Enhanced intensification of hourly rainfall extremes due to urban warming in Phoenix, Arizona

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1 Motivation

- Short-duration extreme rainfall events are the main trigger of flash and pluvial floods in cities.
- Depending on the local climate zone and urban fabric that affect meteorological variables such as air temperature, humidity, and aerosol concentration, the built environment can either intensify or reduce extreme rainfall intensity.
- Here, we examined how urbanization in a large metropolitan area characterized by open low-rise buildings, affected sub-daily extreme rainfall intensities over the period between 2000 and 2018.
- The research was conducted in the metropolitan region of Phoenix, Arizona, which is supported by a large and dense rain-gauge network (168 stations, Fig. 1).

2 Study area

- The urban area of Phoenix (Fig. 1) is comprised of several incorporated cities and is generally flat with some hilly terrain.
- The climate is classified as arid (BWh in the Köppen-Geiger Climate classes), meaning it is generally hot and has low precipitation throughout the year.
- CONUS-wide LCZ map were used for the characterization of the urban surface cover. The Phoenix urban area is largely built (57% of the area) with 88% of it being open low-rise buildings and the rest being large low-rise buildings (LCZ 6 and 8, respectively, Fig. 1).
- The population increased from 2.9 million to 4.1 million residents between 2001 and 2019, which is reflected in an increase in built area (Fig. 2).

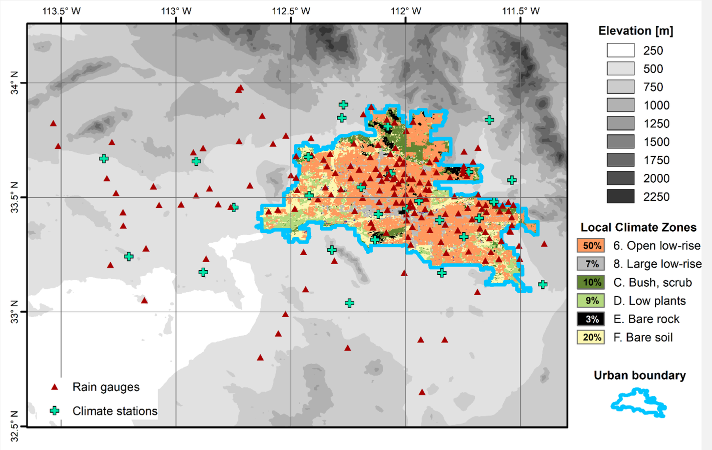

Fig. 1. A map showing the extent of the Phoenix metropolitan region (border with blue line). Red triangles mark the locations of the 10-min rain-gauges (141) and green plus symbols mark the locations of the stations with also temperature sensors (27) showing the 168 rain-gauges used.

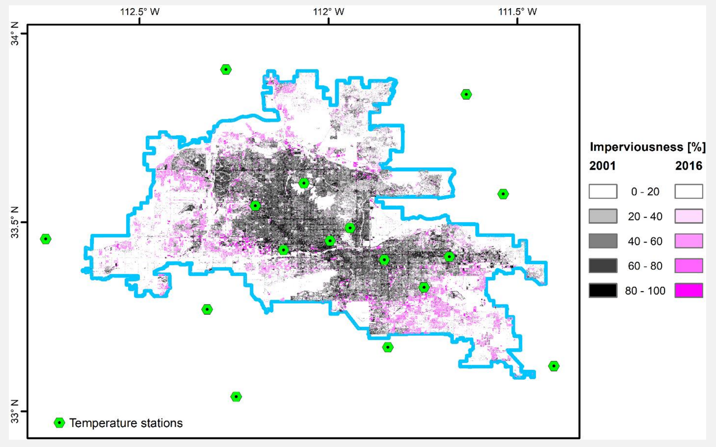

Fig. 2. A map of the Phoenix metropolitan region with the % of imperviousness reported for the year 2001 (blackish color scale) and the % of imperviousness that was added by 2016 (purplish color scale).

