ENVIRONMENTAL HEALTH PERSPECTIVES
ehponline.org

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doi: 10.1289/ehp.0901879 (available at http://dx.doi.org/)
Online 23 June 2010

NIEHS
National Institute of
Environmental Health Sciences

National Institutes of Health
U.S. Department of Health and Human Services

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Running Title: Urban Form and Extreme Heat Events

Keywords: extreme heat events, sprawl, public health, climate change

Acknowledgements: This research was supported by a grant from the National Center for Environmental Health of the U.S. Centers for Disease Control and Prevention. The authors would like to acknowledge the valuable contributions of Jason Vargo in compiling the data used in this study.

None of the authors has any competing financial interests.

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Abstract

Background: Extreme heat events are known to be increasing in frequency in large U.S. cities and are responsible for a greater annual number of climate related fatalities, on average, than any other form of extreme weather. In addition, low density, sprawling patterns of urban development have been associated with enhanced surface temperatures in urbanized areas.

Objectives: This study examines the association between urban form at the level of the metropolitan region and the frequency of extreme heat events over a five decade period.

Methods: We employ a widely published metric of urban form (a "sprawl" index) to measure the association between urban form in 2000 and the mean annual rate of change in extreme heat events between 1956 and 2005.

Results: Our results find the rate of increase in the annual number of extreme heat events between 1956 and 2005 in the most sprawling metropolitan regions to be more than double the rate of increase observed in the most compact metropolitan regions.

Conclusions: The design and management of land use in metropolitan regions may offer an important tool for adapting to the heat-related health effects associated with ongoing climate change.

Background

Extreme heat is an important cause of morbidity and mortality. During an average summer about 400 Americans succumb to extreme heat (Moore et al. 2002). Heat-related deaths tend to occur during heat waves. The 1995 Chicago heat wave killed more than 500 people over five days (Whitman et al. 1997), and the 2003 European heat wave is estimated to have killed more than 70,000 people over a few months (Robine et al. 2008). Risk factors for dying during a heat wave include being very old or very young; being homebound, confined to bed, or unable to care for oneself; being socially isolated; lacking air conditioning; and suffering from psychiatric or cardiopulmonary disease (Bouchama et al. 2007; Naughton et al. 2002). Importantly, most heat wave deaths occur in cities, a long-recognized result of the urban heat island effect (Clarke 1972).

The urban heat island effect is a phenomenon through which cities exhibit higher temperatures than surrounding countryside. This temperature differential, which can exceed 10°C, results from several factors: loss of vegetation with accompanying loss of evapotranspiration; dark surfaces with low albedo (i.e., surface reflectivity), which absorb and then re-radiate heat; building configurations that trap heat; and the concentrated generation of heat from generators, vehicles, and other sources (Oke 1982). Thus, urban form can intensify extreme heat events in cities.

Cities have significantly decentralized over recent decades in a pattern known as urban "sprawl." Sprawl features geographic expansion over large areas, low-density land use, low land use mix, low connectivity, and heavy reliance on automobiles relative to other modes of travel (Squires 2002). This trend has several impacts on health, including reduced physical activity, worsened air pollution, increased risk of motor vehicle injuries, and others (Frumkin et al. 2004). Low density patterns of land use also have been associated with enhanced surface temperatures in cities (Stone and Norman 2006), raising the prospect that sprawl could have an effect on the probability and/or intensity of heat waves.

This is salient because extreme heat events in cities have become more common in recent decades (Gaffen and Ross 1998; Gershunov et al. 2009), a trend that is expected to continue with climate change (Solomon et al. 2007). If urban sprawl contributes to heat waves, this could have implications for heat wave preparedness and could inform decisions about future patterns of urban development.

This paper reports a study of the association between urban form and extreme heat events. Specifically, we test the hypothesis that sprawling patterns of metropolitan land use are more closely associated with the rate of increase in extreme heat events over a five decade period than compact patterns of metropolitan land use.

