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The growing threat of heat disasters

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LETTER

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Heat is the number one weather-related killer in the United States and indoor exposure is responsible for a significant portion of the resulting fatalities. Evolving construction practices combined with urban development in harsh climates has led building occupants in many cities to rely on air conditioning (AC) to a degree that their health and well-being are compromised in its absence. The risks are substantial if loss of AC coincides with a hot weather episode (henceforth, a heat disaster). Using simulations, we found that residential buildings in many US cities are highly vulnerable to heat disasters—with more than 50 million citizens living in cities at significant risk. This situation will be exacerbated by intensification of urban heat islands, climate change, and evolving construction practices. It is therefore crucial that future building codes consider thermal resiliency in addition to energy efficiency.

Introduction

Invention and commercialization of air conditioning (AC) has caused major changes in building construction practices across the world. Passive strategies such as natural ventilation and thermal mass that historically used to keep buildings cool have increasingly been replaced by AC. In addition, AC is noted as a key factor in urban expansion in harsh climates such as southwest US (Arsenault 1984, Baniassadi *et al* 2018a). As a result, today's building stock, especially in North America, is heavily dependent on AC. According to the US Census Bureau, the percentage of new construction residences with AC has increased from 49% in 1973 to 93% in 2016 (see figure 1 for regional comparison). Furthermore, the US Energy Information Agency reports that as of 2015, 87% of homes in the country were equipped with some type of AC (EIA 2015).

Over-reliance on AC can lead to severe overheating of interior spaces in its absence (Baniassadi and Sailor 2018), exposing building occupants to dangerous levels of heat (MCDPH 2016). In such situations, prolonged heat exposure and inadequate thermoregulation can damage multiple organ systems and disrupt vital metabolic functions, resulting in a

range of adverse health effects including heat illnesses (e.g. heat cramps, heat exhaustion, heat stroke), dehydration, fluid and electrolyte imbalance, sleep loss, heart disease, renal disease, exacerbation of respiratory disease, and death (Basu *et al* 2012, Winquist *et al* 2016, Obradovich *et al* 2017, Sheridan and Allen 2018). Notably, extreme heat exposure was implicated as a contributing factor in approximately 7412 fatalities in the US between 1999 and 2010 (CDC 2012). Several societal, infrastructural and technological improvements (e.g. better access to healthcare, access to electricity and AC, and adaptive measures) have resulted in an overall decline in the relative impacts of heat events on human health over the past decades (Gasparrini *et al* 2015, Hondula *et al* 2015, Sheridan and Allen 2018). Nevertheless, extreme temperatures continue to be a major health concern around the world (Bobb *et al* 2014, Gronlund *et al* 2018), especially in the face of climate change (Pachauri *et al* 2014) and population ageing (Benmarhnia *et al* 2015). Studies examining mortality during past extreme events have found that 50%–85% of fatalities occurred in the decedent's own home (Fouillet *et al* 2006, Cadot *et al* 2007, CDC 2013). More generally, nearly 40% of heat-related deaths in the US occur inside a permanent home (NWS 2016). Nevertheless, a properly sized and

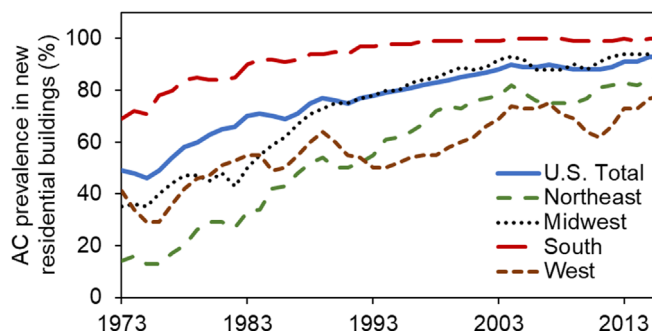
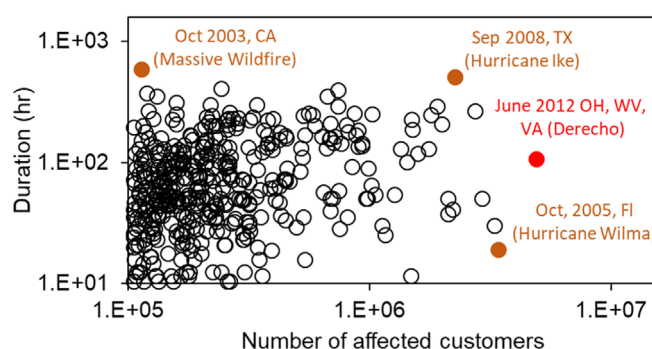
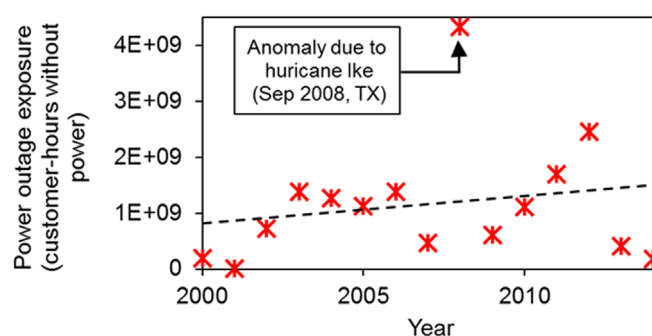


Figure 1. Growing rate of AC penetration into US residential building stock. Data from US Census Bureau.



(a)



(b)

Figure 2. (a) Magnitude and duration of power outages in the US from 2000 to 2015. Incidents lasting less than 10 h or affecting less than 100 000 customers are excluded. A notable example is the June 2012 Midwest storm event (derecho) that coincided with a heatwave. Reportedly, 20 people died due to exposure to heat inside buildings that lost AC due to the power outage. However, evidence from previous events suggests that this number is a significant underestimation of actual death toll due to AC loss (Fowler *et al* 2013). (b) Annual trend of total exposure to power outages (customers affected \times power outage duration). Raw data from the US Department of Energy.

operating AC system prevents overheating inside residences under most conditions (Sailor 2014). Hence, almost all morbidity and mortality due to indoor exposure to heat results from a lack of functioning AC under conditions that require mechanical cooling. For example, in 2016, in 61 out of 154 heat-related deaths in Maricopa County, AZ, indoor place of injury was reported as the cause of death. Notably, in all cases, AC system was not functioning due to system failure or lack of power (MCDPH 2016). The risks are significantly higher for more vulnerable groups such as the elderly or people with limited financial resources (Mitchell and Chakraborty 2015, Putnam *et al* 2018).

A recent example occurred during the power outage caused by Hurricane Irma in Florida in the summer of 2017, when eight people living in an assisted living facility died from exposure to high indoor temperatures (Reisner *et al* 2017).

Despite ongoing improvements in the resilience of power infrastructure, the risk of major power outages will persist and potentially grow (Yang *et al* 2017). Our analysis of electric disturbance data shows that between 2000 and 2014, in the US alone, 525 incidents of power outages lasting longer than 10 h and with more than 100 000 affected customers were reported (figure 2(a)). While more than 90% of the failures were

Table 1. Population and weather conditions of all selected cities.

Metropolitan area	Population	Temperature during the hypothetical heat disaster (°C)		
		Maximum	Minimum	Mean
Atlanta	5789 700	36.7	20	28.7
Boston	4794 447	37.2	22.8	29.0
Chicago	9512 999	35	23.3	28.9
Dallas	7233 323	38.9	24.4	32.0
Denver	2853 077	40	13.9	26.4
Detroit	4297 617	34.4	21.7	27.1
Houston	6772 470	39.4	23.3	30.7
Los Angeles	13 310 447	25.6	16.7	20.9
Miami	6066 387	35.6	25	29.7
Minneapolis	3551 036	35.6	21.7	27.3
New York	20 153 634	33.9	22.8	27.1
Philadelphia	6070 500	36.7	21.1	29.3
Phoenix	4661 537	44.4	29.4	37.3
Riverside	4527 837	38	17	27.4
San Diego	3317 749	28.9	17.2	22.9
San Francisco	4679 166	32.8	11.7	19.2
Seattle	3798 902	31.8	14	22.8
St Louis	2807 002	38.3	23.3	30.8
Tampa	3032 171	34.4	23.9	29.0
Washington, DC	6131 977	26.7	19.4	22.6

caused by weather-related disturbances (including system overload during heat waves Auffhammer *et al* 2017), human causes such as vandalism, equipment failure, and load shedding are also reported. In addition, national security authorities are increasingly concerned by the prospect for cyber terrorism or state-sponsored attacks on power generation and transmission infrastructure (Xiang *et al* 2017). Figure 2(b) shows a general increasing trend in exposure risk to power outages (number of customers \times duration of power outages). These data highlight the vulnerability of power generation and transmission infrastructure to weather-related perturbances, particularly in the face of an anticipated increase in number and severity of extreme weather events (e.g. hurricanes, heat waves) (Bartos *et al* 2016).

