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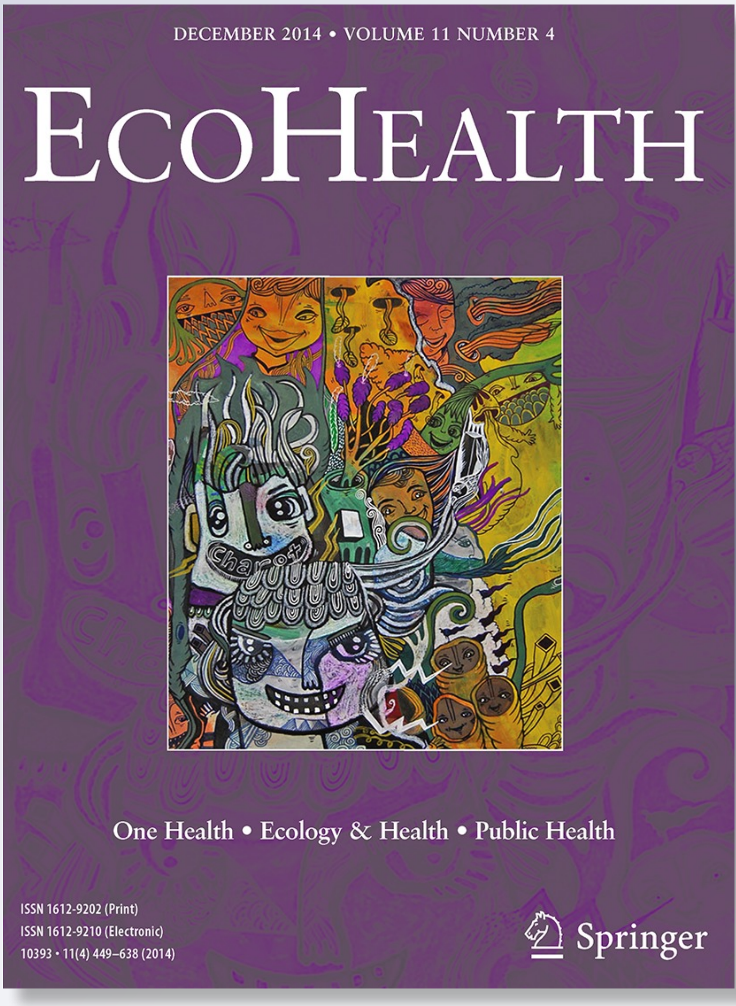

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Original Contribution

Assessing Variability in the Impacts of Heat on Health Outcomes in New York City Over Time, Season, and Heat-Wave Duration

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Abstract: While the impacts of heat upon mortality and morbidity have been frequently studied, few studies have examined the relationship between heat, morbidity, and mortality across the same events. This research assesses the relationship between heat events and morbidity and mortality in New York City for the period 1991–2004. Heat events are defined based on oppressive weather types as determined by the Spatial Synoptic Classification. Morbidity data include hospitalizations for heat-related, respiratory, and cardiovascular causes; mortality data include these subsets as well as all-cause totals. Distributed-lag models assess the relationship between heat and health outcome for a cumulative 15-day period following exposure. To further refine analysis, subset analyses assess the differences between early- and late-season events, shorter and longer events, and earlier and later years. The strongest heat–health relationships occur with all-cause mortality, cardiovascular mortality, and heat-related hospital admissions. The impacts of heat are greater during longer heat events and during the middle of summer, when increased mortality is still statistically significant after accounting for mortality displacement. Early-season heat waves have increases in mortality that appear to be largely short-term displacement. The impacts of heat on mortality have decreased over time. Heat-related hospital admissions have increased during this time, especially during the earlier days of heat events. Given the trends observed, it suggests that a greater awareness of heat hazards may have led to increased short-term hospitalizations with a commensurate decrease in mortality.

Keywords: heat waves, extreme weather events, environmental epidemiology, comparative risk assessment, climatology

INTRODUCTION

Research assessing the impacts of excessive heat upon human health has grown significantly over the past decade, across several broad themes. Much effort has identified the relative vulnerability of different demographic groups, including age, sex, race, health status, poverty status, and social isolation (Bouchama et al. 2007). Broad geographic differences in vulnerability have been assessed (e.g., Medina-Ramón and Schwartz 2007; Gosling et al. 2007; Hajat et al. 2005), along with local variability (e.g., Hondula et al. 2013; Uejio et al. 2011). Individual heat events have been thoroughly analyzed, especially the Western European heat

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wave of 2003 (e.g., Schär et al. 2004). Many studies have looked at the long-term heat-health relationship in locations; those that have evaluated trends have generally showed a decreasing vulnerability to heat (e.g., Bobb et al. 2014; Kyselý and Plavcová 2012; Matzarakis et al. 2011; Sheridan et al. 2009; Barnett 2007; Davis et al. 2002).

To date, the most common health outcome that is evaluated in literature is mortality. As heat has been shown to exacerbate numerous health problems, typically either all-cause mortality or a range of broad causes such as cardiovascular or respiratory disease are studied (Basu 2009). With improved access to data sets, morbidity outcomes such as ambulance calls (e.g., Bassil et al. 2009, 2011; Golden et al. 2008), emergency room visits (e.g., Linares and Díaz 2007), or hospital admissions for a variety of causes (e.g., Lee et al. 2012; Ostro et al. 2010; Michelozzi et al. 2009; Hansen et al. 2008) have also been studied. Heat-related hospital admissions can clearly be correlated with the heat (Sanchez et al. 2010; Knowlton et al. 2009); beyond this, there have been consistently observed increases in respiratory admissions (Monteiro et al. 2013; Lin et al. 2009, 2012a; Knowlton et al. 2009; Michelozzi et al. 2009; Mastrangelo et al. 2007) with mixed results for cardiovascular diseases (Lin et al. 2009; Knowlton et al. 2009; Michelozzi et al. 2009; Mastrangelo et al. 2007; Kovats et al. 2004) during hot weather.

Heat watch–warning systems (HWWS) have become more sophisticated and commonplace in recent years (e.g. Sheridan and Kalkstein 2004; Pascal et al. 2006; Michelozzi et al. 2010). Due to their recentness, studies examining the efficacy of HWWS have been limited with some studies suggesting promising results (Toloo et al. 2013). Ebi et al. (2004) concluded that the Philadelphia HWWS saved 117 lives in its first several years of existence, and while Morabito et al. (2012)show mixed results in their analysis of Florence, they note decreased odds ratios for those 75 and older, with a shorter heat impact, after the implementation of the HWWS. Fouillet et al. (2008) noted lower mortality in France from a 2006 event than a 2003 event, for which HWWS and greater awareness are credited. Toulemon and Barbieri (2008) carry this research further, and suggest that, following the 2003 event, greater awareness and mitigation efforts resulted in a lower overall mortality rate in France lasting more than 2 years after the event.

The assessment of the impacts of heat on human health is further complicated by several factors. In the short term, seasonality is considered a potential confounder, as in some studies early-season heat events are shown to have a greater impact than later season heat waves (e.g., Sheridan et al. 2009), even with lower absolute temperatures; factors such as seasonal acclimatization and a diminishing pool of susceptible people are suggested as potential reasons (Rocklöv et al. 2011). Further, there is a well-recognized 'heat-wave effect', that is, a non-linear health response to a sequence of Rocklöv et al. 2011 what would be expected if those days did not occur sequentially (Rocklöv et al. 2011, 2012; Anderson and Bell 2010). In assessing health response, there have been numerous attempts to quantify mortality displacement, or 'harvesting', as it has been observed that mortality falls below expected levels soon after a heat wave, suggesting a portion of those who died in a heat wave would have died soon thereafter. To assess harvesting, time series analyses such as distributed-lag non-linear models (Gasparrini and Armstrong 2010) have been used to assess non-linear and delayed impacts of heat. Estimates of the net effect of harvesting vary widely, with some studies suggesting nearly all deaths are short-term displacement in some cases (Hajat et al. 2006), while others suggest lower values around 25% (Kaiser et al. 2007; Toulemon and Barbieri 2008), and the results are spatially variable (e.g., Baccini et al. 2013; Hajat et al. 2006). When stratified by cause, results vary substantially (Hajat et al. 2006).

