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Effects of complex terrain on the near-surface wind field of 10 December 2021 Kentucky tornado

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SUMMARY:
Tornadoes cause significant damage and fatalities in many parts of the world which has led great interest in the tornado-based design of the structures. Recently, the American Society of Civil Engineers (ASCE) added tornado design into a structural design standard. However, unlike 'standard' wind load design, terrain effects on near-surface wind fields are currently not accounted for in tornado design which could have critical impacts on a structure. Due to lack of direct measurement, researchers developed other methods to model near-surface wind field of tornadoes. One method is the tree-fall model which utilizes the tree-fall pattern to estimate parameters of different vortex models and compares the obtained maximum wind speed with structural damage. Tree-fall models can improve our understanding of the near-surface wind field of tornadoes and its impact on tornado designs of structures. In this paper, an observational analysis of tree-fall patterns from 2021 Kentucky tornado which was filtered using a "grid" averaging method to model the near-surface wind field and to investigate the effects of terrain. Finally, insight of an improvement to the current near-surface wind speed model by adding terrain effect is proposed.

Keywords: terrain effects, tree-fall pattern, near-surface wind field

1. Introduction

Tornadoes have caused the most catastrophic wind related damage in the US (NOAA, 2021). Due to its catastrophic and transient nature, engineers and scientists have developed a high interest in tornado-based design. However, lack of direct tornado observations has slowed down our understanding of the physics of tornadoes. Furthermore, complex terrain effects can drastically affect the near-surface wind field of tornadoes further complicating the problem. Due to lack of real observations, scientists and engineers shifted to alternative methods. One of the previous works include an analytical simulation of near-surface wind model utilizing tree-fall patterns in forested areas (Rhee and Lombardo 2018) to match the observations which is further described in the following section. Also, recent rapid advancement in computing power has enabled more robust and efficient numerical simulation of tornadoes including the investigation of its effects due to complex terrain (Lewellen, 2012; Satrio et al. 2020). Although our understanding of tornadoes improved, the effects due to complex terrain are significantly understudied and not accounted for in current structural designs.

2. Near-surface wind field estimation

One of the several methods of modeling a tornadic near-surface wind field is the tree-fall pattern method based on a simplified Rankine vortex model (Rhee and Lombardo 2018). The tree-fall model assumes a steady state vortex and the mathematically expressed as the following:

$$V_{rot}(r) = \begin{cases} V_{max}\left(\frac{r}{RMW}\right)^{\varphi}, \; for\ r \leq RMW \\ V_{max}\left(\frac{RMW}{r}\right)^{\varphi}, \; for\ r > RMW \end{cases} \tag{1}$$

where V_{rot} is the rotational speed at different radius, V_{max} is the maximum speed at RMW, RMW is the radius where maximum wind speed occurs, φ the decay exponent. The model is a simple but powerful tool for estimating near-surface wind fields with robust results. Please refer to Rhee and Lombardo (2018) for further details.

3. LAND BETWEEN THE LAKES, KENTUCKY TORNADO

In December 2021, two tornadoes with intensities of EF-3 and 4 passed through the south and north region respectively of the Land Between the Lakes National Recreation Area (LBL) as shown in Fig. 1 (left). Both tracks stretched from start to end for about 20 km (through LBL) over a relatively complex terrain. Accordingly, the fallen trees showed several different patterns which suggests that terrain at LBL is ideal for examining the effects of complex terrain on tornadoes. Also, an example of a region near the middle of the north track where both complex terrain and its effects on tree-fall pattern is observable is shown in Fig.1 (right). The fallen trees were obtained by manually tagging them on top of aerial drone images using ArcGIS.