Methods

This analysis examined the correlation between the sprawl index (based on land use data from 2000) and the rate of increase in extreme heat events over a five-decade period (1956-2005). Each of these variables is defined below, followed by a description of the analytical approach.

Sprawl Index for U.S. Metropolitan Regions

To quantify metropolitan land use patterns, we make use of a sprawl index developed by Ewing et al. (2003a). Based on four spatial elements of physical form combined through principal components analysis, including the centeredness, connectivity, density, and mix of land uses within metropolitan regions, the sprawl index quantifies the spatial configuration and centralized intensity of land use within 83 of the largest U.S. metropolitan regions based on data from the 2000 Census and other national surveys. Previous work has found the index to be a reliable predictor of travel behavior, physical activity, vehicular safety, and air quality across the metropolitan regions for which values are available (Ewing et al. 2003a, Ewing et al. 2003b, Stone 2008; Trowbridge et al., 2008). We include in our study 53 of the 83 regions for which the sprawl index is available and which are included in the National Climate Data Center extreme heat events database, described in the next section. Table 1 describes each component of the composite sprawl index.

Extreme Heat Event Data

The extreme heat event data employed in this study are drawn from a heat stress index maintained for 187 U.S. cities by the National Climatic Data Center (NCDC) of the National Oceanic and Atmospheric Administration (http://lwf.ncdc.noaa.gov/oa/climate/research/heatstress/). The index is based on a measure of apparent temperature (A) that reflects both temperature and humidity and is derived through the following equation: A (°C) = $-1.3 + 0.92T + 2.2e$, where T is ambient air temperature (°C) and e is water vapor pressure (kPa) (Steadman 1984).

Extending the work of Gaffen and Ross (1998), the NCDC heat stress index classifies an extreme heat event as any day in which the minimum, maximum, or average apparent temperature exceeds the 85th percentile of the base period (1961-1990) for each first-order weather station included in the database. Prior work has demonstrated the 85th percentile of apparent temperature to be associated with elevated levels of heat-related mortality (Kalkstein and Davis 1989).

As increasing trends in minimum temperatures have been shown to be most closely associated with adverse health outcomes (Kalkstein and Davis 1989), we quantify the average annual change in minimum temperature heat events over the most recent 50 year period for which data is available, 1956 – 2005. To be included in the dataset, a metropolitan region must have complete data on extreme heat events for 42 of the 50 years in the study period. For each metropolitan region in the dataset, we measure the inter-annual change in the number of extreme heat events and then average these inter-annual changes over the full study period to derive the mean annual change in extreme heat events per region.

Analysis

To test the hypothesis that urban form is associated with the rate of change in extreme heat events, we measure the correlation between the mean annual change in the number of extreme heat events between1956 and 2005 and each region's sprawl ranking in 2000. We then perform a t-test to gauge the statistical significance of a linear association. As our interest is in measuring the influence of the spatial pattern of urban development on extreme heat events rather than population characteristics, we control for the influence of metropolitan population size in 2000 and the rate of metropolitan population growth since 1950 on trends in extreme heat events through the derivation of partial correlation coefficients. It should be noted that geographic variation in regional climates is internally controlled in the extreme heat event measure, which employs region-specific temperature thresholds (i.e., the 85th percentile of a long term temperature trend for each MSA) to identify extreme temperature episodes.

Results

An analysis of trends in excessively hot days over the period of 1956 to 2005 finds the frequency of extreme heat events to be increasing significantly on an annual basis. Extending the trend measured by Gaffen and Ross (1998) by an additional decade, our analysis finds the mean annual number of extreme heat events in major U.S. cities to have increased by 0.20 days per year [95% confidence interval (CI), 0.14–0.26], consistent with 10 more events per city, on average, in 2005 than in 1956.