Assessments of heat-related morbidity have been used to suggest that changes in morbidity rates in one direction may be related to mortality rates changing in the opposite direction, that is, that people either seek out medical assistance beforehand or die before having the opportunity (Linares and Díaz 2007). While hospitalization has been considered a factor in some heat-related mortality studies (e.g. Son et al. 2012; Stafoggia et al. 2008), relatively few studies have examined mortality and morbidity concomitantly (Nitschke et al. 2007, 2011; Hansen et al. 2008; Kovats et al. 2004; Danet et al. 1999).

Hospitalization data for New York City and/or New York State have been studied in a number of studies in recent years with regard to the impacts of atmospheric conditions (Fletcher et al. 2012; Lee et al. 2012; Lin et al. 2009, 2012a, b), generally focusing upon specific causes. In this study, we expand upon this research and examine the impacts of hot days and heat events on mortality and morbidity using a synoptic climatological methodology and distributed-lag models, for New York City for the period 1991–2004. We aim to explore variability in human vulnerability in dimensions that have been less commonly studied in the heat-health literature, assessing the differences between mortality and morbidity, the variability in these responses across time (by subdividing the period of record into two), by seasonality (partitioning spring from summer), and by length of heat event.

Materials and Methods

Mortality and hospital admission data have been acquired from the National Center for Health Statistics and the New York State Department of Health, respectively. While both data sets are longer, only the overlapping period of 1991–2004 is analyzed in this research. To focus on heat-related changes in morbidity and mortality, only the period April through August is analyzed. In the previous research (Sheridan et al. 2009), mortality response was assessed for anomalously warm weather year-round; in New York, the period April through August encompassed the most significant response. This asymmetric warm season definition also allows an assessment of the impact of early-season heat events.

Data are aggregated to encompass all of New York City, with subsets created for cause of death or hospitalization, inclusive of: heat-related (ICD10: X30), respiratory (ICD10: J00-99), and cardiovascular (ICD10: I00-99) causes. All-cause mortality totals are also analyzed. Total sample sizes for each data set are shown in Table 1; as direct heat-related mortality has a very limited sample size (81) through the period, it is not statistically analyzed further.

Meteorological data for this study are the Spatial Synoptic Classification (SSC; Sheridan 2002) data for La Guardia Airport (LGA) in New York City. The SSC categorizes weather conditions from temperature, dew point, wind speed and direction, pressure, and cloud cover into one of several weather types on a daily basis for a period of record. These weather types can be found in Table 2; the character of these weather types varies spatially, but more critically for this research, temporally, that is, all weather types are warmer in mid-summer than during the spring. The use of these synoptic types thus allows an assessment of health response to an oppressive subset of weather conditions relative to a particular time of year. The SSC is used in several dozen synoptic-based HWWS (Sheridan and Kalkstein 2004) and, while different from single parameter threshold models of identifying heat events, performs as effectively in identifying high mortality days (Hajat et al. 2010).

For each subset of analysis, we applied a distributed-lag model to assess the cumulative impact of weather on health outcome, using the *dlnm* package in R. The model used in this research is

$$\mathrm{Log}(\mathrm{outcome}) = \mathrm{intercept} + \mathrm{weather} + \mathrm{ns(year)} + \mathrm{ns(day)} + \mathrm{DOW}.$$

Outcome is the daily count of each of the seven outcomes shown in Table 1, assuming a Poisson distribution of counts; ns (year) is a natural spline fit to the years of study, with 4 degrees of freedom; ns (day) is a natural spline fit to the days of the year, with 3 degrees of freedom; and DOW is series of dummy variables representing day of week. Weather refers to a series of binary variables created for each respective analysis.

- For assessment of the association between SSC weather type and health outcome, binary variables are created for each weather type in Table 2, except for Dry Moderate (DM) which is used as the reference type. Dry Moderate is used as it most closely represents seasonal climatological normal conditions; the mean apparent temperature on DM days in July is the 83rd percentile of the annual apparent temperature distribution, close to the 84th percentile, the optimal apparent temperature percentage of this data set (the percentile at which overall mortality is lowest).
- For assessment of the association between health outcome and heat events, hot days are identified as being days that are categorized either as the Moist Tropical

Table 1. Sample Sizes of Health Outcomes for New York City, April to August, 1991–2004

Cause	Deaths	Hospital admissions
Heat-related	81*	1,506
Respiratory	24,307	197,868
Cardiovascular	164,202	664,001
Total	395,325	Not available

*Not studied in this research due to small sample size

Table 2. Mean Frequency (*f*, Percent of Days) and Character [1600 Local Standard Time (LST) Temperature (Tp, °C), 1600 LST Dew Point (Tdp, °C), 0400 LST Temperature (Ta, °C)] of Each SSC Type for April and July at La Guardia Airport, Along with Total Sample Size (*n*) in Study

		April				July			
SSC type	*n*	*f*	Tp	Tdp	Ta	*f*	Tp	Tdp	Ta
Dry Polar (DP)	195	17.9	10	−4	4	7.0	24	12	18
Dry Moderate (DM)	527	29.3	26	11	18	23.9	28	13	20
Dry Tropical (DT)	147	5.9	24	3	13	8.1	34	17	25
Moist Polar (MP)	122	10.6	8	4	6	1.1	18	16	18
Moist Moderate (MM)	384	14.0	12	7	9	17.8	24	19	21
Moist Tropical (MT)	412	6.9	20	11	12	27.7	29	20	22
Moist Tropical Plus (MT+)	150	1.9	22	13	16	6.9	32	21	26
Transition (TR)	205	13.5	14	3	9	7.5	27	15	22

Plus (MT+) or Dry Tropical (DT) weather type, based on results shown below and also demonstrated in the previous research to be most connected with adverse health outcomes (Sheridan and Kalkstein 2004). The length of a heat event is determined by the consecutive day in sequence of either MT+ or DT.[1] In analyses of day in sequence, binary variables are created for each day in sequence from 1 to 7. For the collective analysis of heat events, two binary variables are created; one of it was the first or second day of a heat event, to identify shorter events or the early days of longer events; another for the third or greater day, to identify longer events. Days that are not part of a heat event serve as the reference type.

In all analyses, relative risks (RRs) are calculated to assess vulnerability. The effects of weather are assessed as zero-day, as well as cumulative 15-day lags, with the lags are constrained to fit a natural spline with 5 df. For heat hospitalizations, the small sample size resulted in less stable results when longer lags were examined, and for this paper cumulative 5-day lags (constrained by a spline with 3 df) are examined. Different degrees of freedom for the splines were assessed, with negligible impact upon the statistical significance of the results.

RRs are analyzed for the period as a whole, as well as by subsets divided by season and year, based on the results discussed in "Overview" section.

[1]A heat event is inclusive of all days that fall into either category, and many heat events will have some DT days and some MT+ days; toggling back and forth does not reset the length of heat wave as long as either of these occur.

Results

Overview

Several analyses are used to assess how to define hot weather and heat events, along with how to partition the data set. Similar to existing literature (Sheridan and Kalkstein 2004), the largest increases in RR for all-cause mortality during the period of analysis occur with the DT and MT+ weather types, with zero-day lag RRs of 1.062 (95% CI 1.045, 1.079) and 1.050 (1.033, 1.068), respectively (Fig. 1), the only weather types for which increases are statistically significant. Zero-day lag RRs for heat hospitalizations for DT and MT+ are 15.780 (10.100, 24.645) and 9.530 (6.020, 15.060), respectively, with a marginally significant RR of 2.110 (1.285, 3.740) for MT. Based on these results, the definition of hot weather is set to be inclusive of days classified as either MT+ or DT.

