6A.3 HEAT WAVE MORTALITY IN LARGE U.S. CITIES

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1. INTRODUCTION

The ability of societies to adapt to ongoing and future climate variations will be critical in determining the ultimate effects of human-induced climate change. With respect to climate change impact research, heat-related mortality remains one of the most important topics, for obvious reasons. In previous work, our research team demonstrated that excess heat-related deaths have declined in major urban areas of the United States as a whole and in most cities where heat mortality is important (Davis et al., 2002, 2003a,b). Specifically in Philadelphia, Pennsylvania, the primary urban area examined in this work, excess deaths declined from an average of about 57 per year per million people in the 1960s and 1970s to only about 12 per year per million people in the 1990s. We attributed these declines to a suite of technological and biophysical adaptations, including improvements in medical care, increased access to air conditioning, and more proactive public measures by localities to warn the populace of heat impacts and to provide remediation to those individuals and groups most in danger.

Our prior work, however, did not address the specific issue of "heat waves." Mortality was examined on hot days independently of whether they occurred as isolated hot days or within a run of consecutive hot days. In this research, we examine heat waves specifically.

There is no standard, widely accepted definition of a "heat wave." One could develop a meteorological definition based on a run of extreme days, with the definition of "extreme" linked to the underlying temperature distribution (e.g., Robinson, 2001). We could then determine if above normal mortality occurred during these runs (Davis et al., 2004a).

Alternatively, one could examine the response variable, in this case mortality, and calculate to what extent high mortality events are linked to above normal heat events.

We selected the latter approach in this research, although both approaches are equally sound methodologically. Thus, our heat wave definition is driven by the mortality response and might not be appropriate for other applications.

Our underlying null hypothesis is that heat wave mortality in Philadelphia has not changed over time. There are a variety of issues that can confound interpretation that we also address.

a) Is there evidence of short-term "mortality displacement" —abnormally low mortality rates on the days immediately following killer heat waves? Some theories suggest that extreme events disproportionately impact the weaker individuals within a cohort, leaving behind a healthier group of individuals who are more resistant to subsequent extremes. With respect to daily mortality counts, this would result in lower than normal deaths rates for a period of days after a mortality-generating heat wave. This is important because analyses of total deaths associated with heat waves should take into account any below normal death totals related to mortality displacement.

b) Does the first heat wave in a year with multiple events generate higher mortality rates than later events? Using similar arguments to the mortality displacement concept, the first heat wave in a season should influence more high-risk individuals than later heat waves, perhaps even if subsequent events are longer or more intense. Furthermore, individuals acclimate to the heat over the course of the season and are perhaps more well-adapted by the second or third summer heat wave.

c) Is there a minimum duration needed for a heat wave to exhibit a mortality impact? If so, this would suggest that individual hot days are less significant than consecutive hot days in which individuals do not receive sufficient respite from the heat to recover physiologically.

d) Is relative heat (departures from some moving normal) as important as absolute temperatures in producing a mortality response? Within a given city, does a heat wave in early May, for example, in which temperatures average 5°C above normal have the

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same mortality impact as a similar heat wave in July or August?

In this report, we examine all of these issues in detail for Philadelphia. Our goal is to clearly develop and test the analytical methods on one city before applying our approach to other large urban areas in the United States.

2. DATA

Daily all-causes mortality counts are recorded from National Center for Health Statistics data archives (1998) for the counties in the Philadelphia Metropolitan Statistical Area based upon the 1990 definition. The daily frequencies are then standardized relative to the mean population distribution of the United States in the year 2000 in ten age groups using the widely-accepted direct standardization procedure (Anderson and Rosenberg, 1998). The resulting daily time series of standardized deaths allows for comparisons both between cities and within a given city over time as the underlying age distribution changes. We examine records for 1964–1998 excluding the years 1967–1972 when the date of death was not available.

