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Predicting indoor heat exposure risk during extreme heat events

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HIGHLIGHTS

- We measure heat and humidity in 285 New York City residences in the summertime.
- Indoor conditions show between-home variability but respond to outdoor conditions.
- Heat wave simulations show that the indoor heat index can reach dangerous levels.
- Indoor heat danger is underappreciated and likely to increase with climate change.

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ABSTRACT

Increased heat-related morbidity and mortality are expected direct consequences of global warming. In the developed world, most fatal heat exposures occur in the indoor home environment, yet little is known of the correspondence between outdoor and indoor heat. Here we show how summertime indoor heat and humidity measurements from 285 low- and middle-income New York City homes vary as a function of concurrent local outdoor conditions. Indoor temperatures and heat index levels were both found to have strong positive linear associations with their outdoor counterparts; however, among the sampled homes a broad range of indoor conditions manifested for the same outdoor conditions. Using these models, we simulated indoor conditions for two extreme events: the 10-day 2006 NYC heat wave and a 9-day event analogous to the more extreme 2003 Paris heat wave. These simulations indicate that many homes in New York City would experience dangerously high indoor heat index levels during extreme heat events. These findings also suggest that increasing numbers of NYC low- and middle-income households will be exposed to heat index conditions above important thresholds should the severity of heat waves increase with global climate change. The study highlights the urgent need for improved indoor temperature and humidity management.

1. Introduction

Heat waves are typically defined as prolonged periods of elevated temperature and humidity (D'Ippoliti et al., 2010; Smith et al., 2013). These events are associated with increases in morbidity and mortality, and extreme heat waves can cause public health emergencies. In summer 2003, a 9-day heat wave in Western Europe caused between 50,000 and 70,000 excess deaths (Larsen, 2006; Robine et al., 2008). Although most analyses of historical and future heat-related mortality have focused on increases in outdoor ambient temperature, the majority of fatal heat exposures in the developed world occur indoors. In New York City (NYC), over 80% of heat strokes citywide have been attributed to exposure at home (New York City Department of Health and Mental Hygiene, 2013), and during the 2003 European heat wave, 50% of the observed fatalities in France occurred in homes (a figure that does not include deaths in hospitals that may have resulted from residential heat exposure) (Fouillet et al., 2006). For the United States (US) and Europe, climate models predict increases in the frequency and duration of extreme summertime temperatures (Duffy and Tebaldi, 2012; Karl et al., 2008), heat wave intensity and frequency (IPCC, 2007; Meehl and Tebaldi, 2004), and heat-associated morbidity and mortality

Abbreviations: NYC, New York City; T, temperature; DP, dew point temperature; HI, heat index; Head Start, Endotoxin, Obesity, and Asthma in NYC Head Start; NAAS, New York City Asthma and Allergy Study; NLDAS, North American Land Data Assimilation System; GLDAS, Global Land Data Assimilation System.

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(Hayhoe et al., 2010; Huang et al., 2011; Knowlton et al., 2007; Lin et al., 2012). An "analog city" approach has estimated, for example, that a heat wave analogous to the 2003 European event would lead to a tenfold increase in annual heat-related deaths in the city of Chicago (Hayhoe et al., 2010). Given this background, a thorough evaluation of key heat exposure environments is imperative; yet our understanding of heat and humidity conditions in the indoor residential environment is extremely limited.

The few studies that have attempted to characterize summertime conditions in the indoor residential environment (Arena et al., 2010; Franck et al., 2013; Mavrogianni et al., 2010; Mirzaei et al., 2012; Nguyen et al., 2013; Tamerius et al., 2013; White-Newsome et al., 2012; Wright et al., 2005) have demonstrated that temperature and humidity vary significantly across homes, despite similar outdoor conditions. Indoor environments are influenced by stable attributes (such as building type, window placement, and socioeconomic status) as well as behavioral factors such as cooking, bathing, and use of air conditioning (Tamerius et al., 2013; Yik et al., 2004). Like other health risks, heat stress is more likely to have adverse effects, including fatalities, among residents at the lower end of the socioeconomic spectrum (Harlan et al., 2006; Klinenberg, 2002). Improving public health measures designed to mitigate the effects of extreme heat necessitates accurate characterization of the range of heat and humidity conditions experienced in residential environments.

In this study, we analyze the association between indoor heat and humidity measurements recorded in 285 low- and middle-income New York City homes during the summer (June–September) and concurrent outdoor conditions. We use these observed relationships to build models to predict the response of indoor temperature and humidity to a range of outdoor conditions. Employing these models, we simulate expected indoor conditions during two extreme heat events: the 10-day 2006 NYC heat wave and a 9-day event that is an NYC analog of the 2003 Paris heat wave. In these simulations we employ a heat index (HI) measure that is commonly used to issue heat advisories in many US cities, including NYC (US Department of Commerce, 2010). The heat index is an important indicator of health risk because it combines temperature and humidity, both of which modulate the human body's ability to dissipate heat (Havenith, 2005).