There is no standard definition of the duration necessary to define a heat wave, or event longer than "ordinary" hot weather (Robinson 2001). In many studies, the exceedance of some threshold over two consecutive days is used, although analyses have evaluated event thresholds between 2 and 4 days (Hajat et al. 2006; Anderson and Bell 2009; Mastrangelo et al. 2007). In evaluating duration impacts in this research, no clear break is identified with the day in sequence of a heat event, with all-cause mortality RRs rising more or less linearly from 1.038 (1.023, 1.053) on Day 1 to 1.218 (1.143, 1.298) on Day 6 of a heat event, and heat hospitalizations increasing from 2.448 (1.649, 3.634) to 62.430 (42.011, 92.776) (Table 3). To assure a reasonable sample size for the heat waves analyzed, a threshold of three consecutive days of DT or MT+ weather type is set for heat-wave

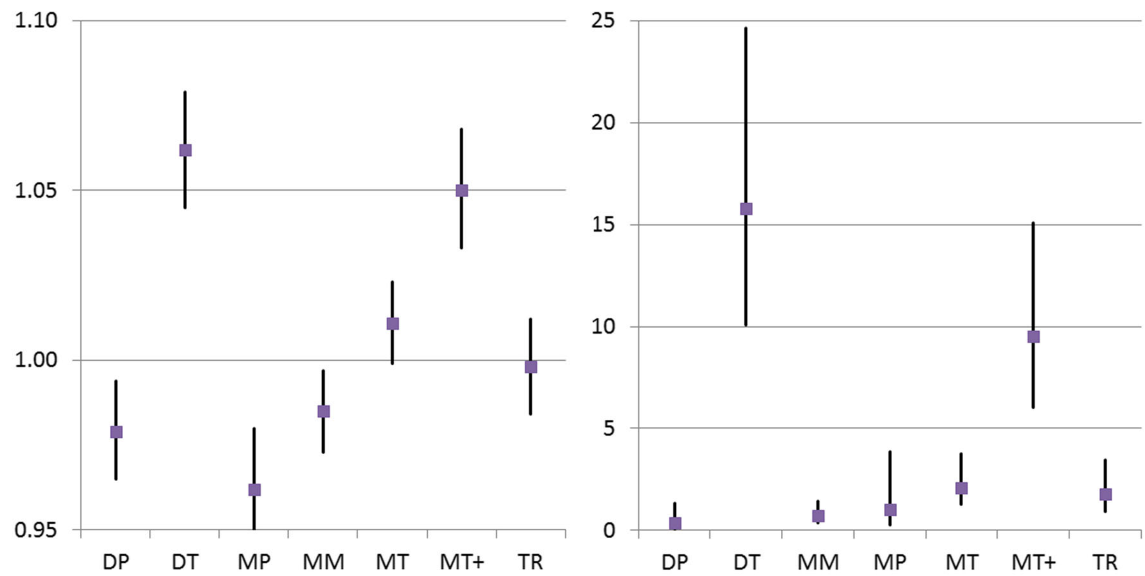

Figure 1. Zero-day lag relative risks (RR) and 95% confidence intervals for all-cause mortality (*left*), and heat hospitalizations (*right*) by SSC type, full period of analysis.

designation. Over the entire study period, a total of 228 short-term *hot days* (*HD*), comprising the one- or two-day heat events as well as the first or second days of a longer heat event, are identified. A total of 31 events yield 69 *heat-wave days* (*HW*), comprising the third day of a heat event onwards.

To assess temporal variability in health response, several break points are assessed with regard to heat hospitalizations and all-cause mortality. A seasonal break point is assessed, to separate 'early-season heat waves' (April and May, hereafter *Spring*) from those that occur during meteorological summer (June, July, and August, hereafter *Summer*). For interannual trends, the largest break points, defined as the greatest mean difference before and after the break point, for heat hospitalizations and all-cause mortality are identified as occurring between 1996 and 1997. Anomalous mortality, defined as the residual from the equation defined above, decreases from 28.7 deaths per heat-wave day between 1991 and 1996 to 18.1 between 1997 and 2004. Heat hospitalizations increase between periods, from 9.62 to 11.07 hospitalizations per heat-wave day. For the analyses performed below, nearby breakpoints (using between 1995–1996 and 1999–1999) were also evaluated, and had little effect on the overall significance of the results.

Health Outcomes, Zero-Day Lag

In examining solely the zero-day lag impacts, that is, neglecting any lagged effects or displacement that may occur, statistically significant increases occur in *all-cause mortality* as well as *heat hospitalizations*, across nearly all ways in which the data set is subdivided (Table 4). Analyzed as a whole, the RR of heat-related mortality is 1.042 (1.030, 1.055) on *hot days*, increasing to 1.127 (1.104, 1.150) on *heat-wave days*; the respective RRs for heat hospitalizations are 3.905 (2.907, 5.246) and 25.891 (20.300, 33.022). When analyzing the different subsets described above, nearly all RRs are associated with statistically significant increases in mortality and morbidity, with a range from 1.039 to 1.157 across the subsets of all-cause mortality; for the much smaller sample of heat hospitalizations, the range is 2.847–33.151. For both of these health outcomes, RRs are higher during longer-term events than shorter-term; the difference between longer and shorter events is statistically significant across most subsets in summer, and generally near significant in spring. When comparing spring and summer subdivisions by length of heat event, for all-cause mortality there is almost no difference between spring and summer in terms of short-term events, while the RR is marginally higher in summer for longer-term events. Conversely, for heat hospitalizations, the RR is actually larger in spring than summer during the first and second days of a heat event; this difference is statistically significant when the full period of record is analyzed. Overall RRs are also generally higher in the first half of the period of record than the second half, although many of these differences are not statistically significant.

Table 3. Zero-Day Lag RRs by Day in Sequence (DIS) of MT+ or DT and All-Cause Mortality and Heat Hospitalizations, with 95% Confidence Intervals in Parentheses

DIS	*n*	All-cause mortality	Heat hospitalizations
1	154	1.038 (1.023, 1.053)	2.448 (1.649, 3.634)
2	74	1.053 (1.031, 1.074)	6.371 (4.563, 8.895)
3	31	1.075 (1.042, 1.108)	11.186 (7.596, 16.473)
4	18	1.142 (1.098, 1.187)	30.966 (22.457, 42.700)
5	12	1.212 (1.157, 1.269)	39.906 (28.593, 55.694)
6	6	1.218 (1.143, 1.298)	62.430 (42.011, 92.776)

DIS = 7 is not shown as the sample size is only 2.

Table 4. Relative Risks and 95% Confidence Intervals for Hot Days (HD) and Heat Wave Days (HW); Zero-Day Lag Only

	Mortality			Hospitalizations		
	All-cause	Cardiovascular	Respiratory	Heat	Cardiovascular	Respiratory
Full season						
1991–2004						
HD	**1.042 (1.030,1.055)**	**1.045 (1.027,1.064)**	**1.066 (1.023,1.110)**	**3.905 (2.907,5.246)**	1.002 (0.989,1.014)	1.014 (0.989,1.039)
HW	**1.127 (1.104,1.150)**	**1.191 (1.157,1.227)**	1.015 (0.945,1.091)	**25.891 (20.3,33.022)**	0.981 (0.959,1.002)	1.009 (0.966,1.055)
1991–1996						
HD	**1.041 (1.022,1.060)**	**1.048 (1.021,1.076)**	**1.019 (0.958,1.084)**	**3.801 (2.136,6.762)**	1.007 (0.990,1.025)	0.997 (0.968,1.027)
HW	**1.144 (1.107,1.182)**	**1.232 (1.176,1.291)**	1.045 (0.932,1.171)	**25.46 (15.979,40.565)**	0.981 (0.948,1.015)	1.036 (0.978,1.099)
1997–2004						
HD	**1.042 (1.024,1.059)**	**1.049 (1.024,1.074)**	**1.097 (1.039,1.157)**	**4.731 (3.437,6.513)**	1.000 (0.983,1.017)	**1.038 (1.001,1.076)**
HW	**1.110 (1.081,1.140)**	**1.164 (1.121,1.208)**	0.987 (0.899,1.084)	**26.691 (20.187,35.291)**	0.982 (0.955,1.009)	1.002 (0.943,1.065)
Spring						
1991–2004						
HD	**1.045 (1.024,1.067)**	1.018 (0.988,1.05)	1.031 (0.960,1.108)	**12.895 (7.485,22.215)**	1.009 (0.985,1.033)	0.973 (0.940,1.007)
HW	**1.087 (1.047,1.129)**	**1.089 (1.03,1.151)**	1.116 (0.981,1.270)	**33.151 (17.259,63.677)**	0.992 (0.949,1.036)	0.946 (0.885,1.012)
1991–1996						
HD	**1.044 (1.014,1.075)**	1.031 (0.988,1.077)	0.991 (0.889,1.106)	**17.087 (5.498,53.097)**	1.009 (0.977,1.042)	0.971 (0.926,1.018)
HW	**1.120 (1.056,1.188)**	**1.130 (1.036,1.233)**	1.145 (0.929,1.412)	**25.619 (3.998,164.17)**	1.006 (0.939,1.078)	0.996 (0.896,1.107)
1997–2004						
HD	**1.047 (1.017,1.077)**	1.015 (0.972,1.059)	1.055 (0.959,1.161)	**11.062 (6.163,19.857)**	1.006 (0.973,1.040)	0.983 (0.937,1.032)
HW	**1.058 (1.006,1.113)**	1.056 (0.981,1.137)	1.096 (0.926,1.297)	**26.674 (14.249,49.935)**	0.981 (0.928,1.038)	0.929 (0.852,1.013)
Summer						
1991–2004						
HD	**1.041 (1.025,1.057)**	**1.056 (1.033,1.08)**	**1.086 (1.034,1.141)**	**3.533 (2.433,5.129)**	1.002 (0.988,1.016)	**1.043 (1.01,1.077)**
HW	**1.144 (1.116,1.173)**	**1.234 (1.192,1.278)**	0.988 (0.906,1.078)	**24.892 (18.44,33.603)**	0.980 (0.957,1.004)	**1.057 (1.001,1.117)**
1991–1996						
HD	**1.039 (1.015,1.064)**	1.015 (0.972,1.059)	1.037 (0.962,1.118)	2.847 (0.817,9.918)	1.013 (0.994,1.033)	1.019 (0.983,1.055)
HW	**1.157 (1.111,1.205)**	1.056 (0.981,1.137)	1.026 (0.894,1.178)	**21.693 (8.341,56.415)**	0.979 (0.943,1.017)	1.061 (0.993,1.133)
1997–2004						
HD	**1.039 (1.018,1.06)**	**1.062 (1.032,1.093)**	**1.113 (1.042,1.19)**	**4.536 (3.038,6.773)**	1.000 (0.981,1.019)	**1.072 (1.022,1.125)**
HW	**1.127 (1.092,1.164)**	**1.204 (1.153,1.257)**	0.949 (0.846,1.064)	**26.796 (18.794,38.204)**	0.986 (0.956,1.016)	1.057 (0.978,1.143)

