Building Thermal Performance, Extreme Heat, and Climate Change

Matthew J. Nahlik[1]; Mikhail V. Chester, Ph.D., M.ASCE[2]; Stephanie S. Pincetl, Ph.D.[3]; David Eisenman[4]; Deepak Sivaraman, Ph.D.[5]; and Paul English, Ph.D.[6]

Abstract: The leading source of weather-related deaths in the United States is heat, and future projections show that the frequency, duration, and intensity of heat events will increase in the Southwest. Presently, there is a dearth of knowledge about how infrastructure may perform during heat waves or could contribute to social vulnerability. To understand how buildings perform in heat and potentially stress people, indoor air temperature changes when air conditioning is inaccessible are modeled for building archetypes in Los Angeles, California, and Phoenix, Arizona, when air conditioning is inaccessible is estimated. An energy simulation model is used to estimate how quickly indoor air temperature changes when building archetypes are exposed to extreme heat. Building age and geometry (which together determine the building envelope material composition) are found to be the strongest indicators of thermal envelope performance. Older neighborhoods in Los Angeles and Phoenix (often more centrally located in the metropolitan areas) are found to contain the buildings whose interiors warm the fastest, raising particular concern because these regions are also forecast to experience temperature increases. To combat infrastructure vulnerability and provide heat refuge for residents, incentives should be adopted to strategically retrofit buildings where both socially vulnerable populations reside and increasing temperatures are forecast. **DOI:** 10.1061/(ASCE)IS.1943-555X.0000349. *© 2016 American Society of Civil Engineers.*

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Introduction

Heat is the leading source of weather-related deaths in the United States, and predictions show increased frequency, duration, and intensity of heat events into the future, particularly in the Southwest (NWS 2013; Bartos and Chester 2014). Approximately 200,000 heat-related deaths are projected to occur in 12 U.S. cities by the end of the century because of climate warming (Petkova et al. 2014). To date, research examining heat vulnerability has focused on socioeconomic variables, such as age, preexisting health conditions, social isolation, and linguistic isolation, but there remains a dearth of knowledge around how the design of urban form contributes to social vulnerability. For example, a study of the July 2006 heat wave in California estimated that an additional 16,000 emergency room visits and 1,200 hospitalizations occurred from heat-related illnesses (Knowlton et al. 2009). Additionally, the populations most vulnerable to heat have been found to be people of racial and ethnic minorities, people at extremes of age, or people with preexisting medical conditions (Basu and Ostro 2008; Kovats and Hajat 2008; Kilbourne 1997).

Beyond this understanding of social vulnerability, the contributions of building infrastructure to heat vulnerability have not been rigorously explored. Most existing research that examines the relationship between buildings and heat impacts focuses on urban heat island or how lack of refuge from heat can further complicate existing health conditions (Semenza et al. 1996; Stone et al. 2010; Luber and McGeehin 2008). Moreover, lack of air-conditioning access or the inability to afford electricity to operate air conditioning has been linked to heat-related morbidity and mortality (Kovats and Hajat 2008; Semenza et al. 1996). The only identified research to explore interactions between buildings and social vulnerability examines energy efficiency of buildings and how construction materials influence the consumption of energy for air conditioning (Sadineni et al. 2011a; Wright et al. 2002). Beyond building energy efficiency and consumption, current research has not adequately assessed how existing building envelopes may perform during periods of extreme heat.

Cities in the Southwest are particularly vulnerable to climate change with fast-growing populations, and significant increases in temperature forecast for the coming century (Rotstayn et al. 2012; Bartos and Chester 2015). With a population of nearly 10 million people spread over 12,300 km^2 (4,751 mi^2), Los Angeles County includes many climates particular to diverse geographies, such as the Pacific Coast of California, the Sonoran Desert, and the Santa Monica, San Bernardino, and San Gabriel mountains. Geographical variations across the county result in highly variable summer temperatures, from cool climates with less

[1]Research Scientist, Dept. of Civil, Environmental, and Sustainable Engineering, Arizona State Univ., Tempe, AZ 85287-3005. E-mail: mattnahlik@gmail.com

[2]Assistant Professor, Dept. of Civil, Environmental, and Sustainable Engineering, Arizona State Univ., Tempe, AZ 85287-3005 (corresponding author). E-mail: mchester@asu.edu

[3]Director and Professor-in-Residence, California Center for Sustainable Communities at UCLA, Institute of the Environment and Sustainability, Univ. of California, Los Angeles, CA 90095. E-mail: spincetl@ioes.ucla.edu

[4]Professor, Dept. of Medicine and Dept. of Public Health, Univ. of California, Los Angeles, CA 90095. E-mail: deisenman@mednet.ucla.edu

[5]Energy Economist and Analyst, Pacific Northwest National Laboratory, U.S. Dept. of Energy, Washington, DC 20585. E-mail: deepak.sivaraman@pnnl.gov

[6]Branch Scientific Advisor, Environmental Health Investigations Branch, California Dept. of Public Health, Sacramento, CA 95814. E-mail: paul.english@cdph.ca.gov

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than 1,000 cooling degree days (CDD) from June to September near the Pacific Coast to climates further inland that require nearly 4,000 CDD each summer, as described by the five different California Energy Commission (CEC) climate zones shown in Fig. 1 (CEC 2006). By comparison, Maricopa County, Arizona (whose county seat is Phoenix), has 4.1 million residents and spans 23,900 km^2 (9,230 mi^2) of central Arizona in a relatively homogeneous subtropical desert climate with daily high temperatures greater than 38°C (100°F) from June to September (U.S. Climate Data 2015).

