Evaluating the Potential of Irrigation for Mitigating Urban Heat: Trade-off between Water Use and Heat Mitigation Capacity

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Abstract

Our world has been continuously urbanized and is currently accommodating more than half of the human population in cities. Despite that cities cover only less than 3% of the Earth's land surface area, they emerged as focal points of human activities, and confront numerous environmental challenges as a result of changes in landscapes, hydroclimate, ecosystems, and biodiversity. In particular, the built environment usually experiences exacerbated heat stress induced by global climate and landscape changes, commonly known as the urban heat island effect. Urban irrigation, as a climate adaptation and mitigation strategy, is effective in cooling the built environment, but exhibits large uncertainties in the trade-off between water use and heat mitigation capacity. Here we show the efficiency of cooling effect induced by irrigation of urban vegetation, represented by a novel metric, viz. urban water capacity, analogous to the heat capacity, across the contiguous United States (CONUS) during summertime via numerical simulations. The urban water capacity is calculated as the average irrigation depth per degree of urban temperature reduction; the values are 4.52 ± 0.77 mm day–1 °C–1 and 7.27 ± 1.27 mm day–1 °C–1 (mean ± standard deviation) for surface and near-surface air cooling, respectively, over the CONUS. The robustness of urban water capacity is further exemplified in an extreme heat wave event, during which the warming anomaly is partially offset by the additional cooling from urban irrigation. Estimates of water capacity provide a quantitative metric for evaluating the efficacy of irrigation in urban planning under current heat stress and future warming.

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Background and Motivation

Urban irrigation: a climate adaptation and mitigation strategy

- Effective in cooling the built environment
- Large uncertainties in the trade-off between water use and heat mitigation capacity
- Dependence on irrigation scheduling, watering amount, and geographical and climatic backgrounds

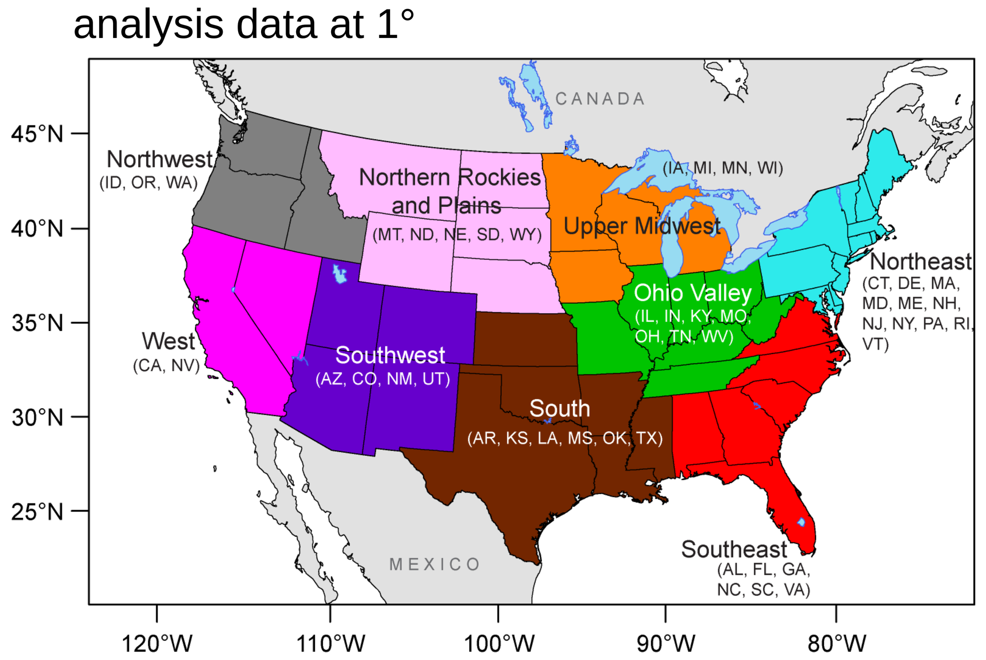
Research objective: quantify the trade-off between irrigation water use and the cooling effect it can provide in various climate regions

