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Predicting Indoor Heat Exposure Risk during Extreme Heat Events

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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.

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Keywords

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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 (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). 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 51021 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, Figure 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, 1.5m 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 ±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: the John F. Kennedy and LaGuardia International Airport stations and the Central Park station, over the summers of 2001 – 2011 (June 1 – September 30). The mean across the three stations was used as the hourly NYC average. If an hourly observation was missing for one or two stations, the mean was calculated excluding these. 4.7% of the hourly observations had no data recorded at any of the three stations, and for these hours the outdoor temperature and/or dew point were singly imputed from the North

American Land Data Assimilation System (NLDAS) gridded data set (Mitchell et al. 2004). In a comparison of all summertime hours from 2001–2011, the Pearson’s correlation coefficients for the association between the observed NYC data and the NLDAS gridded data are 0.91 (temperature) and 0.88 (dew point). Dew point temperature was set equal to temperature for the 0.04% of the outdoor observations with mean dew point temperatures that exceeded mean temperatures. Outdoor heat index was calculated as for the indoor data.

2.4 Indoor-Outdoor temperature and humidity relationships

After testing the appropriateness of a linear fit for the indoor-outdoor relationship (see Supplemental Material, Figure S4), bivariate multilevel regression models with random intercepts and slopes were used to analyze the association between outdoor and indoor measures of temperature, humidity, and heat index. These multilevel models account for the clustering of hourly temperature and humidity observations within residences, and allow for between-residence variation in the relationship between the outdoor and indoor climate metrics. In each model, the outdoor metric was lagged behind the indoor metric by an interval that was determined as the best-fitting predictor of the indoor metric via the evaluation of R-squared values from simple linear regressions (3 hours for temperature, 1 hour for dew point temperature, and 2 hours for heat index). We also investigated the effect of thermal inertia within the sample homes by adding terms corresponding to the outdoor T/DP/HI with lags of 1 and 2 days (i.e., 24 hours and 48 hours). These lag terms were found to be significant and to improve the overall model fit, and were consequently included in the final models. We also tested including an indicator variable for study cohort (Head Start vs. NAAS) in the models as a proxy for the effect of low vs. middle income, but this was not found to be significantly associated with indoor levels of T/DP/HI and was therefore not included in the final models.

The final models therefore took the following form:

> Indoor (T/DP/HI) ~
>
> outdoor (T/DP /HI) + lag_1day_outdoor (T/DP/HI) + lag_2days_outdoor (T/DP/HI), with random intercept and slope (residence as the grouping variable). The parameters from these models are listed in Table 1.

Because we observed that the variability of indoor T and HI across households increased linearly with increasing outdoor T and HI (Figure 1), we also built simple linear regression models to estimate the standard deviation among our sampled homes at varying levels of outdoor T and HI.

2.5 Simulated indoor conditions during heat waves

We used two heat wave scenarios to simulate New York City indoor heat and humidity conditions. The first heat wave scenario was the July 27-August 5, 2006 heat wave in NYC. We compared this event to a second heat wave scenario synthesized to be the same magnitude and intensity as the 2003 heat wave in Paris. For the 2006 NYC event we used the observed outdoor T and DP values from our outdoor dataset to compute the outdoor HI levels for NYC across the 10 days of this heat wave. (Note – none of the sample residences were monitored for indoor temperature and humidity during this 10-day span).

For the ‘2003-like’ heat wave, outdoor 3-hourly temperature and dew point measurements were downloaded from the Global Land Data Assimilation System (GLDAS) (Rodell et al. 2004) for both NYC and Paris. The overall magnitude of the August 5–13, 2003 European heat wave was first characterized as the average GLDAS HI in Paris for those 9 days relative to the distribution of average GLDAS HI conditions in Paris for all continuous summertime 9-day periods during 2001–2011 (see Supplemental Material, Figure S2). This analysis revealed that the 9-day HI event in Paris was more than 4 standard deviations above the Parisian summertime mean. We then calculated the normal cumulative percentile for each 3-hourly HI value in Paris during August 5–13, 2003 relative to the distribution of all 2001–2011 summertime HI values at that same 3-hourly time. The resultant time series of August 5–13, 2003 outdoor HI cumulative percentile values for Paris was then used, together with GLDAS HI moment statistics for NYC (i.e. 2001–2011 summertime means and standard deviations for each 3-hour interval) to generate a ‘2003-like’ heat wave time series of outdoor HI for NYC.