2. Methods

2.1. Residences in the study sample

The residences monitored for indoor temperature and humidity in this study were the homes of participants in two recruitment research studies in the New York City area: 1) Endotoxin, Obesity, and Asthma in NYC Head Start (Head Start); and 2) New York City Neighborhood Allergy and Asthma Study (NAAS) (Olmedo et al., 2011; Rotsides et al., 2010). Briefly, the Head Start cohort is a cohort of children from low-income families who attended Head Start programs serving neighborhoods with high asthma prevalence in NYC. The NAAS cohort was selected from enrollees in a major employer-based health insurance plan. It is a cross-section of largely middle-income families living in Manhattan, Queens, Brooklyn, and the Bronx.

The scheduling of indoor monitoring sessions was determined by the availability of study staff and residents; thus while monitoring sessions sometimes overlapped, in general the homes were not monitored concurrently. The duration of individual monitoring sessions was between 1 and 13 days, taking place between the years 2003–2006 for the Head Start cohort and 2008–2011 for the NAAS cohort. For this study, we restricted the sample to those residences monitored during the months of June, July, August, and September. These months were chosen as they lie outside the October 1–May 31 "Heat Season" for New York City, during which building owners are required to provide tenants with residential heating (NYC Department of Housing Preservation and Development, 2013). We also selected only those homes with at least 4 consecutive days (96 consecutive hours) of indoor monitoring, and included only the first monitoring period for those homes monitored multiple times. The final study subset contained 51,021 observation-hours (approximately 2100 days of observations) across 285 residences: 140 in the Head Start cohort and 145 in the NAAS cohort. The median length of the indoor monitoring period was 7 days. Outdoor HI conditions on the days when home observations were conducted were representative of summer conditions in New York City during the entire 2001–2011 period (see Supplemental material, Fig. S3).

Most of the sampled residences were apartments, over half had 4 or fewer total rooms (equivalent to a 2-bedroom apartment), and nearly 90% were situated between the 1st and 6th floors of their buildings (see Supplemental material, Table S1). The sample had a greater proportion of freestanding houses than the NYC mean. The average number of rooms and of bedrooms per residence was likewise slightly above the NYC mean (see Supplemental material, Table S1).

Although the homes do not constitute a random sample of NYC households, we believe that this sample is broadly representative of the residential conditions of lower- and middle-income families with children in NYC. In our sample, 49% of the homes were the residences of families enrolled in the low-income Head Start program, whose income cutoffs for NYC are currently set at about 127% of the federal poverty level. The other 51% of homes were the residences of middle-income families (see Supplemental material, Table S1). Families with children comprise 31% of the approximately 3 million total households in NYC (U.S. Census Bureau, 2011).

We did not have data on the prevalence or use of air conditioning in our sample. However, a 2007 survey indicated that 12.5% of New York City adults did not have a functional air conditioner in their homes, with this prevalence rising with decreasing income (New York City Department of Health and Mental Hygiene, 2007); consequently, it is likely that at least some of our sample homes did not have functioning air conditioning units.

2.2. Indoor temperature and humidity monitoring

HOBO H08-003-02 data loggers (Onset Computer Corporation) were installed for periods of 4–13 days in the homes of the study participants, 1.5 m above the floor and away from windows and drafts. Data loggers in the Head Start cohort were placed in the child's bedroom (or the location where the child spent the most time), while the monitors in NAAS homes were placed in the living room. These data loggers record both temperature and relative humidity, with accuracy for temperature of ± 0.7 °C and for relative humidity of $\pm 5\%$. Measurements were recorded at 5-minute intervals, from which we calculated hourly averages. As a measure of absolute humidity, dew point temperature (DP, °C) was calculated from temperature and relative humidity using the following formula (Lawrence, 2005):

$$\alpha = (17.625 * T/(243.04 + T)) + \ln(RH/100)$$
$$DP = (243.04 * \alpha)/(17.625 - \alpha),$$

where T is temperature in degrees Celsius and RH is relative humidity in percent. Heat index is a combination of temperature and humidity that is used by the NYC Department of Health and Mental Hygiene to determine thresholds for the issuance of heat warnings and heat advisories. In this study, heat index was calculated using the R "weathermetrics" package, which utilizes the source code for the US National Weather Service's online heat index calculator (National Weather Service, 2013).

2.3. Outdoor temperature and humidity data

Outdoor temperature and humidity data consisted of hourly temperature and dew point temperature readings from the three main National Oceanic and Atmospheric Association (NOAA) stations for NYC: