Published in final edited form as:

Indoor Air. 2017 July ; 27(4): 840–851. doi:10.1111/ina.12367.

Predictors of summertime heat index levels in New York City apartments

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Abstract

Background—During heat waves, fatal overexposure to heat most often occurs at home. It is not known how factors such as building size, floor level, and different types of air conditioning (AC) contribute to excess indoor heat.

Methods—We monitored indoor temperature and humidity in 36 apartments in New York City during summers 2014 and 2015, and used these values to calculate the indoor heat index (HI). We investigated the role of AC type and building-level factors on indoor HI using multilevel regression models.

Results—34 of 36 homes had AC. Central and ductless AC types were associated with the coolest indoor conditions; homes with window and portable AC were significantly warmer. Apartments on the top floor of a building were significantly hotter during heat advisory periods than other apartments regardless of the presence of AC. High indoor HI levels persisted in some homes for approximately one day following the end of the two heat advisory periods.

Conclusions—We provide concrete evidence of higher heat levels in top floor apartments and in homes with certain types of AC. High heat levels that persist indoors after outdoor heat has subsided may present an underappreciated public health risk.

Keywords

Indoor temperature; Heat index; Air Conditioning; Heat waves; Housing; Health

INTRODUCTION

Heat is the single largest weather-related factor associated with mortality in the United States (NWS Office of Climate, Water, and Weather Services). High levels of heat and humidity can overwhelm the body's ability to maintain temperature homeostasis, which is normally achieved through vasodilation and perspiration (Kovats and Hajat 2008). Consequences of rising internal temperatures are well documented and include adverse health outcomes such as heat stress, heat stroke, and death (Bouchama and Knochel 2002). Other less severe health consequences have also been associated with exposure to heat, as

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indexed by emergency department visits and emergency medical calls (Hess et al. 2014b; Uejio et al. 2015).

Importantly, the home environment is increasingly understood as potentially dangerous during heat waves. In New York City (NYC), 80% of heat stroke fatalities between 2000–2011 were attributed to exposure at home (Wheeler et al. 2013). During the same decade, deaths occurring at home in NYC were found to increase during heat wave periods as compared to other warm days (Madrigano et al. 2015). Relocating vulnerable individuals away from hot home environments is one possible strategy to reduce this risk and is operationalized by the opening and promotion of public-access “cooling centers” in NYC and other cities. Many vulnerable individuals, however, do not make use of these resources due to lack of mobility or transport, or a preference to stay at home. A 2011 survey estimated that over half a million NYC residents were at “high heat-health risk”, meaning they were both aged over 65 years and had self-reported poor or fair general health status. Forty-nine percent of these “high heat-health risk” individuals reported staying home during very hot weather regardless of their ability to stay cool there (Lane et al. 2014).

Though clearly important, to date little research has been conducted to investigate the role of housing factors in vulnerability to heat stress. Some studies did find an association between top floor location and mortality during the 1995 Chicago heat wave (Semenza et al. 1996), and older building age, lack of insulation, and top floor location were associated with mortality among the elderly during the 2003 heat wave in France (Vandentorren et al. 2006). Previous work has demonstrated that the level of indoor heat associated with an observed level of outdoor temperature varies across residences (Franck et al. 2013; Nguyen et al. 2013; Tamerius et al. 2013; White-Newsome et al. 2012), particularly during heat waves (Quinn et al. 2014). None of this work, however, has been able to explore the role of AC in this variability.

Several recent recommendations have highlighted the need for further study of the role that structural and behavioral factors may play in exposure to heat inside residential housing (Kinney et al. 2015) and the evaluation of interventions that can help abate these effects (Hess et al. 2014a; Maller and Strengers 2011).

Here we investigate the role of AC and building-level factors on temperature and heat index (HI) inside 36 NYC apartments during the summer season. Our aims were, first, to evaluate differences in indoor temperature by AC type over the summer season; and second, to investigate these differences during periods of elevated heat risk (heat advisory periods or “heat waves”).

METHODS

Study Duration and Recruitment

The study was conducted over two summer seasons: June 1–September 30, 2014 (Summer 1) and June 1–September 30, 2015 (Summer 2). Participants were recruited jointly by Columbia’s NIEHS Center for Environmental Health in Northern Manhattan and by WeACT for Environmental Justice, an environmental justice organization located in Harlem, NYC.

Recruitment was done via a convenience approach using email and personal outreach, with any household in the boroughs of Manhattan, Brooklyn, and the Bronx eligible to participate if the head of household was over 18 years of age and the family did not plan to be away from their NYC residence for more than three weeks during the summer. An active email account was also required as follow-up surveys were distributed in this manner. The study protocols and procedures were approved by the Institutional Review Board of Columbia University's Medical Center.

Baseline health and housing information

An initial home visit was conducted at study enrollment to install temperature and humidity monitors in the home and to collect data on variables including: number and ages of household members, approximate hours spent at home, respiratory or cardiovascular diagnoses in the household, number of rooms and bedrooms in the residence, number and direction of windows, floor level of residence, type of air conditioning system, locations of air conditioning units, and building size and age. We also asked about the activities typically conducted in the household to reduce heat exposure during hot weather. The full initial survey can be found in the Supplemental Material.