As illustrated in Figures 1 and 2, the rate of increase in annual extreme heat events over this 50 year period varied significantly by metropolitan form. While the average annual number of extreme heat events increased during this period across all cities, the most sprawling cities (top quartile) experienced a rate of increase in extreme heat events more than double that of the most compact cities (bottom quartile). Between 1956 and 2005, the most compact cities experienced an average increase in the number extreme heat events of 5.6 days [95% confidence interval (CI), 0.9–10.3], while the average annual number of events increased by 14.8 days [95% confidence interval (CI), 7.9–21.7] in the most sprawling cities. Variation in the size or rate of growth in metropolitan populations was not found to diminish the measured statistical association between land use patterns and the rate of increase in extreme heat events in these cities ($r = 0.34$; $p < 0.05$). These findings are consistent with the hypothesis that urban sprawl contributes to EHE frequency.

Discussion and Conclusions

This analysis yields two principal findings. First, the annual occurrence of extreme heat events continues to increase in large metropolitan regions of the United States. This finding, previously demonstrated by Gaffen and Ross (1998) for the period of 1949 - 1995, is extended here to 2005 for 53 metropolitan regions for which both apparent temperature and sprawl index values are available. Second, the rate of increase in extreme heat events is higher in sprawling than in more compact metropolitan regions, an association that is independent of climate zone, metropolitan population size, or the rate of metropolitan population growth.

The mechanisms of extreme heat events in cities are complex. Cities are typically characterized by lower rates of evapotranspiration and lower albedo than rural areas, as a result of reduced vegetative cover and the increased presence of darkly hued bituminous roofing and paving materials. Urban areas are further characterized by higher thermal loads than rural areas, owing to the concentrated presence of generators, air conditioning units, motor vehicles, and other heat sources. While our data do not permit an assessment of the relative contribution of each of these factors, the loss of vegetative cover is well established to be a principal driver of the urban heat island effect (Oke 1982; Stone and Norman 2006). The availability of data on rates of deforestation across the continental United States between 1992 and 2001 enables an assessment of the association between changes in regional vegetative cover over time and extreme heat events during a portion of our study period.

The U.S. National Land Cover dataset provides maps of 21 categories of land cover across the continental United States between 1992 and 2001. For each of the 53 metropolitan regions in our study, we measured the area of forest canopy change over this ten year period and associated it with the sprawl index and the rate of change in extreme heat events. The results of this analysis indicate that the rate of deforestation in the most sprawling metropolitan regions is more than double the rate in the most compact metropolitan regions. For those regions in the top quartile of the sprawl index, 187 km^2 [95% confidence interval (CI), 33.4–339.8] of forest were lost during this decade, compared to 72 km^2 [95% confidence interval (CI), 1.4–143.3] for those regions in the bottom quartile of the sprawl index. This analysis further finds the rate of tree canopy loss to be significantly associated with the rate of increase in extreme heat events over time, when controlling for metropolitan population size and growth rate ($r = 0.30$; $p < 0.05$). Based on this assessment, there is evidence to suggest that sprawling patterns of urban development may be influencing the frequency of extreme heat events through their effects on regional vegetative land cover.

The mechanisms through which extreme heat translate into human health effects are also complex. The incidence of heat-related illness in the United States has been level or slightly declining despite rising average temperatures since roughly 1980, with significant variability depending on incidence of heat waves (CDC 1995; CDC 1999; CDC 2002). This relatively stable mortality rate is presumably due to increased prevalence of protective factors such as air conditioning. Differences in the incidence of heat-related morbidity and mortality between sprawling and compact cities has not been examined, and our data do not allow for such a comparison. It is possible that protective factors have thus far outweighed the influence of urban form on the incidence of heat-related illness. Projecting forward, however, the exposure amplification associated with sprawl may be increasingly important as average ambient temperatures continue to climb and eventually outpace physiologic adaptation thresholds in many regions. Indeed, as Shanghai's urban heat island has grown, there has been an increase in heat-related mortality rates, suggesting the potential for a similar trend in association with urban sprawl (Tan et al. 2010). This question deserves further study.

