Anthropogenic Amplification of Heat Waves Across CONUS: Detection, Attribution, and Urban Implications

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Summary

- Temperature extremes—heat waves and cold snaps—pose escalating risks to urban infrastructure, public health, and energy systems. This study quantifies changes in temperature extremes across CONUS (1950–2005) using CMIP5 CCSM4 climate model simulations under three forcing scenarios: natural-only, greenhouse-gas-only, and all-forcings combined. Heat waves (≥6 consecutive days exceeding the 99th percentile) showed significant intensification under anthropogenic forcing, with a CONUS-mean trend of +5.02 events/year ($p < 0.001$). Attribution analysis revealed an anthropogenic amplification factor of 3.51× relative to natural variability. Spatially, the Southwest, West, and Florida exhibited the strongest heat wave intensification, coinciding with regions of rapid urbanization. These findings underscore the urgent need for climate-adaptive urban planning and heat mitigation strategies in rapidly growing U.S. cities.

Data

Model: NCAR CCSM4 (CMIP5)
Resolution: 0.9375° × 1.25°
Study Area: Latitudes from 49.345°N × 24.743°N
Longitudes from -124.78°E × -66.95°E
Period: 1950–2005
Variables: tasmax, tasmin (Daily Maximum, Minimum Near-Surface Air Temperature)
Scenarios:
•*nat*: Natural forcing only
•*ghg*: Greenhouse gas forcing only
•*all*: All forcings combined (*nat* + *ghg* + land use)

Extreme Event Definitions

Thresholds (from nat scenario, 1950–2000):
•Heat wave: 99th percentile of daily max temp
•Cold snap: 1st percentile of daily min temp
Event Criteria:
•Heat wave: ≥6 consecutive days above threshold
•Cold snap: ≥6 consecutive days below threshold
•Gridcell-level identification with run-length encoding

Attribution Framework

Optimal Fingerprinting Regression: Heat wave frequency modeled as $Y = \beta_{all} \cdot X_{all} + \beta_{nat} \cdot X_{nat} + \varepsilon$. Attribution scaling factor computed as $\beta_{eff} = \beta_{all} / \beta_{nat}$. Statistical significance assessed via linear regression p-values for CONUS.

Threshold & Spatial Patterns

Scenario	Heat Wave (°C)	Cold Snap (°C)
nat	37.72	-26.65
all	38.62 (+0.90)	-25.13 (+1.52)
ghg	38.36 (+0.64)	-24.03 (+2.62)

Both heat wave and cold snap thresholds shift to hotter regimes under anthropogenic forcing, with cold snap thresholds showing larger absolute changes.

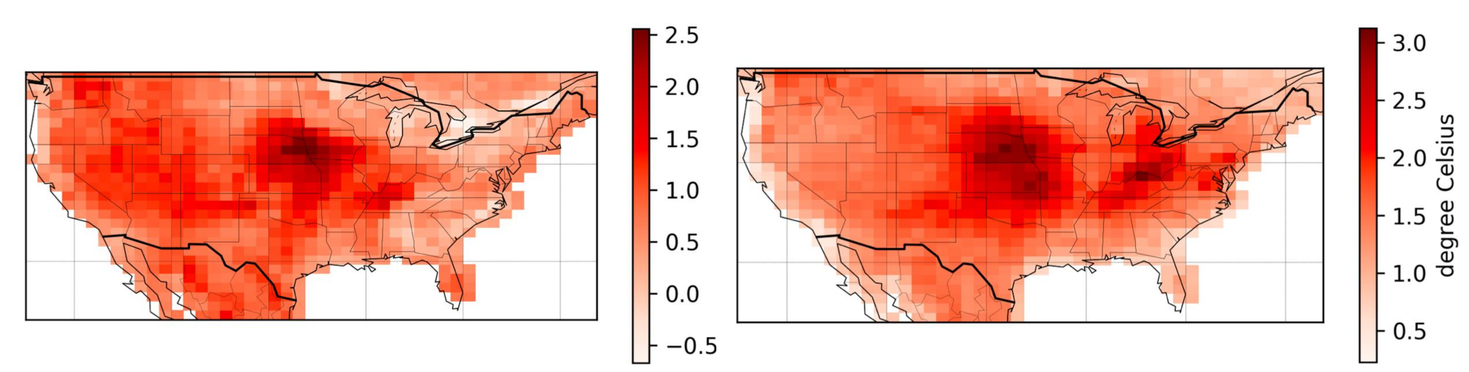

Fig: Difference threshold for heattwaves of *all (left)* and *ghg* (right) vs *nat*