Both Los Angeles and Maricopa counties are characterized by extensive medium-to-low density infrastructure deployed predominantly in the latter half of the twentieth century. Fig. 1 shows the incorporated, urbanized areas for the Los Angeles and Phoenix regions and an overview of their common building types. The Los Angeles County map shows the incorporated urban census tracts, and California Energy Commission climate zones are shown (average temperature ranges: 6 to 55–69°F; 8 to 55–73°F; 9 to 58–74°F; 14 to 45–84°F; 16 to 38–78°F). The Maricopa County map highlights the urban census tracts for Phoenix and has a label

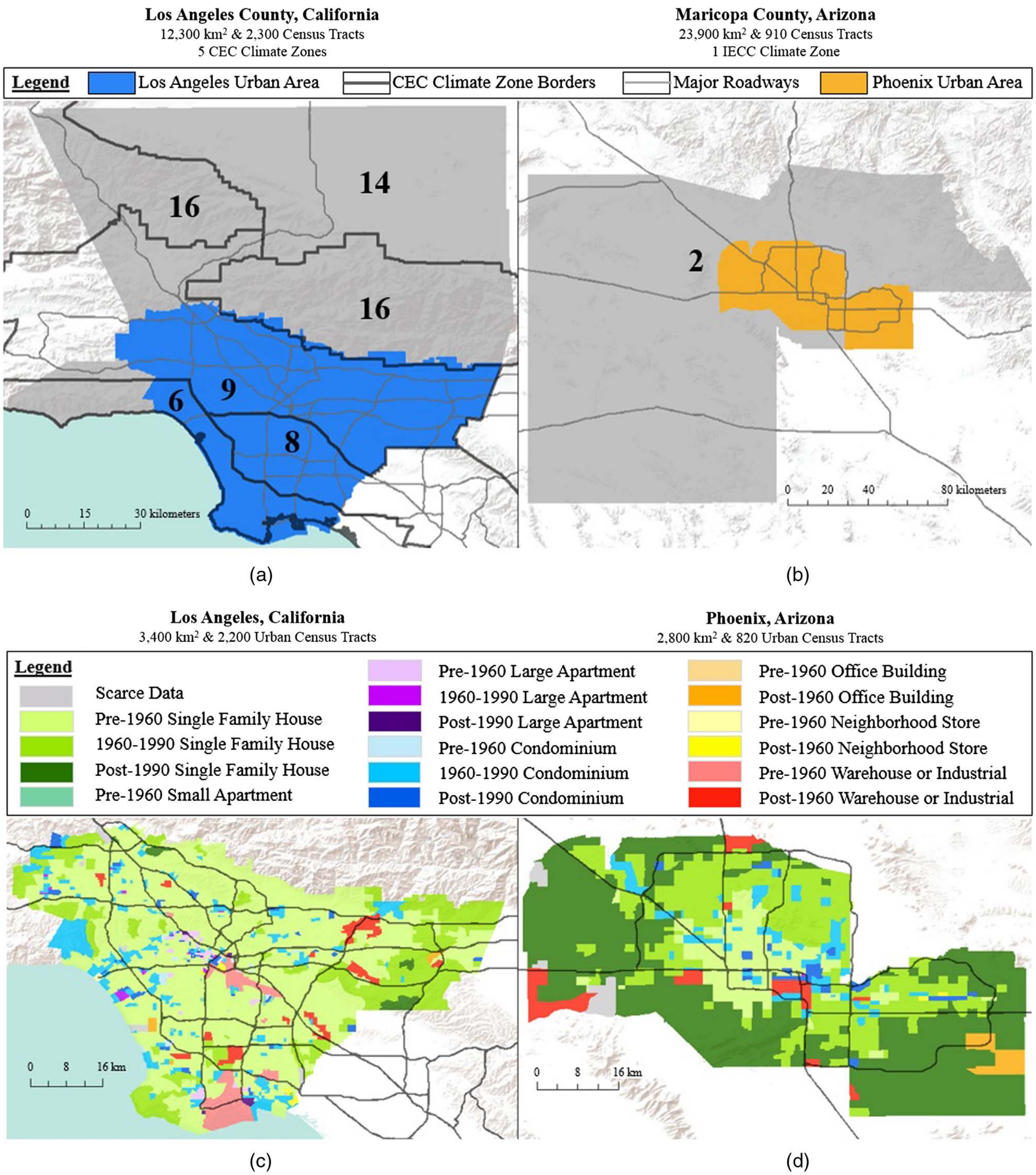

Fig. 1. (a and b) Climate zones and (c and d) building stock for Los Angeles and Maricopa counties, respectively

for the single International Energy Conservation Code (IECC) climate zone that encompasses the whole county. Figs. 1(c and d) shows the building types that occur most often in each census tract according to each region's assessor data. Low-density development in the form of single-family homes is the most common building type across both urban areas, with small pockets of higher-density apartments, condominiums, and commercial areas in each city comprising a minority of the developed land. Building thermal characteristics vary because of differences in construction practices and materials, such as wall composition, insulation, windows, and building size (Reyna and Chester 2015). Los Angeles is an older region with an average building construction year of 1957, compared with Phoenix's 1984 average year of construction (LAAO 2012; MCAO 2012). The ability of buildings across both regions to keep conditioned indoor space cool is characterized.

Existing research has focused on building energy consumption, typically from heating and cooling systems, but isolated assessment that characterizes where heat-vulnerable buildings perform better or worse has been missing. Understanding building energy use is important because energy consumption around the world continues to increase and is driven largely by the heating and cooling loads of buildings (Pérez-Lombard et al. 2008; Zhao and Magoulès 2012; Palmer et al. 2013). Additionally, building energy simulation has been combined with geospatial modeling and a prototyping approach to estimate energy consumption at a citywide resolution (Heiple and Sailor 2008; Howard et al. 2012). Although existing studies have focused on energy consumption trends and individual building thermal performance to shelter residents from heat (Sailor 2014), citywide performance of building thermal envelopes should be explored by using diverse archetypes.

An understanding of the performance of buildings to keep indoor air space cool during heat events is important when assessing how vulnerable populations should be prioritized when electricity is unavailable because of an overtaxed grid, lost generation capacity, or inability of residents to pay for air conditioning. A novel approach to building infrastructure heat performance assessment is developed in which a single metric is used to compare individual buildings and average neighborhood results in cities. These results are used to answer the following questions: (1) How, at a citywide level, can building thermal performance for retaining cool air be characterized? (2) Do buildings with worse thermal envelope performance exist where increasing temperatures are forecast? (3) Where can building envelope improvements most effectively improve thermal performance?

