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Household accessibility to heat refuges: Residential air conditioning, public cooled space, and walkability

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Abstract

Access to air conditioned space is critical for protecting urban populations from the adverse effects of heat exposure. Yet there remains fairly limited knowledge of the penetration of private (home air conditioning) and distribution of public (cooling centers and commercial space) cooled space across cities. Furthermore, the deployment of government-sponsored cooling centers is likely to be inadequately informed with respect to the location of existing cooling resources (residential air conditioning and air conditioned public space), raising questions of the equitability of access to heat refuges. We explore the distribution of private and public cooling resources and access inequities at the household level in two major US urban areas: Los Angeles County, California and Maricopa County, Arizona (whose county seat is Phoenix). We evaluate the presence of in-home air conditioning and develop a walking-based accessibility measure to air conditioned public space using a combined cumulative opportunities-gravity approach. We find significant variations in the distribution of residential air conditioning across both regions which are largely attributable to building age and inter/intra-regional climate differences. There are also

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regional disparities in walkable access to public cooled space. At average walking speeds, we find that official cooling centers are only accessible to a small fraction of households (3% in Los Angeles, 2% in Maricopa) while a significantly higher number of households (80% in Los Angeles, 39% in Maricopa) have access to at least one other type of public cooling resource such as a library or commercial establishment. Aggregated to a neighborhood level, we find that there are areas within each region where access to cooled space (either public or private) is limited which may increase heat-related health risks.

Keywords
Accessibility, walkability, climate change, extreme heat

Introduction

The link between temperature extremes and human morbidity and mortality is well established. Currently, heat is a leading cause of weather-related mortality in many developed countries. In the United States, heat exposure resulted in 3,332 deaths between 2006 and 2010 (Berko et al., 2014). It is estimated that the 2003 European heatwave contributed to 70,000 excess mortality events across 16 countries (Robine et al., 2008) and in May 2015, extreme temperatures were blamed for 2,500 deaths in India (Das, 2015). In addition, heat exposure is known to cause distinct clinical illnesses (e.g. heat cramps, heat exhaustion, heat stroke) which often require medical attention. Heat exposure is also known to exacerbate preexisting conditions (e.g. respiratory and cardiovascular disease) contributing to additional emergency room visits, hospitalizations and premature death (Berko et al., 2014; Luber and McGeehin, 2008). Although heat has long been a public health issue, programs and policies in the United States which explicitly address and manage health risks associated with heat exposure are relatively new (Maller and Strengers, 2011). Furthermore, general circulation models predict increasing annual average temperatures and the increasing frequency, severity and duration of heatwaves (defined as a period of unusually hot and/or humid weather) potentially increasing the likelihood of morbidity and mortality resulting from heat exposure (Karl and Melillo, 2009; Solomon et al., 2011). To address the health risks associated with heat, new strategies to combat heat-related morbidity and mortality will be needed to offset the consequences of expected increases in heat exposure.

Epidemiological studies have shown that the presence and use of air conditioning (AC) can significantly reduce the health risks associated with higher temperatures (Anderson and Bell, 2009; Ferreira Braga et al., 2001; Kilbourne et al., 1982; O'Neill et al., 2005; Ostro et al., 2010). However, there is limited knowledge of the extent of residential access to AC within a city and whether this infrastructure is equitably distributed (Bell et al., 2009; O'Neill et al., 2005). The epidemiological studies have largely focused on the protective effects of residential AC ownership and use but there has not yet been a study which assesses the potential for publically available cooled space (instead of, or as a complement to, home AC) to mitigate heat-health risks. Despite a lack of research regarding the protective effects of public cooled space, the known association between residential AC and lower incidences of heat-related illness and death has prompted many regions to establish public cooling center networks. These networks are comprised of designated public spaces which serve as air conditioned heat refuges for those who may not have in-home access to AC or those who may not be able to afford to use it (Uejio et al., 2011).

While there is limited systematic and scientific knowledge regarding the composition, operation, and effectiveness of cooling center networks, a recent public health evaluation of the Phoenix Heat Relief Network (set in Maricopa County, AZ) provides insights for one geographic setting (Berisha et al., in review; Maricopa County Department of Public Health (MCDPH), 2015b, 2015c, 2015d). In Maricopa County, the cooling center network is comprised of a mixture of community centers, senior citizen centers, libraries, places of worship, humanitarian organizations, and government buildings. Some of the cooling centers are facilities operated by local governments, but many other facilities participate voluntarily. The network structure is thus more emergent than intentional, and the nature of the network may result in uneven spatial and temporal coverage of facility location and open hours (Uebelherr et al., 2015). Most facilities in the Phoenix Heat Relief Network operate as a cooling center continuously throughout the region's persistently hot summer months instead of activating during specific heat emergencies or warning periods as designated by the National Weather Service or public health agencies. In 2014, it was estimated that at least 1,500 people used cooling center facilities on a daily basis, although the specific motivation of these visits, as driven by heat exposure or desire for other services offered at facilities, was difficult to ascertain. The network clearly helped many people in the region cope with summer heat, however, many of those who visited facilities spent more than an hour in the publicly accessible cooled space, and many thousands of bottles of water were distributed over the course of the summer (Berisha et al., in review; MCDPH, 2015b, 2015c, 2015d). It was unclear from the public health evaluation if the formal cooling center network is an effective or useful resource for all individuals seeking cooling relief in Maricopa County. A 2015 survey of 337 households in the County found that more than 75% of households in areas with a high incidence of heat-related illness were unaware of their availability (MCDPH, 2015a).