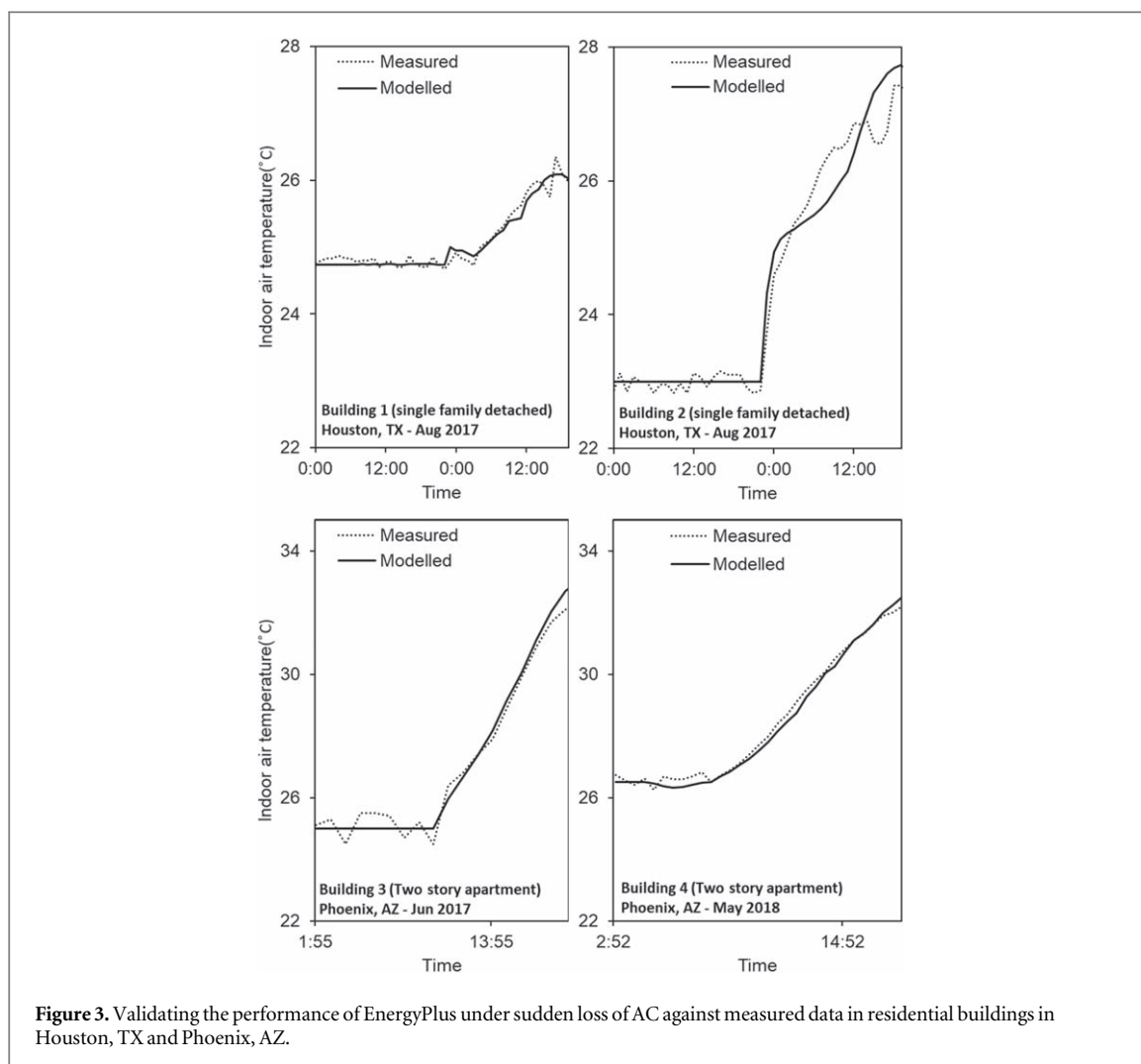
In contrast to AC equipment failure in a single home, a major power outage would diminish individuals' ability to take refuge from heat in other buildings within the community (Fraser *et al* 2016). Moreover, because of the large scale of utility system outages, the capacity of medical facilities to respond to the situation may be substantially challenged (Bernard and McGeehin 2004). We refer to this scenario as a heat disaster. With the predicted increase in the number and intensity of heat events in many densely populated areas around the world, the chance of a heat disaster in population hubs is increasing (Ballester *et al* 2011, Diffenbaugh *et al* 2017, Matthews *et al* 2017). Considering the AC-dependency of the US building stock (figure 1), the frequency of major power outages (figure 2), and the numerous urban areas with predicted warming due to a combination of climate change and intensification of the urban heat islands

(Dosio *et al* 2018, Krayenhoff *et al* 2018, Zhao *et al* 2018), we believe that in the US, the question is when (not if) a large scale heat disaster can be expected. Therefore, we seek to quantify the possible overheating outcomes of hypothetical heat disasters in residential buildings in major metropolitan areas (listed in table 1) in the continental US. The locations considered in this study account for more than a third of the country's population (123 million people). We used validated whole-building energy models to simulate the thermal conditions inside a large sample of archetypical detached single-family residential buildings (the most common type of residential building in the US EIA 2015) during a heat disaster and identify the effects from a changing building stock and urban climate.