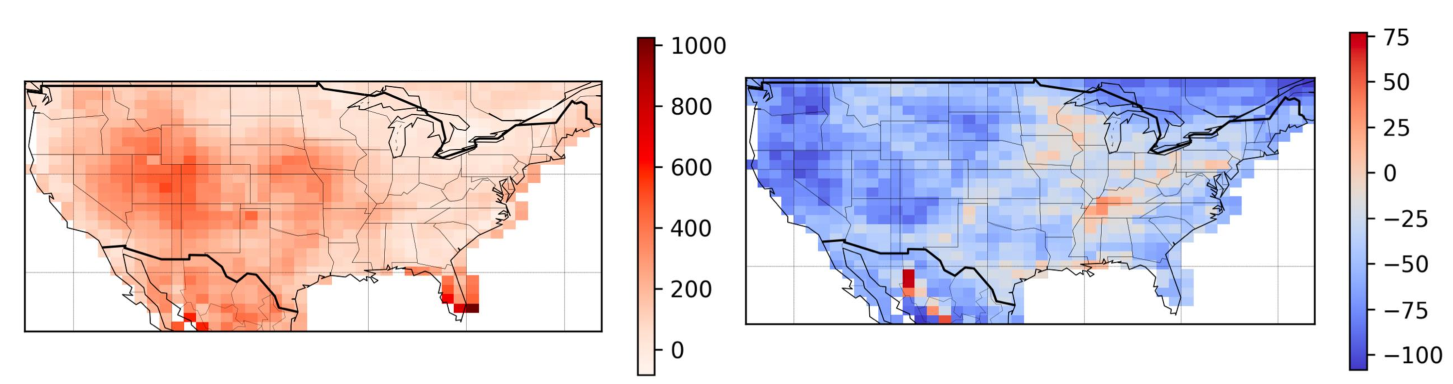

Fig: Difference of total number of hot (left) and cold (right) days of *all* vs *nat*

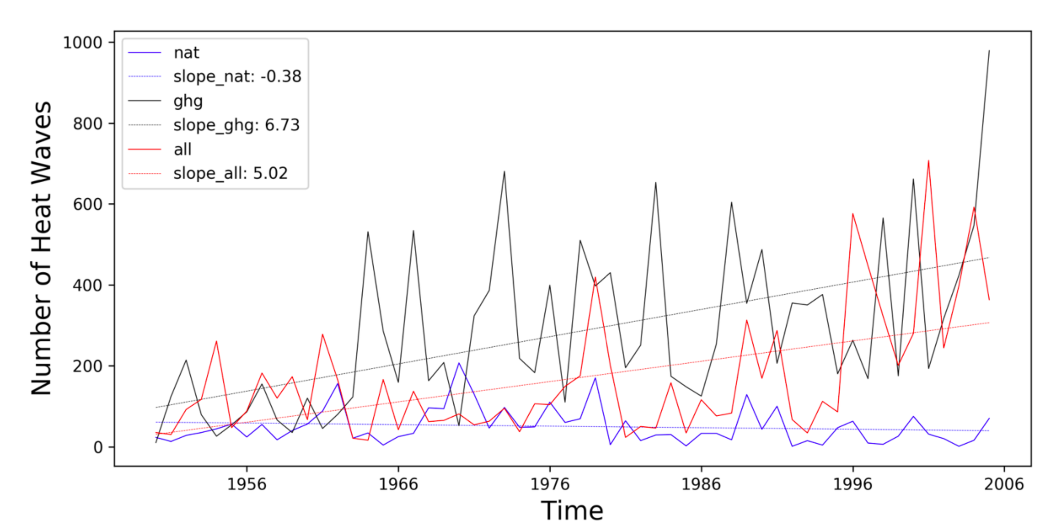

Fig: Trends in count of heatwaves/year with respect to threshold of *nat*.
Slope for *all* is 5.02 heatwaves/year (p value: 0.000028, high confidence)

