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Impact of Urban Representation on Simulation of Hurricane Rainfall

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Key Points:

- Quantitative Precipitation Forecasts over urban areas from landfalling hurricanes are sensitive to urban representation in Weather Research and Forecasting (WRF) simulations
- The consideration of urban physics in the WRF model simulation helped improve the urban rainfall simulations
- Representing urban morphology helped simulated heavy rain hotpots and simpler physics better simulated regional rains

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract

Taking the examples of Hurricane Florence (2018) over the Carolinas and Hurricane Harvey (2017) over the Texas Gulf Coast, the study attempts to understand the performance of slab, single-layer Urban Canopy Model (UCM), and Building Environment Parameterization (BEP) in simulating hurricane rainfall using the Weather Research and Forecasting (WRF) model. The WRF model simulations showed that for an intense, large-scale event such as a hurricane, the model quantitative precipitation forecast over the urban domain was sensitive to the model urban physics. The spatial and temporal verification using the modified Kling-Gupta efficiency and Method for Object based Diagnostic and Evaluation in Time Domain suggests that UCM performance is superior to the BEP scheme. Additionally, using the BEP urban physics scheme over UCM for landfalling hurricane rainfall simulations has helped simulate heavy rainfall hotspots.

Plain Language Summary

In the wake of the continuing threat of urban flooding following landfalling hurricanes, understanding the possible interplay between the urban landscape and hurricane rainfall is an emerging research area. Prior studies have shown that the micro-climate of the urban regions can modify rain over the city centers and periphery. However, most urban rainfall modification studies have considered thunderstorms and local convective storms in developing this understanding. However, an intriguing question is whether the urban land surface has any feedback on rainfall due to large systems such as hurricanes. This question was addressed here using a state-of-the-art weather model considering three different representations of urban surfaces. The analysis showed that the simulated hurricane rainfall corresponding to Florence (2018) and Harvey (2017) is sensitive to the choice of the urban model physics used. The results suggest that the model better simulates the environmental conditions and spatial distribution of rainfall using single-layer urban physics.

1. Introduction

Tropical cyclone (TC) based rains impact floods and potentially affect a large population and economy (HFIP annual report, 2017). Intensive literature has focused on rainfall variation in urban environments (Liu & Niyogi, 2019). Urbanization affects rainfall patterns and magnitude through (a) changing mesoscale convection and atmospheric convergence zone (Niyogi et al., 2011; Shepherd, 2005), (b) altering local microclimate through surface roughness (Zhong et al., 2015), (c) urban heat island (Oke et al., 2017), and (d) anthropogenic aerosols (Schmid & Niyogi, 2017). Most of these findings have resulted from studies that evaluated rainfall changes from mesoscale frontal passages or thunderstorm events (Dou et al., 2015; Lorenz et al., 2019; Niyogi et al., 2020). However, the impacts of urban landscapes from large-scale events such as tropical cyclones are of great concern and a topic of emerging importance (Zhang et al., 2018). Tropical systems have a cyclonic intense low-pressure

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center over a large swath with distinct pressure differences and convergence/divergence fields. It is unknown whether the urban representation can affect the rainfall characteristics within these parameters. Consequently, studying the impact of urban parameterization on hurricane rainfall has been limited.

Assessing the ensuing flood potential of a hurricane in urban areas requires sophisticated parameterizations and multi-scale modeling approaches through enhanced simulation of spatial rainfall patterns, intensity, and duration (Gamarro et al., 2019; Zhang & Smith, 2003). In the numerical weather prediction models, such as the WRF model (Skamarock & Klemp, 2008), the urban land surface can be represented with different degrees of sophistication. For example, a single-layer urban canopy model (UCM) parameterization scheme uses a two-dimensional street canyon to compute the momentum, turbulence and heat fluxes. The different urban surfaces considered in UCM are roofs, walls, and roads (Chen et al., 2011). Another detailed representation of the urban canyon, especially regarding the turbulence and urban canyon mixing processes, was proposed by Martilli et al. (2002) as the multi-layer Building Environment Parameterization (BEP) scheme.

The BEP scheme considers a three-dimensional urban structure, vertically distributed momentum, the effect of vertical (walls) and horizontal (streets and roofs) surfaces on momentum, heat sources and sinks, turbulent kinetic energy, and potential temperature. Studies are conducted on the sensitivity of different urban parameterization schemes for heavy rainfall events. For example, BEP performs better than the UCM in case of rainfall events over Mumbai (Patel et al., 2019; Paul et al., 2018) and boundary layer processes (Teixeira et al., 2019). However, there are limited or no studies that assess the impacts of urban representation on rainfall from landfalling hurricanes. Therefore, in this study, we will attempt to evaluate the performance of the urban parameterization schemes in WRF for the rainfall estimates from two landfalling hurricanes in two cities.

