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Spatiotemporal trends in human vulnerability and adaptation to heat across the United States

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ABSTRACT

Many studies have connected excess heat to increased human mortality, but comparatively few have examined long-term temporal trends in this relationship. This study examined temporal trends in mortality associated with heat waves in 51 metropolitan areas in the United States for the period 1975–2010, using three different definitions of heat wave. Collectively, all three metrics showed a linear decline in human vulnerability to heat over time, while the number of heat events has generally increased. By the final decade of the study period, only six to seven cities were associated with statistically significant increases in mortality during heat waves. This trend, while generally declining, was variable on an individual metropolitan-area level. Contributing factors to this variability include the occurrence of an extreme heat wave affecting the overall relationship in heat wave and human mortality, and the variability in heat events over a given period. The observed broad adaptation in the human population to extreme heat, however, should be viewed in a cautionary sense. Even with decreased rates in overall human vulnerability, a greater number of heat events is expected in the future given anthropogenic climate change. Combined with an increasing population of susceptible individuals as society ages, human vulnerability to heat will remain a critical challenge for the "anthropocene" in the coming decades.

1. Introduction

Humans have modified the thermal landscape on many spatiotemporal levels, and changes in this thermal landscape have in turn had numerous impacts on human health and well-being. One such impact is exposure to extreme temperatures. Ample epidemiological research has examined the association between heat and negative human-health outcomes. These studies have shown that impacts generally occur once a thermal metric exceeds a certain threshold (e.g., Gosling et al., 2009; Kovats and Hajat, 2008; Basu and Samet, 2002). This relationship is widespread, with people in many locations experiencing negative health effects from direct exposure (e.g., heat stroke), as well as indirect effects on cardiovascular and respiratory systems, on the warmest days (e.g., Gasparrini et al., 2015; Kalkstein and Davis, 1989) across different climate types (e.g., Bobb et al., 2014; Curriero et al., 2002) and levels of development (e.g., McMichael et al., 2008). Assessments have broadly aimed to further understand this relationship by examining how human vulnerability to extreme heat is affected by age, sex, race, health, or socioeconomic status (Gronlund et al., 2014; Bouchama et al., 2007), and how this relationship varies on smaller sub-urban scales (e.g., Hondula et al., 2015).

One long-term historical analysis (Carson et al., 2006) covering the 20th century in London showed an overall decreased sensitivity of society to temperature extremes. This decrease was generally attributed to improved health care, better working conditions, residential climate control, as well as greater awareness of the potential dangers of extreme heat, particularly in the developed world. As data sets have become longer and more readily available, temporal trends in heat-related mortality over recent decades have been studied more frequently (e.g., Ng et al., 2016; Gasparrini et al., 2015; Sheridan and Lin, 2014; Bobb et al., 2014; Kyselý and Plavcová, 2012; Matzarakis et al., 2011; Sheridan et al., 2009; Barnett 2007; Davis et al., 2003b). These studies show a generally decreasing vulnerability to heat in the human population, although considerable variability exists in the magnitude of this trend. Further, while health care and awareness have mostly improved over time, assessing their relative roles is difficult, as well as the potential

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role of heat warning systems that have become more commonplace (Boeckmann and Rohn, 2014).

For several reasons, it is difficult to know how human vulnerability to extreme heat is changing at present, and how it will continue to change into the future (Sheridan and Allen, 2015). Heat events have increased in many areas (Perkins et al., 2012; Smith et al., 2013), and will very likely continue to do so with global anthropogenic climate change (e.g., Lau and Nath, 2012). In many cases, local increases in temperature are related to the urban heat island (e.g., Tomlinson et al., 2011; Zhou and Shepherd, 2010). With steadily increasing numbers of urban areas across the globe, exposure of residents to these urban effects will likely grow (McCarthy et al., 2010). Beyond these larger impacts, individual vulnerability to extreme heat is profoundly affected by one's own physical thermoregulation and ability (or inability) to alter ambient conditions. Therefore, factors such as increased use of air conditioning have modulated human vulnerability to heat over time. These factors clearly involve socio-economic, behavioral, and physiological processes that are difficult to disentangle (Boeckmann and Rohn, 2014).

This study assesses trends and variability in human vulnerability to heat across 51 largest metropolitan areas (all cities with population of at least 1 million in 2010; Fig. 1) in the United States from 1975 to 2010. We evaluate the spatiotemporal trends in human vulnerability during long heat events over the full period of record, with one of the longest continuous data sets of daily mortality available. Within this broad goal, we focus on several uncertainties in the current literature base: the pace of temporal trends in heat vulnerability, the impact of the choice of periods of analysis, acclimatization, and the role of the extreme heat wave. Specifically, with our analysis we aim to answer the following questions: how human vulnerability to heat events has changed over time, what factors can be associated with the observed trends in human vulnerability across space and time, and how the trends in human vulnerability guide predictions into the future, given changing human-Earth dynamics.

2. Research framework, data, and methods

2.1. Data on human mortality from heat events

While morbidity outcomes, such as ambulance calls or hospitalizations, are increasingly studied (e.g., Fuhrmann et al., 2016; Schmeltz et al., 2015; Saha et al., 2015; Bassil et al., 2010), the majority of heat-related health assessments have involved data on human mortality (Kovats and Hajat, 2008). These data are readily available, and they present an accessible metric to denote the long-term vulnerability of the human population to extreme heat. The relationship between heat and health is typically assessed via mortality data from all causes or critical subsets such as cardiovascular disease, (Kovats and Hajat, 2008), since analyzing only deaths that are officially described as heat-related (ICD10: ×30) significantly underestimate heat's true toll (e.g., Dixon et al., 2005).

Nevertheless, these broad aggregations create uncertainty based on how 'expected' mortality is determined. With the well-established seasonal cycle in overall mortality (i.e., the winter peak), for example, subtracting the seasonal cycle leaves ambiguity in understanding the specific impact of early-season heat waves. These heat waves occurring early in the warm season may have greater impacts on people than events later in the year (e.g., Nairn and Fawcett, 2014; Barnett et al., 2012; Sheridan et al., 2009). Rocklöv et al. (2009) suggested that seasonal acclimatization may explain