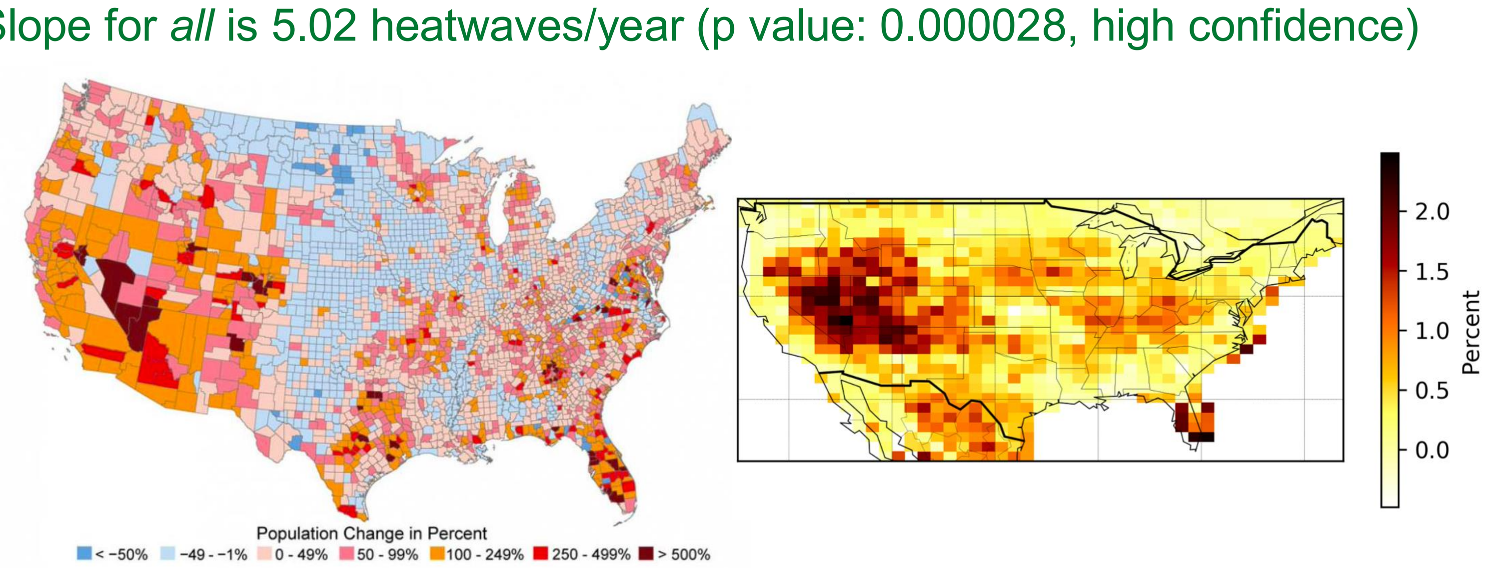

Fig: Change in Population from 1970 to 2008 (left), rate of change of heatwaves in CONUS

Spatial Hotspots

Regions with strongest heat wave intensification:
•**Southwest CONUS:** Highest frequency increase
•**West North Central:** Strong positive trends
•**Florida:** Coastal vulnerability amplification
These regions coincide with areas of rapid population growth and urbanization, suggesting compounding effects of climate change and urban heat island intensification.

Urban Vulnerability: Major U.S. Cities

City	Population (2013)	Growth 2000–2013 (%)	Heat Wave Trend (events/year)	Cold Snap Trend (events/year)
San Antonio, TX	1,409,019	+21.0	**+0.735**	+0.038
Indianapolis, IN	843,393	+7.8	**+0.625**	+0.103
Phoenix, AZ	1,513,367	+14.0	**+0.608**	-0.034
Columbus, OH	822,553	+14.8	**+0.540**	-0.034
Jacksonville, FL	842,583	+14.3	**+0.526**	0.000
Dallas, TX	1,257,676	+5.6	**+0.513**	+0.041
Chicago, IL	2,718,782	-6.1	+0.321	+0.109
Houston, TX	2,195,914	+11.0	+0.075	-0.085
Los Angeles, CA	3,884,307	+4.8	+0.147	**-0.287**

Cities with rapid population growth (San Antonio, Phoenix, Indianapolis) show the steepest heat wave intensification trends. Negative values for cold snaps indicate decreasing frequency.

Implications for Urban Resilience

- Heat wave intensification directly impacts cooling demand for data centers and grid stability. The 50-year return level for heat waves under all-forcing is 971 events/year, far exceeding natural variability.
- Southwest, West, and rapidly urbanizing cities (Phoenix, San Antonio, Indianapolis) require urgent investment in heat mitigation—green infrastructure, reflective surfaces, and cooling centers.
- **Future Directions:** Extension to compound heat-drought events, multi-model CMIP6 ensemble analysis, and integration with urban energy system models to quantify infrastructure vulnerability at city scale.

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