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Targeted implementation of cool roofs for equitable urban adaptation to extreme heat

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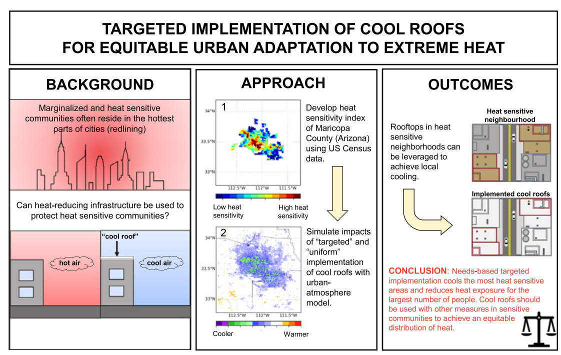
HIGHLIGHTS

- Low-income and communities of color are highly exposed to extreme urban heat.
- Urban meteorology intersects the built environment and human heat sensitivity.
- Urban atmosphere model compares scenarios for installing cool roofs in heat zones.
- Targeted cool roofs to hottest zones reduces exposure for largest number of people.
- Needs-based targeted infrastructure promotes equitable heat adaptation in cities.

GRAPHICAL ABSTRACT



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ABSTRACT

Cities are facing the twin pressures of greenhouse gas driven climatic warming and locally induced urban heating. These pressures are threatening populations that are sensitive to extreme heat due to sociodemographic factors including economic means. Heat-reducing infrastructure adaptation measures such as reflective "cool" materials can reduce urban temperatures. Here we examine the needs-based equity implications associated with heat-reducing cool roofing in Maricopa County, Arizona through application of high-resolution urban-atmospheric simulations. We simulate heatwave conditions and evaluate the air temperature reduction arising from uniform cool roof implementation (i.e., the entire urbanized county), and contrast results against simulated cooling impacts of needs-based targeted cool roof implementation in sociodemographically heat sensitive areas. We find that installing cool roofs uniformly, rather than in a targeted fashion, provides on average 0.66 °C reduction in the highest heat sensitivity area and 0.39 °C temperature reduction in the lowest heat sensitivity area due in part to a higher roof area density in the heat sensitive area. Targeting cool roof implementation yields 0.45 °C cooling in the most sensitive areas compared to 0.22 °C cooling in the least sensitive areas, meaning that needs-based targeted cool roofs in high sensitivity areas provide more relief than cool roofs targeted at low sensitivity areas, thus providing more cooling where it is most needed. Needs-based targeted implementation has the dual benefits of concurrently producing more than twice as much cooling and reducing heat exposure for the largest absolute number of individuals in the densely populated, highly heat sensitive areas. Targeting cool

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roof implementation to high heat sensitivity areas, however, does not achieve thermally equal temperatures in Maricopa County because the high sensitivity areas were substantially warmer than low sensitivity areas prior to implementation. This study illustrates the utility of a new "Targeted Urban Heat Adaptation" (TUHA) framework to assess needs-based equity implications of heat-reducing strategies and underscores its importance by examining the impacts of cooling interventions across sociodemographically heterogeneous urban environments.

1. Introduction

Twenty-first century cities are facing the compounding impacts of climatic change at multiple scales due to greenhouse gas (GHG)-induced global warming and locally-induced warming from the built environment (Georgescu et al., 2013; Krayenhoff et al., 2018). These two factors are creating increasingly extreme climatic conditions in urban environments globally with significant implications for human health and wellbeing. The adverse impacts of extreme heat on human mortality and morbidity are particularly striking and have been widely reported (Oudin Åström et al., 2011). Excess mortality rates of 30-130% during heat wave conditions have been reported in cities on several continents, including Ahmedabad, India (Azhar et al., 2014); Chicago, US (Whitman et al., 1997); Paris, France (Dhainaut et al., 2004); Moscow, Russia (Revich and Shaposhnikov, 2012); and Melbourne, Australia (Nitschke et al., 2011). Additionally, extreme urban temperatures strain resource capacity through increased demand for electricity and water (Guhathakurta and Gober, 2007; Li et al., 2019). Extreme urban temperatures are therefore global public health and natural resource problems that will become ever more pressing as GHG-induced climate warming and urban development continue to occur throughout the 21st century (Costello et al., 2009; Broadbent et al., 2020a).

Cities in the Southwestern United States (US), which are projected to have 13 to 36 additional extreme heat days (99th percentile for reference period 2000-2009) per year by 2100 (Krayenhoff et al., 2018), are representative of the growing risk of 21st century urban climatic warming. Projections for end of 21st century climate suggest that heat exposure (i.e., number of hours of extreme heat multiplied by the number of individuals exposed to this heat) could increase by as much as 40 times by 2100 in Southwest cities due to high-intensity GHG emissions, urban development, and population growth (Broadbent et al., 2020a). Therefore, without GHG emissions abatement, the climatic and demographic trends in this region will compound the number of individuals exposed to extreme temperatures and, in the absence of effective adaptations, prolonged exposure will have serious implications for human health and well-being.

A wide range of sociodemographic and environmental factors influence the distribution of heat vulnerability among urban residents and city neighborhoods. The types of people most likely to experience heat-related morbidity and mortality (i.e., heat sensitive individuals) are persons of advanced or young age and those living with mental or physical disabilities or chronic health problems (Luber and McGeehin, 2008). Important environmental risk factors that explain high heat vulnerability in city neighborhoods include land cover characterized by more impervious surfaces and less vegetation as well as housing where occupants lack access to air conditioning (Harlan et al., 2013; Reid et al., 2009). Higher surface temperatures in neighborhoods with larger proportions of low-income and racial minority residents are commonly reported in many cities (e.g., Mitchell and Chakraborty, 2018; Johnson et al., 2012; Harlan et al., 2006). An epidemiological review of heat-related health studies showed there are racial and socioeconomic disparities in all these factors at individual and community levels that place people of color and low-income residents at high risk for negative heat-health effects (Gronlund, 2014). Thus, uneven heat vulnerability throughout US urbanized areas is driven by complex dynamics of the population heat sensitivity, heterogeneous land cover and associated microclimates, and the historical legacy of housing discrimination through financial disinvestment known as "redlining" (Hoffman et al., 2020). Importantly, a dearth of essential infrastructure and services, plus lower capacity for adaptation, amplify the adverse impacts of extreme heat for sensitive populations. For example, inequities in temperature-reducing ecological resources like urban green space (Jenerette et al., 2011), technological resources like energy-efficient housing (Hoffman et al., 2020) and air conditioning (O'Neill et al., 2005) are common in US cities. Without access to temperature-reducing services and resources, many households in marginalized communities lack the capacity to adapt to increasingly extreme city temperatures.

An emerging method to tackle the threat of rising urban temperatures is heat-reducing infrastructure (Santamouris, 2014; Krayenhoff et al., 2021; Ko, 2018). Architects, planners, and engineers have developed and implemented a variety of infrastructure adaptation technologies to ameliorate extreme temperatures and reduce population exposure to heat, such as green infrastructure (e.g., street trees and green roofs), reflective urban materials (e.g., cool roofs), and shade-providing grey infrastructure (e.g., shade structures). Urban tree-planting initiatives, with the goal of increasing canopy cover, have been widely adopted in cities throughout the US (McDonald et al., n.d.). Street trees provide efficient cooling for pedestrians at street level by reducing radiant temperature (Thom et al., 2016) and the local air temperature cooling effect of urban trees can be substantial with appropriate species and landscape design (Jenerette et al., 2007). Moreover, trees can provide a variety of additional ecosystem services such as wildlife habitat, flood mitigation, and carbon sequestration (Mullaney et al., 2015). However, in arid and semi-arid environments, maintaining non-native healthy trees requires maintenance and application of scarce water resources, which contributes to lower canopy cover, particularly in low-income urban neighborhoods (Jenerette et al., 2011). A strong positive relationship between high income, white residents, and vegetation abundance in urban neighborhoods is widely known in urban ecology as the "luxury effect" (Hope et al., 2003). Although trees are widely considered an effective heat-reducing adaptation, it is important to consider alternative cooling measures that do not place undue additional stress on already limited resources (e.g., water) in semi-arid and low-income cities and neighborhoods.

This study performs a spatial assessment of the thermal implications associated with cool roof implementation targeted at sociodemographically heat-sensitive areas across Maricopa County's (Arizona, US) urbanized areas. The urbanized area in the county is a sprawling desert metropolis of interconnected municipalities, anchored by the city of Phoenix, the 5th largest in the US by population. We use a combination of process-based climate modeling and demographic statistical analyses to explore the implications of targeted implementation of cool roofs. Cool roofs are highly reflective rooftops typically constructed from reflective coatings, single-ply membranes, and cool metal roofing materials. Our analysis focuses on cool roofs because in the semi-arid desert of the Southwestern US, reflective surfaces mitigate heat by reducing surface and air temperatures while conserving scarce water resources. Additionally, cool roofs are more effective as a cooling measure over areas with a year-round warm climate (e.g. Arizona), as the wintertime penalty is reduced in warmer compared to colder climates (Georgescu et al., 2014).

Despite the need to reduce extreme heat exposure among sociodemographically heat sensitive communities (i.e., those communities that most require heat mitigation), landscape modification policies in the Phoenix area remain largely focused on reducing temperatures to attract business and tourism, and favor homeowners who can afford to maintain vegetated landscapes (Harlan et al., 2019). However, it is feasible to install cool roofs in low-income and heat sensitive neighborhoods throughout Maricopa County by taking advantage of greater roof area availability in these neighborhoods. Cool roofs can be implemented with relative ease on public and private properties to provide neighborhood cooling. Our focus exclusively on cool roofs does not imply that municipalities in Maricopa County (or the Southwest region) should pursue a heat adaptation strategy focused exclusively on cool roofs. Rather, by systematically examining a single heat adaptation measure (as opposed to a blend of measures), this study is the first to provide direct insight about the needs-based equity implications of heat-reducing cool roofs.

Cool roof implementation efforts have been less prevalent than urban forestry (tree canopy/urban greening) programs in US cities. Nevertheless, numerous cities offer incentives to businesses and homeowners for adopting cool roofs (e.g., https://coolroofs.org/resources/rebates-and-codes). An examination of climate action/adaptation plans for 40 US cities from 2011 to 2020 found that only 19 specifically mentioned cool roofs as a heat adaptation strategy (Nazli Aragon, personal communication, July 7, 2020). Most cool roofs function principally by reflecting solar radiation and evidence suggests they are effective at reducing city-scale (Broadbent et al., 2020b) and building-scale (Baniassadi et al., 2019) temperatures in the sunny and warm US Southwest. The reflection of solar radiation is manifest as a decrease in absorbed shortwave radiation for a particular urban facet and recent research has demonstrated that high reflectivity coatings lead to approximately 0.2–0.6 °C per 0.1 neighborhood albedo increase (Krayenhoff et al., 2021). A prominent example of cool roof implementation is Los Angeles (California), which has added provisions to municipal codes requiring new roofing materials to meet reflectivity standards (see Title 24; https://www.dgs.ca.gov/BSC/Codes); the city has also begun actively painting roads with reflective coatings with the goal of reducing temperatures throughout the urban environment (Middel et al., 2020).