Methodology

Citywide assessments of building thermal performance in Los Angeles and Phoenix are developed. Characteristic building types and vintages are used to represent the existing building stock. By using county assessor databases, building model archetypes are designed for current and historical vintages and climate zones in each city. Then, the material properties of these buildings are defined according to historical and current construction codes, and each model is used to develop a simulation of uniform extreme heat exposure to monitor the rate at which indoor temperature changes in response to outside heat. This provides a climate-controlled measure of performance based on the rate at which indoor air temperature increases. A numerical index of thermal performance is developed for each building from these simulations. Building thermal performance is considered explicitly and not the potential cooling effects from building orientation or urban vegetation, which have been shown to be significant (Jenerette et al. 2007, 2011), or the heat gains from machinery, appliances, or people inside the buildings.

Building Archetypes

Characteristic building archetypes are created for each city by considering function (residential and commercial), vintage, and climate zone. The assessor databases of Los Angeles and Maricopa counties provide a comprehensive list of buildings along with characteristics such as building use type, building size, and year of construction, which are used to create typologies (LAAO 2012; MCAO 2012). In Los Angeles, only 1% of land parcels by count are vacant or contain an uninhabitable structure, 66% of parcels contain a single-family house, and 21% of parcels contain a multifamily structure. Phoenix is similar to Los Angeles in that 66% of parcels by count contain single-family houses, and 13% contain multifamily structures, but up to 15% of parcels are vacant or contain an uninhabitable structure.

Given that both cities grew predominantly during the middle to latter half of the twentieth century, many similar styles and construction practices were used (Whittemore 2012; Heim 2001). As such, four residential and three commercial building forms are selected to characterize structures in both cities. A single-family house, condominium, small apartment building (up to 10 units), and large apartment building (10 or more units) are each archetyped with different sizes and properties for three distinct periods: pre-1960, 1960–1990, and post-1990, which follow waves of growth in Los Angeles and also align with growth patterns in Phoenix (Whittemore 2012). A neighborhood store, office building, and warehouse/light manufacturing facility for two distinct vintages, pre-1960 and post-1960, are designed to comprise the nonresidential building stock. The pre-1960 and post-1960 periods are selected because double-pane windows became the common material of choice rather than single-pane at this time. Post-1990 residential buildings are distinguished as a vintage because they are at least 20% larger on average than buildings constructed from 1960 to 1990, and the building volume and outside surface area both affect thermal properties (LAAO 2012; MCAO 2012). In addition to the aforementioned building types and vintages, three additional building archetypes are created with specific climate considerations for Los Angeles because of the diverse weather in the county. A list of the 39 resulting structures and their characteristics for both locations are shown in Table 1.

After characterizing vintage bins and physical sizes of the seven major building forms according to the county assessor data, material properties for each archetype are defined according to building standards. Climate zones are an important consideration for building construction because regulations require minimum insulation R-values for wall and roof materials (ASHRAE 2004). The IECC defines seven climate zones for the continental U.S., with Los Angeles residing in Zone 3 and Phoenix in Zone 2 (ICC 2006). Because Phoenix is covered by only one hot and dry IECC climate zone, each building type and vintage requires a single set of minimum wall and roof insulation properties for 18 distinct building archetypes (ASHRAE 2004). The CEC defines their own state climate zones to account for large variations across counties like Los Angeles, which spans five state climate zones as shown in Fig. 1 (CEC 2006). Zones 6, 8, 9, and 14 of the CEC cover 99% of parcels in Los Angeles and require identical insulation specifications for each building type and vintage, creating 18 building archetypes specific to the city. Zone 16 of the CEC, for mountainous and semiarid high altitude areas, mandates stricter insulation requirements for buildings with concrete walls, which necessitates the addition of three archetypes (CEC 2013). Phoenix's

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Table 1. Building Archetypes and Details for Los Angeles and Phoenix

