An Eddy Injection Method for Large-Eddy Simulations of Tornado-Like Vortices

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1) Idealized Modeling of Tornadoes

- In a series of studies, we are investigating the effects of turbulence in the boundary layer of tornado-like vortices.
- Our overall approach is to specify a region of updraft forcing (gray shading below) and a constant domain-wide rotation rate Ω.

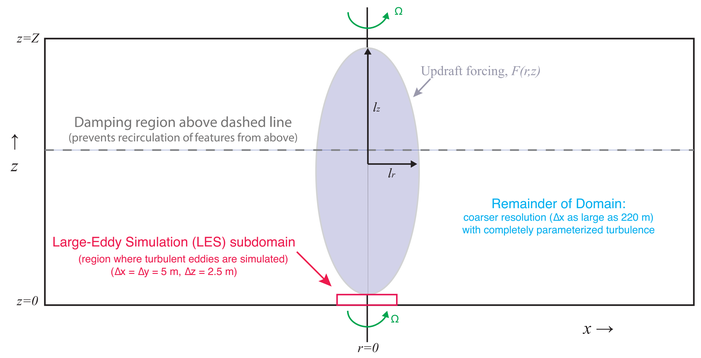

Fig 1. Conceptual schematic of the modeling framework.

- Within the red box (4 km x 4 km x 1 km), we use grid spacing small enough ($\Delta x = \Delta y = 5$ m, $\Delta z = 2.5$ m) to resolve turbulent eddies and near-surface wind gusts.
- For further details: Rotunno et al. (2016, JAS, pg 3843) and Bryan et al. (2016, submitted to MWR).
- For this presentation: $z_0 = 0.2$ m, $W = 80$ m s^{-1}, $S_r = \Omega\, l_r / W = 0.01$.

2) An Axisymmetric Simulation

• To reduce overall cost, we "spin up" a mature vortex to a quasi-steady state using an axisymmetric model.

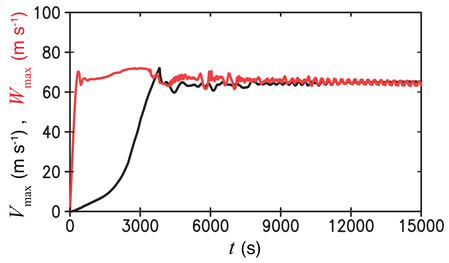

Fig. 2. Time series of maximum tangential velocity (black) and maximum vertical velocity (red) in the axisymmetric model simulation.

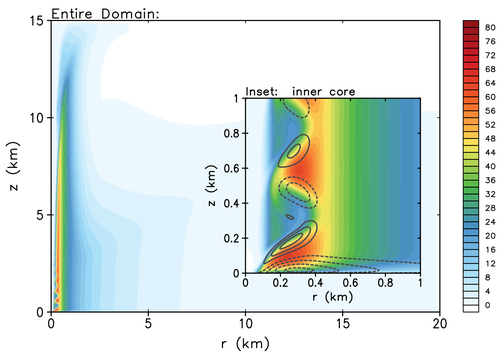

Fig. 3. Output from the axisymmetric model: shading is tangential velocity (m s^{-1}) and gray contours (in the inset) are radial velocity every 10 m s^{-1}. These are the initial conditions for subsequent 3D simulations.

3) 3D Baseline Simulation (without eddy injection)

• Axisymmetric model output (Fig 3) is interpolated onto a 3D grid. Random perturbations are added, and the simulation is integrated for 2,000 s.

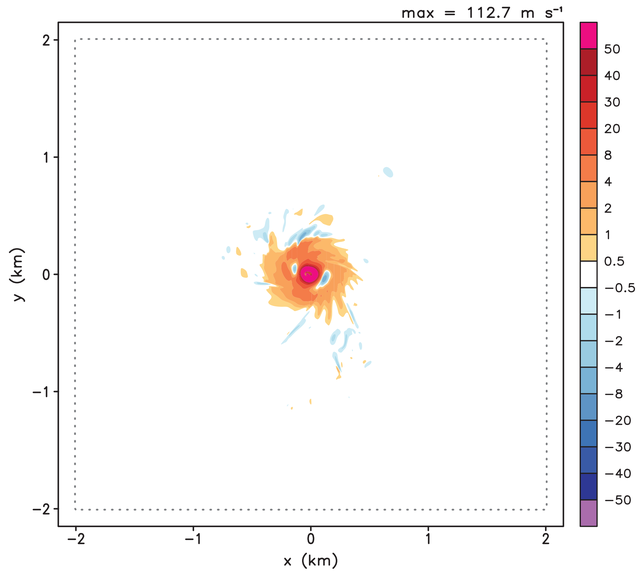

Fig. 4. Instantaneous vertical velocity (m s^{-1}) at 25 m AGL in the Baseline simulation. The dotted-gray lines denotes the boundaries of the LES subdomain ($\Delta x = \Delta y = 5$ m).