For example, for the Paris heat wave, the first 3-hourly period of this event (00:00 – 03:00 on August 5, 2013) had an outdoor HI of 21.45°C corresponding to the 98.63rd percentile relative to the distribution of all summertime 00:00-03:00 values for 2001–2011. This finding was used to select the 98.63rd percentile from a normal distribution of HI conditions in NYC for those hours of the day. These values (HI of 25.61°C at 00:00, 24.91°C at 01:00, and 24.96°C at 02:00) became the first 3 hours of the 2003-like heat wave. This process was repeated for the rest of the Parisian heat wave event to create the full 2003-like heat wave analogy of outdoor HI for NYC.

Indoor HI values in NYC for both heat wave scenarios (2006 and 2003-like) were then estimated using Model 3 (Table 1). Rather than generate a single, mean indoor HI value for each 3-hourly interval, we estimated the expected distribution of indoor HI conditions across our sample of NYC residences using the predicted mean value in conjunction with the predicted heat-index-dependent standard deviation of the observations, which was estimated by regressing indoor HI values against 3-degree bins of outdoor heat index values (Figure 1). The resulting time series of indoor HI conditions provides rich estimates of the range of conditions that would be experienced during each heat wave.

2.6 Indoor heat danger thresholds

Estimating the effects of indoor heat and humidity exposure on human health is difficult given the lack of research on this topic. Here, we propose three putative indoor heat danger thresholds, with the understanding that these should be regarded merely as plausible guidelines until a greater understanding of the risks of indoor heat exposure can be established (Anderson et al. 2013). We used two approaches in generating these thresholds: the first utilizes the overall distribution of indoor summertime HI over the years 2001–2011 as predicted by our model, while the second maps indoor values to existing outdoor thresholds. For threshold 1 (orange lines in the figure, 33.7°C/93°F), we chose the 99th percentile of all predicted indoor summertime heat indices in our study residences over summers 2001–2011. Thresholds 2 and 3 employ the current outdoor HI threshold that is used by the NYC Department of Health and Mental Hygiene to issue heat advisories for the city. This outdoor threshold, two or more days with outdoor HI greater than 35°C (95°F) (US Department of Commerce 2010), was chosen in part because of its correlation to increases in citywide mortality. We used our regression model to predict the 95th and 99th percentiles of the indoor HI in our study homes when the outdoor heat index reaches 35°C for 2+ days. Threshold 2 (red lines, 35.6°C/96°F) represents the 95th percentile of this predicted indoor heat index, while threshold 3 (purple lines, 37.9°C/100°F) represents the 99th percentile.

3. Results

We quantified the association between summertime outdoor and indoor temperature (T), dew point temperature (DP), and heat index (HI) in 285 low- and middle-income homes in New York City. The homes are typical of those inhabited by NYC families in this socioeconomic category, though not a random sample of all low- and middle-income housing in the city. We found that indoor and outdoor DPs were the most strongly associated of the three pairs of variables, with indoor hourly DP increasing by 0.66° C for every 1°C increase outdoors, holding 24-hour and 48-hour-lagged DP constant (Table 1), while indoor hourly T and HI increased by 0.20° C and 0.24°C, respectively, for every 1°C increase outdoors, holding 24-hour and 48-hour lags constant. The indoor diurnal cycles of T and HI lagged the larger amplitude outdoor cycles by an average of 2–3 hours. In contrast, neither indoor nor outdoor DP was characterized by a consistent diurnal cycle (see Supplemental Material, Figure S1). We also found that the variability of indoor T and HI across households increased linearly with increasing outdoor T and HI (Figure 1).