Region and use	Building type	Vintage	Climate zone	Total size [m^2 (ft^2)]	Number of dwelling units	Number of floors	Wall construction	Insulation thickness [mm (in.)]	Window-pane type	BHPI
Los Angeles; residential	Single family	Pre-1960	CEC: 6, 8, 9, 14	140 (1,500)	1	1	Concrete block	25 (1)	Single	44
		Pre-1960	CEC: 16	140 (1,500)	1	1	Concrete block	35 (1.4)	Single	52
		1960–1990	CEC: 6, 8, 9, 14	180 (1,940)	1	1	Concrete block	35 (1.4)	Double	91
		1960–1990	CEC: 16	180 (1,940)	1	1	Concrete block	100 (4)	Double	99
		Post-1990	CEC: 6, 8, 9, 14, 16	250 (2,700)	1	2	Frame wall	125 (5)	Double	77
	Condominium	Pre-1960	CEC: 6, 8, 9, 14	170 (1,800)	2	1	Concrete block	25 (1)	Single	25
		Pre-1960	CEC: 16	170 (1,800)	2	1	Concrete block	35 (1.4)	Single	26
		1960–1990	CEC: 6, 8, 9, 14, 16	460 (4,930)	4	2	Frame wall	75 (3)	Double	55
		Post-1990	CEC: 6, 8, 9, 14, 16	560 (6,040)	4	2	Frame wall	125 (5)	Double	81
	Small apartment	Pre-1960	CEC: 6, 8, 9, 14, 16	140 (1,540)	2	2	Frame wall	50 (2)	Single	12
		1960–1990	CEC: 6, 8, 9, 14, 16	350 (3,720)	4	2	Frame wall	75 (3)	Double	30
		Post-1990	CEC: 6, 8, 9, 14, 16	420 (4,480)	4	2	Frame wall	125 (5)	Double	63
	Large apartment	Pre-1960	CEC: 6, 8, 9, 14, 16	490 (5,250)	6	2	Frame wall	75 (3)	Single	25
		1960–1990	CEC: 6, 8, 9, 14, 16	780 (8,400)	8	4	Frame wall	125 (5)	Double	43
		Post-1990	CEC: 6, 8, 9, 14, 16	1,210 (13,000)	12	7	Metal curtain wall	75 (3)	Double	21
Los Angeles; commercial	Neighborhood store	Pre-1960	CEC: 6, 8, 9, 14, 16	330 (3,600)	—	1	Frame wall	75 (3)	Single	59
		Post-1960	CEC: 6, 8, 9, 14, 16	650 (7,000)	—	2	Frame wall	125 (5)	Double	26
	Office building	Pre-1960	CEC: 6, 8, 9, 14, 16	740 (8,000)	—	4	Brick wall	50 (2)	Single	43
		Post-1960	CEC: 6, 8, 9, 14, 16	2,260 (24,300)	—	9	Metal curtain wall	75 (3)	Double	90
	Warehouse	Pre-1960	CEC: 6, 8, 9, 14, 16	1,150 (12,400)	—	1	Frame wall	25 (1)	Single	99
		Post-1960	CEC: 6, 8, 9, 14, 16	2,120 (22,800)	—	2	Frame wall	50 (2)	Double	99
Phoenix; residential	Single family	Pre-1960	IECC: 2	140 (1,500)	1	1	Concrete block	25 (1)	Single	30
		1960–1990	IECC: 2	180 (1,940)	1	1	Concrete block	50 (2)	Double	66
		Post-1990	IECC: 2	250 (2,700)	1	2	Frame wall	150 (6)	Double	38
	Condominium	Pre-1960	IECC: 2	170 (1,800)	2	1	Concrete block	25 (1)	Single	12
		1960–1990	IECC: 2	460 (4,930)	4	2	Frame wall	75 (3)	Double	26
		Post-1990	IECC: 2	560 (6,040)	4	2	Frame wall	150 (6)	Double	45
	Small apartment	Pre-1960	IECC: 2	140 (1,540)	2	2	Frame wall	50 (2)	Single	6
		1960–1990	IECC: 2	350 (3,720)	4	2	Frame wall	75 (3)	Double	14
		Post-1990	IECC: 2	420 (4,480)	4	2	Frame wall	150 (6)	Double	32
	Large apartment	Pre-1960	IECC: 2	490 (5,250)	6	2	Frame wall	75 (3)	Single	12
		1960–1990	IECC: 2	780 (8,400)	8	4	Frame wall	125 (5)	Double	21
		Post-1990	IECC: 2	1,210 (13,000)	12	7	Metal curtain wall	75 (3)	Double	10
Phoenix; commercial	Neighborhood store	Pre-1960	IECC: 2	330 (3,600)	—	1	Frame wall	75 (3)	Single	27
		Post-1960	IECC: 2	650 (7,000)	—	2	Frame wall	125 (5)	Double	12
	Office building	Pre-1960	IECC: 2	740 (8,000)	—	4	Brick wall	50 (2)	Single	19
		Post-1960	IECC: 2	2,260 (24,300)	—	9	Metal curtain wall	75 (3)	Double	53
	Warehouse	Pre-1960	IECC: 2	1,150 (12,400)	—	1	Frame wall	25 (1)	Single	47
		Post-1960	IECC: 2	2,120 (22,800)	—	2	Frame wall	50 (2)	Double	74

climate is most similar to CEC Zone 9, which covers much of central Los Angeles and causes the building archetypes in each city to have similar material properties as described in Table 1 (ICC 2006; CEC 2006).

The thermal envelope of each of the 39 building archetypes consists of a foundation, wall construction, attic, insulation material, window types, and roofing material, which are each specified by using climate zone information, building codes, and American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) energy standards. A concrete slab-on-grade foundation is used because basements are not common in either region. Building codes in Los Angeles and Phoenix dictate structural systems that account for potential earthquakes and other natural events (ICBO 2012; CBSC 2012). Wooden frame walls tend to be the most common support structure (LAAO 2012; MCAO 2012). Some of the older (pre-1960) building archetypes use concrete and brick wall construction, depending on the building function, whereas taller building archetypes (more than four floors) require metal fabrication for support (ICBO 2012). Insulation types and thicknesses are specified by using ASHRAE energy standards, which dictate the minimum acceptable thickness and insulation R-value according to the wall construction materials and the climate zone of the building (ASHRAE 2004; CEC 2013).

Typically, wooden frame walls and buildings located in colder climates require insulation with the largest R-values and best thermal containment properties. Double-pane windows were first manufactured in the 1940s and became prolific in building construction during the 1960s (Jester 2014) and are considered the standard window type used in building archetype vintages post-1960. Roofing material are specified for each archetype according to common building practices for each type and vintage, with all single-family houses and condominiums having shingled roofs, apartment buildings having either shingle or lightweight concrete roofs, and commercial buildings fitted with lightweight concrete material on top of flat roofs to facilitate machinery and maintenance activities (CBSC 2012). With the geometry and material characteristics specified, a building thermal performance simulation is implemented to estimate how each archetype performs during extreme heat events.

Analyzing Archetype Buildings in Extreme Heat

The transient system simulation tool (TRNSYS) is used to assess the thermal envelope performance for each of the 39 archetype models during a uniform and prolonged period of extreme heat. TRNSYS is a state-of-the-art building energy simulation model that allows for the assessment of energy consumption and creation of an indoor temperature profile (Klein and Al 2010). For the purpose of these simulations, extreme heat is defined as a daily maximum temperature that exceeds a threshold of the 97.5th percentile of historical summer temperatures in the area, which is consistent with other publications (Meehl and Tebaldi 2004; Grossman-Clarke et al. 2010). In Los Angeles, an ambient air temperature of 37°C (99°F) is used, along with a relative humidity of 9% for the extreme heat threshold, whereas an ambient air temperature of 44°C (111°F) and 2% relative humidity are used for Phoenix (Bartos and Chester 2014). These threshold values are used as the characteristic extreme heat weather information, along with typical irradiance, illuminance, sky cover, and wind direction values for simulations in each city. The goal is to estimate how building internal temperatures change in response to outside heat when air conditioning is not used.

To isolate and assess only the performance of the building thermal envelope, each archetype simulation exposes the building to the aforementioned outside extreme heat temperature over a prolonged period and records how the building indoor temperature changes from an initial set point. Not included are the effects of a diurnal outside temperature change, shade or urban form that might affect indoor temperature, or occupant behavior. The goal instead is to focus explicitly on characterizing the building thermal performance when these factors are controlled for, to give insight into the characteristics of building infrastructure across heat-vulnerable cities that are undesirable. As such, building envelope performance is simulated in TRNSYS after inputting each building archetype model, defining the material composition of each envelope component, and assuming that no internal gains or mechanical heating or cooling systems would be used. These inputs and assumptions are used by TRNSYS to calculate how the indoor temperatures would change on the basis of air infiltration into the conditioned spaces and the thermal conductance and resistance of the defined materials. The temperature information and associated values used to develop the building heat performance metric during an example simulation is shown in Fig. 2.

