SIMULATED EFFECTS OF URBAN ENVIRONMENTS ON THE DYNAMICS OF A SUPERCELL THUNDERSTORM

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EXECUTIVE SUMMARY

This study used real-data simulations to quantify the impacts of a large Great Plains (U.S.) urban area on the evolution and strength of a supercell thunderstorm. Simulations with urban areas are compared to those without, with the aid of hierarchical clustering analysis, to form statistically similar groups of simulations. We investigated the effects of the storm with various city-relative paths as well as the storm lifecycle stage during urban interactions. These comparisons concentrate on differences in boundary layer characteristics prior to storm formation as well as changes in supercell structure, dynamics, and evolution. Additionally, we performed a factor separation analysis to determine which aspects of the urban area (i.e., roughness or thermal differences) have the most effect. The results suggest that the urban area, particularly surface roughness, can have a significant impact on storm strength, and that these modifications change based on the city-relative path of the storm.

RESEARCH CHALLENGE

Earth's population is increasingly concentrated in urban areas, with nearly two-thirds of the world's population expected to live in urban areas by 2050. As the number of people within cities grows, it is becoming more important to understand and to correctly predict the interactions between urban environments and the atmosphere. As such, many studies have investigated the effect of urban areas on weakly forced precipitation systems. However, interactions between urban areas and synoptically-active convection, such as supercells, remain relatively unexamined.

METHODS AND CODES

Using the Weather Research and Forecasting (WRF) [1] model—a community mesoscale numerical weather prediction model—we investigated a total of 134 simulations of a supercell thunderstorm to quantify the impacts of a large Great Plains urban area on the evolution and strength of a supercell thunderstorm. In order to properly resolve complex urban structure, all simulations were run on a 500-m horizontal grid over a 250-km x 250-km grid. In addition, to resolve the atmospheric boundary layer well, 120 vertical grid points were used, with 20 in the lowest 1.5 km above ground. In all, over 29.7 million points were integrated over 75,600 time steps for each simulation. Ten of the simulations contained homogeneous land use (CTRLE) to serve as a comparison point for simulations with urban areas. An urban area simulated to have both increased surface roughness and thermal properties characteristic of manmade surfaces (i.e., "full physics") was placed in 108 gridded locations (WestF and EastF) throughout the domain to determine effects of the city-relative path of the storm. At eight of these city locations (four near the middle (East) and four near the beginning (West) of the storm's track), two additional simulations were performed with only either thermodynamic (WestT and EastT) or roughness (WestR or EastR) properties of the urban area simulated, providing an additional 16 simulations.

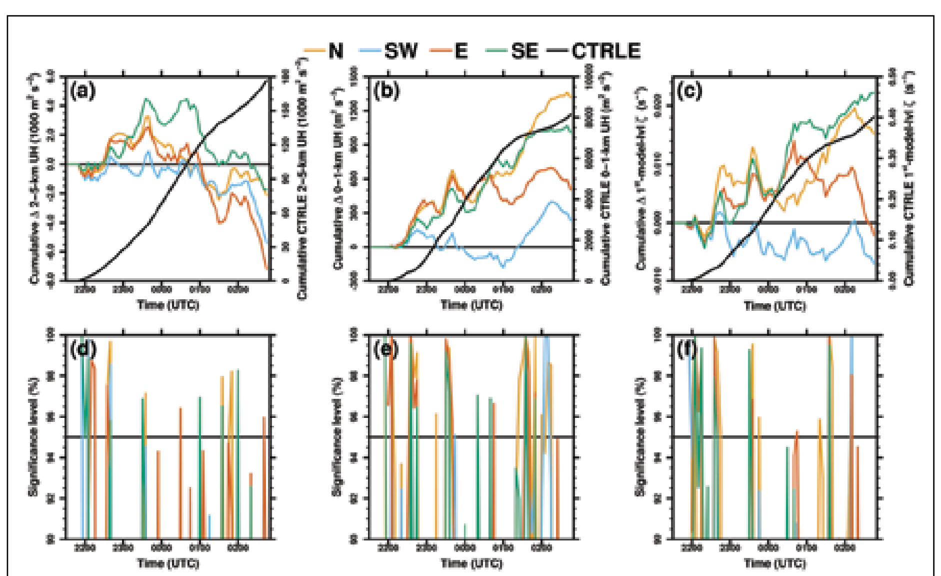

Figure 1: Cumulative CTRLE group average (black) and accumulated difference from CTRLE of N (yellow), SW (blue), E (red), and SE (green) groups of (a) mid-level (2- to 5-km) storm strength, (b) low-level (0 to 1-km) storm strength, and (c) near-surface circulation strength as a function of time.

