A Simple Boundary Layer Parameterization of Heterogeneous Land Surfaces Applied to Convective Updraft Prediction

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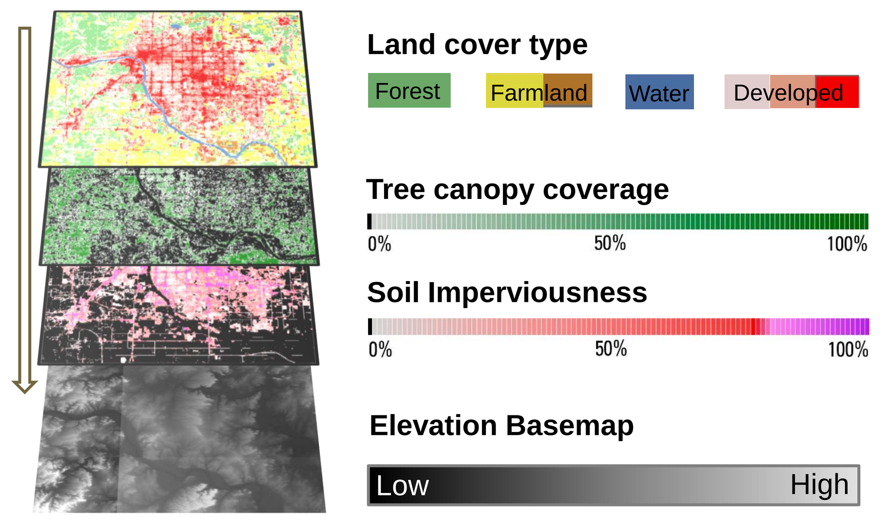
Modeling a Heterogenous Land Surface

Goal: Quickly estimate the differences in temperature and humidity near a complex land surface.

Approach: Because traditional large-eddy simulations are computationally expensive for their high temporal accuracy, this model is a simplified downscaling parameterization that calculates the mean conditions of the roughness boundary layer, constructed as follows:

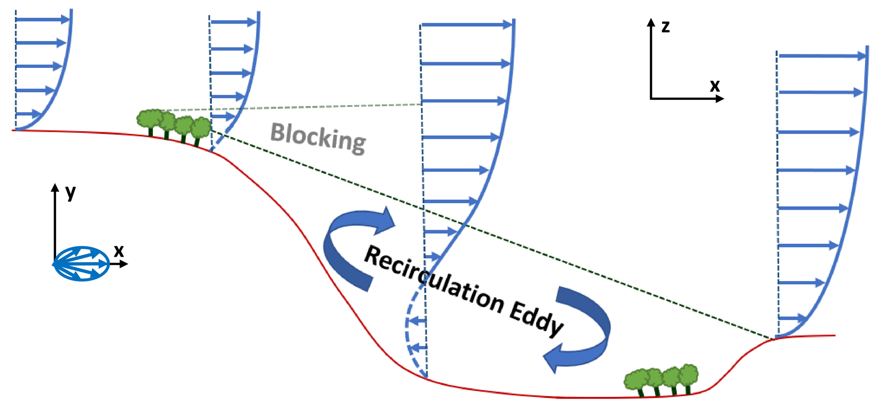
Step 1: Initialize land surface using geographic information systems (GIS) layers.

Inputs include land cover, tree canopy percentage, and soil imperviousness at 30 m resolution. Elevation data at roughly 10 m resolution is transformed to a 30 m grid, preserving subgrid roughness and steepness.[1]



Step 2: Calculate mean surface windfield based on Jackson-Hunt theory.

Wind blocking is treated as a deviation from the standard logarithmic wind profile using a wind blocking scheme developed by DTU.[2] Likewise, recirculation eddies are mapped as a function of wind direction. Variation of roughness lengths (and zero-plane displacements) due to land cover affect the downwind momentum profiles as well.



Step 3: Compute surface heat and moisture fluxes.