Creating an Index of Thermal Envelope Performance

The results of the TRNSYS simulation for each of the 39 building archetypes are used to formulate a building heat performance index (BHPI), which is a novel description of how quickly the inside temperature of each building increases during the simulation period. A single metric of thermal performance is suitable for this analysis because it can be used to compare results from different building types and vintages and average neighborhood-level results across cities. In Fig. 2, archetype simulation results for a pre-1960 single-family house in Phoenix are presented. Constant extreme heat outside temperature is shown along with changing inside temperature. Also highlighted in Fig. 2 are the critical values for the formulation of the BHPI. The formulated BHPI is defined as the time elapsed (Δt) for the indoor temperature to increase (ΔT) from 25 to 32°C (77 to 90°F). Therefore, a building with a low BHPI is less thermally preferable than a building with a high BHPI. Each simulation was initiated with an indoor temperature of 25°C (77°F) because that is a typical temperature for an indoor conditioned space in the summer months of each region and falls within the ASHRAE thermal comfort zone when outside humidity is less than 10% (Hoyt et al. 2013). Additionally, an analysis of the CEC residential appliance saturation study finds that 25°C (77°F) is a typical cooling set point for Los Angeles air conditioning (CEC 2009). The index ending temperature of 32°C (90°F) is selected because it is outside the ASHRAE thermal comfort zone at which residents would need to find other shelter from heat. The temperature of 32°C

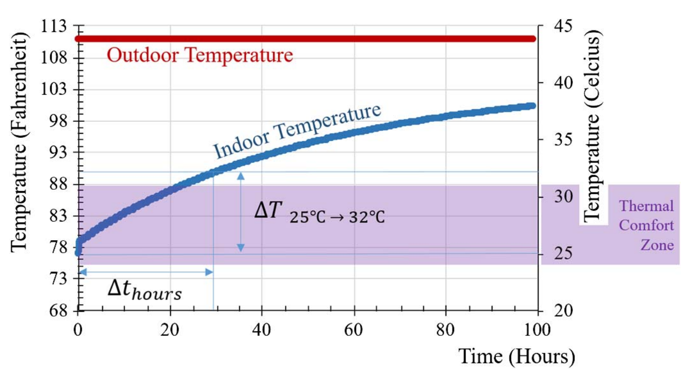

Fig. 2. Extreme heat simulation for a pre-1960 single-family house in Phoenix

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(90°F) is a common one at which heat-related morbidity and mortality increases (Maricopa County Department of Public Health 2012; California Office of Statewide Health Planning and Development 2012). By using fixed beginning and ending temperatures to define the BHPI, building performance is simply described as a measure of elapsed time (in hours) to cover a fixed temperature change.

Comparisons of building performance between the two cities are valid when assessing the same conceptual definition for extreme heat (exceeding the 97th percentile of historical high temperatures in the area) and recognizing that buildings have historically been constructed differently in each city to adapt to local climate conditions. Comparing building thermal performance during extreme heat in each city is logical because the definition of extreme heat is constant, along with the BHPI definition. In contrast, comparing buildings across both cities can be more difficult because, although the BHPI definition is the same, extreme outdoor heat is based on different temperatures for each city and influences the BHPI results independently for each city. For example, a single-family house analyzed during extreme heat conditions in Phoenix would not have the same BHPI if analyzed during extreme heat conditions in Los Angeles because of the different building envelope compositions and outside temperatures used during simulation. Given these analytic limitations, each citywide analysis is assessed independently with a specific group of building archetypes and associated heat performance indices.

Assigning Archetype Performance Indices to Existing Building Stock

Every existing building in each county is assigned to a specific building archetype on the basis of a property use code and construction year data. Because the building archetypes are characterized from an analysis of the existing building stock in each city, property use codes provided in each county assessor database can be categorized in one of three ways: (1) matching one of the 39 building archetypes; (2) a parcel without a building; or (3) a parcel that has a building that does not fit one of the created building archetypes. Using this categorization of property use types and the year of building construction, each of the 2.2 million parcels in Los Angeles County and 1.5 million parcels in Maricopa County is assigned to a building archetype with a BHPI, or to no building archetype and a BHPI of zero. By this process, 98% of parcels in Los Angeles are assigned a BHPI, whereas only 2% of parcels contain a habitable structure that does not match a archetype. Parcel coverage in Phoenix is 96%. The building prototyping approach generates 40 BHPIs (39 building models and one BHPI of zero for vacant land or uninhabitable structures), which are used to characterize the thermal performance of every parcel in the two cities.

After each parcel is assigned a BHPI, the results are aggregated to a census tract geography to analyze the building thermal performance patterns in neighborhoods. Los Angeles has 2.2 million parcels in 2,300 census tracts, whereas Phoenix has 1.5 million parcels contained in 910 census tracts (U.S. Census Bureau 2010). When aggregated to a census tract geography, the urbanized incorporated areas of both cities have a higher data density with more land parcels (and associated BHPIs) contained in each urban census tract. This is in contrast to the more rural census tracts of each city that contain fewer, albeit larger, land parcels. This method of aggregating individual building heat performance up to a larger urban geography should be recognized as one of many variables that contribute to assessing indoor heat stress. Because urban form factors such as building density, landscaping, or interaction with urban open spaces are not assessed, the results represent only one variable that may ultimately contribute to public health impacts. The results are calculated for both Los Angeles and Maricopa counties, but the visual representations focus on the data-dense urban census tracts of Los Angeles and Phoenix.