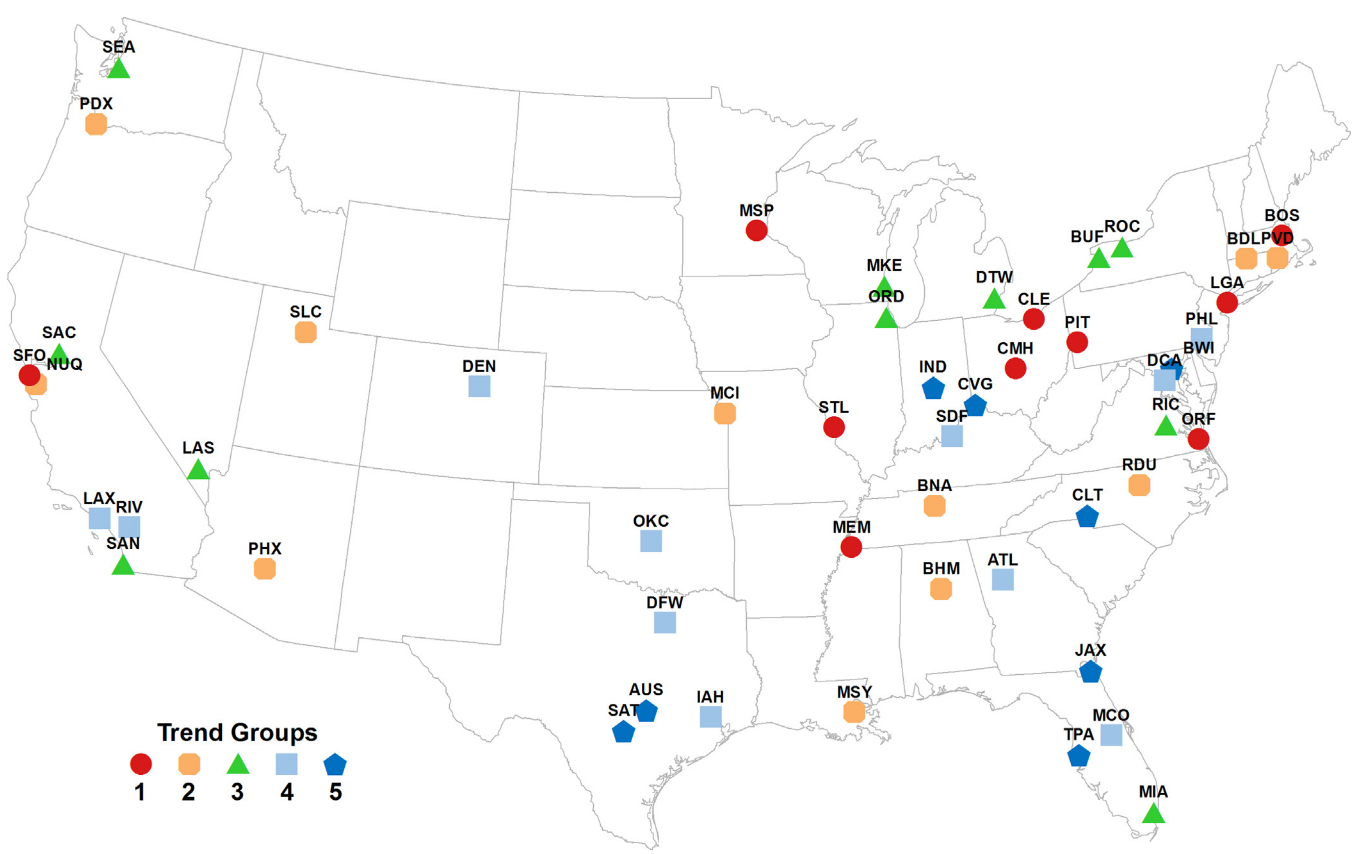

Fig. 1. Map of the 51 metropolitan areas in this research, and their temporal trend groupings discussed in Section 3.2. See Table 1 for the names of cities denoted by abbreviations.

this seasonal variation in impact, as well as the fact that there may be fewer susceptible people later in the season, if the most vulnerable have already died.

On shorter time scales, data on human mortality exhibits variability when examined for periods during and after heat events. Many studies have added a heat-wave effect, in which a longer heat event produces a response exceeding what would generally be expected if each day were examined individually (e.g. Turner et al., 2013; Rocklöv et al., 2012; Anderson and Bell, 2011). Also, in many cases, mortality decreases below expected levels after a heat event. This decrease suggests that some of those who died in a heat wave may have died soon anyway, and thus their deaths were slightly forwardly 'displaced' (e.g. Saha et al., 2014). To assess the delayed and cumulative impacts of heat, time series analyses such as distributed-lag non-linear models (DLNM; Gasparrini and Armstrong, 2011) have been widely used in recent years. Estimates of displacement of short-term mortality vary widely (Baccini et al., 2013; Toulemon and Barbieri, 2008; Kaiser et al., 2007; Hajat et al., 2006).

In this research, the National Center for Health Statistics for the United States provided data for human mortality for the period 1975–2010. Deaths were binned to daily all-cause totals at the county level. We analyzed daily totals for categories of "all ages" and "only those 65 and older", to account for population aging over the period of the study. We calculated daily totals for metropolitan areas, as defined by the United States Census in 2010. All days in which mortality was at least four standard deviations above the expected value (calculated using the splines discussed in Section 2.3 below) were examined for singular, non-heat related events. This procedure removed from analysis a total of 28 days across the 51 cities (16 days related to airplane crashes; 3 days each to terrorism, tornado, and fire; 2 days to building collapses; and 1 day each to a bus crash, ferry sinking, and hurricane). Further, due

Table 1
The 51 metropolitan areas used in this research, their 2010 populations, sample sizes of heat-wave days for each of the three definitions, and apparent temperature threshold values (°C).

Metropolitan area	Airport	Population	Sample sizes			Temperature Threshold	
	Code	(millions)	NF14	AT95	AT97	95th	97th
Atlanta	ATL	5.3	78	260	136	29.6	30.4
Austin	AUS	1.7	79	223	111	32.8	33.3
Baltimore	BWI	2.7	72	207	112	28.6	29.5
Birmingham	BHM	1.1	80	247	126	30.8	31.5
Boston	BOS	4.5	71	217	99	24.5	25.9
Buffalo	BUF	1.1	75	239	113	23.5	24.7
Charlotte	CLT	2.2	77	210	118	29.6	30.5
Chicago	ORD	9.5	75	220	116	26.5	27.9
Cincinnati	CVG	2.1	74	232	127	27.6	28.7
Cleveland	CLE	2.1	75	219	107	25.2	26.4
Columbus	CMH	1.9	76	238	119	27.0	28.2
Dallas	DFW	6.4	82	262	126	32.5	33.3
Denver	DEN	2.5	73	215	87	22.4	23.2
Detroit	DTW	4.3	76	233	117	25.5	26.7
Hartford	BDL	1.2	71	214	102	25.7	27.0
Houston	IAH	5.9	73	243	114	33.4	34.0
Indianapolis	IND	1.9	78	239	123	27.5	28.8
Jacksonville	JAX	1.3	64	182	89	31.5	32.1
Kansas City	MCI	2.0	80	274	132	29.3	30.6
Las Vegas	LAS	2.0	86	298	141	32.1	33.2
Los Angeles	LAX	12.8	85	270	136	22.4	23.2
Louisville	SDF	1.2	81	265	133	29.7	30.8
Memphis	MEM	1.3	85	262	129	32.0	33.0
Miami	MIA	5.6	67	190	92	32.6	33.1
Milwaukee	MKE	1.6	76	189	84	24.5	26.0
Minneapolis	MSP	3.3	75	218	99	25.5	26.9
Nashville	BNA	1.7	80	241	132	29.7	30.7
New Orleans	MSY	1.2	72	232	111	33.0	33.7
New York	LGA	19.6	75	232	102	27.1	28.3
Oklahoma City	OKC	1.3	83	284	136	30.2	31.0
Orlando	MCO	2.1	59	167	69	31.6	32.2
Philadelphia	PHL	6.0	74	230	113	28.3	29.3
Phoenix	PHX	4.2	79	215	95	36.1	36.8
Pittsburgh	PIT	2.4	79	256	113	25.3	26.4
Portland	PDX	2.2	72	172	95	21.6	22.9
Providence	PVD	1.6	75	234	103	25.0	26.4
Raleigh	RDU	1.1	74	238	121	29.7	30.4
Richmond	RIC	1.2	76	225	106	29.7	30.5
Riverside	RIV	4.2	85	297	143	27.7	28.6
Rochester	ROC	1.1	75	217	116	24.1	25.5
Sacramento	SAC	2.1	71	186	99	25.6	26.8
Saint Louis	STL	2.8	74	262	132	30.7	31.7
Salt Lake City	SLC	1.1	81	266	135	24.5	25.5
San Antonio	SAT	2.1	70	189	87	32.3	32.8
San Diego	SAN	3.1	87	345	186	24.0	24.9
San Francisco	SFO	4.3	65	131	73	17.8	18.9
San Jose	NUQ	1.8	60	129	64	21.9	23.1
Seattle	SEA	3.4	72	174	91	19.1	20.3
Tampa	TPA	2.8	66	164	77	32.5	33.0
Virginia Beach	ORF	1.7	76	217	95	29.6	30.5
Washington	DCA	5.6	77	235	94	29.7	30.7

to incomplete data, all of 1990 was eliminated for the metropolitan areas of Austin, Dallas, Houston, and San Antonio. All of 2008 was also omitted for the metropolitan area of Atlanta due to irregularities in county coding.

2.2. Weather data and determination of heat wave

Several different thermal metrics may provide assessments of exposure to heat. These metrics include air temperature (e.g., Linares et al., 2016), an apparent-temperature metric such as Heat Index or Humidex (e.g., Willers et al., 2016; Anderson and Bell, 2011), physiological heat load indices such as the UTCI (e.g., Burkhart et al., 2015), and synoptic categorizations such as the Spatial Synoptic Classification (e.g., Urban and Kyselý, 2014; Hondula et al., 2014).

This study uses the Steadman (1984) apparent temperature (AT) variable, calculated from hourly temperature, dew point, and wind speed data downloaded from the National Centers for Environmental Information (NCEI; formerly the National Climatic Data Center). We chose an airport to represent each metropolitan area (Table 1). The Steadman AT is among the most commonly used metrics for heat-related studies (Anderson et al., 2013). While in some locations, temperature alone is appropriate for heat warnings, the AT forms the basis for many similar metrics used in heat warnings. The AT accounts for humidity, which allows comparison across the diverse climate zones of the US. Because the relationship between weather and human health is stronger with daytime AT in some areas and nighttime AT in others (e.g., Davis et al., 2016), we used a daily mean AT to account for these differences. As NCEI controls the quality of the data, we did not process the data further, except to classify as missing any AT observation for which one or more of the individual variables used in its calculation was absent.