The resulting mortality time series exhibits strong seasonal variability with higher mortality in winter than in summer (Davis et al., 2004b), superimposed on a long-term declining trend in mortality rates. To remove both of these effects, we calculated a moving 60-day average and refer to all mortality counts as departures from this value. The 60-day filter was chosen to balance the need to identify short-term responses to heat waves that could last for several weeks while simultaneously attempting to remove any biases that might result from the strong seasonal cycle. Our analysis is confined to the months of April–September because there was no evidence of any major heat-related events for any year between October and March. However, data from the months outside of our April–September window were used in computing the 60-day filter.

Weather data were gathered from the Philadelphia International Airport weather station. After examining a variety of weather variables, including maximum, average, and minimum temperatures and dew point temperatures, we chose 7 a.m. LST apparent temperature (AT) (Steadman, 1979, 1984) as our independent variable as it consistently demonstrated the strongest mortality response. This result is in agreement with prior research suggesting that the lack of evening respite during a heat wave could be more physiologically important than the intensity of the afternoon heat load (Kalkstein and Davis, 1989; Smoyer et al., 2000).

3. METHODS

As our goal is to examine heat waves, we first identify “heat events” as runs of two or more consecutive days of above normal 7 a.m. ATs with the normal defined as the 30-day moving average. This first pass identified 547 heat events in the 29-year record at Philadelphia. Excess mortality was calculated for each heat event (total excess deaths and average excess deaths per day).

The next step is to identify extreme mortality events—these are the events that occur at the extremes of the annual distribution of mortality during heat events. In most years in Philadelphia, there is a clear distinction between extreme mortality events and those that are near the long-term mean. For each year, the extreme mortality events are flagged. Even though all of these events occurred during runs of at least two consecutive days of above normal temperatures, this is not evidence that temperatures were unusually high.

We then identify the maximum 7 a.m. AT within each heat event and label the heat events associated with extreme mortality events. We remove from the group of extreme mortality events those events that were not associated with unusually elevated temperatures. This leaves us with a group of extreme mortality events that include at least one day of extreme heat during a run of warmer than normal days. We label this group of events “killer heat waves.”

Examination of the population of all maximum 7 a.m. ATs within heat events shows that there are some events with high temperatures not associated with extremely elevated mortality. To better identify this set of “non-killer heat waves,” we calculate the least-squares regression line through the maximum 7 a.m. ATs that were associated with mortality events and then identify all temperature events that are within two standard deviations of the residuals from the best-fit line. This procedure identifies “potentially killer heat waves” and the events within this set that are not associated with elevated mortality are thus categorized as “non-killer heat waves.”

This analysis results in four possible categories of heat events:

“Killer Heat Waves”: high mortality associated with extreme heat;

“Non-Killer Heat Waves”: heat waves with no excess mortality;

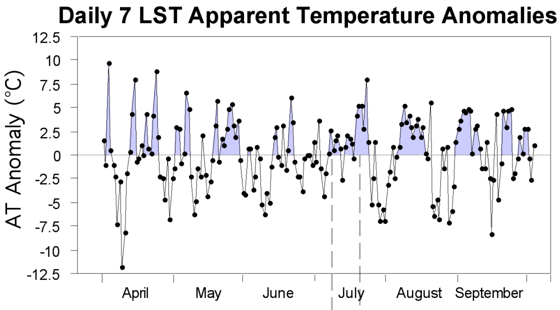
High Mortality, Normal Heat: high mortality events not linked to a heat wave; and

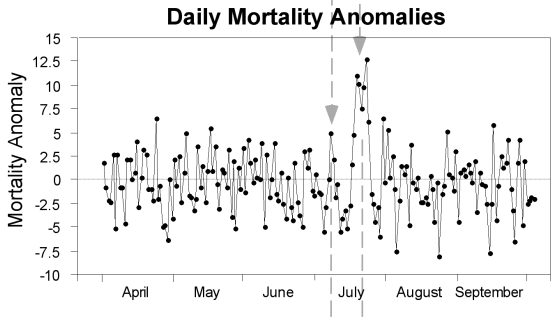
Normal Mortality, Normal Heat: near normal mortality and temperatures.