Indoor temperature and humidity measurements

Indoor temperature and humidity readings were captured using Maxim Integrated DS1923 Hygrochron iButton sensors. These loggers record temperature measurements within the range of -10°C – 65°C with an accuracy of $\pm 0.5^{\circ}\text{C}$, and RH measurements within the range 0–100% with an accuracy of 0.6%. Between two and four sensors were installed in each participant's home, depending on the size of the residence. At a minimum, one sensor was installed in the home's main living room and another in the study participant's main bedroom. The sensors were attached to walls or furniture at a height of approximately 1.5m, away from windows and heating devices and out of direct sunlight. They were programmed to log measurements every hour, and remained in the residences for 5–6 months, at which time they were removed and the data downloaded. Duplicate loggers were co-installed side by side in a subset of the homes to assess inter-sensor reliability.

Outdoor temperature and humidity measurements

Hourly outdoor meteorological measurements were drawn from temperature and dew point temperature readings provided by the National Oceanic and Atmospheric Association (NOAA) for New York City's Central Park weather station, the closest NOAA weather station to the residences in this study.

Analysis of nighttime bedroom temperature across the summer season

Our analysis of indoor heat across the entire summer season focuses on temperature, in order to relate our findings to the few published health-related recommendations for temperature ranges in residential environments (CIBSE 2013; Ormandy and Ezratty 2012). Because we were interested in evaluating the effectiveness of different AC systems, we concentrated our analysis on those rooms and times of day when the occupants were most likely to be at home and using AC. Our initial surveys indicated that many residents were absent from home

during the day but at home at night. AC use was also reported to be highest at night. We therefore restricted our analysis to bedrooms during the hours of 12am – 6am, a period that we believe isolated those times and locations when occupancy and AC use were most likely to coincide. We compared mean nighttime bedroom temperatures by AC type and also investigated differences between indoor and outdoor temperature.

Because we were also interested in the effectiveness of AC on particularly hot days, we conducted a separate analysis of nighttime bedroom temperature on the hottest 10% of summer nights, defined as those nighttime periods (12am–6am) following days on which outdoor maximum temperature exceeded its 90th percentile over Summers 1 and 2. This outdoor threshold was 31.7°C, and there were 17 nights over the two summers that met this criterion.

Heat Wave Analysis

We chose heat index (HI) as our primary outcome variable of interest during extreme heat episodes due to the relevance of both environmental temperature and humidity on the ability to dissipate excess heat from the human body (Davis et al. 2016), and because HI is the metric used to determine when to issue heat advisories in New York City (US Department of Commerce). Hourly indoor and outdoor HI values were calculated from temperature and RH using the weathermetrics package in R (Anderson et al. 2013a), which uses the algorithm employed by the U.S. National Weather Service to calculate HI.

Heat advisories are issued in New York City when the heat index (HI) is forecast to reach 95°F (35°C) for two consecutive days or to surpass 100°F (37.8°C) for any length of time (US Department of Commerce 2010). No heat advisories were issued during the first summer of monitoring, while two heat advisories were issued during Summer 2015. “Heat Wave 1” corresponded to July 19–20, 2015, when the maximum outdoor HI reached 101.8°F (38.8°C); and “Heat Wave 2” corresponded to July 28–29, 2015, when outdoor HI reached 95.1°F (35.1°C). For comparative purposes we also chose a four-day reference period that began approximately one week prior to the first heat advisory period, when temperatures were seasonable for July. Dates of the reference period were July 12–15, 2015; maximum outdoor HI during this period was 86.9°F (30.5°C).

We built multilevel models using the nlme package in R (Pinheiro et al. 2016) to evaluate the role of AC types and building factors on indoor HI during the heat waves. Hourly indoor HI values were the outcome variable in models with predictors including household- and building-level factors as well as outdoor HI variables. Outdoor HI was lagged 3 hours behind indoor HI since initial data exploration indicated that this lag was the most strongly correlated with hourly indoor HI. We also included outdoor HI lagged 24 hours behind indoor HI to account for day-to-day thermal inertia in the building (lags of more than 1 day were not significant and not retained in the models).

For this analysis, we used all the hourly data across all rooms in the home and all times of day, and adjusted for possible occupancy and AC use patterns via the inclusion of covariates for room type and time of day. A number of building-level variables were explored for inclusion in the models; those that were eventually excluded due to lack of influence on

indoor HI were: number of rooms in home, number of dwellings in the building, floor level of home, total number of household members, and year of building construction.

Our final models for hourly indoor HI were fit using separate three-level random-intercept multilevel regression models for each heat wave and the reference period, as follows:

$$HI_{ijk} = \alpha_{jk[i]} + \beta_1 X_{i1} + \beta_2 X_{i2} + \beta_3 X_{i3} + \epsilon_i \quad [1]$$

$$\alpha_{jk} = a + b_2 U_{j2} + b_3 U_{k3} + \eta_{jk} \quad [2]$$

Where:

- The outcome variable, HI_{ijk} , represents hourly observations of indoor HI for hour i in room j and household k .
- The vector X_1 represents a matrix of covariates that vary at the same level as the individual HI observations (Level 1); that is, in time. In this case X_1 represents same-hour and 24-hour-lagged outdoor HI, and dummy variables for time of day (morning, day, evening, night).
- The vector X_2 represents a matrix of covariates varying at the location of individual temperature/humidity loggers (the “room” level of the home, Level 2): these included presence of AC in the room, and bedroom versus other room.
- The vector X_3 represents a matrix of covariates that vary at the household level (Level 3): AC type and top floor location.
- ϵ_i is the within-household variation not explained by the predictors X_1 , X_2 , and X_3 .
- The intercept, α_{jk} , incorporates error terms U_j and U_k that allow it to vary by room and household.

