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Investigating how terrain modifies wind speeds and central pressure deficit in tornadic wind field

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SUMMARY

To facilitate a proper tornado-resistant design, it is important to understand how the presence of various types of terrain affects wind speeds and central pressure deficit in tornadic wind fields. To study this, a coupled simulation approach that nests a high-fidelity, ultra-fine-resolution engineering Large Eddy Simulation (LES) within a Cloud Model 1 (CM1) simulation of a tornadic supercell is applied. The following five idealized terrain configurations are considered: 1) a control run with flat ground, 2 & 3) an idealized hill with steep and gradual slopes having the height of 25.4 m; and 4 & 5) an idealized escarpment with steep and gradual slopes having the height of 25.4 m. Results suggest that terrain increases the central pressure deficit, the peak wind speed and the width of the high wind speed region in the tornado swath, enhancing tornado intensity.

Keywords: *Terrain, Tornado, Wind speed, Pressure deficit*

1. INSTRUCTION

Increasing property loss induced by recent tornadoes has justified the implementation of the tornado-resistant design. Although the pressure calculation equation has been provided in Chapter 32 of ASCE7-22, some coefficients in the equation are still based on simplifications and assumptions due to the lack of research and field measurement. When determining wind loading under synoptic winds using the wind pressure equation, the modification of terrain on wind speeds has been reflected on Kzt. For the tornado-resistant design, a similar coefficient is needed to modify the wind speeds in tornadic wind field due to the presence of terrain. Despite previous studies on the influence of terrain on tornado characteristics (e.g., Golden, 1968; Hardy, 1971; Evans and Johns, 1996; LaPenta et al., 2005; Lewellen, 2012; Coleman, 2010; Karstens et al., 2013; Nasir and Bitsuamlak, 2016; Lyza and Knupp, 2018; Houser et al., 2020; Wagner et al., 2021; Satrio et al., 2021), many of these studies were completed for a single case, and often, the results of one study conflicted with the results of another, (e.g., the tornado intensified going uphill in one study while it weakened going uphill in another). To bridge this research gap and facilitate a proper tornado-resistant design, the objective of this study is to understand how the presence of various types of terrain affects wind speeds and central pressure deficit in tornadic wind fields.

2. NUMERICAL SIMULATION METHODOLOGY

To investigate the effects of terrain on tornadoes, this study utilizes a tornado-scale, fine-resolution engineering LES model driven by output of the storm-scale Cloud Model 1 (CM1). Velocity and pressure data output from CM1 provide the input to the LES model. In this study, five terrain configurations are considered: 1) flat ground (no terrain) in the control run; 2) an idealized “steep” hill with a height of 25. 4 m in the case of 0.50_hill, 3) an idealized “gradual” hill with a height of 25. 4 m in the case of 0.25_hill, 4) an idealized “steep” escarpment with a height of 25. 4 m in the case of 0.50_escarpment, and 5) an idealized “gradual” escarpment with a height of 25. 4 m in the case of 0.25_escarpment.

3. RESULTS AND DISCUSSION

The along-track maximum values and the time history of pressure deficient are extracted. All terrain cases achieved higher pressure deficits (lower central pressure) than the control run, and those increased pressure deficits manifest even before the tornado’s central axis encounters the terrain. However, the effect of terrain on pressure deficit is complex, with periods of increases and decreases as the vortex translates. If the terrain slope is weak, the deficit decreases when the vortex ascends the escarpment, and then becomes stable as it moves on the elevated platform, although there is some variability. In the hill cases, the deficit reduction starts when the vortex reaches the crest in the 0.5_hill scenario, while the deficit reduction starts halfway up the uphill segment in the 0.25_hill case.