2. Experimental Setup

2.1. Study Domains for Hurricane Florence and Harvey

Hurricane Florence was one of the cyclones that made landfall near Wrightsville Beach, North Carolina (NC), at 11:15 UTC on 14 September 2018, and produced catastrophic floods. It made landfall with an intensity of 958 mb and wind speed of up to 47 $ms^{-1,}$ thus causing a high storm surge (275–400 cm) and heavy rainfall (500–762 mm). Considering the landfalling extent within Florence's path, data availability, affected areas, populations, and ease of representation of the interactions, we selected Fayetteville as the study domain focus (35° 3′N, 78° 52′W). Moreover, Fayetteville is the sixth-largest city (388.7 km^2) in NC and received over 400 mm of rainfall during the event (https://www.nhc.noaa.gov/data/tcr/AL062018_Florence.pdf).

Hurricane Harvey landed as a category-4 storm along the Texas coast, 50 km east of Corpus Christi, at 03:00 UTC on 26 August 2017. It maintains a minimum pressure of 937 mb, a sustained wind of up to 59.2 ms^{-1}, maximum inundation level of 183–305 cm above ground level with unprecedented rainfall of ∼1,525 mm (https://www.nhc.noaa.gov/data/tcr/AL092017_Harvey.pdf). The study domain focuses on Houston (29° 44′N, 95° 21′W), the largest city (1,722 km^2) in Texas. Houston received two-thirds of its annual rainfall from the hurricane (over 800 mm). Selecting these two hurricanes enabled us to evaluate and validate the footprint of the findings over two relatively different urban areas.

2.2. WRF Configuration and Observations

The Advanced Research WRF model version 4.3 (WRF-ARW V4.3) is used in the study. The Fayetteville and Houston simulations are conducted using two different domain configurations. Hurricane Florence (Harvey) is simulated using three horizontally nested domains at 1:3 ratio, where the outermost domain consists of 120 × 90 (140 × 100) grids at a spatial resolution of 12 km. The second domain contains 199 × 160 (199 × 160), and the third has 355 × 250 (232 × 232) grids. The spatial extent of the domains is shown in Figure 1. A total of 60 vertical levels are used in the simulations, with the lowest model level located at 26 m from the surface, indicating 13 levels below 1 km to capture the urban boundary layer. The common physics options used in the simulations are the Thompson microphysics scheme (Thompson et al., 2008); RRTMG as shortwave and longwave schemes (Iacono et al., 2008); Mellor–Yamada–Janjic Scheme as Planetary Boundary Layer (Janjic, 1994; Mesinger, 1993); Unified Noah land surface model (Tewari et al., 2004); Tiedtke Scheme (Tiedtke, 1989; Zhang et al., 2011) as cumulus parameterization scheme only for the outermost domain. Preliminary simulations were

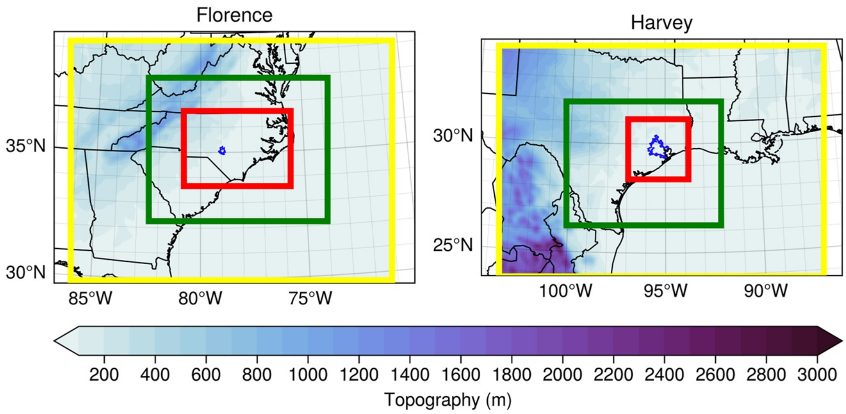

Figure 1. Weather Research and Forecasting domain configuration for Hurricane Florence (left) and Harvey (right) simulations. The telescopic yellow, green, and red boxes represent the outermost, inner, and inner-most domains respectively. The background shows the topography, and the blue outline within the innermost domain represents Fayetteville and Houston urban areas.

tested for the model configuration to accurately simulate the hurricane track and storm characteristics. The simulations were performed considering: (a) a control experiment with an urban slab model (NUCM), (b) a single-layer UCM, and (c) multi-layer BEP urban physics (BEP). All other physics schemes remain the same for the simulations.