Building Thermal Performance Results

The building envelopes of both Los Angeles and Phoenix are found to have the worst average thermal performance in the older areas of each city, with the outcome influenced by the various types of existing buildings, the material properties of these buildings, and the climate conditions of the area. The BHPIs for the 39 archetype models are used to compare buildings and understand how the existing building stock contributes to citywide vulnerability to extreme heat. In Los Angeles, the 21 calculated BHPIs are within 12–99 h, and the 18 Phoenix BHPIs are within 6–74 h (Table 1), with the lowest BHPI times representing the buildings with the worst thermal performance. Although newer buildings typically use more thermally preferable materials, relative extreme heat (extreme heat events occur at lower temperatures in Los Angeles than in Phoenix) and geometry (particularly, size and fenestration area) play a crucial role in the overall performance. The BHPI results show how the combination of these factors sometimes indicates that older buildings are more thermally preferable than some newer buildings by slowing the rate at which the indoor temperature rises. In Fig. 3, the BHPIs are rank ordered and grouped by city to show how building types compare in each city. In the figure, the archetypes are presented from worst to best thermal envelope performance for all building archetypes in each city. Overall, Phoenix buildings comprise 8 of the 10 highest BHPIs and only 2 of the 10 lowest BHPIs of the 39 total buildings, which indicates that they warm faster during periods of extreme heat than most Los Angeles buildings. Apartment buildings comprise 7 of the 10 worst thermally performing buildings, whereas commercial buildings comprise three of the five best performing across both cities and all vintages. The thermal performance of individual buildings paired with the development patterns of both cities over time heavily influences the census tract–level performance summaries for both Los Angeles and Phoenix.

In Los Angeles and Phoenix, building thermal performance correlates with building age, as the buildings of each city with the worst thermal envelopes are located in the oldest areas. The neighborhoods of Los Angeles have sprawled outward from the downtown and south city areas, as shown by the quartile distribution maps in Fig. 4. The quartile distribution maps for the urban areas of Los Angeles and Phoenix are presented. The darker shades represent the 25% with the worst thermal performance or oldest developed census tracts, and the lighter shades represent the 25% best thermally performing or youngest buildings in each city. The average year of building construction was found as 1957 and has a citywide standard deviation of 18 years. The heat performance index for census tracts in Los Angeles has a strong and positive 0.7 correlation with the age of the buildings, which indicates that older buildings will warm more quickly during periods of extreme heat. Because buildings in Los Angeles have been constructed over many decades, individual building thermal performance in neighborhoods is highly variable, with an average index of 52 h and a standard deviation of 14 h for all tracts, and the worst average BHPI of 20 h was found for one tract. In contrast, Phoenix has grown substantially over the last 50 years, with an average building construction year of 1984 and a standard deviation of 9 years. The average BHPI for census tracts in Phoenix has a 0.3 statistical correlation with building age, indicating that older areas of the city show a weak but positive correlation to poor thermal performance. The building composition of Phoenix is

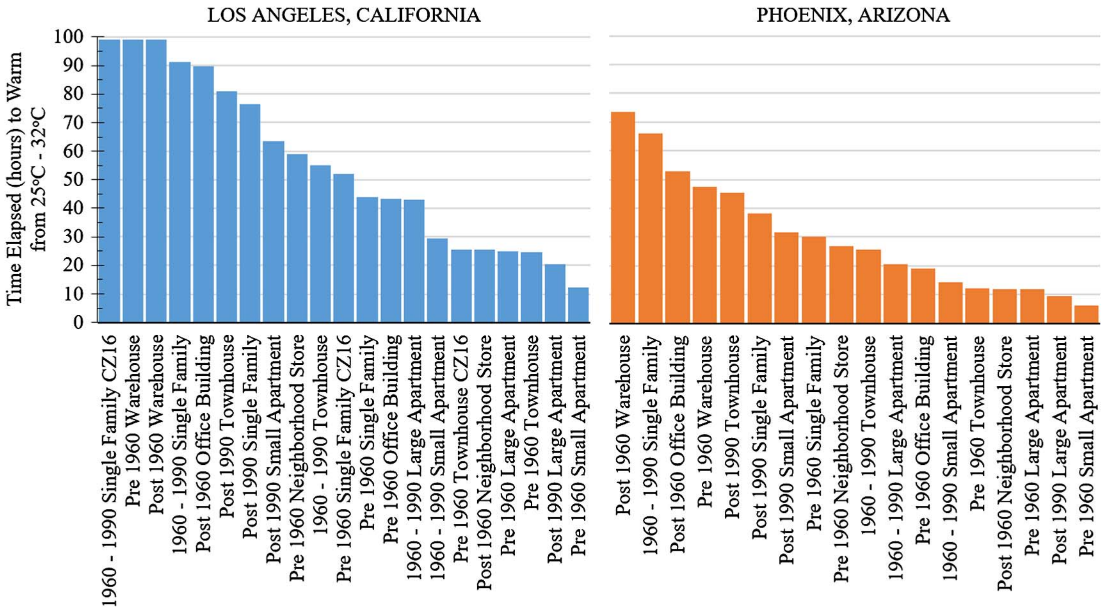

Fig. 3. Comparative building heat performance indices by building types

much newer and more homogenous than Los Angeles, which leads to a worse average BHPI of 45 h and a lower standard deviation of 10 h across the city. Fig. 4 shows the relationship between average building age [Fig. 4(a)] (which, along with building geometry, drive the thermal envelope material properties) and thermal performance [Fig. 4(b)], but urban vulnerability in each city is also influenced by other underlying factors.

For Los Angeles County, the worst thermally performing census tracts contain predominately single-family homes and apartment buildings constructed before 1960. These structures were built with single-pane windows, thinner mass walls, and less insulation, all of which were common practice at the time and contribute to thermal envelope performance during heat events. Commercial and industrial buildings have poorer thermal performance because of their large size and, particularly for office buildings and stores, large fenestration areas that allow the building envelope to warm more quickly. These building types dominate as the most common structure in only 10 census tracts of Los Angeles. In contrast, the remaining neighborhoods of Los Angeles most commonly contain residential buildings, with 67% of census tracts dominated by single-family homes constructed before 1960 and 21% containing predominately single-family houses and condominiums constructed from 1960 to 1990. The pre-1960 small and large apartment building archetypes warm the fastest during extreme heat, as shown by the fewest hours for the BHPI of these buildings. Their predominance in the housing supply causes Los Angeles to perform worse during heat waves on average because 7% of the habitable building stock is apartment buildings, contrary to Phoenix where only 1% of the stock is apartment buildings of any vintage. Neighborhood stores and office buildings are the second-worst thermally performing buildings (shown by a low BHPI) but comprise only 2% of building stock in each city. The greater range of building performance indices found in Los Angeles can be attributed to the older building stock and higher share of medium-density apartment buildings, which warm more quickly when exposed to heat.

