Impacts of Turbulence on Hurricane Intensity

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LONG-TERM GOALS

Our recent studies have shown that hurricane boundary layer turbulence, which must be *parameterized* in the current-generation weather-prediction models, plays a significant role in controlling the hurricane intensity. We find that *horizontal* turbulence, particularly in the radial direction (i.e., towards or away from the hurricane center), plays an important role in regulating hurricane intensity. The long-term goal of this project is thus to improve the hurricane intensity forecast by developing a more physically based horizontal turbulence parameterization scheme for hurricanes.

OBJECTIVES

The effects of turbulence on simulated hurricanes can be quantified if the turbulence is resolved in the numerical model. Thus, one objective of the current project is to perform a set of large-eddy simulations (LES) with increasing resolution (grid spacing as small as ~30 m) until the bulk statistics such as maximum intensity and turbulence eddy fluxes are converged. These simulations will then be analyzed to estimate eddy-diffusion coefficients for use in weather-prediction models.

APPROACH AND WORK PLAN

Because of the multi-scale nature of hurricanes, the proposed large-eddy simulation work is a challenging computational problem. A three-dimensional research cloud model (CM1) with horizontal grid stretching capability is being configured for the convergence test. In addition, the Weather Research and Forecasting (WRF) model (ARW core) is being used as a weather-prediction model to examine the eddy-diffusion coefficients obtained from CM1 and WRF simulations in both idealized and real-data hurricane cases.

The PI, Dr. Yongsheng Chen, will analyze the existing high-resolution WRF simulations, implement the findings from WRF and CM1 simulations in new real-data WRF retrospective forecasts, and supervise a graduate student as part of this project.

Dr. George Bryan, the developer of CM1 model, will conduct numerical simulation and analysis of idealized hurricanes using the CM1 model.

Dr. Richard Rotunno will synthesize WRF and CM1 simulations and design a new radial-turbulence parameterization scheme for weather-prediction models with typical resolution of O(1km).

Convergence tests at eddy-resolving resolution using CM1 were performed. Effects of turbulence mixing length scales and surface exchange coefficients on the hurricane intensity at typical model resolutions were systematically conducted using CM1 and compared to recent observational studies. The sensitivities of hurricane intensity, structure and its environment to changes in the horizontal turbulence mixing length scale and horizontal resolution were studied using WRF for several real hurricane cases.

WORK COMPLETED

In order to complete the CM1 convergence tests at eddy-resolving resolution, more computing resources were needed than was available to us at SHARCNET (the supercomputing center we had originally planned to use for this project). We were able to obtain the needed computing time at the National Center for Supercomputing Applications (NCSA) at the University of Illinois. Several dozen simulations were conducted using 62-m grid spacing, and a few runs were conducted using 31-m, to test the basic experimental design. To our knowledge, this is the first time anybody has attempted to use grid spacing as small as 31-m to simulate turbulence within the eyewall of hurricanes (where surface windspeeds are strongest). The preliminary results showed, surprisingly, that turbulence was not developing in most of the high-resolution mesh as theory suggested it should. Instead of completing the planned 15-m simulations, we instead ran a large number of 62-m runs to determine what aspect of the model setup was preventing turbulence from forming. We found that certain properties of the inflowing boundary-layer air from the coarser mesh were ultimately causing the lack of turbulence development. A method to circumvent this problem was developed; a journal article on this topic is under preparation. Additional computing time was acquired, scheduled for late 2012 or early 2013, for completion of the statistical convergence tests (with 31-m and 15-m grid spacing).

The existing WRF large-eddy simulations were analyzed. The estimated horizontal turbulence mixing length scale falls in the range of 150~2000m, in agreement with previous studies. The impact of changing horizontal turbulence mixing length scale (l_h) on the hurricane intensity, structure, and its environment were investigated using WRF model to simulate Hurricane Danielle (2010) and Hurricane Earl (2010).

