Urban Heat Islets: Street Segments, Land Surface Temperatures, and Medical Emergencies During Heat Advisories

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Objectives. To examine the relationships among environmental characteristics, temperature, and health outcomes during heat advisories at the geographic scale of street segments.

Methods. We combined multiple data sets from Boston, Massachusetts, including remotely sensed measures of temperature and associated environmental characteristics (e.g., canopy cover), 911 dispatches for medical emergencies, daily weather conditions, and demographic and physical context from the American Community Survey and City of Boston Property Assessments. We used multilevel models to analyze the distribution of land surface temperature and elevated vulnerability during heat advisories across streets and neighborhoods.

Results. A substantial proportion of variation in land surface temperature existed between streets within census tracts (38%), explained by canopy, impervious surface, and albedo. Streets with higher land surface temperature had a greater likelihood of medical emergencies during heat advisories relative to the frequency of medical emergencies during non–heat advisory periods. There was no independent effect of the average land surface temperature of the census tract.

Conclusions. The relationships among environmental characteristics, temperature, and health outcomes operate at the spatial scale of the street segment, calling for more geographically precise analysis and intervention. (*Am J Public Health.* Published online ahead of print May 21, 2020: e1–e8. doi:10.2105/AJPH.2020.305636)

The urban heat island effect—or the fact that urbanized areas tend to experience higher temperatures, especially during heat waves—is a prominent public health concern for the 21st century. Climate change is bringing both warmer and more extreme weather throughout the world, increasing the frequency and intensity of heat waves.[1] At the same time, more than half of the world's population now lives in urban areas, meaning more people are exposed to the consequences of these heat waves.[2] People who are exposed to elevated heat levels are vulnerable to a variety of maladies, including heat stroke, the exacerbation of other medical conditions, and even death.[3–6] The urban heat island effect is often treated as a comparison between rural areas and cities, the latter of which are characterized by features that raise temperatures, including increased levels of pavement, decreased coverage by tree canopy, and decreased albedo (i.e., light energy that is reflected rather than absorbed).[7–9] These same environmental characteristics, however, vary within cities, as well—from neighborhood to neighborhood and even block to block. For this reason, we propose the concept of urban heat islets: that the elevated temperatures associated with a city are particularly concentrated in more localized pockets therein, or "islets"; in turn, we hypothesized that the corresponding health consequences of exposure to heat will follow this localized pattern.

The vulnerability of a population to health consequences from a heat wave is often modeled in terms of 3 main considerations: exposure to elevated heat, sensitivity of a population to stressful conditions (e.g., disadvantaged populations are more sensitive), and adaptivity, or the ability to take action to mitigate risk, such as accessing air conditioning.[10] A number of studies have revealed that variations in land surface temperature create differing levels of exposure across a city,[11–13] generating meaningful disparities in the health outcomes of local populations.[14–18] In this article, we narrowed the geographic focus a step further, focusing on individual street segments. Just as factors critical to the urban heat island effect, such as pavement, canopy, and albedo, are more characteristic of some neighborhoods than others, they also vary from street to street within neighborhoods. It thus would seem feasible that exposure to elevated heat might vary at this microspatial scale, creating urban heat islets, where individual streets are substantially warmer than the streets around them. These would then generate health disparities for places no more than a few blocks away from each other. Though other studies on the urban heat island effect have examined census

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tracts and even the smaller census block group, this is the first study, to our knowledge, to test the effects at the spatial resolution of the street segment.

In the current study, we (1) tested for the presence of urban heat islets—that is, meaningful variations in land surface temperature between streets in the same neighborhood—and (2) examined whether these street-level variations in heat resulted in localized differences in vulnerability to health emergencies during heat waves. We did so by combining 4 main data sets for the City of Boston: measures of land surface temperatures and related environmental characteristics from remote sensing for 30-meter-by-30-meter grid cells,[19] reports of medical emergencies from 911 dispatches, contextual information about land use and demographics, and daily weather measurements. Although the focus was primarily on variations in exposure, we additionally tested questions pertaining to sensitivity and adaptivity. Specifically, we examined whether communities with more sensitive populations or with greater challenges in escaping heat are more vulnerable to the elevated temperatures of urban heat islets. We operationalized the former through demographic measures often correlated with higher disease prevalence and thus greater risk during heat waves (e.g., low socioeconomic status, minority race/ethnicity) and the latter through access to air conditioning.