Previous city-scale modeling analyses of heat-reducing measures (like cool and green roofs) have largely assumed a uniform implementation of infrastructure across urban areas (Georgescu et al., 2013; Salamanca et al., 2016; Stone et al., 2013). However, a recent study revealed cooling benefits of non-uniform cool roof implementation in US cities (Yang and Bou-Zeid, 2019), noting that uniform coverage is "unrealistic." Yang and Bou-Zeid (2019) simulated different scenarios of targeted cool roof implementation and found that cooling was modulated by the shape and location of the metropolitan area; however, they did not consider the spatial patterns of heat sensitivity and vulnerability in their simulations. Sharma et al. (2018) did directly consider spatial patterns of social vulnerability in simulations of green roofs in Chicago (Illinois) – they simulated uniform green roofs and compared simulated roof surface temperatures and electricity consumption with a map of heat vulnerability to identify high-priority areas for green roof implementation. We build on these studies by directly accounting for spatial patterns of sociodemographically defined sensitivity when simulating targeted implementation of heat mitigation measures at the city scale. City-scale numerical studies of heat-reducing infrastructure to date have been useful for establishing the upper limit of cooling derived from heat-reducing infrastructure measures, but have largely not spoken to feasibility or equitable access to cooler environments nor addressed disparities in population heat exposure and heat health vulnerability.

An equitable distribution of heat-reducing infrastructure can be defined in several ways, such as a spatially equal distribution of services, ability to pay for services, or a distribution of interventions determined by the number of residents who will benefit more from remedies (Heckert and Rosan, 2016). A city may adopt a needs-based approach that targets the most vulnerable parts of the city or they may attempt a population-focused approach by seeking to maximize cooling for the most individuals in the city. Many urban greening organizations and initiatives have already adopted needs-based approaches, implementing targeted programs by focusing more resources on – and increasing services in – low-income areas (e.g., "Choice Neighborhoods" program from the US Department of Housing [https://www.hud.gov/cn] and the "Greening of Detroit" non-profit organization [https://www.greeningofdetroit.com/]). Here we consider the cooling effectiveness of targeted heat-reducing cool roofs in Maricopa County from both needs-based and population-focused perspectives.

Understanding the potential cooling effectiveness of targeted heat-reducing measures is required to minimize vulnerability to increasing heat extremes for sensitive populations located in neighborhoods with the highest temperatures. In light of this knowledge gap, we ask the following research questions:

1) What are the relative cooling impacts in sociodemographically high heat sensitive and less heat sensitive areas from uniform implementation of cool roofs throughout the urbanized area of Maricopa County?
2) Does uniform application of cool roofs improve thermal equity of daytime outdoor thermal environments across urban Maricopa County?
3) How much cooling occurs in the most heat sensitive areas from needs-based targeted implementation of cool roofs compared to a uniform implementation across the entire Maricopa County urban environment?
4) In which urban areas does cool roof implementation provide the most reduction in heat exposure for the greatest number of people?

This work is motivated by the goal of producing evidence-based guiding principles on where to implement targeted heat-reducing measures that prioritize equitable distribution of urban thermal environments.

2. Methodology

2.1. Site description and background

Maricopa County (2019 population of 4.5 million [https://www.census.gov/programs-surveys/popest.html]) is located in central Arizona and contains >20 contiguous municipalities anchored by Phoenix, the state's capital and largest city and county seat (Fig. 1). The region has been a focal point for heat exposure and climate adaptation research globally, due to the extreme climate and rapid regional urban development (Chow et al., 2012). The county is in a Tropical and Subtropical Desert Climatic region, characterized by very hot conditions and periods of convective thunderstorms common during the North American Monsoon season. The average daily maximum temperatures (1981–2010) are about 40.4 °C during June, July, and August; although extremely hot days can reach as high as 50 °C during summer (National Weather Service - NWS Phoenix, 2020). Additionally, 2020 was a record summer for extreme temperatures in Phoenix with 53 days > 43 °C (110 °F) and 28 days with daily minima > 32 °C (90 °F) (National Weather Service - NWS Phoenix, 2020). The Maricopa County Department of Public Health recorded an average of 57 heat deaths per year between 2001 and 2010 and an average of 147 heat deaths per year between 2011 and 2020. Record numbers of confirmed heat-associated deaths were observed each year between 2016 and 2020 (154, 179, 182, 199, and 323, respectively)

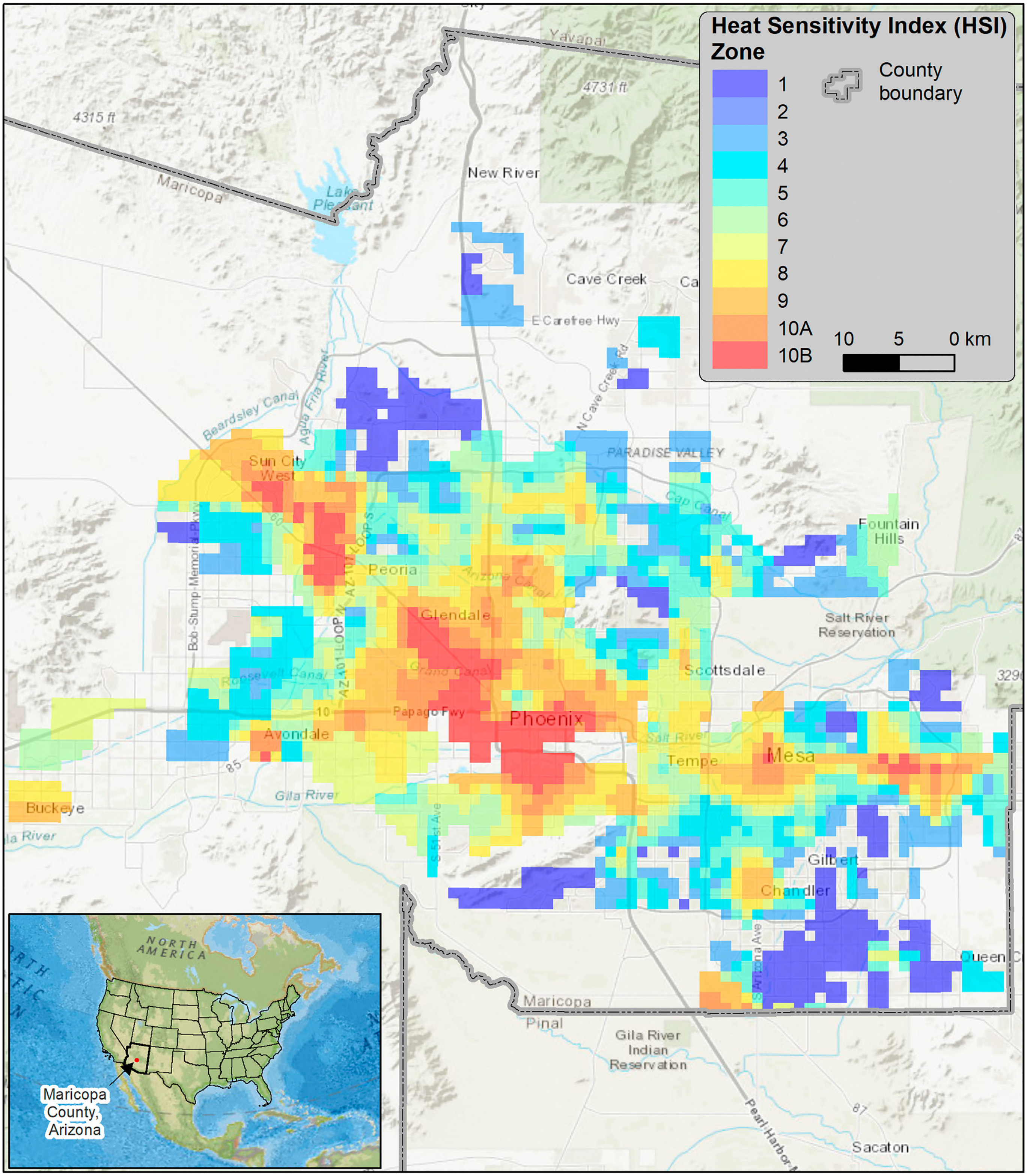

Fig. 1. Map of heat sensitivity index (HSI) zones in Maricopa County, Arizona. HSI 1 = lowest heat sensitivity and HSI 10 = highest heat sensitivity. Note that HSI zone 10 is subdivided into zone 10A (very high heat sensitivity) and zone 10B (extremely high heat sensitivity). The inset shows the location of Maricopa County.

(https://www.maricopa.gov/1858/Heat-Surveillance). Putnam et al. (2018) investigated the relationship between temperature and heat-associated deaths in Maricopa County in 2016 using a time series regression model; they did not find that meteorological conditions predicted the larger than usual number of deaths, which suggests that other factors such as sociodemographic vulnerability may be responsible for the increase of observed heat-related deaths. Regional climate models of mid-21st century Phoenix project an increase in the frequency, intensity, and duration of extreme heat events beyond what the region is currently experiencing

(Grossman-Clarke et al., 2014). Hondula et al.'s (2014) projections of 2050 heat-related mortality in Maricopa County predict that change in heat-related deaths would range from a 95% decrease to a 359% increase, depending on the urbanization scenario and exposure variable utilized. These projection studies do not consider socioeconomic drivers of heat vulnerability.

The distribution of elevated temperatures from GHG-induced climate change is essentially uniform throughout Maricopa County. However, the historical trajectory of urban development centered around Phoenix has contributed to microclimate heterogeneity in rising temperatures within the county (Ruddell et al., 2009). Summer-time differences in evening and nighttime air temperatures can exceed 5 °C between downtown Phoenix and its surrounding desert environment (Brazel et al., 2000). There is also temperature variability among urban neighborhoods throughout the county with specific urban areas experiencing above average temperatures. Historically, the highest surface and air temperatures are experienced in the urban core in neighborhoods with the greatest percentages of Latinx, Black, and low-income residents (Harlan et al., 2013). Redlining in the housing industry dating to the early 20th century, and continuing even after the passage of the 1968 Fair Housing Act, resulted in intentional disinvestment in communities of color and produced the environmental conditions that led to higher temperatures and greater population vulnerability to extreme heat in low-income areas (Harlan et al., 2019).

Spatial epidemiological heat research in Maricopa County has found that summertime heat-related mortality is greater among persons who live in neighborhoods with higher percentages of low-income people of color and elderly living alone (Harlan et al., 2013). In tandem, uneven urban development and racial discrimination that relegate many people of color to hotter neighborhoods also create a low-income population that lacks the economic, technological (e.g., air conditioning), and ecological resources (e.g., tree canopy) to reduce chronic exposure to high temperatures and heat stress (Harlan et al., 2006; Declet-Barreto et al., 2013). The spatial patterns of inequity and related adverse impacts on human health, as well as Arizona's arid climate, establish a clear rationale for targeted implementation of cool roofs in Maricopa County to reduce extreme heat exposure in the most heat vulnerable areas and improve needs-based equity across the region.