Urban water capacity: average irrigation depth per degree of urban temperature reduction (analogous to heat capacity) [mm day^{-1} °C^{-1}]

Methodology

Coupled WRF-LSM-urban modeling system:

- WRF-ARW version 4.0
- Simulation domain: contiguous U.S. (CONUS) – 8 climate regions
- Resolution: 5-km, 32 model eta levels, 3-hr outputs
- Initial and boundary conditions: 6-h NCEP FNL operational global analysis data at 1°



- NLCD 2011 + MODIS + NUDAPT (major cities)
- Unified Noah land surface model + single layer urban canopy model

Urban irrigation simulation and scenario design:

- Three summers in 2012–2014
- Five scenarios (control case 0 and irrigation scenarios 1–4)

	Daily irrigation duration	Local time	Threshold
0	No irrigation		
1	1 h nighttime	2100-2200	Field capacity
2	2 h daytime, 2 h nighttime	0900-1100, 2100-2300	Field capacity
3	2 h nighttime	2100-2300	Porosity
4	2 h daytime, 2 h nighttime	0900-1100, 2100-2300	Porosity

- Irrigation depth of urban grid = Irrigation volume / grid spacing^2
- Cooling effect: surface / 2-m air temperature reduction

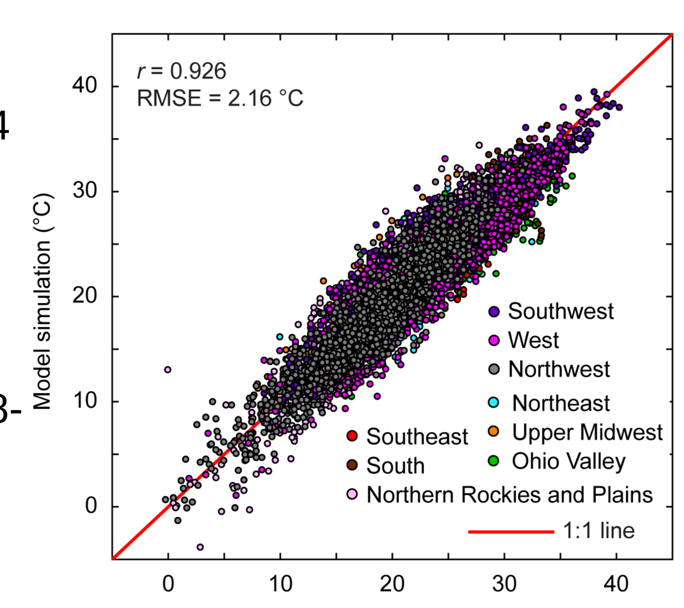
Model Evaluation

Station measurement (air):