Importantly, determining the health impacts of extreme temperature can be challenging because it requires both an identification of elevated temperature in a particular place and a way to control for the baseline vulnerability of that population to medical emergencies. There are 2 main ways to accomplish this. The first is to model morbidity risk curves across different temperatures and combine them with measured temperature differences to quantify morbidity associated with elevated heat.[14] Here we took a second approach, which is to specifically analyze days with elevated temperatures and control for each location's baseline vulnerability for medical emergencies.[16] Specifically, we focused on the likelihood of medical emergencies on heat advisory days (rather than the more stringent criterion of a heat wave) for each street and controlled for the rate of medical emergencies on that street during the spring, fall, and winter.

METHODS

In this study, we leveraged 4 main data sources. First, the Urban Heat Island Database[7,19] documented land surface temperature and associated environmental characteristics derived from remote sensing data for 30-meter-by-30-meter grid cells across greater Boston. Second, the City of Boston provided 911 dispatches for emergency services, including medical emergencies, from November 1, 2010, to June 17, 2014, a period spanning the initial availability of complete digitized records to the transition to a new recording system. Third, we drew demographic data for census tracts from the US Census's American Community Survey (2010–2014 estimates). Fourth, we accessed National Oceanic and Atmospheric Administration data on temperature and humidity for all days in the study period from the Boston Logan Airport station (#USW00014739). We analyzed all data specifically within the boundaries of Boston, as this is the geographic extent of the 911 dispatches; all other data sets stretch beyond the city.

Geographic Coordination of Data

We coordinated and supplemented the 4 main data sets by using the Boston Area Research Initiative's Geographical Infrastructure for Boston,[20] which links all land parcels (i.e., addresses) identified in the City of Boston's Tax Assessments to US Census Topographically Integrated Geographic Encoding and Referencing (TIGER) line street segments (i.e., the undivided length of street between 2 intersections or an intersection and a dead end, including both sides of the street) and nests them within census tracts. There are 24 718 street segments in Boston's 178 census tracts that fell within the Urban Heat Island database's grid (of 24 891 total). The average street segment in Boston is approximately 75 meters, meaning that most segments passed through (i.e., intersected) multiple grid cells. We thus calculated remote sensing measures for streets in a 3-step process. We first identified every grid cell that each street segment intersected. We then calculated the proportion of the street segment that fell in each of these grid cells (e.g., a street segment might pass through 3 grid cells, with 1 grid cell containing 50% of the street's length and the other 2 each containing 25% of its length). We then used these proportions to calculate weighted versions of the remote sensing measures.

We created the same measures for census tracts by weighting the values for all grid cells contained partly or wholly within the census tract, thereby capturing conditions at locations not touching street segments. More simply, 911 dispatches come with unique identifiers for parcels that link to the Geographical Infrastructure for Boston, based on information provided to the dispatcher; we linked dispatches that could not be matched in this way based on a source latitude–longitude to the nearest street (we attached 94% of cases to a street through these techniques). See Table 1 for descriptive characteristics for all variables.

Measures

The Urban Heat Island Database[19] contained 4 measures for each 30-meter-by-30-meter grid cell in Boston, drawn from multiple sources. We estimated land surface temperature by combining Landsat 5 Thematic Mapper 120 meter and Landsat 7 Enhanced Thematic Mapper+ 60 meter (National Aeronautics and Space Administration and US Geological Survey, Greenbelt, MD) brightness temperature observations in summer intervals (June 1–August 31) from 2002 to 2008. We screened brightness temperature data for clouds[21] and atmospherically corrected for scattering and haze effects.[22] We then converted brightness temperature to land surface temperature and downscaled to 30 meters by estimating emissivity values from 30-meter surface reflectance data.[23] Landsat data were collected at 10:20 AM local time. Note that temperatures were somewhat higher than one might expect as land surface temperature is typically 5 °F to 11 °F higher than the air temperature experienced by people (mean = 98.6 °F [37.0 °C] for streets).