Methods

Whole-building energy model and archetype sets

We used whole-building energy simulations to study the response of the current building stock to a heat disaster in the 20 largest metropolitan areas in the US. To model the thermal response of buildings under a heat disaster, we used EnergyPlus, a state-of-the-art and validated simulation tool developed by the US Department of Energy (Crawley *et al* 2001). EnergyPlus is a physics-based model that dynamically solves the energy and mass balance equations for all interior spaces within a building while accounting for all modes of heat transfer across system boundaries and heat sources within each zone. Hence, while the model's original purpose was calculating the energy



demand of various components of buildings, it can be used to simulate passive performance of buildings, i.e. without heating and cooling systems. Henninger and Witte (2014a, 2014b) provide a comprehensive list of prior validation studies that demonstrate the appropriateness of EnergyPlus for such studies. All these tests are based on the ANSI/ASHRAE standard 140, ‘the Standard Method of Test for the Evaluation of Building Energy Analysis Computer Programs’. In addition to the numerous validation studies in the literature, we conducted our own validation of Energy Plus for the specific purposes of this study by comparing its predicted indoor temperature during a summertime power outage in four residential buildings (two in Houston Texas, and two in Phoenix, AZ) with measured data. After characterizing the buildings, we equipped them with 3–4 temperature sensors to log indoor temperature rise after AC loss. In Phoenix, we mimicked a power outage scenario by switching off the AC. In Houston, the power outage happened because of Hurricane Harvey and was not intentional. Figure 3 shows the measured data plotted against EnergyPlus simulation results for all four cases.

To generate a sample representing the residential building stock in each city, we used the archetypes

provided by the Office of Energy Efficiency and Renewable Energy of the US DOE. The building archetypes represent baseline buildings compliant to consecutive versions of the International Energy Consumption Code (for years 2006, 2009 and 2012, respectively) for each climate. Therefore, the generated sample mostly represents buildings constructed or retrofitted after 2000. According to retrofit and energy audit data reported in Residential Energy Consumption Survey by US Department of Energy (EIA 2015), a majority of buildings in these regions underwent various types of energy retrofits in the last two decades. This includes more than 60% of total US houses that installed insulation, weatherization measures, and double pane windows. Therefore, it is safe to assume that a large portion of pre-2000 buildings are retrofitted to the same baseline (IECC 2006) standard modeled in this study. The other advantage of using a sample focused on relatively newer buildings is that it provides a better window into the future, as the building stock is continuously changing. The building sample in each metropolitan area included 18 archetypes. Modeled buildings varied in direction, basement type, and various physical properties that determine the energy efficiency of buildings and are

set by the energy code version. This includes but is not limited to insulation in exterior surfaces, thermal conductivity and shortwave transmissivity of windows, and air-tightness. The only change we made to the models was implementing a power outage scenario during which the AC system, electric equipment, and interior lights become unavailable for 63 h period (from 9 AM on the first day until the midnight of the third day). We also assumed that occupants would keep the blinds closed and open windows when there is benefit to it (Indoor Temperature – Outdoor Temperature $>2^{\circ}\text{C}$). Hence, the result presented in this study are reproducible by performing the described alternations to publicly available Energyplus files from the Office of Energy Efficiency and Renewable Energy of the US DOE in <https://energycodes.gov>. In addition, to facilitate data reproduction, we have put all the altered Energyplus input files, the required weather files, and the necessary post-processing scripts in the online repository dedicated to this study (refer to the acknowledgment section).

Climate data

In addition to the building characteristics, EnergyPlus requires hourly outdoor weather data—e.g. temperature, solar radiation intensity, and wind speed—as boundary conditions of the modeled system. In this study, we used Typical Meteorological Year version 3 (TMY-3) that we downloaded from EnergyPlus website (www.energyplus.net/weather). TMY-3 is a hypothetical year generated using Sandia model that represents the current climate based on historical observations at a representative weather station within each city. For each climate, we looked for the hottest three-day period based on 3 d average temperatures, representing the hottest heat event that occurs during a typical summer. Table 1 shows the minimum, maximum, and mean temperatures of the hypothetical heat disasters for each city as well as its population. To investigate the possible effects from a warming urban climate (both due to the climate change signal and local urban warming), the same set of simulations was repeated with modified weather data in which the temperatures were increased uniformly by 1°C .

In most cities, TMY-3 data are only available for major airport stations, typically in less dense parts of cities. Hence, the spatial variations of urban climates and urban heat island effects are not captured in this study. In addition, using TMY-3 data is a conservative assumption as it does not include the recorded extremes.

Overheating metric and criteria

An important limitation in assessing overheating inside residential buildings is the lack of guidelines and thresholds to define it (Anderson *et al* 2013, Holmes *et al* 2016). Holmes *et al* (2016) reviewed most available overheating metrics (mostly, in non-residential

environments) and assessed their suitability to be used for studying health outcomes from indoor exposure to heat in residential buildings. They suggested Discomfort Index (DI), the average of dry and wet-bulb temperature, as a highly applicable surrogate. Hence, similar to a majority of recent papers in the literature, we used DI in this study. Since EnergyPlus does not directly output wet-bulb temperature, we calculated it based on dry-bulb temperature and relative humidity using equation (1) (Stull 2011):

$$T_{wb} = T_a \tan[0.151977(\text{RH}\% + 18.313659)^{1/2}] + \tan(T_a + \text{RH}\% - \tan(\text{RH}\% - 1.676331) + 0.00391838(\text{RH}\%)^{3/2} \times \tan(0.023101\text{RH}\%) - 4.686035. \quad (1)$$

Here, T_{wb} is the wet-bulb temperature, T_a is the dry-bulb air temperature, and RH is the relative humidity. According to available guidelines, an average healthy adult will not be able to maintain a constant core body temperature (even under lightest activity level) when exposed to DI values above 28°C (Epstein and Moran 2006). The same threshold was used in this study to define the building overheating threshold. As age and pre-existing conditions affect the body's resilience to heat (Son *et al* 2011), the selection of this threshold is a conservative assumption. Therefore, using a lower threshold to represent vulnerable groups would yield more extreme results than those reported here. To provide a more tangible demonstration of this metric, figure 4 shows the DI threshold of 28°C in a plot of dry-bulb temperature versus relative humidity.