RESULTS

We obtained successful idealized simulations of hurricanes using grid spacing as small as 31 m. To our knowledge, this is the first time anybody has attempted to explicitly resolve turbulence in hurricanes over such a large domain that encompasses the eye, eyewall, *and* rainbands. As expected, the interface between the eye and eyewall of the simulated hurricane is especially turbulent; see, e.g., Fig. 1a. This is the region we are most interested in analyzing. However, we did encounter an unexpected problem getting boundary-layer (i.e., surface-based) turbulence to develop outside the eyewall in these simulations, as indicated by the large area without blue or red shading *within* the green circle in Fig. 1a. To determine the cause of this problem, we ran several 62-m simulations with different model settings, initial conditions, and boundary conditions. (Because nobody has ever done simulations like this before, there wasn't any guidance for what settings mattered most.) It turns out that more careful treatment of the transition zone near the edge of the fine-mesh domain was necessary. We ultimately decided to turn off the parameterized turbulence scheme in the coarse mesh domain just outside of the green circle shown in Fig. 1. This approach allows the simulated boundary layer (i.e., near-surface flow) to collapse to a very small depth. Very high vertical wind shear near the surface results from this approach which then readily produces turbulence when it flows into the fine-mesh domain, as shown in Fig. 1b. Because the resulting flow is more turbulent, we are able to estimate bulk properties of the turbulence like effective eddy viscosity and turbulence length scale, which is the ultimate goal of this project; results from this part of our analysis are preliminary, and will be reported after the 31-m and 15-m resolution simulations are completed.

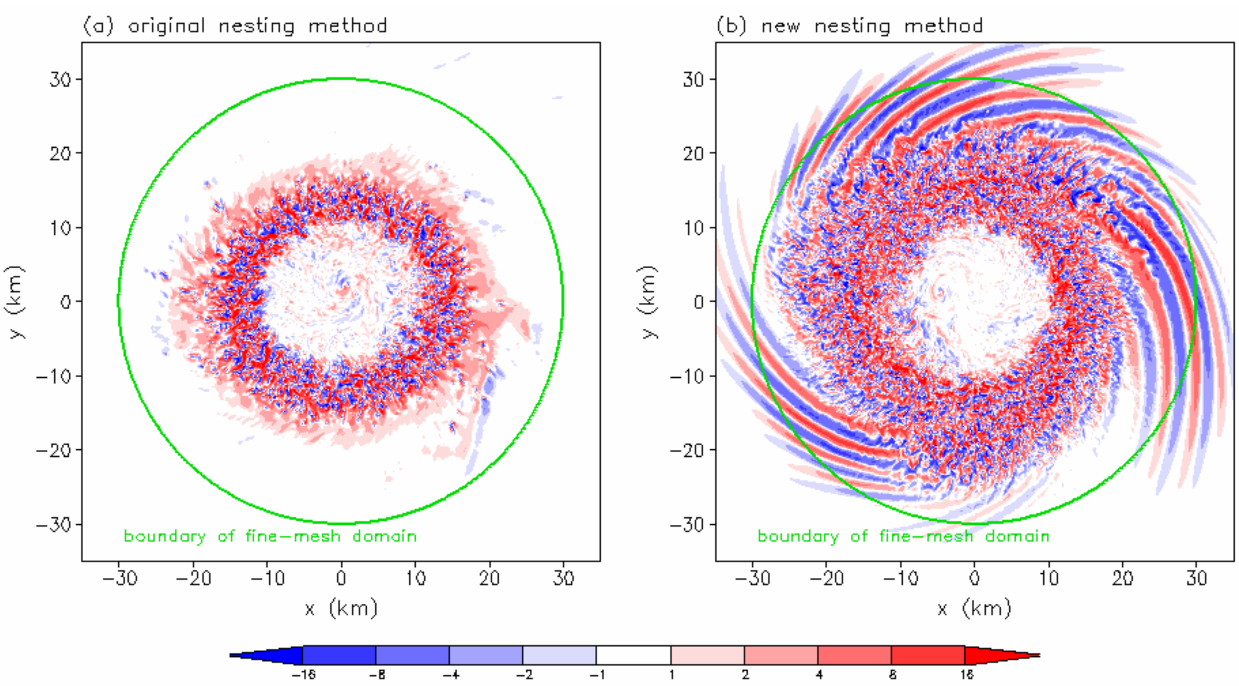

Fig. 1: *Numerical model (CM1) output from eddy-resolving simulations using 62-m grid spacing (a) using the original nesting method, and (b) using a newly developed nesting method. Color shading is vertical velocity (m s^{-1}) at 500 m above sea level. The green square shows the boundaries of the fine-mesh domain.*