We calculated albedo, or percentage of solar radiation reflected rather than absorbed by land cover, on a scale from 0 to 1 (mean = 0.13 for streets) from combined Landsat (30 meters) and Moderate Resolution Imaging Spectoradiometer (MODIS; 500 meters) observations in summer intervals (June 1–August 31) from 2003 to 2008 at

TABLE 1—Characteristics of Streets and Census Tracts: Boston, Massachusetts

	Mean ±SD or Count (%)
Street segments (n = 24 718)	
Main street	9109 (36.9)
Length	83.02 ±77.22
Predominant land use	
3-family residence	1 769 (7.2)
Mixed single- and 2-family residence	2 514 (10.2)
Commercial	2 025 (8.2)
Single-family residence	3 174 (12.8)
Exempt	1 097 (4.4)
Condominiums	1 452 (5.9)
Mixed-use commercial	483 (2)
No parcels	12 204 (49.4)
Land surface temperature	98.55 ±5.52
% canopy	0.10 ±0.14
Albedo	0.13 ±0.02
% impervious surface	0.77 ±0.23
Medical emergencies (heat advisory days)	0.17 ±1.03
Medical emergencies (non–heat advisory period)	5.9 ±28.57
Census tracts (n = 178)	
Land surface temperature	99.24 ±3.88
% canopy	0.21 ±0.09
Albedo	0.12 ±0.01
% impervious surface	0.67 ±0.15
% Black	0.22 ±0.25
% Latino	0.19 ±0.15
% Asian	0.09 ±0.10
Population density	25 499.4 ±17 929.31
Median household income, $	62 710.22 ±31 908.47
% access to air conditioning	0.27 ±0.21

Source. Main street and land use classification and length were drawn from BARI's Geogrpahical Infrastructure.[20] Land surface temperature, canopy, albedo, and impervious surface coverage were drawn from the Urban Heat Island Database.[19] Medical emergencies were drawn from City of Boston 911 dispatches. Demographic data were drawn from the US Census Bureau's American Community Survey 2010–2014 estimates.

approximately 10:20 AM local time to produce 30-meter raster cells.[24] We obtained percentage of land covered by tree canopy corresponding approximately to the year 2010 from the 30-meter National Land Cover Database (from 0 to 1; mean = 0.10).[25] We aggregated percentage of land area with impervious surface (e.g., pavement) to 30-meter pixels from a 1-meter grid generated by orthophotography data provided by MassGIS for 2015 by mean value per pixel (from 0 to 1; mean = 0.77). We then used geographic overlap of individual grids with each street segment and each census tract to calculate weighted averages of these 4 measures at those geographic scales (see Geographic Coordination of Data).

Heat advisory days. We determined heat advisory days from National Oceanic and Atmospheric Administration weather records using the National Weather Service's guidelines. Specifically, a day's maximum heat index had to rise to or above 105 °F (47.4 °C), per the following formula:

$$
\begin{aligned}
Index_{heat} = & -42.379 + (2.04901523\times T) \\
& + (10.14333127\times rh) \\
& - (0.22475541\times T\times rh) \\
& - \left(6.83783\times10^{-3}\times T^{2}\right) \\
& - \left(5.481717\times10^{-2}\times rh^{2}\right) \\
& + \left(1.22874\times10^{-3}\times T^{2}\times rh\right) \\
& + \left(8.5282\times10^{-4}\times T\times rh^{2}\right) \\
& - \left(1.99\times10^{-6}\times T^{2}\times rh^{2}\right)
\end{aligned} \tag{1}
$$

where T is temperature and rh is relative humidity. There were 25 heat advisory days in Boston over the period studied. These all occurred from June to September.