We simulated indoor HI in our study residences during two heat wave scenarios: the 10-day 2006 NYC heat wave and a more extreme event modeled on the 9-day 2003 European heat wave (see Methods). For the 2006 event (Figure 2a), we estimate that average indoor HI values would have fluctuated between 27°C and 32°C. The hottest 5% of these homes, however, would reach peak indoor HI values of ≥ 39°C. When the 2003-like event was simulated (Figure 2b), average indoor HI levels were slightly warmer than in the 2006 event (28–33°C), while HI in the hottest 5% of homes reached a peak of 41°C, and did not drop below 34°C for the entire duration of the episode.

We compared these predicted conditions to our three potential indoor heat danger thresholds: 33.7°C (93°F), 35.6°C (96°F), and 37.9°C (100°F). During the 2006 heat wave, a small fraction of homes exceeded the low and intermediate thresholds each day, with an increase on the three hottest days (Figs 2a and 2c). The 2003-like event (Figs 2b & 2d) produced higher indoor HI levels. More than 27% of residences exceeded the lowest threshold every day, while over 45% exceeded it at the peak of the heat wave (Table 2). 2.5% of residences remained above the lowest threshold for the duration of the event, even during its coolest moments (Figure 2d). The most extreme threshold was reached or exceeded by 3–10% of households each day.

Because heat wave duration has been associated with increasing mortality (Anderson and Bell 2010; D’Ippoliti et al. 2010; Fouillet et al. 2006), we assessed cumulative indoor exposure to high HI levels for these scenarios. Averaging modeled daily HI levels over the

10 days of the 2006 heat wave (Figure 3a), we estimate that average daily maximum HI would have exceeded the low, intermediate and extreme thresholds in 16%, 6% and 1% of households, respectively (Figure 3b). During the 2003-like event, the distribution of event-averaged daily maximum HI values broadens and shifts to the right (Figure 3c), with approximately 37%, 19% and 6% of study homes exceeding the three thresholds, respectively (Figure 3d).

Daily minimum HI is an indicator of nighttime relief from heat and humidity. In France during the 2003 heat wave, both the number of hot days (Fouillet et al. 2006) and elevated nighttime temperatures (Laaidi et al. 2012) were associated with mortality, suggesting that unremitting exposure to elevated HI may be particularly dangerous to human health. Our model predicts that indoor minimum HI values would have remained higher than outdoor values for a substantial fraction of homes (blue lines, Figure 2), indicating that some residences would maintain unrelenting high HI levels even when it is cooler outdoors. Averaging daily minimum HI over the 2006 heat wave, we predict that 1.7%, 0.2%, and 0% of homes would respectively exceed the low, intermediate, and high thresholds during the night (Figure 3b). For the 2003-like event, the corresponding figures were 5.2%, 1.1%, and 0.1%: more than 3 times as high (Figure 3d).

4. Discussion

Heat waves are a regular feature of the current climate system in temperate countries. We expect climate change will exacerbate summertime heat exposure risk by increasing the frequency, severity, and/or duration of heat waves (IPCC 2007). Our response to this public health threat needs to be informed by a thorough evaluation of indoor conditions and their association with specific health outcomes. Currently, building owners in New York City are required by law to provide a minimum level of heating to their tenants during the cooler seasons, yet no corresponding regulation exists for cooling during warmer seasons. Understanding how health risk varies as a function of indoor heat and humidity exposure would provide a scientific foundation for the re-evaluation of policies such as these in light of climate change; however, these determinants of risk have yet to be ascertained. With the goal of assessing vulnerability and improving heat wave preparedness, a detailed characterization of indoor heat and humidity conditions across a range of housing types and in multiple urban and non-urban environments is a vital next step.