It has long been understood that thresholds for health impacts from heat vary spatially, with generally higher thresholds observed in warmer locations. Thus, to standardize assessment across all metropolitan areas, we converted all daily mean ATs to percentile values relative to the full 1975–2010 period of analysis. Actual AT threshold values vary widely across metropolitan areas, given the diverse climate of the US. For instance, the 95th percentile of daily mean AT is below 20 °C in Seattle and San Francisco, and ranges up to 36.1 °C in Phoenix and 33.4 °C in Houston. Because greater impacts occur with longer heat events (e.g. Sheridan and Lin, 2014), a minimum duration threshold is also common to define a heat event, typically ranging from two to four days (e.g. Lee et al., 2016).

For comparison purposes, we used three different methods to identify the days for a heat wave:

- The third (or greater) consecutive day in which the AT is at the 95th percentile or greater (AT95);
- The third (or greater) consecutive day in which the AT is at the 97th percentile or greater (AT97); and
- A heat wave day defined by an *excess heat factor* in Nairn and Fawcett (2014; NF14). The excess heat factor is defined as the exceedance of the previous three-day mean AT above the 95th percentile threshold, multiplied by the difference between the three-day mean AT and the mean of the prior 30 days. Nairn and Fawcett (2014) provide the full equation. Effectively, this equation favors extended hot periods that are preceded by cooler conditions.

2.3. Calculating relative risks of mortality

- Relative risks of mortality were calculated for:
- Each of the 51 metropolitan areas;
- All-ages mortality and mortality of only those 65 and older;
- The entire 36-year period of 1975–2010, and 28 rolling 9-year periods (1975–1983, 1976–1984 . . . 2002–2010); and
- The three different definitions of heat event listed above.

We calculated relative risks with a distributed-lag non-linear model that assesses the cumulative impact of weather on health outcome (Gasparrini et al., 2010)., using the dlnm package in R. The resulting model is:

$$\text{Log}\,(\textit{Mortality}) = \text{intercept} + \textit{heat-wave day} + \text{ns}\,(\textit{time}),\ \text{where:}$$

- *mortality* is the daily mortality total, either for all ages or only those 65 or over, assuming a Poisson distribution of counts;
- ns (*time*) is a natural spline fit to the period with nine degrees of freedom per year, to account for long-term changes in baseline mortality as well as seasonal variations. Nine degrees of freedom is somewhat higher than the typical range of other DLNM studies

Table 2
All-age relative risks for the 51 metropolitan areas for the three heat-wave metrics, and their 95% confidence intervals. Gray values are not statistically significant.

	AT95	AT97	NF14		AT95	AT97	NF14
All metros	**1.087 (1.073,1.101)**	**1.123 (1.098,1.148)**	**1.122 (1.097,1.146)**	Minneapolis	1.053 (1.002,1.106)	1.095 (1.009,1.188)	1.123 (1.027,1.228)
Atlanta	1.023 (0.982,1.065)	1.057 (0.999,1.118)	1.039 (0.967,1.117)	Nashville	1.084 (1.023,1.150)	1.124 (1.042,1.212)	1.063 (0.963,1.173)
Austin	1.052 (0.963,1.149)	1.074 (0.943,1.224)	1.081 (0.939,1.245)	New Orleans	1.070 (1.010,1.134)	1.077 (0.991,1.171)	1.083 (0.981,1.196)
Baltimore	1.064 (1.013,1.117)	1.066 (0.995,1.141)	1.172 (1.081,1.271)	New York	1.101 (1.081,1.122)	1.219 (1.181,1.258)	1.252 (1.208,1.297)
Birmingham	1.144 (1.079,1.212)	1.187 (1.106,1.275)	1.268 (1.161,1.384)	Oklahoma City	1.086 (1.025,1.152)	1.098 (1.016,1.185)	1.102 (0.997,1.219)
Boston	1.076 (1.039,1.115)	1.133 (1.077,1.193)	1.138 (1.062,1.218)	Orlando	1.070 (0.997,1.148)	1.062 (0.961,1.173)	1.032 (0.926,1.150)
Buffalo	1.087 (1.024,1.155)	1.115 (1.017,1.222)	1.108 (0.995,1.235)	Philadelphia	1.078 (1.046,1.112)	1.117 (1.069,1.166)	1.085 (1.030,1.144)
Charlotte	0.968 (0.896,1.047)	0.968 (0.877,1.067)	1.003 (0.896,1.123)	Phoenix	1.097 (1.046,1.151)	1.182 (1.099,1.272)	1.081 (1.004,1.164)
Chicago	1.096 (1.065,1.128)	1.134 (1.093,1.177)	1.244 (1.186,1.304)	Pittsburgh	1.061 (1.021,1.103)	1.089 (1.027,1.154)	1.078 (1.010,1.150)
Cincinnati	1.096 (1.042,1.154)	1.173 (1.095,1.257)	1.071 (0.980,1.170)	Portland	1.201 (1.118,1.290)	1.302 (1.183,1.433)	1.212 (1.099,1.336)
Cleveland	1.042 (0.990,1.098)	1.060 (0.985,1.141)	1.068 (0.983,1.162)	Providence	1.140 (1.082,1.200)	1.266 (1.162,1.380)	1.318 (1.187,1.464)
Columbus	0.982 (0.924,1.043)	0.931 (0.854,1.013)	0.930 (0.836,1.035)	Raleigh	1.073 (0.973,1.183)	1.100 (0.950,1.273)	0.971 (0.823,1.146)
Dallas	1.043 (1.008,1.079)	1.079 (1.029,1.132)	1.040 (0.978,1.105)	Richmond	1.019 (0.949,1.094)	1.035 (0.922,1.163)	1.044 (0.926,1.177)
Denver	1.110 (1.042,1.182)	1.070 (0.973,1.176)	0.992 (0.902,1.091)	Riverside	1.055 (1.012,1.099)	1.060 (0.997,1.127)	1.080 (1.003,1.163)
Detroit	1.149 (1.108,1.192)	1.210 (1.150,1.273)	1.152 (1.082,1.227)	Rochester	1.149 (1.065,1.239)	1.047 (0.940,1.166)	1.021 (0.901,1.157)
Hartford	1.106 (1.034,1.182)	1.143 (1.033,1.264)	1.268 (1.119,1.438)	Sacramento	1.159 (1.086,1.236)	1.177 (1.081,1.282)	1.055 (0.954,1.167)
Houston	1.014 (0.977,1.052)	1.056 (1.005,1.109)	1.008 (0.947,1.074)	Saint Louis	1.077 (1.039,1.117)	1.141 (1.085,1.200)	1.188 (1.114,1.268)
Indianapolis	1.075 (1.013,1.141)	1.113 (1.027,1.206)	1.166 (1.050,1.294)	Salt Lake City	1.020 (0.949,1.096)	1.053 (0.953,1.162)	0.995 (0.883,1.120)
Jacksonville	1.090 (1.005,1.181)	1.073 (0.963,1.195)	1.229 (1.083,1.395)	San Antonio	1.016 (0.949,1.087)	1.014 (0.913,1.126)	1.033 (0.911,1.170)
Kansas City	1.096 (1.051,1.142)	1.180 (1.108,1.256)	1.333 (1.221,1.454)	San Diego	1.029 (0.987,1.072)	1.053 (0.994,1.115)	1.088 (1.010,1.173)
Las Vegas	1.019 (0.967,1.073)	1.019 (0.945,1.099)	1.035 (0.949,1.130)	San Francisco	1.068 (1.008,1.132)	1.125 (1.039,1.217)	1.009 (0.932,1.094)
Los Angeles	1.094 (1.070,1.118)	1.147 (1.113,1.182)	1.141 (1.098,1.186)	San Jose	1.248 (1.131,1.377)	1.465 (1.259,1.704)	1.134 (0.989,1.299)
Louisville	1.053 (0.995,1.113)	1.015 (0.934,1.104)	0.974 (0.882,1.076)	Seattle	1.176 (1.108,1.248)	1.270 (1.167,1.382)	1.139 (1.047,1.239)
Memphis	1.169 (1.109,1.232)	1.252 (1.162,1.349)	1.369 (1.255,1.493)	Tampa	1.013 (0.964,1.064)	1.036 (0.965,1.112)	1.011 (0.941,1.086)
Miami	1.039 (1.001,1.078)	1.033 (0.981,1.087)	1.010 (0.954,1.070)	Virginia Beach	1.001 (0.941,1.066)	1.054 (0.954,1.164)	1.080 (0.970,1.203)
Milwaukee	1.099 (1.028,1.176)	1.228 (1.103,1.368)	1.257 (1.125,1.404)	Washington	1.051 (1.007,1.098)	1.073 (1.002,1.149)	1.065 (0.994,1.142)