Previous surveys of individual-level strategies to cope with hot weather reveal that official cooling center networks are not the only resource that people use to stay cool (Hayden et al., 2011; Kalkstein and Sheridan, 2007; MCDPH, 2015a). One strategy is to use non-residential air conditioned space that is publically available, sometimes at a cost, such as shopping malls, restaurants, grocery stores, and movie theaters. There is currently little to no information regarding the distribution of these facilities and who may have access to them creating a somewhat limited view of the options for and behaviors of people in a city when seeking heat refuge. To more effectively and efficiently deploy resources to mitigate the health risks associated with heat, a better understanding of public and private cooling resources within a city and which households have access to them is needed.

Much of the research on the health-related impacts of heat has focused on socio-economic vulnerabilities (Harlan et al., 2006; Reid et al., 2012, 2009; Stafoggia et al., 2006; Uejio et al., 2011). Studies that have included information about AC availability and health outcomes nearly unanimously conclude that AC is a significant protective factor (Kovats and Hajat, 2008; Naughton et al., 2002; O'Neill et al., 2005; Ostro et al., 2010). Multiple authors have suggested that increasing prevalence of home AC is a major contributor to decadal-scale declines in heat-related mortality observed in many developed countries (Davis et al., 2003; Gasparrini et al., 2015), although one study suggested that increases in AC prevalence was not a significant contributor (Bobb et al., 2014). Given the apparent importance of AC, we were motivated to explore how the availability of private and public access to AC is distributed across cities. To effectively address public health needs associated with heat, cities should consider differences in privately held resources and public accommodations. Residential AC is the primary example of a privately-held cooling resource. Publicly accessible cooled spaces include county cooling centers, commercial space, and other buildings which may serve as a heat refuges. Establishing where in a city lower penetration of residential AC exists is important as it means that there is a potential vulnerability that could be mitigated with the deployment of a county cooling center. Beyond private cooling resources, knowledge of existing public cooling resources can help to effectively locate future cooling resources to areas with few opportunities. Neighborhood-scale knowledge of the distribution of AC, both private and public, can help cities effectively plan for resource investment to mitigate heat vulnerability.

Using Los Angeles County, California and Maricopa County, Arizona (whose seat is Phoenix), we study how in-home AC and public cooled space are distributed across heat vulnerable cities. These areas encompass two of the most populous metropolitan regions in the southwestern United States and high summer temperatures and heatwaves in both counties have been associated with elevated risks of adverse heat-health outcomes (Petitti et al., in press; Sheridan et al., 2012). We assess the availability of residential AC and accessibility to publicly cooled space at a census tract scale in both regions to (i) develop a framework for comprehensively inventorying privately and publicly accessible cooled space across cities, and (ii) create new insight into the equitability of access to public cooled space including county cooling centers, libraries, and commercial establishments.

Residential access to AC

We start by assessing the prevalence of private AC, namely central AC in residential buildings, to identify which areas of each county have lower penetration of the resource thereby a greater need for access to public AC. While the presence and use of residential AC have been shown to reduce the risk associated with heat-related mortality and morbidity during heatwaves, research studying the protective effects of residential AC at the regional level has commonly been limited by a lack of fine-scale (e.g., parcel-level) knowledge of which households have access to—and are able to use—this infrastructure. To address this gap, new methods are needed to develop a systematic understanding of where this infrastructure has been deployed and what that means for social heat vulnerability. There are several types of in-home AC units including central AC, room or window unit AC, and evaporative cooling systems. The relative performance of room/window units and evaporative systems during heatwaves compared to central AC has not been established and it is unclear if these types of units are effective in reducing the health risks associated with heat exposure.

We estimate the prevalence of central air conditioning (CAC) at the household scale to highlight areas where this infrastructure is lacking and thus, where residents may need to rely on other cooling resources when temperatures exceed healthy thresholds. The presence of CAC may not universally lower risks associated with heat and there are scenarios in which even those households which have CAC may also need to utilize cooling center infrastructure. For example, some households may face constraints in CAC use due to the associated electricity costs, other households may be unable to afford repairs to broken CAC units, and others may prefer not to use CAC based on personal comfort preferences and/or environmental concerns (Hayden et al., 2011; MCDPH, 2015a).

The presence of CAC at the household level is identified through building characteristic data available in the county assessor's databases and from the American Household Survey (AHS), which details the presence of CAC as well as other building level characteristics, such as age and type (e.g. single family, multifamily) (Census, 2010b; Los Angeles County Assessor Office, 2009; Maricopa County Assessor Office, 2010). Los Angeles and Maricopa assessor databases contain different levels of detail regarding CAC. In Los

Angeles, the assessor's database details the presence of CAC in single family homes and small (< 4 stories) multi-family buildings but does not include these details for other residential buildings, such as large multi-family buildings. The presence of CAC in these buildings was estimated with the AHS (Census, 2010b). In contrast, the Maricopa assessor database contains information on the presence of CAC for all residential building types.