Values in bold represent statistically significant increases

The results for cardiovascular mortality roughly coincide with all-cause mortality, though are slightly weaker; no statistically significant results are identified with cardiovascular hospitalizations. Some statistically significant increases in respiratory mortality and hospitalizations are seen during the summer, with none in spring.

Assessing the Lag Effect of Health Outcomes

Supporting existing research (e.g., Anderson and Bell 2009), peak vulnerability to heat events typically occurs either the day of hot weather or one day afterward. For all-cause mortality for the full period of record (Fig. 2), RRs decline after Lag 0 except for summer heat-wave days, where the RR is slightly higher at Lag 1. In examining subsets of analysis, RR is statistically significantly elevated for heat-wave days in the summer from the day of a heat-wave day to Lag 3, for all other subsets, no statistically significant increases occur at greater than Lag 1. Evidence of mortality displacement becomes apparent after 3 days for spring hot days. Similar patterns in the results are seen with cardiovascular mortality (not shown), with somewhat amplified vulnerability; increased RR is statistically significant through an 11-day lag for summer heat-wave days. For respiratory mortality, much weaker relationships are seen; for summer heat-wave days, increased risk is statistically significant for Lag 0 and 1; for no other subsets are statistically significant results observed.

In examining hospital admissions, heat hospitalizations show a similar general pattern to all-cause mortality, with the sharpest increases in risk at Lag 0 (Fig. 3). RRs are generally higher in spring than summer, though this reflects the smaller sample size in spring and that very few heat-related hospital admissions occur outside of hot weather days. In contrast to all-cause mortality, RRs remain elevated out to longer lags; aside from April to May hot days (for which statistical significance extends out to only Lag 1), for all other subsets, statistically significant increases in risk extend to Lag 3 after hot weather. The relationship between hot weather and cardiovascular and respiratory hospital admissions (not shown) is weaker. For respiratory admissions, increased RR is observed out though Lag 9 with summer hot days, but no increased risk is observed with summer heat-wave days or any spring subset. No cohesive statistically significant results show up for any subset of cardiovascular hospitalizations.

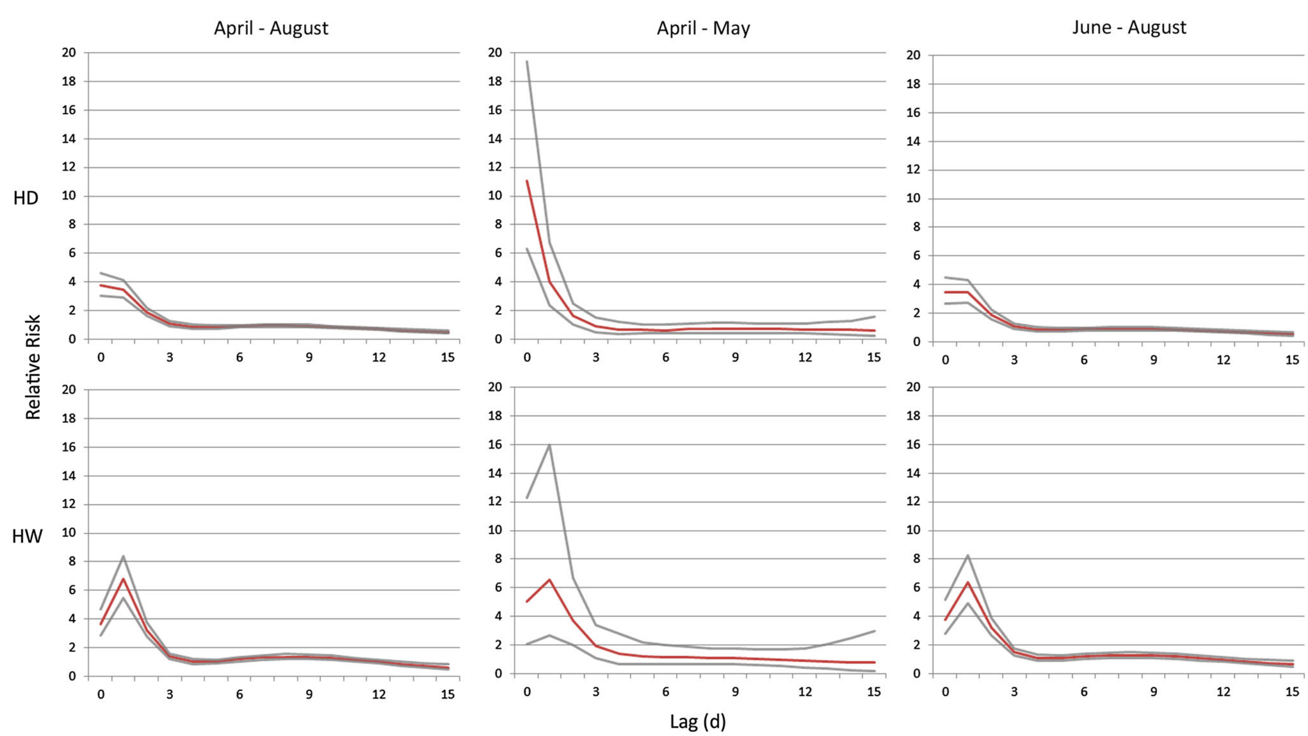

Figure 2. Lag structure of relative risks of all-cause mortality with 95% confidence intervals for 1991–2004 for different seasonal subsets and for hot days (HD) and heat wave days (HW), relative to days that are neither.