The initial and boundary conditions are generated from the National Centers for Environmental Prediction (NCEP) Reanalysis data, available at 0.25° × 0.25° horizontal resolution and six hourly intervals. The simulations for Hurricane Florence start on 2018-09-12 at 12:00 UTC and ends on 2018-09-18 at 00:00 UTC, and for Hurricane Harvey simulations start on 2017-08-24 at 12:00:00 UTC and end on 2017-08-29 at 00:00:00 UTC. The first 12 hr are discarded as spin-up time. We have also performed simulations with 0, 6, 12, 18, and 24 hr of spin-up time to account for the uncertainty (Figures S5 and S6 in Supporting Information S1). The International Geosphere–Biosphere Programme—Moderate Resolution Imaging Spectroradiometer (MODIS) land-use is used in both simulations (Figure S1 in Supporting Information S1).

The National Weather Service Advanced Hydrologic Prediction Service stage IV rainfall data is used to evaluate the simulations with a spatial resolution of 4 km and a temporal resolution of 1 hr. The observational hurricane track data were obtained from the National Oceanic and Atmospheric Administration reports (Blake & Zelinsky, 2018; Stewart & Berg, 2019).

Generally, a single number is used to evaluate the rainfall time series over the urban areas to express the similarity between the simulated and observed rainfall values. Here, we use the modified Kling-Gupta Efficiency matric (KGE′) to evaluate the model performance, described by correlation, variability, and mean bias (Gupta et al., 2009; Kling et al., 2012). A KGE equal to one indicates a perfect match between the simulations and observations.

$$\mathrm{KGE}' = 1 - \sqrt{(r-1)^2 + (\beta-1)^2 + (\gamma-1)^2} \tag{1}$$

$$\beta = \frac{\mu_s}{\mu_o} \tag{2}$$

$$\gamma = \frac{\sigma_s/\mu_s}{\sigma_o/\mu_o} \tag{3}$$

where r is the Pearson correlation coefficient for simulations (s) and observations (o), β is the bias ratio, γ is the variability ratio, μ is the mean observation, and σ is the standard deviation.

For spatial verification of the rainfall, the Method for Object-based Detection and Evaluation (MODE) for Time Domain (MTD) (Bullock et al., 2016) is used, which is an extension of objected based approach along the time domain (i.e., a 3D verification technique). The following attributes are used in the analysis of the simulations.