Our findings indicate that indoor heat and humidity in selected low- and middle- income New York City households are strongly associated with conditions in the outdoor environment, and that there is considerable between-home variability in the levels of indoor T/DP/HI that accompany a given set of outdoor conditions. We find that during heat waves, HI levels in many households regularly reach levels that are potentially dangerous for human health.

At their most basic, these findings help account for the historically observed increase in mortality during heat waves. More importantly, our analysis shows that indoor HI conditions vary substantially among low- and middle-income households, and that large populations are potentially subject to high HI levels. Health risks during heat waves may thus not only be a function of known vulnerabilities (including advanced age and chronic illness), but also of characteristics of the built environment and the capacity of residents to control their indoor environments. Indeed, the wide range of conditions that we observed indoors, relative to outdoors, indicates that many low- and middle-income New Yorkers are ill equipped to mitigate excess heat and humidity in their homes.

Our study has a number of limitations. First, our thresholds of indoor heat risk are speculative and have yet to be established via research that links indoor heat and humidity exposures with health outcomes. As stated above, these thresholds, while built from the outdoor thresholds that themselves have been corroborated with population-level health outcomes, must remain “best guesses” until further research can more definitively establish health-relevant indoor heat and humidity thresholds.

Second, we had no data on which households were using air conditioning during the indoor monitoring periods. Survey figures suggesting that only 12.5% of New York City homes lacked a functioning air conditioning unit as of 2007 are at best a crude guess as to the prevalence of air conditioning use in our sample. While this information gap prevented us from identifying the modifying effect of air conditioning on the indoor environment, it does not affect our conclusion that a significant percentage of New York City homes are likely to exceed putative heat danger thresholds during heat waves. The fact that our analyses were conducted using data collected in a mixture of households – those with air conditioning and those without – make our estimates conservative as to the heat danger that may exist in some homes.

We chose, furthermore, not to stratify our analysis by other potentially modifying factors, such as floor level and building type. We could not be certain that adding these variables into our analysis would not also introduce sources of unmeasured confounding: for example, either of these variables could be associated with the use of air conditioning. In future studies, collection of more detailed information about home and residence characteristics would allow exploration of modifying factors.

Lastly, New York City has not to date experienced a heat wave as extreme as the one that Europe experienced during 2003. To simulate the 2003-like event we were forced to extrapolate a series of conditions that have never yet been observed in NYC. The main limitation that this imposes on our analysis is that we are unsure if the observed linear relationship between outdoor and indoor metrics would remain linear at these values of outdoor T/DP/HI. If the relationship were to plateau at these yet-unforeseen levels, perhaps because of a sudden increase in air conditioning use, our findings would overestimate the danger of an extreme heat wave. On the other hand, if air conditioning efficacy were to decrease during an extreme event, e.g. due to an overburdened power supply, the slope of the indoor-outdoor relationship could steepen.

5. Conclusions

Should heat wave frequency and intensity increase in the coming decades, exposure to dangerous heat and humidity levels will increase. The majority of heat-related fatalities occur at home, yet indoor conditions and their association with specific health outcomes have not been characterized. Indeed, heat exposure warnings are based on outdoor conditions, where people spend little time. Our findings on summertime heat and humidity levels in a subset of low- and middle-income New York City homes add substantially to the current knowledge of actual conditions in the urban residential environment. Modeling the associations between indoor and outdoor measures of heat and humidity allows us to estimate indoor heat index levels during heat waves. We find that a substantial fraction of homes exceed dangerous heat thresholds during these extreme events. This result underscores the urgent need for improved awareness and management of indoor heat and humidity in cities at risk for heat waves.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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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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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.

