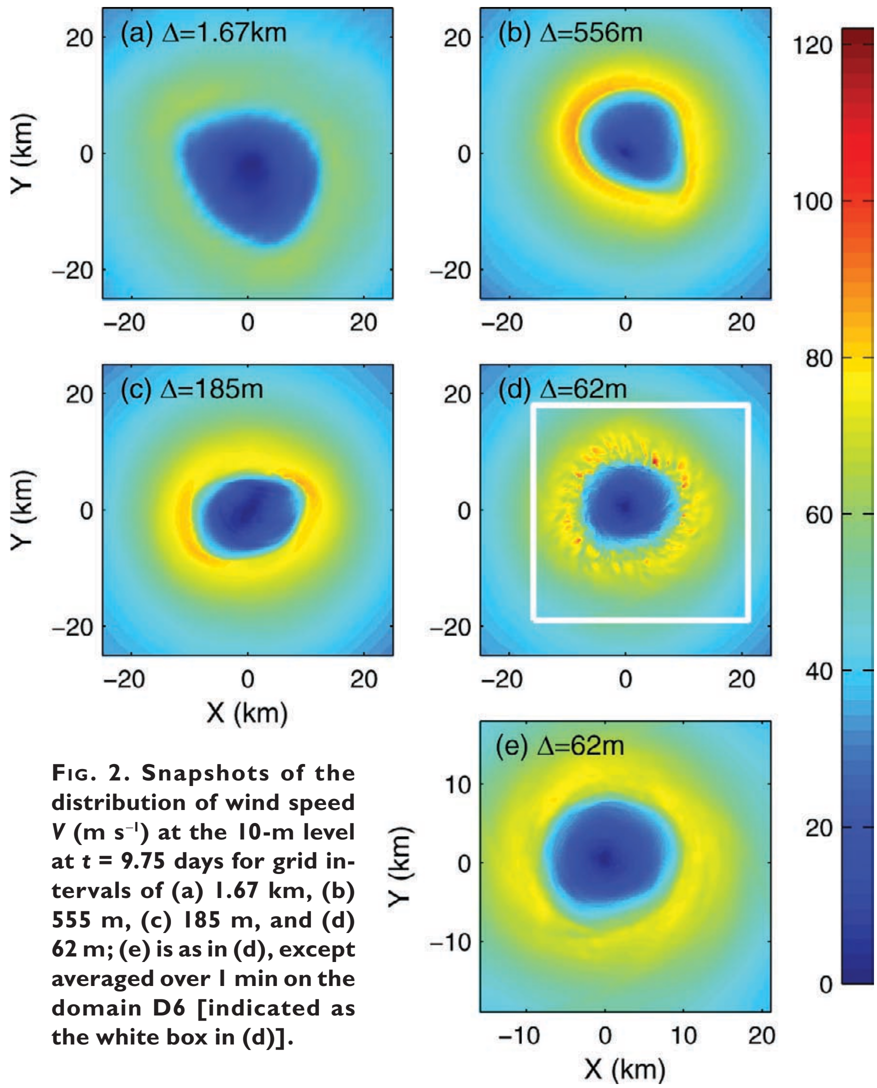

Fig. 2. Snapshots of the distribution of wind speed *V* (m s^{-1}) at the 10-m level at *t* = 9.75 days for grid intervals of (a) 1.67 km, (b) 555 m, (c) 185 m, and (d) 62 m; (e) is as in (d), except averaged over 1 min on the domain D6 [indicated as the white box in (d)].

That the turbulent eddies in Fig. 2d represent three-dimensional turbulent motion is evidenced by the vorticity-magnitude isopleths in Fig. 3a.[5] A plan view of vorticity in Fig. 3b reveals curved, elongated structures that resemble features seen in observational studies of the inner edge of the eyewall of intense hurricanes such as Isabel (2003). In that storm, dropsonde-derived winds of 107 m s^{-1} were observed in association with such filaments. Further, data from a low-altitude (450 m) eyewall penetration of Hurricane Hugo (1989) revealed intense turbulence with a preferred length scale of roughly 1 km. These observations lend support to the remarkably strong simulated maximum instantaneous winds in the simulation. Thus, while no observations present definitive verification of the simulated structures, there is support for the general result from experiment D6 of strong, three-dimensional turbulence along the inner edge of the eyewall of intense hurricanes.

These simulations strongly suggest that passing to a sub-100-m grid produces a simulation of an idealized tropical cyclone with at least partially resolved turbulence in the inner core. That is, the turbulence has changed from being almost entirely subgrid-scale (and therefore parameterized) to partially grid resolved. Ideally, one would like to continue to perform experiments with increasing resolution until the statistics are converged; unfortunately the present experiments already have required computational resources far beyond any such experiment that has previously been attempted, so a rigorous

[5] The authors are currently working on a more detailed analysis that supports this conclusion and estimates the effect of the turbulence on the axisymmetric-mean vortex.