The presence of CAC differs between the two regions and is likely influenced by average regional temperatures and the relative age of the residential infrastructure. In Maricopa, where daily summer maximum temperatures typically exceed 40°C, we find that approximately 95% of all households have CAC. In addition to the desert climate, the high prevalence of CAC may also be due to the relative age of buildings in the region. In 1950, around the time that installation of in-home CAC began to take hold, approximately 350,000 people lived in the region (Cooper, 1998). By 2010, Maricopa County was home to four million people largely housed in homes built after the widespread use of CAC became common (Census, 2010a). The 5% that do not have CAC typically rely on evaporative cooling systems, and are mostly found in the oldest residential developments in the region (Figure 1). In contrast, Los Angeles, which is spread across five different climate zones that range from a moderate coastal climate to a high desert climate located in the northeast corner of the region (California Energy Commission (CEC), 2014), CAC is not nearly as common. While less than 50% of households have CAC, the distribution of households with central AC is skewed towards the areas of the region which experience higher average daily summer temperatures. The results show that there is limited residential availability of CAC, with less than 30% of the households possessing CAC along the coastline and in the Los Angeles Basin, where the typically moderate weather is influenced by the proximity of the Pacific Ocean. As average daily temperatures increase relative to the distance from the ocean, the presence of household CAC also increases. In the San Fernando and San Gabriel Valley, which experience summer highs typically 7°C warmer than the temperatures on the coast, 60% of all households have CAC. Moving northeast into the high desert where average summer temperatures are 12°C warmer, 82% of residential households have CAC (National Climate Data Center (NCDC), 2015). Similar to Maricopa, areas associated with newer development within each climate region in Los Angeles tend to have a higher penetration of CAC.

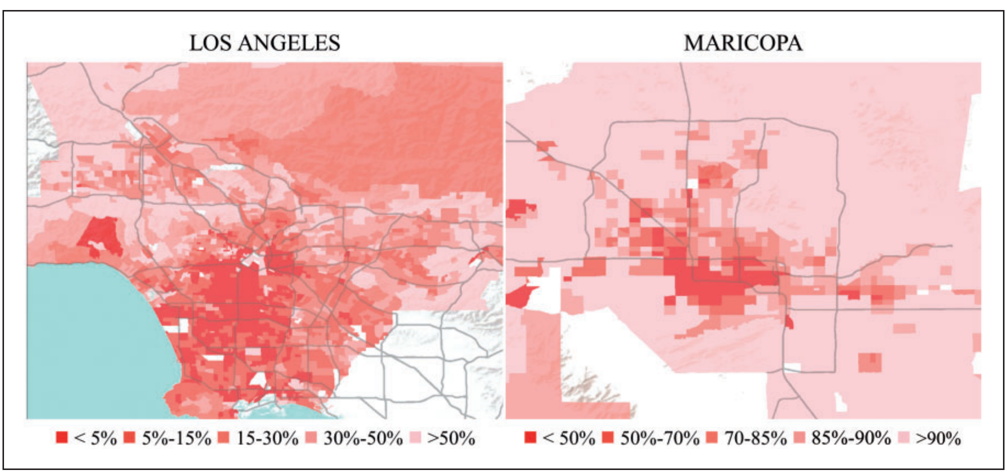

Figure 1. Proportion of households with central air conditioning (note the differing scales).

Access to public cooled space

As with residential AC, little is known about the distribution and availability of cooling centers and it is unclear whether these resources are deployed to effectively mitigate health risks. Additionally, most attention is focused on the availability of county cooling centers and there remains limited insight into how publicly accessible cooled commercial space is distributed.

The location of county cooling centers is determined by the availability of government buildings, social services, and volunteer organizations. While some cooling centers are established by government agencies, other facilities participate in the network on a volunteer basis. This results in an ad hoc network that may not be optimally located to serve particularly vulnerable populations. In addition to designated cooling centers there may also be other public places which, by virtue of being air-conditioned, may help to reduce the health-related risks of heat. We explore the distribution of official cooling centers and other public spaces (collectively referred to as cooling resources) that could provide heat relief. We then develop household level accessibility measurements to these locations.

Measurements of accessibility, defined as the relative generalized transportation costs of reaching activity locations from given origins, has been a research topic in transportation planning, urban planning and geography for many decades (Geurs and Van Wee, 2004; Hansen, 1959; Langford et al., 2012; Luo and Qi, 2009). Generalized transportation costs include both monetary (e.g. Transit Fare) and non-monetary (e.g. Time) costs of a journey. Fundamentally, accessibility studies aim to understand the impact of urban form (spatial distribution of origins and activity locations) and the transportation system (network connectivity and modal options) on an individual's ability to fulfill needs and desires (Scott and Horner, 2008). Accessibility methods have been utilized to understand transportation related exclusion, health care facility service areas, economic impacts of transportation infrastructure investment, the effect of public transit on employment opportunities, and the existence of food deserts (Páez et al., 2012).

Because historic land use and transportation policies have led to the separation of land uses which then contributes to disproportionate individual access to goods and services, household accessibility metrics are an essential tool to assess inequalities (Geurs and Van Wee, 2004; Newman and Kenworthy, 1996). Two of the most common methods of developing an accessibility measurement are the cumulative opportunities and gravity-based approaches. Cumulative opportunities typically consider the total number of opportunities within a given distance or travel-time threshold (e.g. total number of employment opportunities within 30 kilometers). Gravity-based approaches consider the generalized costs associated with reaching alternative destinations such that opportunities with lower generalized costs receive a larger weighting than opportunities associated with higher generalized costs (Páez et al., 2012). Where previous accessibility studies are often based on the generalized costs between centroid locations, increasing computational power and spatially disaggregate data allow for the development of accessibility measurements at a more granular scale. Using a modified cumulative opportunity and gravity-based approach we estimate household level access to cooling resources to understand access disparities across each region.