3 Trend detection

- Trends in extreme rainfall intensity were computed based on the annual maxima series.
  - Fitted a simple linear regression and used the Theil-Sen slope estimation method to compute the trend. Afterward, we used the Mann-Kendall test to detect whether the trend is significant (Fig. 3).
  - Used Prosdocimi et al. (2019)'s areal model that pools information across stations in the urban and rural regions (Table 1) to enhance the statistical evidence of changes in extreme rainfall intensities.
    - Fitted a regression model using log-transformed annual maxima values with time as a covariate at each station. Then used a Bayesian framework to estimate the area-specific trend signal and significance of the test statistic.
- In addition to extreme rainfall, trends were also calculated for temperature (Fig. 4a) and AOD (Fig. 4c).

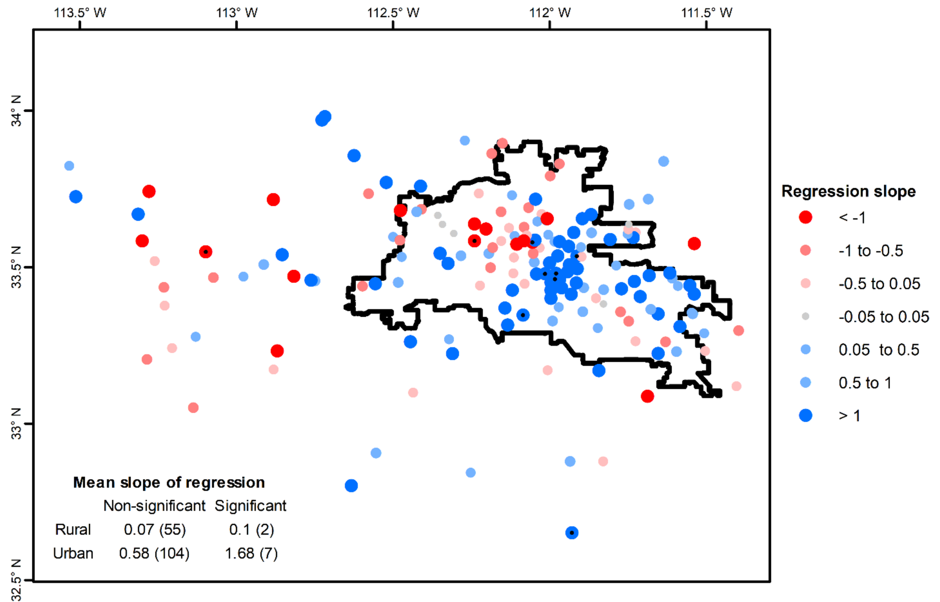

Fig. 3. Trends in maximum annual 10-min rainfall intensity [mm h^{-1} y^{-1}] between 2000 and 2018 computed with a simple linear regression. Red colors represent a negative trend. Blue colors represent positive trends. The magnitude of the regression is expressed by the symbol size. The mean values of the trends are summarized in the inset table (in brackets – the number of stations the value is computed for). Black dots mark stations with statistically significant regression (at 5% level).

Table 1. Regional trends [mm h^{-1} y^{-1}] in annual maximum 10-min and hourly rainfall intensity in urban and rural regions.

Region	Duration	Posterior mean of trend	Significant trend
Urban	10 min	0.53	Yes
	1 h	0.6	Yes
Rural	10 min	0.18	No
	1 h	0.2	No