Each of the 547 heat events in Philadelphia is classified into one of the four categories listed above and the characteristics of the groupings are examined for both within-category temporal changes as well as across-category differences.

4. RESULTS

An example of a typical daily time series of mortality and temperature is presented for April–September, 1977 (Figure 1). This season had 17 heat events (defined as at least two consecutive days with 7 a.m. ATs above the 30-day moving average) (Figure 1a). By inspection, only one or two heat events seem to be linked to high mortality (departures from the 60-day moving average) (Figure 1b). There appears to be a slight elevation in mortality during the heat event of July 5-10 and a much larger mortality event linked to the following heat event of July 17-22. But there is no obvious mortality response to previous or subsequent heat events in 1977. A plot of 7 a.m. AT (Figure 1c) shows that the large mortality event had the highest combination of heat and humidity of the summer, with morning ATs above 27°C for five consecutive days and peaking above 32°C.





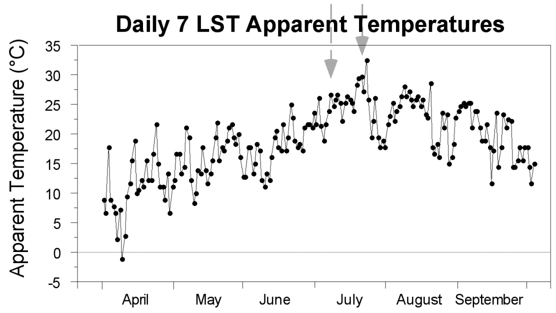
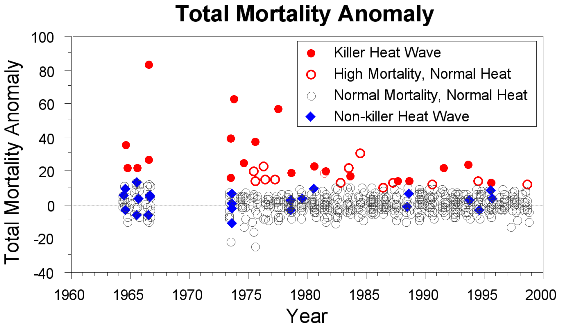


Figure 1a (top): Daily temperature anomalies (departures from the 30-day centered moving average) for the period of April through September, 1977 in Philadelphia, Pennsylvania. Heat events (two or more consecutive days of above normal apparent temperatures) are shaded.
Figure 1b (middle): Daily mortality anomalies (departure from the 60-day centered moving average) for the same period.
Figure 1c (bottom): Daily 7 a.m. LST apparent temperatures (°C) for the same period.

Based on this year alone, there is evidence for a strong mortality response during some heat waves, the possibility of within-season acclimatization, and some evidence of mortality displacement following large mortality events.

Figure 2a depicts the time series of total event mortality with each of the 547 heat events identified in Philadelphia, categorized into one of four categories with respect to mortality and heat wave status. Figure 2b shows the time series of maximum 7 a.m. LST AT within each heat event grouped into the same four categories. High mortality events are presented as red circles and high mortality events during heat waves ("killer heat waves") are filled red circles. It is immediately clear that most high mortality events are also linked to high temperatures. However, there are some high mortality events unrelated to heat ("high mortality, normal heat"), but these are less common (the first ones are not found until 1975). Throughout the data record, there are numerous "non-killer heat waves" (blue diamonds). In fact, most years with killer heat waves also had non-killer events.