Lastly, we fit the models with a first-order autocorrelation (AR1) structure to account for correlation of observations in time.

To explore the question of the persistence of high indoor HI beyond the end of a heat wave, we isolated a set of days for each of the two heat wave episodes that were similar in outdoor HI to the day following the end of each heat wave: the “post-heat-wave” day. We defined similar days as days during summer 2015 when the maximum daily outdoor HI came within 1°C of its value on the “post-heat-wave” day. To test this effect we built multilevel regression models in which we included an indicator variable for the “post-heat-wave” day along with our usual predictors (AC type, top floor location, outdoor HI).

RESULTS

Outdoor temperature during the study period

As compared to temperatures recorded at the Central Park weather station between the years 1981–2010, average temperature during Summer 1 (June–September 2014) was 0.1°C cooler than the 30-year mean, and no heat advisories were issued. Summer 2 (June–September 2015) was 1.3°C warmer than normal, and two heat advisories were issued, as mentioned above. A plot of outdoor temperature during the monitored seasons is included in the Supplementary Material, Figure S1s.

Household characteristics

A total of 36 households participated in the study: 21 in Summer 1 and 30 in Summer 2. 15 homes participated across both seasons. Descriptive characteristics of the households can be found in Table 1. All of the homes were located in multifamily housing (e.g. apartment buildings, condominiums, and row houses), with half the homes (18 units) in medium-size buildings containing 20–99 dwellings, an additional 14 homes in large buildings with upwards of 100 dwellings, and only four homes situated in buildings with fewer than 20 dwellings. The mean building height was 13.4 floors (range, 3–32 floors). The vast majority of the buildings (94%) had brick exteriors, with only two buildings having mostly glass exteriors.

The most prevalent type of AC in our study sample was window air conditioning (24 homes). This type of AC system consists of one or more self-contained units that fit into a window sash or into a specially prepared sleeve in a wall. Four homes had “ductless” or “mini-split” AC systems: this type of AC is generally considered to be more efficient than window AC because of the separation of the condenser unit (installed outdoors) from the blower unit (installed indoors). Five homes had central air conditioning, which is a building-wide system of centrally cooled air distributed to individual rooms through the building ductwork. A single home employed a freestanding portable air conditioner, and two homes had no AC units at all (Table 1). Type of AC was not associated with other dwelling-level characteristics such as rental vs ownership status, number of units in building, number of rooms in the home, total number of windows in the home nor with the primary orientation of the windows (data not shown). Type of AC was significantly associated with the year of building construction, with central and ductless air conditioning systems more likely present in newer homes (one-way ANOVA p-value = 0.02).

The most common strategy in response to the question: “On a very hot day, what actions do you typically take to stay cool at home?” was “Use an air conditioner” (33/92%), followed by “close the shades on the windows” (22/61%) and “use an electric fan” (20/56%). Other strategies such as opening windows and intentionally leaving home for a cooler location were much less common, reported by 19%, 25%, and 6% of households, respectively. Strategies that were volunteered by the study participants included: Drink water (4/11%), Take a cool shower (5/14%), Use the pool (1/3%), wear less clothing (1/3%).

Among the 34 households with AC, self-reported AC use in the home was greater at night and on very hot days. On a typical summer day, participants reported using AC for an

average of 4.8 hours during the daytime (defined as 7am–7pm), increasing to 8.2 hours during the nighttime (7pm–7am). On a very hot day, AC use increased to 6.7 hours during the daytime. The greatest reported AC use was during the nighttime on a very hot day, when 30 of 34 participants reported using AC for all 12 hours of the night (See Supplementary Material, Figure S2). Among those households whose AC systems allowed them to set a desired temperature (26 households or 76% of the 34 households with AC), the mean self-reported usual temperature setting was 21.3°C (70.4°F, range 63–76°F), which is 4.2°C (7.6°F) cooler than the 25.6°C (78°F) setting recommended by New York’s office of Emergency Management to conserve energy during hot weather (NYCEM 2016).

Nighttime Bedroom Temperature by AC Type

Comparing nighttime temperature in bedrooms by AC type across the summer seasons, we observed that central AC was associated with the coolest temperatures, followed by ductless AC. Rooms with window and portable AC were warmer. Over all summer nights, the mean temperature across all homes was 25.5°C, but the means ranged from 24.0°C (homes with central AC) to 27.4°C (the single home with portable AC, Table 2a). Homes with window AC (the most prevalent AC type in this sample) had a mean temperature of 25.6°C. Notably, mean nighttime bedroom temperatures were higher than the corresponding outdoor temperature levels across all AC types when considering summer as a whole (bold numbers in Table 2a).

On the hottest 10% of nights (Table 2b), mean temperature across all homes rose one degree Celsius, to 26.5. The means by AC type typically rose about one degree as well as compared to the AC-specific average across all summer nights, with the exception of a 2.3 degree increase (to 28.3°C) in the homes with no AC. While the indoor-outdoor difference typically decreased on these hottest nights, the mean nighttime temperature was still *above* the outdoor temperature in all homes except those with central AC. These differences can be visualized in Figure 1, which also demonstrates that there was considerable variability in indoor temperature within each AC category. Window AC (the most prevalent AC type in this population) had the most variability, with some temperature values far below the outdoor levels and some far above them. In pairwise comparisons by AC type, the differences in indoor HI between central AC and no AC/ window AC were statistically significant, while none of the other types of air conditioning were significantly different from any of the others (Figure 1).