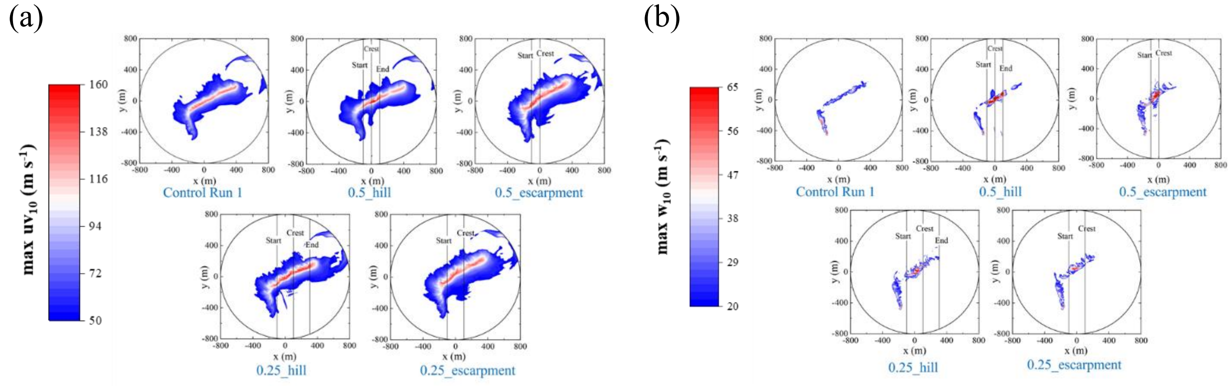

Figure 1: a) Along track maximum horizontal velocity and b) maximum vertical velocity at 10 m AGL. The vertical black lines indicate where uphill segments begin (marked with ‘Start’); where the uphill stops (marked with ‘Crest’) and where the downhill ends (End).

The along-track horizontal wind velocity and vertical velocity at 10 m AGL (uv10 and w10) both become greater in all the idealized terrain cases, as shown in Fig. 1. The highest peak uv10 is found in the hill cases, specifically on the uphill segment in the 0.25_hill case, and on the downhill segment in the 0.5_hill case. The different terrain-relative locations of the max uv10 indicate the slope of the terrain is important, even with the same terrain shape. The increase in horizontal winds due to the presence of terrain also widens the footprint of the region experiencing high wind speeds. Compared to a hill, the escarpment terrain presents a more pronounced increase in the area with velocities greater than 50 m s-1. In contrast, the hill does not noticeably expand the footprint for the area with velocities greater than 75 m s-1 for the 0.5_hill case and even reduces the affected region in the 0.25_hill case, whereas the escarpment terrain still leads to an increased footprint at this higher velocity level.

The vertical profiles of core radius, maximum horizontal velocity and angular momentum at three representative time instants (i.e. different terrain-relative positions) are shown in Fig. 2. The results show that terrain clearly alters the maximum horizontal winds in tornadic wind fields by increasing speeds at lower vortex heights and decreasing velocity at higher elevations. The gradual slope cases have even greater wind speeds than the steeper slope simulations, especially as the tornado moves to the terrain-relative locations at T2 and T3. Moreover, the slope effect is more pronounced for the horizontal velocity in the hill terrain than in the escarpment. Extending this logic to damage potential, the damage extent from high wind speeds is higher for buildings located on crest of terrain (T2) as well as on the downhill segment or the top of escarpment (T3).