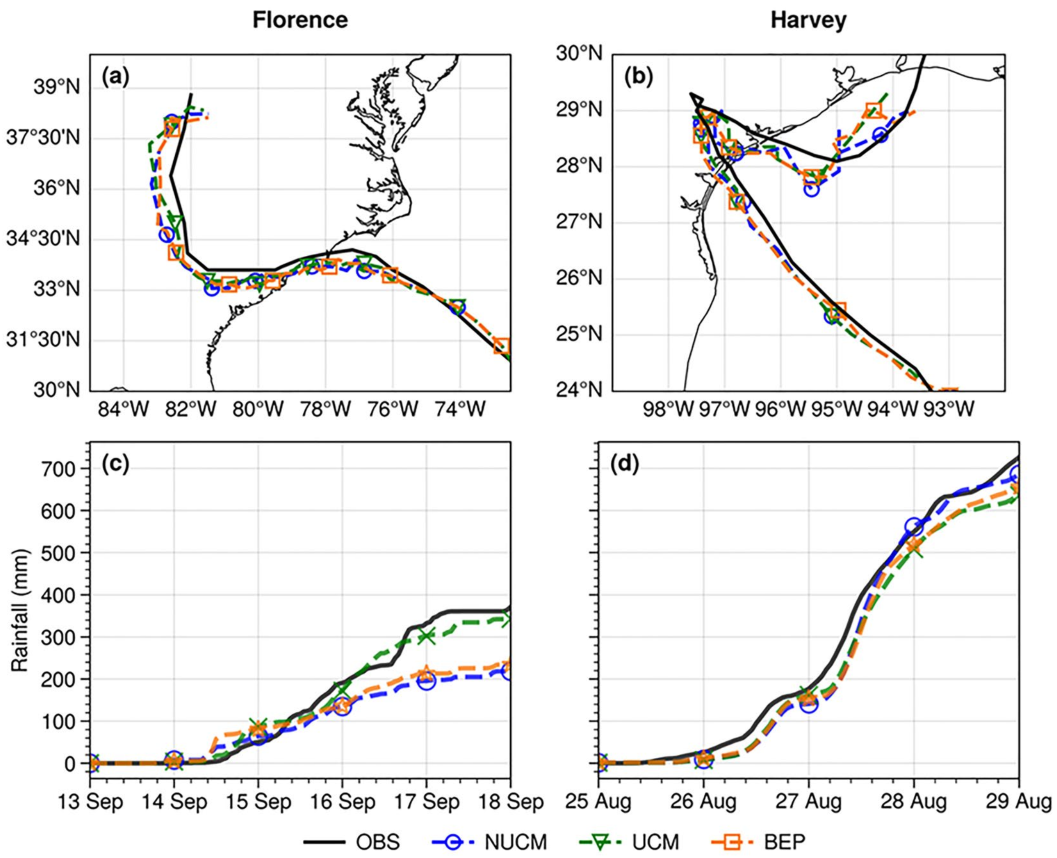

Figure 2. The top row (a and b) represents the model (NUCM, Urban Canopy Model, and BEP) simulated tracks against observations (OBS) for Florence and Harvey. The bottom row (c and d) shows the average rainfall (mm) over Fayetteville and Houston urban areas.

1. Spatial Centroid Distance is the average distance between the centroids of the two objects, that is, observations and simulations.
2. Time Centroid Delta is the average difference between the time coordinated of the centroids.
3. Axis Difference is the average of the smaller angles made by the axis of the objects.
4. Speed Delta is the difference between the lengths of the velocity vectors of the two objects.
5. Direction Difference is the angle that the two velocity vectors make with each other.
6. Volume Ratio is the forecast volume ratio to the observed object.

3. Results and Discussions

The hurricane tracks of Florence and Harvey simulated by the two experiments agree with the observations, despite some differences during the dissipation phase (particularly for Hurricane Harvey) (Figures 2a and 2b). The differences between model simulations and observations are limited to a few kilometers from the initialization to landfall. The model simulated accumulated rainfall over the landfall cities is shown in Figures 2c and 2d. The rainfall analysis indicates that the UCM performs relatively well over Fayetteville than the others. On the other hand, BEP and NUCM simulations also show comparable results up to 16 September 2018, at 00 UTC. After that, it shows slight deviations in the rainfall amounts, eventually leading to underestimation (Figure 2c). In the case of Harvey, all the simulations can produce similar amounts of rainfall, that is, 686 mm (NUCM), 636 mm (UCM), and 655 mm (BEP). However, all the model simulations are unable to produce total accumulated rainfall amounts of 726 mm over the Houston region (Figure 2d).

The performance of the simulations is shown in Table 1. The KGE′ results show that UCM outperforms other simulations in the model simulations. The bias ratio of BEP for the Florence simulation is the least, while the

Table 1
KGE′ and Its Components Scores

Simulations	KGE′	r	β	γ
NUCM (F)	0.41	0.48	1.08	1.26
UCM (F)	**0.57***	**0.58***	1.06	**1.01***
BEP (F)	0.37	0.42	**1.04***	1.24
NUCM (H)	0.66	0.82	0.74	**1.13***
UCM (H)	**0.695***	**0.84***	**0.79***	1.14
BEP (H)	0.69	0.82	0.78	1.13

Note. The Florence and Harvey simulations are denoted by F and H, respectively. Bold and asterisk (*) symbols represent the best score from the simulations.

variability ratio of NUCM for Harvey simulations is the least. Both cases indicated that the WRF model could reasonably capture the rainfall amount when the explicit urban parameterization scheme that accounted for urban morphological features was implemented. Moreover, using relatively complex schemes such as BEP may not improve the accumulated rainfall over the UCM, indicating model improvement in relation to the synoptic dynamics and rainfall distribution (Figure 2c). Data assimilation could be one of the ways to improve precipitation features (Osuri et al., 2015; Routray et al., 2010; Zhang et al., 2021).

We further extend the analysis spatially and temporally using MODE (Table 2). The MODE analysis is consistent with the KGE′ results that the UCM performs well in most parameters. A significant difference is evident in the Florence simulated rainfall, particularly at the 99th percentile, whereas all other rainfall percentiles show similar values. Moreover, up to the 50th percentile, the rainfall values are close to the observations, and after that, model simulations produce more rainfall. From the above results, in both spatial and temporal changes, UCM performs better than the BEP and NUCM, and using urban models is expected to improve the TC characteristics.

