Investigation of the Impact of Terrain and Buildings on Tornado Dynamics Using High-Resolution Simulations

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Background

Tornado dynamics are sensitive to changes in near-surface flow characteristics, and thus it is likely that terrain or buildings can substantially alter the three-dimensional winds in tornadoes. Some evidence exists from damage surveys that terrain may impact tornado dynamics. Lewellen (2012) found that tornado winds speeds were sometimes maximized in a valley, similar to past damage surveys. Karstens et al. (2013) noted areas of enhanced tree damage where valleys accelerated the flow. In addition to terrain impacts, the presence of manmade structures may also change the tornado's near-surface wind distribution and affect the corner flow region. The purpose of this study is to examine terrain and building impacts on tornado wind speeds. Understanding how terrain and manmade structures modify tornado risk is critical, particularly in tornado-prone regions with complex terrain such as the Southeast United States.

LES Model and Immersed Boundary Method

Model Grid Points	175, 175, 99
Horizontal Grid Spacing	2.5 m
Vertical Grid Spacing	2.5 m
Virtual Boundary Points	2000 by 2000
Control Simulation Type	Medium-swirl
Building Types	Large Commercial Building: (100 m by 100 m by 15 m) Tall Tower: (35 m by 35 m by 100 m) Residential Buildings: (15 m by 15 m by 7 m)
Terrain	Sinusoidal variations: amplitudes from 10 to 150 m and horizontal wavelength of 1 km, ascending/descending slopes

- Immersed boundary methods are often used to represent terrain in fluid dynamic models (Goldstein et al. 1993; Lewellen 2012)
- The Immersed Boundary Method (IBM) described in Saiki et al. (1996) has been implemented into the LES model (Maruyama 2011; Bodine et al. 2016)
  - Virtual boundary points are used to represent the horizontal distribution of terrain or building heights at a finer resolution than the LES model grid
  - External forces are imposed on the Navier-Stokes equation so the surface's velocity is constant (e.g., 0 m/s for a stationary domain)
  - External force is greater if the model wind speed differs from the boundary speed

External Force Equation

$$\mathbf{F}(\mathbf{x}_s, t) = \alpha \int_0^t (\mathbf{U}(\mathbf{x}_s, t) - \mathbf{v}(\mathbf{x}_s, t))\, dt + \beta(\mathbf{U}(\mathbf{x}_s, t) - \mathbf{v}(\mathbf{x}_s, t)).$$

External Force at Model Grid Point

$$\mathbf{F}_{i,j} = \frac{1}{N_b} \sum_{n=1}^{N_b} D_{i,j}(\mathbf{x}_s)\mathbf{F}_n(\mathbf{x}_s),$$

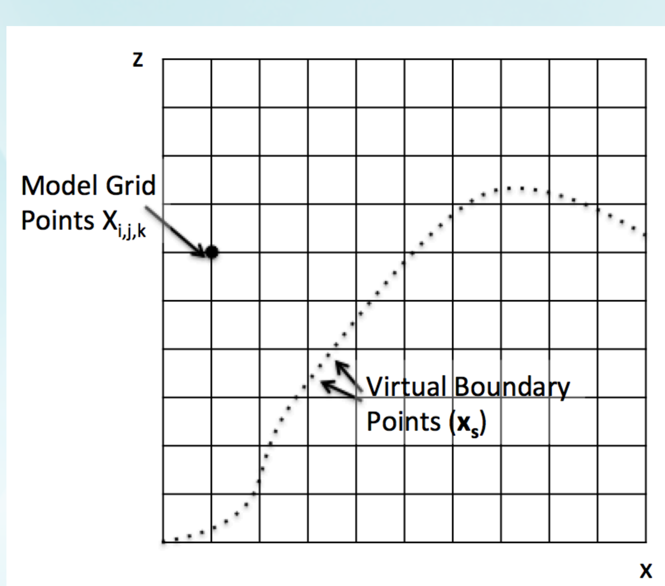

Fig. 1: Model grid (solid lines) with virtual boundary points (x_s).

