The Influence of Turbulence Memory on Idealized Tornado Simulations

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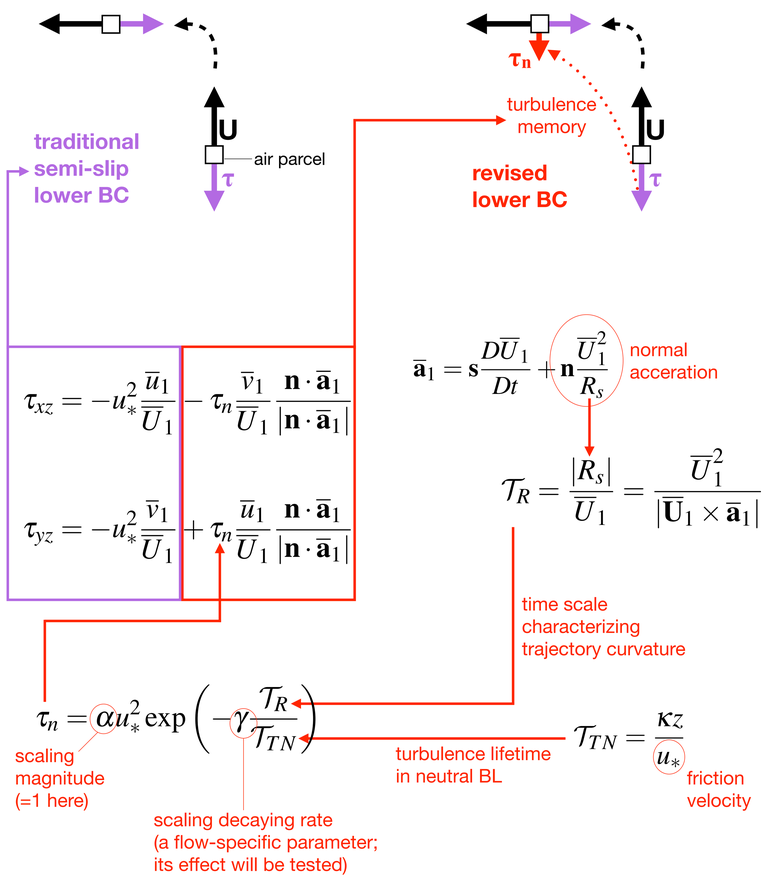
MOTIVATION

1. Turbulent motions are typically not equilibrated with resolved flow fields due to non-zero lifetime.
2. The traditional lower boundary condition (BC) of atmospheric modeling assumes instant equilibrium between surface drag (caused by turbulence) and wind, neglecting turbulence lifetime (i.e., "turbulence memory").
3. Accounting for the effect of turbulence memory on the lower BC leads to surface drag magnitude and direction different from equilibrium-state values.
4. Modifying the surface drag, an important mechanism enhancing the convergence of angular momentum, may influence tornado intensities.

A REVISED LOWER BOUNDARY CONDITION ACCOUNTING FOR TURBULENCE MEMORY ASSOCIATED WITH CURVED TRAJECTORIES



LARGE-EDDY SIMULATION OF TORNADOES USING CLOUD MODEL 1 (CM1)

Study	Current Study	Bryan et al. (2017)	Nolan et al. (2017)
Amplitude of Updraft Forcing (Fiedler chamber)	**0.359 m s^{-2}**	0.359 m s^{-2}	0.359 m s^{-2}
Coriolis Parameter	**5.334 x 10^{-4} s^{-1}**	5.334 x 10^{-4} s^{-1}	5.334 x 10^{-4} s^{-1}
Domain	**24 km x 24 km x 15 km**	40 km x 40 km x 15 km	40 km x 40 km x 15 km
Inner Domain	**4 km x 4 km x 1 km**	4 km x 4 km x 1 km	4 km x 4 km x 1 km
Inner Domain Grid Spacing ($\Delta x \times \Delta y \times \Delta z$)	**10 m x 10 m x 10 m** **25 m x 25 m x 25 m**	5 m x 5 m x 2.5 m	2.5 m x 2.5 m x 1.25 m 5 m x 5 m x 2.5 m 10 m x 10 m x 5 m 20 m x 20 m x 10 m
Lower BC	**semi-slip (OLD-)** **revised one (NEW-)**	semi-slip	no-slip
Roughness Length (z0)	**0.2 m**	0.2 m	0.2 m
Lateral BC	**open (with perturbation except for NOPERT)**	closed, free-slip	closed, free-slip
Upper BC	**closed, free-slip**	closed, no-slip	closed, no-slip

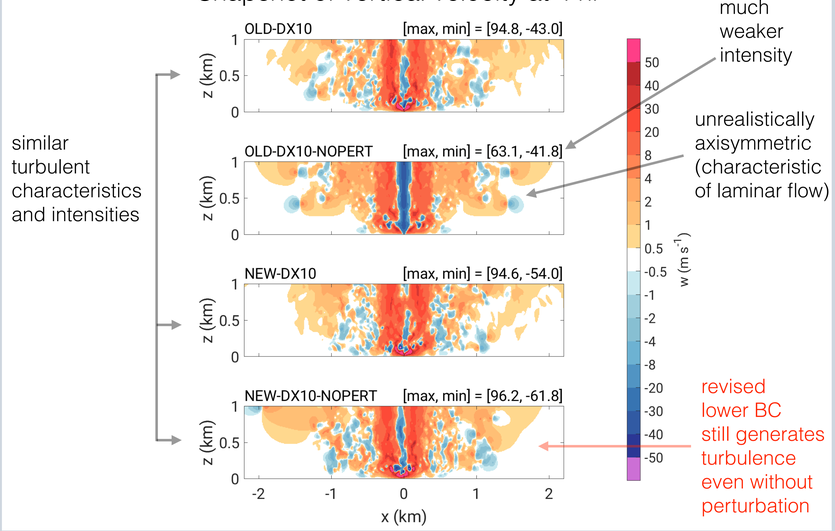
The simulation time of the current study is 6 hr, and after 4 hr is considered as quasi-steady state.