It is well-documented that because of acclimatization, the outdoor threshold from which heat has an impact on mortality depends varies by region. Accordingly, in indoor settings, there are guidelines to account for the effects of climate on thermal comfort thresholds (adaptive thermal comfort models). However, as figure 4 shows, thermal comfort and health-implicating heat are distinct and thus, it is not possible to use the same associations for the overheat threshold used here. Until future research results in reliable climate-specific indoor heat thresholds, it will not be possible to account for the effects of climate variations on indoor heat thresholds. Therefore, similar to the majority of recent studies that used DI (Ren *et al* 2014, Alam *et al* 2016, Holmes *et al* 2016, Ramakrishnan *et al* 2016), we assumed the same threshold across all climates.

Results

We conducted whole-building simulations of archetypical buildings exposed to the hottest 3 d period in a 'typical' summer in each city, with the power outage initiated at 9 AM local time (a total outage time of 63 h). The archetype building set included buildings that vary in orientation, foundation type, and different construction characteristics governed by the energy

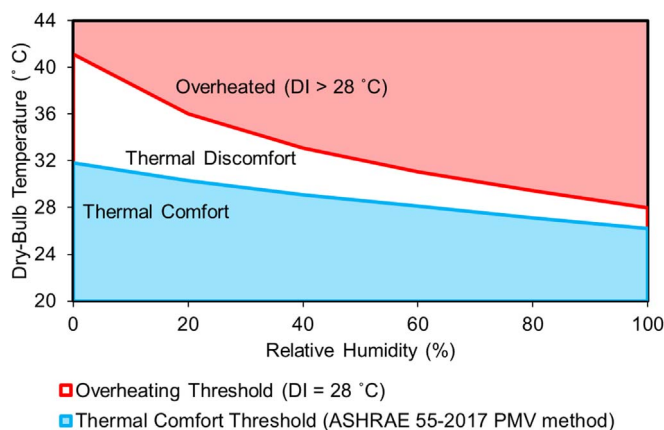


Figure 4. The overheating threshold (DI of 28 °C) used in this study demonstrated in a plot of dry-bulb temperature versus relative humidity. Thermal discomfort that is a highly studied subject is different from health-implicating exposure to heat. While occupants can be unsatisfied with their thermal environment, they might still be safe from any danger posed by the heat. In this study, our focus was on the overheat region (red).

standard version (2006, 2009, and 2012) that they are compliant with. Hence, all variables reported in the following figures are averages over the entire archetype sample. Since the energy standards are location-specific, each city has its own archetype set. Figure 5 shows two different aspects of buildings' resilience to heat disasters: (1) the time it takes the interior space to exceed the overheating threshold for the first time; and (2) the total number of overheated hours during the heat disaster.

In addition, since the health outcome of a heat disaster is expected to be directly related to the number of people it affects, in figure 6, we plotted the same average overheat time variables while including population of each metropolitan area as a third variable.