The difference between the total accumulated rainfall between different simulations is shown in Figure 3. It can be observed that urban parameterization significantly affects the rainfall amounts and associated spatial patterns. Considering the BEP (at Florence), rainfall bands with higher amounts are in the south of Fayetteville (outside of the urban region) (Figures 3b and 3c). While in the case of Harvey, similar rainfall bands covered west of Houston (Figures 3e and 3f). On the other hand, UCM (Florence) simulations show higher rainfall over Fayetteville and a reduction over Houston (Figures 3a and 3d). One of the reasons for such discrepancies in the rainfall amounts is due to the shape, size, and location (coastal or inland) of the cities (Schmid & Niyogi, 2013; Yang et al., 2019; W. Zhang et al., 2022; Y. Zhang et al., 2022). For instance, Houston is located in the coastal area with an area of 1,722 km^2, while Fayetteville is an inland city (135 km from the coast) with a footprint of 388 km^2. The total accumulated rainfall from the observation and simulations is shown in Figure S1 in Supporting Information S1.

The UCM and BEP schemes could capture the rainfall patterns more accurately than the NUCM due to their urban morphology considerations. The BEP contains high-rise buildings, so the momentum loss increases due

Table 2
MODE Time Domain Analysis

Simulation	Spatial centroid distance	Time centroid delta	Axis difference	Speed delta	Direction difference	Volume ratio
NUCM (F)	22.69	1.11	55.141	0.83	**0.41**	0.76
UCM (F)	**20.41***	**−0.1**	**46.578**	**0.57**	3.95	**0.82**
BEP (F)	22.63	0.5	52.97	0.79	0.89	0.77
NUCM (H)	4.87	−3.15	**3.926***	**0.58***	22.4	**0.85***
UCM (H)	**4.22***	−3.03	5.793	0.62	**20.61***	**0.85***
BEP (H)	5.72	**−2.97***	6.079	0.64	20.9	0.84
	10th Percentile	25th Percentile	50th Percentile	75th Percentile	90th Percentile	99th Percentile
OBS (F)	1.89	4.31	8.48	16.48	30.48	72.43
NUCM (F)	0.99	3.4	9.52	20.78	38.22	86.23
UCM (F)	0.93	3.47	9.2	20.8	38.28	84.8
BEP (F)	0.98	3.44	9.49	21.45	40.68	103.41
OBS (H)	1.68	4.24	8.82	16.88	28.41	70.76
NUCM (H)	0.61	3.06	8.98	20.89	40.67	105.43
UCM (H)	0.67	3.35	9.34	21.47	40.22	100.2
BEP (H)	0.68	3.23	9.39	21.85	41.21	103.95

Note. Bold and asterisk (*) represent the best score from the simulations.