Table 2. Vortex parameters at z = 10 m from experiments D3–D6 at Day 9.75. The quantity V_{max} is the instantaneous maximum wind speed and v_{max} is the azimuthally averaged tangential wind, which occurs at the radius r_{max}. The potential intensity is an estimate of the maximum possible tangential wind according to the theory of Emanuel [1997; see his Eq. (8)].

Experiment (finest domain)	V_{max} (m s^{-1})	v_{max}/Potential intensity (m s^{-1})	r_{max}(km)
D3	62	50/50	16.7
D4	87	71/55	12.2
D5	86	74/57	10.6
D6	122	67/56	9.9

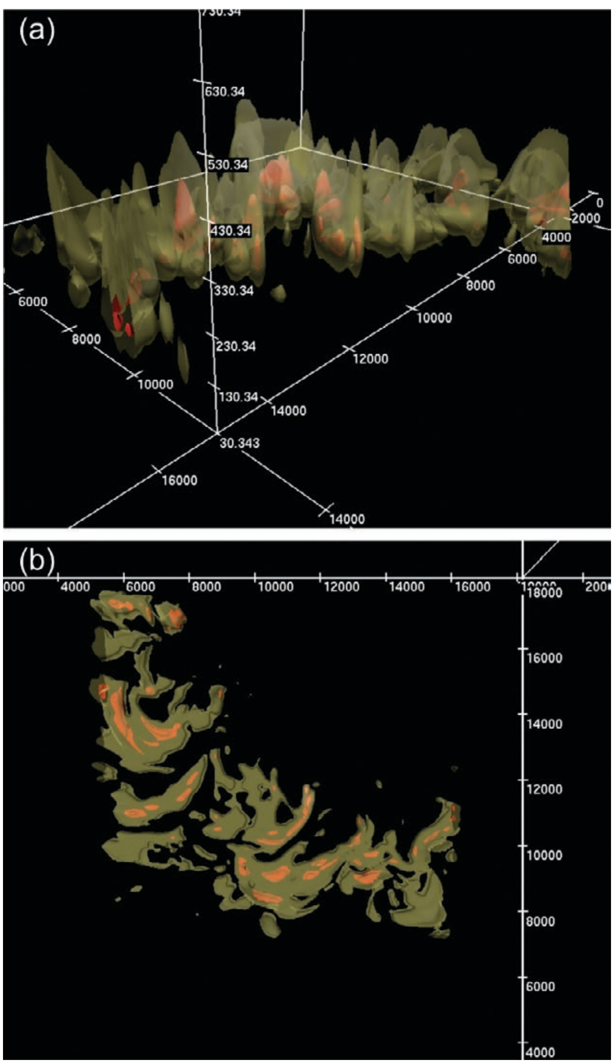

Fig. 3. Three-dimensional isopleths of vorticity magnitude (orange = 0.3 s^{-1}, transparent green = 0.2 s^{-1}) at t = 9.75 days in D6 from (a) a side view and (b) a top view.

convergence test must be left for future research. Our goal is to test whether such simulations can be used to estimate eddy-diffusion coefficients for use in coarser models that must parameterize the effects of all turbulent motions.

CONCLUSIONS. We report on work using the ARW run at resolution high enough to allow three-dimensional turbulent motions in an idealized tropical cyclone. The model used initial conditions similar to those of previous axisymmetric-modeling studies, but by virtue of its three dimensionality, it develops energetic 3-dimensional turbulent eddies when the grid interval falls below approximately 100 m.

We suggest that decreasing the grid interval from 1.67 km to 185 m produces tropical cyclones with increasing maximum wind speed because without resolved turbulence, the parameterized horizontal diffusion essentially decreases the effects of diffusion as the grid interval is decreased. With the removal of the parameterization and the appearance of turbulence for sub-100-m integrations, the resulting mean tropical-cyclone intensity begins to decrease, while the maximum wind increases sharply in the turbulent gusts. This dependence of mean tropical cyclone intensity on the effects of resolved turbulence is consistent with that found by varying the degree of parameterized turbulent diffusion in a recent axisymmetric modeling studies. In short, the larger the turbulent diffusion, the weaker the intensity of the simulated vortex. This dependence underlines the quantitative importance of the internal turbulent diffusion in a tropical cyclone (about which little is known) for both high-resolution numerical simulations and real-time predictions of tropical-cyclone intensity.

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