Assessing the Surface Urban Heat Island and Urban Extreme Precipitation Anomalies: An Analysis of Richmond, Virginia

Aasma Acharya*, Zafer Boybeyi, James L. Kinter, Luis E. Ortiz
Department of Atmospheric, Oceanic and Earth Sciences, George Mason University

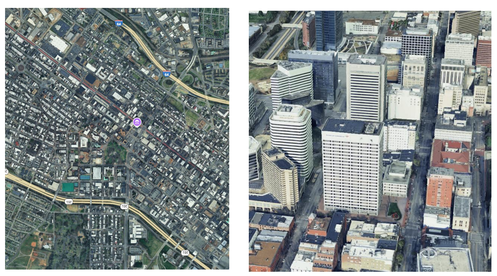
Introduction

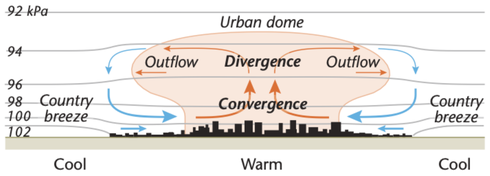
This study evaluates the spatial distribution of summertime urban extreme precipitation in a midsized U.S. city, Richmond, Virginia. Using high-resolution hourly precipitation (4 km/hourly) and land surface temperature (5 km/hourly) datasets for the period of 2011–2021, we investigate the intensity and frequency of extreme rainfall events under strong Surface Urban Heat Island (SUHI) conditions. We observed a consistently elevated intensity of SUHI over the Richmond urban core, with peak anomalies occasionally exceeding 5°C during the afternoon. The strongest SUHI effects were aligned with high-density built-up areas of Richmond and its suburbs. Composite analysis of hourly extreme precipitation anomalies under strong surface urban heat island (SUHI) conditions (i.e., above-average SUHI) reveals a clear spatial enhancement downwind of the Richmond urban core, aligned with the prevailing 700 hPa wind direction. On average, this downwind region received up to 4.5 kg/m² more rainfall per hour during elevated SUHI periods, particularly in the hours following peak heat. In contrast, the upwind regions show negative or near-zero anomalies, suggesting little to no enhancement. These findings indicate that extreme precipitation events downwind are likely influenced by afternoon convection. While large-scale atmospheric systems may influence regional rainfall, the consistent localization of extremes in the southeastern urban core and downwind region suggest a thermally driven enhancement linked to urban heating.

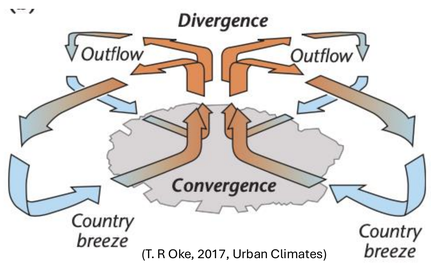
Research questions

- **Does Richmond exhibit observable signatures of urban influence on short-duration extreme precipitation, such as downwind intensification or spatial shifts in rainfall patterns?**
- **Do these spatial signatures remain consistent under strong surface urban heat conditions?**

Background







(T. R Oke, 2017, Urban Climates)

Methodology

Study area

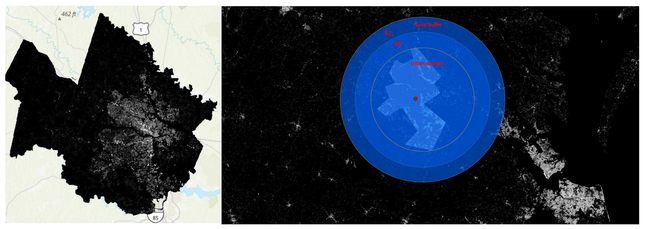
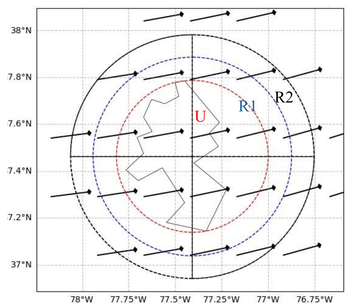


Fig: a) Total built-up surface raster at 100 m resolution (Global Human Settlement Layer (GHSL). b) Spatial delineation of urban-nonurban buffer around the Richmond urban core

Wind Direction-Based Classification of the study domain



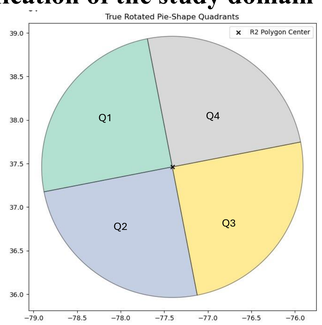
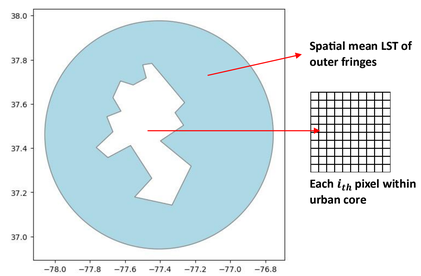


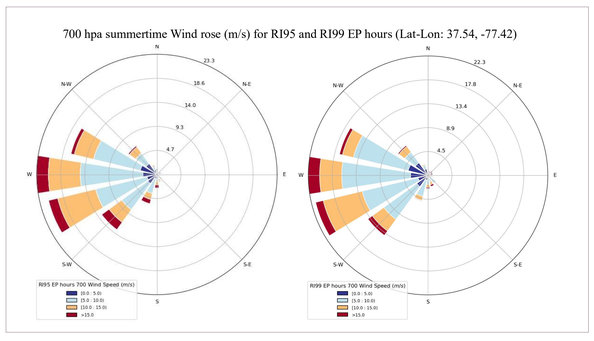
Fig: a) Overlay of urban (U) and extended (R1 and R2) buffer domains with summer-mean 700 hPa wind vectors, showing predominant southwesterly flow. b) Rotated section of usual quadrant division from figure a, aligned with the mean wind direction to define dynamic upwind and downwind regions

