9B.1 CLIMATE CHANGE ADAPTATIONS: TRENDS IN HUMAN MORTALITY RESPONSES TO SUMMER HEAT IN THE UNITED STATES

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1. INTRODUCTION AND CONTEXT

In most major U.S. cities, human mortality rates increase as high temperatures, often combined with high humidity, generate uncomfortable conditions (Kalkstein and Davis, 1989; Kalkstein and Greene, 1997). The U.S. National Weather Service issues local heat advisories using a Heat Index that is based upon the Apparent Temperature (AT)—a variable that combines temperature and atmospheric moisture (Steadman, 1979). There is evidence that ATs have increased over time, thereby raising the level of weather stress experienced by the general population, particularly in summer (Gaffen and Ross, 1998). Whether these AT increases are related to human-induced climate change, natural climate variability, urbanization influences, or other factors, it is important to determine the impact higher ATs have had on the populace to allow for possible future predictions.

In this analysis, we examine daily human mortality with respect to afternoon ATs in 28 of the largest U.S. cities. In most cities, mortality increases as ATs become more extreme. We define the point at which mortality begins to increase significantly above the baseline as the Threshold Apparent Temperature (TAT). Thus, days in which the TAT is exceeded exhibit elevated death rates on average.

Theoretically, a wide range of adaptation responses is possible as ATs increase. If TATs remained constant over time and death rates increased, this would be a scenario in which little or no adaptation had occurred. If TATs increased at approximately the same rate as ATs (a simple translation of the mortality–AT distribution) and death rates remained approximately steady, this would signify some level of adaptation, since mortality started to increase at a higher AT value than in the past. Finally, if the TAT no longer existed despite increasing ATs, complete adaptation would have occurred and this city would have become effectively immune to heat-related mortality.

Our goal is to examine decadal-scale changes in human mortality rates on days when ATs are high. We will examine both fixed and variable TATs to determine how death rates are related to the changing background climate. Our results should provide some evidence of the extent to which adaptations to heat stress have occurred throughout the United States since the 1960s.

2. DATA AND METHODS

Daily mortality data were collected from the National Center for Health Statistics archives and include information about each individual who died in the United States from 1964–1998. Our data set consists of 29 non-consecutive years of information because the date of death was not recorded in these files from 1967–1972.

The number of deaths is totalled on a daily basis for 28 of the largest Metropolitan Statistical Areas (MSAs) in the United States which also had high quality hourly surface weather observations for a commensurate period. Data are organized at the county-level based upon the MSA classifications in 1990. Mortality rates vary with demographic changes between MSAs as well as within each MSA over time. To make the data comparable, we performed an age standardization procedure using standard epidemiological methods (Anderson and Rosenberg, 1998). The resulting standardized daily death rates (per 1,000,000 population) can be directly compared both over time and between cities.

The mortality records are organized into three "decades:" 1960–70s (1964–1966 and 1973–1979; 10 total years); 1980s (1980–1989; 10 years); and 1990s (1990–1998; 9 years). The sixties and seventies are combined into one "decade" because high quality daily data were unavailable throughout much of the 1960s.

Surface airways observations were extracted from appropriate stations for each MSA. As our focus is on summer mortality, 4 p.m. LST AT is used as the independent variable. Upon examining the data for possible lag relationships, we determined that a one-day lag (with deaths following the offending weather event) provided the best fit.

Because of the inherent seasonality in mortality at all cities in this study (Davis et al., 2002a), mortality counts were de-seasoned on a daily basis by subtracting from each observation the median mortality for that month (Davis et al., 2002a,b). This procedure removes potential biases that might arise by comparing hot days or heat waves in July vs. September, for example. Thus, the

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dependent variable used throughout the study is total daily mortality age-adjusted to a standard normal ("standardized") and then adjusted again by month ("deseasoned").