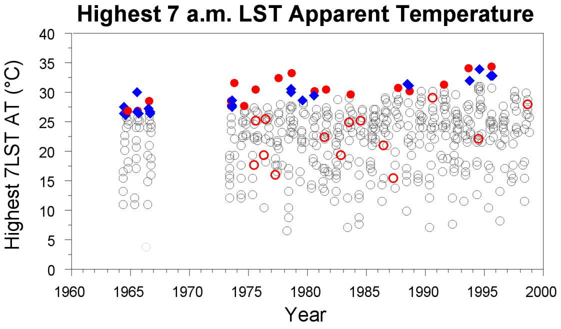


Figure 2a (top): Time series of total event mortality with each heat event categorized into one of four categories with respect to mortality and heat wave status ("killer heat waves"—filled red circles; "high mortality, normal heat"—open red circles; "non-killer heat waves"—filled blue diamonds; "normal mortality, normal heat"—gray circles).
Figure 2b (bottom): Time series of maximum 7 a.m. AT within each heat event categorized into one of four categories with respect to mortality and heat wave status (labeled as in Figure 2a).

To test our null hypothesis of no change in heat wave mortality over time, we regress mortality during all "killer heat waves" versus year (Figure 3a). There is a statistically significant decline in mortality over time (p ≤ 0.05) suggesting that we can reject this null hypothesis. But it is possible that this result is biased by longer heat waves early in the record (resulting in more total heat wave deaths). To examine this possibility, we computed average daily mortality during all "killer heat waves." The regression results (not shown) confirm our rejection of the null hypothesis, so heat wave duration is not a biasing factor.

Interestingly, the decline in heat wave mortality occurred during a period of increasing ATs during heat waves (Figure 3b). Maximum ATs during killer heat waves increased at a faster rate over time (0.18°C/yr) than maximum ATs during all other heat events (0.09°C/yr).

Why are some heat waves killers while others are benign? To attempt to answer this question, we examined the underlying characteristics of each group.

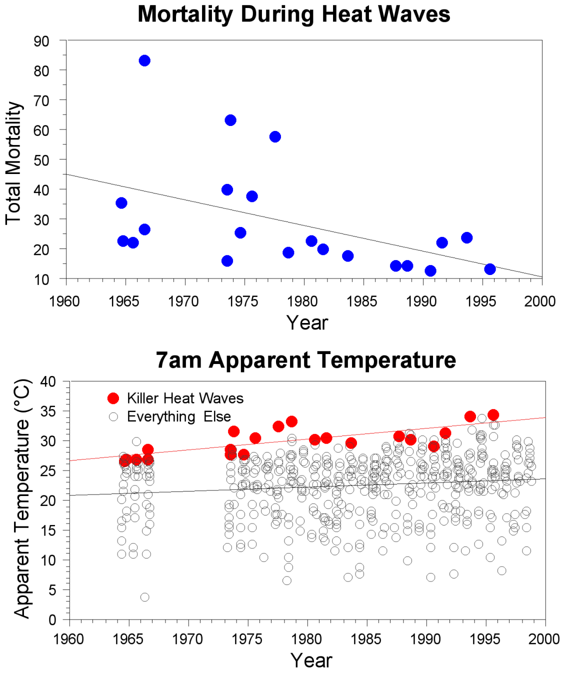


Figure 3a (top): Total excess mortality during "killer heat waves" vs. time. There is a statistically significant negative trend in these data ($p \leq 0.05$). Figure 3b (bottom): Maximum 7 a.m. AT during "killer heat waves" vs. time (red filled circles and 7 a.m. AT during all other heat events vs. time (gray circles). There is a statistically significant ($p \leq 0.05$) positive trend in each group. The magnitude of the trend through "killer heat waves" (0.18°C/yr) is twice that of the trend through the other events (0.09°C/yr).

We first investigated the importance of the order of the event in years with multiple heat waves. Histograms were plotted for "killer" and "non-killer" heat waves (Figure 4). Of the 20 "killer" heat waves, 14 were the first heat wave within that year (in seven of these 14 cases, it was the only heat wave of the year). However, there is no demonstrable preference for the occurrence of "non-killer heat waves." Of the 20 "killer heat waves" in our record, 16 were found in July, two happened in August, and one event occurred in both June and September.