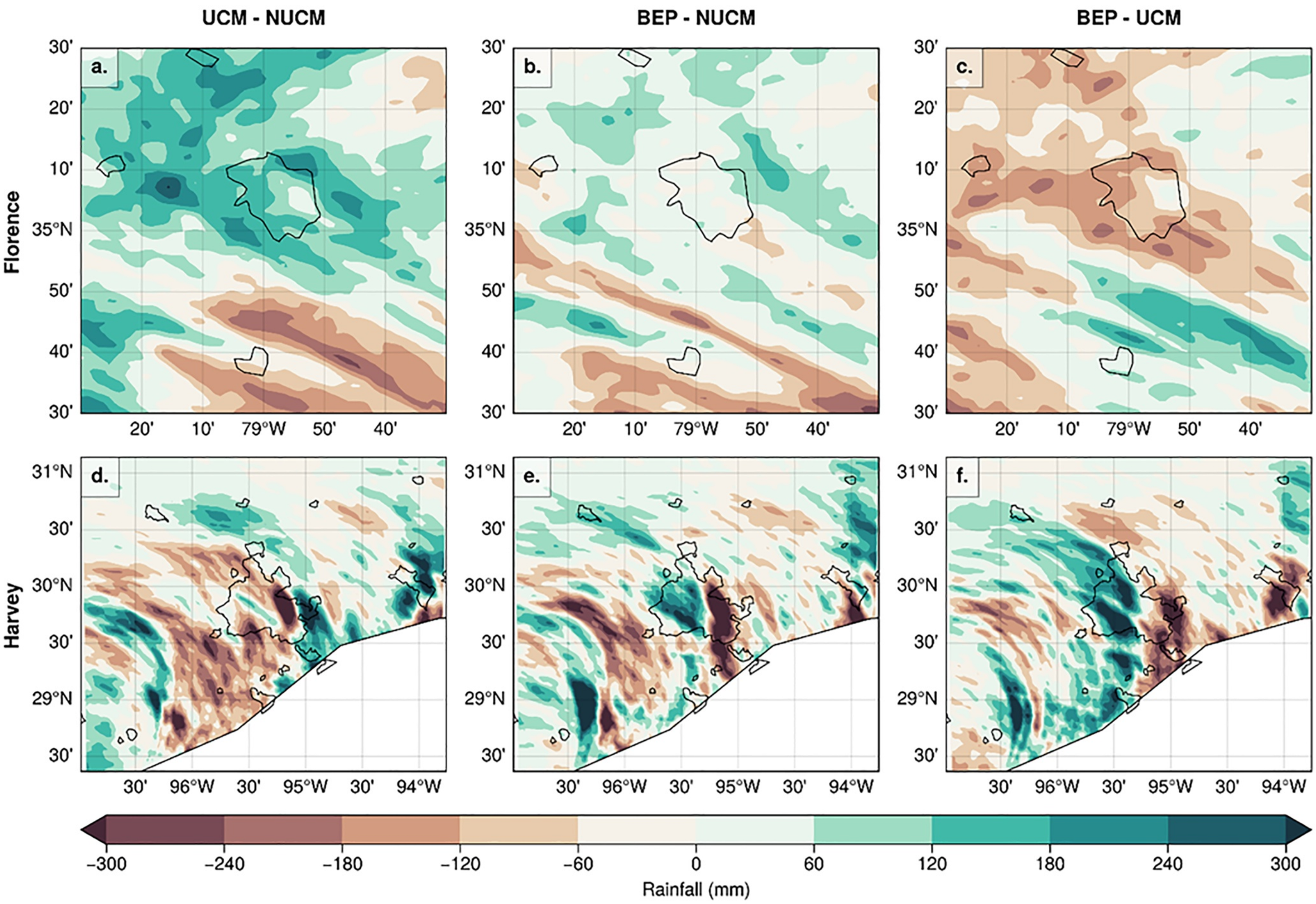

Figure 3. Spatial differences in the total accumulated rainfall (mm) between (a) UCM-NUCM (positive means Urban Canopy Model is higher), (b) BEP-NUCM (positive means BEP is higher), and (c) BEP-UCM (positive means BEP is higher) simulations for Florence. (d–f) are the same as (a–c) but for Harvey.

to a horizontal surface and momentum exchange due to the vertical surface, thus leading to a reduced 10 m wind speed within the urban areas (Figures 4b and 4e). The observed reduction in wind speed from the BEP scheme is consistent with the study by Hendricks et al. (2021), indicating the dominant behavior of the urban surface. The UCM shows higher wind speed over the urban regions because the horizontal wind speed in the UCM is calculated using the exponential function of roughness length, building height, zero plane displacement height and Obukhov length. Since cyclones consist of exceptionally high wind speeds, translating into relatively higher 10 m wind speeds over urban areas.

The deep convection also affects the hurricane rainfall bands as a function of heat fluxes and storm-relative helicity (SRH) (Onderlinde & Nolan, 2016). The sensible heat flux is responsible for the land-atmosphere coupling strength (Chen & Zhang, 2009). In contrast, SRH represents the interaction between updrafts and vertically sheared environment (generally used for predicting potential tornadic developments), thus, controlling the degree of organization and severity of the convection. The surface energy balance and SRH equations are provided in the supplementary material.

In both hurricane cases, the BEP has relatively higher SRH (Figures 5c and 5f), and sensible heat flux (Figures S3a and S4a in Supporting Information S1) than the UCM over Houston and Fayetteville. The change in the sensible heat flux leads to the changes in the height of the urban boundary layer which impacts the convergence zones. The higher sensible heat flux (urban surface warming) affects the location and intensity of up and down drafts, thus, redistributes and enhances the rainfall (Figures S7 and S8 in Supporting Information S1) (Zhang et al., 2018). Here, it is essential to highlight that the UCM and BEP calculate the sensible heat fluxes differently. The UCM scheme uses Monin–Obukhov similarity theory and the Jurges formula to calculate sensible heat flux (Kusaka et al., 2001). While BEP considers the three-dimensional structure of the urban region along with the