2.2. Climate model description and setup

We simulate temperature impacts associated with deployment of cool roofs using numerical simulations performed with the Advanced Research (ARW) version 3.6.1 of the Weather Research Forecasting (WRF) regional climate model (Skamarock and Klemp, 2008). WRF-ARW is a state-of-the-art, processed based, regional weather forecasting and climate model with a long record of urban meteorological and climatological applications (Krayenhoff et al., 2021; Chen et al., 2011). WRF requires meteorological initial and boundary conditions, which we obtained from the ERA-Interim reanalysis dataset (European Centre for Medium-Range Weather Forecasts (ECMWF), 2009). Urban areas are represented with the multilayer Building Effect Parameterization (BEP) (Martilli et al., 2002) and the natural areas are represented using the Unified Noah land surface model (Tewari et al., 2007). Urban land cover is obtained from a high resolution (1 m) land cover dataset, including spatially explicit urban fraction and vegetation characteristics (Li et al., 2014). We define three urban categories based on plan-area-ratios derived from Li et al. (Li et al., 2014), which approximate the Local Climate Zones (LCZs) 1 (compact high-rise), 6 (open low-rise), and 9 (sparsely built) (Stewart and Oke, 2012). LCZs are a climatic land-use categorization system that classifies land-uses into similar groups based on characteristic diurnal pedestrian-level air temperature regimes (see Stewart and Oke, 2012 for more details). WRF was setup with three nested domains, centered over Maricopa County, with horizontal grid spacings of 16 km, 4 km, and 1 km. The innermost domain has 156 by 156 grid squares in the north-south and east-west directions with 42 vertical levels defined. The lowest vertical level is located at street level approximately 2 m above ground, so that pedestrian air temperature is directly modeled, not diagnosed. See Broadbent et al. (2020b) for a full description of setup and parameters used in these model integrations. All simulations were initialized on 11 July 2006, allowing 9 days of model "spin-up" prior to the heatwave case study. Data from the spin-up period were excluded from the subsequent analysis. This WRF setup and parameters were extensively evaluated against in situ hourly air temperature observations by Broadbent et al. (2020b), who found adequate model performance for Maricopa County at locations in the urban environment with a predicted root-mean-square error of 2.6 °C and mean bias error of −0.5 °C.

2.3. Heat sensitivity index (HSI) calculation

To design targeted heat mitigation scenarios based on population sensitivity to heat, we developed a heat sensitivity index (HSI) for census tracts in Maricopa County (Fig. 1). In our HSI, we excluded census tracts with a 2017 population density of <300 persons per square kilometer. We included 830 of 916 total census tracts (90.6%) in Maricopa County. We created our HSI as a modified version of the index of heat vulnerability in Reid et al. (2009) and Harlan et al. (2013), conforming to Tate's (2013) definition of a deductive index of hazards vulnerability (i.e., containing less than ten normalized indicators). Our HSI is defined as:

$$HSI_i = \sum_{i=1}^{n} \left(\ddagger_{i,v} + \ddagger_{i,v+1} + \ldots + \ddagger_{i,v+n}\right)$$

where $\ddagger$ is the z-score of the vth indicator in Census Tract i, and $HSI_{i,}$ is the sum of scores in Census Tract i. We included only population heat sensitivity descriptor variables in our HSI—omitting the built environment exposure descriptors—because we quantify exposure using simulated WRF air temperatures. The population heat sensitivity descriptors we used are a subset of sociodemographic variables known to influence heat-related mortality and morbidity (Harlan et al., 2013; Reid et al., 2009; Johnson et al., 2012).

To derive the HSI we obtained tract-level race, ethnicity, age, and household size data from the 2010 US Census of Population and Housing (US Census Bureau; American Community Survey, 2010). We also obtained data on poverty, disability, educational attainment, and nutritional assistance from the 2015 American Community Survey 5-Year Estimates. We used the R package *censusapi* (2020) to retrieve data tables from the US Census Bureau data application programming interface. We then created census tract-level variables that represent the individual characteristics positively associated with increased heat-related vulnerability. As a first step in HSI construction, we assessed the statistical correlation between markers of sociodemographic heat sensitivity (percentage not white, living in poverty, no high school diploma, and receiving nutritional assistance), and heat sensitivity related to age, social isolation and mental or physical disability (percentage 65 or older, living with a disability, and living alone) (Table 1). The very high positive correlations among the four socioeconomic heat sensitivity variables are statistically significant. The percentage of persons 65 or older, percentage with a disability, and percentage living alone are correlated positively with each other but tend to be negatively correlated with race/ethnicity, poverty, education, and food assistance. The population mean percentages and correlation patterns show that multiple variables, known to public health researchers as risk factors for heat-related illness, occur in this sample and they are statistically related to each other in meaningful ways.

We normalized each variable by recoding as z-scores and added the z-scores of all variables together for each census tract (HSI z-score range among census tracts was −7.19 to 13.55). The HSI was then resampled to a 1 km grid, matching the WRF modeling domain, and divided into deciles based on the HSI values (as shown by color-coding in Fig. 1).

Table 1
Summary of means (standard deviations [sd]) for percentages of population and Pearson correlations for variables used to calculate the Heat Sensitivity Index (HSI) for census tracts in Maricopa County, AZ. Data from 2010 US Census and 2015 American Community Survey.

	Percent persons of color (1)	Percent living in poverty (2)	Percent no High School Diploma (3)	Percent receiving nutritional assistance (4)	Percent 65 or older (5)	Percent with a disability (6)	Percent living alone (7)
Mean (sd)	40.7 (25.8)	17.4 (15.0)	14.2 (12.9)	12.9 (12.3)	13.1 (15.0)	10.9 (5.4)	24.6 (12.1)
(1)							
(2)	0.77***						
(3)	0.87***	0.79***					
(4)	0.83***	0.86***	0.85***				
(5)	−0.49***	−0.26***	−0.26***	−0.31***			
(6)	−0.17***	0.03	0.06	0.04	0.71***		
(7)	−0.19***	0.10**	−0.15***	−0.05	0.38***	0.45***	

** Denotes significance at the 0.01 level.
*** Denotes significance at the 0.001 level.

This process yielded 10 evenly sized "HSI zones" ranging from high sensitivity (coded as 10) to low sensitivity (coded as 1). The HSI zones have the same plan area, but each zone has a unique total roof area, meaning more (less) cool roofs can be installed in areas with a greater (lower) roof density. Hereafter, we will use the terms "zone" or "area" when referring to the HSI deciles. Lastly, to obtain higher precision results among the highest heat sensitivity areas, we subdivided the highest sensitivity zone (i.e., zone 10) into two equally sized zones representing very high sensitivity areas (coded as 10A) and extremely high sensitivity areas (coded as 10B; Fig. 1).

2.4. WRF heat wave simulations

Our simulations focus on a 5-day extreme heat wave case study period (July 20 – July 24, 2006), which was one of the hottest 5-day events recorded in Maricopa County during the period 1980-2010 (see Broadbent et al., 2020b). We first simulated the heat wave case study period without any cool roofs implemented (i.e., control simulation). We then conducted a series of simulations wherein cool roofs were implemented by increasing rooftop reflectivity from 0.16 to 0.88. This roof reflectivity was chosen to represent the maximum reflectivity of a very high performing reflective roof coating, including 3 years of deterioration (https://www.energystar.gov/productfinder/product/certified-roof-products/). In total, we conducted 9 simulations with cool roofs implemented in different HSI zones throughout Maricopa County (see Table 2 and Fig. 1 for reference). We simulated a targeted needs-based implementation of cool roofs by systematically increasing their spatial extent, starting with the extremely heat sensitive zone (10B) and moving outwards into lower heat sensitivity areas in the county. We calculated the impacts of cool roofs on air temperature by comparing simulated air temperature against the control simulation. Here we focus on the absolute cooling impacts of cool roofs, meaning that we do not analyze the normalized cooling impacts (i.e., cooling per m^2 of cool roof implemented) as this was the focus of previous work (see Broadbent et al., 2020b).

Table 2
Summary of WRF simulations conducted and corresponding level cool roof installation. See Fig. 1 for a visual representation of the HSI zones.

Simulation name	Cool roofs implemented in:
Control	No cool roofs
Cool all	Cool roofs installed on all roofs in Phoenix
Cool 1	Cool roofs installed on all roofs in HSI zone 1 (lowest heat sensitivity zone)
Cool 1 and 2	Cool roofs installed on all roofs in HSI zones 1 and 2
Cool 1 - 3	Cool roofs installed on all roofs in HSI zones 1 to 3
Cool 7-10	Cool roofs installed on all roofs in HSI zones 7–10 (A&B)
Cool 8-10	Cool roofs installed on all roofs in HSI zones 8–10 (A&B)
Cool 9-10	Cool roofs installed on all roofs in HSI zones 9 and 10 (A&B)
Cool 10A and 10B	Cool roofs installed on all roofs in HSI zones 10A & 10B
Cool 10B	Cool roofs installed on all roofs in HSI zone 10B (highest heat sensitive zone)

2.5. Framework for targeted adaptation to urban extreme heat

A major limitation besetting urban heat mitigation research is a general lack of consistency and standardization in the way that cooling impacts are modeled and evaluated (Krayenhoff et al., 2021). Since the impact of cool roofs are partially "non-local" (i.e., cool air is transported from the atmosphere above the cool roofs to downwind areas without cool roofs), it is particularly important to have a clear definition of the area over which the temperature reduction resulting from heat-reducing measures is defined. With that in mind, we developed a framework for measuring the impacts of targeted urban heat adaptation to urban extreme heat. The framework for Targeted Urban Heat Adaptation (TUHA) permits assessment of the thermal equity implications of cooling derived from heat-reducing adaptation measures by clearly defining different scales of implementation (of cool roofs in this case) and air temperature reduction evaluation as follows (also see Fig. 2):

- "**Widespread impacts of uniform implementation**" – for this case cool roofs are applied to all roofs in the urban area and the temperature impacts are assessed at the scale of the entire urban area. This method is commonly used in heat mitigation modeling studies (Fig. 2a).
- "**Local impacts of uniform implementation**" – this case also includes uniform implementation of cool roofs across the entire urban area, but the cooling is evaluated in a specific high heat sensitivity area (Fig. 2b).
- "**Local impacts of targeted implementation**" – cool roofs are implemented in a targeted area (i.e., a high heat sensitivity area) and the cooling impact is only evaluated in that specific area (Fig. 2c). The notion of 'high heat sensitivity' has no specific definition in the TUHA framework and can be defined by the user. For example, in this work we define high sensitivity areas as those with HSI ratings of 9 or 10.
- "**Local impacts of expanding implementation zones**" – in this case implementation of cool roofs extends beyond the high heat sensitivity area to nearby zones, but the impacts are only evaluated in the high sensitivity area (Fig. 2d).

The TUHA framework will be referred to throughout the results and discussion sections. It allows us to evaluate factors such as the magnitude of local and non-local cooling impacts and the optimum level of cool roofing implementation for achieving air temperature cooling in the highest heat sensitivity areas of Maricopa County.