These findings have clear implications for public health officials and urban planners. Most importantly, there is a need to incorporate land use patterns into models that project climate change impacts over time in urban areas. Anticipating the increased exposure to extreme heat in cities, planners can work to control extreme temperatures through such strategies as preservation of regional green space; the installation of street trees, more reflective surfaces on roads and buildings, and green roofs; and replacement of vehicular travel by transit, walking, and bicycling – features all promoted through more compact design. Models suggest that urban albedo and vegetation enhancement strategies have significant potential to reduce heat-related health impacts (Silva et al. 2010). These risk reduction strategies must be complemented by strategies that identify and protect vulnerable populations, standard elements of heat wave preparedness plans (Bernard and McGeehin 2004).

Such strategies, fortunately, do more than reduce the risk of heat waves. Sprawl is associated with a wide range of adverse exposures, including ozone exceedances

(Stone 2008) and poor water quality (Tu 2008), and adverse health outcomes, from obesity (Ewing 2003b, Lopez 2004) to decreased physical activity (Garden 2009, Rashad 2009) to fatal road traffic injuries (Ewing 2003c, Lucy 2003, Schlundt 2004). Interventions that increase density, green space, and public transit offer considerable co-benefits by reducing air pollution levels and the risk of injuries, and promoting physical activity (Younger et al. 2008). They also increase urban resiliency to other climate-related risks such as severe precipitation events; trees, for example, play a key role in managing stormwater runoff and flooding. Given the increasing frequency and severity of environmental hazards such as heat, urban design strategies will play an important role in reducing vulnerability, promoting health, and building resilience.

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Table 1. Derivation of the sprawl index

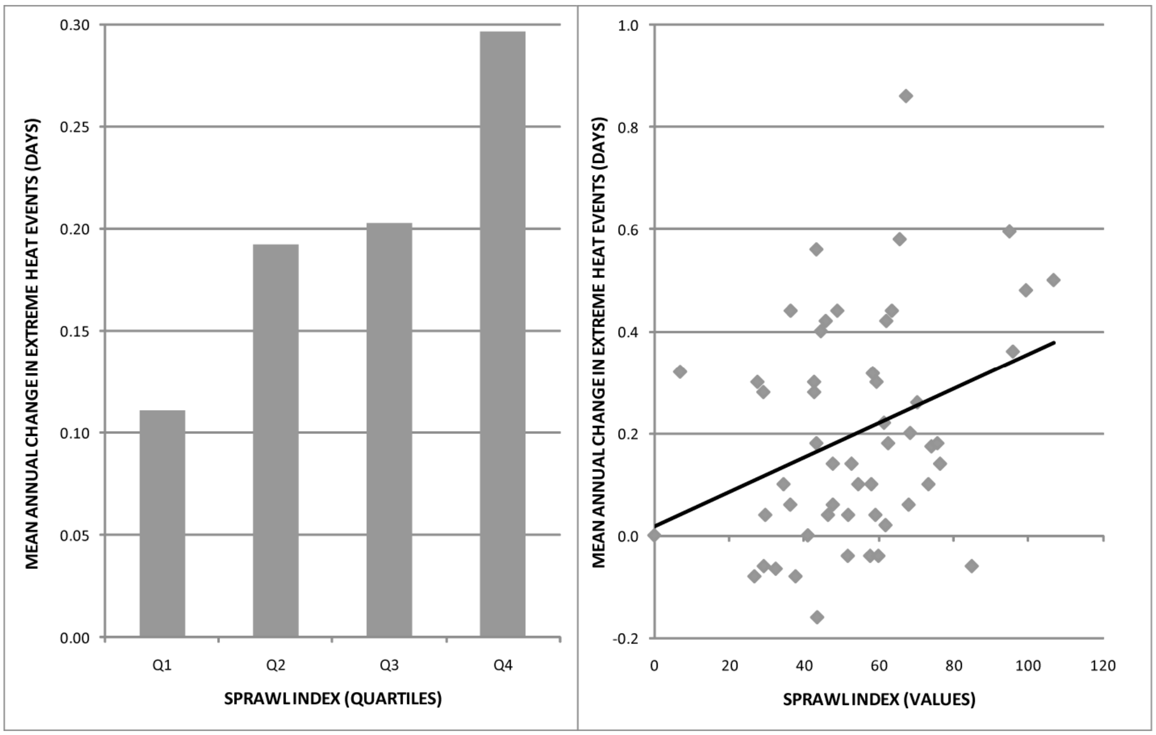
Variable[a]	**Derivation**
Centeredness	The centeredness variable is a measure of the degree of mono or polycentrism within a metropolitan region and is based on three indicators: a density gradient, the percentage of the metropolitan population within a fixed radius of the central business district, and the number of population centers as defined by proximity of census tracts to regional density maxima.
Connectivity	The connectivity variable is a measure of the density of the street network and was based on the average block size and the percentage of blocks less than approximately 500 feet on a side (consistent with the dimension of a traditional urban block). As block size increases, the number of street intersections per unit of area decreases, which serves as an indicator of street network density.
Density	A composite density factor was derived through principal components analysis incorporating measures of gross population density, the proportion of metropolitan populations living at very low or very high densities, and the proximity of census tracts to urban centers.
Land Use Mix	Three elements of land use mix were integrated into a single, composite measure through principal components analysis. These elements include the ratio of jobs to population, the diversity of land uses, and the accessibility of residential uses to non-residential uses at the level of the transportation analysis zone and within a one mile radius.
Sprawl Index	A composite measure of urban compactness or sprawl was developed through an integration of these four urban form factors through principal components analysis.