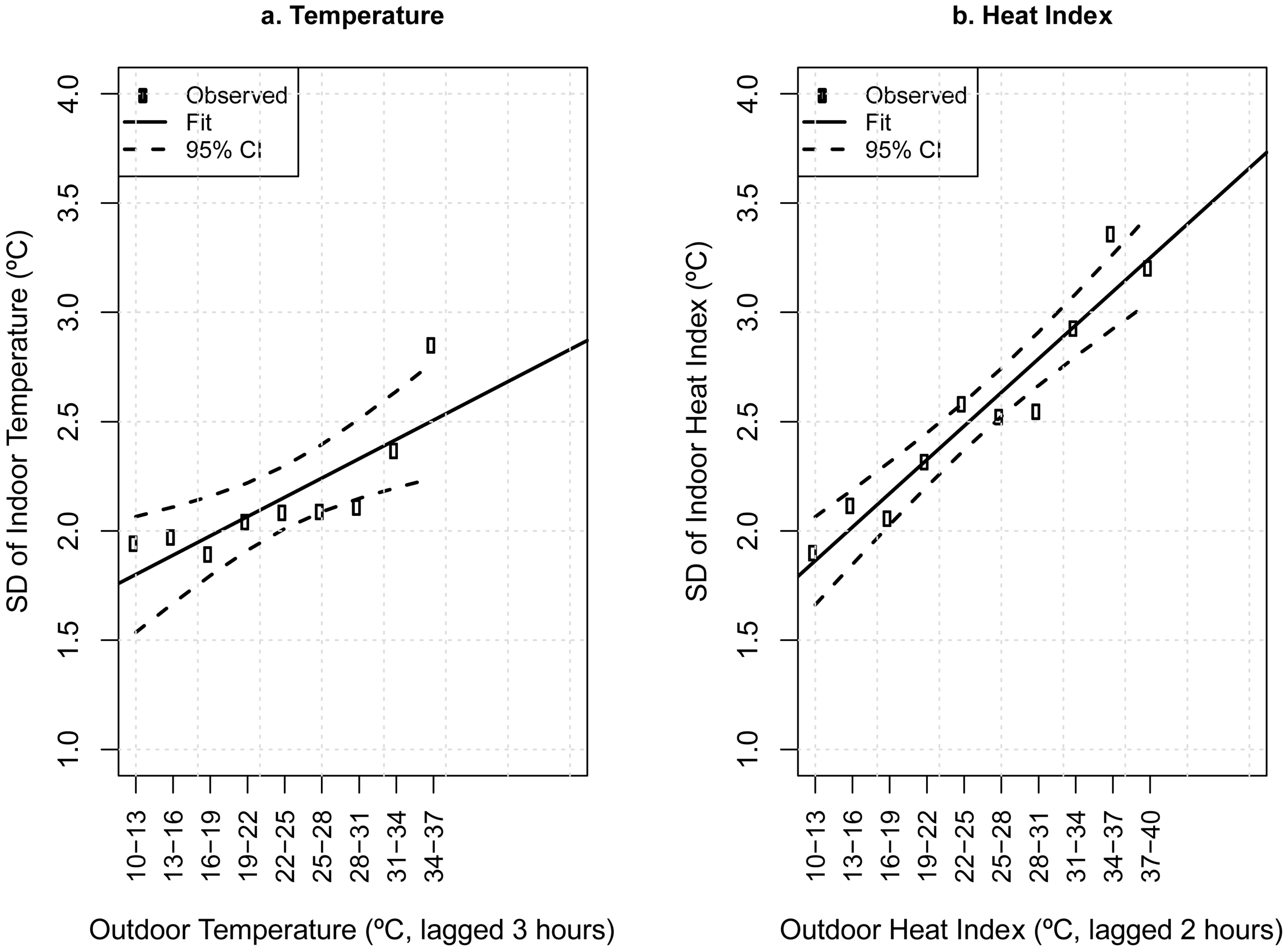

Figure 1. Standard Deviation of Indoor Temperature and Heat Index

1a) Temperature: 9 bins of 3 degrees each; 1b) Heat Index: 10 bins of 3 degrees each. Regression equations: Temperature: Indoor_T_SD = 1.51 + 0.029*(outdoor_T_lag3hrs); Heat Index: Indoor_HI_SD = 1.35 + 0.051*(outdoor_HI_lag2hrs). For both T and HI, the standard deviation of the indoor values increases as the outdoor value increases, suggesting higher between-home variability during hotter conditions. Although we did not have data on air conditioning use or prevalence, the increasing variability may be a result of air-conditioning use in some homes. Air-conditioning would stabilize indoor T and HI even as outdoor conditions warm. Meanwhile, T and HI would continue to increase in residences without air conditioning.