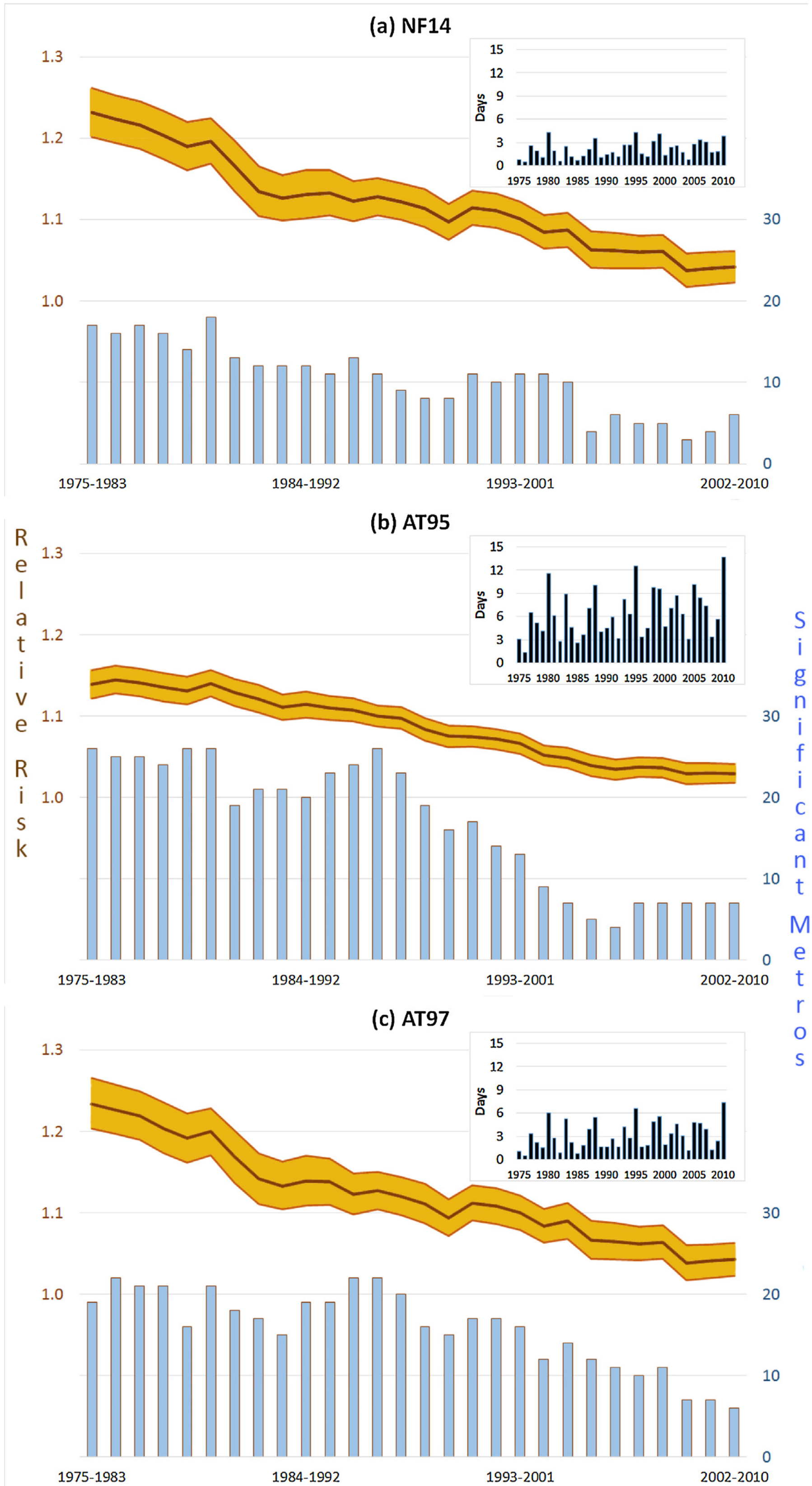

Fig. 2. Pooled relative risk (RR) of all-age mortality on heat-wave days (defined for each of the three heat wave definitions) compared to non-heat wave days across all regions in the study, shown in brown line with 95% confidence interval in gold. Blue bars represent the number of individual cities that are statistically significant at a = 0.05. Inset box shows mean number of heat-wave days by year across all 51 metropolitan areas.

(e.g. Rocklöv et al., 2012; who use six). Since heat events in some places occur outside meteorological summer, however, properly modeling the season cycle was necessary. Allowing nine degrees of freedom were the fewest for which the residuals were not temporally autocorrelated, hence properly modeling seasonal changes; and

- *heat-wave day* refers to an array of binary variables created for each of the three definitions for heat-wave days. The occurrence of a heat-wave day is noted by a 1, and all other days by a 0.

Relative risks (RR) were thus calculated to assess human vulnerability to heat waves, with the reference cases being non-heat-wave days. We set the model to examine the cumulative impact of heat over a 10-day period. The model fit the lagged effects of heat to a natural spline with 4° of freedom. We performed sensitivity analyses on lengthening the lag period and changing the number of degrees of freedom, with negligible impact upon the statistical significance of the results detected. We considered periods of analysis shorter than nine years, but in many cases, too few events were available for statistically robust results. Days with missing mortality data (the cases described in Section 2.1) and days with missing AT data (fewer than 1 percent of all days at all stations) were omitted from analysis.

3. Results

3.1. Overall human vulnerability to heat and temporal trends in heat-wave days and mortality

The three heat-wave definitions are associated with different sample sizes (Table 1); as expected, AT95, by definition the most inclusive, identified the greatest number of heat-wave days ($\mu = 6.3$ days per station-year), with smaller sample sizes using the AT97 (3.1 days per station-year) and NF14 (2.1 days per station-year) metrics. Given that definitions of heatwave are relative to the local climate, sample sizes are roughly similar from city to city. Where variability exists, particularly using the NF14 definition, larger sample sizes are generally found at more continental locations, indicating that unusually hot weather tends to *persist* longer at these places.

The overall all-age mortality response to the three heat-wave metrics varies inversely with the sample sizes (Table 2). The largest overall risks are associated with AT97 (RR = 1.123) and NF14 (RR = 1.122) heat events, and lesser risk with AT95 (RR = 1.087). A greater number of metropolitan areas have statistically significant increases using AT95, however, due to sample size. Spatially, across all definitions, greater risk is generally seen across metropolitan areas in the northeastern, midwestern, and west coast areas than at inland locations, although exceptions exist.

Meta-analysis of the relationship between heat and all-age mortality across all 51 cities showed a clear, collective decline (Fig. 2) using all three heat-wave metrics. This trend falls from a relative risk of 1.23/1.14/1.23 for NF14/AT95/AT97 days in 1975–1983 to 1.04/1.03/1.04 in 2002–2010. The decrease is generally linear, although the slope decreases towards the end of the record. The largest year-on-year national decreases occurred in the first nine-year period when a substantial regional-to-national heat wave was not included (e.g., after 1980 and 1995). Fewer metropolitan areas have statistically significant results over time as well, falling from 18 to 26 (depending on heat-wave definition) of the 51 metropolitan areas at their peak, to only 6–7 having statistically significant results by the 2002–2010 period. Analysis of the 65-and-over subset of the data yielded similar results (Fig. A1). Vulnerability of this 65-and-over group was somewhat higher than the all-age vulnerability towards the beginning of the period of study, with a convergence of relative risks by the end. Due