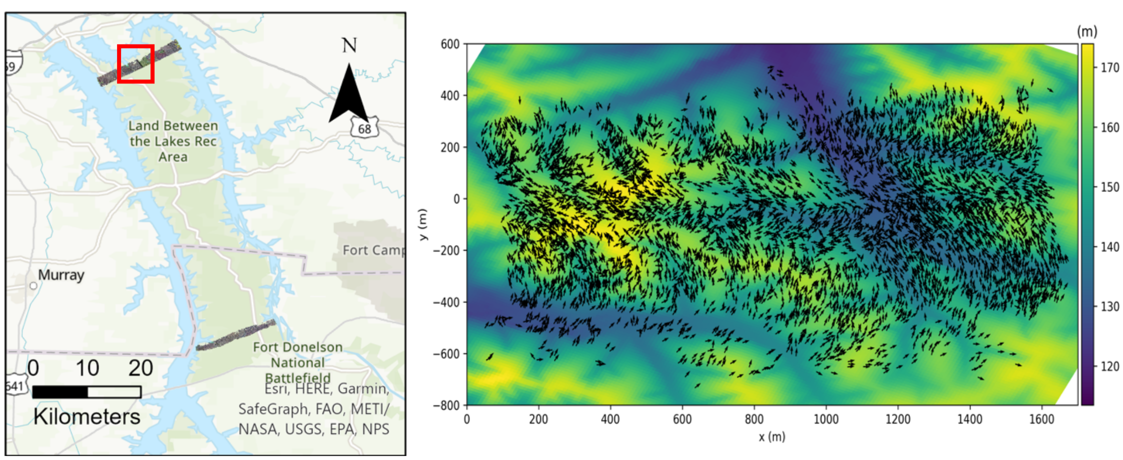

Figure 1. North and south tornado track of LBL area plotted on top of topographic map (left) with zoomed tree-fall pattern of red-boxed region (right)

Obtained trees were filtered with a "grid" averaging method for visualization purposes and to reduce the complexity within the pattern as shown in Fig. 2. The averaged tree-fall pattern along the transect clearly displayed a transition in the patterns where a rapid change in terrain was observed and further analysis was conducted. Areas in the two red boxes and the orange exhibit fallen trees under terrain influenced wind field. Trees in the red boxes fell in directions parallel to the crest commonly observed in complex terrain regions (Bosart, 2006; Tang, 2016). On the other hand, trees in the orange box fell perpendicular to the crest. Tree-fall pattern shown in the purple box is similar to the ideal pattern described in Rhee and Lombardo, 2018 which indicates that trees fell mostly due to tornadic wind field under little or no terrain influence. Finally, shown in the white box is a horizontal strip where the core vortex of the tornado passes. In this region, the tree-fall pattern is heavily influenced by the vortex itself. In the previously mentioned LES studies, as the tornado approaches the crest of a hill, it generates a low swirl field on the leeward side of the hill which is replaced by a high swirl field as it passes over the crest which can cause a chaotic tree-fall pattern and the "circulating" pattern near the end of the crest in the white box (Satrio, 2020) which might have caused the pattern. Further investigation is required to clearly identify the cause of the changed patterns.