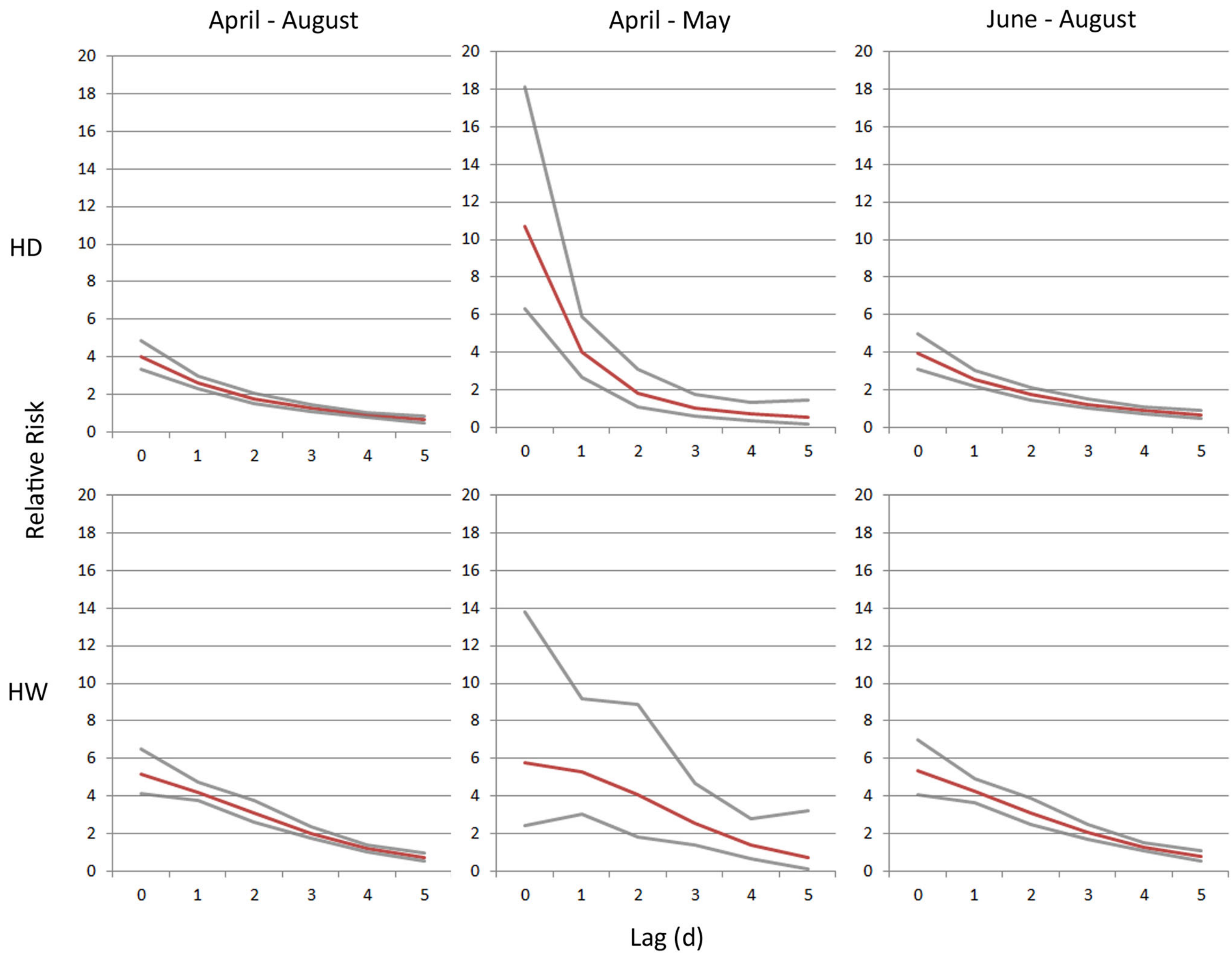

Figure 3. Same as Fig. 2, except for heat hospitalizations.

The lagged impacts can be further analyzed by temporal subset (shown for summer only, Fig. 4). For the early period of 1991–1996, statistically significant increases in risk are observed for Lags 0–3 (heat-wave days) and 0–1 (hot days), while for 1997–2004, the increased risk is only observed on Lags 0–2 and 0–1, respectively. For heat-wave days, RRs are lower in the later period for all lags except Lag 0 and are statistically significantly lower at Lags 1 and 2. For hot days, there is a greater suggestion of mortality displacement in the earlier period than the later period, although the differences are not statistically significant.

For heat hospitalizations, a somewhat different pattern emerges. When analyzed with a distributed-lag model out to 5 days, in the more recent period, a sharper peak in hospitalizations on the day of hot weather (for both hot days and heat-wave days) occurs, with lower RRs later on. Due to a small sample size, these differences are not significant, but it is noteworthy that this same pattern occurs with both temporal subsets.

Health Outcomes, Cumulative Impact

In assessing the cumulative impact of heat on mortality over a 15-day period, similar broad patterns are observed, with increased divergence in the RR values (Table 5). For all-cause mortality, once short-term displacement is accounted for, the RR on hot days decreases to a non-significant 1.023 (0.978, 1.071); none of the subsets are significant. The RR for heat-wave days increases more substantially to 1.264 (1.193, 1.340); all of the summer subsets are significant; none of the spring subsets are significant. Over time, statistically significant differences are seen in the cumulative RR values on summer heat-wave days, with an RR of 1.519 (1.360, 1.696) for the 1991–1996

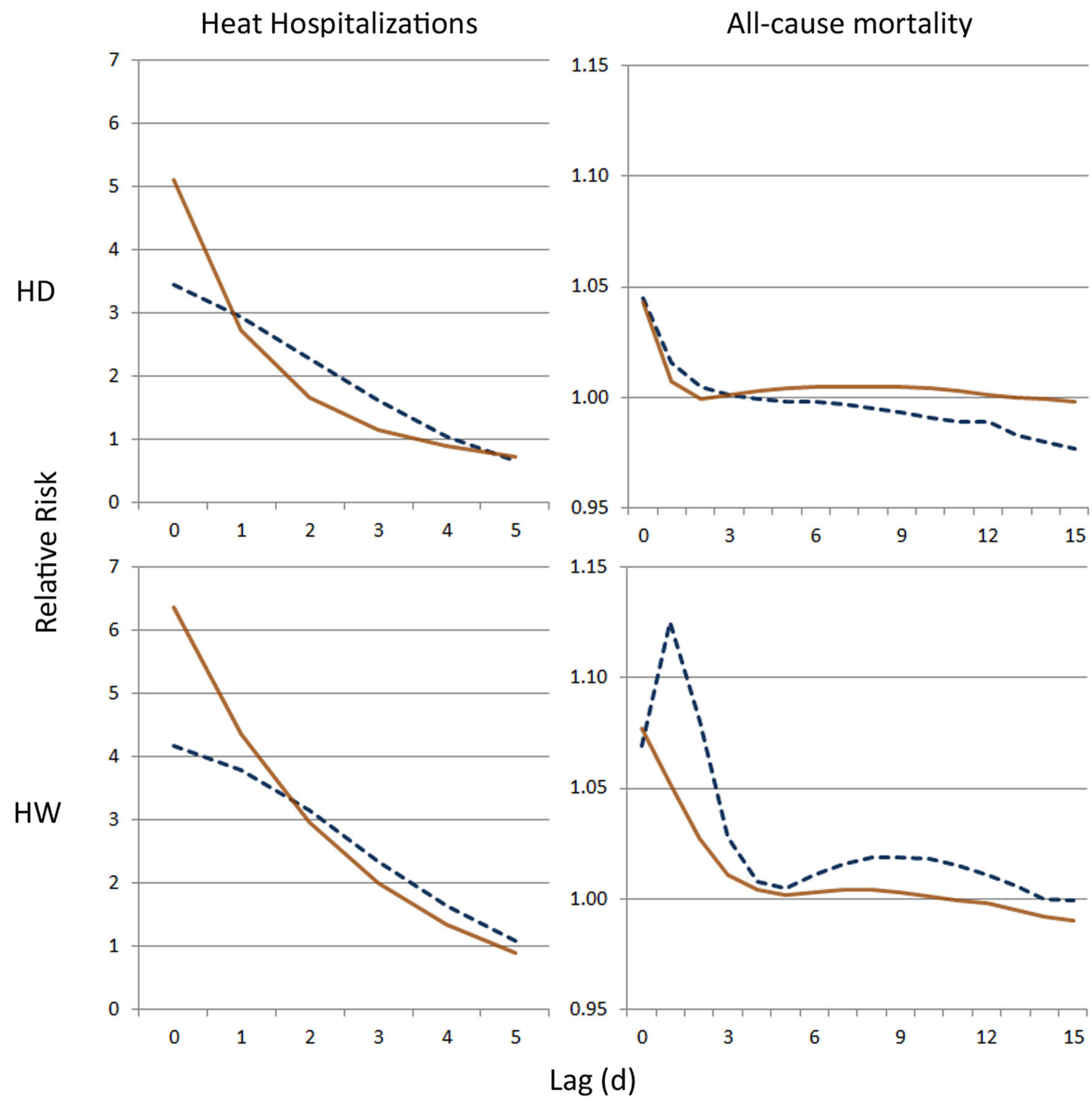

Figure 4. Lag structure of relative risks of all-cause mortality and heat hospitalizations for 1991–1996 (*dashed line*) and 1997–2004 (*solid line*) for summer for hot days (HD) and heat wave days (HW), relative to days that are neither.

period decreasing to 1.175 (1.068, 1.293) for 1997–2004. Similar results are observed for cardiovascular mortality; for respiratory mortality, no subsets are statistically significant.