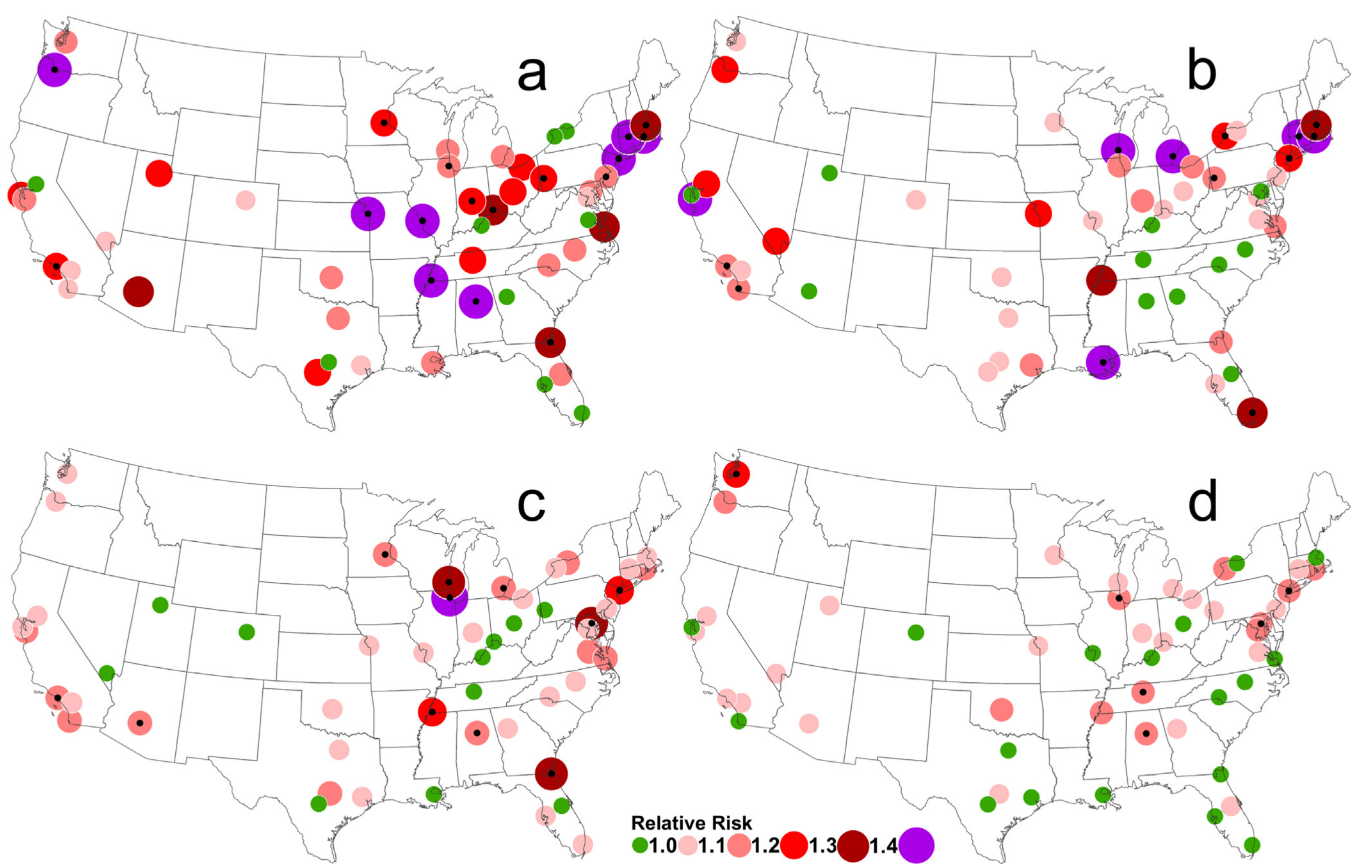

Fig. 3. Relative risks of all-age mortality on heat-wave days using the NF14 definition, by metropolitan area for (a) 1975–1983; (b) 1984–1992; (c) 1993–2001, (d) 2002–2010. Statistically significant values are shown with a dot in the center of the circle.

to the similarity of the results, we discuss only the all-age mortality subset below.

These trends of decreased human vulnerability to heat have occurred alongside a an increase in the number of heat events during the period of analysis, regardless of which metric is used. The linear slope upwards is from 14 to 16% per decade across the three heat-wave definitions. Very substantial interannual variability exists, however, with notable hot summers such as 1980, 1995, and 2010, and relatively cool summers such as 1976 and 2004, standing out.

3.2. Spatiotemporal changes in heat vulnerability

The overall decline in human vulnerability to heat is spatially broad, affecting all regions of the country (Figs. 3–5). Relative risks in the 1975–1983 period exceed 1.2 in many metropolitan areas, particularly the northeastern megalopolis along with a broad area of the southeast and lower Midwest that was affected by the 1980 heat wave. The high vulnerability in these latter areas recedes in later periods, with a greater number of metropolitan areas not showing a statistically significant increase in mortality on heat-wave days. Across the upper Midwest and northeast, many metropolitan areas show significant heat vulnerability for longer periods, particularly those areas affected by the 1988 and 1995 heat events. By 2002–2010, almost all metropolitan areas show a considerable reduction in human vulnerability to heat, with the exception of Seattle.

It might be expected that any variations in trends can be grouped, at least partially, by geography due to climate types. Our results, however, do not support this expectation. The likely explanation is the complexity of human heat vulnerability in cities, which is affected not only by climate, but also differences in socioeconomic, demographic, housing, and infrastructure factors. We heuristically identified four patterns for trends in vulnerability according to the NF14 metric. We then created objective criteria to classify each metropolitan area based on its trend (Fig. 6):

1. A generally consistent decline denoted by more than 50% of the year-to-year changes being negative, and the overall trend was also negative;
2. A large decrease in vulnerability during the late 1980s or early 1990s, followed by relatively little change, as denoted by a higher average vulnerability before 1988 than after 2000, and a range in relative risk of at least 0.5 before the year 2000;
3. A period of consistently increasing vulnerability through the late 1980s and mid 1990s, usually followed by a decline or rebound in vulnerability before the year 2000. Also, relatively little change over the last decade, as denoted by less maximum vulnerability during the periods before 1988 and after 1999 than during the years between;
4. Little variability and negligible trends where all locations consistently showed moderate year-to-year changes and an overall range in relative risk less than 0.3; and
5. Locations that do not fit the other four groups.

The groups are somewhat different for the AT95 and AT97 metrics, but the specific group memberships are less important than the understanding that considerable variability exists in the trends among locations. It is helpful to show how individual cities can display trends that are not very similar to the composite trends comprised of all metropolitan areas. Further, the graphs of individual cities show that few locations offer any contradiction