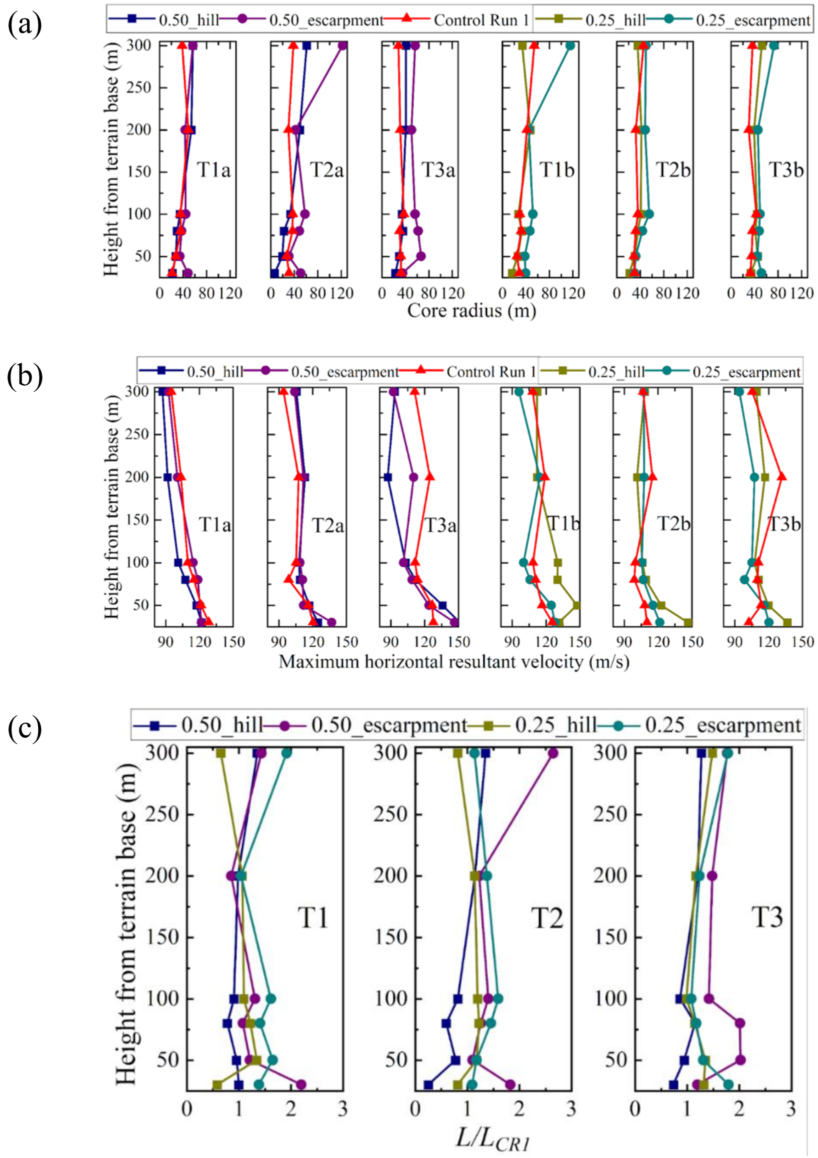

Figure 2: Vertical profiles (30m to 300m) of a) core radius (m), b) maximum horizontal resultant velocity (m s-1). The left three figures are for hill and escarpment cases with a slope ratio of 0.5, with T1a, T2a and T3a representing when the tornado vortex reaches the uphill segment, crest, and downhill segment (in the hill simulations) or elevated platform (in the escarpment simulations); and the right three figures are for hill and escarpment with a slope ratio of 0.25, with T1b, T2b and T3b defined the same as T1a, T2a and T3a, respectively.

4. CONCLUSIONS

This study applies an ultra-fine-resolution LES driven by CM1 output to investigate how terrain affects wind speeds and central pressure deficit in tornadic wind fields. A flat control run (no terrain), and idealized hills and escarpments with two slope ratios are implemented in the LES domain. The following conclusions are drawn: 1) All terrain cases achieved higher pressure deficits (lower central pressure) than the control run. 2) The along-track horizontal wind velocity and vertical velocity at 10 m AGL (uv10 and w10) both become greater in all the idealized terrain cases. Specifically, the horizontal and vertical velocities at 10-m AGL (above ground level) are stronger with terrain and the location of the maximum pressure deficit occurs along the uphill segment for all idealized cases except the steep hill. The precise location of the maximum wind velocities and pressure deficits varies with the terrain shape and slope. And 3) Terrain increases the maximum horizontal winds at lower vortex heights, but decreases velocity at higher elevations. The gradual slope cases experience greater wind speeds than the steeper slope simulations. The obtained results can be used to develop the Kzt coefficient in the tornadic wind pressure calculation equation in Chapter 32 in ASCE 7.

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