Building and Environment 78 (2014) 81–88

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Risks of summertime extreme thermal conditions in buildings as a result of climate change and exacerbation of urban heat islands

David J. Sailor*

Department of Mechanical and Materials Engineering, Portland State University, Portland, OR, USA

ARTICLE INFO

Article history:
Received 9 February 2014
Received in revised form
13 April 2014
Accepted 16 April 2014
Available online 28 April 2014

Keywords:
Urban heat islands
Heat waves
Climate change
Infiltration
Thermal comfort

ABSTRACT

This study explores the role of global and local warming on indoor thermal environments of representative buildings in two warm climate cities in the U.S. (Chicago IL, and Houston TX). It uses downscaled climate change scenarios to drive whole-building model simulations of representative apartment buildings. Simulations were conducted under (a) current conditions; (b) conditions that include a global warming effect; and (c) conditions that include global warming with concurrent intensification of the urban heat island. Building thermal conditions are assessed for typical operating conditions, for conditions associated with failure of cooling equipment, and for complete power loss during a heat wave.

Simulations show that warming by itself may have minimal effects on indoor thermal comfort in summer. For example, in Houston the Predicted Percent Dissatisfied (PPD) comfort metric was approximately 5–6% for current and future climate scenarios under normal operating conditions. Under conditions of AC failure, however, this increased to 61.9% for the current climate and 71.4% for the 2050 climate. In the case of Chicago PPD was between 6.2% and 7.9% for all climate scenarios when equipment operated normally. Under conditions of equipment failure, however, PPD increased to 34.1% for the current climate and 39.2% for the 2050 climate. In simulations for both cities, a complete power failure resulted in peak temperatures that were approximately 2 °C cooler than the case of AC failure only. This is due to reduction in internal gains during a power blackout.

1. Introduction

One of the fundamental purposes of buildings is to serve as protection from the ambient environment. Buildings provide shelter from wind and precipitation, but also act as buffers against heat in summer and cold in winter. Building energy codes and standards help to ensure that the building thermal envelope and the installed Heating, Ventilation, and Air-Conditioning (HVAC) systems are able to maintain the building's interior environment within reasonable bounds. Such comfort boundaries are typically defined based on temperature and humidity limits (e.g., as specified in ANSI/ASHRAE Standard 55 [1]). Building designers and engineers employ complex whole-building energy simulation software that assists them in sizing and selecting HVAC equipment. These simulation models integrate information regarding building geometry, construction materials, and anticipated building use patterns (e.g., occupancy, lighting, and plug loads) with typical meteorological year (TMY) weather data to estimate building performance under typical conditions (based on 30-years of historical weather data for the nearest airport weather station).

A reasonable question is whether buildings designed and constructed to operate under climatic conditions of the past 30 years will be resilient to weather conditions experienced during the lifetime of the building and its installed equipment. Prompted by concerns of a warming climate, this manuscript addresses two questions: (1) to what extent is building thermal performance compromised when the building is exposed to significantly warmer conditions than it was designed for? and (2) how is this compromised performance further impacted when a heat wave is coincident with a major loss of power/HVAC equipment failure?

1.1. Local climate and the urban heat island effect

Cities tend to be warmer than their natural (unbuilt) surroundings. This urban heat island (UHI) phenomenon is a result of a number of factors including the prevalence of thermally massive and low reflectivity surfaces, the general lack of surface moisture, and waste heat emissions from energy-consuming activities [2]. Urban heat islands are temporally and spatially complex. One can

---

* Tel.: +1 503 725 4265; fax: +1 503 725 8255.
E-mail addresses: sailor@pdx.edu, sailor@cecs.pdx.edu.

http://dx.doi.org/10.1016/j.buildenv.2014.04.012
0360-1323/

define a UHI based on differences in surface temperatures or air temperatures. Furthermore, air temperature heat islands can be defined at a range of vertical heights above the surface.

It is the urban canopy air-temperature UHI that is most relevant with respect to direct effects on building occupants. For buildings located in or near the centre of a large city, the summertime urban canopy UHI tends to be largest in the early morning hours [2,3]. In fact, numerous studies have found remarkably similar results regarding summer differences in UHI magnitudes from day to night. For example, in an observationally-validated modelling study of the London heat island, Bohnenstengel et al. [4] found locations within the city centre to be 4–5 °C warmer than rural locations in the early morning hours. The same study found that the UHI in early afternoon was no more than 1 °C. In a similar study of London, Kolokotroni and Giridharan [5] found that summer daytime UHI magnitude was relatively small (<1 °C) from 10 am to 6 pm, while throughout most of the night the UHI magnitude remained relatively constant at 2–3 °C. Chan [6] found similar summertime results for Hong Kong: the nocturnal UHI was between 2 and 3 °C while during the day it was consistently between 0.5 and 1.0 °C. In a long-term analysis of 32 years of observational data for Buenos Aires, Camilloni and Barracand [7] found that night time UHI magnitudes were typically about 2 °C while the daytime UHI was negligible. Likewise, in a study of summer (July 2006 and 2007) UHI in Bucharest, Cheval et al. [8] found daytime UHI in the range of −1 to +1 °C and night time UHI on the order of 2.5–3 °C. So, as a general conclusion it is reasonable to state that near surface air temperature heat island magnitudes in summer are typically less than 1 °C, while at night the UHI magnitude may approach 2–5 °C. Actual UHI magnitudes depend on many factors including synoptic weather conditions (e.g., heat islands are typically greater during calm conditions).