Accessibility methods

Cooling resources. We consider three types of publicly accessible cooled space: county cooling centers, libraries, and public/commercial space. The first category is official cooling centers which are established by local agencies as air-conditioned public places of refuge. These facilities are generally targeted towards those without AC at home, the elderly, and the homeless, though they are open to the public. In addition to providing a cooled space, these centers sometimes provide additional services, including basic medical care. The second category is public libraries, which are not members of the official cooling center network. While these spaces are not intended for use as heat relief locations, they are public spaces available at no cost to all residents, including vulnerable and homeless individuals (American Library Association (ALA), 2012). The third category consists of public and commercial spaces including malls, restaurants, and museums. As with libraries, these spaces are not primarily intended as spaces of heat relief, but the cooled space can be thought of as an ancillary benefit to those who seek out goods and services at these locations.

Data sources. Household accessibility to cooling resources is estimated using spatially disaggregated data for residential and cooling center locations. Residential and cooling center locations were developed from several data sources. Residential locations were determined from Los Angeles and Maricopa property assessment rolls which include information on property use and building type for all taxable land parcels (Los Angeles County Assessor Office, 2009; Maricopa County Assessor Office, 2010). There are approximately 2.1 million residential parcels in Los Angeles and 1.1 million in Maricopa. Residential parcels, ranging from single family homes to large multi-family apartment complexes, were weighted by the total number of dwelling units on each parcel to understand cooling center accessibility at a household scale. Addresses of official cooling centers were geocoded from information provided by the Los Angeles County Emergency Survival Program and the Maricopa Association of Governments (the regional agency responsible for network coordination) for the 2014 cooling center network (County of Los Angeles, 2014; Maricopa Association of Governments (MAG), 2014). In 2014, there were 142 official cooling centers in Los Angeles and 45 in Maricopa. It should be noted that the locations of cooling centers may change from year to year depending on voluntary participation which would affect our results. Public library locations in Los Angeles and Maricopa were geocoded through an address database (Publiclibraries.com, 2015). Libraries already serving as official cooling centers were excluded to prevent double counting. Libraries associated with educational institutions and specialty interests were excluded from the analysis as they are unlikely to serve the general population. The locations of other public spaces which may serve as cooling resources were also determined from property assessment rolls. For interregional comparisons, a crosswalk was developed to link similar property use and building codes between the two counties. Public spaces that directly offer goods or services to the general public were selected as potential cooling resource locations. It is assumed that individuals would need to remain in a cooled space for a prolonged time period to receive effective heat relief. Therefore, we have excluded public building types where the estimated transaction time is less than 30 minutes. By this definition county parcels coded as indoor shopping malls, movie theatres, and restaurants are accepted as potential cooling resources, while banks and gas stations (services <30 minutes) and commercial offices and private social clubs (not for the general public) were excluded.

Accessibility measurement. Measures of accessibility for residential access to cooled space were based on the distance between any pair of cooling resource locations and individual residential parcels. While motorized modes of transportation are often utilized in accessibility studies, we developed an accessibility metric based strictly on pedestrian access. In this way, we defined a metric that describes accessibility for a particularly vulnerable subset of the population (those without motorized transport). In a recent survey of Maricopa County cooling centers, more than one-third of all patrons walked to the facility (Berisha et al., In Press; MCDPH, 2015d). Additionally, while previous accessibility metrics are often based on generalized costs between centroid to centroid or centroid to specific locations, we developed our accessibility metrics for individual households. Using this approach, individual household accessibility metrics can be aggregated to any geographic scale to allow for commensurate comparisons with socio-economic information.

Cooling center accessibility is defined by three parameters: walking time, walking speed, and the existing street network. The National Household Travel Survey (NHTS) is used to assess typical walking durations to set the maximum walk time for those attempting to seek heat relief. The 75th percentile for walking duration for non-leisure trips, 15 minutes, was selected as the maximum time for this analysis (US Department of Transportation (USDOT), 2009). The 15 minute time horizon was then coupled with average walking speeds for sedentary elderly (1.4 kilometers per hour), average elderly (3.5 kilometers per hour), and active adults (5.6 kilometers per hour) to estimate maximum walking distances (d_o) (Bohannon and Andrews, 2011). These distances (0.33, 0.89, and 1.4 kilometers respectively) were assessed within the regional road networks to establish catchment areas for each cooling resource. Assuming individuals would select the shortest path, ArcGIS's Network Analyst tool was used to generate the catchment areas for every cooling resource location (Environmental Systems Research Institute (ESRI), 2015). The tool relies upon a path-based algorithm which computes linear distance along a network from a specified origin. All roadway types except those designated as freeways or highways were included. As these catchment areas are defined by the street network, it is assumed that all pedestrian travel occurs along adjacent sidewalks. We acknowledge that the design of certain streets (particularly those without sidewalks or that are not pedestrian friendly) may be inimical to walking, but we were not able to identify information on the "pedestrian friendliness" of streets to incorporate into our assessment. Potential shortcuts through open space parcels are excluded from the analysis. A residential parcel (i) is considered to have access to a cooling resource (j) if it falls within the catchment area of cooling resource (j) (Figure 2).

Households are considered to have access to a cooling resource (j) if they fall within its catchment area which is defined by the geometry of the street network and maximum walking distance.