The surface temperature is computed for each grid point using a Deardorff force-restore model,[3] represented mathematically below. Vertical movement of heat and moisture is solved iteratively and depends on the windfield momentum profile as well as the given meteorological boundary conditions (preferably a nearby atmospheric sounding).

$$\frac{\partial T_s(x,y,t)}{\partial t} = \frac{C_{eff}}{\tau}\left(R_{net}(x,y,t) - H_{sfc}(x,y,t) - LE\,(x,y,t)\right) - \frac{2\pi}{\tau}(T_s - T_{deep})$$

Radiation — Sensible Heat — Latent Heat — Deep Soil Correction

Step 4: Evaluate SBCAPE from the temperature and humidity in the roughness boundary layer.

A control value of surface-based convective available potential energy (SBCAPE) is obtained from a sounding over relatively smooth terrain. Local deviations from this value are calculated by:

$$\Delta\text{SBCAPE} = \int_0^h g\,\frac{T_{v,parcel} - T_{v,sounding}}{T_{v,sounding}}\,dz$$

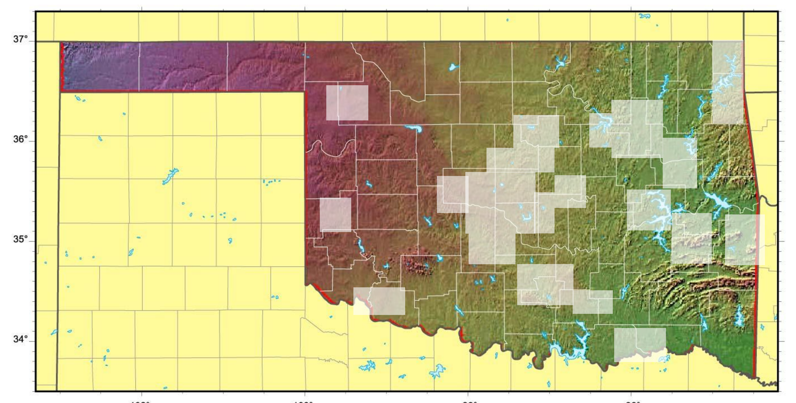
References

1. Noilhan, J. & Lacarrère, P. (1995). "GCM Grid-Scale Evaporation from Mesoscale Modeling." *Journal of Climate,* 8, *2*, 206-223.
2. Mortensen, N.G.; Landberg, L.; Rathmann, O.S.; Frank, H.P.; Troen, I.B.; Petersen, E.L. (2001). "Wind atlas analysis and application program (WAsP)." Wind Energy Department, Technical University of Denmark: Risø-R-1239(EN).
3. Deardorff, J.W. (1978). "Efficient Prediction of Ground Surface Temperature and Moisture, With Inclusion of a Layer of Vegetation." *Journal of Geophysical Research*, 83, *24*, 1889-1903.
4. Kellner, O. & Niyogi, D. (2012). "Land Surface Heterogeneity Signature in Tornado Climatology? An Illustrative Analysis over Indiana, 1950–2012."

Do tornado paths depend on local SBCAPE differences?

Sample: 41 significant (EF2-EF5) tornadoes in Oklahoma from 2011-2018

	EF2	EF3	EF4	EF5
Distribution:	24	10	6	1
From QLCS:	6	1	0	0

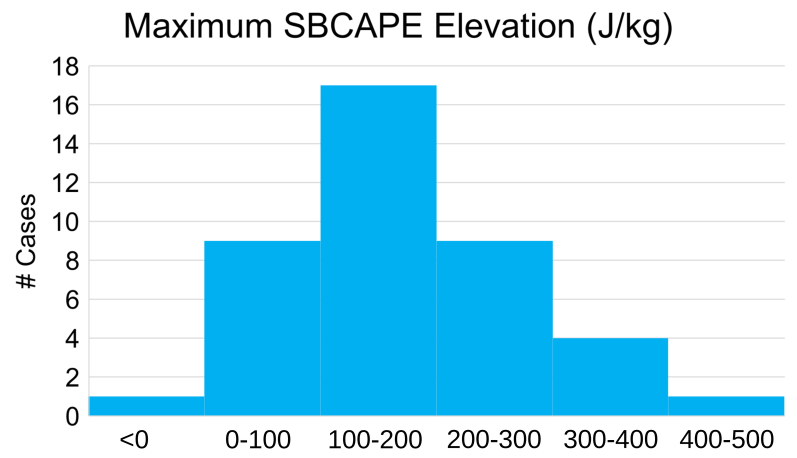


Map of all simulation domains (gray)

Approach: For each tornado case, land surface parameterizations were constructed on top of GIS inputs that extend at least 8 km beyond each tornado path vertex. Publicly available meteorological data, including the nearest atmospheric sounding, radar loops, and mesonet recordings, provided event-specific inputs to calculate the wind, temperature, and humidity fields prior to convection. The primary metric for comparison, localized SBCAPE, was selected under the hypothesis that local buoyancy gradients likely determine where new updrafts/inflows originate upon the arrival of convective conditions.