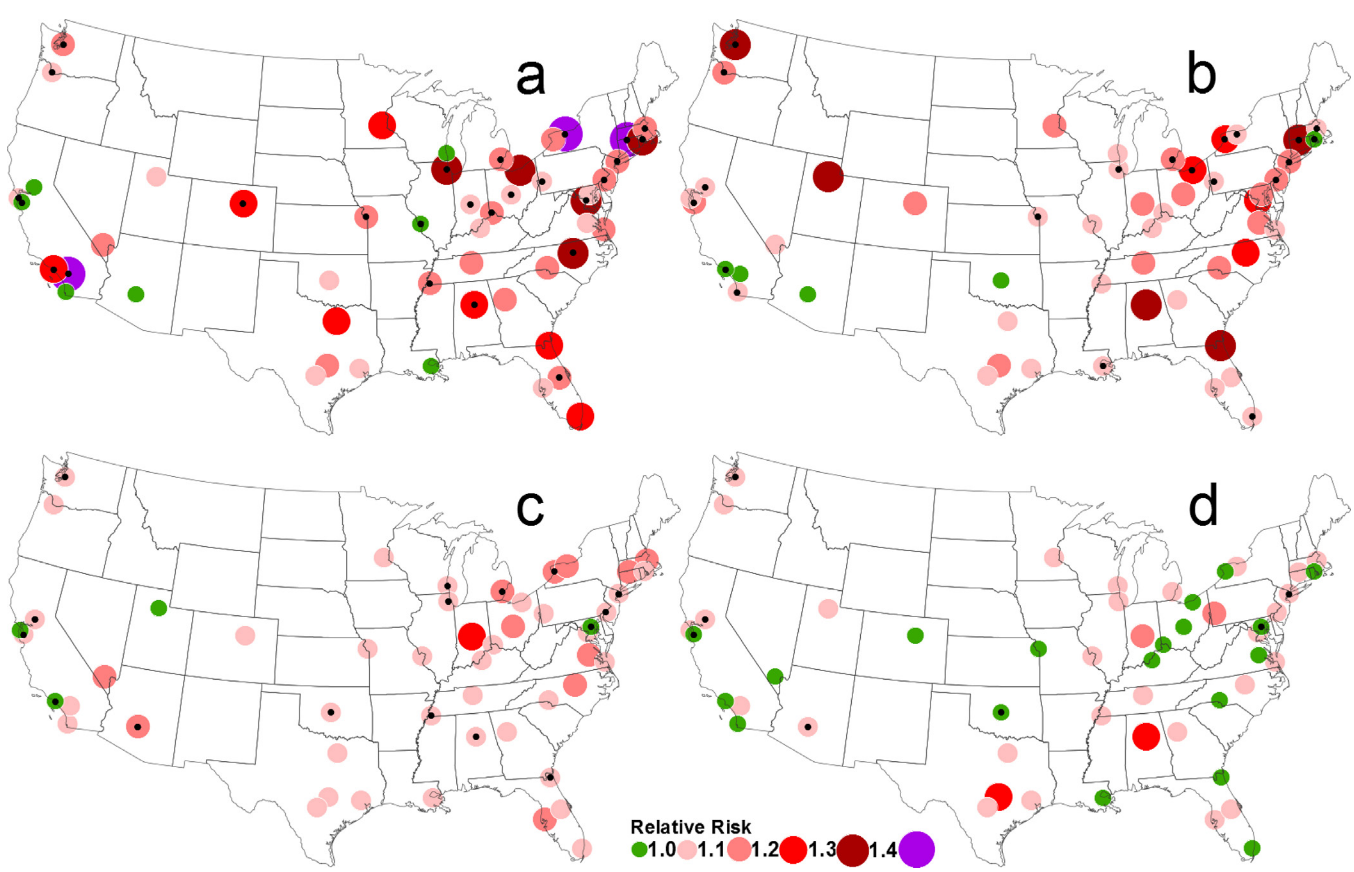

Fig. 4. Relative risks of all-age mortality on heat-wave days using the AT95 definition, by metropolitan area for (a) 1975–1983; (b) 1984–1992; (c) 1993–2001, (d) 2002–2010. Statistically significant values are shown with a dot in the center of the circle.

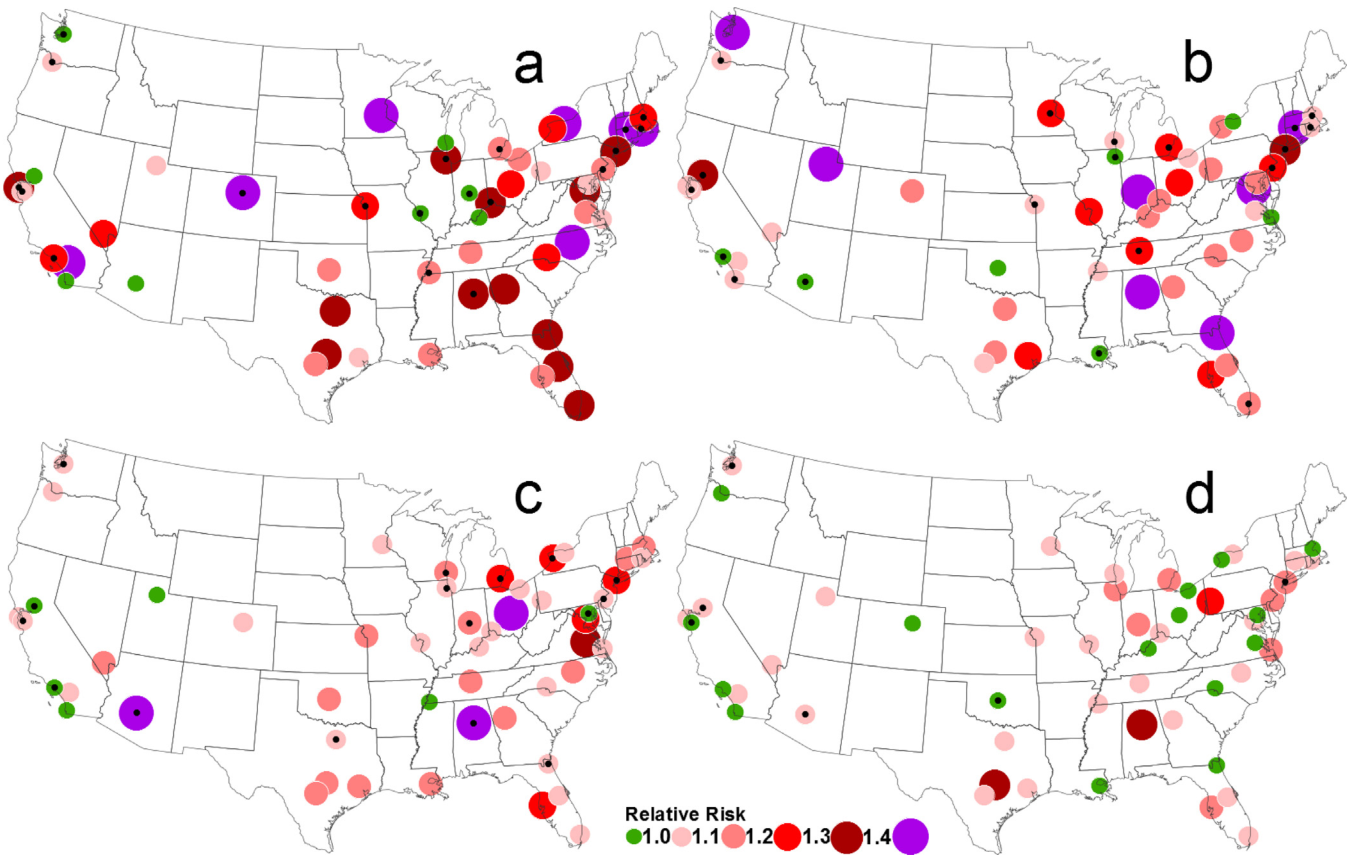

Fig. 5. Relative risks of all-age mortality on heat-wave days using the AT97 definition, by metropolitan area for (a) 1975–1983; (b) 1984–1992; (c) 1993–2001, (d) 2002–2010. Statistically significant values are shown with a dot in the center of the circle.

to the composites. The most substantial trends have leveled off in the last decade of the study period, as most locations ended the period with relative risks of mortality on heat-wave days clustered near 1.0.

Only in New York City, by far the largest metropolitan area in the US, was mortality statistically significantly increased on heat-wave days in every permutation examined. While the city was regularly affected by heat waves, no singular event stood out above others. New York City is therefore grouped into the *consistent decline* trend of group #1. This group is the most geographically cohesive, as almost all metropolitan areas are located within the northeastern quadrant of the country. The region stretches from the city of Boston toward the southwest through New York City, Pittsburgh, Cleveland, Columbus, and St. Louis (Fig. 1). The metropolitan areas of Indianapolis, Cincinnati, and Dallas, however, also display consistent declines through the late 1990s, before increasing enough for classification into separate groups (Fig. 6). Occupying a much broader region, several generally smaller metropolitan areas, comprising group #2, show a sudden change in human vulnerability to heat, which suggests the influence of outlier events. That is, these places experienced impactful heat waves during the 1970s or 1980s, and vulnerability decreased after that event was excluded from the rolling average (e.g., Memphis Fig. 7).

Conversely, the gradual increase in vulnerability throughout the 1980s, followed by a steady decline in the 1990s before becoming steady after the year 2000, suggests another cause for Group #3. These locations experienced very few extreme-heat events before 1990. Except for the city of San Diego, all locations experienced more events later in the period, which is contradictory to the pattern of increasing vulnerability in the 1980s and decreasing vulnerability in the 1990s. This pattern is likely explained by the first few events having greater impacts due to a lack of experience and preparation in the human population. As heat became more regular late in the period, cities and residents became better at managing and adapting to it.

The metropolitan areas in group #4 displayed the most consistent vulnerability over time (i.e., little to no trends) during the study period. Most of these cities are in the southern half of the country and regularly experience dangerous heat waves (e.g., Atlanta, Houston, Riverside, Oklahoma City, Dallas). All cases except Los Angeles experienced enough heat to ensure that the public is at least somewhat acclimatized. Population changes are not consistent in this group, so their consistent vulnerabilities likely result from a combination of local climates and city planning and infrastructure.

Eight metropolitan areas do not fit into the first four classifications, so they are together in group #5. All locations are east of the Rocky Mountains, in the eastern two-thirds of the country, and have seen several years of heat waves, but none experienced extreme events during the study period. Five of the eight metropolitan areas displayed patterns similar to group #1 (steady decline) during the first half of the study period, but increases in latter parts of the study period or other anomalies caused them to stand out. Only two other locations in group #5 (Austin and Tampa) displayed notable increases during the total period without any years of consistent decrease. So, while it is clear that most study sites have seen a decrease in vulnerability, that pattern does not apply everywhere.

4. Discussion

Results of this study have shown that, when evaluating the role of excessive heat on human health, the nature of weather conditions play an important role. Because many locations, particularly in the middle latitudes, will experience some anomalously high temperatures every year, the period of analysis is important, as the inclusion or exclusion of unusually strong or long-lasting heat events can affect the overall assessment of human response. The impact of extreme heat waves on the overall relationship between heat and human health is substantial. Extreme heat waves appear in several cases in this research. They can be more substantively seen in studies that have examined the 2003 heat wave in Europe (e.g. Conti et al., 2005), particularly in places where excessively hot conditions are infrequent. Some studies have suggested that, after winters in which few mortalities occurred, a greater pool of susceptible people will be vulnerable to the heat (Rocklöv et al., 2009; Stafoggia et al., 2009).