For heat hospitalizations, all subsets analyzed show a statistically significant increase in RR on hot days and heat-wave days, with much higher values on heat-wave days across all subsets. Cumulative impacts for cardiovascular and respiratory admissions are much more modest, with little consistency observed.

Discussion

Several key themes emerge from the results of this research. In terms of overall vulnerabilities, these results support much previous research, showing an increase in morbidity and mortality during heat events. The nature of these increases, however, is variable across season, time period, lag, and cause of death or hospitalization. Regarding causes, the clearest, most consistent relationships are observed between heat events and all-cause and cardiovascular-related

Table 5. Same as Table 4, Except for 15-Day Cumulative Relative Risk (5-Day Cumulative Risk for Heat Hospitalizations)

	Mortality			Hospitalizations		
	All-cause	Cardiovascular	Respiratory	Heat	Cardiovascular	Respiratory
Full season						
1991–2004						
HD	1.023 (0.978, 1.071)	1.035 (0.969, 1.104)	1.001 (0.859, 1.167)	**14.984 (8.012, 28.023)**	0.874 (0.835, 0.916)	0.772 (0.707, 0.844)
HW	**1.264 (1.193, 1.340)**	**1.445 (1.329,1.570)**	1.022 (0.836, 1.250)	**123.458 (74.88, 203.552)**	1.034 (0.973, 1.098)	**1.134 (1.007, 1.278)**
1991–1996						
HD	0.973 (0.906, 1.046)	1.048 (0.944, 1.164)	0.808 (0.627, 1.041)	**45.369 (12.496, 164.725)**	0.880 (0.820, 0.944)	0.771 (0.686, 0.866)
HW	**1.407 (1.282, 1.543)**	**1.603 (1.402, 1.832)**	1.382 (0.997, 1.914)	**208.95 (79.444, 549.575)**	1.019 (0.928, 1.119)	1.146 (0.975, 1.346)
1997–2004						
HD	1.036 (0.975, 1.101)	1.077 (0.988, 1.175)	1.057 (0.865, 1.293)	**13.959 (6.375, 30.567)**	0.885 (0.833, 0.940)	**0.832 (0.732, 0.945)**
HW	**1.163 (1.077, 1.256)**	**1.357 (1.217, 1.512)**	0.831 (0.640, 1.079)	**179.605 (91.684, 351.838)**	1.057 (0.979, 1.142)	1.132 (0.958, 1.338)
Spring						
1991–2004						
HD	1.004 (0.917, 1.100)	0.986 (0.862, 1.130)	1.029 (0.755, 1.402)	**31.978 (3.567, 286.718)**	0.931 (0.840, 1.033)	0.704 (0.611, 0.812)
HW	1.130 (0.987, 1.294)	1.131 (0.926, 1.382)	1.057 (0.671, 1.666)	**316.282 (30.245, 3307.411)**	0.896 (0.772, 1.041)	1.213 (0.984, 1.494)
1991–1996						
HD	0.903 (0.775, 1.052)	1.110 (0.882, 1.396)	0.553 (0.798, 1.200)	–	0.888 (0.749, 1.053)	0.644 (0.510, 0.812)
HW	1.543 (0.909, 2.619)	1.094 (0.493, 2.428)	5.182 (0.825, 32.533)	–	1.250 (0.684, 2.284)	1.476 (0.633, 3.440)
1997–2004						
HD	1.037 (0.905, 1.189)	0.978 (0.799, 1.200)	1.056 (0.684, 1.629)	**18.886 (2.582, 138.165)**	0.941 (0.812, 1.090)	0.732 (0.595, 0.900)
HW	1.053 (0.892, 1.242)	1.079 (0.844, 1.379)	1.002 (0.591, 1.701)	**737.97 (95.214, 5719.771)**	0.905 (0.757, 1.082)	1.232 (0.958, 1.586)
Summer						
1991–2004						
HD	1.052 (0.993, 1.115)	**1.090 (1.002, 1.185)**	1.013 (0.829, 1.238)	**14.164 (6.555, 30.607)**	0.903 (0.854, 0.955)	0.922 (0.814, 1.044)
HW	**1.324 (1.234, 1.421)**	**1.610 (1.457, 1.780)**	1.000 (0.780, 1.282)	**154.761 (83.812, 285.771)**	**1.070 (1.000, 1.146)**	1.066 (0.912, 1.245)
1991–1996						
HD	0.956 (0.871, 1.049)	1.035 (0.901, 1.187)	0.805 (0.577, 1.122)	**26.29 (2.723, 253.872)**	0.899 (0.826, 0.978)	0.884 (0.768, 1.018)
HW	**1.519 (1.360, 1.696)**	**1.838 (1.565, 2.160)**	1.416 (0.955, 2.101)	**211.894 (37.017, 1212.935)**	1.003 (0.905, 1.111)	1.114 (0.938, 1.323)
1997–2004						
HD	1.086 (0.998, 1.182)	**1.174 (1.042, 1.322)**	0.985 (0.741, 1.308)	**17.154 (6.391, 46.041)**	0.926 (0.856, 1.001)	1.069 (0.880, 1.299)
HW	**1.175 (1.068, 1.293)**	**1.453 (1.271, 1.661)**	0.748 (0.535, 1.045)	**198.44 (87.474, 450.174)**	**1.135 (1.037, 1.243)**	0.906 (0.718, 1.143)

mortality, as well as heat-related hospital admissions. Cardiovascular illness has been shown to be a critical factor in all-cause mortality in heat events (e.g. Bouchama et al. 2007), and given the high percentage of overall deaths that are cardiovascular in nature that all-cause and cardiovascular-related deaths would show similar trends is not surprising. The extremely high RRs for heat-related hospital admissions during heat events have also been shown elsewhere (Khalaj et al. 2010; Knowlton et al. 2009; Mastrangelo et al. 2007). The comparatively weaker results for respiratory mortality have some support in existing literature (e.g., Basu and Ostro 2008), although most studies that have assessed respiratory mortality have noted an increase during heat events (Basu 2009). Regarding cardiovascular and respiratory hospital admissions, some weak indication of short-term increases in respiratory morbidity and cumulative increases in cardiovascular morbidity are observed, though they are not as consistent. The temporal pattern of these responses resembles what Lin et al. (2009) also found for New York City, although their work showed greater statistical significance. Beyond this, the results in this research are generally in line with the mixed results for cardiovascular diseases (Lin et al. 2009; Knowlton et al. 2009; Michelozzi et al. 2009; Mastrangelo et al. 2007; Kovats et al. 2004) during hot weather, and other researchers (Michelozzi et al. 2009) have also noted the disparity between cardiovascular morbidity and mortality response. The results here are also weaker than the broadly observed increases in respiratory admissions (Monteiro et al. 2013; Knowlton et al. 2009; Michelozzi et al. 2009; Mastrangelo et al. 2007), though it should be noted that for Lag 0 at least, during June–August statistically significant increased risk is observed.

There has been increased interest in examining the role of intraseasonal acclimatization upon the heat-health relationship, as research has suggested that early-season heat waves may be more impactful (e.g., Ng et al. 2013; Guirguis et al. 2013; Sheridan and Kalkstein 2004; Hajat et al. 2002). In this research, this acclimatization was assessed by subdividing 'spring' (April and May) from 'summer' (June through August). That the SSC weather types change in character over the course of the season is relevant here, as heat events identified in the spring would be less oppressive in an absolute sense than the summer, although their anomaly from the seasonal normal is greater. In comparing seasons, for a 0-day lag only, statistically similar results are observed between spring and summer for most causes, in particular for short-term heat events. For longer heat events, results are generally stronger in summer, especially for cardiovascular mortality.

A stronger seasonal distinction emerges when examining the collective impact of heat events via assessing the cumulative relationship between heat events and health outcomes. In this research, all results during spring (except for direct heat-related hospital admissions) are no longer statistically significant once the 15-day cumulative lag effects are assessed, suggesting substantial mortality displacement occurs. For summer, there is generally no statistically significant increase in risk during shorter-term heat events (first or second days) once lags are accounted for, while for longer events (third day or longer) statistically significant increases still are observed. This distinction may address the ambiguous results shown in literature with regard to harvesting, with some studies showing substantial harvesting percentages (e.g. Hajat et al. 2006), while others that have focused on individual extreme heat events have shown lower values (e.g. Kaiser et al. 2007; Toulemon and Barbieri 2008).