A modified cumulative opportunities and gravity-based approach is used to estimate an accessibility index for each residential parcel in Los Angeles and Maricopa. First, each type of cooling resource (j) is assigned a weight (w_j) which describes the utility derived at each type of facility, based on the quality of relief available at the facility and estimates of the time an individual can stay there and the associated monetary cost (Table 1). Locations where an individual may stay for extended periods of time for little to no monetary cost receive higher weightings than facilities with shorter lengths and higher associated costs. For example, official cooling centers which are dedicated to providing heat relief and where an individual is free to stay as long as the center is open received a higher weight than a restaurant where heat relief is an ancillary benefit to goods and services which have a monetary cost and a potential time limit. Facility types were determined using assessor database property use codes. Second, the total amount (K) of each type of cooling center accessible by an individual residential parcel (i) is determined by overlaying the catchment areas and residential parcel locations. Traditionally, accessibility measurements often consider the utility of each additional location to be equivalent. For an individual household, each cooling center (j) may provide the same heat relief utility; however, the

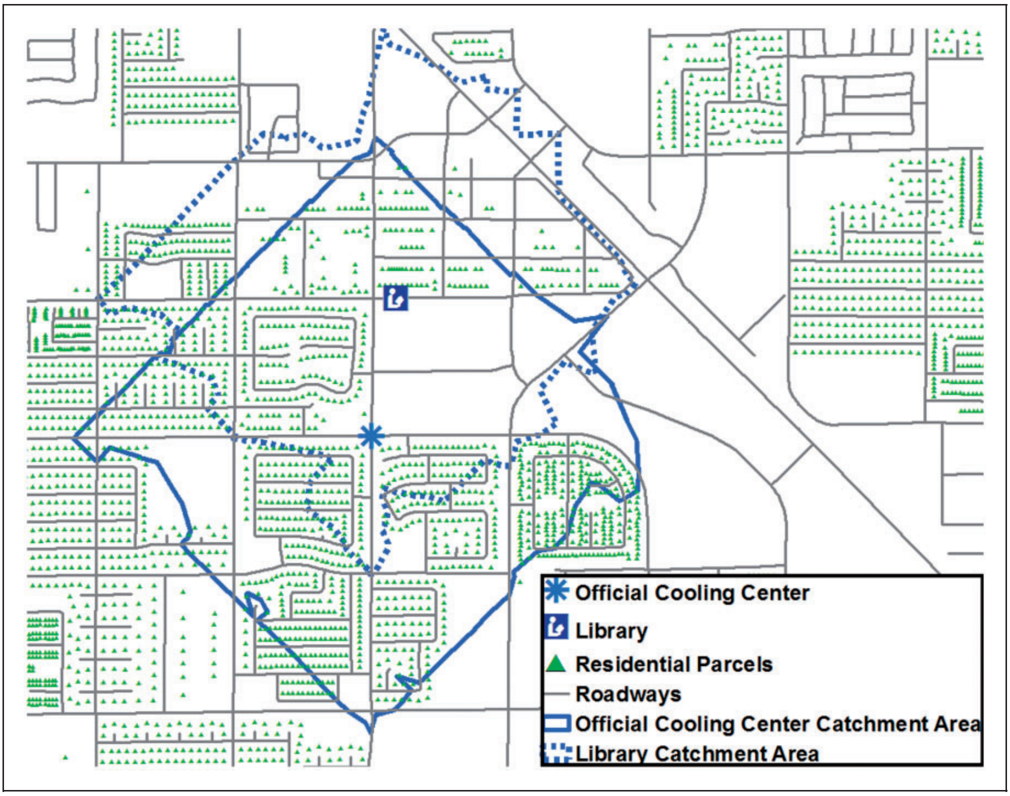

Figure 2. Residential access to cooling resources by catchment area method.

Table 1. Cooling resource types and associated accessibility weights.

Facility type (*j*)	Length of stay (hours)	Estimated cost ($)	Weight (w_j)
Official cooling centers	4+	None	2
Libraries	4+	None	1
Indoor shopping mall	4+	None–Low	0.5
Outdoor shopping center with multiple retail locations	1–4	Low	0.4
Department store/big box retail	1–4	Low	0.4
Supermarket/grocery store	1–2	Low	0.35
Museums	4+	Medium	0.3
Hotel/Motel	Indefinite	High	0.3
Movie theater, bowling alley, indoor miniature golf, ice & roller skating rink	1–4	Medium	0.25
Restaurant/Bar	1–2	Low–High	0.2
General/Unspecified commercial retail	1	Low–High	0.2
Amusement facilities	4+	High	0.1

temporal aspect of access should be considered when developing an accessibility metric. Because an individual may only occupy a single space at any time, the utility of each additional cooling center diminishes. We included a constant (x_j) to describe the diminishing marginal utility of each additional cooled space that is accessible from each residential parcel. This is analogous to the travel friction coefficient (B) utilized in gravity based methods (Hansen, 1959). The accessibility measure at a residential parcel (i) can be expressed as:

$$A_i = \sum_{j \in S_j} \sum_{k=1}^{K_{ij}} W_j * d_{ij}^{-\mathrm{B}} * k^{-x_j}$$

where S_j is the set of all cooling centers j within a specified threshold distance from residential parcel i and d_{ij} is the walking distance between i and j. Since there are no studies that describe the declining marginal utility of access, we considered four values (0, 1, 1.25, 2) for the diminishing utility coefficient to evaluate the sensitivity of the accessibility measure to this parameter. Because accessibility is determined at distances less than 1.4 km, we utilize zero for the travel friction coefficient based on the underlying assumption that there would be no deterrence over such short distances though we included it in the index formulation for future research.

To develop a neighborhood-level accessibility index, household-level accessibility measurements were aggregated at the census tract (Census, 2014). The mean of household accessibility scores are utilized to characterize neighborhood level accessibility.

Results

Cooling resources are unevenly distributed throughout each region resulting in differing accessibility measurements from one census tract to another. The spectrum of residential access to publically available cooled space ranges from neighborhoods which have access to many locations, to neighborhoods where residents would not have access to even a single public cooling resource. We find that the land use characteristics, roadway network, walking speeds, total cooling resource opportunities, and declining marginal utility coefficient can all have large impacts on index values.