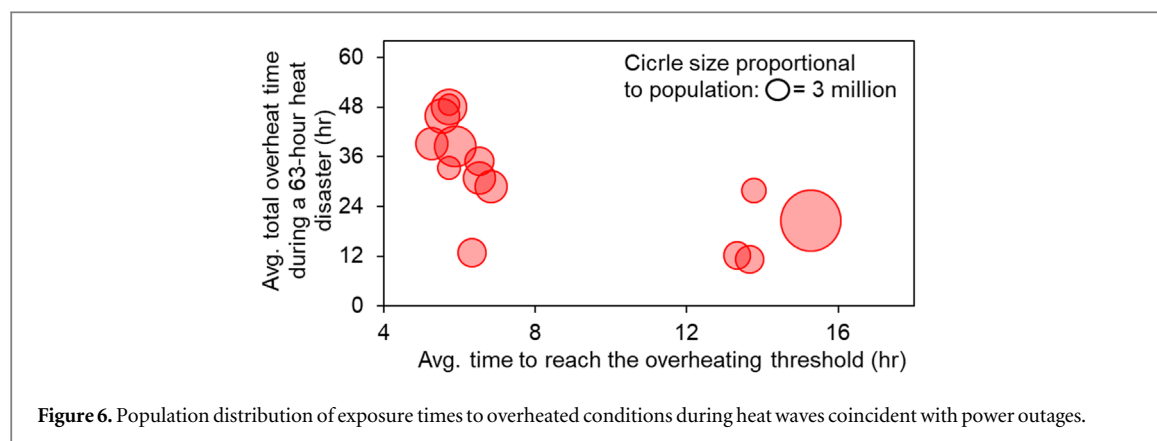
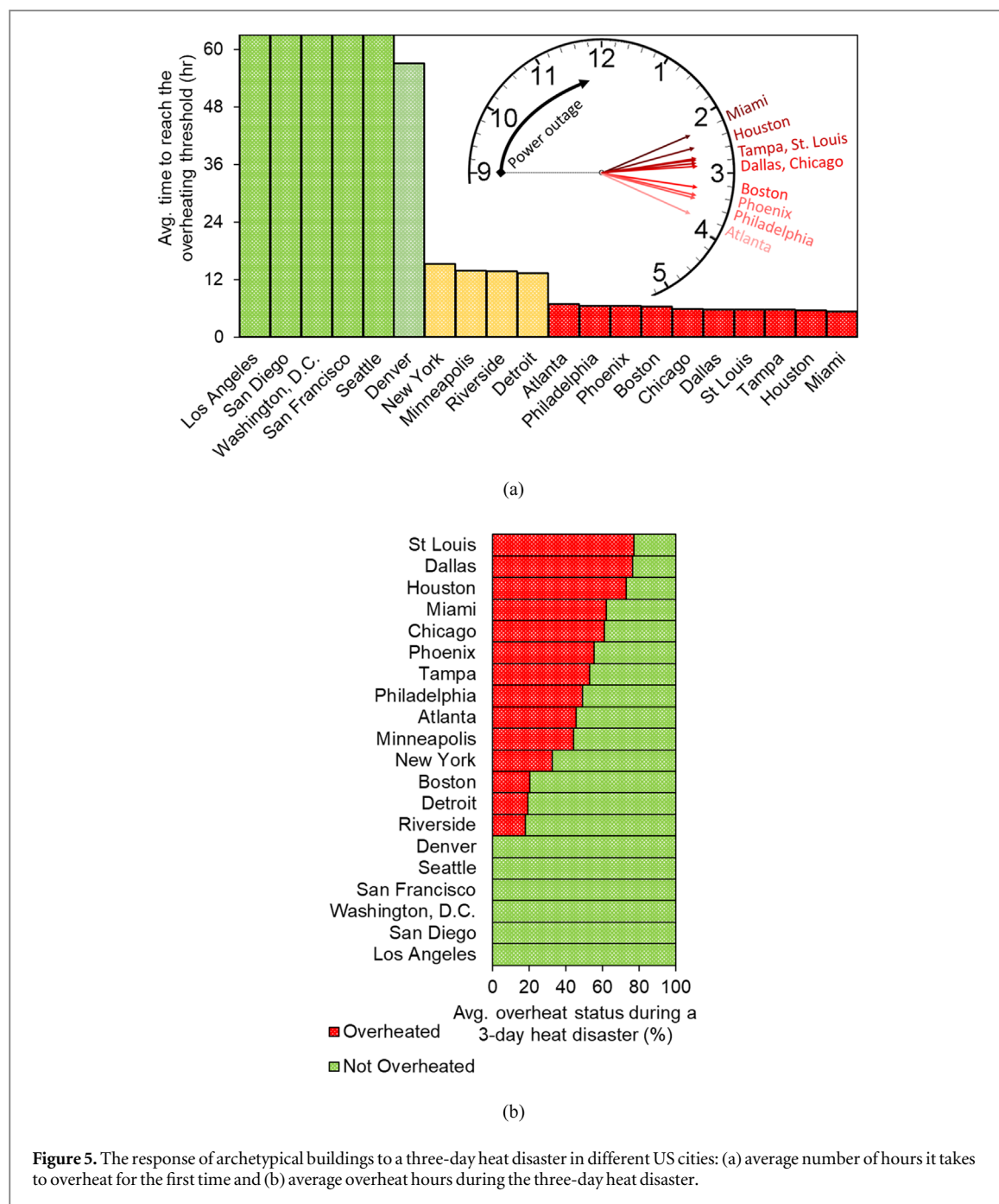
As the second step, to identify how recent trends in energy efficient construction practices affect the resilience of buildings to heat disasters, we compared the performance of two sub-sets of the modeled buildings, designed to meet the 2006 and 2012 versions of the International Energy Conservation Code (IECC). This comparison highlights the direction toward which the residential building stock is evolving. In addition, we performed a sensitivity analysis to identify the magnitude of the adverse effects from warming of urban climates due to local (urban heat island effect) and global (climate change) signals. Figure 7 shows the two different scenarios in comparison to the baseline, which is the building compliant with the IECC 2006 energy standard simulated under current climate. The first scenario is the building compliant with the newer energy standard (IECC 2012) simulated under current climate while the second scenarios is the baseline building (IECC 2006) simulated under the 1 °C warming.