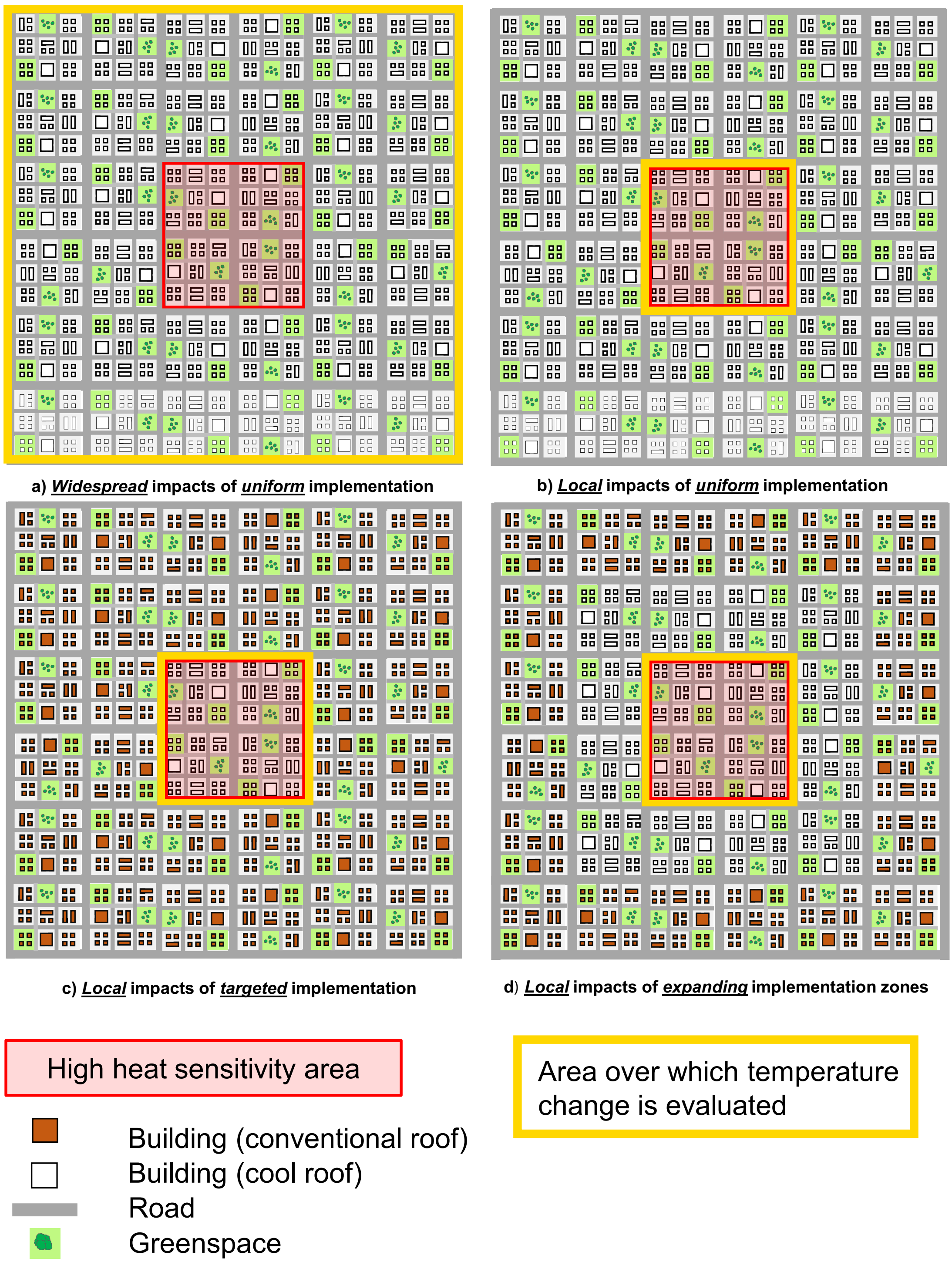

Fig. 2. Schematic illustrating the Targeted Urban Heat Adaptation (TUHA) framework. The four panels show a near identical urban area with hypothetical buildings, streets, and greenspace. Additionally, each panel shows the area in the hypothetical city where heat sensitive residents live (indicated with a red box). Each panel contains a different distribution of conventional roofs (i.e., shingle, tile etc.; shown in brown) and cool roofs (shown in white). Each panel also shows a different definition of the area over which temperature change is evaluated (yellow box). The following scenarios emerge (panel a) "Widespread impacts of uniform implementation" – for this case cool roofs are applied to all roofs in the urban area and the temperature impacts are assessed at the scale of the entire urban area (yellow box covers the whole urban area). (panel b) "Local impacts of uniform implementation" – this case also includes uniform implementation of cool roofs across the entire urban area, but the cooling is evaluated in a specific high heat sensitivity area (i.e., the red box and yellow box comprise the same area). (panel c) "Local impacts of targeted implementation" – cool roofs are implemented in a specific area (i.e., high heat sensitivity; red box) and the cooling impact is only evaluated in that specific area (i.e., the red box and yellow box comprise the same area). (panel d) "Local impacts of expanding implementation zones" – in this case cool roof implementation extends beyond the high heat sensitivity area to nearby zones but the impacts are only evaluated in the high sensitivity area (i.e., the red box and yellow box comprise the same area). This study will consider the impacts of all four combinations of cool roof implementation and scales of cooling evaluation represented in this figure.

3. Results

3.1. Air temperature impacts of cool roofs implementation

The simulated air temperature cooling impacts of cool roofs are predominately confined to daytime hours, which is consistent with previous research (Cao et al., 2015) . Here we will focus on daytime cooling impacts, defined as 11 am–6 pm because this is when people often experience the most severe outdoor heat stress. Though cool roofs also cool indoor building temperatures, we will focus exclusively on simulated outdoor temperatures in this study.

3.1.1. Air temperature impacts of uniform implementation of cool roofs

The widespread simulated impacts of uniform implementation of cool roofs across the entire urban environment (Fig. 2a) in Maricopa County lead to an average cooling of 0.56 °C during daytime hours. There is spatial variability in the magnitude of cooling from uniform implementation with areas downtown experiencing more cooling (approximately 1 °C of cooling) than areas on the urban-rural fringe (approximately 0.25 °C of cooling) (Fig. 3). Fig. 4 shows the daytime local cooling impacts of uniform implementation (as defined in Fig. 2b) in each HSI zone. The data contained in each box represents cooling derived from all pixels and all daytime hours (11 am to 6 pm) in each HSI zone; therefore, Fig. 4 includes the spatial and temporal variability of daytime cooling derived from implementation of cool roofs in Maricopa County. The local cooling impacts of uniform implementation range from 0.39 °C in HSI 1 (lowest heat sensitivity) to 0.66 °C in HSI 10B (highest heat sensitivity) (Fig. 4). The amount of cooling increases from lower sensitivity to higher sensitivity zones, indicating that under uniform implementation of cool roofs high heat sensitivity areas are projected to receive more cooling than low heat sensitivity areas. Greater absolute cooling occurs in zone 10B than zone 1, in part, because zone 10B has 2.5 times higher roof area density than zone 1 (Table S.1), which means that more total surface area can be coated with cool roofing in the high heat sensitivity areas. It is not happenstance that low socioeconomic areas (e.g., Zone 10) have higher roof area, as these areas historically have higher density housing and less ground area of greenspace. These results demonstrate that rooftop area is a key variable that constrains the magnitude of cooling that can be achieved from implementation of cool roofs throughout the urban environment.

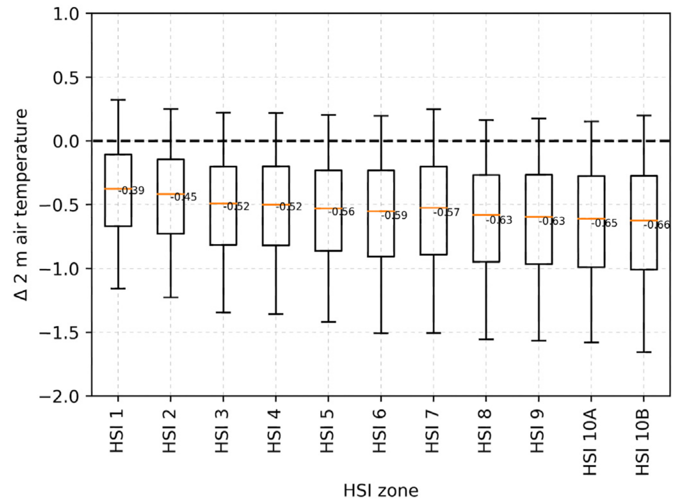

Fig. 4. Boxplots of WRF-simulated neighborhood air temperature impacts of uniform cool roof implementation (i.e., as shown schematically in Fig. 2b). We calculate the daytime (11 am–6 pm local time) air temperature change in each HSI zone when cool roofs are applied to all buildings in the city. The boxes represent the median and inter-quartile range, while the whiskers indicate the 5th and 95th percentiles. The mean temperature change of each HSI zone is also indicated. Variation of the change in daytime air temperature includes both spatial and temporal (i.e., over multiple heat wave days) variability.

Although the higher heat sensitivity areas receive more daytime cooling than the low sensitivity areas in absolute terms, the amount of cooling derived from uniform implementation of cool roofs is not enough to achieve equitable thermal conditions across all areas in Maricopa County. Even with the maximum implementation of cool roofs, the air temperature in HSI zones 7 through 10 is projected to remain warmer than the control air temperature in HSI zones 1 through 3. This is shown in Fig. 5 – which is much like Fig. 4 but shows the absolute temperatures (not temperature differences) – by observing that the red boxes (control air temperature) for HSI zones 1 to 3 are at least 1 °C cooler than the blue boxes (temperature with uniform cool roofs) for HSI zones 7 to 10. These results illustrate that a uniform application of cool roofs alone cannot provide enough cooling to provide equitable thermal environments in Maricopa County.