Threshold Apparent Temperature Calculation

In general, there is no relationship between mortality and AT. But for some cities, as ATs become higher, mortality also increases. In Cleveland, for example, death rates are significantly elevated when the 4 p.m. AT exceeded 28°C on the previous day (Figure 1a). The "Threshold Apparent Temperature" (TAT) is the AT at and above which mean mortality rates are significantly elevated above the long-term mean. For each city, TATs are calculated by computing the mean mortality for a 2°C AT moving window incremented by 1°C AT. For each 2°C wide class interval, a one-sample, one-tailed *t*-test is performed to determine if the mean mortality is significantly greater than zero (alpha≤0.05). Then, considering higher ATs, the first class interval for which we reject the null hypothesis that the mortality rate is not different from zero is identified as a potential TAT. If all higher AT categories have mean mortality rates greater than zero, then a final *t*-test is performed to determine if all observations equal to and above the TAT candidate have mortality that is significantly greater than zero. The TAT is chosen as the mean AT of the lowest AT class interval that meets the above criteria. For high ATs, the class interval sample sizes become small, so we only utilize class intervals with sample sizes of at least five days.

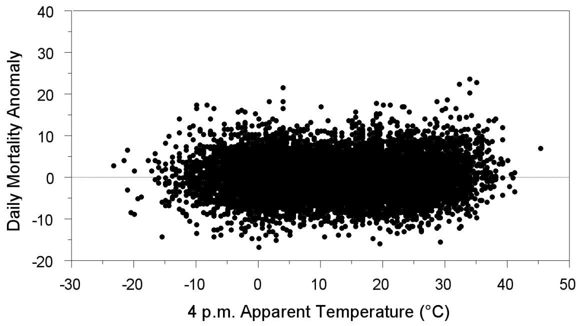

Figure 1a. Daily mortality anomalies vs. daily 4 p.m. apparent temperature in Cleveland, Ohio, Metropolitan Statistical Area.

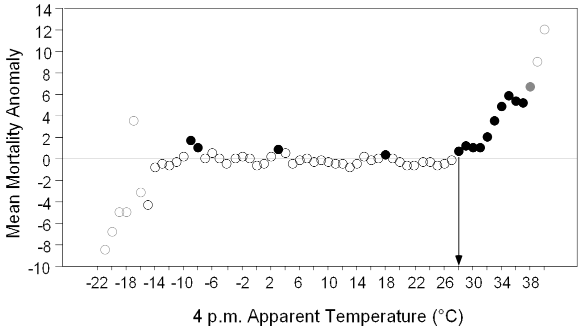

Figure 1b. Average de-seasoned population-adjusted daily mortality for 2°C AT class intervals plotted at the interval midpoint for the Cleveland MSA. Filled circles represent class intervals with significantly elevated mortality based upon a one-sample, one-tailed *t*-test (alpha=0.05). Class interval means depicted by open circles do not have significantly elevated mortality. Gray circles are used for class intervals with five or fewer observations. As indicated by the arrow, the Threshold apparent temperature is determined to be 28°C.

In Cleveland, for example, mortality is significantly above zero for the class interval from 27.0°C–28.9°C, based on a one-tailed *t*-test (Figure 1b). Mean mortality is above normal for all higher AT class intervals, excluding those with small sample sizes. Based on the candidate TAT of 28°C, an additional *t*-test is performed to determine if mortality is significantly elevated for all days with 4 p.m. ATs greater than or equal to 28°C. When this test is passed at the 0.05 level, the TAT for Cleveland is determined to be 28°C.

3. RESULTS

Apparent Temperature Trends

For each of the 28 MSAs, we calculated the number of days per year on which the 1960s–70s TAT was exceeded and performed linear least-squares regression through the annual frequencies. Gaffen and Ross (1998) indicated that ATs above the 85th percentile for most cities were steady or increasing from 1949–1995. Our results, based on a mortality-derived TAT that is MSA-specific, generally support their findings (Figure 2). Nine MSAs have significantly increasing weather stress, six of which are in the southern United States. All but three of the remaining stations exhibit increasing TAT exceedances over time but the changes are not significant. Only one station, San Francisco, has significant declines over time.

Figure 2. Trends in Threshold Apparent Temperature exceedances from 1964–1998 (exceedances/year). Stations with filled bars have statistically significant trends at the 0.05 level.

Mortality Rates Using a Constant TAT

The TAT was calculated for each MSA using mortality data from the 1960s and 1970s only. This TAT was then applied to the two later decades to determine if the established weather–mortality relationship had changed over time.