There are substantial interregional and intraregional differences for residential access to cooling resources. These are detailed in Table 2 which shows the proportion of residential parcels served by the various types of cooling resources in Los Angeles and Maricopa counties for the three catchment area sizes. Residential access to official cooling centers is low in both counties because there are a limited number of these facilities. At average walking speeds, official cooling centers serve an average of 460 residential parcels in Los Angeles and 430 in Maricopa. In total these cooling center networks are accessible only to a small fraction of households in each county, approximately 3% and 2%, respectively. While there are slight interregional differences in access to official cooling centers, which might be expected given that Los Angeles has three times as many locations as Maricopa, there are notable differences among the other two categories. Interregional accessibility differences are a function of the total number of locations but are also dependent on the density of the built environment. Areas with higher building densities lead to shorter distances travelled between origin and destination. Additionally, high intersection densities increase the connectivity to the network leading to larger catchment areas (Leslie et al., 2007; Scott and Horner, 2008).

We quantified the effect of intersection and parcel density on access to cooling resources. Figure 3 illustrates the parcel and intersection density distributions for census tracts in

Table 2. Proportion of households served by at least one cooling resource by resource type and walking speed.

	Official cooling center			Library			Commercial		
Walking speed	Slow	Average	Fast	Slow	Average	Fast	Slow	Average	Fast
Los Angeles	0.3%	3%	10%	1%	11%	29%	36%	80%	91%
Maricopa	0.3%	2%	5%	0.2%	2%	7%	7%	39%	69%

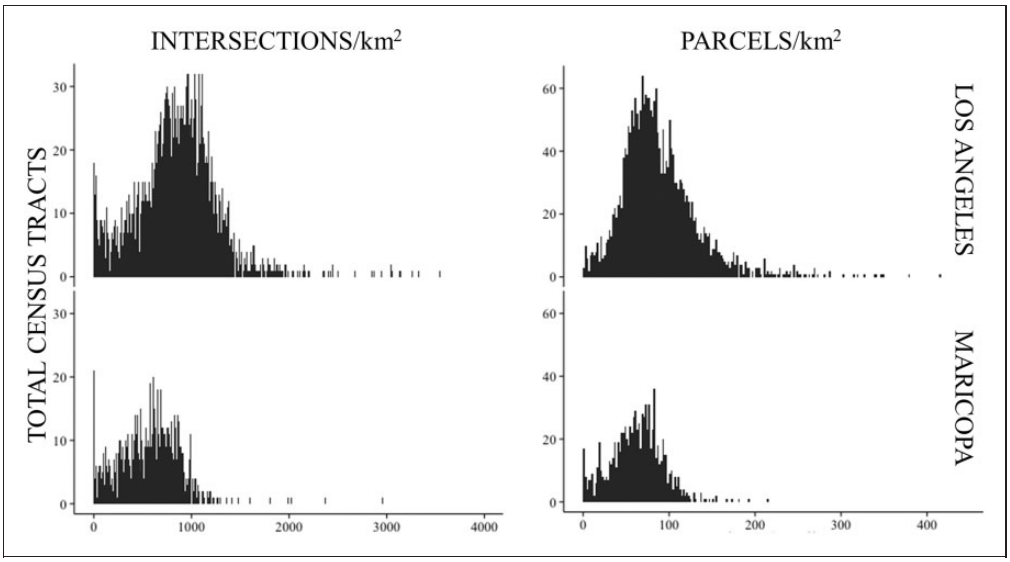

Figure 3. Intersection and parcel density by census tracts.

Los Angeles and Maricopa. The mean parcel density in Los Angeles is 870/km^2 while the mean intersection density is 89/km^2. In contrast, the Maricopa means are 580 parcels/km^2 and 63 intersections/km^2. In addition to having a built environment more suited for walkable access, the zoning paradigm in Los Angeles is more heterogeneous than Maricopa, which decreases the relative distances between residential and non-residential parcels. Based on these characteristics alone, it can be expected that residents in Los Angeles would have greater access to cooling resources of any kind than their counterparts in Maricopa.

Developing an accessibility index with household level resolution makes it easier to understand inter- and intra-regional accessibility differences. Aggregated at the census tract scale, the results illustrate how access to cooled space differs across the two regions; it also indicates which areas may be particularly vulnerable due to a lack of available cooling resource infrastructure. Moreover, individual walking speed and the declining marginal utility coefficient have a significant impact on the accessibility index (Table 3). Across all permutations, census tracts in Los Angeles consistently have higher accessibility scores than those in Maricopa. The most significant factor impacting the inter-regional accessibility score discrepancy is the relative proximity of commercial space and residential parcels. The interregional differences are the most pronounced when the marginal utility coefficient is zero, i.e., each cooled space has equal weight in terms of its utility (Table 3).

Table 3. Mean Census Tract Accessibility Index Score.[a]

Declining utility coefficient	Walking speed	Los Angeles	Maricopa	Correlation with parcel and intersection density
0	Slow	1.58	0.14	0.38
	Average	16.60	1.60	0.45
	Fast	39.89	5.29	0.46
1	Slow	0.53	0.09	0.41
	Average	1.80	0.55	0.48
	Fast	2.69	1.21	0.46
1.25	Slow	0.46	0.08	0.41
	Average	1.36	0.48	0.45
	Fast	1.99	1.02	0.41
2	Slow	0.34	0.07	0.40
	Average	0.87	0.38	0.37
	Fast	1.31	0.76	0.32

[a]In addition to total resource opportunities, index scores are influenced by the declining utility coefficient, walking speed, parcel density and intersection density.