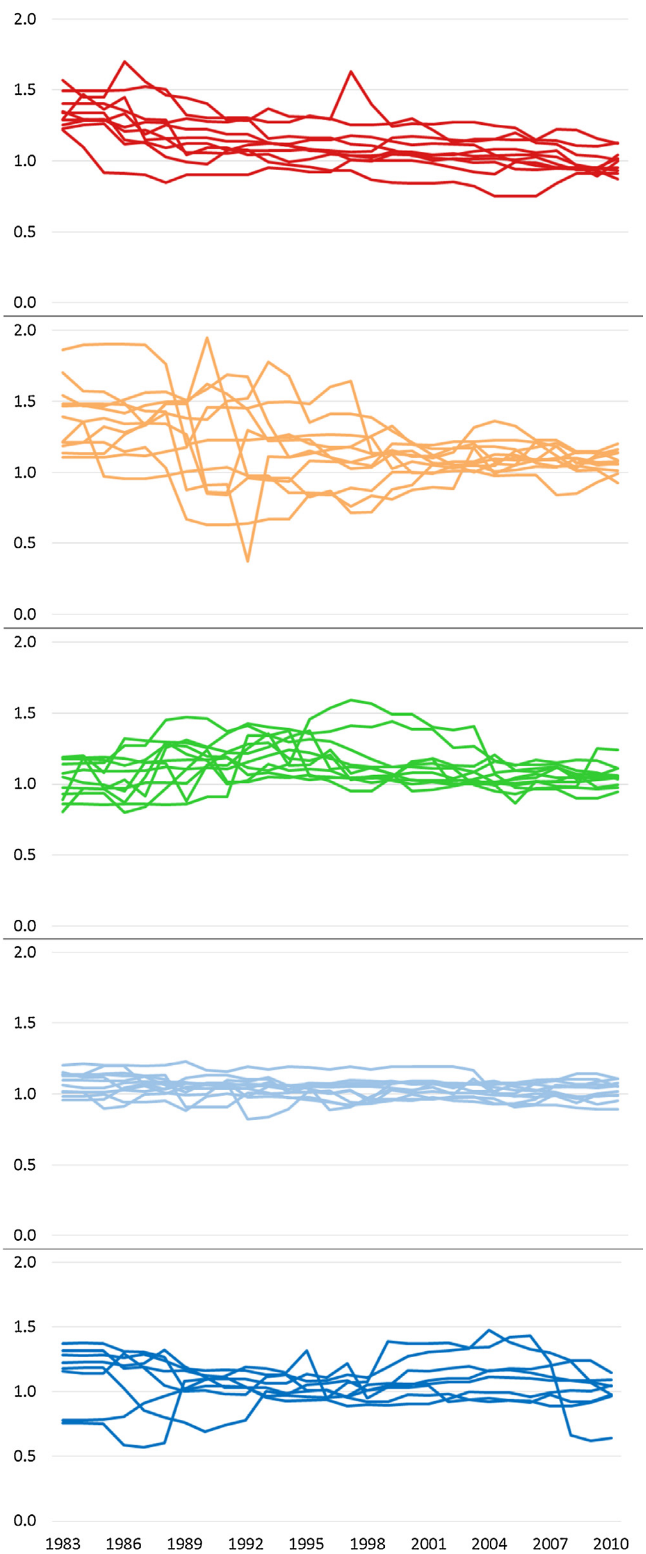

Fig. 6. The five groups of trend patterns using NF14 heat-wave definition and all-age mortality. Lines represent individual metropolitan areas; line colors correspond with groups shown in Fig. 1.

These factors noted, the overall downward trend in mortality during extreme temperature events over the decades in the US broadly aligns with the overall increase in life expectancy during the same period. Large decreases in death rates are also due to many of the causes of death most affected by the heat, such as cardiovascular disease (Sidney et al., 2016). The clear and sharp decreases at some locations after substantial heat events, in particular 1980 and 1995, also suggest that greater awareness of heat-related issues impacts human vulnerability.

How human vulnerability to heat will vary into the future will be affected by many factors, some of which will be substantially different than in the past. The most salient difference will be the likely change in large-scale heat events associated with anthropogenic climate change. Many studies have suggested that these events will increase substantially in the future (e.g., Diffenbaugh and Ashfaq, 2010). Some studies suggested that current-day anomalously very hot summers, such as the summer of 2003 in western Europe, may become far more common by the end of the 21st century (Beniston, 2004). Further, hot weather is projected to reach some areas that have experienced it infrequently so far, such as the highlands of Africa (Garland et al., 2015).

Translating future climate scenarios into projections of human vulnerability is difficult (Sheridan and Allen, 2015). Beyond the uncertainty in climate itself, substantial ambiguity exists in demographic changes and adaptation that affect model simulations. These uncertainties can lead to very large differences in projections, depending upon the assumptions made (e.g., Petkova et al., 2016; Sheridan et al., 2012). Increased use of air conditioning has been one of the mechanisms of adaptation associated with decreasing heat vulnerability, particularly in the US (O'Neill et al., 2005; Davis et al., 2003a). The percentage of houses with some form of air conditioning has increased from 57% in 1980 to 87% in 2009 (EIA, 2011). As air conditioning is nearly ubiquitous in homes in the warmer climates of the US, further reductions in heat vulnerability will be difficult. An exception is the marine climates of the Pacific Northwestern US, the only region where fewer than half of all houses have air conditioning.

Further, the increased use in air conditioning creates issues of physical and social justice. Modeling studies have shown clear increases in vulnerability to heat stress in areas with a substantial urban heat island (e.g., Conlon et al., 2016; Heaviside et al., 2016; Burkhart et al., 2015). Beyond the modifications of built environments themselves, some of the increase in human vulnerability in heat islands may be a product of waste heat from air conditioning, though partitioning the specific contributions is difficult. Modeling of the urban heat island in Phoenix suggests that the waste heat released by air conditioning systems increased air temperature by more than 1 °C in some locations (Salamanca et al., 2014). In Paris, increases in air conditioning projected by the year 2020 are associated with a 2 °C increase in urban heat island (Tremeac et al., 2012). These studies suggest a feedback in which the urban heat island creates cooling demands that exacerbate the heat island further, leaving those without access to air conditioning even more vulnerable to the heat. Globally, the prevalence of air conditioning generally correlates with wealth (McNeil and Letschert, 2008).

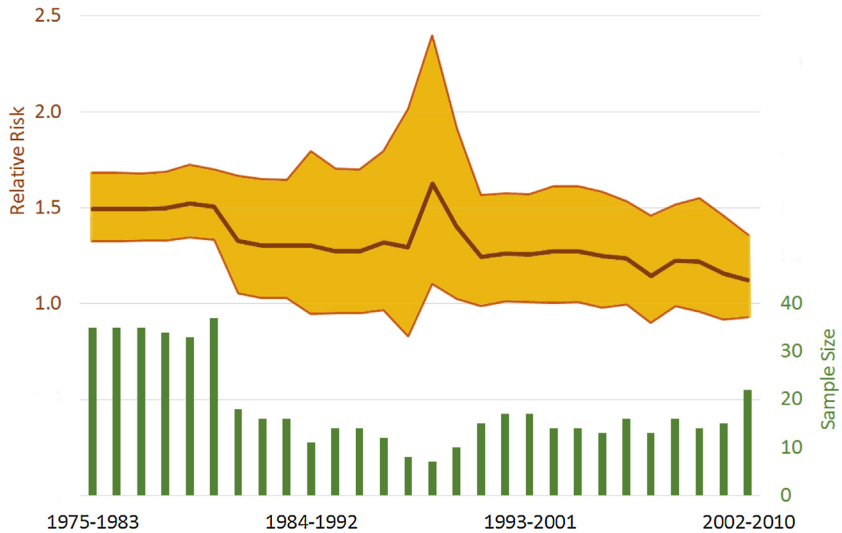

Fig. 7. Relative risk and confidence intervals, along with sample size, for rolling nine-year periods for Memphis, using the NF14 definition of heat-wave days and all-age mortality.

Prevalence has increased substantially in East Asia and Australia, and is projected to grow in South Asia (Isaac and Van Vuuren, 2009). The increase could result in 12% of all energy carbon emissions relating to air conditioning. Thus, air conditioning increases global anthropogenic warming, and at the same time, enhances urban heat islands in many regions that are presently heavily urbanizing.