Previous simulations of idealized hurricane using WRF (ARW) model were diagnosed. The horizontal turbulence mixing length (l_h) was estimated by computing the explicitly resolved eddy momentum flux and by assuming traditional K-theory. It was found that the strongest eddy activities are located in the leading edge of the near-surface inflow layer beneath the eyewall, where the estimated l_h is between 150 m ~ 2 km. The variations resulted from changing the filtering scales. Eddies associated with storm asymmetries or convective vortices with horizontal scales ranging from 20 km to 3 km were first filtered out. In general, the larger the filtering scale is, the smaller is the l_h. The values of l_h are consistent with previous numerical results (Bryan 2011) and observational study (Zhang and Montgomery 2012).

Sensitivities of the hurricane intensity to the horizontal turbulence mixing length were studied in real hurricane case simulations (Chen and Kurkute 2012). In particular, Hurricane Danielle (2010) and Earl (2010) were simulated using the WRF (ARW) model. The storm-following and quadruply nested domains with resolutions of 36-12-4-1.33 km were utilized. Both Danielle and Earl were strong Category 4 hurricanes. The maximum surface winds (v_{max}) at peak intensity were 115 knots (59 m/s) and 125 knots (64 m/s) respectively. The sensitivity experiments of varying c_s thus l_h (since $l_h = c_s * \Delta x$) are shown in Fig. 2. Consistent with the idealized CM1 hurricane simulations, the maximum intensities of the forecasted hurricanes decrease with increasing c_s (l_h). The change in the maximum wind, for example by doubling l_h from default 333 m to 667 m, can be as large as 16 m/s in Earl simulations. The storm structures are also altered when l_h is changed. Large l_h produces gently sloped eyewall with weaker thermal gradient and wind shear. In the case of Hurricane Danielle, a concentric eyewall and eyewall replacement cycle occurs when the horizontal diffusion is turned off. In summary, the hurricane intensity and structure are sensitive to the parameterized horizontal turbulence mixing. In these two real-case studies presented here, other physical processes also contributed to intensity forecast errors; an optimal l_h could not be determined. However the default value of l_h=333 m is still in the estimated range, and it produces reasonable maximum intensities for both hurricanes. More real cases including weaker tropical cyclones will be conducted in future to examine the effect of varying l_h.