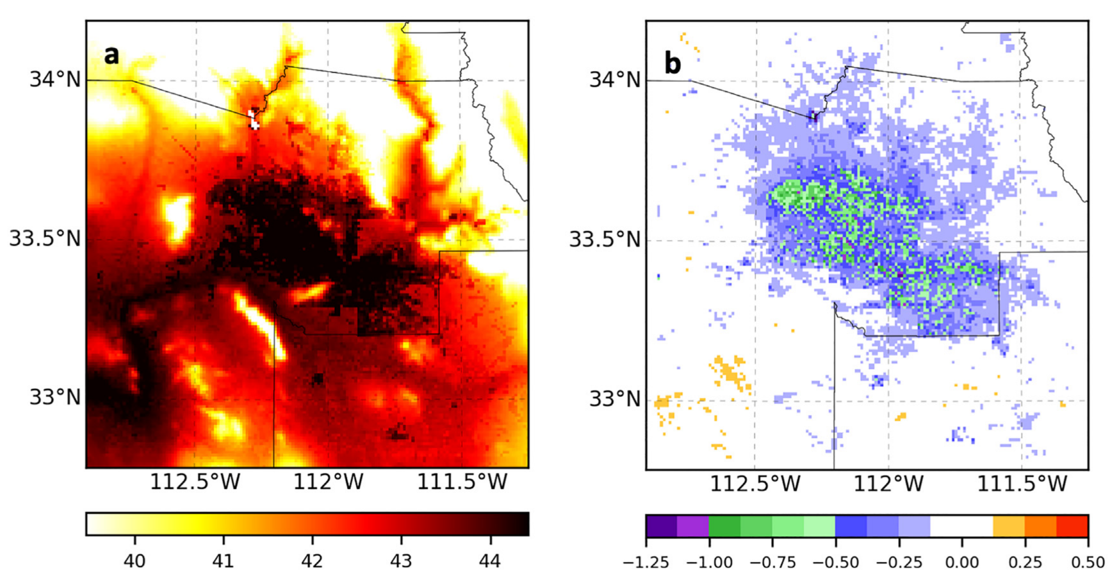

Fig. 3. (a) WRF-simulated average daytime (11 am–6 pm local time) 2 m air temperature during the July 20–24, 2006 heat wave and (b) simulated change in daytime 2 m air temperature during heat wave due to uniform implementation of cool roofs in all HSI areas. The outline of Maricopa County is shown in black.

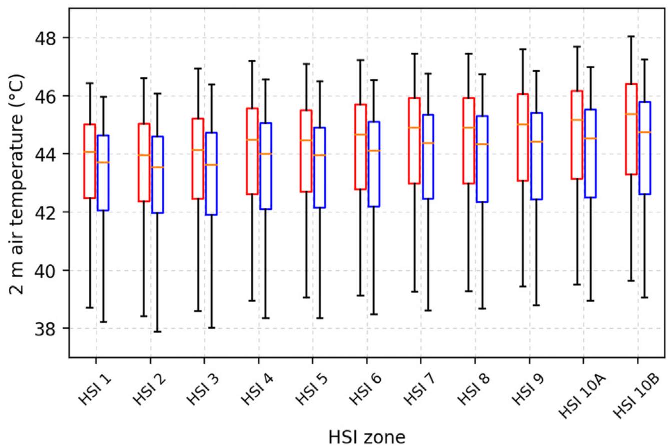

Fig. 5. Boxplots of WRF-simulated daytime (11 am–6 pm) absolute air temperature in each HSI zone with no cool roofs (CONTROL; red) and cool roofs applied to all buildings in the city (COOL ALL; blue). The boxes represent the median and inter-quartile range, while the whiskers indicate the 5th and 95th percentiles, including both spatial and temporal variation in the daytime air temperature.

3.1.2. Air temperature impacts of needs-based targeted implementation of cool roofs

The local impacts of needs-based targeted implementation (i.e., as illustrated in Fig. 2c) are projected to have a smaller cooling impact than the local impacts of uniform implementation (i.e., Fig. 2b). The local cooling impacts of targeted implementation are smaller than uniform implementation because cooled air is no longer transported from the areas upwind of the locations where cool roofs are implemented. To investigate targeted impacts, we plot average daily composites of temperature change within zone 10B (extreme heat sensitivity area) occurring due to different scales of cool roofing implementation across the county (Fig. 6). For example, in Fig. 6a, the magenta curve (labeled "cool all", i.e., uniform implementation) represents the mean cooling ($\pm$1 sd of spatial variability) derived in zone 10B when cool roofs are applied to all roofs in the county. The dark red curve (labeled "cool 10B only") represents the mean cooling ($\pm$1 sd of spatial variability) derived in zone 10B when cool roofs are applied to zone 10B only. Targeted implementation in zone 10B (curved labeled 'cool 10B only' in Fig. 6a) yields an average of 0.45 °C of cooling within zone 10B, as compared to 0.66 °C with uniform implementation (curved labeled 'cool all' in Fig. 6a). By contrast, targeted implementation of cool roofs in the lowest heat sensitivity areas (curve labeled "cool 1-3" in Fig. 6b) would provide 0.22 °C of cooling within zone 1, as compared with 0.39 °C under uniform implementation of cool roofs (curve labeled "cool all" in Fig. 6b). This indicates that needs-based targeted implementation of cool roofs is projected to provide more than twice as much cooling in high heat sensitivity areas than in low heat sensitivity areas. As noted above, the total rooftop area that could be converted to cool roofs in zone 10B is 2.5 times more than the rooftop area in zone 1.

To further explore the subtleties of needs-based implementation of cool roofs in Maricopa County we turn to local impacts of expanding implementation zones (i.e., as illustrated in Fig. 2d). We find that the local cooling impacts simulated for zone 10B (extreme heat sensitivity) will reach 77% of the maximum possible cooling impact (i.e., the cooling derived from uniform implementation) if cool roofs are implemented in zone 10 only, and 88% of the maximum impact if implementation of cool roofs is expanded to high heat sensitivity zones 9 and 10 (Fig. 6a). In other words, installing cool roofs across the entire urban area would merely increase the cooling in zone 10B by 14%, relative to cooling derived from a targeted implementation of cool roofs in zones 9 and 10. These results imply that the cooling impacts of cool roofs are predominately local and if one is targeting cooling in the extremely

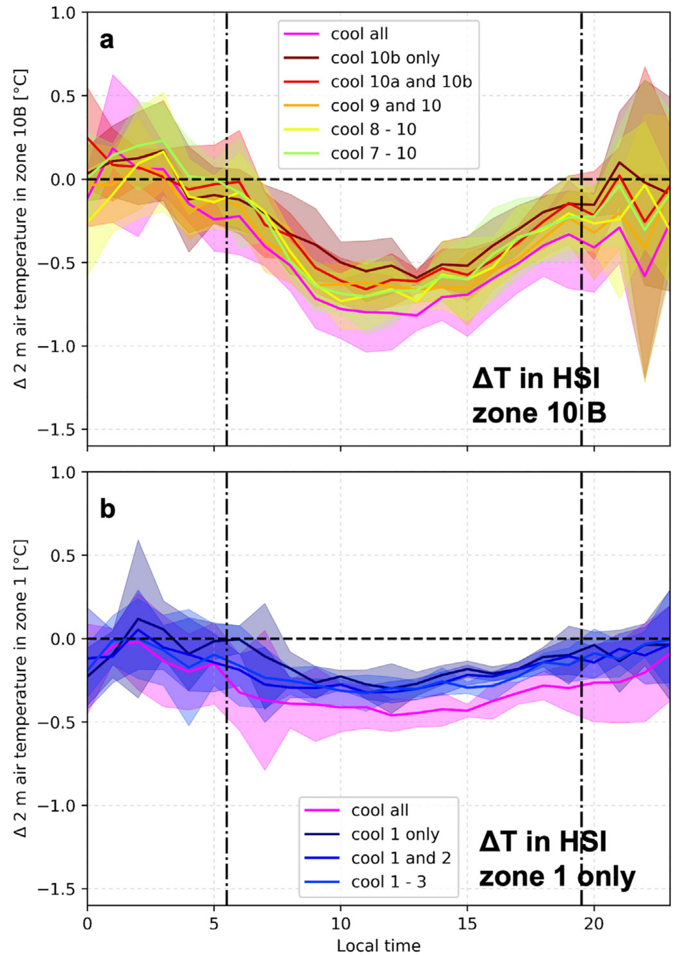

Fig. 6. Diurnal composites of spatial average change in WRF-simulated pedestrian-level air temperature for period July 21st–July 26th, 2006 in (a) zone 10B and (b) zone 1 resulting from cool roof implementation in expanding implementation zones (different cool roof implementation zones indicated by color coded lines). Shading about each curve indicates 1.0 standard deviation of temporal (not spatial) variability.

heat sensitive areas of Maricopa County (i.e., zone 10B), installing cool roofs beyond HSI zones 9 and 10 will provide minimal additional benefits in zone 10B. The cooling impacts of expanding implementation zones are less effective at reducing temperatures in the least heat sensitive areas (i.e., zone 1); increasing implementation of cool roofs through zones 1-3 has negligible impacts on the magnitude of simulated cooling in zone 1 (Fig. 6b).

3.2. Population-weighted impacts of cool roofing implementation

In addition to the absolute temperature impacts it is also important to consider the population-weighted impacts of cool roofing implementation. In which areas does implementation of cool roofs provide the most cooling for the most people? Here, population-weighted impacts are calculated by counting the number of hours of extreme heat that occur in each WRF grid cell and multiplying by the population of each grid cell (hereafter referred to as "person hours" of exposure; refer to Broadbent et al. (2020a)). We examined three different extreme heat thresholds to calculate person hours of heat exposure: 35 °C, 40 °C, and 45 °C. The 35 °C and 40 °C thresholds represent Maricopa County's maximum daily high temperatures for "minimum risk" of all-cause mortality and "excessive risk" of heat-related hospitalizations, respectively (Petitti et al., 2016). Additionally, 45 °C is used as an extreme heat threshold based on a 2005 Phoenix heat wave study (Ruddell et al., 2009). Herein, we used the "no cool roof" control simulation and the cool roof scenarios (Table 2) to calculate the total avoided person hours of extreme heat exposure derived from cool roofs (Tables S.2, S.3, and S.4). For example, in Table S2, each row represents the number of avoided person hours (using the 35 °C heat threshold) in each HSI zone, corresponding to the different cool roof implementation scenarios.

3.2.1. Population-weighted impacts of uniform implementation of cool roofs

The total projected exposure to extreme temperatures during a 5-day heat wave in Maricopa County (i.e., the sum of all person hours in the county) depends strongly on the extreme heat threshold used. During the heat wave we project the following total person hours of heat exposure in Maricopa County: 846.7 million (35 °C threshold), 472.5 million (40 °C threshold), and 89.5 million (45 °C threshold) (Fig. S.1). Uniform implementation of cool roofs would avoid the following person hours throughout the county: 19.9 million person hours of 35 °C exposure (2.3% of 846.7 million), 41.2 million person hours of 40 °C exposure (8.7% of 472.5 million), and 33.1 million person hours of 45 °C exposure (37.0% of 89.5 million) (Tables S.2–4). Cool roofs are more effective at reducing population exposure to the most dangerous temperatures (i.e., >45 °C) during this extreme heat wave (i.e., the percentage of total person hours of exposure avoided is greater for temperatures >45 °C than for temperatures at 40 °C and 35 °C). Of those 33.1 million avoided person hours of extreme heat exposure, a total of 11.3 million (i.e., the sum of values in HSI 9, HSI 10A, and HSI 10B) – more than one third of all person hours – are avoided in zones 9 and 10. Moderate reductions in exposure are projected across medium to high sensitivity areas (zones 4 through 8) with a cumulative total 17.0 million person hours avoided in those five zones. Finally, in the three lowest heat sensitivity zones (1 through 3) the smallest reductions in exposure are projected with about 4.78 million person hours (i.e., the sum of values in HSI 1, HSI 2, and HSI 3) avoided due to uniform implementation of cool roofs. Moreover, in these lower heat sensitivity zones the population will tend to be better equipped to adapt to heat through social, behavioral, and technological mechanisms.