As the marginal utility coefficient increases, that is, that each additional accessible cooled space is worth less and less to those seeking a heat refuge, the relative difference between the two counties decreases. Higher coefficients may offer a more balanced view of cooling resource accessibility by limiting the range of accessibility scores. When all accessible cooled spaces are weighted equally, the range of accessibility scores is significantly impacted by mixed use neighborhoods where residents have access to numerous locations. Further research is needed to determine an appropriate coefficient, which likely varies for each cooling resource type. Also noted in Table 3 is the correlation between accessibility scores with parcel and intersection density. The coefficient of determination (R^2) ranges between 0.32 and 0.48 between the 12 permutations which means that parcel density and intersection density are important determinants of access to publically available cooled space. While the variance is not fully explained by parcel and intersection densities, these measures may be good starting points to evaluate neighborhood access to other goods and services.

Accessibility scores vary across each region and tend to be highest in urban areas and lowest in fringe suburbs. Figure 3 illustrates the mean accessibility score for Los Angeles and Maricopa counties at the census tract scale. These scores reflect all three walking speeds and a marginal utility coefficient of 2. At slow walking speeds, access scores tend to be highest in older areas of each region. At the neighborhood scale we find that cooling resources are more accessible in Los Angeles than in Maricopa County. In the Los Angeles Basin and San Fernando Valley area of Los Angeles, most neighborhoods have access to at least at least one cooled space within 0.87 km. At 1.4 km the only areas of Los Angeles with limited access are the neighborhoods located in Palos Verdes, the Santa Monica Mountains, and the San Gabriel Mountains. Palos Verdes is a large, affluent, residential neighborhood located just north of Long Beach, CA with relatively low intersection and parcel density as well as a limited number of cooling resources. Intuitively, one might expect the neighborhoods associated with the Santa Monica and San Gabriel foothills and mountains to have limited access due to the topography and limited development.

Table 4. Proportion of census tracts with an average accessibility score of zero.

	Walking speed		
	Slow	Average	Fast
Los Angeles	4%	1%	0.4%
Maricopa	25%	9%	5%

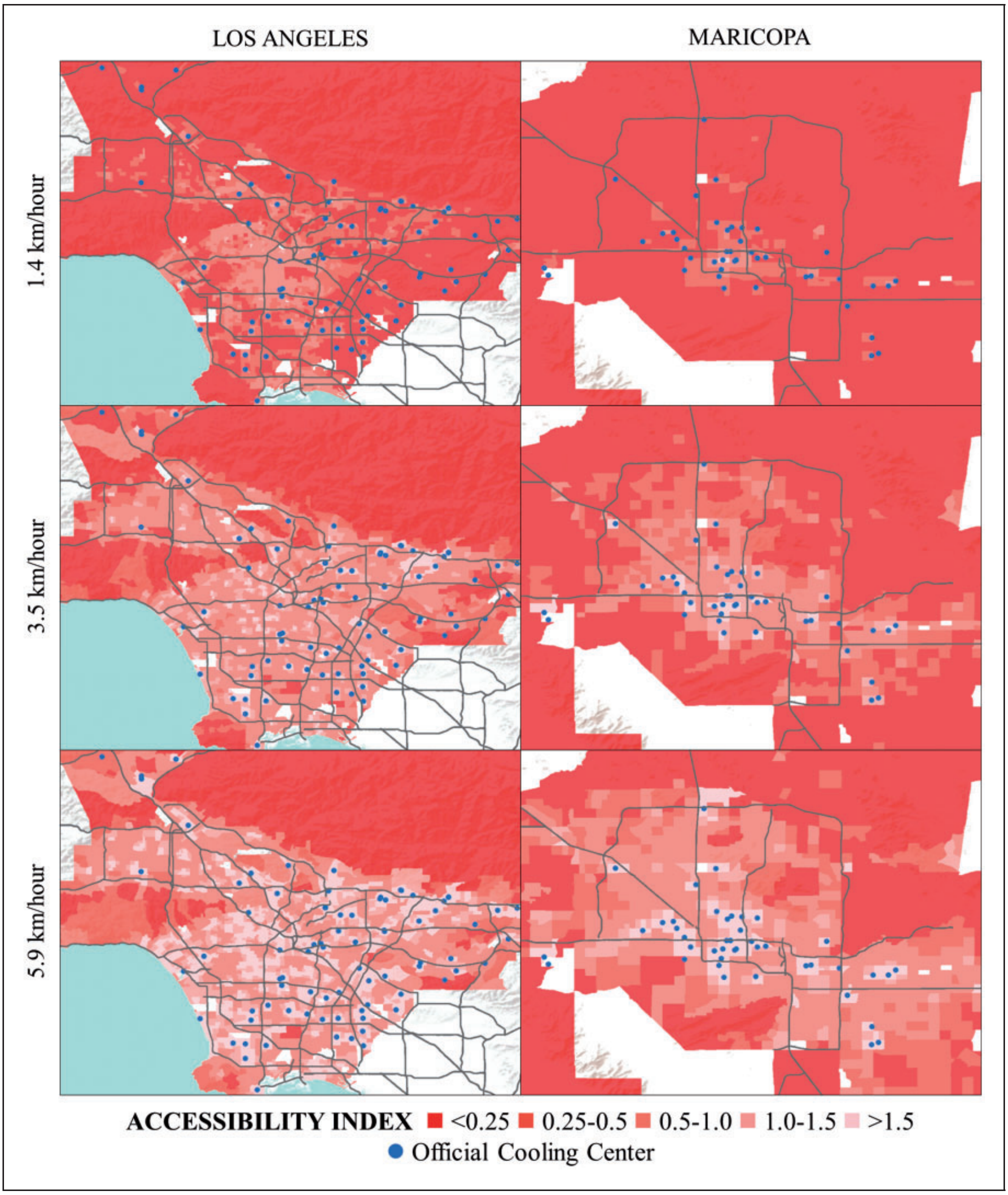

Figure 4. Neighborhood accessibility to cooling resources.