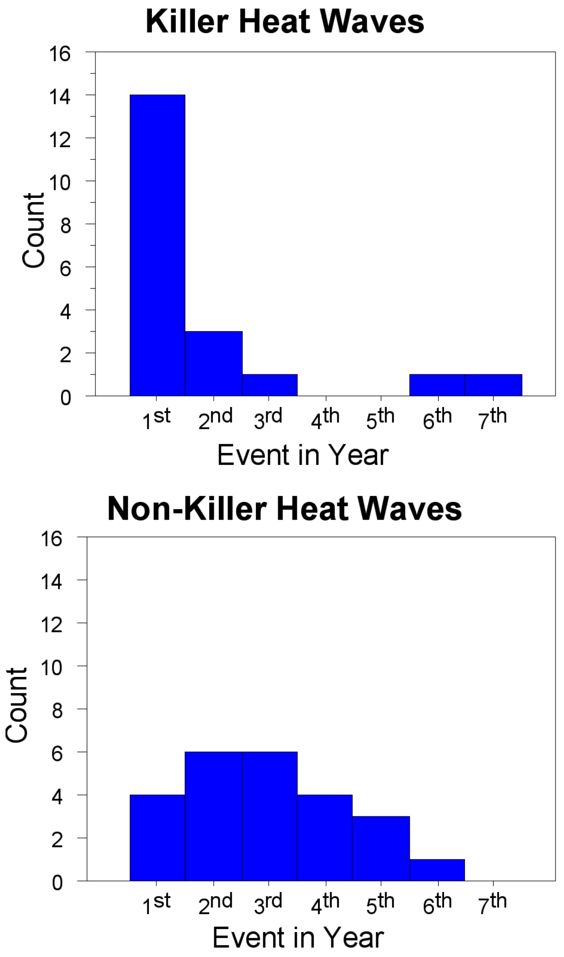


Figure 4: The distribution of the order of occurrence (within each year) of "killer" and "non-killer" heat waves.

We also examined heat wave duration as a determinant of total mortality. Figure 5 shows that all "killer heat waves" lasted at least four days whereas the overall heat event length distribution was heavily weighted towards short events.

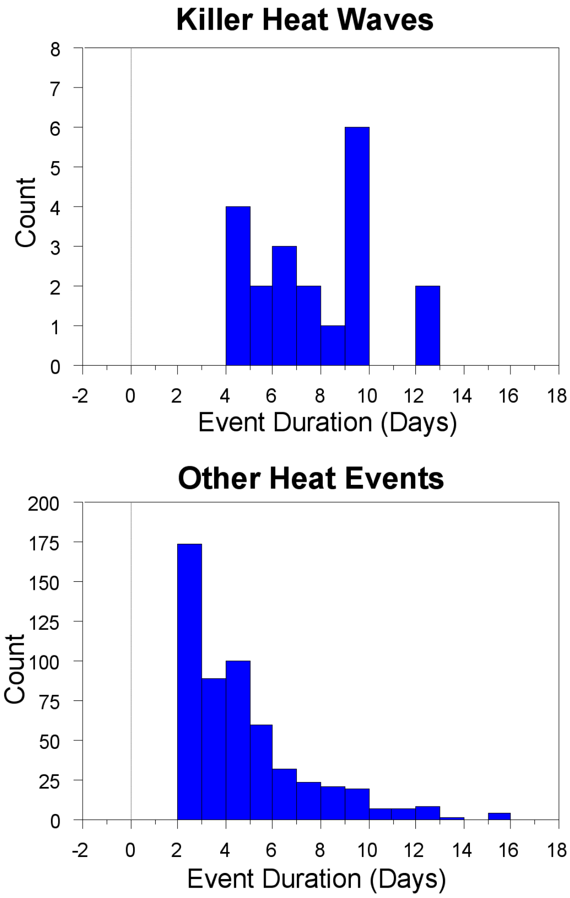


Figure 5: The frequency distribution of heat event duration (days) for "killer heat waves" and for all other heat events.

