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Passive Survivability in Residential Buildings during Heat Waves under Dynamic Exterior Conditions

Timothy Aduralere[1], Jacqueline Isaacs[1], David Fannon[2,3]*

[1] Department of Mechanical Engineering, Northeastern University, Boston, MA
[2] Department of Civil and Environmental Engineering, Northeastern University, Boston, MA
[3] School of Architecture, Northeastern University, Boston, MA

*Corresponding email: d.fannon@northeastern.edu

ABSTRACT
The increased frequency of heat waves around the world has prompted numerous studies to improve building resilience and maintain thermal comfort in the face of extreme conditions. However, previous studies rely on the assumption of steady-state conditions, including external temperature, which limits real-world applicability, demanding a more practical perspective. This paper presents the use of recorded heat wave temperatures for a specified location to simulate the effect of extreme temperatures on the interior temperature of buildings when air conditioning is not used. The objective of this study is to determine how a building becomes uninhabitable during extreme heat and to effectively compare the changes in internal temperature of different building types during heat waves and standard climatic conditions.
Residential buildings were modeled using OpenStudio and simulated using EnergyPlus 8.7.0. for modified weather data files using recorded historical heat wave events. The results obtained provide a method for dynamic simulation of extreme events, establish a framework for policies supporting passive survivability in construction and consequently, reduce heat-related mortality.

KEYWORDS
Heat waves, Passive survivability, Energy Simulation, Thermal Comfort

INTRODUCTION
Heat waves are sometimes described as silent killers (Carroll, 2002) that often disproportionately affect vulnerable populations. To better understand and respond to such disasters, modeling and numerical simulations promise to identify critical thresholds, formulate parameters to estimate the damage, and evaluate possible design responses. In order to analyze the effect of a heat wave duration in the simulations carried out in this research, a heat wave will be defined as a period of at least three days, where the daily maximum temperature exceeds a threshold of the 97.5th percentile of the distribution of maximum temperatures observed in a given location (Meehl and Tebaldi, 2004).

Climate Change and Heat Waves
Nearly all extreme weather events are exacerbated by climate change. A 2016 report notes that "If an extreme event truly is rare in the current climate, then almost by definition it required some unusual meteorological situation to be present, and the effect of climate change is a contributing factor (National Academies of Sciences, 2016)." The influence of global warming on heat waves is particularly direct. It is very likely that human influence has contributed to observed global scale changes in the frequency and intensity of daily temperature extremes since the mid-20th century, and likely that human influence has more than doubled the probability of occurrence of heat waves in some locations

(Intergovernmental Panel on Climate Change (IPCC), 2013). Heatwaves are a dangerous natural hazard, and one that requires increased attention (World Meteorological Organization and WHO, 2015), therefore a diverse body of prior research on heat waves includes exploring the risk and damage, providing recommendations for community adaptation, and identifying personal safety practices.

Overheating in Buildings
Building HVAC systems are designed to provide conditions of acceptable human comfort. While a complex and nuanced field, indoor human thermal comfort is generally held to occur in a range of operative temperatures from 67ºF (19ºC) to 82ºF (28ºC), assuming low air velocities, < 40 fpm (0.2032 m/s), and moderate relative humidity (<65%) for sedentary subjects wearing western-style clothing (ASHRAE, 2017; ASHRAE, 2016). In older people, however, this range is narrower because their responses to changes in body temperature are altered (Güneş and Zaybak, 2008). Regardless of these standards, in buildings without mechanical cooling, or where systems are not functioning, indoor conditions can significantly exceed comfort conditions, rendering survivability–rather than comfort–the objective.

Researchers and policymakers are turning to energy simulation to understand the performance of buildings in extreme conditions, for example, to estimate how quickly indoor air temperature of buildings increase during extreme heat. Nahlik et al. (2017) simulated 39 building prototypes in Los Angeles and Phoenix and found that older buildings are more vulnerable to extreme heat than newer buildings because their interiors warm the fastest. Based on these data, the researchers proposed a new metric for building vulnerability to extreme outdoor heat called Building Heat Performance Index (BHPI). However, these results used a constant outdoor air temperature, which is not a good representation of actual exterior conditions. Using EnergyPlus to simulate the effectiveness building modifications to terrace houses in Greater London, UK, Porritt et al. (2012) showed that investments like insulation, solar controls, and ventilation could help reduce building overheating during heat waves.