1.2. Climate change

Global climate change is likely to add to the UHI and to be magnified in cities in summer due to feedback mechanisms involving air conditioning of buildings [9–11]. Specifically, as the global climate warms energy use for air conditioning will increase and urban residents are likely to spend even more time indoors. These effects will interact with other risk factors related to building construction and insulation levels [12]. For example, Riberon [13] demonstrated that in the case of the 2003 heat wave in France individuals living on the top floor of uninsulated buildings had mortality risk that was roughly four times that of the general population. Further exacerbating these conditions is the continuing densification of urban populations. These trends will lead to increased waste heat emissions associated with air conditioning and will further increase summertime outdoor air temperatures.

Diurnal variation of warming under climate scenarios is perhaps more important than the annual or even daily averages; although, it is far less studied. Most future climate assessment efforts focus on seasonal or annual increases in air temperature. Even the most detailed analyses resulting from downscaling of climate model simulations generally present only daily maximum and minimum temperatures. Results from such studies consistently suggest that minimum temperatures are expected to increase more than maximum temperatures, resulting in a decrease in the diurnal temperature range [14,15]. Nevertheless, it is possible that for some locations and some seasons a different trend may emerge. In any case, climate model predictions for changes in maximum and minimum temperatures can be used to construct hourly profiles of air temperatures under climate change scenarios [16].

1.3. Context for this study

Urban warming associated with concurrent global warming and urban growth will take place amid a backdrop of increasingly stressed electric utility grids and will, in some areas, result in increased frequency of utility system failures. Such events will have significant consequences for the health and comfort of building occupants [17].

This study explores the role of global and local warming on the indoor thermal environments of representative apartment buildings in two distinctly different warm climate cities. These scenarios are studied both in the context of typical operations and under the scenario of power outages and equipment failures during heat waves.

2. Methods

Climate change scenarios are used in this study to construct whole-building model simulations of representative apartment buildings. In each case, the building design and sizing of cooling equipment are based on current building codes and Typical Meteorological Year-TMY weather data from local airports. Simulations are conducted under (a) current climate (CC) conditions; (b) conditions that include a global warming effect (2050); and (c) conditions that include global warming with a concurrent increase in the urban heat island magnitude (2050UHI). In each scenario, model analysis focusses on the hottest week of the summer in each city and explores the case of normal HVAC operations and the case of a system failure (e.g., no air conditioning during the episode) and a complete power outage.

2.1. Building energy simulation software

The building simulation software used in this study is EnergyPlus (v8.1) from the U.S. Department of Energy. EnergyPlus is a widely accepted simulation engine for modelling annual building energy consumption [18]. Released in April 2001, EnergyPlus replaced its predecessors BLAST and DOE-2 which had some technical and structural limitations. EnergyPlus takes as input information related to building location, geometry, and construction materials. It also allows the user to specify detailed schedules related to occupancy, lighting, plug loads, and thermostat set points. Once the building model (idf file) is fully defined it is coupled with a Typical Meteorological Year (TMY) data file. However, as desired, the default TMY file for a particular modelling location can be replaced with a user-modified weather file to reflect current local conditions, or test conditions.

EnergyPlus also provides for extensive customizable output reports. It is relatively easy to extract thermal conditions (e.g., dry bulb and wet bulb temperatures) as well as hours that zone cooling set points are not met within each modelled zone. Furthermore, within its “Occupant Comfort Data Summary” EnergyPlus can track a number of thermal comfort metrics including Fanger’s Predicted Mean Vote (PMV) and Predicted Percent Dissatisfied (PPD) [1]. Detailed summaries of these and many other thermal comfort variables are provided in several recent review articles [19,20].

In a subset of simulations the failure of air conditioning was implemented in EnergyPlus by modifying the thermostat set point schedule to artificially allow indoor air temperatures to rise without the prospect of turning on air conditioning. Specifically, the set point for cooling was set to an artificially high and unrealistic level of 45 °C for the period of failure. The case of a complete loss of power was simply accomplished by setting to zero all internal electric loads (lights, plugs, and HVAC) during the outage period. It should be noted that each simulation used EnergyPlus defaults for