Heat Wave Analysis

Outdoor temperature for the month of July 2015 can be seen in Figure 2. The two heat wave periods and the reference period are highlighted. In our analysis of indoor HI during these three periods, we observed similar differences by AC type as we had seen in our earlier analysis (Figure 2). Again, homes with no AC were the warmest both during the reference period and both heat waves (Figure 3), followed by homes with window AC, ductless AC, and central AC respectively (no households enrolled in the study during Summer 2 had portable AC). Top-floor homes were much warmer than homes on other floors both during the reference period and both heat waves, irrespective of AC type (Figure 4).

Results of Multilevel Models

The results from our multilevel models are presented in Figure 5 (full tabular results are available in the Supplemental Material, Table S1). The results indicate that the contribution of the 3-hour-lagged and 24-hour-lagged outdoor HI variables to indoor HI during the reference period and the two heat waves is consistently and significantly positive; however, the coefficients associated with the outdoor variables are quite small. Coefficients for the outdoor-indoor association are between 0.02 and 0.11 for each 1°C increase in outdoor HI; thus a 10-degree increase in outdoor HI is associated with between 0.2–1.1°C higher indoor HI. The categorical “time of day” variable and binary “room type” variable are also often significant to the models; their contribution to indoor HI levels is likewise small (all coefficients less than 1.0°C). Meanwhile, the coefficients associated with AC type and with top floor location are large. Top floor location was significantly associated with approximately 2°C higher HI during the reference period, and 3.3–3.7°C higher HI during the two heat waves, adjusting for AC type and the other covariates in the model. Central AC was associated with indoor HI values that were on average 2.2°C cooler than homes with no AC during the reference period, and more than 4°C cooler during the two heat waves.

Although some associations did not reach statistical significance in our sample of 30 homes, the trend in the impact of AC types on indoor HI is clear. Central AC was associated with the coolest indoor HI, and homes with ductless AC were second coolest. Homes with window AC were still between 1.1 and 2.6°C cooler as compared to homes with no AC, but several degrees warmer on average than homes with central AC. We had limited power to detect significant effects within our sample of 30 households, but found that indoor HI in homes with central AC was significantly different from homes with no AC during Heat Wave 1 only.

Indoor HI Persistence

In Figures 3 and 4, the official heat advisory periods are highlighted with a red box. We have also extended the graphs to include the indoor HI for two days beyond the end of these heat advisory periods. It is visually apparent that at least some homes exhibited a persistence of elevated indoor HI values for approximately one day after the end of the heat advisory periods, particularly during Heat Wave 2. We found that the effect of the “post-heat-wave” day was significant in our models, implying that indoor HI was significantly warmer on the day following each heat wave, compared to other days with similar outdoor conditions and adjusting for AC type and top floor location (Figure 6, full results can be found in the Supplemental Material).

DISCUSSION

Previous work has demonstrated the association between summertime outdoor and indoor temperature and heat index in NYC (Quinn et al. 2014; Tamerius et al. 2013; Uejio et al. 2015), but none of this prior work has been able to incorporate air conditioning as a predictor of indoor conditions. In the present study, we confirm the contribution of outdoor conditions, but further show that dwelling-specific predictors contribute to the indoor heat

index, with top floor location significantly associated with higher HI, and different AC types associated with different indoor heat levels.

It is difficult to know whether the heat levels we observed in our sample of homes are associated with health risk, as we lack human health data to estimate the association between adverse health events and indoor conditions. Lacking this data, we also cannot establish health-relevant thresholds for indoor temperature and humidity (Anderson et al. 2013b). A few organizations have nonetheless proposed indoor heat guidelines: for example WHO Europe suggests that the range of indoor temperature that presents “minimal risk” to the health of the elderly is 18–24°C (Ormandy and Ezratty 2012). Meanwhile, the UK’s Chartered Institution of Building Engineers (CIBSE) has suggested indoor thermal thresholds for overheating, which include a bedroom-specific overheating threshold of 26°C and a lower “sleep impairment” threshold of 24°C (CIBSE 2013). The CIBSE recommendation is that temperature in bedrooms should not exceed these thresholds for more than 1% of the occupied time on an annual basis (Mavrogianni et al. 2015). Although the relevant thresholds may certainly be different in the northeastern United States than in Europe, it is notable that in this sample of homes, *mean* nighttime bedroom temperature in homes with no AC equaled the 26°C overheating threshold; while during the hottest 10% of summer nights the average temperature in several categories of homes (no AC, window AC, portable AC) exceeded this threshold. Even more homes exceeded the 24°C “sleep impairment” threshold as a matter of course: only homes with central AC had mean temperature lower than this across the summer as a whole. On the hottest 10% of nights, homes with central AC surpassed this threshold as well.

A key finding from this work concerns the high levels of temperature and HI that we observed indoors despite the fact that most households used AC. The prevalence of AC in this sample (34 out of 36 homes or 94% of the sample) is only slightly higher than the prevalence of AC in New York City households overall, estimated at 89% in 2011 (Lane et al. 2014). AC use was the most frequently cited heat adaptation strategy among our participants, and was reported at higher rates than in previous studies elsewhere in the United States. For example, elderly residents of Detroit more often opened windows or doors and/or turned on fans than used AC (White-Newsome et al. 2011), and an evaluation of heat watch warning systems in four North American cities indicated that respondents cited “avoiding the outdoors” more than using AC during extreme heat events (Sheridan 2007). Further, although all households with AC in our study reported setting their AC temperature to levels that were below the recommended 78°F (25.6°C), only homes with central AC actually maintained mean bedroom temperatures lower than this on hot summer nights (Table 2).