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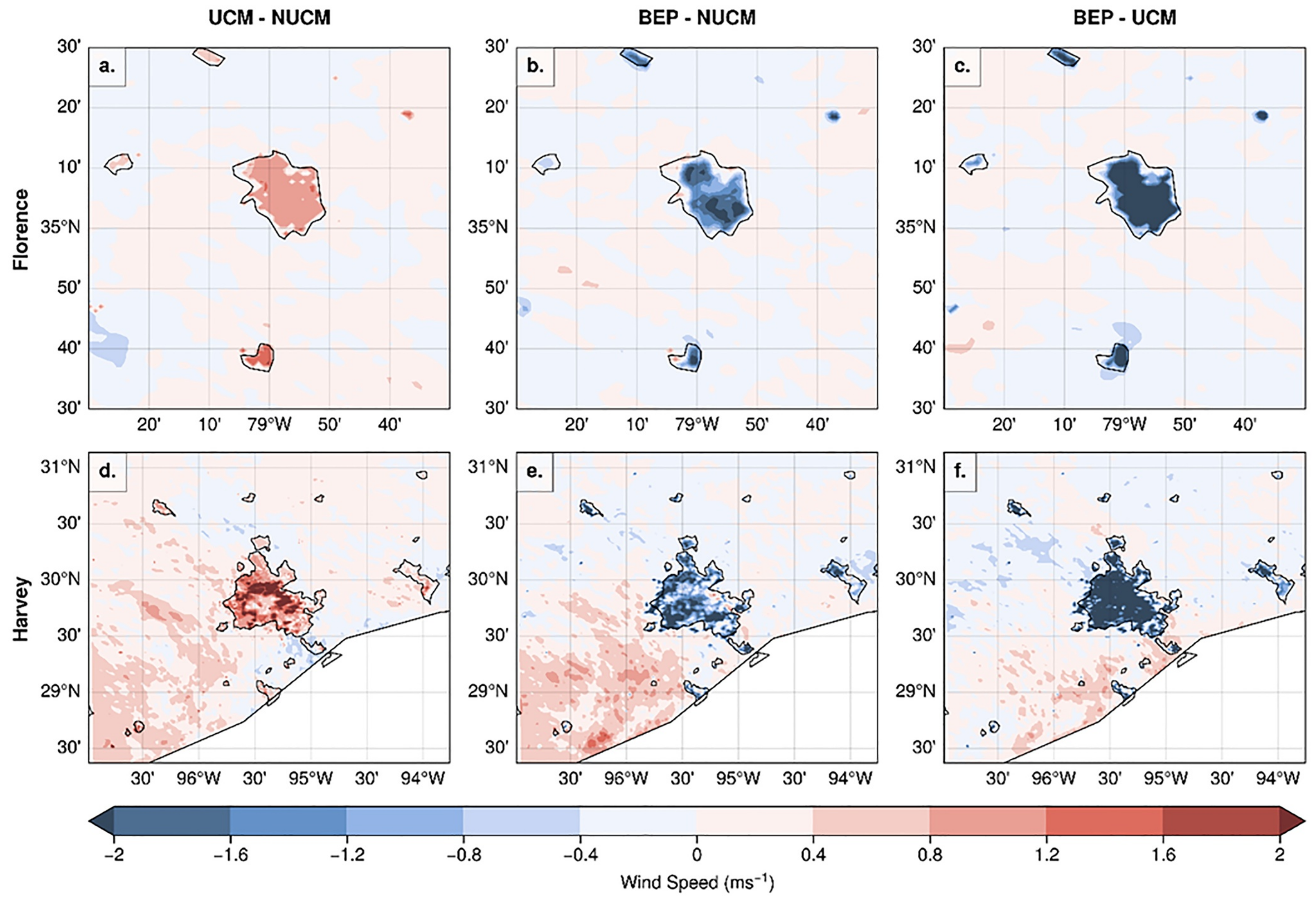

Figure 4. Same as Figure 3 but for the mean 10 m wind speed (m s^{-1}).

shadow, reflection and trapping of the radiation leading to relatively higher sensible heat flux than UCM during the daytime (Huang et al., 2019; Wang et al., 2021).

The UCM produces higher 10 m local winds than the BEP which is associated with the drag effects produced by the urban scheme (Hendricks et al., 2021; W. Zhang et al., 2022; Y. Zhang et al., 2022). As a result, the combined effect of urban surface drag and sensible heat flux lead to the changes in the location and intensity of the rainfall bands. The urban modification to the TC rainfall bands is evident, and better performance of the UCM model may be attributed to the higher 10 m wind speed and a lower sensible heat flux than the BEP model that appear to impact the convergence zones leading to the redistribution of the rainfall bands.

4. Conclusions

The study sought to understand the effect of considering slab, single and multi-layer urban canopy models in simulating the post-landfall (Hurricane Florence over Fayetteville, NC and Hurricane Harvey over Houston, TX) hurricane rainfall. The inclusion of the urban parameterization in the high-resolution WRF model showed promising results, indicating representation of urban-scale processes is crucial in simulating the improved rainfall amounts for a landfalling hurricane. Our findings suggest that UCM provides better rainfall estimates than the BEP model. One of the reasons for this improvement is attributed to the 10 m wind speed and sensible heat flux variations in the UCM model thus affecting the rainfall spatial changes. The analysis also suggests that the city's size and (probably) shape may also be responsible in determining the location of the rainfall bands. For example, Houston (a relatively higher urban footprint than Fayetteville) receives higher accumulated rainfall using the BEP than the UCM. In the case of Fayetteville (smaller footprint), the UCM simulation showed higher accumulated rainfall than the BEP scheme. Many cases with multiple cities of different shapes and footprint sizes are needed to make this statement robust for landfalling hurricanes, which could be future scope of the study.