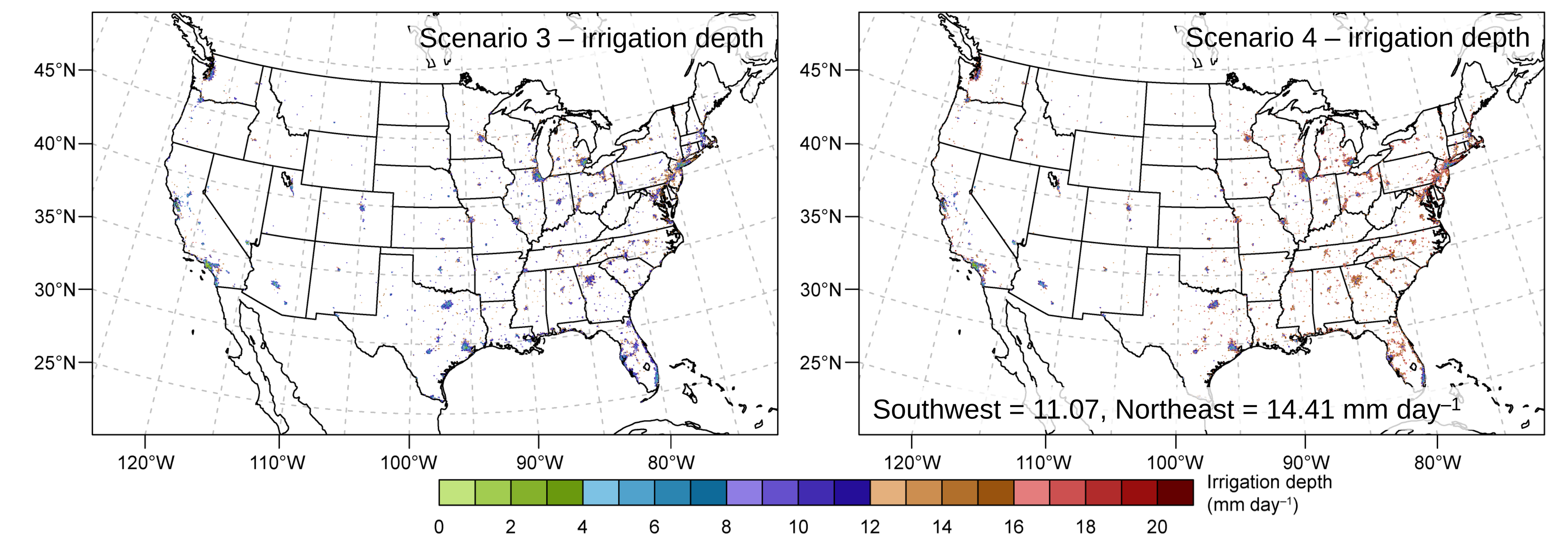
- 135 stations from Global Historical Climate Network-Daily database (64 urban, 71 non-urban)
- r = 0.926, RMSE = 2.16 °C

Remotely sensed data (surface):

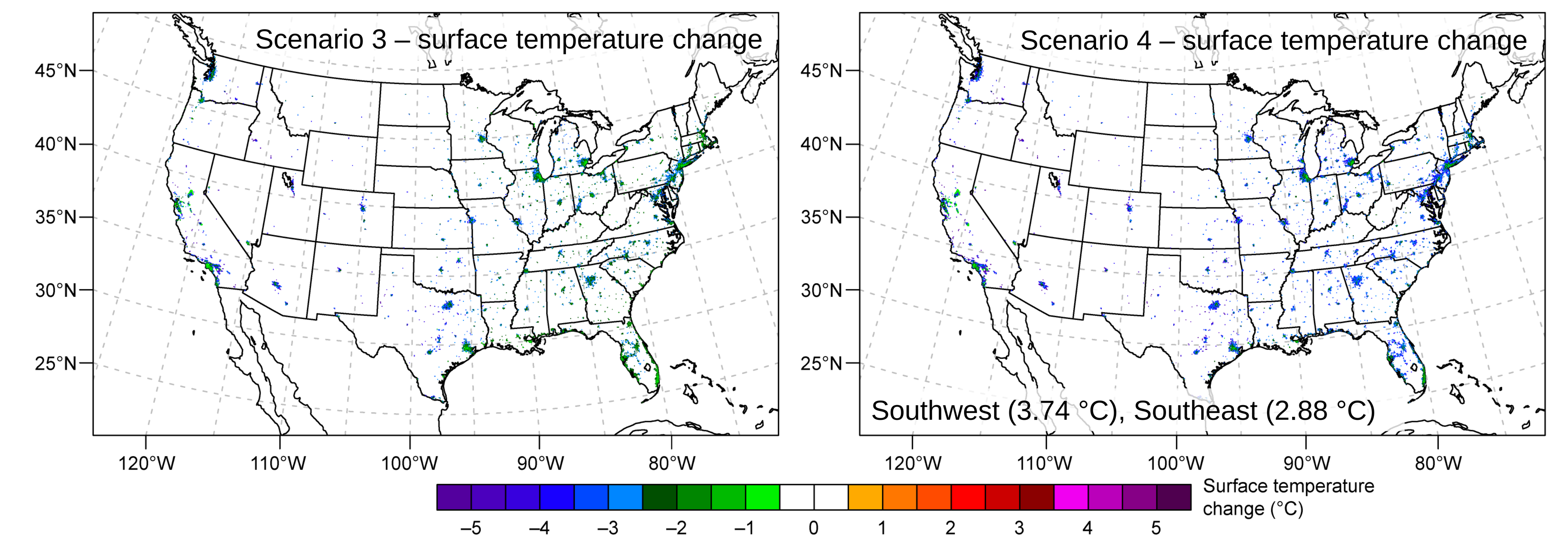
- MOD11B2 and MYD11B2 (5.6 km, 8-day composites)
- June 25–July 2, 2012 (min cloud)
- r = 0.970, RMSE = 3.35 °C