We tabulated medical emergencies from 911 dispatch records. We used 18 case types, including cardiac arrest, generic illness, and seizures, capturing a broad range of events that might be exacerbated by exposure to elevated heat (see Table A, available as a supplement to the online version of this article at http://www.ajph.org, for complete list). We tabulated emergencies occurring every day on every street to create 2 variables: the count on heat advisory days (total: 4348 medical emergencies) and the count during the non–heat advisory period (January–May and October–December; total: 148 438 medical emergencies). We excluded those occurring during June through September on days without heat advisories to avoid any unaccounted-for lagged effect of a heat advisory.

Indicators of sensitivity and adaptivity. We drew indicators of sensitivity from the US Census's American Community Survey 2010-to-2014 estimates for census tracts, including the racial/ethnic composition of the neighborhood (log-transformed for analyses) and median income. We also included population density as a potential confound with both the number of people who might experience a medical emergency and aspects of urban form. For adaptivity, we calculated the proportion of residential units in each census tract with air conditioning from City of Boston's Property Assessments. Each of these variables served 2 purposes. First, they acted as control variables, particularly accounting for any additional vulnerability to medical emergencies during a heat advisory that is independent of the local land surface temperature. Second, we examined their interaction with land surface temperature to see if they exacerbated or mitigated the impacts of urban heat islets.

Street context. The Geographical Infrastructure for Boston provided information on urban form that may be correlated with both the experience of land surface temperature (i.e., owing to the thermal properties of buildings and spaces)[26] and aspects of sensitivity (i.e., the types or density of people who live in or frequent a place) relative to other streets in a neighborhood. These included its classification as a main street (i.e., determined by MassGIS as being a highway, numbered route, or arterial or collector). A second variable is a 7-group typology based on the land-use categories of its parcels (generated by a cluster analysis of the representation of the 19 land-use types used by the City of Boston's Property Assessor; see Table 1 for list of types and O'Brien et al.[20] for more detail); an eighth category comprises all street segments with no parcels and thus no clear land use (11 685 streets with no buildings, most of which are small or trivial streets).

Analysis

We used hierarchical linear models, nesting each street segment within the tract containing the greatest number of parcels on the street. The models simultaneously tested the effects of factors at each of the geographic scales while holding features of the other level constant, taking the form:

$$(2)\ Y_{jk} = b_{0k} + b_1{}^{*}x_{(1)jk} + \ldots + b_n{}^{*}x_{(n)jk} + r_{jk} \quad \text{street equation}$$

$$(3)\ b_{0k} = \gamma_{00} + \gamma_{01}{}^{*}x_{(01)k} + \ldots + \gamma_{0n}{}^{*}x_{(0n)l} + \mu_{0k} \quad \text{tract equation}$$

where b and γ are parameter estimates for predictors at the street and tract levels, respectively, and r and μ are error terms at the street and tract levels, respectively. Y_{jk} is the value of the dependent variable for the jth street in the kth census tract.

For the first part of the analysis, Y_{jk} was land surface temperature, which was a normally distributed variable, permitting the use of an identity link. The models included main street classification, land use type, and environmental characteristics from remote sensing at the street level, and population density and environmental characteristics at the tract level. For the second part of the analysis, Y_{jk} was the count of medical emergencies on heat advisory days. It featured a highly skewed distribution; only 15% of street segments had any medical emergencies on heat advisory days, and nearly half of those (921 segments, or 48%) had only 1 such event, resulting in an average of 0.17 medical emergencies per street. For this reason, we elected to use a logit link to predict whether a given street experienced at least 1 medical emergency across the heat advisory days in the study period. The models included land surface temperature, main street classification, and land-use type at the street level, and land surface temperature, measures of racial/ethnic composition, median household income, population density, and percentage of homes with access to air conditioning at the tract level. We ran models in the lme4 package in R version 1.1-21 (linear mixed effects modeling using "Eigen" and S4; R Foundation, Vienna, Austria).