Although there is substantial observational evidence supporting AC as protective against heat-related morbidity and mortality (Bouchama and Knochel 2002; New York City Department of Health and Mental Hygiene 2006; Ostro et al. 2010; Semenza et al. 1996), the results presented here suggest that AC may not be a one-size-fits-all panacea to mitigate heat stress in indoor environments. Our finding that central AC provided statistically significant reductions in heat exposure, as compared to window AC, is in line with the conclusions of the few previous studies that have examined the effect of AC type on

mortality. A study of 72,740 death index records for decedents in the United States between 1980–1985 found a significantly reduced risk of death on hot days among those with central AC but not those with room AC (Rogot et al. 1992), although room AC was protective in the smallest homes (those containing three or fewer rooms). In another study, central AC, but not room AC, explained a portion of observed differences by race in heat-related mortality in four U.S. cities (O'Neill et al. 2005).

Our observations also indicate that some homes exhibited high HI values for at least a day after the conclusion of the two heat advisory periods. Epidemiologic studies have often noted a brief lag in mortality following a heat wave. A classic pattern that has been observed is a gradual increase in daily mortality as the heat wave increases in duration, followed by a drop in mortality when the heat wave ends. The peak in daily mortality often occurs 1–2 days following the peak in outdoor temperature. This pattern was seen, for example, in the 1995 Chicago heat wave (McGeehin and Mirabelli 2001), in Milwaukee the same year (CDC 1996), in the 2003 French heat wave (Fouillet et al. 2006), in Victoria, Australia in 2009 (Department of Health & Human Services 2012), and in a study summarizing mortality due to ischemic heart disease over all the heat waves in Germany in the years 2001–2010 (Zacharias et al. 2014). The current study lends a possible exposure-based explanation for this observed lag. We speculate that thermal inertia is at play in retaining heat inside these homes, such that multiple days of rising outdoor temperatures over the summer season cause indoor heat to build up and even continue to rise for a time after the outdoor temperatures have subsided to levels that are more seasonable. If this finding is reproduced in future research efforts, it will have real implications for public health preparedness. For example, amending heat wave action plans to ensure that all prevention activities continue for a few days after the peak in outdoor heat might lead to a discernable reduction in lives lost during extreme heat events.

This study was subject to several limitations. The research was conducted in a relatively small convenience sample of 36 homes. The generalizability of the findings to other dwellings in NYC and to highly vulnerable populations, such as those who are elderly and have chronic health conditions, is thus limited. The sample size considerations also led to relatively large confidence intervals around some of our predictors of interest, such as AC type. In this sample we were not able to capture every combination of pertinent variables: for example, no top floor homes in the study had central AC. Another limitation is that we used central (Central Park Station) weather recordings for the outdoor HI levels in our models, as we did not have site-specific outdoor temperature and humidity measurements.

Despite the advantages provided by our ability to record the types and locations of AC units in the homes, we did not have information on the specific wattage and capacity of the AC systems, and had no way to record actual AC use – that is, to determine when AC was actually being used in the homes. We included variables in our models for time of day and type of room (bedroom vs. other room) and found that they responded as expected, indicating that AC use was presumably higher at night and in bedrooms. Similarly, we lacked information on the specific timing of other behaviors that might affect indoor heat, for example window shading and window opening. As our initial surveys indicated that these behaviors were not common in this population, we believe our results concerning AC

type and apartment location are likely to be robust to the influence of these behaviors. Further research to determine whether and how increased prevalence of such cooling behaviors might influence indoor heat is certainly warranted, however.

The findings presented here raise many questions for future research about the protective capacity of different AC systems and other housing-level factors against excess heat. There are also other reasons to be cautious about public health policies that rely on residential AC for protection against heat stress. AC use contributes to greenhouse gas emissions and releases heat into the outdoor environment, ironically contributing to the very effects it seeks to diminish; namely the health impacts of global warming and the urban heat island effect. Concerns have also been raised that increased dependence on AC as a mechanism to reduce heat stress could paradoxically increase household vulnerability to heat: both because increased AC use at a metropolitan scale increases pressure on the power grid and causes brownouts and blackouts, rendering AC useless (Anderson and Bell 2012; Kinney et al. 2015; Maller and Strengers 2011); and because over-reliance on this “technical” fix may result in a population unaware of other, less energy-intensive strategies that can be used to cool rooms and bodies (such as nighttime window opening, proper use of fans, cooling the body with water and adjusting clothing) (Brown and Walker 2008). In this study, “alternative” strategies other than AC were infrequently employed: only slightly over half of respondents reported shading their windows to reduce exposure to heat, and only one-fifth opened their windows, even at night when outdoor conditions were cooler than indoor conditions. These results indicate that there is ample room for promotion of non-AC-dependent cooling strategies in the NYC residential environment, and for addressing barriers to their adoption, such as the fear of noise, insects, and crime that may impede window opening in some homes. Concurrently, more research is needed on how to reduce heat exposure in top floor dwellings; for example with “cool” roof coatings, improved ventilation, and increased use of insulation.