METHODS
This study uses dynamic meteorological conditions of Fresno, CA during a major historic heat wave as a case study to determine their impact on the interior temperature of buildings. Two typical, residential building prototypes were simulated with the EnergyPlus software. Clear differences were found between the effect of heat wave weather data and typical meteorological conditions on interior temperatures without air conditioning.

Software
Simulations were carried out using the EnergyPlus v8.7.0 (EnergyPlus, 2018)—an open-source, whole-building energy modeling engine developed by the US Department of Energy. Widely-used in research and practice, EnergyPlus performs dynamic thermal and building energy simulations to yield hourly results for a whole year or period thereof, in this case a heat wave. EnergyPlus simulates sub-hourly timesteps through an iterative calculation procedure to improve the accuracy of its results. Simulations were controlled, and input files were edited using the Open-studio plugin (OpenStudio, 2018) for Trimble SketchUp® (Trimble Sketchup, 2018) and the EneryPlus IDF editor (EnergyPlus, 2018).

Building Prototype
To support replication, this study adapted residential prototype building models developed by the Pacific Northwest National Laboratory (PNNL) under the Department of Energy's

Building Energy Codes Program. The present study considers the single-family detached house (SF), and the multi-family (MF) low-rise apartment building, both illustrated in Figure 1.

The prototype building models are intended to be representative of homes in the state of California (PNNL, 2006). The material properties of the SF and MF buildings were defined with the assumption that the existing buildings during the 2006 heat wave considered in this research satisfies the 2006 version of the International Energy Conservation Code (IECC). Consequently, the minimum requirements given by the IECC for Fresno, located in Climate Zone 3B, were employed as the building construction properties in its entirety.

Major features and characteristics are summarized in table 1.

Table 1. Comparison of major features of the building prototypes.

Feature	Single-Family	Multi-Family
Total floor area	148.6 m^2	204.9 m^2
Stories	1	2
Bedrooms	3	3
Wall R-Value	13 (hr °F ft^2)/BTU	13 (hr °F ft^2)/BTU
Ceiling R-Value	30 (hr °F ft^2)/BTU	30 (hr °F ft^2)/BTU
Window U-Value	0.65 BTU/(hr °F ft^2)	0.65 BTU/(hr °F ft^2)
HVAC	NA (turned off for study)	NA (turned off for study)

To support this research, the available prototype models were upgraded from EnergyPlus version 5.0.0 to version 8.7.0, and associated errors and warnings corrected. Finally, to represent the performance of a building without air conditioning during a heat-wave, HVAC schedules were set to prevent the equipment from operating.

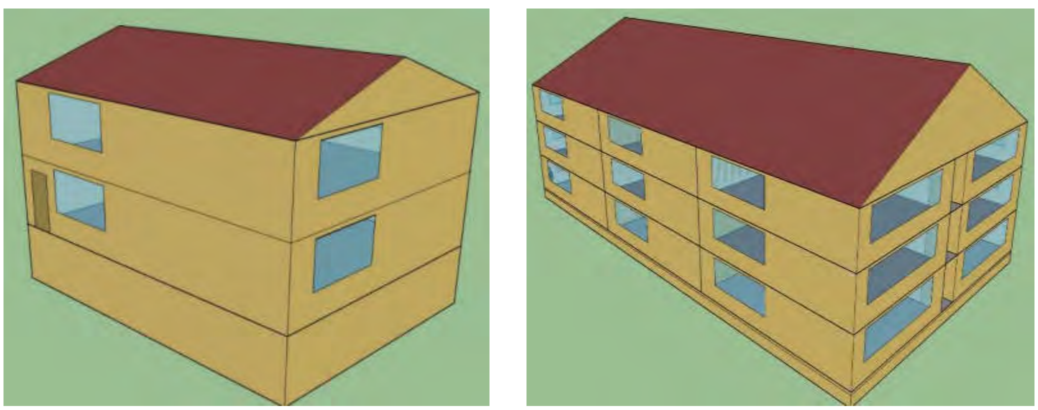


Figure 1. 3D representations of the Single-family (SF) detached residential prototype (left) and the Multi-family (MF) low-rise apartment residential prototype (right).