The two-part temporal analysis in this research collectively shows a trend toward somewhat lower all-cause and cardiovascular mortality impacts (with some of the differences statistically significant), with generally similar heat-related hospitalizations over time. As stated above, a number of studies have noted the general decline in heat-related mortality over time across the developed world; the decreases observed here may be attributed to increased air conditioning, along with improvements in care for some factors associated with increased heat vulnerability (e.g. cardiovascular illness) as well as decreases in the percentage of the population with behaviors that increase risk, such as smoking (Bobb et al. 2014).

This noted, interesting temporal patterns emerge, with the later period showing a shorter duration in which all-cause mortality is observed to significantly increase, along with a sharper increase in heat-related hospital admissions followed by a steeper decrease in the days afterward. This decrease in heat-related mortality, coupled with the observed changes in the pattern of hospitalizations, suggests that there may also be a greater awareness of the dangers of heat, perhaps due to HWWS (e.g., Toloo et al. 2013). Thus, a greater amount of hospitalizations in the short term during a heat event could be associated with an overall decrease in mortality (e.g. Ebi et al. 2004). This said, given the different responses across season and length of heat event, and marginal significance to the present results, further research should be undertaken to evaluate the significance of these trends.

Several limitations should be acknowledged with this study. First, the synoptic meteorological approach, in particular the SSC approach, identifies heat events based on varied seasonal thresholds and using a holistic assessment of the day, resulting in a somewhat different identification of heat events from other methods. That said, the collective ability of the SSC to identify increases in mortality is similar to other metrics (Hajat et al. 2010). To simplify our analyses, a number of decisions were made in terms of how to partition our data set. Different definitions of the warm season as well as the way years were subsetted could affect the results, although several permutations that we evaluated as the research progressed did not suggest the conclusions would be different. Similarly, we assessed the impacts of varying the lag structure or length, and this did not appreciatively affect the outcome (unless the lag was entirely ignored). While we did test the robustness of the selection of breakpoint year, our grouping together of multiple years does mask that there is still substantial year-to-year variability in health response as well as heat events within each of the subsets. Still other factors, such as atmospheric pollution levels, which have a complicated confounding relationship with high temperature events (Reid et al. 2012), and have been associated with hospitalizations in New York (Jones et al. 2013; Garcia et al. 2011) are not separately examined here.

Conclusions

In this study, hospital admissions and mortality have been systematically analyzed across heat events; the results support some previous research that has observed somewhat divergent results between mortality and morbidity outcomes (Nitschke et al. 2007; Kovats et al. 2004). There is a clear variability in health response during heat events in New York City, depending upon health outcome, season, time, duration, and whether or not lagged effects are accounted for. Among the SSC weather types, DT and MT+ are the two most affiliated with negative health outcomes, as is the case with previous research. Impacts are generally greatest on a 0-day lag in most cases, with a 1-day lag slightly higher in a few subsets. Mortality displacement is noticeable in many of the mortality analyses performed. Mid-summer, long-duration heat events clearly still have a statistically significant impact on overall heat-related hospitalization and all-cause and cardiovascular-related mortality, although the effects on mortality may be diminished more recently. For shorter-term events or early-season events, the impacts are more variable, with the suggestion that much of the impact is short-term displacement. Further research with additional data, and for additional locations, should work to assess the spatio-temporal consistency in these trends.

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References

Anderson BG, Bell ML (2009) Weather-related mortality, how heat, cold, and heat waves affect mortality in the United States. *Epidemiology* 20:205–213

Anderson BG, Bell ML (2010) Heat waves in the United States: mortality risk during heat waves and effect modification by heat wave characteristics in 43 U.S. Communities. *Environmental Health Perspectives* 119:210–218

Baccini M, Kosatsky T, Biggeri A (2013) Impact of summer heat on urban population mortality in Europe during the 1990s: an evaluation of years of life lost adjusted for harvesting. *PloS ONE* 8:e69638

Barnett AG (2007) Temperature and cardiovascular deaths in the US elderly: changes over time. *Epidemiology* 18:369–372

Bassil KL, Cole DC, Moineddin R, Craig AM, Wendy Lou WY, Schwartz B, Rea E (2009) Temporal and spatial variation of heat-related illness using 911 medical dispatch data. *Environmental Research* 109:600–606

Bassil KL, Cole DC, Moineddin R, Lou W, Craig AM, Schwartz B, Rea E (2011) The relationship between temperature and ambulance response calls for heat-related illness in Toronto, Ontario, 2005. *Journal of Epidemiology and Community Health* 65:829–831

Basu R (2009) High ambient temperature and mortality: a review of epidemiologic studies from 2001 to 2008. *Environ Health* 8:1–13

Basu R, Ostro BD (2008) A multicounty analysis identifying the populations vulnerable to mortality associated with high ambient temperature in California. *American Journal of Epidemiology* 168:632–637

Bobb JF, Peng RD, Bell ML, Dominici F (2014) Heat-related mortality and adaptation to heat in the United States. *Environmental Health Perspectives*. doi:10.1289/ehp.1307392

Bouchama A, Dehbi M, Mohamed G, Matthies F, Shoukri M, Menne B (2007) Prognostic factors in heat wave-related deaths, a meta-analysis. *Archives of Internal Medicine* 167:E1–E7

Danet S, Richard F, Montaye M, Beauchant S, Lemaire B, Graux C, Cottel D, Marécaux N, Amouyel P (1999) Unhealthy effects of atmospheric temperature and pressure on the occurrence of myocardial infarction and coronary deaths a 10-year survey:

The Lille-World Health Organization MONICA Project (Monitoring Trends and Determinants in Cardiovascular Disease). *Circulation* 100:e1–e7

Davis RE, Knappenberger PC, Novicoff WM, Michaels PJ (2002) Decadal changes in heat-related human mortality in the Eastern US. *Climate Research* 22:175–184

Ebi KL, Teisberg TJ, Kalkstein LS, Robinson L, Weiher RF (2004) Heat watch/warning systems save lives: estimated costs and benefits for Philadelphia 1995–1998. *Bulletin of the American Meteorological Society* 85:1067–1074

Fletcher BA, Lin S, Fitzgerald ED, Hwang SA (2012) Association of summer temperatures with hospital admissions for renal diseases in New York State: a case-crossover study. *American Journal of Epidemiology* 175:907–916

Fouillet A, Rey G, Wagner V, Laaidi K, Empereur-Bissonnet P, Tertre AL, Frayssinet P, Bessemoulin P, Laurent F, Crouy-Chanel PD, Jougla E, Hemon D (2008) Has the impact of heat waves on mortality changed in France since the European heat wave of summer 2003? A study of the 2006 heat wave *International Journal of Epidemiology* 37:309–317

Garcia VC, Gego E, Lin S, Pantea C, Rappazzo K, Wootten A, Rao ST (2011) An evaluation of transported pollution and respiratory-related hospital admissions in the state of New York. *Atmospheric Pollution Research* 2:9–15

Gasparrini A, Armstrong B (2010) Time series analysis on the health effects of temperature: advancements and limitations. *Environmental Research* 110:633–638

Golden JS, Hartz D, Brazel A, Luber G, Phelan P (2008) A biometeorology study of climate and heat-related morbidity in Phoenix from 2001 to 2006. *International Journal of Biometeorology* 52:471–480

Gosling SN, McGregor GR, Páldy A (2007) Climate change and heat-related mortality in six cities. Part 1: model construction and validation. *International Journal of Biometeorology* 51:525–540

Guirguis K, Gershunov A, Tardy A, Basu R (2013) The impact of recent heat waves on human health in California. *Journal of Applied Meteorology Climatology* 53(1):3–19

Hajat S, Armstrong B, Baccini M, Biggeri A, Bisanti L, Russo A, Páldy A, Menne B, Kosatsky T (2006) Impact of high temperatures on mortality: is there an added heat wave effect? *Epidemiology* 17:632–638

Hajat SA, Ben G, Gouveia N, Wilkinson P (2005) Mortality displacement of heat-related deaths: a comparison of Delhi, Sao Paulo, and London. *Epidemiology* 16:613–620

Hajat S, Kovats RS, Atkinson RW, Haines A (2002) Impact of hot temperatures on death in London: a time series approach. *Journal of Epidemiology and Community Health* 56:367–372