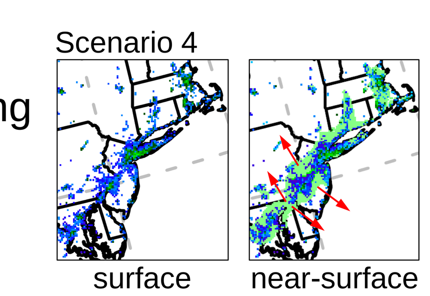
Urban Irrigation Water Use and Cooling Effect



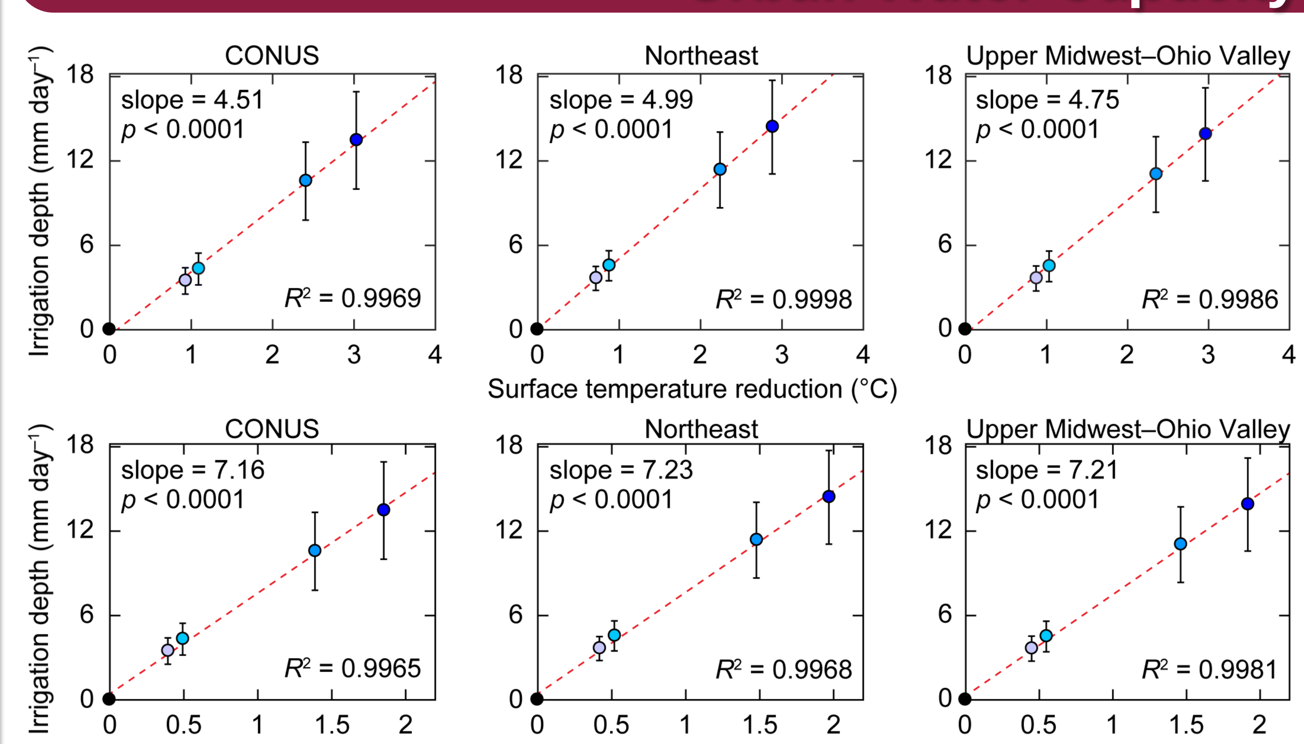
- Daily mean irrigation depth: 3.47 – 13.46 mm day^{-1} (four scenarios)
- Spatial variability: difference in urban fractions, evapotranspiration, and groundwater recharge