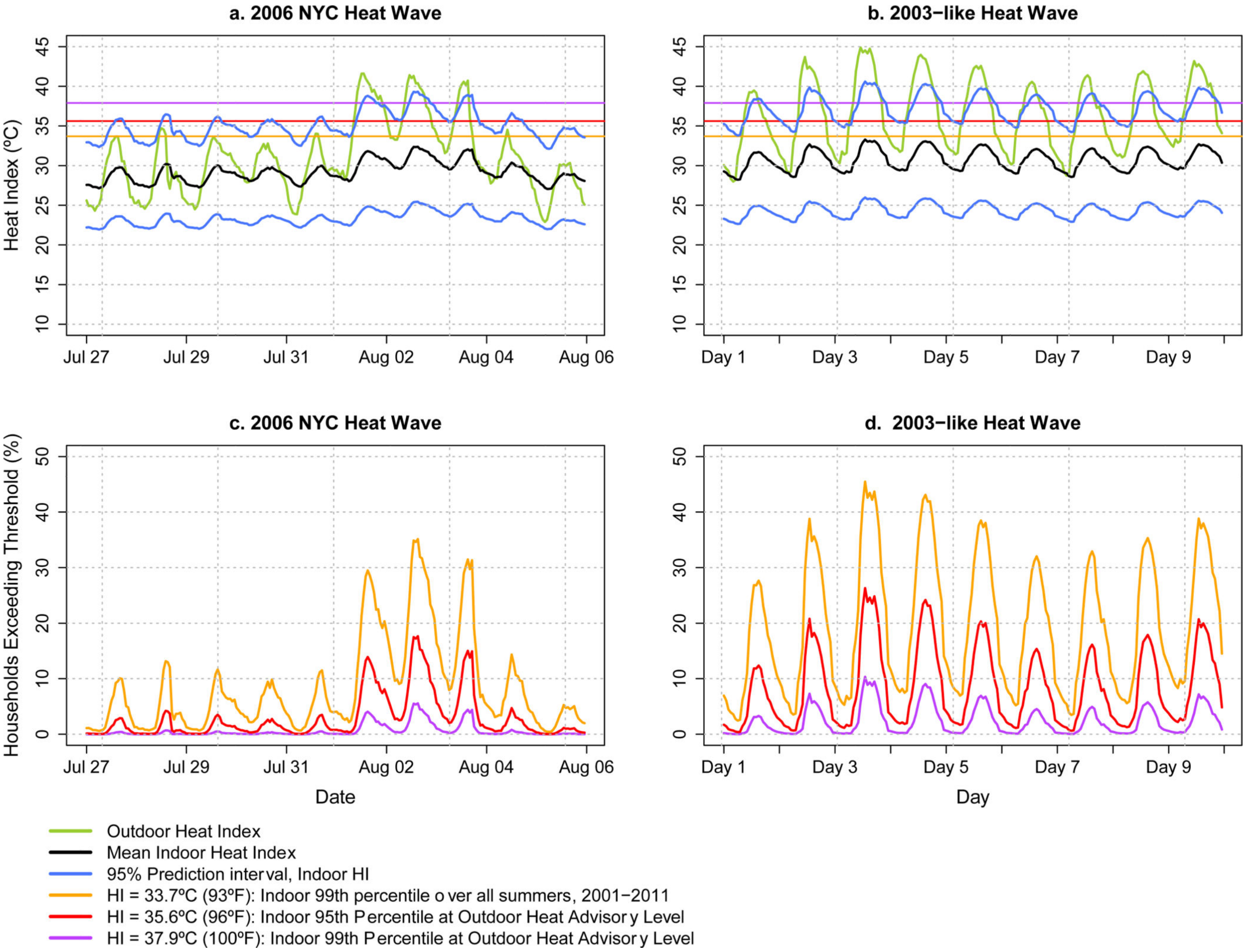

Figure 2. Hourly time series of predicted indoor HI and of predicted HI threshold exceedance during two simulated heat waves