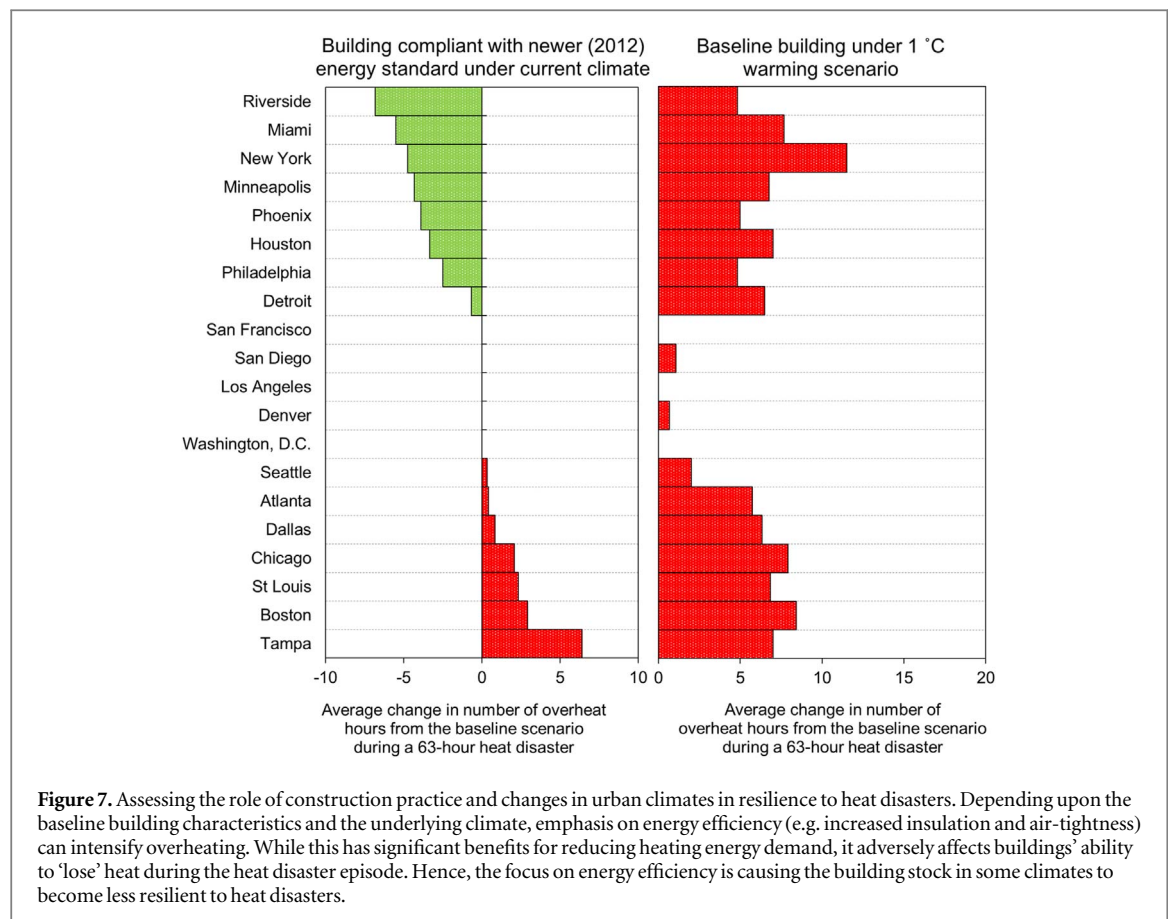
Discussion

As seen in figure 5(a), in half of the simulated locations, on average, the conditions inside buildings will exceed

the overheating threshold in five to seven hours. Hence, a power outage starting early enough in the day would cause most residents in these cities to experience uncomfortable indoor temperatures during the first night—a critical exposure period as most people remain indoors. In addition, exposure to heat at night prevents physiological recovery from high daytime temperatures which is imperative for adequate thermoregulation (Hanna and Tait 2015). The very young and the elderly may be among the most vulnerable to the health effects of nighttime overheating. Moreover, figure 5(b) shows that in 10 out of the 20 modeled metropolitan areas, the average overheat time during the three-day heat disaster was more than 50% of the total period, suggesting a more serious risk associated with longer power outage episodes. Notably, in all cities with high total overheat fractions (e.g. Miami, Phoenix), minimum ambient temperature and/or relative humidity remain relatively high. Therefore, buildings in these locations will not benefit from nighttime cooling and would be already overheated by the morning of the following day. This further highlights the importance of nighttime minimum temperatures in determining the heat exposure outcome of a heat disaster, highlighting another undesirable outcome of both local (urban heat island) and global (climate change) contributors of urban warming that are mostly reported to affect the nighttime temperatures (Oke 1981, Donat and Alexander 2012). As figure 6 shows, there are nine major US cities in which buildings would potentially overheat in less than seven hours and remain overheated for at least a 40% of the outage period. The total population of this subset cities is around 52 million people.