Location and Climate data

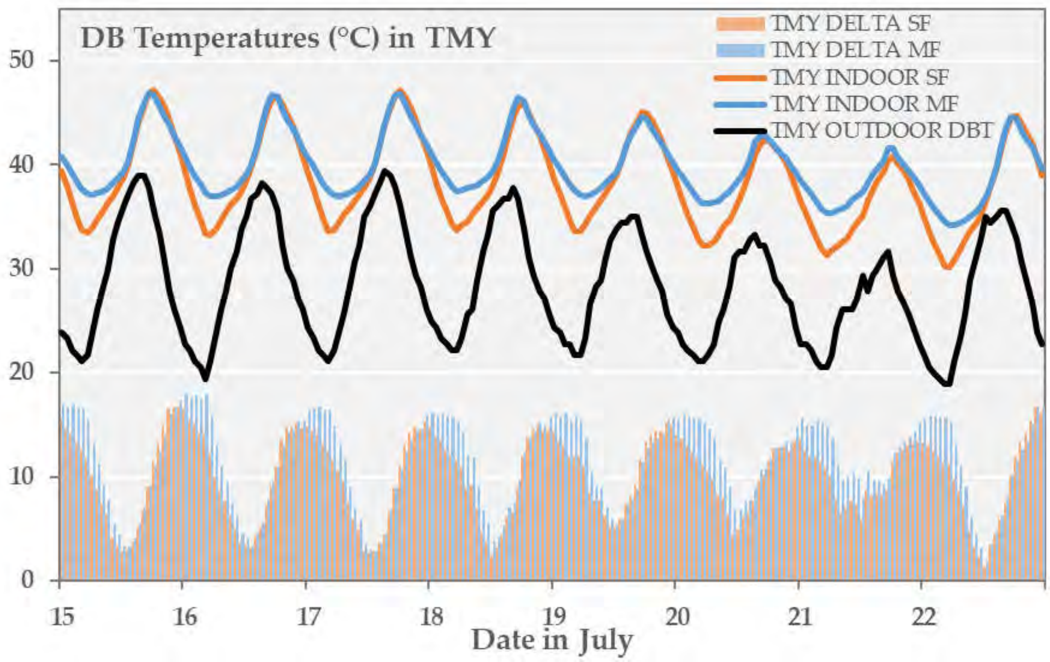
This study uses Fresno California, and the 2006 heatwave, as a case study. Located in California's central valley, Fresno experiences a semi-arid climate (ASHRAE Zone 3B, CA climate zone 13). Climate data from Fresno Yosemite International Airport (36.7758° N, 119.7181° W, elevation 102 meters) was used. Energy plus uses data files in the EnergyPlus Weather (EPW) file format to represent exterior conditions. Each prototype was simulated with two different weather files: one representing the Typical Meteorological Year (TMY) for Fresno; and the second based one consisting of measured extreme weather in this location. The base TMY weather file was produced by the National Renewable Energy Laboratory's

(NREL's) Analytic Studies Division for the TMY3 process, using selected hourly data to represent standard climatic conditions. The second weather file contains the record of meteorological data for 2006, a year when this area experienced a major, multi-day heat event, and was purchased from White Box Technologies. Of interest is the 2006 summer heat wave, covered using a run period of July 15th – 22nd.

RESULTS

Dynamic thermal simulations were carried out for the two cases considered.

a)



b)

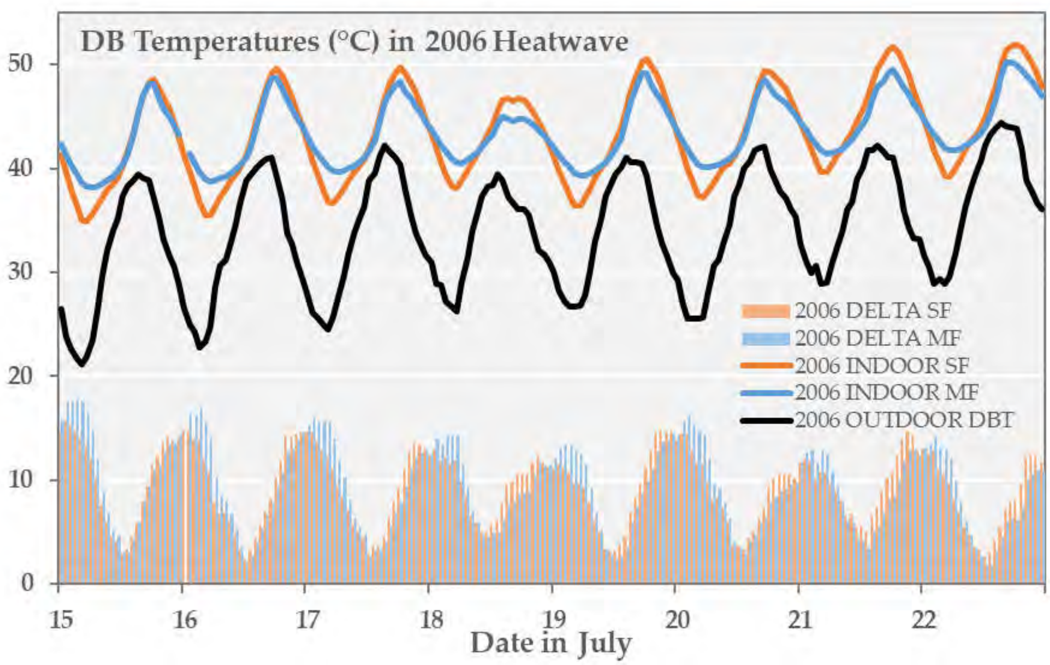


Figure 2. Outdoor Air Temperature and simulated indoor dry-bulb temperatures and deltas for the dates of the study period considering a) Typical conditions (TMY), and b) the 2006 heat wave. Diurnal patterns in absolute temperature are visible, as is the clear trend of increasing temperature in the heatwave, and the declining delta-T.

Figure 2 shows the effect of an extreme heat period lasting 8 days (July 15th – 22nd) on a single-family and multi-family residential building.

DISCUSSION

Figure 2 shows that the natural, diurnal variation of outdoor air temperature is approximately 15°C in July from warmest (midday) to coolest (predawn). This is apparent and similar in magnitude in both the typical year and under a heat wave. Notably, the indoor temperature closely follows the pattern of varying outdoor dry bulb temperature. All windows were treated as non-operable, therefore the indoor temperature always remains above the outdoor dry bulb temperature, suggesting that skin conduction is always a neat heat loss, while internal and especially solar gains are responsible for the increased temperature. Further, the relatively low-mass of the prototype buildings does little to damp the diurnal oscillation from dynamic thermal simulation. The MF building exhibits longer lags and less variation, due to higher mass and a lower surface-to-volume ratio. In both cases, the rate of conductive heat loss to the exterior is of course dependent on the magnitude of the temperature difference between interior and exterior temperature. These behaviors are not well represented by assuming a constant/steady state outdoor temperature.

In both the TMY and 2006 extreme heat data, the largest magnitude of difference between interior and exterior temperatures (ΔT) typically occurs at night, because the outdoors cools down after sunset, but the house retains some heat. In the heat wave, that difference is smaller, in part because the nights are not cooling off as much, and because the entire system is warmer. The smaller ΔT reduces the loss through envelope convection, so the home cannot shed heat as quickly and continues to grow warmer. Consequently, as the outdoor DB temperature increases with increasing severity of the heat wave, the 2006 Indoor SF and MF increases with decreasing ΔT. This indicates that a more severe heat wave, produces a more uninhabitable building in the absence of mechanical cooling or other strategies.

While not primarily focused on the human physiological consequences, these temperatures are dangerous. The highest temperature observed was 51.96°C, in the Single-Family residential building under the 2006 heat wave, compared to a maximum of 47.15°C in a typical year. Both these thermal conditions are hazardous and potentially fatal to occupants because they exceed body temperature, precluding the body from shedding heat and leading to heat stroke or other heat-related illnesses. It is therefore necessary to have a method that presents an analysis of the indoor conditions of buildings using dynamic exterior conditions.

There are other system-scale effects that can affect heat gain and loss, such as urban heat island effect and the cooling effect from neighborhood vegetation, as well as other cooling strategies such as operable windows that would complicate these models and increase the accuracy of this approach.

CONCLUSIONS

This paper applied dynamic building energy simulation techniques to analyze heat wave effects on the indoor thermal conditions of residential buildings. This is not a complete representation of the scope of the analysis, as site-scale conditions, possible window operation, and other physiological factors such as relative humidity are not included. Additional work is needed to characterize the vulnerability of a building occupants to extreme heat in dynamic conditions, however, thanks to the widespread availability of recorded actual meteorological data, the approach demonstrated here can be applied to a study using dynamic simulation of extreme heat events in any city of interest.

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