Impact of Buildings on Near-Surface Winds

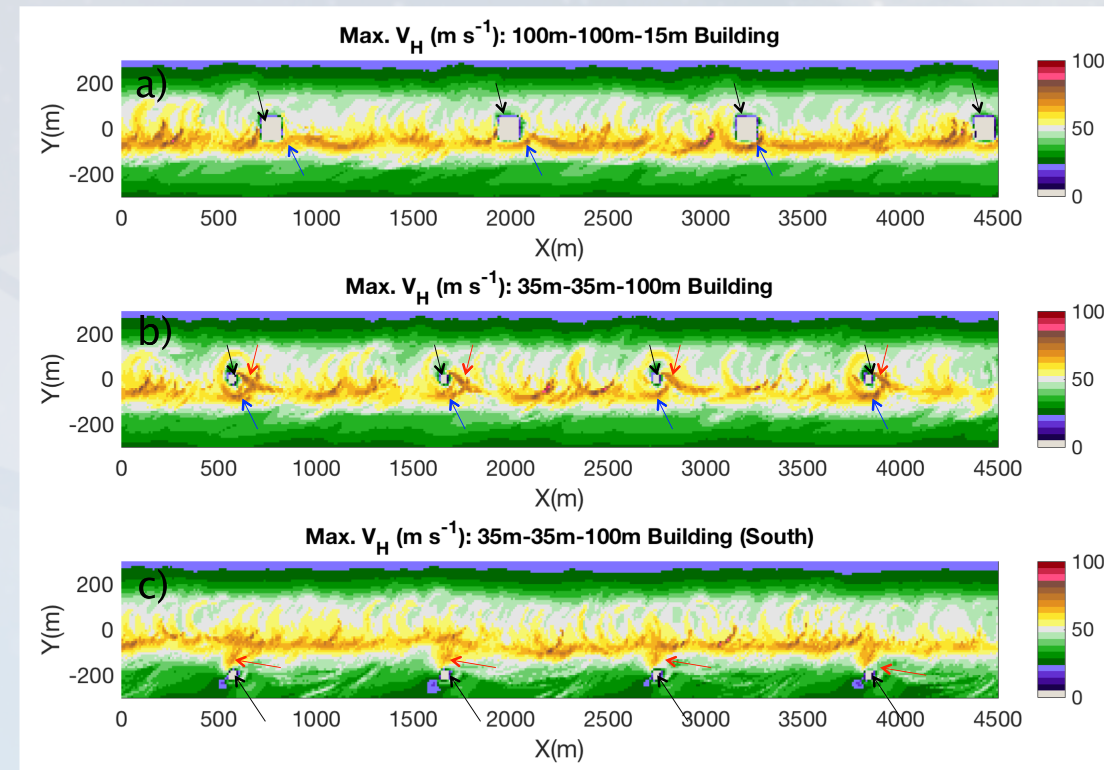

Fig. 2: Maximum along-track 10-m AGL horizontal wind speed for a) large commercial buildings, b) tall towers, and c) tall towers located 200 m south of the tornado's track. The black arrows denote building locations, red arrows show intense inflow bands downstream from the buildings, and the blue arrows show locations of suction vortices on the building edges.