In contrast, Maricopa County, a region that has experienced rapid growth since the early 1990s, has significantly lower accessibility scores across all three walking speeds. In addition to lower building and intersection densities, one of the primary contributors to this difference is the large separation of residential developments from other land uses leading to greater distances between residential locations and cooling resources. Much of the population growth in Maricopa since 1990 has been accommodated by fringe suburban growth which is characterized by large residential developments served by few commercial centers (Census, 2010a; Heim, 2001). One of the most significant contrasts between the two regions is the relative proportion of census tracts which receive an average access score of zero (Table 4).

Figure 4 illustrates the effect of walking speed on mean household accessibility index score for each census tract. Land-use and street network characteristics significantly impact individual access to cooling resources.

Discussion

From our analysis come three major findings. First, officially designated cooling centers are unlikely to serve large portions of the population in both counties. Second, commercial cooled public spaces are widely dispersed and could provide access for large portions of the population in each region. Lastly, land use characteristics and the design of the street network impact individual household accessibility to cooled spaces.

The goal of cooling center networks is to provide relief on particularly hot days and during prolonged heatwaves. However, given the limited number of locations of official cooling centers, there is an underlying assumption that residents have adequate transportation to these locations. This assumption is problematic for several reasons. As we show, these locations can only serve a small fraction of households in each region if the transportation mode utilized was walking. For most households to reach these resources some form of motorized transport would be needed (either personal or public). We could generally expect households with access to automobiles to have the financial means to utilize other relief resources making them unlikely to seek out designated cooling centers. Public transportation provides another potential means for accessing these locations; however, access may not be universally available or practical for several reasons. Public transit use would necessitate heat exposure resulting from ingress/egress (which also requires modest physical activity further exacerbating potential heat stress) and waiting time at transit stop locations increases heat-related health risks which cooling centers attempt to mitigate (Fraser and Chester, in review; Karner et al., 2015). This is potentially more problematic in areas where transit service is infrequent and/or unreliable. For some groups, such as the elderly, which have some of the highest risk levels associated with heat exposure, designated cooling centers may be inaccessible due to a lack of mobility options (Luber and McGeehin, 2008; Taylor and Tripodes, 2001). Designated cooling centers may help reduce risks but the results suggest that they likely serve only a small fraction of households. To increase the effectiveness and coverage of official cooling centers, locations should be optimally chosen to serve those at greatest risk and in accordance with transportation provisions. Future efforts to aid in the optimization of cooling center networks and other public resources aimed at reducing heat exposure could use additional data sources including incidence of heat-related morbidity and mortality and its spatial variability within the city (Harlan et al., 2013; Hondula et al., 2015), vulnerability indicators (Reid et al., 2009), or additional survey-and interview-based data about AC use and constraints (Hayden et al., 2011).

Based on their quantity and distribution, cooled public commercial space has the greatest potential to provide relief during heatwaves to regional populations. However, since these spaces are not intended for use as heat relief locations they likely do not provide ancillary health services to address negative heat-health outcomes. It should be acknowledged that these spaces likely have different operating hours and capacity constraints which cannot be determined through available data. Future research could develop a time- and capacity-dependent accessibility index for these public buildings. While these spaces do not provide the same quality of service that might be found at formally designated cooling centers, they can provide heat relief. Publically accessible cooling resources and the ability of nearby households to utilize these spaces should be considered when deploying additional resources to mitigate the health risks associated with heat exposure. Additionally heat management programs could stress the importance of cooled space and suggest the use of these types of facilities for those without in-home AC and for those whose mobility may be constrained. This analysis reflects a type of theoretical accessibility score, but there could also be important social and cultural dynamics at work in terms of the types of people who are willing to/welcome at/able to visit certain types of locations that could provide additional constraints on accessibility.

In both Los Angeles and Maricopa counties, accessibility to cooling resources decreases when moving from the urban areas to the outlying suburbs. Both counties have developed around the automobile, which resulted in transportation land-use decisions emphasizing automobile mobility over other modes. The disaggregation of land uses (residential and commercial) further increases travel costs for accessing necessary goods and services. The transportation and land-use systems in both regions, which cater to the automobile, place greater generalized transportation costs on the outer regions. The declining accessibility from the core to the outer areas results from decreasing parcel density, decreasing intersection density, and the increasing homogeneity of land use (e.g. separation of residential and commercial land uses). Households in the suburbs have limited access to cooled space via walking and would be the most reliant on motorized forms of transportation in order to access these resources. This effect is more pronounced in Phoenix where residential developments tend to be larger and commercial locations are clustered in commercial parks.

The relative increase in risk for negative heat-health outcomes that may be associated with a lack of access to cooled space may be disproportionate depending on socio-economic variables. Though extreme heat can adversely affect the health of anyone, there are population subsets which may be particularly vulnerable. Previous research has shown these subsets, which include the elderly, low-income, and socially or linguistically isolated, exhibit higher morbidity and mortality incidence rates during hot weather. To minimize overall health risks associated with heat, policies and programs should target areas of cities that lack both the infrastructure to mitigate the effect of heat and those where residents may be more vulnerable to heat based on intrinsic socio-economic characteristics.

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