The analysis of the distribution of land surface temperature examined all streets, including those with no parcels (n = 24 718 segments). We constrained the analysis of medical emergencies during heat advisories to 12 185 street segments in 166 census tracts that had (1) at least 1 parcel, as those without parcels are typically trivial and unlikely to generate emergencies of any kind, especially because of the geocoding procedure of linking emergency dispatches to the nearest parcel whenever possible; (2) no parcel indicated by the City Property Assessor as being part of a hospital, as such parcels would generate a large number of emergencies on any given date and would not be pertinent to this analysis; and (3) all tract-level indicators available (thereby excluding tracts with minimal population).

RESULTS

Land surface temperature varied substantially across the streets of Boston, ranging from 72.4 °F to 116.4 °F (22.4 °C–46.9 °C). These differences in temperature clustered across regions of the city, with the hottest streets in the downtown district and the surrounding high-density neighborhoods and the coolest in suburban neighborhoods, especially those near major parks (Figure A, available as a supplement to the online version of this article at http://www.ajph.org). Census tracts accounted for 62% of the variation, meaning that 38% of the variance in temperature was between streets in the same neighborhood. This nontrivial amount of variation between neighboring streets indicated the presence of urban heat islets whose temperature was notably higher than immediately surrounding areas. Some of these localized differences were particularly striking, as in a single census tract depicted in Figure B (available as a supplement to the online version of this article at http://www.ajph.org), which featured 2 sets of streets in the warmest quartile—a highway ramp on the east side and a commercial district on the western border—alongside cooler residential streets.

An initial model examined which tracts and streets experienced higher surface temperature (Table 2). Streets in neighborhoods with higher population density (b = 11.67; 95% confidence interval [CI] = 9.16, 14.18) tended to be warmer. Meanwhile, main streets were warmer than nonmain streets in the same neighborhood by just under 0.5 °F (~1 °C; b = 0.46; 95% CI = 0.36, 0.56); independently, commercial streets were the warmest by about 2 °F (3.5 °C; 95% CI = 1.94, 2.26) and streets dominated by single-family housing had lower temperatures than all other land uses by nearly 0.5 °F (~1 °C; 95% CI = –0.63, –0.32).

A second model considered how these patterns might be better understood in terms of 3 more proximate environmental characteristics—tree canopy percentage, impervious surface area percentage, and albedo (i.e., reflected light) percentage (Table 2). Streets with higher canopy coverage and albedo had considerably lower temperatures (canopy: b = –1.47; 95% CI = –1.51, –1.44; albedo: b = –1.45; 95% CI = –1.67, –1.22) whereas streets with more impervious surface coverage had higher temperatures (b = 0.66; 95% CI = 0.64, 0.69). The average percentage of canopy cover in a tract also provided a protective factor, predicting lower temperatures for all streets in the neighborhood (b = –1.21; 95% CI = –1.58, –0.83), and impervious surface area in the tract had the reverse effect across streets (b = 0.35; 95% CI = 0.05, 0.65); we found no such effect for a tract's albedo. The consideration of environmental factors accounted substantially for the associations between land-use patterns and temperature, suggesting that these initial relationships were largely attributable to their different levels of canopy, impervious surface area, and albedo.

Urban Heat Islets and Medical Emergencies

The average heat advisory day had 10% more medical emergencies than the average day in the non–heat advisory periods (174 dispatches vs 158 dispatches per day), indicating that elevated temperature did in fact increase vulnerability across the city. Only 1936 street segments (15%) had any medical emergencies on heat advisory days. A street was more likely to have a medical emergency during a heat advisory if it had a higher land surface temperature than other streets in the same neighborhood (b = 0.024; 95% CI = 0.003, 0.045; odds ratio [OR] = 1.02; see Table 3 for all parameter estimates). By contrast, streets in census tracts with higher average temperatures were not more likely to have medical emergencies during heat advisories (b = –0.11; 95% CI = –0.68,

TABLE 2—Estimated Effects of Street and Tract Characteristics on Land Surface Temperatures of Streets in Boston, Massachusetts, From 2002 to 2008, Drawn From Multilevel Models