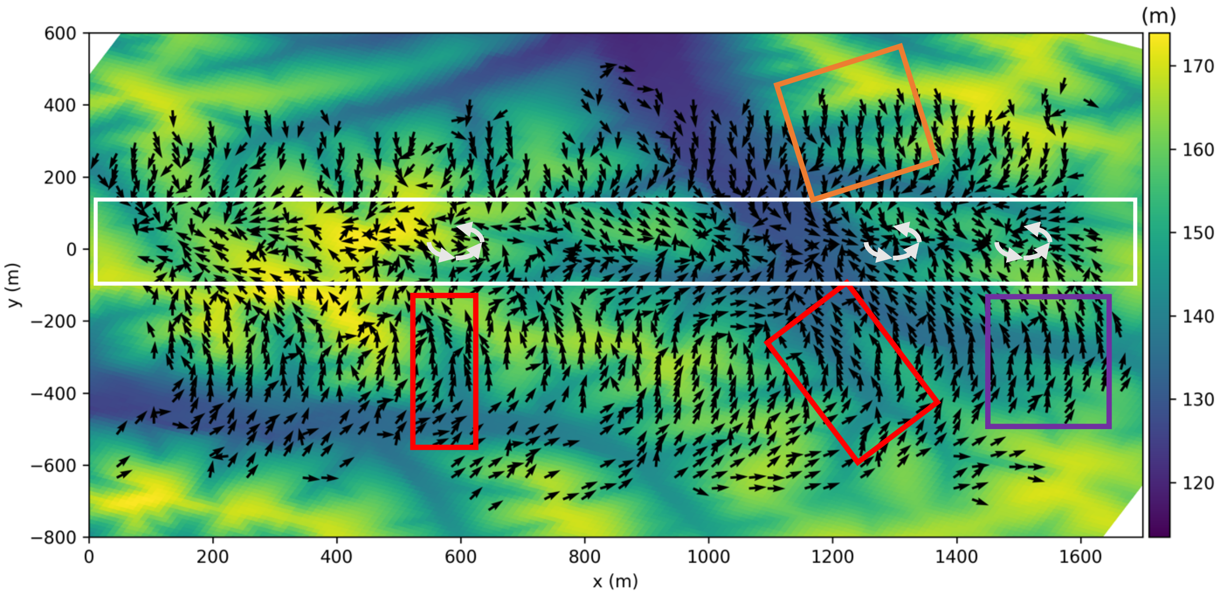

Figure 2. Grid averaged tree-fall pattern plotted over the color plot of terrain height; note that the tornado is translating from the west to east with its path along a horizontal line on y = 0 m

Another effect of the terrain observed in this region is the possible strengthening/weakening of the tornado intensity. As shown in Fig 3, terrain height and the damage width shows a relatively strong negative correlation which indicates that as the elevation decreases (e.g., valley) the damage width increases. This pattern is also observed in both of the LES studies referenced in this paper.

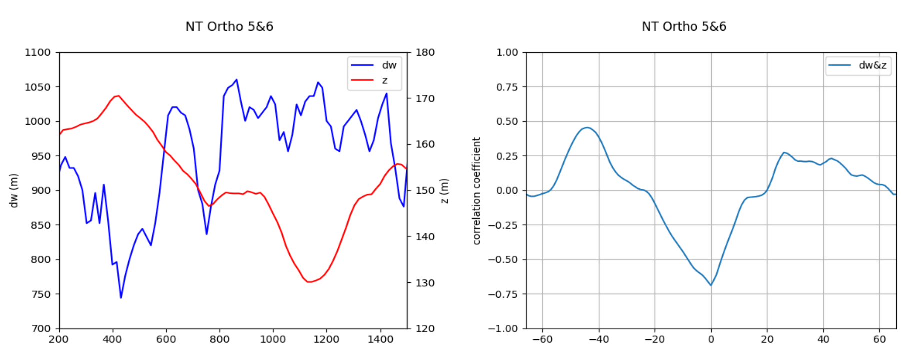

Figure 3. (a) Damage width plotted in blue and terrain height plotted in red along the transect, (b) cross-correlation between damage width and terrain height

4. CONCLUSION AND FUTURE WORK

Existing tree-fall models could be improved by adding the terrain effect element which can greatly help us to improve the accuracy of the model. Furthermore, by doing so, it is possible to finally include the terrain effects of tornadoes in tornado-based designs for more accurate wind loading. The investigation of tree-fall patterns in the LBL area led to observation of several possible terrain effects including trees falling towards the parallel/perpendicular direction to the valley, strengthening/weakening of the tornado intensity. Finally, a swirl mark along the tornado path was also observed which was potentially caused by the terrain effect on the vortex itself. Further and more rigorous analysis of the tree-fall patterns on both tracks is required along with a good establishment of the relationship between terrain and the tornado vortex. The long-term goal of the authors is to successfully develop a tree-fall model with terrain elements included and an empirical equation of the terrain effect on maximum wind speed.

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