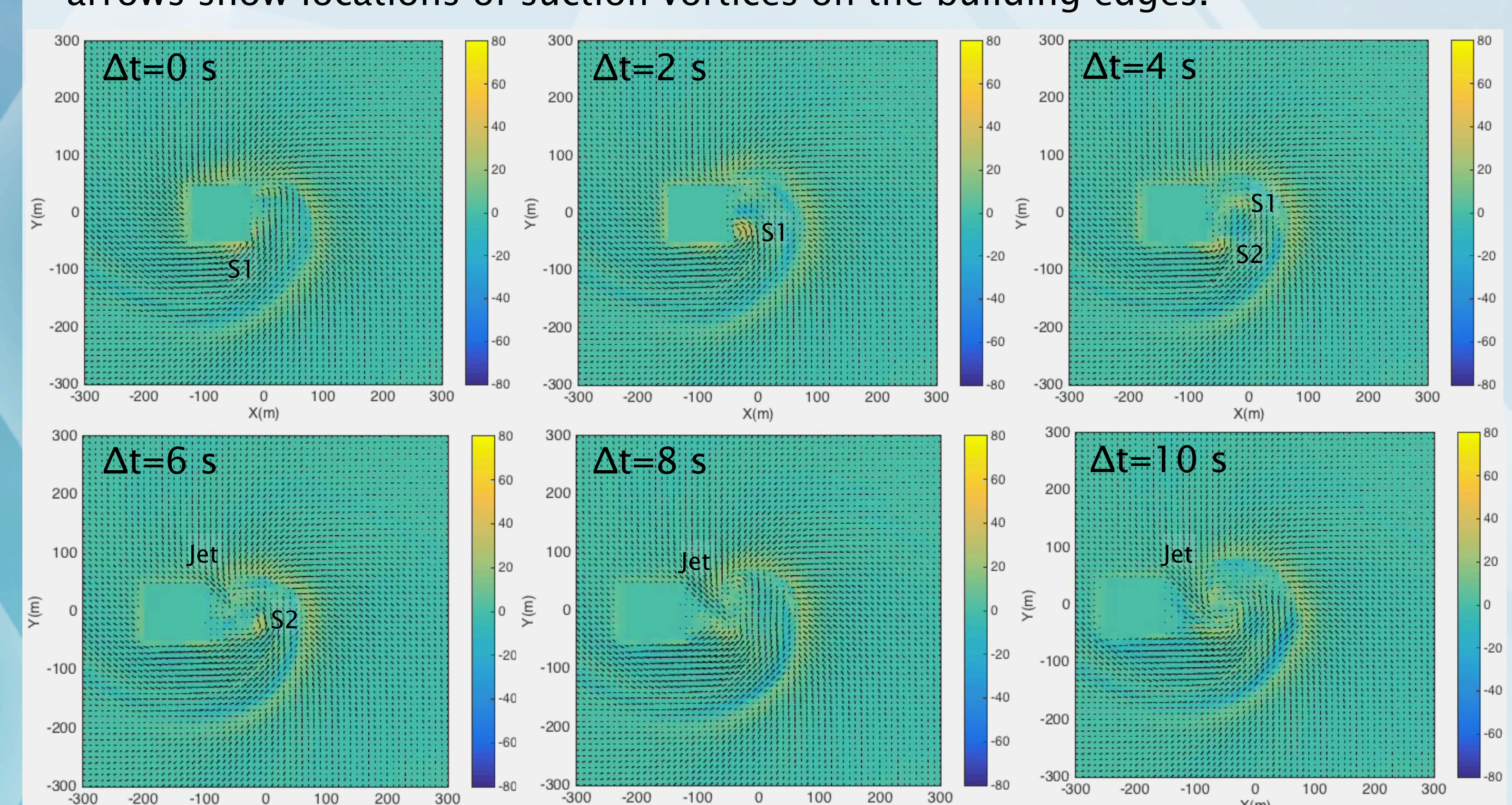

Fig. 3: 10-m horizontal wind vectors and vertical velocities (shaded) showing a time sequence of subvortices (S1, S2) developing and rotating off the southeast corner (Δt=0–6 s) and the development of a jet off the northeast corner of the 100-m by 100-m by 15-m building (Δt=6–10 s).

- Some subvortices collide with the buildings while others rotate around the edge (Fig. 2a)
- An intense, southeasterly inflow jet develops downstream of the tower off the northeast corner of the building (Fig. 2b)
- An enhanced inflow band is produced when the tower is located south of the tornado (Fig. 2c)
- A sequence of subvortices emanates off the southeast corner (Fig. 3)
- The southeasterly jet develops as the tornado moves east of the building and the wake region collapses (Fig. 3)
- Strong convergence impinges upon the building, producing large vertical velocities along the building's side walls (Fig. 3)