	Model 1: Without Environmental Characteristics, b (95% CI)	Model 2: With Environmental Characteristics, b (95% CI)
Street characteristics		
Main street[a]	0.46 (0.36, 0.56)	−0.39 (−0.47, −0.31)
Predominant land use[b]		
3-family mixed	0.64 (0.45, 0.83)	0.35 (0.20, 0.50)
2-family with single-family	−0.08 (−0.24, 0.08)	0.15 (0.02, 0.28)
Pure commercial	2.10 (1.94, 2.26)	1.26 (1.13, 1.39)
Single-family	−0.47 (−0.63, −0.32)	0.07 (−0.05, 0.19)
Exempt	0.06 (−0.15, 0.27)	0.43 (0.27, 0.59)
Condominiums	0.57 (0.37, 0.77)	0.53 (0.37, 0.69)
Mixed commercial	1.79 (1.48, 2.10)	1.11 (0.86, 1.36)
Canopy cover[c]	. . .	−1.47 (−1.51, −1.44)
Albedo[c]	. . .	−1.45 (−1.67, −1.22)
Impervious surface cover[c]	. . .	0.66 (0.64, 0.69)
Tract characteristics		
Population density	11.67 (9.16, 14.18)	0.88 (−1.00, 2.76)
Canopy cover[c]	. . .	−1.21 (−1.58, −0.83)
Albedo[c]	. . .	2.94 (−0.14, 6.02)
Impervious surface cover[c]	. . .	0.35 (0.05, 0.65)

Note. CI = confidence interval. n = 24 718 street segments nested in 178 census tracts. Unstandardized betas drawn from multilevel linear models.

Source. Main street and land use classification and length were drawn from BARI's Geogrpahical Infrastructure.[20] Land surface temperature, canopy, albedo, and impervious surface coverage were drawn from the Urban Heat Island Database.[19] Medical emergencies were drawn from City of Boston 911 dispatches. Demographic data were drawn from the US Census Bureau's American Community Survey 2010–2014 estimates.

[a]A dichotomous variable with "1" equal to variable name.

[b]A series of dichotomous variables reflecting a street's predominant land usage, based on a cluster analysis of land-use types.[20] Streets with no parcels act as the reference group.

[c]Scaled to reflect change in temperature for an increase of 0.1 on a 0–1 scale.

0.46; OR = 0.90). These relationships accounted for the baseline rate of medical emergencies during the non–heat advisory period, demographic characteristics of residents, and features of land use (see Table B, available as a supplement to the online version of this article at http://www.ajph.org, for all results).

Land Surface Temperature, Sensitivity, and Adaptivity

Last, we examined whether the land surface temperature of a street interacted with indicators of sensitivity or adaptivity to either exacerbate or narrow inequalities in medical emergencies during heat advisories (see Table B for all parameter estimates). First, we examined 2 variables that indicated a population with greater prevalence of medical emergencies—median income and proportion Black—and therefore likely greater sensitivity during heat advisories. Neither moderated the relationship between the temperature of the street and the likelihood of a medical emergency during a heat advisory. Second, we examined the percentage of units with air conditioning as a measure of adaptivity, which also did not moderate the relationship between temperature and medical emergencies (based on lack of change in Akaike information criterion).

The final interaction test was with medical emergencies on non–heat advisory days, which is the most direct measure of sensitivity. We compared the effect of land surface temperature on streets with zero medical emergencies during the non–heat advisory period, 1 medical emergency, and 2 or more emergencies. Land surface temperature was more associated with an increased likelihood of medical emergencies on streets that had more medical emergencies during the non–heat advisory period (1 medical emergency: OR = 1.011; 95% CI = 1.007, 1.015; ≥ 2 medical emergencies: OR = 1.019; 95% CI = 1.016, 1.023). In fact, land surface temperature had no discernible effect on streets with no medical emergencies during non–heat advisory periods (OR = 0.999; 95% CI = 0.978, 1.020). This interaction also substantially improved fit of the model (Δ Akaike information criterion = 247).