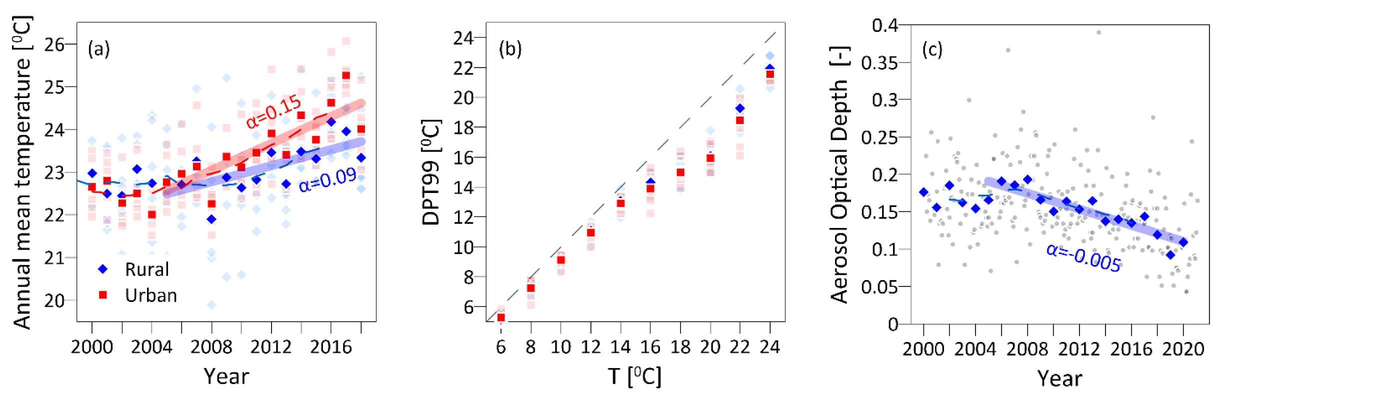

Fig. 4. (a) Annual mean temperature of the urban (light red squares) and rural (light blue diamonds) climate stations. Dark red squares and dark blue diamonds represent the average annual mean temperature for the urban and rural areas (respectively). The dashed blue and red lines represent the 5-year moving window average. Thick blue (urban) and red (rural) lines are the linear trends (α is the slope) computed for the period 2005-2018. (b) 99th percentile dew point temperature (DPT99) – air temperature (T) plot for the same climate stations (red- urban, blue – rural). Dark symbols represent the urban (red) and rural (blue) averages for each temperature bin. (c) Monthly Aerosol Optical Depth (AOD) estimates over the Phoenix metropolitan area (gray dots). The dashed blue line represents the 5-year moving window average for the mean annual AOD (blue diamonds). The thick blue line is the linear trend (α is the slope) computed for the period 2005-2020.

4 Extreme rainfall and temperature relation

- Calculated two sets of scaling rates for each station, one using temperature (Fig. 5a) and the other one using dew point temperature (Fig. 5b).
  - First, classified all wet hours (rainfall intensity >=0.1 mm h^{-1}) and associated temperatures at each rainfall station using the inverse distance weighting method to interpolate from the temperature observations. To minimize biases in the scaling rates caused either by elevation differences between the rainfall and temperature stations or by an excessive distance between them, only chose rainfall stations that were within 3 km from the nearest temperature station.
  - Second, filtered the rainfall data to include only measurements where the temperature was greater than 4°C (0°C for dew point temperature) to eliminate any probability of solid precipitation in the data. Using fixed intervals of temperature (2°C), rainfall data was binned to calculate the 99th percentile (P99) of rainfall for each temperature bin. Only bins with at least 50 rainfall observations were included in the analysis.
  - Third, fitted a linear regression on the logarithm of P99 and the mean temperature of each bin (T) from the first bin to the last bin before the breaking point (i.e. the bin with the highest P99): logP99=α+βT.
  - Finally, estimated the scaling ∂P99/∂T using an exponential transformation of the regression coefficient (β) given by: $\partial P99/\partial T=100(e^{\beta}-1)$.