[a] Each urban form attribute is reported on a scale with a mean value of 100 and a standard deviation of 25 (across the 83 regions included in the Ewing et al. study (2003a)). Higher values of the scores for centeredness, connectivity, density, and land use mix reflect higher intensities of these attributes. Note that the Ewing et al. sprawl index scales in a negative direction (i.e., higher scores denote lower levels of sprawl) and has been modified in this study to scale in a positive direction (i.e., higher scores denote higher levels of sprawl) for ease of interpretation. Table adapted from Stone (2008) and based on description of sprawl index from Ewing et al. (2003a).

Figure 1. Sprawl Ranking and Annual Change in Frequency of Extreme Heat Events by MSA

Figure 2. Annual Change in Frequency of Extreme Heat Events by Sprawl Index


Seattle
Portland
Minneapolis
Milwaukee
Grand Rapids
Detroit
Buffalo
Rochester
Syracuse
Albany
Boston
Providence
Hartford
Cleveland
Akron
Toledo
Chicago
Pittsburgh
Allentown
Philadelphia
Indianapolis
Columbus
Baltimore
St. Louis
Salt Lake City
Colorado Springs
Wichita
San Francisco
Fresno
Las Vegas
Tulsa
Memphis
Knoxville
Greensboro
Norfolk
Raleigh
Greenville
Columbia
Albuquerque
Oklahoma City
Los Angeles
Phoenix
San Diego
Tucson
El Paso
Fort Worth - Arlington
Birmingham
Atlanta
Baton Rouge
Jacksonville
Austin
San Antonio
Tampa
Sprawl Index
< 43
43 - 53
53 - 66
> 66
Average Annual change in EHE days
change <= 0.04 days/year
change 0.04 - 0.3 days/year
change > 0.3 days/year


0.30
0.25
0.20
0.15
0.10
0.05
0.00
MEAN ANNUAL CHANGE IN EXTREME HEAT EVENTS (DAYS)
Q1
Q2
Q3
Q4
SPRAWL INDEX (QUARTILES)
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
MEAN ANNUAL CHANGE IN EXTREME HEAT EVENTS (DAYS)
0
20
40
60
80
100
120
SPRAWL INDEX (VALUES)