DISCUSSION

The analyses offer 2 primary observations regarding land surface temperature and health outcomes in Boston. First, temperature varied street by street both within and between neighborhoods, verifying the existence of urban heat islets. The variation was largely explained by the level of canopy coverage, impervious surface cover, and albedo across streets. Second, these microclimatic variations were consequential for health outcomes as streets with higher temperatures generated more medical emergencies during heat advisory days. This took into account the frequency of medical emergencies on each street during non–heat advisory periods. These results are consistent with previous work at coarser geographic scales[11–13] but are the first, to our knowledge, to demonstrate the relationships between environmental context, land surface temperature, and health outcomes at the level of the street segment.

Almost as notable as the findings for street segments were the comparatively limited findings for census tracts. The land surface temperature of a street was heavily explained by its own environment. The total canopy coverage and impervious surface cover of the census tract had a generalized impact on the streets therein, but the effects were substantially lower than those at the street level, especially for impervious surface cover; albedo, meanwhile, had no tract-wide impacts on streets. This makes sense as canopy is

TABLE 3—Effect of Street- and Tract-Level Land Surface Temperature on the Likelihood of 1 or More Medical Emergencies During Heat Advisory Days on Boston, Massachusetts, Streets From 2010 to 2014, Depending on the Frequency of Medical Emergencies on a Street During the Non–Heat Advisory Period

	Street-Level Temperature, OR (95% CI)	Tract-Level Temperature, OR (95% CI)
Main effect	. . .	0.820 (0.468, 1.438)
Interactions		
Medical emergencies (nonheat)		
None	0.999 (0.978, 1.020)	. . .
1	1.011 (1.007, 1.015)	. . .
≥ 2	1.019 (1.016, 1.022)	. . .

Note. CI = confidence interval. The sample size was n = 12 185 street segments with 1 or more parcels nested in 166 census tracts for which all measures were available. Street segments with a parcel classified as part of a hospital are omitted. Model also controls for street's classification as a main street and predominant land use, and tract's racial/ethnic composition, median household income, population density, and percentage of homes with access to air conditioning (see Table B, available as a supplement to the online version of this article at http://www.ajph.org, for full results). Effects are in terms of a rise in temperature by 1 degree. Akaike information criterion of the initial model was 7538. The model including the interaction with previous medical emergencies had an Akaike information criterion of 7291.
Source. Land surface temperature, data were drawn from the Urban Heat Island Database.[19] Medical emergencies were drawn from City of Boston 911 dispatches. Demographic data were drawn from the US Census Bureau's American Community Survey 2010–2014 estimates.

known to have an impact on air temperature, allowing its cooling effect to diffuse spatially, whereas impervious surface cover and albedo have an impact only on the surface. The remaining effect of impervious surface cover might be attributed to a failure of the methodology for calculating street-level measures to capture nearby parking lots and other paved areas that fall just off the street segment. Likewise, the likelihood of medical emergencies during heat advisories was associated only with the land surface temperature of the street segment; the average temperature across the census tract had no predictive power. This suggests that it is the immediate exposure to the heat that matters, rather than the lingering impacts of the heat after moving from a hot environment to a cooler one. Each of these findings suggests that similar relationships found at higher geographic scales[11–18] might have been partially or entirely artifacts of ecological averaging. For example, a census tract might have warmer-than-average streets that in turn have more medical emergencies during heat advisories, but, when aggregated, this would manifest as a correlation at the neighborhood level.

A third insight of the analysis came from the interaction tests, which found that the existing propensity for medical emergencies moderated the effect of land surface temperature during heat advisories. This interaction indicated that the difference between streets with high and low propensities for medical emergencies was exacerbated during heat advisory days. Streets with no medical emergencies during the non–heat advisory period were essentially unaffected by land surface temperature, whereas all other streets were. This might be expected if some of these streets are unlikely to produce a medical emergency at any time, given the nature of land use or the population who lives there. However, a considerable gap also existed between streets that had 1 medical emergency in the non–heat advisory period and those that had 2 or more, indicating that more sensitive areas have an even greater relative risk during heat advisories. This is consistent with previous findings that those who are older or already suffering from chronic disease (e.g., respiratory, cardiovascular) are more likely to experience emergencies during periods of elevated temperature.[27]

Notably, similar interactions with the density of sensitive populations or adaptability in terms of access to air conditioning were not significant. For the former, it might be that the propensity for medical emergencies captures a population's true sensitivity, rendering interactions with demography irrelevant, even if they act as proxies for sensitivity. This does not, however, explain the lack of interaction with access to air conditioning. It is possible that the risk created by elevated temperature on a street during a heat advisory is not entirely mitigated by access to air conditioning, in part because people do not necessarily choose to use it or do so to limited effect.[28] In addition, people do not spend all of their time indoors during heat advisories and thus are still liable to be exposed to high temperatures when leaving the house.