3.2.2. Population-weighted impacts of targeted implementation of cool roofs

Targeted implementation of cool roofs is ineffective at reducing population heat exposure in low heat sensitivity areas. Implementation of cool roofs across zones 1 through 3 reduce extreme heat exposure (i.e., exposure to >45 °C) across the urban environment by 3.9 million person hours (Table S.4). By contrast, targeted implementation in high heat sensitivity areas is projected to be relatively effective at reducing extreme heat exposure. Fig. 7 shows the total number of person hours of extreme heat exposure (>45 °C) avoided in each HSI zone due to uniform implementation of cool roofs (left) and targeted implementation of cool roofs (right). The effectiveness of targeted implementation can be observed in Fig. 7 by the fact that the bar labeled "HSI 10" on the left and right panels are of similar size (i.e., height). We find that this pattern of targeted cool roof implementation efficacy in high sensitivity zones is consistent across all 3 extreme heat thresholds used (see Figs. S.2–3). Overall, we project that the largest reductions in population exposure due to uniform and targeted implementation of cool roofs occur in the high heat sensitivity areas. This means that needs-based targeted implementation has the dual benefits of simultaneously providing cooling in the areas of greatest need and reducing heat exposure for the largest absolute number of people.

4. Discussion and conclusions

Previous efforts to investigate heat-reducing infrastructure at the city-scale have largely focused on the cooling impacts derived from uniform implementation of measures. Here, we present evidence that

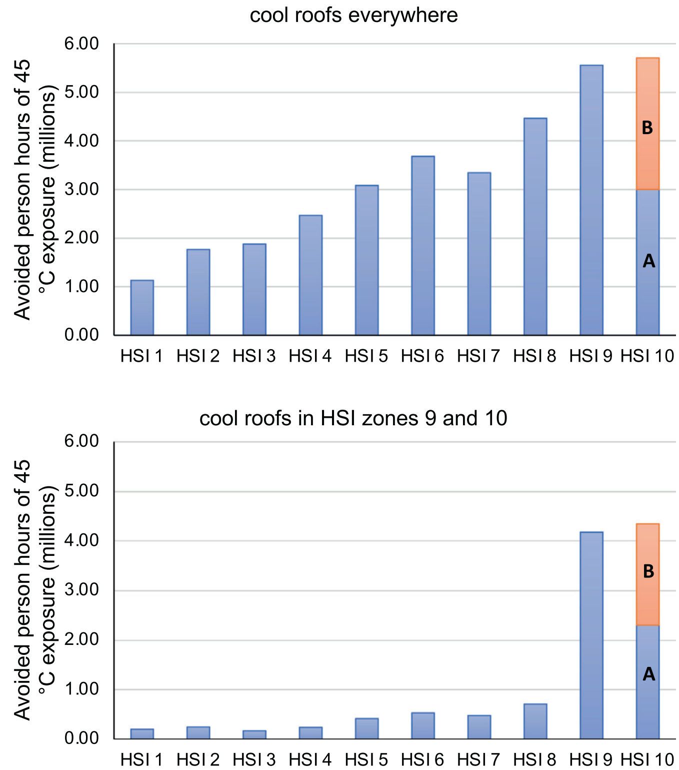

Fig. 7. Avoided population extreme heat exposure by HSI zone for (a) uniform (widespread) cool roof implementations vs. (b) targeted cool roof implementations.

illustrates it is important to understand the impacts of cooling infrastructure targeted at heat vulnerable populations based on the Difference Principle of distributive justice attributed to political philosopher John Rawls (Rawls, 2009). To achieve fairness in the distribution of social goods, Rawls wrote, inequalities in society should be remedied "to the greatest benefit of the least advantaged members of society." We modeled scenarios with deployment of cool roofs in the most heat sensitive areas in order to assess the potential for this heat adaptation strategy to contribute to an equitable distribution of thermal environments. We conducted a novel set of simulations using a physics-based numerical climate model (WRF) to assess systematically the cooling impacts of targeted cool roof implementation in Maricopa County, Arizona. This study has yielded new insights on the equity implications arising from the targeted implementation of cool roofs in urban Maricopa County. The results quantify the needs-based equity implications of thermal adaptation derived from implementation of cool roofs. We suggest that the wider urban climate research community adopt our new needs-based Targeted Urban Heat Adaptation (TUHA) framework (Fig. 2) to examine cooling interventions and associated outcomes elsewhere. We conducted our simulations for one arid metro area during extreme heat conditions likely to become more prevalent under anticipated future climates. Dryland regions (which include arid regions) make up about 40% of the world's surface globally and approximately one third of the global population lives in these regions (http://drylandsystems.cgiar.org/content/worlds-dry-areas), highlighting the importance of extending this work to other urban areas globally.

Our four core findings and associated implications for thermal equity are summarized below:

1. **High heat sensitivity areas are projected to receive more cooling from implementation of cool roofs than low heat sensitivity areas in Maricopa County**, and this applies for both uniform and targeted implementation of cool roofs. Targeted implementation of cool roofs in high heat sensitivity areas is projected to provide more than twice as much cooling (in absolute terms) than targeted

implementation in low heat sensitivity areas (Fig. 6). Therefore, the most heat sensitive population (income insecure, people of color, and isolated elderly) will benefit the most from a targeted needs-based distribution of cool roofs because they will experience the largest absolute reduction in temperature in the county. The greater magnitude of cooling in high heat sensitivity areas is derived largely from an above average building density and rooftop area where cool roof coatings can be installed. Therefore, high heat vulnerability areas could leverage roof area to provide wide-spread cooling without competing for scarcely available space at ground-level.

2. Our simulation results suggest that **the cooling impacts of cool roofs are overwhelmingly local.** We have shown that installing cool roofs exclusively in the two highest heat sensitivity areas (zones 9 & 10 in Fig. 1) can accomplish 88% of the maximum achievable cooling impact (i.e., that derived from uniform implementation) in the highest heat sensitivity part of the county (i.e., zone 10B in Fig. 1). The strongly local impacts of heat-reducing measures suggest that targeted implementation, based on need, is a potentially cost-effective way to improve equity and reduce temperatures in high heat sensitivity areas across Maricopa County. It is therefore possible to provide cooling in the areas of greatest heat sensitivity without installing heat-reducing infrastructure throughout the entire county. Carefully designed needs-based targeted heat infrastructure plans could result in a more efficient allocation of resources and potentially reduce the cost of city cooling efforts. Our findings appear to be at odds with Yang and Bou-Zeids (2019) study of targeted implementation of cool roofs, which emphasizes the benefits of non-local cooling effects for the urban core and suggest that areas *upwind* of the urban core should be prioritized for implementation. However, Yang and Bou-Zeids (2019) simulations of cool roof deployment did not directly consider sociodemographics or needs-based equity, nor did they simulate cities in Maricopa County, and they used a single-layer urban model. Additionally, Yang and Bou-Zeids (2019) case studies were characterized by stronger winds than our heatwave event, which could increase the non-local cooling impacts of cool roofs. Future research is needed to understand the generalizability and applicability of our findings to other meteorological conditions and metropolitan regions.
3. We also report that **cool roofs are projected to be more effective at reducing population-weighted heat exposure in high heat sensitivity areas than in low sensitivity areas**. These trends in population-weighted exposure occur because high heat sensitivity areas are more densely populated than low sensitivity areas and implementation of cool roofs provides more cooling (in absolute terms) in high than low sensitivity areas. Therefore, targeted implementation of cool roofs in Maricopa County would have the dual benefits of providing cooling for heat sensitive people *and* cooling the largest absolute number of individuals (Fig. 7, Tables S.2–4, and Figs. S.1–2). This synergy of heat sensitivity and population density could apply to many US cities, wherein the heat sensitive population is largely located in the more densely inhabited urban core. To better understand the universality of these findings, we suggest our TUHA modeling experiment be replicated in other cities, particularly those with contrasting distributions of urban infrastructure, population density, and sociodemographics.
4. Despite the potential of cool roofs to provide cooling in heat sensitive areas as outlined above, we find that **no amount of cool roof implementation could bring "thermal equity" to Maricopa County (i.e., equal temperatures in all urban areas of the county).** The high heat sensitivity areas with cool roof implementation were hotter than low sensitivity areas prior to implementation of cool roofs; thus, cool roofs cannot entirely offset this temperature differential. Additional complementary heat-reducing measures (e.g., trees and greenspace) are needed in heat sensitive areas to achieve thermal equity, defined as an even distribution of temperatures across Maricopa County. Additionally, efforts to reduce heat sensitivity (e.g., energy and water assistance programs) in high sensitivity areas would further help to close the social equity gap. It should be noted that we assess thermal equity based solely on air temperature, and other climate-relevant variables such as shade provision (i.e., to reduce radiative load) ultimately influence outdoor exposure of urban inhabitants to extreme conditions.

This work has demonstrated that a needs-based targeted implementation of heat-reducing infrastructure in Maricopa County may be an effective way to reduce extreme heat exposure for sensitive populations and move towards equitable access to cooler environments across the county. It is important to acknowledge that smaller-scale, *targeted* applications of cool roofs nevertheless present important practical limitations and challenges. There are several issues that arise when installing cool roofs in low-income neighborhoods, including property ownership, ability of homeowners to pay, and potentially unsuitable building stock. For example, the cooling impacts of cool roofs implemented on steep-pitch roofs are uncertain (our simulations assumed flat rooftops). However, cool roofs are arguably the most versatile and flexible rooftop intervention that can be retroactively installed on rooftops; for example, retrofitting cool roofs is typically easier than photovoltaic modules and green roofs. Another limitation of cool roofs is that the reflectivity of coatings can degrade through time due to weatherization and soiling associated with dust, black carbon, and biomass buildup, with Arizona weathering conditions reported to reduce solar reflectance by up to 5% after 3 years in the field (Ferrari et al., 2014). Encouragingly, cleaning cool roofs and other maintenance measures can help to retain sustained high albedo levels (Levinson et al., 2005). Despite the limitations of cool roofs, there are legislative efforts (e.g., Title 24 in California) that may be used as a model to drive change in Arizona and elsewhere.

Despite the challenges mentioned above, there are clear benefits/advantages to cool roofs for heat reduction, especially in Arizona. Unlike trees, which require space at ground-level, cool roofs are easier to install and maintain with less ongoing maintenance required. Planners and practitioners could take advantage of the abundance of roof area in high heat sensitivity areas to implement cool roofs and deliver neighborhood cooling. Additionally, low-income areas often have more narrow street canyons (higher building height-to-street width ratios), where the cooling benefits of trees may be diminished because buildings also provide shade, which largely nullifies the tree shading benefit (Norton et al., 2015). Furthermore, cool roofs unlike trees (and vegetation more broadly) do not require water resources to maintain long-term viability. Preserving water may be particularly important in arid cities where water resources are stressed and/or in low-income neighborhoods when residents cannot afford to buy water for irrigation.