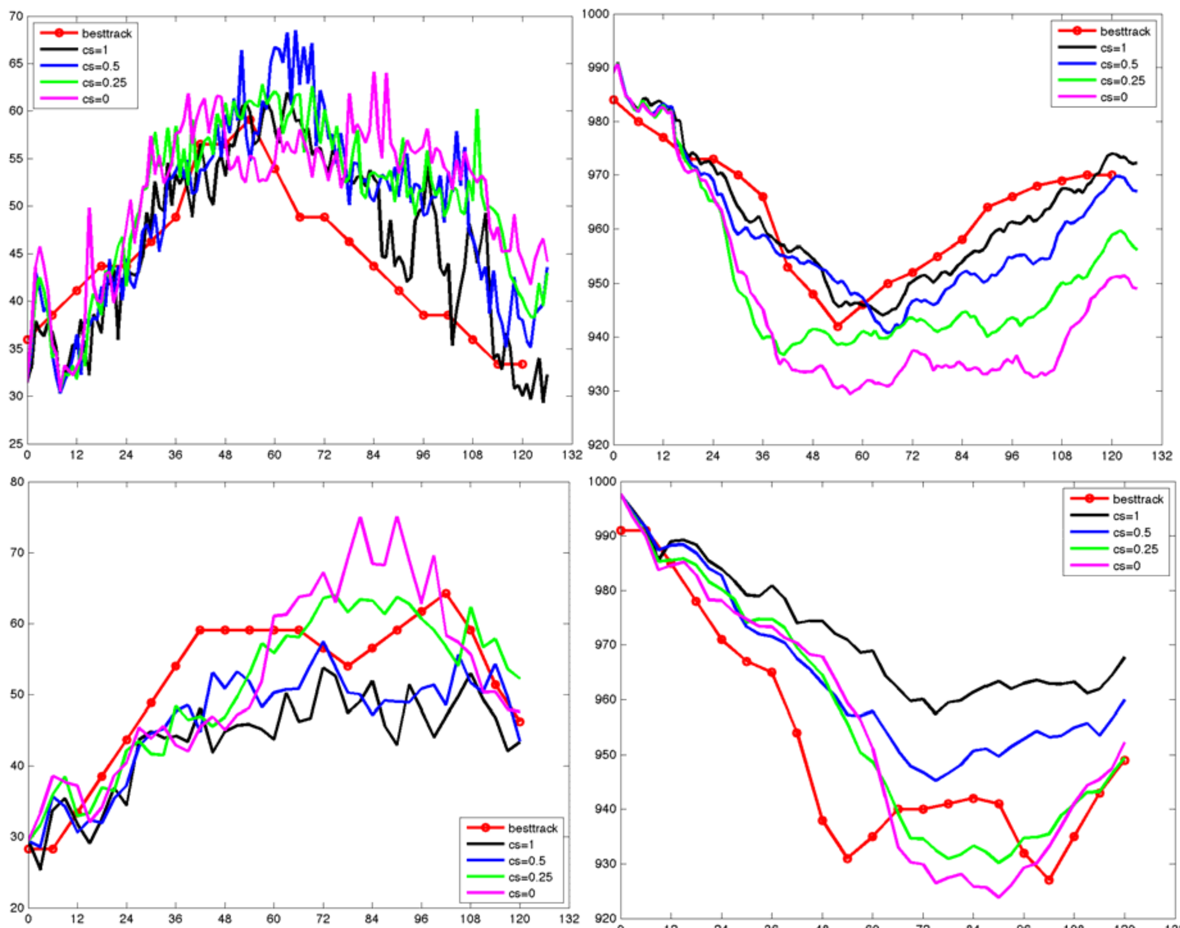

Fig. 2: *Five-day intensity forecasts for Hurricane Danielle (top panels) and Earl (bottom panels) initialized at 12Z 25 August and 00Z 29 August, 2010, respectively. The 10-m maximum winds (unit: ms^{-1}) are shown in the left panels, and the minimum sea-level pressure (unit: hPa) are in the right*

panels. The best track data is in red, the black, blue, green, and magenta curves are experiments with C_s=1, 0.5, 0.25, and 0 respectively, correspondingly l_h=1333 m, 667 m, 333 m, and 0 m (no horizontal diffusion).

IMPACT AND APPLICATIONS

Quality of Life

The ultimate goal of this study is to improve hurricane prediction. Accurate hurricane track and intensity forecasts are crucial to effective protection of people and property.

Specifically, our current results are significant because they have a direct impact on how real-time hurricane forecasting models are designed. The horizontal turbulence parameterization in real-time models is usually configured based on trial-and-error or from theoretical studies that may not apply to hurricanes (e.g., Smagorinsky 1963). Our work is leading towards a physically justifiable turbulence parameterization for real-time models, such as the WRF model that is being used by researchers and forecast centers world-wide.

TRANSITIONS (For the 4 NOPP evaluation factors below, please describe how the results (hardware, software, knowledge) are being utilized by others. Transition is taken to mean, “products which are being incorporated into more developmental (or operational) programs or have already been incorporated in other’s plans.”)

RELATED PROJECTS

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