Next, we compared relative AT departures (from the 30-day moving average) and absolute ATs to determine which variable is better suited to define "killer heat waves." While "killer heat waves" occurred near the positive extremes of absolute 7 a.m. ATs, they fall well within the distribution of relative 7 a.m. AT departures (Figure 6). This indicates that, despite the ability of relative temperature departures to identify early and late season abnormal warmth, the primary determinant of whether a heat event will be a killer lies in the value of the absolute temperature.

Finally, we investigated short-term mortality displacement, the most complex issue. Theoretically, the primary impact of a heat wave will be short term and will exact its toll on the most frail individuals in a cohort. But some individuals will have health repercussions and die later, while others will recover. Thus, there is the possibility of both a period of excess deaths some time after the heat wave peak and particularly, with a more fit population remaining, a period of below normal deaths, which we refer to as mortality displacement in the context of this research. Ultimately, the number of frail individuals will return to pre-heat wave levels.

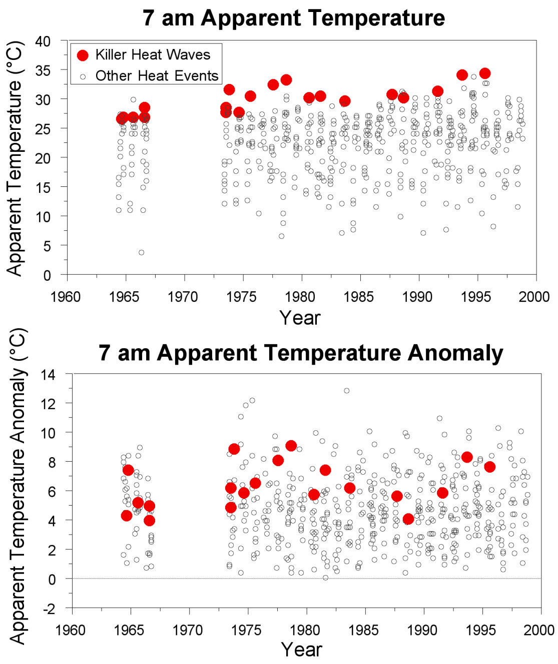


Figure 6a (top): Time series of maximum 7 a.m. AT within each heat event categorized into "killer heat waves" (filled red circles) and all other events (open gray circles).
Figure 6b (bottom): Same as above for maximum 7 a.m. AT departure from the 30-day running mean.

But the heat wave mortality and the possible displacement take place a different temporal scales. The heat wave spike tends to be, on average, more abrupt (with the deaths concentrated over a few days), whereas the displacement is characterized by a broader peak occurring over a longer time period. As motivated by the discussion of Schwartz (2000), we used a series of filters of varying length to examine the existence of mortality displacement following "killer heat waves." We ran a successive series of multiple-day smoothers (4-day through 14-day running means) through the daily mortality anomalies. For each "killer heat wave," we summed the daily mortality anomalies during the smoothed periods that significantly departed (either positively or negatively) from the mean (significance determined by whether the absolute value of the running mean exceeds 2 standard deviations of the mean of all overlapping periods, calculated from full time series, for each filter length). The contribution of mortality displacement to overall heat wave mortality was assessed as the sum of the daily mortality anomalies during significant negative departures divided by the sum of the daily mortality during periods of significant positive mortality departures.