CONCLUSIONS

The ability to manage indoor heat in New York City apartments depends not only on AC presence but also on the type of AC system and on factors such as the apartment’s location within the building. Central and ductless AC were associated with the coolest summertime temperatures, while homes with window and portable AC were warmer. Apartments on the top floor of a building can be significantly hotter during heat waves than other apartments regardless of the presence of AC. These findings can inform heat-risk vulnerability indices, which should be extended to include risk factors associated with housing. Public health practitioners and medical professionals should be aware that AC is not necessarily a panacea against heat stress, particularly if the type of AC is a lesser-performing window or portable unit and if residents live on the top floor of a building. Extreme heat preparedness efforts could also be improved by extending the action period beyond the official end of the heat wave, since high levels of indoor heat may persist after the heat wave has ended. Additional, non-energy-dependent strategies to cool the indoor environment should be explored, particularly in light of predictions for more frequent and intense heat waves in the coming century.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

This work was supported by NIH grants T32 ES023770, P30 ES009089, and GM100467. JS declares partial ownership of SK Analytics.

References

- Anderson GB, Bell ML. Lights out: impact of the August 2003 power outage on mortality in New York, NY. *Epidemiol Camb Mass*. 2012; 23:189–193. DOI: 10.1097/EDE.0b013e318245c61c
- Anderson GB, Bell ML, Peng RD. Methods to calculate the heat index as an exposure metric in environmental health research. *Environ Health Perspect*. 2013a; 121:1111–1119. DOI: 10.1289/ehp.1206273 [PubMed: 23934704]
- Anderson M, Carmichael C, Murray V, Dengel A, Swainson M. Defining indoor heat thresholds for health in the UK. *Perspect Public Health*. 2013b; 133:158–64. [PubMed: 22833542]
- Bouchama A, Knochel JP. Heat Stroke. *N Engl J Med*. 2002; 346:1978–1988. DOI: 10.1056/NEJMr011089 [PubMed: 12075060]
- Brown S, Walker G. Understanding heat wave vulnerability in nursing and residential homes. *Build Res Inf*. 2008; 36:363–372. DOI: 10.1080/09613210802076427
- CDC. Heat-Wave-Related Mortality – Milwaukee, Wisconsin, July 1995. *Morb Mortal Wkly Rep*. 1996. Available: <http://www.cdc.gov/mmwr/preview/mmwrhtml/00042616.htm> [accessed 6 April 2016]
- CIBSE. CIBSE TM52 The Limits of Thermal Comfort: Avoiding Overheating in European Buildings. 2013. Available: <http://www.cibse.org/knowledge/cibse-tm/tm52-limits-of-thermal-comfort-avoiding-overheating> [accessed 19 April 2016]
- Davis RE, McGregor GR, Enfield KB. Humidity: A review and primer on atmospheric moisture and human health. *Environ Res*. 2016; 144:106–116. DOI: 10.1016/j.envres.2015.10.014 [PubMed: 26599589]
- Department of Health & Human Services. January 2009 Heatwave in Victoria: an Assessment of Health Impacts. 2012. Available: [https://www2.health.vic.gov.au/443/about/publications/researchandreports/January 2009 Heatwave in Victoria an Assessment of Health Impacts](https://www2.health.vic.gov.au/443/about/publications/researchandreports/January%2009%20Heatwave%20in%20Victoria%20an%20Assessment%20of%20Health%20Impacts) [accessed 6 April 2016]
- Fouillet A, Rey G, Laurent F, Pavillon G, Bellec S, Guihenneuc-Jouyaux C, et al. Excess mortality related to the August 2003 heat wave in France. *Int Arch Occup Environ Health*. 2006; 80:16–24. DOI: 10.1007/s00420-006-0089-4 [PubMed: 16523319]
- Franck U, Krueger M, Schwarz N, Grossmann K, Roeder S, Schlink U. Heat stress in urban areas: Indoor and outdoor temperatures in different urban structure types and subjectively reported well-being during a heat wave in the city of Leipzig. *Meteorol Z*. 2013; 22:167–177. DOI: 10.1127/0941-2948/2013/0384
- Hess JJ, Eidson M, Tlumak JE, Raab KK, Luber G. An Evidence-Based Public Health Approach to Climate Change Adaptation. *Environ Health Perspect*. 2014a; 122:1177–1186. DOI: 10.1289/ehp.1307396 [PubMed: 25003495]
- Hess JJ, Saha S, Luber G. Summertime Acute Heat Illness in U.S. Emergency Departments from 2006 through 2010: Analysis of a Nationally Representative Sample. *Environ Health Perspect*. 2014b; 122:1209–1215. DOI: 10.1289/ehp.1306796 [PubMed: 24937159]
- Kinney PL, Matte T, Knowlton K, Madrigano J, Petkova E, Weinberger K, et al. New York City Panel on Climate Change 2015 Report Chapter 5: Public Health Impacts and Resiliency. *Ann N Y Acad Sci*. 2015; 1336:67–88. DOI: 10.1111/nyas.12588 [PubMed: 25688947]
- Kovats RS, Hajat S. Heat stress and public health: a critical review. *Annu Rev Public Health*. 2008; 29:41–55. DOI: 10.1146/annurev.publhealth.29.020907.090843 [PubMed: 18031221]