2a & 2c) 2006 NYC heat wave; 2b & 2d) 2003-like heat wave. Green lines: outdoor HI (observed for 2006, simulated for the 2003-like event). Black lines: mean indoor HI. Blue lines: 95% prediction interval of indoor HI. Purple, red, and orange lines: proposed indoor HI thresholds. Plots 2c & 2d show the percent of households that would exceed each threshold (purple, red, and orange) on an hourly basis during the heat wave. A multilevel regression model with random intercept and slope was used to account for clustering of observations within sites and between-site variability.

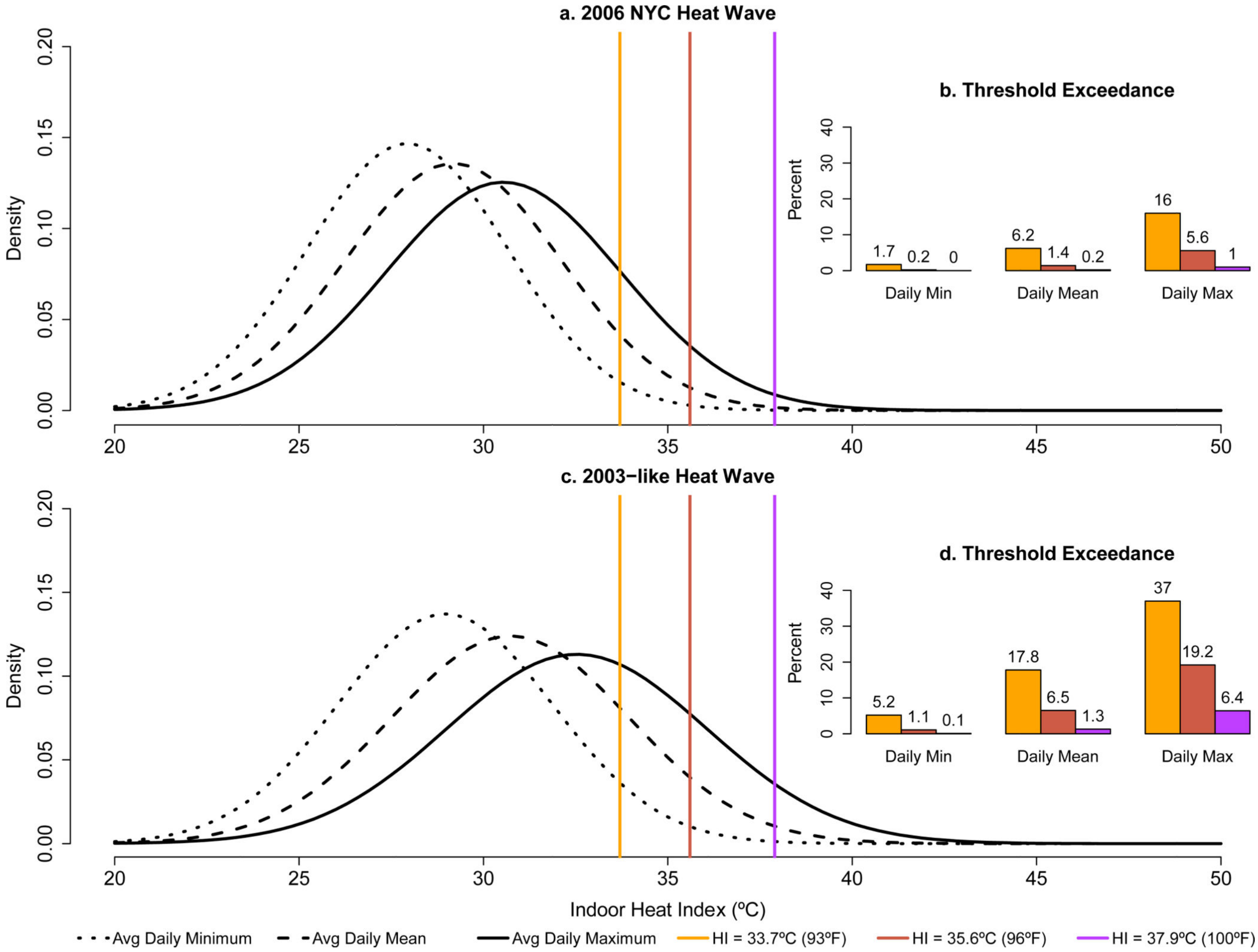

Figure 3. Predicted distribution of event-averaged indoor daily maximum/mean/minimum HI during two simulated heat waves

3a & 3b) 2006 NYC heat wave; 3c & 3d) simulated 2003-like heat wave. Orange threshold represents the 99th percentile of indoor HI over all summers, 2001–2011; Red Threshold: 95th Percentile of indoor HI at Outdoor Heat Advisory Level (35°C/95°F); Purple Threshold: 99th Percentile of indoor HI at Outdoor Heat Advisory Level.

Table 1

Associations between outdoor and indoor hourly T/DP/HI, among 285 residences monitored for 4–13 days in summers 2003–2011.

	Model 1: Temperature (°C)	**Model 2: Dew Point (°C)**	**Model 3: Heat Index (°C)**
Fixed effects estimates:			
Intercept ± SE	26.69 ± 0.10*	14.71 ± 0.15*	27.00 ± 0.12*
Outdoor (same day) ± SE	0.20 ± 0.01*	0.66 ± 0.02*	0.24 ± 0.01*