Another factor that may affect the collective human vulnerability to heat is changes in demography. The percentage of the US population that is 65 years or older has grown steadily for at least the last 100 years (U.S. Census, 2014). It has increased over the time of this study from 25.5 million (11% of the total population) in 1980 to 40.2 million (13%) in 2010. The elderly population will grow at an accelerated rate moving forward, projected to reach 88.5 million (20%) by year 2050. Those 85 and older have grown from 2.2 million (1.0% of the population) in 1980 to 5.7 million (1.9%) in 2010. This group is projected to grow at an even greater pace in the future, reaching a projected 19.0 million (4.3%), by the year 2050. Similar rates of aging are found across many developed nations. The pace of aging will likely increase in many developing nations within the coming decades, with an estimated 1.5 billion persons over 65 globally by year 2050 (Kinsella and He, 2009). Many studies have supported physiological evidence that older populations are disproportionately more prone to hospitalization and death during hot weather (Hansen et al., 2011). As even greater impacts occur on those older than 85 years and also living alone (Willers et al., 2016), the pool of potentially susceptible people is expected to increase greatly moving forward.

5. Conclusions

This analysis of an extended data set has shown that recent decades has experienced a clear decrease in human vulnerability to heat events across the largest metropolitan areas in the US, although heat-related mortality is still statistically significant at the end of the period of analysis. The results are broadly similar to other studies analyzing data for earlier periods in the US (e.g. Bobb et al., 2014; Sheridan et al., 2009; Davis et al., 2003a,b) and more recent time frames elsewhere (e.g., Ng et al., 2016; Kyselý and Plavcová, 2012). The magnitude and rates for this decrease are not consistent across time or space. Our results show smoother temporal patterns than other studies for which individual years form the basis of analysis (e.g. Matzarakis et al., 2011), but the overall relatively linear trend is similar to those with fit lines (e.g. Bobb et al., 2014). Results suggest that the decrease in heat-related mortality collectively has leveled off in recent years, although further studies should test this trend.

Spatially, the patterns in human vulnerability to heat can be somewhat explained by variations in climate. Cooler cities with greater historical mortality levels have experienced greater declines in heat-related deaths (similar to Bobb et al., 2014; Davis et al., 2003a, b), although considerable vulnerability in individual metropolitan areas remains. Nevertheless, the aggregate signal is undeniable, and it is clear that US residents are less likely to die from heat in the 21st century than previously, despite warmer conditions and more frequent heat events in most locations. Changes in awareness, communication, mitigation, and treatment are all likely important factors in the decreases observed, but such improvements are approaching the limits, at least for some of these variables. For example, access to air conditioning is already near 90% in the US, so any future improvements in vulnerability will unlikely result from increased air conditioning. As the US population ages and the climate warms, it is likely that some places may begin to see human vulnerability increase again.

This area of research must continue to meet the challenges of ever increasing changes in populations, climate, and technology, encompassed in the concept of the “anthropocene” (Chin et al., 2016). A consistently decreasing trend in human vulnerability to heat events is encouraging, but we have also seen unexpected spikes in deaths from extreme heat in many locations in the past. Mortality from the heat wave of 2003 in Europe provides one example (Conti et al., 2005). Likewise, fatalities from tornadoes surged by an order of magnitude in 2011 in the US, after having trended downward for several decades and remaining stably low for several more years (Simmons and Sutter, 2014). The 2005 Hurricane Katrina in the US also caused a similar spike in hurricane-related deaths (Willoughby, 2012). Most of these “surprising” events could have been, and sometimes actually were, predicted with better understanding of the weather events and the local populations combined (Simmons and Sutter, 2014; Sharkey 2007; Schmidlin, 2006). Rather than assessing risk by comparing the magnitude of the weather to past events (e.g., this location has not been affected by a heat event in which temperatures exceeded 40 °C in 30 years), it is important to explore how the location has changed since the last event. Factors including increased urbanization and land-use change, older populations, and socioeconomic conditions that preclude access to air conditioning can all affect how a location experiences an extreme heat event. Further, environmental changes leading to an unusual seasonal timing of the event, an extended duration, or a lack of cooling at night, might also change the nature of the impacts. When it comes to protecting people from extreme heat, vigilance is important among researchers, policy-makers, state and city officials, and individual citizens.

Appendix A.

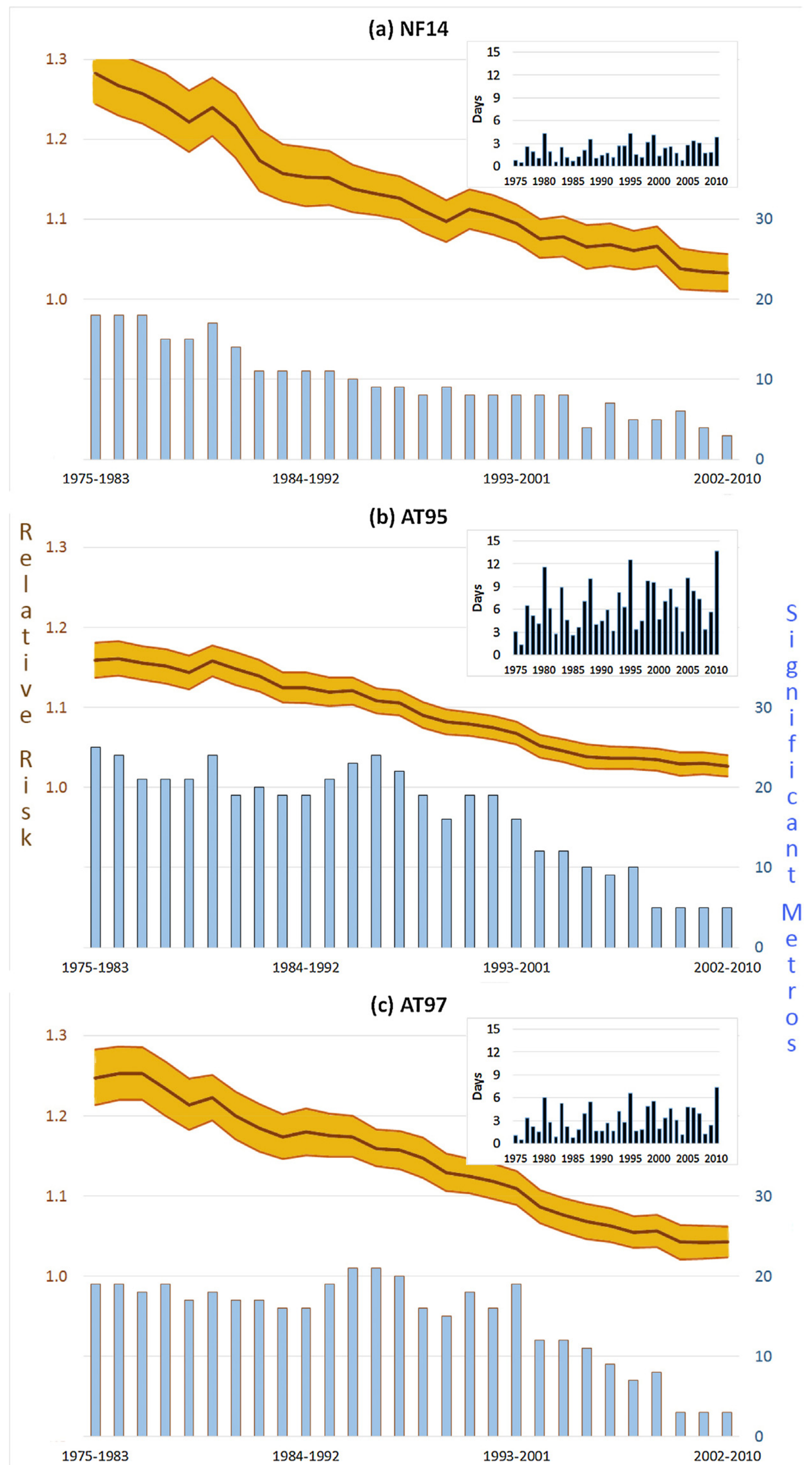

Fig. A1. Pooled relative risk (RR) of 65-and-older mortality on heat-wave days (defined for each of the three heat wave definitions) compared to non-heat wave days across all regions in the study, shown in brown line with 95% confidence interval in gold. Blue bars represent the number of individual cities that are statistically significant at a = 0.05. Inset box shows mean number of heat-wave days by year across all 51 metropolitan areas.

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