We have focused on air temperature as the response variable in this study; however, there are other key response variables to cool roofs that should be considered in a wider context. Cool roofs are also known to reduce building temperatures and demand for air conditioning/electricity (Akbari et al., 2005; Konopacki et al., 1998; Boixo et al., 2012). Therefore, the positive effects of cool roofs for individuals in heat vulnerable areas are likely to be multiplicative. Most notably, savings on energy bills is an important benefit of cool roofs that the community will simultaneously accrue. Those in high sensitivity areas may be less able to afford large electric bills or up-to-date cooling systems, and therefore the substantial building-level cooling that occurs from cool roofs will be directly protective in these instances. Moreover, cool roofs have been shown to improve indoor temperatures during electricity blackout events, potentially protecting people from heat stress when air conditioning is unavailable (Stone et al., 2021). Cool roofs can be implemented relatively quickly as installation is easy compared to other heat mitigation measures (street trees, for example, require time to mature); the ability for municipalities to rapidly adapt urban neighborhoods and see an immediate return on investment is a useful attribute of cool roofs given the economic and political uncertainty many decision-makers commonly face. Lastly, improving thermal comfort, rather than simply reducing air temperature is an important goal for many urban planners and decision-makers. Human thermal comfort is defined by a range of meteorological variables, most notably radiant temperature (shade), airflow, and humidity. Cool roofs are unlikely to be as effective at improving daytime human thermal comfort as trees and other shade providing interventions. This again reinforces the argument that cities will ultimately need to implement a blend of interventions to achieve comprehensive cooling outcomes.

Ultimately, there is no "silver bullet" solution to the problem of urban climatic warming; cities and communities will likely choose to implement a blend of interventions based on a variety of local considerations (i.e., political, practical, aesthetic, economical, and environmental factors). Research assessing benefits of various strategies will require an examination that characterizes impacts and their alignment with locally developed desired outcomes, which will vary from city to city. Our analysis has shown that cool roofs could be an important part of city-scale heat reduction efforts – with notable benefits for cooling heat vulnerable urban areas. However, many cities do not include cool roofs in their climate action/adaptation plans (Nazli Aragon, personal communication, July 7, 2020). We suggest that cool roofing initiatives or policies should be included in the climate adaptation/plans of all US cities, especially those in the US Southwest and Sunbelt. However, in northern cities (e.g., Chicago, New York City etc.) the potential adverse effects of cooling during winter should be considered (Georgescu et al., 2014; Krayenhoff and Voogt, 2010; Yang and Bou-Zeid, 2018). Cool roofs can play an important role in extreme heat mitigation, protecting heat vulnerable populations, and working towards achieving thermally equitable urban environments.

CRediT authorship contribution statement

Ashley Broadbent: Formal analysis, Data curation, Investigation, Methodology, Project administration, Validation, Visualization, Writing - original draft, Writing - review and editing. **Juan Declet-Barreto:** Conceptualization, Methodology, Software, Formal analysis, Investigation, Data Curation, Writing - review & editing, Visualization. **E. Scott Krayenhoff:** Conceptualization; Methodology; Software; Supervision; Writing - review & editing. **Sharon L. Harlan:** Conceptualization, Funding acquisition, Project administration, Writing-original draft; Writing-review & editing. **Matei Georgescu:** Conceptualization; Funding acquisition; Writing - review & editing

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2021.151326.

References

Akbari, H., Levinson, R., Rainer, L., 2005. Monitoring the energy-use effects of cool roofs on California commercial buildings. Energy Build. 37 (10), 1007–1016. https://doi.org/10.1016/j.enbuild.2004.11.013 (Oct.).

Azhar, G.S., et al., 2014. Heat-related mortality in india: excess all-cause mortality associated with the 2010 Ahmedabad heat wave. PLoS One 9 (3), e91831. https://doi.org/10.1371/journal.pone.0091831 (Mar.).

Baniassadi, A., Sailor, D.J., Scott Krayenhoff, E., Broadbent, A.M., Georgescu, M., 2019. Passive survivability of buildings under changing urban climates across eight US cities. Environ. Res. Lett. 14 (7), 074028. https://doi.org/10.1088/1748-9326/ab28ba (Jul.).

Boixo, S., Diaz-Vicente, M., Colmenar, A., Castro, M.A., 2012. Potential energy savings from cool roofs in Spain and Andalusia. Energy 38 (1), 425–438. https://doi.org/10.1016/j.energy.2011.11.009 (Feb.).

Brazel, A., Selover, N., Vose, R., Heisler, G., 2000. The tale of two climates - Baltimore and Phoenix urban LTER sites. Clim. Res. 15 (2), 123–135. https://doi.org/10.3354/cr015123 (Jul.).

Broadbent, A.M., Krayenhoff, E.S., Georgescu, M., 2020a. The motley drivers of heat and cold exposure in 21st century US cities. Proc. Natl. Acad. Sci. U. S. A. 117 (35). https://doi.org/10.1073/pnas.2005492117.

Broadbent, A.M., Krayenhoff, E.S., Georgescu, M., 2020b. Efficacy of cool roofs at reducing pedestrian-level air temperature during projected 21st century heatwaves in Atlanta, Detroit, and Phoenix (USA). Environ. Res. Lett. 15 (8), 084007. https://doi.org/10.1088/1748-9326/ab6a23 (Jul.).

Cao, M., Rosado, P., Lin, Z., Levinson, R., Millstein, D., 2015. Cool roofs in Guangzhou, China: outdoor air temperature reductions during heat waves and typical summer conditions. Environ. Sci. Technol. 49 (24), 14672–14679. https://doi.org/10.1021/acs.est.5b04886 (Dec.).

Chen, F., et al., 2011. The integrated WRF/urban modelling system: development, evaluation, and applications to urban environmental problems. Int. J. Climatol. 31 (2), 273–288. https://doi.org/10.1002/joc.2158 (Feb.).

Chow, W.T.L., Brennan, D., Brazel, A.J., 2012. Urban heat island research in phoenix, Arizona. Bull. Am. Meteorol. Soc. 93 (4), 517–530. https://doi.org/10.1175/BAMS-D-11-00011.1 (Apr.).

Costello, A., et al., 2009. Managing the health effects of climate change. Lancet and University College London Institute for Global Health Commission. Lancet 373 (9676), 1693–1733. https://doi.org/10.1016/S0140-6736(09)60935-1 (Elsevier Limited, May 16).

Declet-Barreto, J., Brazel, A.J., Martin, C.A., Chow, W.T.L., Harlan, S.L., 2013. Creating the park cool island in an inner-city neighborhood: heat mitigation strategy for Phoenix, AZ. Urban Ecosyst. 16 (3), 617–635. https://doi.org/10.1007/s11252-012-0278-8 (Sep.).

Dhainaut, J.F., Claessens, Y.E., Ginsburg, C., Riou, B., 2004. Unprecedented heat-related deaths during the 2003 heat wave in Paris: consequences on emergency departments. Crit. Care 8 (1), 1–2. https://doi.org/10.1186/cc2404 (BioMed Central, Feb. 04).

European Centre for Medium-Range Weather Forecasts (ECMWF), 2009. "ERA-Interim Project." Research Data Archive at the National Center for Atmospheric Research, Computational and Information Systems Laboratory. https://doi.org/10.5065/D6CR5RD9.

Ferrari, C., et al., 2014. Effect of aging processes on solar reflectivity of clay roof tiles. Adv. Build. Energy Res. 8 (1), 28–40. https://doi.org/10.1080/17512549.2014.890535 (Taylor and Francis Ltd.).

Georgescu, M., Moustaoui, M., Mahalov, A., Dudhia, J., 2013. Summer-time climate impacts of projected megapolitan expansion in Arizona. Nat. Clim. Chang. 3 (1), 37–41. https://doi.org/10.1038/nclimate1656 (Jan.).

Georgescu, M., Morefield, P.E., Bierwagen, B.G., Weaver, C.P., 2014. Urban adaptation can roll back warming of emerging megapolitan regions. Proc. Natl. Acad. Sci. U. S. A. 111 (8), 2909–2914. https://doi.org/10.1073/pnas.1322280111 (Feb.).

Gronlund, C.J., 2014. Racial and socioeconomic disparities in heat-related health effects and their mechanisms: a review. Curr. Epidemiol. Reports 1 (3), 165–173. https://doi.org/10.1007/s40471-014-0014-4 (Sep.).

Grossman-Clarke, S., Schubert, S., Clarke, T.R., Harlan, S.L., 2014. Extreme summer heat in Phoenix, Arizona (USA) under global climate change (2041–2070). Erde 145 (1–2), 49–61. https://doi.org/10.12854/erde-145-5 (Sep.).

Guhathakurta, S., Gober, P., 2007. The impact of the Phoenix urban heat island on residential water use. J. Am. Plan. Assoc. 73 (3), 317–329. https://doi.org/10.1080/01944360708977980 (Jun.).

Harlan, S.L., Brazel, A.J., Prashad, L., Stefanov, W.L., Larsen, L., 2006. Neighborhood microclimates and vulnerability to heat stress. Soc. Sci. Med. 63 (11), 2847–2863. https://doi.org/10.1016/j.socscimed.2006.07.030 (Dec.).

Harlan, S.L., Declet-Barreto, J.H., Stefanov, W.L., Petitti, D.B., 2013. Neighborhood effects on heat deaths: social and environmental predictors of vulnerability in Maricopa County, Arizona. Environ. Health Perspect. 121 (2), 197–204. https://doi.org/10.1289/ehp.1104625 (Feb.).

Harlan, S.L., Chakalian, P., Declet-Barreto, J., Hondula, D.M., Jenerette, G.D., 2019. Pathways to climate justice in a desert metropolis. In: Reyes, L.M., Rigg, J. (Eds.), People and Climate Change: Vulnerability, Adaptation, and Social Justice. Oxford University Press, pp. 23–50.

Heckert, M., Rosan, C.D., 2016. Developing a green infrastructure equity index to promote equity planning. Urban For. Urban Green. 19, 263–270. https://doi.org/10.1016/j.ufug.2015.12.011 (Sep.).

Hoffman, J.S., Shandas, V., Pendleton, N., 2020. The effects of historical housing policies on resident exposure to intra-urban heat: a study of 108 US Urban Areas. Climate 8 (1), 12. https://doi.org/10.3390/cli8010012 (Jan.).

Hondula, D.M., Georgescu, M., Balling, R.C., 2014. Challenges associated with projecting urbanization-induced heat-related mortality. Sci. Total Environ. 490, 538–544. https://doi.org/10.1016/j.scitotenv.2014.04.130 (Aug.).

Hope, D., et al., 2003. Socioeconomics drive urban plant diversity. Proc. Natl. Acad. Sci. 100 (15), 8788–8792. https://doi.org/10.1073/PNAS.1537557100 (Jul.).

Jenerette, G.D., Harlan, S.L., Brazel, A., Jones, N., Larsen, L., Stefanov, W.L., 2007. Regional relationships between surface temperature, vegetation, and human settlement in a rapidly urbanizing ecosystem. Landsc. Ecol. 22 (3), 353–365. https://doi.org/10.1007/s10980-006-9032-z (Mar.).