Outdoor (1 day lag) ± SE	0.085 ± 0.002*	0.046 ± 0.003*	0.076 ± 0.003*
Outdoor (2 days lag) ± SE	−0.001 ± 0.002*	−0.020 ± 0.003*	−0.016 ± 0.002*
Random effects Standard Deviation:			
Intercept	1.65	2.55	1.96
Outdoor (same day)	0.16	0.38	0.17
Residual	1.08	1.93	1.41

*p-value < 0.0001

The models are of the form indoor (T/DP/HI) ~ outdoor (T/DP /HI) + lag_1day_outdoor (T/DP/HI) + lag_2days_outdoor (T/DP/HI), with random intercept and slope (residence as the grouping variable). Outdoor predictors are grand mean centered and lagged behind the indoor variables by: 3hrs (T), 1hr (DP), 2hrs (HI).

Table 2

Percentage of households expected to exceed the low, medium, and high thresholds of indoor heat danger on each day of two heat waves (2006 and 2003-like)

2006 Heat Wave										
	Day 1	**Day 2**	**Day 3**	**Day 4**	**Day 5**	**Day 6**	**Day 7**	**Day 8**	**Day 9**	**Day10**
Low threshold (33.7°C)	10.1	13.2	11.7	9.9	11.5	29.5	35.1	31.5	14.3	5.3
Medium Threshold (35.6°C)	2.9	4.2	3.5	2.8	3.5	13.9	17.6	15.0	4.7	1.1
High threshold (37.9°C)	0.4	0.7	0.5	0.4	0.5	4.1	5.6	4.4	0.8	0.1
2003-like Heat Wave										
	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Day 8	Day 9	
Low threshold (33.7°C)	27.7	38.8	45.5	43.1	38.5	32.0	32.9	35.3	38.8	
Medium Threshold (35.6°C)	12.4	20.8	26.3	24.2	20.3	15.4	16.1	17.9	20.7	
High threshold (37.9°C)	3.3	7.3	10.3	9.0	6.9	4.5	4.9	5.7	7.2	