Analysis 1: Maximum SBCAPE deviation upwind of tornado touchdown/intensification

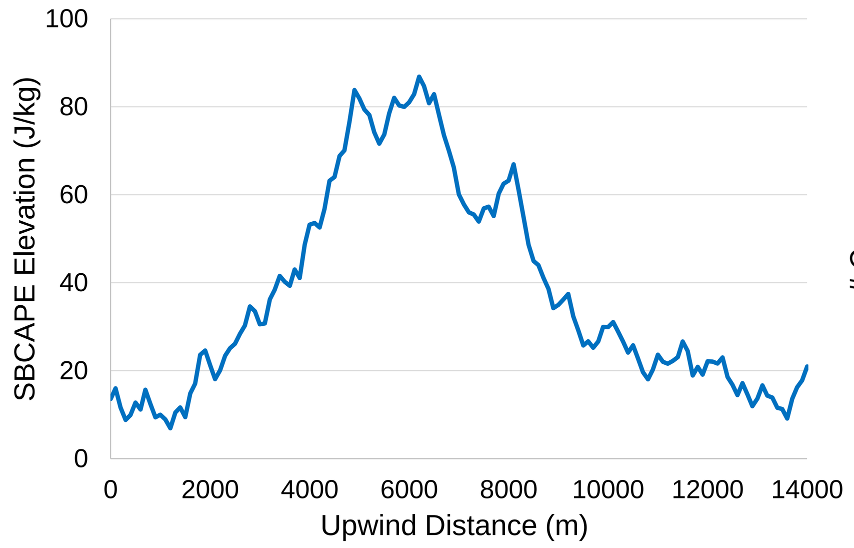
Surface-level air with the greatest buoyancy should have the highest likelihood of forming an updraft in a convective environment. Starting at the point of touchdown (or intensification), the path is extrapolated at 2x the tornado path width, and SBCAPE is integrated areally.

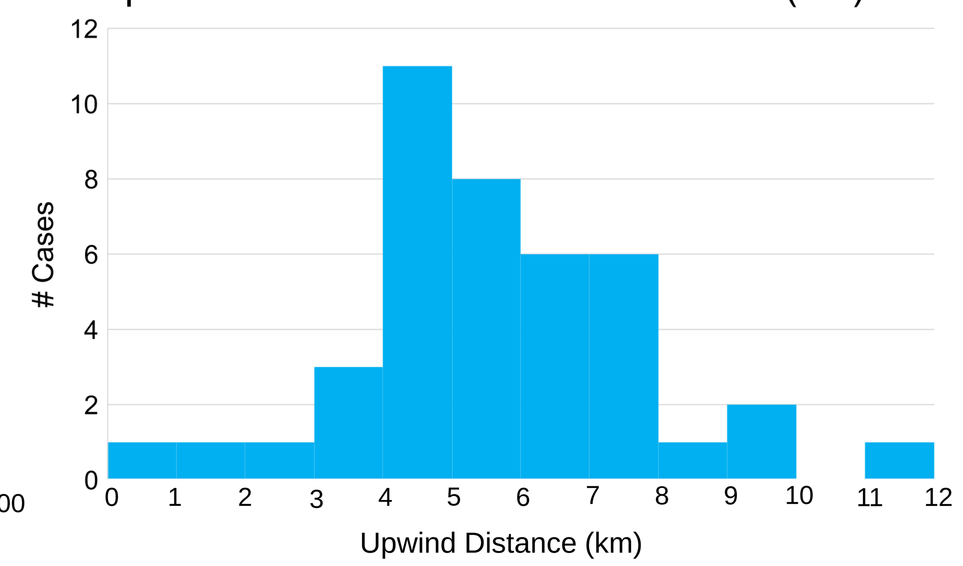


Over 75% of extrapolated paths (31 of 41) include an area with at least 100 J/kg additional SBCAPE, even though such areas make up less than 2% of all simulation domains.