Jenerette, G.D., Harlan, S.L., Stefanov, W.L., Martin, C.A., 2011. Ecosystem services and urban heat riskscape moderation: water, green spaces, and social inequality in Phoenix, USA. Ecol. Appl. 21 (7), 2637–2651. https://doi.org/10.1890/10-1493.1 (Oct.).

Johnson, D.P., Stanforth, A., Lulla, V., Luber, G., 2012. Developing an applied extreme heat vulnerability index utilizing socioeconomic and environmental data. Appl. Geogr. 35 (1–2), 23–31. https://doi.org/10.1016/j.apgeog.2012.04.006 (Nov.).

Ko, Y., 2018. Trees and vegetation for residential energy conservation: a critical review for evidence-based urban greening in North America. Urban For. Urban Green. 34, 318–335. https://doi.org/10.1016/j.ufug.2018.07.021 (Elsevier GmbH, Aug. 01).

Konopacki, S., Gartland, L., Akbari, H., Rainer, L., 1998. Demonstration of Energy Savings of Cool Roofs. https://doi.org/10.2172/296885 (Berkeley, CA, Jun.).

Krayenhoff, E.S., Voogt, J.A., 2010. Impacts of urban albedo increase on local air temperature at daily-annual time scales: model results and synthesis of previous work. J. Appl. Meteorol. Climatol. 49 (8), 1634–1648. https://doi.org/10.1175/2010JAMC2356.1 (Aug.).

Krayenhoff, E.S., Moustaoui, M., Broadbent, A.M., Gupta, V., Georgescu, M., 2018. Diurnal interaction between urban expansion, climate change and adaptation in US cities. Nat. Clim. Chang. 8 (12). https://doi.org/10.1038/s41558-018-0320-9.

Krayenhoff, E.S., et al., 2021. Cooling hot cities: a systematic and critical review of the numerical modelling literature. Environ. Res. Lett. 16, 053007.

Levinson, R., Berdahl, P., Asefaw Berhe, A., Akbari, H., 2005. Effects of soiling and cleaning on the reflectance and solar heat gain of a light-colored roofing membrane. Atmos. Environ. 39 (40), 7807–7824. https://doi.org/10.1016/j.atmosenv.2005.08.037 (Dec.).

Li, X., Myint, S.W., Zhang, Y., Galletti, C., Zhang, X., Turner, B.L., 2014. Object-based land-cover classification for metropolitan Phoenix, Arizona, using aerial photography. Int. J. Appl. Earth Obs. Geoinf. 33 (1), 321–330. https://doi.org/10.1016/j.jag.2014.04.018 (Dec.).

Li, X., Zhou, Y., Yu, S., Jia, G., Li, H., Li, W., 2019. Urban heat island impacts on building energy consumption: a review of approaches and findings. Energy 174, 407–419. https://doi.org/10.1016/j.energy.2019.02.183 (Elsevier Ltd, May 01).

Luber, G., McGeehin, M., 2008. Climate change and extreme heat events. Am. J. Prev. Med. 35 (5), 429–435. https://doi.org/10.1016/j.amepre.2008.08.021 (Elsevier, Nov. 01).

Martilli, A., Clappier, A., Rotach, M.W., 2002. An urban surface exchange parameterisation for mesoscale models. Boundary-Layer Meteorol. 104 (2), 261–304. https://doi.org/10.1023/A:1016099921195 (Aug.).

McDonald, R. et al., "Funding trees for health." Accessed: Nov. 17, 2020. [Online]. Available: https://www.nature.org/content/dam/tnc/nature/en/documents/Trees4Health_FINAL.pdf.

Middel, A., Turner, V.K., Schneider, F.A., Zhang, Y., Stiller, M., 2020. Solar reflective pavements-a policy panacea to heat mitigation? Environ. Res. Lett. 15 (6), 064016. https://doi.org/10.1088/1748-9326/ab87d4 (Jun.).

Mitchell, B.C., Chakraborty, J., 2018. Exploring the relationship between residential segregation and thermal inequity in 20 U.S. cities. Local Environ. 23 (8), 796–813. https://doi.org/10.1080/13549839.2018.1474861 (Aug.).

Mullaney, J., Lucke, T., Trueman, S.J., 2015. A review of benefits and challenges in growing street trees in paved urban environments. Landsc. Urban Plan. 134, 157–166. https://doi.org/10.1016/j.landurbplan.2014.10.013 (Elsevier, Feb. 01).

National Weather Service - NWS Phoenix, 2020. https://w2.weather.gov/climate/xmacis.php?wfo=psr. (Accessed 17 November 2020).

Nitschke, M., Tucker, G.R., Hansen, A.L., Williams, S., Zhang, Y., Bi, P., 2011. Impact of two recent extreme heat episodes on morbidity and mortality in Adelaide, South Australia: a case-series analysis. Environ. Heal. A Glob. Access Sci. Source 10 (1), 1–9. https://doi.org/10.1186/1476-069X-10-42 (May).

Norton, B.A., Coutts, A.M., Livesley, S.J., Harris, R.J., Hunter, A.M., Williams, N.S.G., 2015. Planning for cooler cities: a framework to prioritise green infrastructure to mitigate high temperatures in urban landscapes. Landsc. Urban Plan. 134, 127–138. https://doi.org/10.1016/j.landurbplan.2014.10.018 (Feb.).

O'Neill, M.S., Zanobetti, A., Schwartz, J., 2005. Disparities by race in heat-related mortality in four US cities: the role of air conditioning prevalence. J. Urban Health 82 (2), 191–197. https://doi.org/10.1093/jurban/jti043 (Feb.).

Oudin Åström, D., Bertil, F., Joacim, R., 2011. Heat wave impact on morbidity and mortality in the elderly population: a review of recent studies. Maturitas 69 (2), 99–105. https://doi.org/10.1016/j.maturitas.2011.03.008 (Maturitas, Jun.).

Petitti, D.B., Hondula, D.M., Yang, S., Harlan, S.L., Chowell, G., 2016. Multiple trigger points for quantifying heat-health impacts: new evidence from a hot climate. Environ. Health Perspect. 124 (2), 176–183. https://doi.org/10.1289/ehp.1409119 (Feb.).

Putnam, H., Hondula, D.M., Urban, A., Berisha, V., Iniguez, P., Roach, M., 2018. It's not the heat, it's the vulnerability: attribution of the 2016 spike in heat-associated deaths in Maricopa County, Arizona. Environ. Res. Lett. 13 (9), 094022. https://doi.org/10.1088/1748-9326/aadb44 (Sep.).

R Package 'censusapi', 2020. . [Online]. Available: https://cran.r-project.org/web/packages/censusapi/censusapi.pdf. (Accessed 17 November 2020).

Rawls, J., 2009. A Theory of Justice. Harvard University Press.

Reid, C.E., et al., 2009. Mapping community determinants of heat vulnerability. Environ. Health Perspect. 117 (11), 1730–1736. https://doi.org/10.1289/ehp.0900683 (Nov.).

Revich, B.A., Shaposhnikov, D.A., 2012. Climate change, heat waves, and cold spells as risk factors for increased mortality in some regions of Russia. Stud. Russ. Econ. Dev. 23 (2), 195–207. https://doi.org/10.1134/S1075700712020116 (Mar.).

Ruddell, D.M., Harlan, S.L., Grossman-Clarke, S., Buyantuyev, A., 2009. Risk and exposure to extreme heat in microclimates of Phoenix, AZ. Geospatial Techniques in Urban Hazard and Disaster Analysis. Springer Netherlands, pp. 179–202.

Salamanca, F., Georgescu, M., Mahalov, A., Moustaoui, M., Martilli, A., 2016. Citywide impacts of cool roof and rooftop solar photovoltaic deployment on near-surface air temperature and cooling energy demand. Boundary-Layer Meteorol. 161 (1), 203–221. https://doi.org/10.1007/s10546-016-0160-y (Oct.).

Santamouris, M., 2014. Cooling the cities - a review of reflective and green roof mitigation technologies to fight heat island and improve comfort in urban environments. Sol. Energy 103, 682–703. https://doi.org/10.1016/j.solener.2012.07.003 (May).

Sharma, A., Woodruff, S., Budhathoki, M., Hamlet, A.F., Chen, F., Fernando, H.J.S., 2018. Role of green roofs in reducing heat stress in vulnerable urban communities - a multidisciplinary approach. Environ. Res. Lett. 13 (9), 094011. https://doi.org/10.1088/1748-9326/aad93c (Sep.).

Skamarock, W.C., Klemp, J.B., 2008. A time-split nonhydrostatic atmospheric model for weather research and forecasting applications. J. Comput. Phys. 227 (7), 3465–3485. https://doi.org/10.1016/j.jcp.2007.01.037 (Mar.).

Stewart, I.D., Oke, T.R., 2012. Local climate zones for urban temperature studies. Bull. Am. Meteorol. Soc. 93 (12), 1879–1900. https://doi.org/10.1175/BAMS-D-11-00019.1 (Dec.).

Stone, B., Vargo, J., Liu, P., Hu, Y., Russell, A., 2013. Climate change adaptation through urban heat management in Atlanta, Georgia. Environ. Sci. Technol. 47 (14), 7780–7786. https://doi.org/10.1021/es304352e (Jul.).

Stone, B., et al., 2021. Climate change and infrastructure risk: indoor heat exposure during a concurrent heat wave and blackout event in Phoenix, Arizona. Urban Clim. 36. https://doi.org/10.1016/j.uclim.2021.100787.

Tate, E., 2013. Uncertainty analysis for a social vulnerability index. Ann. Assoc. Am. Geogr. 103 (3), 526–543. https://doi.org/10.1080/00045608.2012.700616 (May).

Tewari, M., Chen, F., Kusaka, H., Miao, S., 2007. Coupled WRF/Unified Noah/Urban-Canopy Modeling System.

Thom, J.K., Coutts, A.M., Broadbent, A.M., Tapper, N.J., 2016. The influence of increasing tree cover on mean radiant temperature across a mixed development suburb in Adelaide, Australia. Urban For. Urban Green. 20, 233–242. https://doi.org/10.1016/j.ufug.2016.08.016 (Dec.).

US Census Bureau; American Community Survey, 2010. American community survey 1-year estimates. http://factfinder.census.gov. (Accessed 15 February 2012).

Whitman, S., Good, G., Donoghue, E.R., Benbow, N., Shou, W., Mou, S., 1997. Mortality in Chicago attributed to the July 1995 heat wave. Am. J. Public Health 87 (9), 1515–1518. https://doi.org/10.2105/AJPH.87.9.1515 (Aug.).

Yang, J., Bou-Zeid, E., 2018. Should cities embrace their heat islands as shields from extreme cold? J. Appl. Meteorol. Climatol. 57 (6), 1309–1320. https://doi.org/10.1175/JAMC-D-17-0265.1 (Jun.).

Yang, J., Bou-Zeid, E., 2019. Scale dependence of the benefits and efficiency of green and cool roofs. Landsc. Urban Plan. 185, 127–140. https://doi.org/10.1016/j.landurbplan.2019.02.004 (May).