Figure 7 provides an example of how energy standards can affect resiliency of buildings to heat. A key point here is that newer and more energy efficient buildings do not necessary correspond to better resiliency to heat. Depending on the underlying climate





and the characteristics of the baseline building, newer versions of energy efficiency standards—often associated with more stringent requirements for ceiling and exterior wall insulation, window properties, and air-tightness of buildings—can potentially make buildings less resilient. This is a previously observed and reported phenomenon in buildings that do not have AC in certain climates (McLeod *et al* 2013, Ren *et al* 2014, Mulville and Stravoravdis 2016, Baniassadi *et al* 2018a, Taylor *et al* 2018). In certain conditions, since stringent energy efficiency requirements essentially decouple the indoor environment from outdoors, buildings will not be able to 'lose' heat easily during the nights. Hence, if not compensated by a proper ventilation strategy, residents in more efficient buildings might be exposed to more overheating. This introduces an important consideration for policy-makers; they should weigh possible trade-offs between energy efficiency and resilience of buildings to heat disasters. Notably, according to the US Energy Information Agency, buildings are responsible for more than a third of CO₂ emissions in the US. Given the direct association between climate change and intensity of local heat waves (Meehl and Tebaldi 2004), disregarding energy efficiency to increase resilience of buildings to heat could contribute to the same mechanisms that are increasing the frequency and intensity of heatwave—creating a positive feed-back loop. Therefore, future building energy codes and

standards should focus more on strategies that increase energy efficiency without compromising the passive survivability of buildings.

Considering the changes from a warming climate, our analysis shows a considerable deterioration of thermal comfort per 1 °C increase in the severity of the heat event. As figure 7 suggests, excluding the cities with no overheating in the baseline scenario, we found an average increase of 7 h in the number of overheating hours per 1 °C increase in the ambient air temperature. It is noteworthy that in this case, impacts from changes in building energy standards and warming of urban climates have the same order of magnitude. Hence, from a policy standpoint, both should be pursued simultaneously. However, these findings are specific to IECC 2006 and IECC 2012 and the arbitrary warming magnitude of 1 °C. Accordingly, different warming magnitudes or code change levels may result in different relative impacts. Nevertheless, we project that combined efforts to mitigate urban heat and applying resiliency measures in individual buildings could be highly effective in dealing with potential heat disasters.

The results presented here highlight a potential threat that may be exacerbated by ongoing changes in building practices and warming of urban climates. The residential building stock in the US is highly dependent on AC. Hence, a large scale loss of power during an extreme heat event would likely lead to

considerable adverse health outcomes. Given the ongoing stresses on the US electric utility grid and projected urban warming, future research should focus on measures to increase the resilience of buildings to heat and provide corresponding guidelines for inclusion in building design. Thermal mass, proper design to maximize ventilation benefits, and control of radiative heat gain via shading elements and reflective surfaces are strategies proven to enhance passive performance of buildings (McLeod *et al* 2013, Ren *et al* 2014, Mulville and Stravrovadis 2016, Baniassadi *et al* 2018a, 2018b, Taylor *et al* 2018). Reviving these strategies in 21st century buildings can effectively improve their resilience to heat disasters and climate change while increasing their energy efficiency.

Currently, there are no mandates regarding passive survivability of buildings in the US. Even the most stringent non-mandated building rating systems (such as The Living Building Challenge) do not have specific provisions with respect to power outages and heat. Based on our findings, we suggest that similar to fire hazards, there should be guidelines and mandates with respect to the passive survivability of buildings. We suggest using the same compliance paths commonly used in energy efficiency codes. At the simplest form, similar to the 'prescriptive' path in ASHRAE 90.1 or IECC, based on climate, above-mentioned strategies that result in higher passive survivability can be mandated. Existing literature on passive cooling strategies as well as future research on climate-specific designs can help build guidelines for each climate and building type. In addition, similar to the 'performance' path in existing energy codes, passive survivability can be regulated by setting specific performance targets during power outages. In this case, we suggest the use of time factor—the time it takes the indoor thermal conditions to reach a certain threshold—during a power outage in the day with 90th percentile of historic daily mean temperature as the passive survivability metric. The same simulation procedures (that already exists for the performance path in energy codes) can be applied for this proposed passive survivability path. As a result, designers will be mandated to ensure occupant's safety during heat disasters of a certain duration and intensity. Future research on relationships between indoor thermal conditions and health outcomes could help establish reliable climate-dependent thermal and temporal thresholds to be used in building codes.

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Author roles as follows

DS: conceptualization, writing—review and editing, funding acquisition, supervision, resources, investigation; AB: investigation, formal analysis, writing—original draft, methodology, data curation; CO: writing—review and editing, investigation; OW: conceptualization, funding acquisition, writing—review and editing, investigation.

Data availability

All text-based Energyplus input files, post-processing scripts, and weather data required to reproduce the findings of this study are accessible through: the OpenScienceFramework (https://osf.io/97vrn/?view_only=afd03b6769c94e65bf988a592708d465).

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