The best-performing census tract are found in the older neighborhoods of Phoenix and are heavily influenced by the abundance of single-family homes of all vintages. The most common building type found in nearly 72% of census tracts is a post-1960 single-family home, which is consistent with the rapid growth of the Phoenix area over the last 50 years. Single-family houses in Phoenix that were constructed after 1990 warm at nearly twice the rate as homes built in 1960–1990 (according to BHPI hours), largely because of the increased floor area and resulting surface area and fenestration objects exposed to sunlight. Commercial buildings were the most common type found in only 2% census tracts and do not heavily influence neighborhood-level average thermal performance. After finding the BHPI patterns for both Los Angeles and Phoenix, future temperature projections can be compared to infrastructure performance to explore the areas where retrofits should be focused to better protect socially vulnerable populations.

Temperature-Weighted Thermal Performance

Temperature projections are paired with the building heat performance index to identify the areas where improvement efforts should be targeted. The CSIRO-Mk3-6-0.5 global climate model was used to project future temperatures for both cities up to 2050 and identify the 97.5th percentile of high temperatures to represent the likelihood of experiencing extreme heat (Rotstayn et al. 2012; Bartos and Chester 2015). As a result of the diversity in climate zones in Los Angeles, only 27% of census tracts in the county are projected to experience the extreme heat temperature of 37°C (99°F) by 2050, and these tracts are situated further inland away from the Pacific Coast. In contrast, 68% of census tracts in Maricopa County are projected to experience temperatures greater than the 44°C (111°F) threshold of extreme heat by 2050 (as defined for this project) and potentially even greater temperatures in the urban core because of urban heat island effects. The average census tract performance indices are weighted by multiplying by the predicted future 97.5th percentile temperature for that census tract divided by the maximum future predicted temperature for that city. The temperature-weighted results are shown in Fig. 4(c).

Identifying building vulnerability to heat that includes considerations for future extreme heat temperatures can help provide a clearer comparison between Los Angeles and Phoenix and identify target neighborhoods for mitigation measures. The weighted

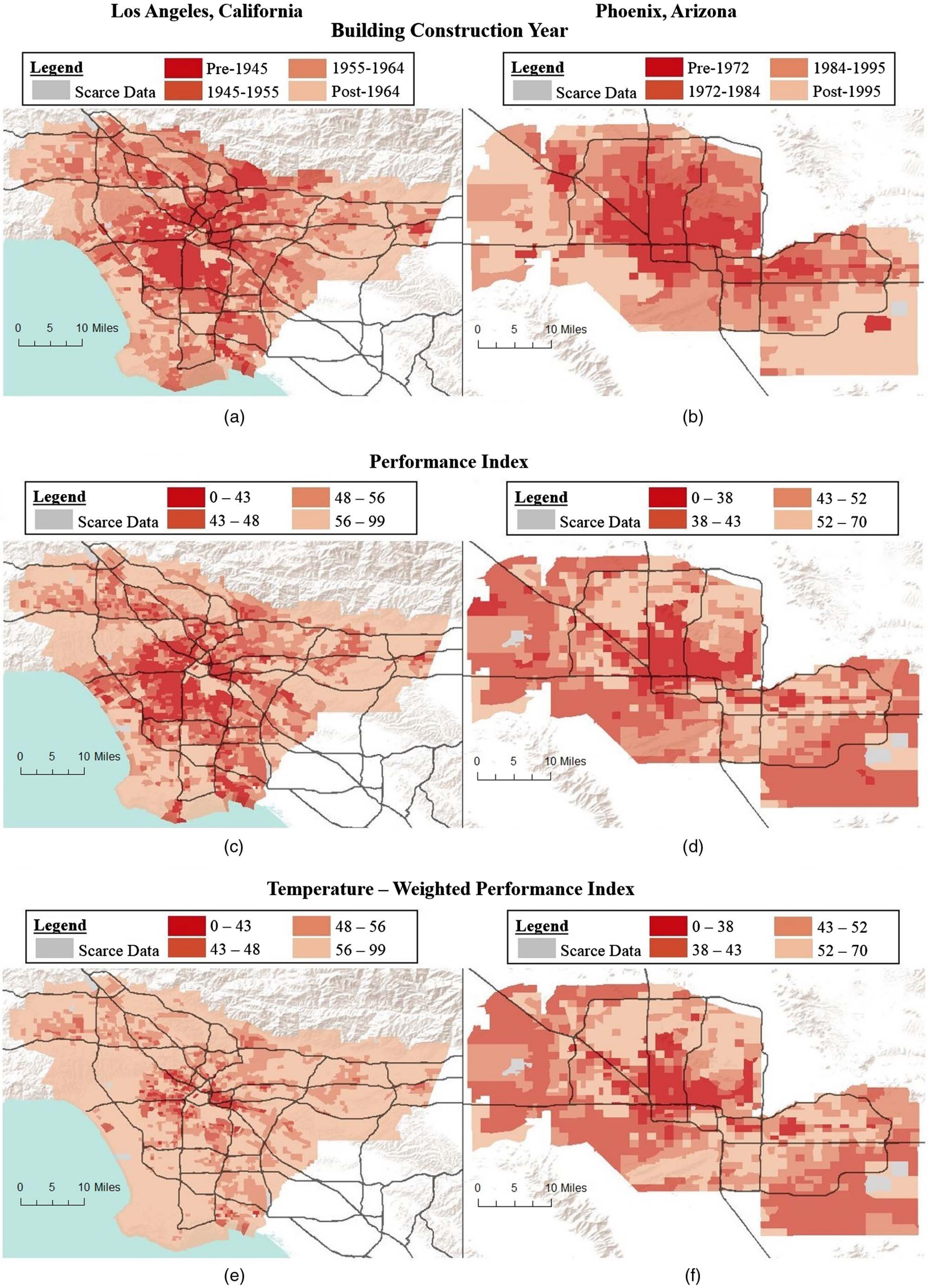

Fig. 4. (a and b) Building construction year; (c and d) thermal performance; and (e and f) temperature-weighted thermal performance by census tract for Los Angeles and Phoenix, respectively