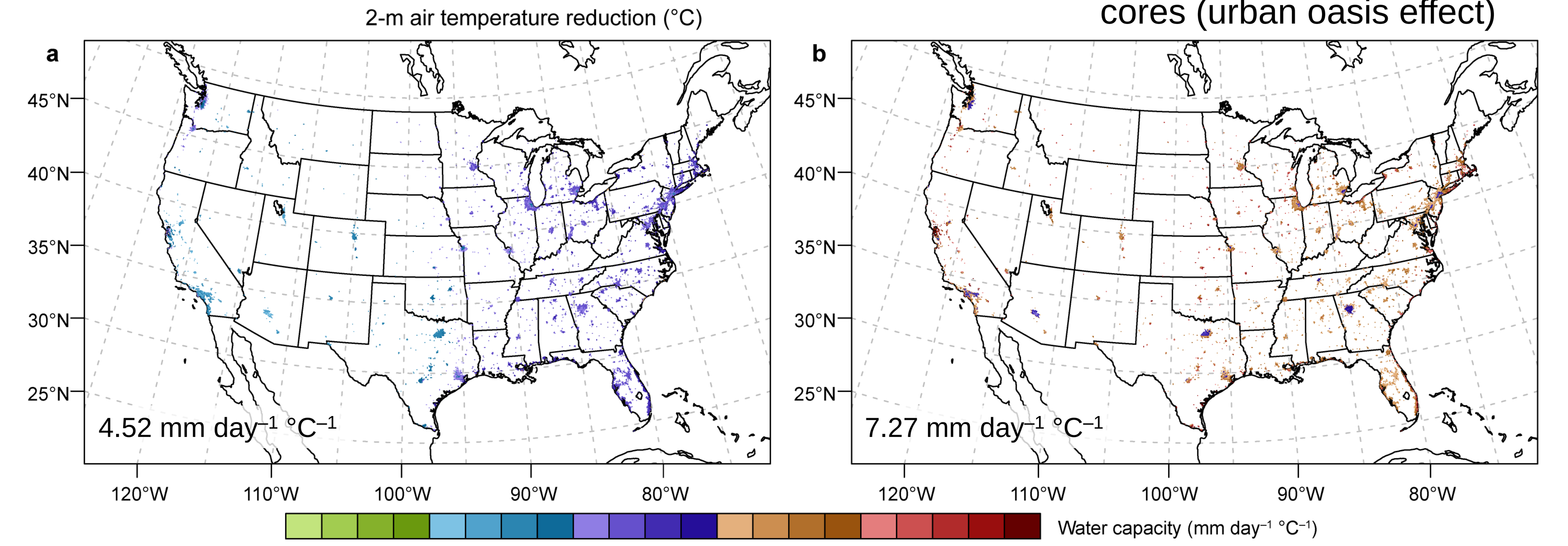
- Greater amount of irrigation → higher temperature reduction
- Intra-city variability: less cooling in urban cores, smaller area of surface cooling
- Scenario 4: surface cooling = 3.04 °C, near-surface cooling = 1.86 °C
- Cooling due to: increased soil moisture, decreased sensible heat, changed latent heat, increased ground heat (higher thermal conductivity)