Determining Surface Urban Heat Island (SUHI) from Land Surface Temperature (LST)



$$SUHI_{t,each\ grid\ cell} = LST_{i_{th,urban}(t)} - \overline{LST_{outer\ fringes}}(t)$$

(700 hpa summertime hourly wind rose) during EP hours



Results

Surface Urban Heat Island (SUHI) characteristic of Richmond

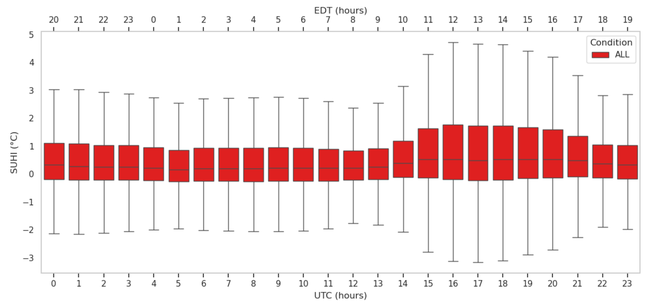


Fig. a) Distribution of hourly SUHI intensity across 2011-2021

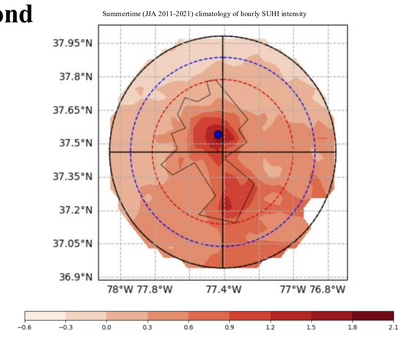
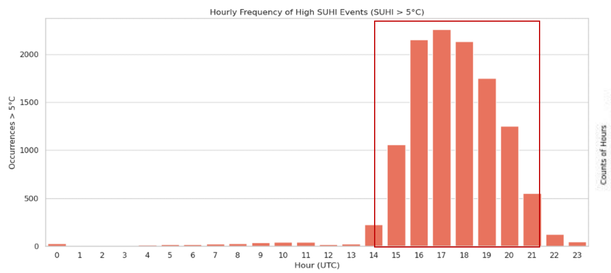


Fig. b) Seasonal mean SUHI intensity showing urban-rural contrast

Diurnal characteristics of Summertime SUHI events and Urban Precipitation Extremes



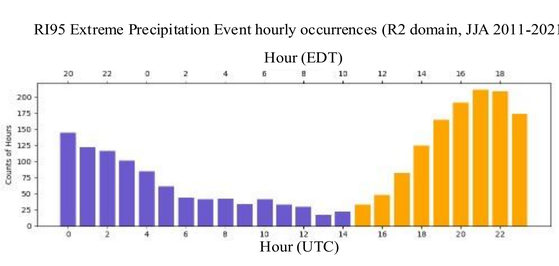


Fig. a) Hourly frequency of high SUHI events (SUHI > 5 °C) over Richmond, VA (JJA, 2011–2021). b) total number of hours with precipitation exceeding the 95th percentile (RI95) at each UTC hour

Analysis of Rainfall Extremes under Strong SUHI cases

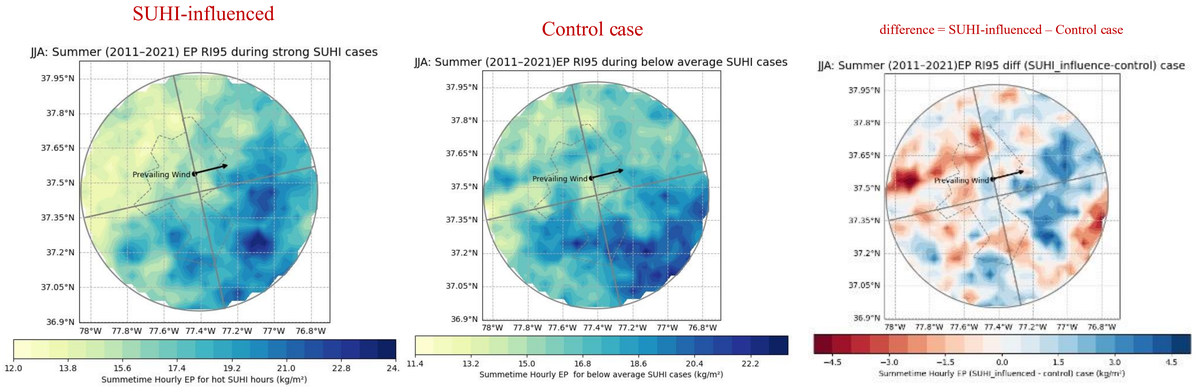


Fig: Spatial composites of hourly extreme precipitation (RI95 and RI99) a) during above- average SUHI conditions and b) below-average SUHI conditions for the Richmond urban core. 1st composite includes a +3-hour window following each SUHI threshold exceedance to capture lagged response of precipitation to the temperature while 2nd composite only includes remaining hours that's not in composite 1st. c) Composite anomaly of extreme hourly precipitation (EP95) between SUHI-influenced hours and non-SUHI control hours during JJA (2011–2021).

Conclusions and Future work

- Localized clusters of heavy rainfall over the southeastern portion of Richmond and in the downwind region, coinciding with elevated urban heat were observed

Future work will

- Explicitly assess the statistical significance of these spatial patterns.
- Conduct further analysis to isolate the effect of urban thermal forcing on the observed spatial distribution of intense rainfall.

References and Supplementals