- Lane K, Wheeler K, Charles-Guzman K, Ahmed M, Blum M, Gregory K, et al. Extreme heat awareness and protective behaviors in New York City. *J Urban Health Bull N Y Acad Med*. 2014; 91:403–414. DOI: 10.1007/s11524-013-9850-7
- Madrigano J, Ito K, Johnson S, Kinney PL, Matte T. A Case-Only Study of Vulnerability to Heat Wave-Related Mortality in New York City (2000–2011). *Environ Health Perspect*. 2015; 123:672–678. DOI: 10.1289/ehp.1408178 [PubMed: 25782056]
- Maller CJ, Strengers Y. Housing, heat stress and health in a changing climate: promoting the adaptive capacity of vulnerable households, a suggested way forward. *Health Promot Int*. 2011; 26:492–498. DOI: 10.1093/heapro/dar003 [PubMed: 21307023]
- Mavrogiani A, Taylor J, Davies M, Thoua C, Kolm-Murray J. Urban social housing resilience to excess summer heat. *Build Res Inf*. 2015; 43:316–333. DOI: 10.1080/09613218.2015.991515
- McGeehin MA, Mirabelli M. The potential impacts of climate variability and change on temperature-related morbidity and mortality in the United States. *Environ Health Perspect*. 2001; 109:185–189. [PubMed: 11359685]
- New York City Department of Health and Mental Hygiene. NYC Vital Signs Investigation Report: Deaths Associated with Heat Waves in 2006. 2006.
- Nguyen JL, Schwartz J, Dockery DW. The relationship between indoor and outdoor temperature, apparent temperature, relative humidity, and absolute humidity. *Indoor Air* n/a–n/a. 2013; doi: 10.1111/ina.12052
- NWS Office of Climate, Water, and Weather Services. Weather Fatalities. 2012. Available: <http://www.nws.noaa.gov/om/hazstats.shtml> [accessed 31 December 2013]
- NYCEM. NYCEM – Plan for Hazards – Extreme Heat. 2016. Available: <http://www1.nyc.gov/site/em/ready/extreme-heat.page> [accessed 20 March 2016]
- O'Neill MS, Zanobetti A, Schwartz J. Disparities by race in heat-related mortality in four US cities: The role of air conditioning prevalence. *J Urban Health Bull N Y Acad Med*. 2005; 82:191–197. DOI: 10.1093/jurban/jti043
- Ormandy D, Ezratty V. Health and thermal comfort: From WHO guidance to housing strategies. *Energy Policy*. 2012; 49:116–121. DOI: 10.1016/j.enpol.2011.09.003
- Ostro B, Rauch S, Green R, Malig B, Basu R. The effects of temperature and use of air conditioning on hospitalizations. *Am J Epidemiol*. 2010; 172:1053–1061. DOI: 10.1093/aje/kwq231 [PubMed: 20829270]
- Pinheiro, J., Bates, D., Sarkar, D., R Core Team. *Nlme Linear Nonlinear Mix. Eff Model*. 2016. Package Version 3.1-127 Available: <http://cran.r-project.org/package=nlme> [accessed 25 April 2016]
- Quinn A, Tamerius JD, Perzanowski M, Jacobson JS, Goldstein I, Acosta L, et al. Predicting indoor heat exposure risk during extreme heat events. *Sci Total Environ*. 2014; 490C:686–693. DOI: 10.1016/j.scitotenv.2014.05.039
- Rogot E, Sorlie PD, Backlund E. Air-conditioning and Mortality in Hot Weather. *Am J Epidemiol*. 1992; 136:106–116. [PubMed: 1415127]
- Semenza JC, Rubin CH, Falter KH, Selanikio JD, Flanders WD, Howe HL, et al. Heat-Related Deaths during the July 1995 Heat Wave in Chicago. *N Engl J Med*. 1996; 335:84–90. DOI: 10.1056/NEJM199607113350203 [PubMed: 8649494]
- Sheridan SC. A survey of public perception and response to heat warnings across four North American cities: an evaluation of municipal effectiveness. *Int J Biometeorol*. 2007; 52:3–15. DOI: 10.1007/s00484-006-0052-9 [PubMed: 17024398]
- Tamerius JD, Perzanowski MS, Acosta LM, Jacobson JS, Goldstein IF, Quinn JW, et al. Socioeconomic and Outdoor Meteorological Determinants of Indoor Temperature and Humidity in New York City Dwellings. *Weather Clim Soc*. 2013; 5:168–179. DOI: 10.1175/WCAS-D-12-00030.1 [PubMed: 24077420]
- Uejio CK, Tamerius JD, Vredenburg J, Asaeda G, Isaacs DA, Braun J, et al. Summer indoor heat exposure and respiratory and cardiovascular distress calls in New York City, NY, U.S. *Indoor Air*. 2015; doi: 10.1111/ina.12227
- US Department of Commerce N. National Weather Service New York, NY Excessive Heat Page. Available: <http://www.weather.gov/okx/excessiveheat> [accessed 17 March 2016]