CASE DESCRIPTION AND QUASI-STEADY STATE RESULTS

- **OLD/NEW**: traditional or revised lower boundary condition.
- **DX10/DX25**: inner-domain grid spacing = (10 m)^3 or (25 m)^3.
- **NOPERT**: no initial and lateral boundary random perturbation (otherwise the simulations always start with initial random perturbation and runs with lateral boundary random perturbation of θ with magnitude of 0.25 K).
- **γ0.1/γ0.05**: γ = 0.1 or 0.05 (otherwise the revised lower boundary condition's γ is 1).

Case	Lower BC	Random Perturbation	Inner-domain Grid Spacing	γ	max(u_θ) (m s^{-1})	max($-u_r$) (m s^{-1})	max(w) (m s^{-1})
OLD-DX10	traditional	yes	(10 m)^3	—	**117.0**	**83.3**	**107.8**
OLD-DX10-NOPERT	traditional	no	(10 m)^3	—	**91.9**	**65.8**	**64.3**
NEW-DX10	revised	yes	(10 m)^3	1	**117.4**	**83.2**	**110.8**
NEW-DX10-NOPERT	revised	no	(10 m)^3	1	**120.2**	**85.1**	**107.9**
NEW-DX10-γ0.1	revised	yes	(10 m)^3	0.1	**118.4**	**84.1**	**107.8**
NEW-DX10-γ0.05	revised	yes	(10 m)^3	0.05	**119.0**	**85.7**	**106.5**
OLD-DX25	traditional	yes	(25 m)^3	—	**94.1**	**72.2**	**75.8**
OLD-DX25-NOPERT	traditional	no	(25 m)^3	—	**72.0**	**54.9**	**42.2**
NEW-DX25	revised	yes	(25 m)^3	1	**95.7**	**73.2**	**73.9**
NEW-DX25-NOPERT	revised	no	(25 m)^3	1	**93.0**	**71.6**	**71.7**
NEW-DX25-γ0.1	revised	yes	(25 m)^3	0.1	**95.2**	**73.8**	**76.1**
NEW-DX25-γ 0.05	revised	yes	(25 m)^3	0.05	**106.6**	**77.5**	**99.6**

Snapshot of vertical velocity at 4 hr



EFFECTS OF TURBULENCE MEMORY

Inner-domain Δx = 10 m

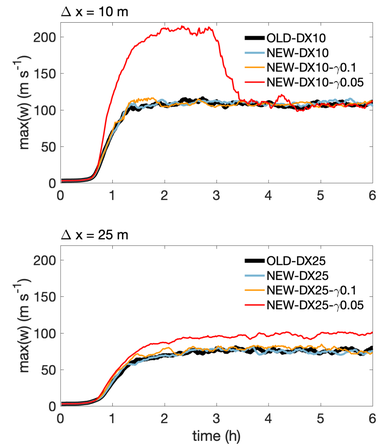
- For γ = 0.05, the strong intensification is by ~100% for 2 hours in the transient state.
- The effect of turbulence memory decreases once the tornadoes reach a quasi-steady state.

Inner-domain Δx = 25 m

- Coarser grid spacing gives weaker tornadoes.
- For γ = 0.05, the intensification is by ~35% in the quasi-steady state.

Discussion

- Higher first grid level gives longer turbulence lifetime.
- Finer grid spacing simulates more turbulence directly, while coarser grid spacing models more effect of turbulence.



Maximum vertical velocity in transient state

Factors influencing γ

- In neutral static stability, γ = 1.
- Atmospheric stability and canopy can lead to the γ parameter space ranging from 0.1 to 10.
- Other environmental conditions (e.g., surface heterogeneity, baroclinicity, and nonstationarity) can further expand γ parameter beyond [0.1, 10].

CONCLUDING REMARKS

- A revised lower boundary condition is proposed to account for the effect of turbulence memory associated with curved trajectories.
- The influence of turbulence memory on idealized tornado simulations:
  1. The dynamical instability makes the simulations less sensitive to small temperature perturbations in the initial and lateral boundary conditions.
  2. If the decaying rate is slow enough (e.g. γ = 0.05), tornadoes will be intensified.
  3. The effect is dependent on the height of the first grid level.

REFERENCES

1. Bryan, G. H., N. A. Dahl, D. S. Nolan, and R. Rotunno, 2017: An eddy injection method for large-eddy simulations of tornado-like vortices. *Mon. Wea. Rev.*, **145**, 1937–1961.
2. Nolan, D. S., N. A. Dahl, G. H. Bryan, and R. Rotunno, 2017: Tornado vortex structure, intensity, and surface wind gusts in large-eddy simulations with fully developed turbulence. *J. Atmos. Sci.*, **74**, 1573–1597.
3. Wang, A., Y. Pan, and P. Markowski: The influence of turbulence memory on idealized tornado simulations (to be submitted to *Mon. Wea. Rev.*)