The summer of 1964 is used as an example (Figure 7). The heat wave that peaked on day-of-year (DOY) 183 was obviously linked to high mortality, even though it was, uncharacteristically, the third heat wave of the season in 1964. The mortality peak is followed by a few days of low mortality totals that are immediately proceeded by another heat wave (beginning around DOY 199) that exhibits only a minor mortality spike. The lack of deaths during this latter event could be attributed to some combination of mortality displacement and within-season acclimatization. This latter heat wave is then followed by a period of below-normal deaths that is longer than the previous mortality displacement. It is possible, perhaps likely, that this longer period is linked to the original "killer heat wave" of DOY 183. The 4-day filter of course is successful in identifying the sort-term mortality peak surrounding the DOY 183 event, but both displacement periods are longer and less well-defined. Thus, there is no significant mortality displacement identified for a 4-day event (Table 1). But longer filters (9 and 14 days) both still isolate a heat wave mortality spike but also identify significant displacement that averages from 32 to 38 percent of the heat-wave related mortality count. Because of the low daily mortality totals beginning around DOY 211, the mortality displacement is evidenced more than one month after the "killer heat wave." (Recall that the impacts of possible seasonality biases have been removed by smoothing the mortality time series.)

Because mortality displacement is primarily of interest in relation to high mortality events, we examined the five heat waves with the highest death totals (Table 1, presented for a selected subset of filter lengths). In some cases, no periods of significant negative mortality anomalies followed a "killer heat wave." Heat waves that produced smaller mortality responses would have small mortality displacement that becomes increasingly difficult to detect amidst the background noise—therefore, our top five heat waves are found early in the record. In general, mortality displacement increases as a function of filter length. There is great variation both between heat waves and for different filter lengths within given heat waves, so it is difficult to generalize these results.

Mortality Displacement (percentage)

	Filter Length				
Event	4-day	5-day	7-day	9-day	14-day
6/29/64–7/4/64	—	32.7 (32)	47.3 (32)	68.7 (34)	87.8 (38)
6/27/66–7/14/66	29.8 (18)	29.8 (16)	31.4 (15)	31.7 (16)	54.3 (20)
8/27/73–9/8/73	21.7 (19)	55.4 (47)	41.3 (16)	51.6 (48)	53.8 (1)
8/1/75–8/6/75	38.1 (28)	50.5 (29)	57.7 (25)	62.3 (27)	—
7/17/77–7/22/77	27.5 (7)	30.0 (7)	—	—	—

Table 1. Mortality displacement expressed as a percentage of heat wave mortality for the five largest "killer heat waves" for five different filter lengths (running means). The numbers in parentheses are the number of days between the smoothed period with the greatest positive and greatest negative mean mortality associated with each event.

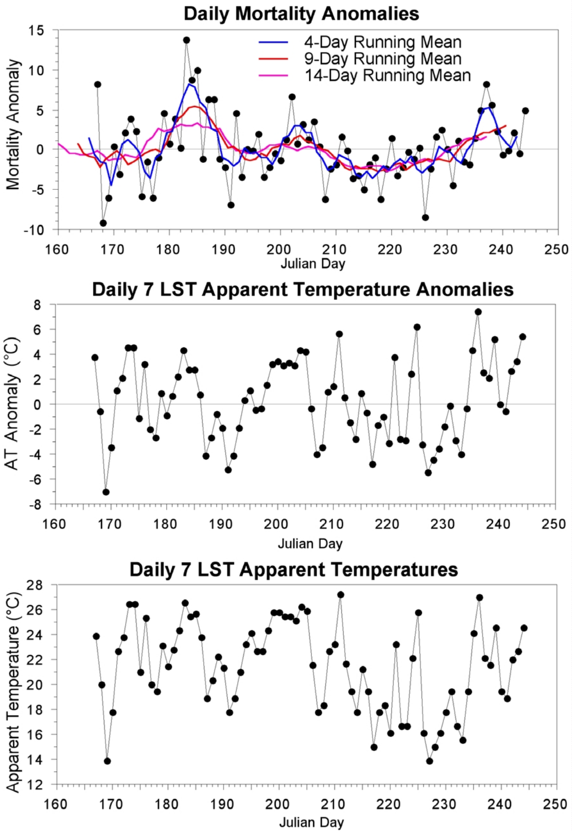


Figure 7a (top): Daily mortality anomalies for the summer of 1964. Various length running means are superimposed on the daily anomalies (4-day running mean—blue line; 9-day running mean—red line; 14-day running mean—magenta line).