Urban Water Capacity

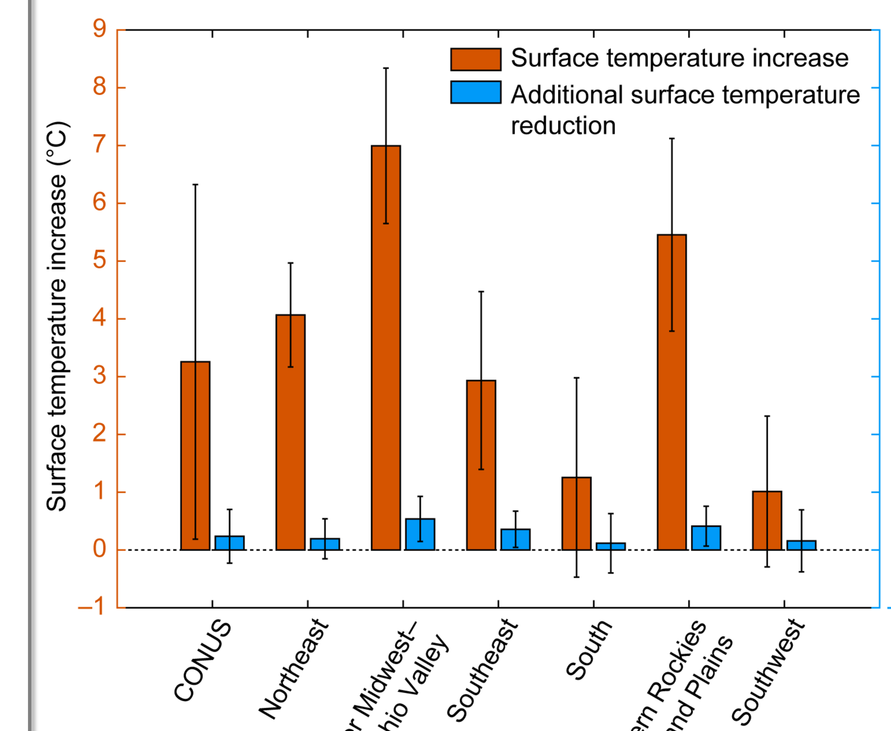


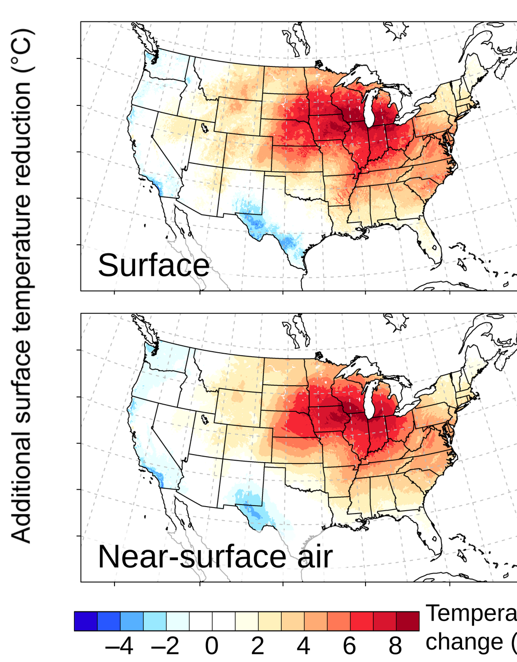
- R^2 > 0.96 for all climate regions [linear regression]
- Urban water capacity for surface < near surface cooling
- For surface cooling: lowest water capacity in Southwest, but highest in Northeast and Southeast
- Higher water capacity in urban cores (urban oasis effect)



Efficacy of Urban Irrigation in Extreme Heat

- Extreme heat: a climate analogue (future climate),
- The most extreme heat wave: 1200 UTC, July 1–0900 UTC, July 8, 2012 (based on 7-day moving windows, exceeds 99th percentile)
- Surface temperature increase: positive anomaly = $T_{HW,0} – T_{norm,0}$
- Additional cooling = $(T_{HW,0} – T_{HW,4}) – (T_{norm,0} – T_{norm,4})$ (for scenario 4)





- Intensification of irrigation-induced cooling is in line with positive temperature anomalies (greater reduction)
- Potential of urban irrigation in combating elevated thermal stress under future climate
- Relatively consistent urban water capacity under both normal and heat wave conditions (proportional)

Conclusion and Perspective

- We proposed the use of *urban water capacity* to ease the comparison of the trade-off between water use and cooling effect among cities and regions on the same ground
- Effectiveness of urban irrigation in alleviating thermal stress
- Urban water capacity is a convenient measure for urban planners to assess environmental and economic co-benefits
- Operational uses under current and future climate (e.g., irrigation–cooling conversion)
- Caution needs to be taken for arid or semi-arid regions
- Future improvement of the numerical simulation

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