- US Department of Commerce N. Weather Forecast Office – New York, NY. 2010. Available: http://www.erh.noaa.gov/okx/wwa_definitions_new.html [accessed 9 July 2013]
- Vandentorren S, Bretin P, Zeghnoun A, Mandereau-Bruno L, Croisier A, Cochet C, et al. August 2003 heat wave in France: risk factors for death of elderly people living at home. *Eur J Public Health*. 2006; 16:583–591. DOI: 10.1093/eurpub/ckl063. [PubMed: 17028103]
- Wheeler K, Lane K, Walters S, Matte T. Heat Illness and Deaths – New York City 2000–2011 (Cover story). *MMWR Morb Mortal Wkly Rep*. 2013; 62:617–621. [PubMed: 23925170]
- White-Newsome JL, Sánchez BN, Jolliet O, Zhang Z, Parker EA, Dvonch JT, et al. Climate change and health: indoor heat exposure in vulnerable populations. *Environ Res*. 2012; 112doi: 10.1016/j.envres.2011.10.008
- White-Newsome JL, Sánchez BN, Parker EA, Dvonch JT, Zhang Z, O'Neill MS. Assessing heat-adaptive behaviors among older, urban-dwelling adults. *Maturitas*. 2011; 70:85–91. DOI: 10.1016/j.maturitas.2011.06.015 [PubMed: 21782363]
- Zacharias S, Koppe C, Mücke H-G. Influence of Heat Waves on Ischemic Heart Diseases in Germany. *Climate*. 2014; 2:133–152. DOI: 10.3390/cli2030133

Figure 1. Distribution of hourly nighttime Temperature in bedrooms by AC Type

* p-value < 0.05. P-values are from bivariate linear multilevel models grouped by household and by sensor.

Figure 2. Outdoor and Indoor heat index values by AC Type, July 2015, with Reference, Heat Wave 1, and Heat Wave 2 periods highlighted.

Figure 3.
Indoor heat index by AC Type during Heat Waves Summer 2015.

Figure 4.
Indoor heat index by Top Floor location during Heat Waves Summer 2015.

Figure 5.

Adjusted Beta Coefficients from Multilevel Models, for Reference period, Heat Wave 1, Heat Wave 2. Predictors are: top floor vs. other floor (topfloor: TRUE); outdoor HI at lag 3 (out_hi_lag3); outdoor HI at lag 24 (out_hi_lag24); indicators for time of day (evening, day, and morning, with night as the reference period); bedroom vs. other room (is_bedroom); presence of AC unit in the room (loc_has_AC: TRUE); and AC type (window, ductless, or central AC versus the reference group of no AC). Black lines indicate the 95% confidence interval. Green diamonds indicate statistical significance at $p < 0.05$.

Figure 6.

Daily mean indoor HI on days following the end of the two heat waves in 2015 compared to other days with similar outdoor HI. Shaded area: middle 50% of data. Outliers defined as points >1.5 times the interquartile range from quartiles 1 and 3.

* p-value < 0.05 from multilevel models adjusting for daily mean outdoor HI, AC type, and top floor location, with household as the grouping variable.

Table 1

Descriptive characteristics of 36 households.

Characteristic	Mean (range)
Total Household Members	2.4 (1–5)
Age of household members (years)	33.6 (2–90)
Rooms in home	3.8 (1–9)
Bedrooms in home	1.9 (1–4)
Floors in building	13.4 (3–32)
Year of construction	1944 (1870–2012)
	Count (percent)
Rent vs. Own	
Rent	25 (69%)
Own	11 (31%)
AC type	
Window unit	24 (67%)
Central	5 (14%)
Ductless	4 (11%)
Portable	1 (3%)
None	2 (6%)
Units in building	
2–4	3 (8%)
10–19	1 (3%)
20–99	18 (50%)
100+	14 (39%)
Primary material of building's exterior	
Brick/Stone	34 (94%)
Glass	2 (6%)
Located on top floor of building	
Yes	4 (11%)
No	32 (89%)
Located on top two floors of building	
Yes	8 (22%)
No	28 (78%)
Strategies to stay cool at home on a very hot day	
Use an air conditioner	33 (92%)
Use an electric fan	20 (56%)
Open the windows	7 (19%)
Close the shades on the windows	22 (61%)
Leave home and go to a cooler location during the day	9 (25%)
Leave home and go to a cooler location during the night	2 (6%)

Table 2

Mean [SD] nighttime bedroom temperature and indoor-outdoor temperature differences by type of AC system, over: a) all nights across Summers 1 and 2; b) hottest 10% of nights.

AC Type	a) Temperature (°C), all summer nights		b) Temperature (°C), hottest 10% of nights [*]	
	Mean [SD]	Indoor-outdoor difference, mean [SD]	Mean [SD]	Indoor-outdoor difference, mean [SD]
None (n = 2)	26.0 [2.0]	<i>4.7 [2.1]</i>	28.3 [0.9]	<i>2.7 [1.9]</i>
Portable [†] (n = 1)	27.4 [1.5]	<i>6.9 [2.3]</i>	28.5 [1.0]	<i>6.4 [1.5]</i>
Window (n = 24)	25.6 [2.1]	<i>4.2 [3.1]</i>	26.6 [2.3]	<i>0.8 [2.9]</i>
Ductless (n = 4)	25.2 [1.7]	<i>3.9 [3.2]</i>	25.7 [2.2]	<i>0.2 [3.1]</i>
Central (n = 5)	24.0 [1.7]	<i>2.8 [2.7]</i>	25.3 [1.3]	<i>-0.4 [2.2]</i>
All Homes	25.5 [2.1]	<i>4.2 [3.1]</i>	26.5 [2.3]	<i>0.8 [2.9]</i>

^{*} Hottest nights defined as the 12am–5am period following days on which outdoor maximum temperature exceeded the 90th percentile of daily maximum temperature over Summers 1 and 2 (31.7°C).

[†] The household with portable AC participated only during Summer 1.