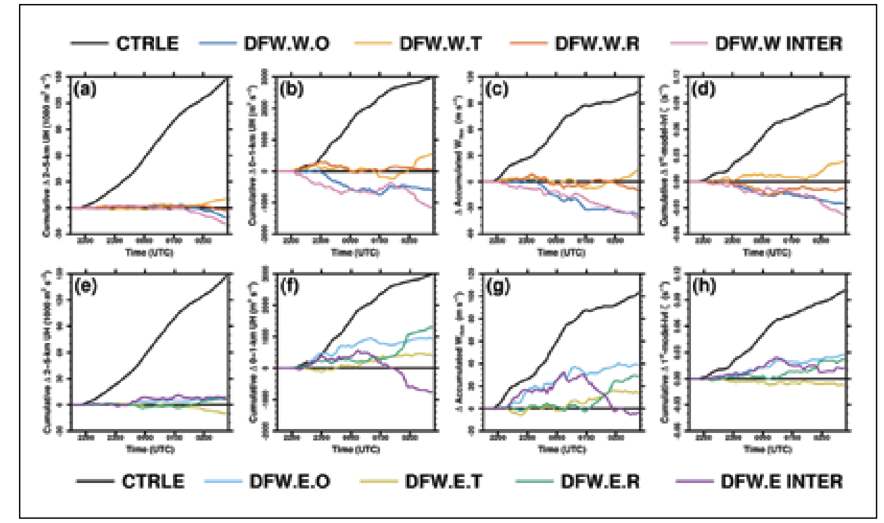

Figure 2: Cumulative CTRLE group average (black) and accumulated difference from CTRLE of urban simulations (colored lines) of mesocyclone-averaged [(a) and (e)] mid-level (2- to 5-km) storm strength, [(b) and(f)] low-level (0 to 1-km) storm strength, [(c) and (g)] maximum updraft speed, and [(d) and (h)] near-surface circulation strength.

RESULTS AND IMPACT

We compared full-physics urban simulations to CTRLE with the aid of hierarchical clustering analysis (HCA) to form statistically similar groups of simulations. In this analysis, we investigated the effects of the storm having various city-relative paths, as well as the storm lifecycle stage during urban interactions. These comparisons concentrate on differences in boundary-layer characteristics prior to storm formation as well as changes in supercell structure, dynamics, and evolution. The results (Fig. 1), suggest that when the storm passes to the north of or directly over the city center late in its life cycle, low-and mid-level storm rotation strength increases, and the center of rotation tracks farther south. Although differences in mid-level rotation are minimal when the storm tracks south of the city, low-level rotation increases, especially late in the storm's lifetime.

Using the 16 individual physical models (i.e., surface roughness or thermodynamic urban properties only), we undertook a factor separation approach to determine the relative importance of the roughness and thermal characteristics of urban areas on storm modification. Results (Fig. 2) generally suggest that surface roughness and its interactions among thermodynamic properties are the dominant contributors to urban-induced effects on storm strength and evolution. Additionally, the amplitude of interactions between shear and thermodynamic modifications is often similar in magnitude to either effect individually.

Most investigations of near-surface urban properties and urban-storm interactions have focused on the impact of the thermal effects of cities, but the results of this investigation argue for a greater focus on the implications of urban surface roughness. Unlike the full-physics simulations, those simulations with the city parameterized only as a roughness element, and with a long urban-storm interaction, resulted in the largest differences from nonurban simulations of any of the factor-separation analyses.

WHY BLUE WATERS

While HCA has been used previously for attribution of variations in synoptic and mesoscale fields to various factors, this is the first time it has been used to analyze storm-scale modifications. Given their large scale of motion, synoptic [O (1000 km)] and mesoscale [O (100 km)] phenomena are generally more predictable than severe storms [O (10 km)], thus few simulations are required to attribute large-scale field variations to modifications in boundary conditions and parameterization options. However, to perform attribution of small-scale effects to various factors in a real-data (i.e., nonidealized) simulation, many simulations are required to ensure that the simulated changes are significant. The general hindrance to such an analysis is the large computational requirement; hence, the resources made available on Blue Waters were vital to this work. While each simulation was relatively small, the large quantity of simulations needed to produce significant results required the large computational and data storage capacities of Blue Waters.

Larissa Reames graduated from the University of Oklahoma in May 2017 with a Ph.D. in meteorology. There, her work was directed by David Stensrud at Pennsylvania State University. She currently is a postdoctoral research associate at the National Oceanic and Atmospheric Administration's National Severe Storms Laboratory.