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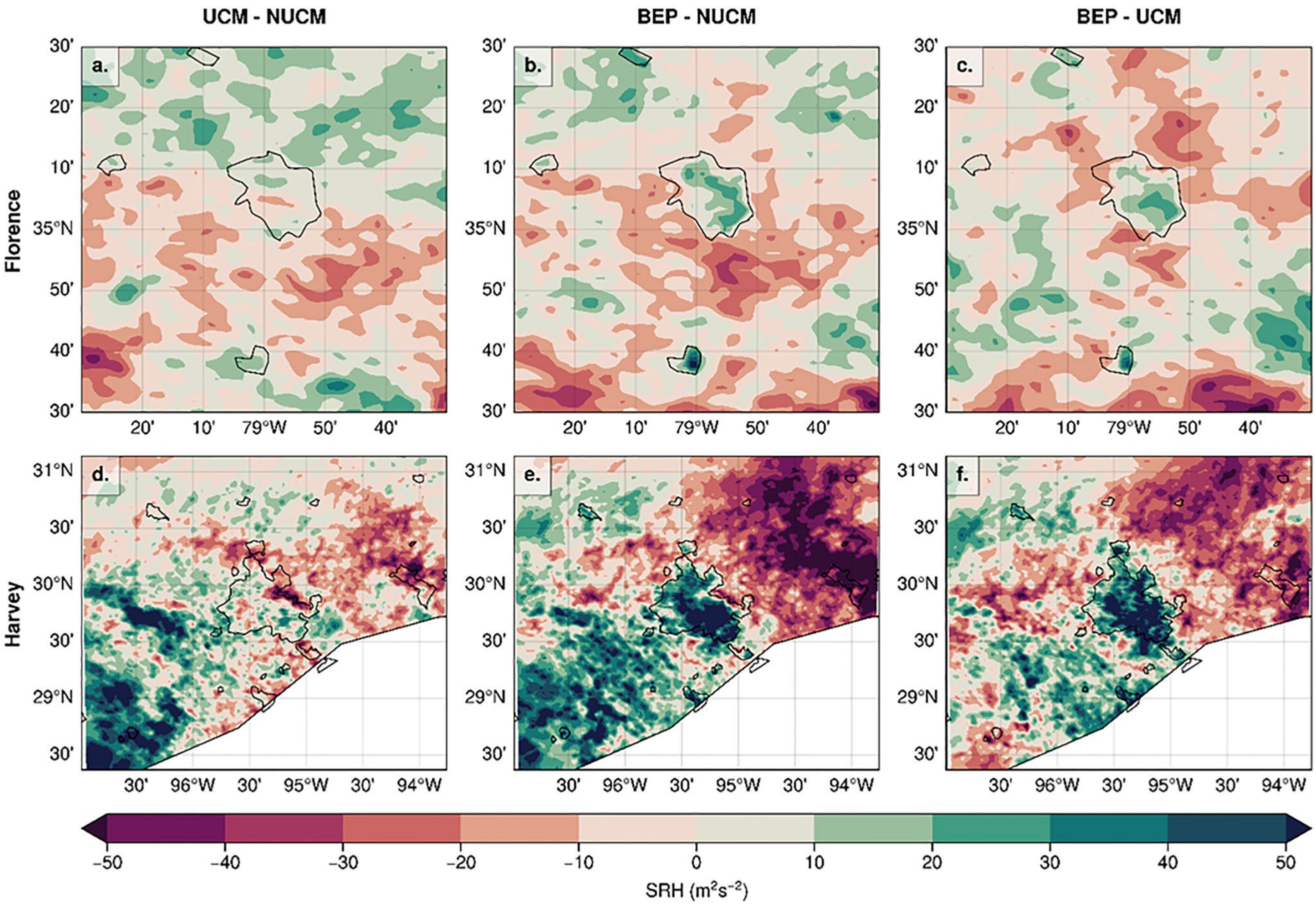

Figure 5. Same as Figure 3 but for mean storm-relative helicity ($m^2\ s^{-2}$).

Data Availability Statement

The data associated with this paper is publicly accessible through the online, open-access repository of Zenodo (https://doi.org/10.5281/zenodo.8333196) to support data citation, quality, and reuse by the scientific community.

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