Hajat S, Sheridan SC, Allen MJ, Pascal M, Laaidi K, Yagouti A, Bickis U, Tobias A, Bourque D, Armstrong BG, Kosatsky T (2010) Which days of hot weather are identified as dangerous by heat-health warning systems? A comparison of the predictive capacity of different approaches *American Journal of Public Health* 100:1137–1144

Hansen A, Bi P, Nitschke M, Ryan P, Pisaniello D, Tucker G (2008) The effect of heat waves on mental health in a temperate Australian city. *Environmental Health Perspectives* 116:1369

Hondula DM, Davis RE, Rocklöv J, Saha MV (2013) A time series approach for evaluating intra-city heat-related mortality. *Journal of Epidemiology and Community Health* 67(8):707–712

Jones RR, Özkaynak H, Nayak SG, Garcia V, Hwang SA, Lin S. 2013. Associations between summertime ambient pollutants and respiratory morbidity in New York City: Comparison of results using ambient concentrations versus predicted exposures. *Journal of Exposure Science and Environmental Epidemiology* 23:616–626

Kaiser R, Le Terte A, Schwartz J, Gotway CA, Daley WR, Rubin CH (2007) The effect of the 1995 heat wave in Chicago on all-cause and cause-specific mortality. *American Journal of Public Health* 97:158–162

Khalaj B, Lloyd G, Sheppeard V, Dear K (2010) The health impacts of heat waves in five regions of New South Wales, Australia: a case-only analysis. *International Archives of Occupational and Environmental Health* 83:833–842

Knowlton K, Rotkin-Ellman M, King G, Margolis HG, Smith D, Solomon G, Trent R, English P (2009) The 2006 California heat wave: impacts on hospitalizations and emergency department visits. *Environmental Health Perspectives* 117:61–67

Kovats RS, Hajat S, Wilkinson P (2004) Contrasting patterns of mortality and hospital admissions during hot weather and heat waves in Greater London, UK. *Occupational and Environmental Medicine* 61:893–898

Kyselý J, Plavcová E (2012) Declining impacts of hot spells on mortality in the Czech Republic, 1986–2009: adaptation to climate change? *Climatic Change* 113:437–453

Lee CC, Sheridan SC, Lin S (2012) Relating weather types to asthma-related hospital admissions in New York State. *EcoHealth* 9:427–439

Lin S, Luo M, Walker RJ, Liu X, Hwang SA, Chinery R (2009) Extreme high temperatures and hospital admissions for respiratory and cardiovascular diseases. *Epidemiology* 20:738–746

Lin S, Hsu WH, Van Zutphen AR, Saha S, Luber G, Hwang SA (2012) Excessive heat and respiratory hospitalizations in New York State: estimating current and future public health burden related to climate change. *Environmental Health Perspectives* 120:1571–1577

Lin S, Luo M, Insaf T, Hwang SA (2012) The effects of ambient temperature variation on respiratory hospitalizations in summer, New York State. *International Journal of Occupational and Environmental Health* 18:188–197

Linares D, Díaz J (2007) Impact of high temperatures on hospital admissions: comparative analysis with previous studies about mortality (Madrid). *European Journal of Public Health* 18:317–322

Mastrangelo G, Fedeli U, Visentin C, Milan G, Fadda E, Spolaore P (2007) Pattern and determinants of hospitalization during heat waves: an ecologic study. *BMC Public Health* 7:1–8

Matzarakis A, Muthers S, Koch E (2011) Human biometeorological evaluation of heat-related mortality in Vienna. *Theoretical and Applied Climatology* 105:1–10

Medina-Ramón M, Schwartz J (2007) Temperature, temperature extremes, and mortality: a study of acclimatisation and effect modification in 50 US cities. *Occupational and Environmental Medicine* 64:827–833

Michelozzi P, de'Donato FK, Bargagli AM, D'Ippoliti D, De Sario M, Marino C, Schifano P, Cappai G, Leone M, Kirchmayer U, Ventura M, di Gennaro M, Leonardi M, Oleari F, De Martino A, Perucci CA (2010) Surveillance of summer mortality and preparedness to reduce the health impact of heat waves in Italy. *International Journal of Environmental Research and Public Health* 7:2256–2273

Monteiro A, Carvalho V, Velho S, Sousa C (2013) The accuracy of the heat index to explain the excess of mortality and morbidity during heat waves–a case study in a Mediterranean climate. *Bulletin of Geography. Socio-Economic Series* 20:71–84

Morabito M, Profili F, Crisci A, Francesconi P, Gensini GF, Orlandini S (2012) Heat-related mortality in the Florentine area (Italy) before and after the exceptional 2003 heat wave in Europe: an improved public health response? *International Journal of Biometeorology* 56:801–810

Ng CFS, Ueda K, Ono M, Nitta H, Takami A (2013) Characterizing the effect of summer temperature on heatstroke-related emergency ambulance dispatches in the Kanto area of Japan. *International Journal of Biometeorology* 2013:1–8

Nitschke M, Tucker G, Bi P (2007) Morbidity and mortality during heatwaves in metropolitan Adelaide. *Medical Journal of Australia* 187:662–665

Nitschke M, Tucker GR, Hansen AL, Williams S, Zhang Y, Bi P (2011) Impact of two recent extreme heat episodes on morbidity and mortality in Adelaide, South Australia: a case-series analysis. *Environ Health* 10:42

Ostro B, Rauch S, Green R, Malig B, Basu R (2010) The effects of temperature and use of air conditioning on hospitalizations. *American Journal of Epidemiology* 172:1053–1061

Pascal M, Laaidi K, Ledrans M, Baffert E, Caserio-Schönemann C, Le Tertre A, Manach J, Medina S, Rudant J, Empereur-Bissonnet P (2006) France's heat health watch warning system. *International Journal of Biometeorology* 50:144–153

Reid CE, Snowden JM, Kontgis C, Tager IB (2012) The role of ambient ozone in epidemiologic studies of heat-related mortality. *Environmental Health Perspectives* 12:1627–1630

Robinson PJ (2001) On the definition of a heat wave. *Journal of Applied Meteorology* 40:762–775

Rocklöv J, Ebi K, Forsberg B (2011) Mortality related to temperature and persistent extreme temperatures: a study of cause-specific and age-stratified mortality. *Occupational and Environmental Medicine* 68:531–536

Rocklöv J, Barnett AG, Woodward A (2012) On the estimation of heat-intensity and heat-duration effects in time series models of temperature-related mortality in Stockholm, Sweden. *Environ Health* 11:1–12

Sanchez CA, Thomas KE, Malilay J, Annest JL (2010) Nonfatal natural and environmental injuries treated in emergency departments, United States, 2001–2004. *Family & Community Health* 33:3–10

Schär C, Vidale PL, Lüthi D, Frei C, Häberli C, Liniger MA, Appenzeller C (2004) The role of increasing temperature variability in European summer heatwaves. *Nature* 427:332–336

Sheridan SC (2002) The redevelopment of a weather type classification scheme for North America. *International Journal of Climatology* 22:51–68

Sheridan SC, Kalkstein LS (2004) Progress in heat watch-warning system technology. *Bulletin of the American Meteorological Society* 85:1931–1941

Sheridan SC, Kalkstein AJ, Kalkstein LS (2009) Trends in heat-related mortality in the United States, 1975–2004. *Natural Hazards* 50:145–160

Son JY, Lee JT, Anderson GB, Bell ML (2012) The impact of heat waves on mortality in seven major cities in Korea. *Environmental Health Perspectives* 120:566–571

Stafoggia M, Forastiere F, Agostini D, Caranci N, De'Donato F, Demaria M, Michelozzi P, Miglio R, Rognoni M, Russo A, Perucci CA (2008) Factors affecting in-hospital heat-related mortality: a multi-city case-crossover analysis. *Journal of Epidemiology and Community Health* 62:209–215

Toloo G, FitzGerald G, Aitken P, Verrall K, Tong S (2013) Evaluating the effectiveness of heat warning systems: systematic review of epidemiological evidence. *International Journal od Public Health* 58(5):667–681

Toulemon L, Barbieri M (2008) The mortality impact of the August 2003 heat wave in France: investigating the 'harvesting' effect and other long-term consequences. *Population Studies* 62:39–53

Uejio CK, Wilhelmi OV, Golden JS, Mills DM, Gulino SP, Samenow JP (2011) Intra-urban societal vulnerability to extreme heat: the role of heat exposure and the built environment, socioeconomics, and neighborhood stability. *Health Place* 17:498–507