Influence of Terrain on Near-Surface Winds

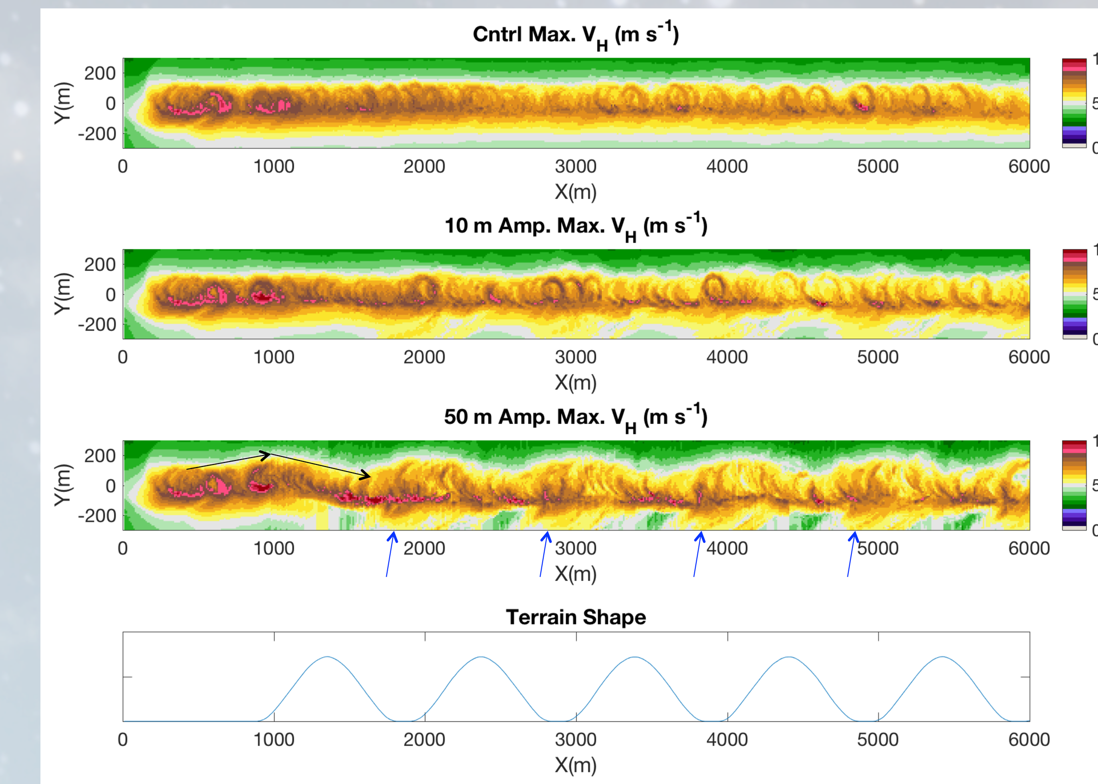

Fig. 4: Along-track 10-m AGL horizontal wind speeds for the control and 10- and 50-m amplitude sinusoidal terrain simulations. Larger path deviations are observed as amplitude increases. Higher variability of horizontal winds are observed in the 50-m simulation, including stronger winds on downhill slopes.

- Suction vortices have shorter lifetimes for higher amplitude terrain, but are often more intense especially on downhill slopes (Fig. 4)
- Larger path deviations are observed as terrain amplitude increases (Fig. 4; black arrows)
- Channeled inflow is often evident in valleys (Fig. 4; blue arrows) and larger-scale updrafts are increased near the hill top (not shown)
- Slight shift toward a higher frequency of EF3–EF5 damage for 50-m simulation, but reduced high-end damage potential for 150-m simulation (Fig. 5)

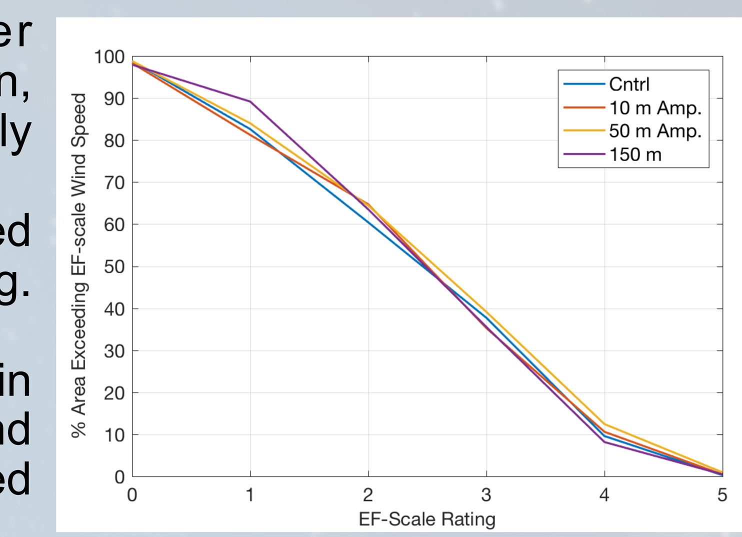

Fig. 5: Percentage of path area exceeding EF-scale wind speeds for different sinusoidal terrain simulations.

Conclusions and Future Work

- The impact of buildings and terrain is simulated using an LES model with an Immersed Boundary Method
- Large buildings influence subvortices and create locally enhanced flow, leading to more complex horizontal wind structure
- Increasing amplitude terrain results in greater spatial variability in tornado path and horizontal wind speeds
- Tornado damage potential may increase depending on terrain geometry
- Currently investigating simulations with different building layouts (e.g., residential areas, downtowns)
- Perform statistical significance testing of wind speed differences for different regions along the track (slopes, heights, building proximity)
- Future work includes implementation of a curvilinear coordinate system version of the LES code and canopy model (Uchida and Ohya, 1999)
- Collaboration with the NWS Morristown is ongoing to investigate damage surveys over complex terrain for comparisons to the LES model

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