Analysis 2: Distance of SBCAPE maximum from point of touchdown/intensification

SBCAPE profiles were taken along each extrapolated tornado track, and the average profile is plotted below (left) with a histogram of the maximum locations from Analysis 1 (right):



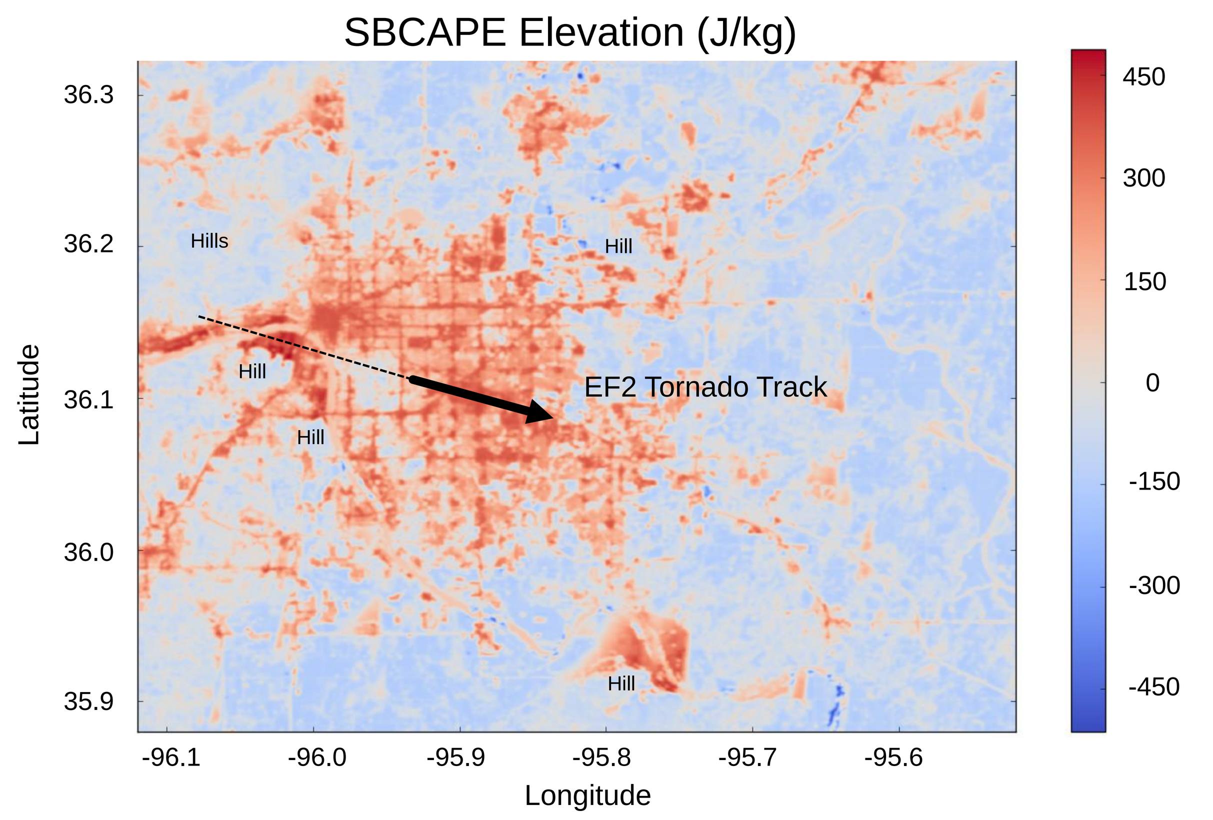


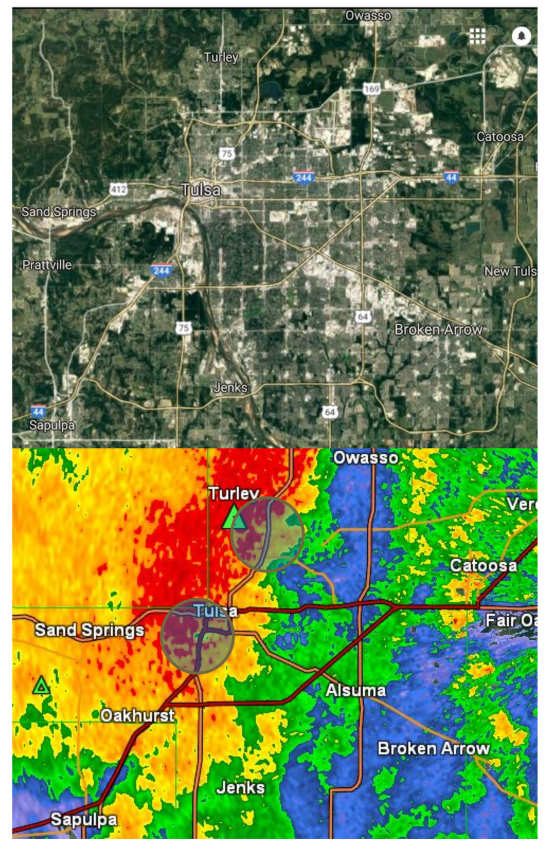
The upwind distance of 3-8 km is significant, likely representing a delay time between updraft initiation and tornadogenesis.

Case Study: Tulsa, OK Tornado of August 6th, 2017

Event Summary: This EF2 tornado touched down 4 miles SE of downtown Tulsa as part of a summer nocturnal quasilinear convective series (QLCS). The radar loop shows a prevailing SW wind before the storm, bringing light showers on a muggy night. As the QLCS approaches, a prominent hook echo forms within the front line above SW Tulsa, which would become the tornado minutes later.

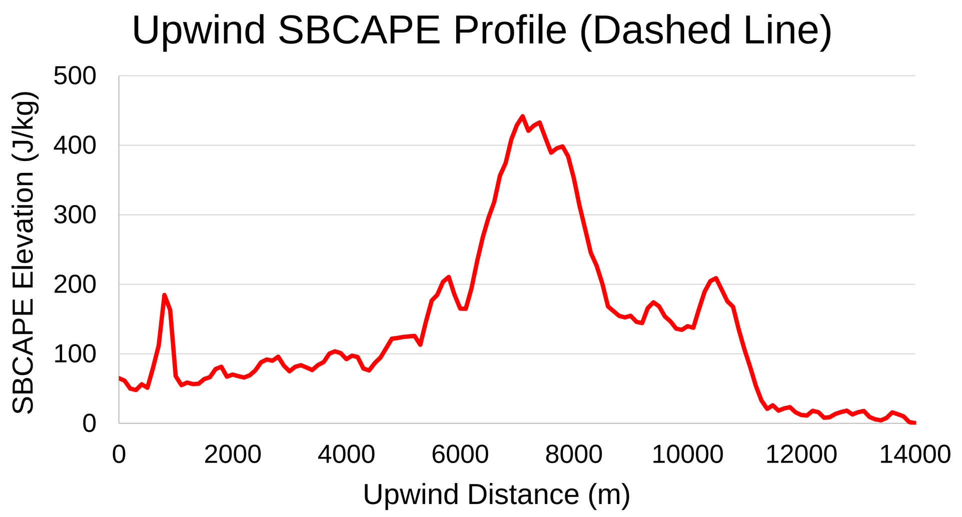
Below is the simulated evening heat island, assuming that nocturnal inversion did not happen under a capping inversion, for comparison with topographical and radar imagery.





Two areas of rotation, only the southern one tightens into a tornado.

Topographical wind blocking combines with the urban heat island effect to create a roughly 5 km² area of maximum SBCAPE approximately 7 km upwind of the touchdown location. This corresponds to a probable updraft at the center of rotation tightening, indicated by a narrow hook echo on radar imagery.



Conclusion and Future Directions

This work suggests a possible link between local SBCAPE maxima and downwind cyclogenesis, with further simulation and observational work required to understand the full mechanism of the updraft in a predictive way. I hope to make the surface layer parameterization available as an interactive module for the Spring 2019 season to test the predictive merit of this model.

Questions, feedback, and collaborations are welcome!