performance indices for Phoenix remain largely unchanged from the original computation (the average tract BHPI is slightly improved from 45 to 46 h) because census tracts are projected to experience similar temperature increases across the study area. Only 290 census tracts (32%) have a BHPI reduced by up to 10%, and six census tracts (1%) have a reduction of 10–20% because they are projected to experience the lowest temperature increases in the future. The average BHPI results of Los Angeles change considerably when weighted according to future temperature forecasts (the average tract BHPI improves from 52 to 62 h) because the highest projected temperature increase in the arid desert is much greater than the slight increases near the Pacific Coast. More than 1,400 census tracts (61%) in Los Angeles have a heat performance index reduced by more than 10%, and 500 of these tracts are reduced by 50% or more. Fig. 4 shows how the most vulnerable areas of Los Angeles shift away from the temperature regulation of the Pacific Ocean and concentrate around the inland urban centers of Pasadena and downtown Los Angeles.

After weighting the performance indices of both cities, the census tracts in Los Angeles are significantly less vulnerable on average than those in Phoenix (the average Los Angeles BHPI is 62 h, which is 26% better than the average Phoenix BHPI of 46 h), and fewer neighborhoods of Los Angeles reach the threshold temperature of 32°C (90°F) in less than 48 h. Certain Los Angeles building archetypes were found to perform worse during extreme heat because of the original construction materials that did not reduce the rate of temperature increase inside the conditioned spaces of each structure. However, the negative effects are not likely to be experienced by many buildings in the area because of mild climate conditions throughout much of the city. Despite newer construction in Phoenix and the use of materials with better thermal conductance and resistance to improve thermal envelope properties, buildings are much more likely to experience extreme heat events in the future and are more vulnerable overall to the negative impacts of these events than those in Los Angeles. The temperature-weighted vulnerability results show that the existing buildings in 85% of census tracts of Los Angeles would survive for more than 48 h on average in extreme heat without air conditioning. For the Phoenix area, buildings in only 39% of census tracts would be able to last for more than 48 h in extreme heat before indoor temperatures rise above the comfort threshold of 32°C (90°F). Quick response times to restore electricity or repair air-conditioning units need to exist in areas where buildings have the worst-performing thermal envelopes, or programs must be in place to provide access for residents to other heat refuges.

Discussion

The research describes building thermal performance during extreme heat and identifies two key points for future mitigation: (1) Los Angeles contains few urban neighborhoods where an aging building stock is coupled with projected future extreme heat to cause high building thermal vulnerability, whereas large portions of Phoenix contain a thermally vulnerable building stock with projected future temperature increases; and (2) retrofitting options exist to slow the rate of indoor temperature rise and should be prioritized according to regions in each city where significant vulnerability reductions can occur. Although this study uses Los Angeles and Phoenix as case studies because they are the two largest cities in the Southwest, the method for capturing building thermal performance would be applicable to other cities that want to assess the rate of indoor temperature change during extreme outside temperatures and identify strategies for improvement. It is acknowledged that many other variables can affect indoor air temperature and that the results isolate the building envelope characteristics that lead to a building warming more quickly. The subsequent discussion focuses on the building envelope in which the BHPI provides insight.

By identifying the most vulnerable areas of both Los Angeles and Phoenix from the existing building stock and future temperature forecasts, policymakers can use available resources to focus on the most cost-effective mitigation strategies to reduce future extreme heat vulnerability. Improving the thermal envelopes of buildings through a variety of strategies will help slow indoor temperature rise. Previous publications have examined the contribution of individual envelope components and orientation of the structure to the overall thermal performance of a building and found that walls and fenestration objects are the largest contributors to temperature rise in conditioned spaces (Sadineni et al. 2011b; Cheng et al. 2005). Although the effects of building orientation on thermal performance were not considered, upgrading windows from single-pane to insulated double-pane can improve BHPI by 25%, and increasing insulation thickness by 40% can lead to as much as a 30% improvement to BHPI. Upgrading to more-efficient windows and adding insulation with higher thermal resistance to walls shared with unconditioned spaces (i.e., garages, attics, or patios) were found as the two most effective improvements for residential buildings in the desert Southwest, which is consistent with other literature (Sadineni et al. 2011a). For Los Angeles, where nearly half the building stock was constructed before 1960 with single-pane windows, retrofitting with newer insulated window technology and improved thermal conductance would be the most efficient way to slow indoor temperature rise. The Phoenix building stock is younger than that of Los Angeles and generally constructed with double-pane insulated windows, but thermal performance could be improved by upgrading fenestration objects with argon gas– or krypton gas–filled windows and insulated doors or by increasing insulation thickness and thermal resistance, particularly in ceilings that adjoin an unconditioned attic or walls shared with a garage.

To assist the most vulnerable populations when they cannot afford the capital cost of improving their own homes, more aggressive programs could be instituted that cover more of the cost of improving a building thermal envelope. One method could be tightening building codes for low-income housing to require thermally preferable construction materials for building envelopes that offer higher thermal resistance, improved thermal conductance, and reduce air exfiltration. An approach like this could be captured in the U.S. DOE's Building Energy Code Program, which makes recommendations for changing the IECC building codes that are widely adopted across municipalities in the United States. This avenue has been used in the past to improve both residential and construction practices, but special considerations should be given for low-income-housing improvements in the future, as residents of these developments would not be able to afford thermal improvements on their own. Local utility providers in both Los Angeles and Phoenix already provide some financial help to improve insulation and thermal conductance. However, some of the most vulnerable populations have little income and would not be able to provide the upfront investment needed to use any rebates that help reduce total costs over time.

Buildings have successfully provided heat refuge for city populations in the past, but continuing to do so in the future may become difficult without design improvements. Vulnerability to extreme heat is a complex problem that must consider building thermal envelope performance among other urban form and socioeconomic characteristics, and policymakers must decide where to use resources to reduce future morbidity and mortality.

As temperatures are projected to rise in the future and city populations continue to grow, more residents will be at risk for heat-related illnesses, and all possible mitigation measures should be taken to provide cost-effective refuges.

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