Limitations

There were 2 main limitations to this study that bear noting. The first regards the use of Landsat data. The collection of the Landsat data occurred midmorning local time (10 AM), when later afternoon and evening tend to be the most important times for the medical impacts of heat waves[29]; land surface temperature is distinct from the air temperature that people in fact experience, and the 2 are not necessarily linearly related[30]; and the data collection ended in 2008, whereas the 911 dispatches began in 2010. As such, the temperature measure used here is a proxy for what was experienced by people on each street during the study period, assuming at least some stability in the relationship between the relative variation in land surface temperatures across the city's streets and their air temperatures at different times of day, and between 2008 and 2010. Obviously, there will be some violations of these assumptions (e.g., a few neighborhoods underwent substantial restructuring in that time), though this would have been more likely to create noise in the results. As a consequence, it is likely that the significant relationships observed between temperature and medical emergencies were underestimated rather than inflated. Furthermore, some of this would have been controlled for by including land-use variables in the final models, as they are partially responsible for variations in temperature. It is also worth noting that elevated temperature can be associated with greater release of pollutants, potentially constituting a mediating or parallel mechanism for affecting health.

Second, the analysis was of medical emergencies generated on a street, which does not entirely specify why those individuals were there. It is likely that in many cases they were residents of the street, but they might also have been shopping, working, or passing by. Nor do we know if they were indoors or outside, or what they were doing while they were there. These specific details about the people's activities and how they interact with urban heat islets suggest a next set of questions for future research.

Public Health Implications

Our findings provide clear lessons for policymakers and practitioners regarding the nuanced landscape of heat exposure and vulnerability to medical emergencies on heat advisory days. These might be contextualized within the Centers for Disease Control and Prevention's Climate-Ready States and Cities Initiative 5-step framework for Building Resilience Against Climate Effects, which runs from forecasting climate impacts to developing, implementing, and evaluating a climate impact plan. Urban heat islets are relevant at all stages of this cycle. For example, Landsat data are available globally for forecasting which streets experience the highest temperatures in each neighborhood; this might also be done through original data collection. In either case, leaders can anticipate the localized impacts of heat waves. This information could then inform interventions focused both on mitigating exposure to urban heat islets or supporting adaptability that might undercut this exposure. The former could include directing investment in white and green roofs and increased canopy[31,32] to specifically target heat islets. The latter could entail communicating information directly to the community, encouraging people on those streets to cool their own homes or go to local cooling centers during heat advisories[33]; where such messages are insufficient, governments and nonprofits could intervene directly in these high-risk areas to support residents. Cities might also evaluate how well-placed cooling centers are. These microspatial effects of temperature would call for cooling centers that are distributed more densely and with greater precision; for instance, it would seem ideal that they be near heat islets without forcing people to walk on such streets to access cooling. Throughout, there is an opportunity to leverage the insights here to enable more precise preparation for and response to heat advisories. AJPH

CONTRIBUTORS

D. T. O'Brien developed the hypotheses and led the writing of the article. B. Gridley contributed to hypothesis development and led all data analysis. A. Trlica and J. A. Wang gathered and constructed the sensor data and assisted with data analysis. A. Shrivastava contributed to hypothesis development. All authors contributed to writing and editing of the article.

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CONFLICTS OF INTEREST

The authors report no conflicts of interest.

HUMAN PARTICIPANT PROTECTION

Use of administrative records was permitted by the City of Boston, and all work was approved by the Northeastern University institutional review board.

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