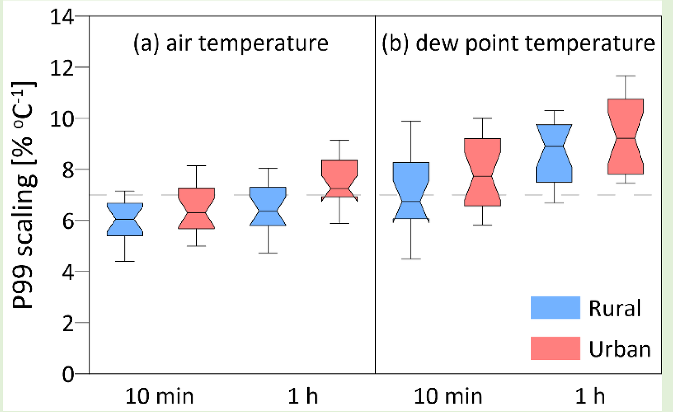

Fig. 5. Box-plots of 10-min and hourly extreme rainfall intensity (99th percentile, P99) scaling with temperature for the rain-gauges located in urban (red, 20 stations) and rural (blue, 18 stations) areas. The scaling is computed with air temperature (a) and with dew point temperature (b). The dashed line represents the theoretical ≈7% °C^{-1} extreme rainfall intensification rate obtained from the Clausius–Clapeyron (CC) relation.

5 Urban humidity analysis

- In cases where the atmospheric moisture is not sufficient to saturate the air column, the intensity of short-duration extreme rainfall is not enhanced with increasing temperatures.
- Extracted the information of the 99th percentile of dew point temperature (DPT99) against T using the same binning strategy as the one used to extract the P99-T relation.
- Plotted the DPT99-T relation for eight ground stations representing the urban area and eight ground stations representing the rural area.
- Located the point of inflection where DPT99 deviates from the 1:1 relationship between the two variables (Fig. 4b). The lower the temperature of the inflection point is, the more moisture-limitations are controlling the scaling of rainfall extreme with temperature entailing sub-CC rates rather than CC rates.

6 Heavy rainfall and urban heat island

- Correlated the intensity of the urban heat island (UHI) with the diurnal timing of heavy rainfall (Fig. 6).
- The eight urban stations and eight rural stations described in the previous section were used to calculate the diurnal cycle of the UHI as the difference between the mean urban and mean rural temperatures in each hour.
- Used the stations located in the urban area to compute the percentage of occurrence of heavy rainfall intensity in each hour of the day. Heavy rainfall for this analysis is defined as rainfall exceeding the 90th percentile (P90).

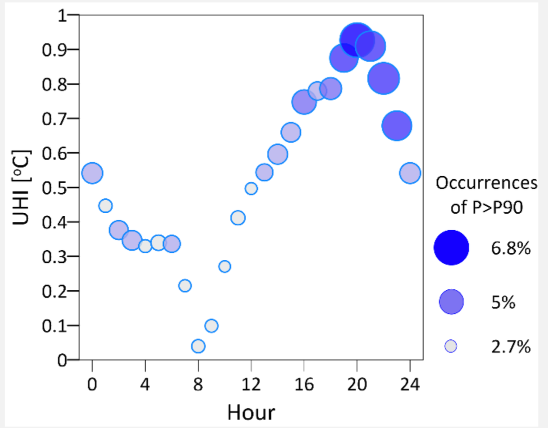

Fig. 6. The diurnal cycle of UHI. The size of the symbols shows the diurnal distribution of the occurrences of rainfall intensity (P) above the 90th percentile (P90).

Further read:
Huang, J., Fatichi, S., Mascaro, G., Manoli, G., Peleg, N. (2022). Intensification of sub-daily rainfall extremes in a low-rise urban area. *Urban Climate*, *42*, 101124.

7 Conclusions

- **In the urban area, rainfall extremes intensify at a much higher rate than its rural surroundings.**
- **The scaling rate between sub-daily extreme rainfall intensity and temperature was found to roughly follow the theoretical Clausius-Clapeyron scaling rate of 7% °C^{-1} in the urban and rural areas.**
  - **For this reason, concluded that the enhanced rainfall intensity is a consequence of the larger increase in air temperature in the city, which has increased significantly more than in the rural areas in the last two decades likely because of urbanization.**
- **Other than the change in urban temperature, have not noticed any considerable changes in humidity or increase in aerosol levels that would affect dynamic storm properties.**

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