Figure 7b (middle): Daily apparent temperature anomalies for the same period.

Figure 7c (bottom): Daily 7 a.m. LST apparent temperatures (°C) for the same period.

5. DISCUSSION

Mortality rates associated with heat waves declined significantly in Philadelphia from 1964–1998. This supports the findings of our previous research in which we did not distinguish between heat waves and isolated hot days. Furthermore, maximum morning ATs within heat waves have increased over time at twice the rate of the AT change during all other heat events. This result suggests that the population is adapting to extreme heat events so that the temperature required to induce a mortality response in Philadelphia is progressively becoming more rare.

The first heat wave within a season tends to be associated with the highest mortality rates, even when it is followed by subsequent heat waves with higher temperatures and/or longer durations. This is possible evidence that some level of within-season acclimatization is occurring. It is also conceivable that mortality displacement is occurring at the seasonal scale—that the first heat wave kills the more susceptible members of the population and the remaining cohort is, on the whole, more capable of dealing with significant heat stress. Both of these factors are probably in play simultaneously.

Because each "killer heat wave" has a unique mortality and AT signature, it is difficult to generalize some issues like mortality displacement for all heat waves. The practice of overlaying different heat waves (aligned by the hottest day, for example) and averaging mortality across days to identify within-heat wave responses or mortality displacement is problematic for Philadelphia, where the between heat-wave variance is high. Although we identified some mortality displacement, the displacement percentage varies between 22 and 88 percent with lags (following the heat wave) of from one to seven weeks. Clearly, much more research is needed on this issue.

In Philadelphia, every heat wave linked to high mortality lasted at least four days. This result has important implications upon ongoing efforts to forecast health-related impacts, including the Philadelphia heat watch/warning system that was first implemented in 1995 (Kalkstein et al., 1996). From a physiological standpoint, the finding supports the idea that high mortality occurs as a result of accumulated heat load over a longer period of time with little opportunity for respite. Recall that our independent variable is 7 a.m. AT, so "killer heat waves" require at least four consecutive hot, humid mornings.

Our most surprising result is that high mortality is much more closely coupled to high absolute ATs than to relative AT departures from normal. There is substantial evidence of a relative mortality response to heat (e.g. Kalkstein and Davis, 1989; Davis et al., 2002, 2003a,b). For example, higher temperature thresholds must be exceeded to increase mortality in a warm, humid location like Washington, D.C. versus a cooler locale like Boston. We expected a similar response within a given city—that abnormal heat in April, for example, would stress a segment of the population that had not yet been acclimated to summer heat, even though the ATs encountered during an April heat wave would be relatively common in July or August. These findings indicate that an absolute AT threshold must be exceeded to generate a mortality response but that a period of unusual warmth that occurs outside of July or August has little net impact. Our observation that "killer heat waves" are linked to increasingly high ATs over time supports a previous finding (Davis et al., 2003b) of temporally increasing threshold ATs in Philadelphia.

In summary, "killer heat waves" in Philadelphia occur primarily in July when the first runs of consecutive days of high morning temperature and humidity occur. Because the first heat wave tends to be the most deadly, subsequent events in a given summer that occur in August and September or later have little impact. Abnormally high ATs in spring or autumn are not linked to high mortality. Furthermore, the ATs needed to produce a mortality response have increased over time. *In toto*, these results provide support for both within-season acclimatization and significant societal adaptations to increasing heat stress over time.

This detailed climatological case study provides a framework for similar evaluations of other major cities. As with most epidemiological research, the results here may not be generalizeable to other locations with inherently different climates or demographics, but these findings for Philadelphia provide us with a set of potential null hypotheses to be tested. Our next step will be to determine the extent to which these Philadelphia observations are also present in cities in the northeastern and midwestern regions of the United States that in prior research have been shown to be "heat-sensitive" (Davis et al., 2002, 2003a,b).

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