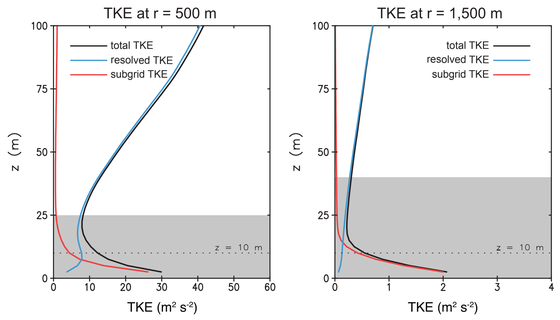

Fig. 5. Profiles of Turbulence Kinetic Energy (TKE) at (a) a ring of radius r = 500 m and (b) a ring of radius r = 1,500 m. The shaded region denotes where subgrid TKE is greater than 10% of total TKE.

4) A Simulation to Generate Eddies

• Because turbulence does not develop naturally at the inflow to the LES subdomain in the Baseline simulation (above), a method was devised to generate turbulence in a separate ("offline") simulation.

Key Features

- Smaller domain, Cartesian geometry (for simplicity).
- Periodic lateral boundary conditions (so eddies can "recycle" through domain, and thus develop to maturity).
- An crucial component: include vortex-scale tendencies (pressure gradient, centrifugal acceleration, radial advection); see Bryan et al. (2016, *Bound.-Layer Meteor.*)

In this case ,we specify:

$R = 2$ km (radius at which turbulence will be "injected" into the tornado simulation)

$V = 10$ m s^{-1} (from the axisymmetric simulation at r = 2 km)

$\partial V/\partial R = -5.6\times10^{-3}$ s^{-1} (radial gradient of V, for large-scale advection; also from the axisymmetric simulation)

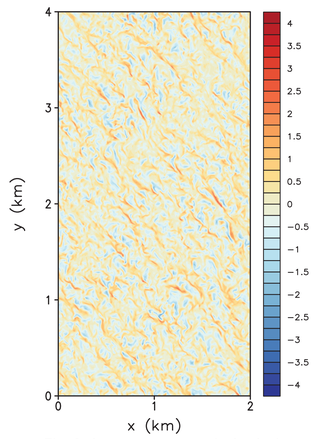

Fig. 6. Instantaneous vertical velocity (m s^{-1}) at 25 m AGL.

5) 3D Simulation with eddy injection

• For this simulation, eddies are "injected" using a nudging technique in a ring at r = 2 km.

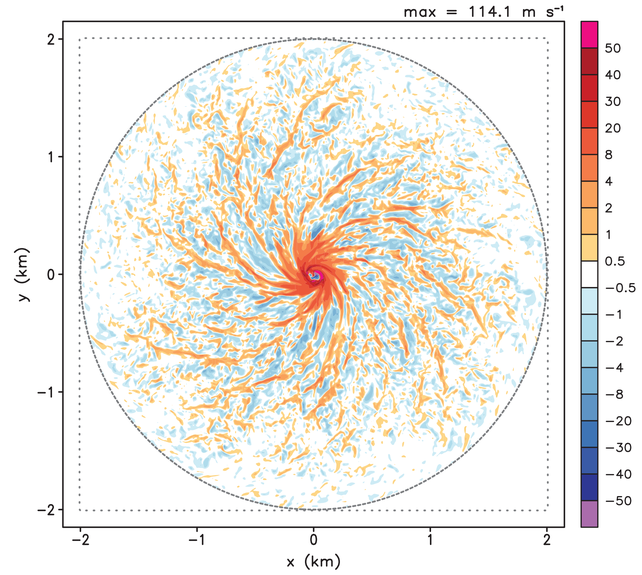

Fig. 7. As in Fig. 4 except for the simulation with eddy injection. The dashed-gray circle denotes where the eddies are injected.

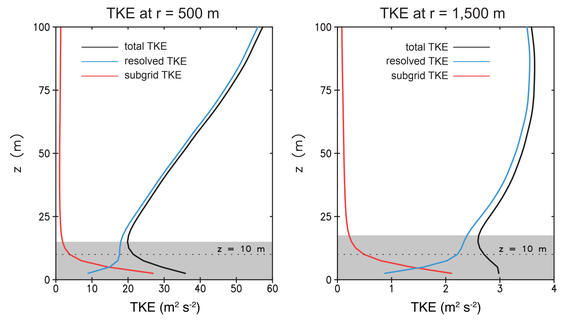

Fig. 8. As in Fig. 5 except for the simulation with eddy injection.

6) Differences

• When turbulence is injected, the inner-core vortex structure is always substantially different, the boundary-layer inflow is typically deeper, and in most cases the maximum instantaneous wind speeds are reduced.

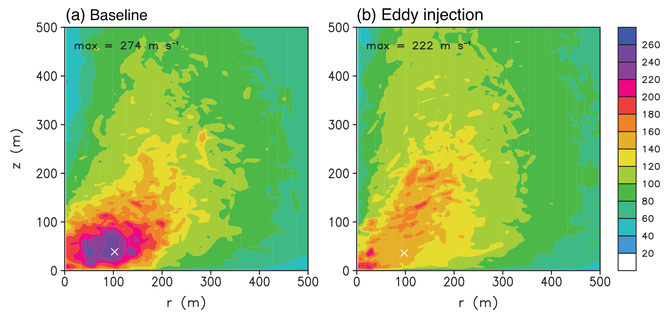

Fig. 9. Maximum values of instantaneous horizontal wind speed (m s^{-1}) in the final 1,000 s of the simulations as a function of radius and height. The white "x" symbols denote the location of maximum time-averaged wind speed.

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