The presence of a TAT in all cities indicates that each MSA was “weather sensitive” to some degree in the 1960s-70s (Figure 3a). But by the 1980s, six cities no longer had elevated mortality and 10 other cities experienced a significant mortality decline. This trend was accentuated in the 1990s when 11 of the 28 MSAs showed no significantly elevated mortality on days when the TAT was exceeded. Of the remaining 17 cities that remained "weather sensitive" in the 1990s, 11 exhibited significant mortality rate declines in either the 1980s, the 1990s, or both, in comparison to the 1960s–70s. In only six of the 28 cities was mortality both elevated and significantly unchanged since the 1960s–70s. The body of evidence supports the premise that the relationship between high temperatures and humidity established in the 1960s and 1970s had changed over time such that people in the same cities had become less influenced by extreme conditions.

Mortality Rates Using a Variable TAT

The TAT might be expected to change over time for a variety of reasons, including not only a changing climate but socioeconomic and adaptation influences. Here, we compute a different TAT separately for each decade using the same technique described earlier and determine daily mean mortality anomalies above each TAT (Figure 3b). Five cities demonstrate full adaptation (no TAT) in the 1980s—Charlotte, Houston, Norfolk, Tampa, and Phoenix. These are southern/southeastern locations where summer heat and/or humidity are common and where we might first expect adaptation effects to be evident. By the 1990s, seven additional cities had no TAT including some more interior MSAs like St. Louis, Kansas City, and Minneapolis. Phoenix had no TAT in the 1980s but a high TAT was evident in the 1990s. In general, northeastern cities remained weather-sensitive throughout the period of record but most showed declining mortality sensitivity to high ATs. Only three of the 28 cities exhibited higher mean daily mortality anomalies in the 1990s than in the 1960s-70s—Baltimore, Cleveland, and Chicago. A major heat wave in July, 1995 in Chicago resulted in very high mortality counts that were significant enough to influence the decadal mean (Semenza 1996; Palecki et al. 2001). Interestingly, despite this event, the Chicago annual mortality anomaly in the 1990s was comparable to that of the 1980s and still lower than the 1960s-70s (see next paragraph).

Comparison of Weather and Mortality Trends

Using a TAT that varies by decade, we totalled the number of “excess deaths” per year on days when the TAT was equalled or exceeded (Figure 4) and compared these values to the trends in TAT exceedances shown in Figure 2. Of the nine cities with significant positive trends in TAT exceedances, six exhibited declining mortality over time. In the three remaining cities, Portland had lower mortality in the 1990s than in the 1980s and in Denver the 1990s mortality was greater than in the 1980s but much lower than the 1960s-70s. Only Atlanta exhibited the “non-adaptation” trend of increasing TAT exceedances and increasing mortality, and even here the mortality increase was very small. In nearly all of the remaining cities where TAT exceedances have remained steady or increased over time (though not significantly so), mortality declined. The outliers are in Seattle, where the weather became slightly less stressful but mortality increased, and San Francisco, where TAT exceedances declined significantly but mortality remained approximately constant.

4. DISCUSSION

In comparison to the 1960s-70s, daily mortality rates on high AT days in the latter two decades have declined significantly in most cities. In some cases, cities that were “weather sensitive” (i.e., exhibited a TAT) in the earlier decades no longer demonstrated such a mortality response in the 1990s. Thus, most cities examined here have experienced either partial or complete adaptation to high heat and humidity by the 1990s. Eleven MSAs exhibited no TAT in the 1990s or “complete adaptation”—most of these were southern cities but a few are northern and interior locations. In general, northeastern cities continued to show some degree of weather sensitivity over time, although the mortality rates declined in these MSAs, nevertheless.

There is overwhelming evidence that a significant adaptation has taken place with respect to U.S. metropolitan mortality since the 1960s. Here we use the term “adaptation” to refer to the cumulative effect of all possible changes, including long-term acclimatization, biophysical responses, and infrastructural and economic changes including increased access to air conditioning, use of more climate-appropriate building materials, improved health care, etc. The net impact of these changes is that the U.S. populace is now much less influenced by high ATs than it was 3-4 decades ago.

5. CONCLUSIONS

Despite an increasingly hot and humid warm season climate in U.S. metropolitan areas, death rates have consistently declined. In many cities where the stressful conditions increased the most, there was no elevated mortality in the 1990s. If the trends over the past three decades continue, we suspect that “adaptations” in their various forms will almost completely mitigate against heat-related mortality in the United States in the near future. Thus, predictions of increasing heat-related mortality in the United States resulting from anthropogenic climate change are unfounded in light of these observed long-term trends.

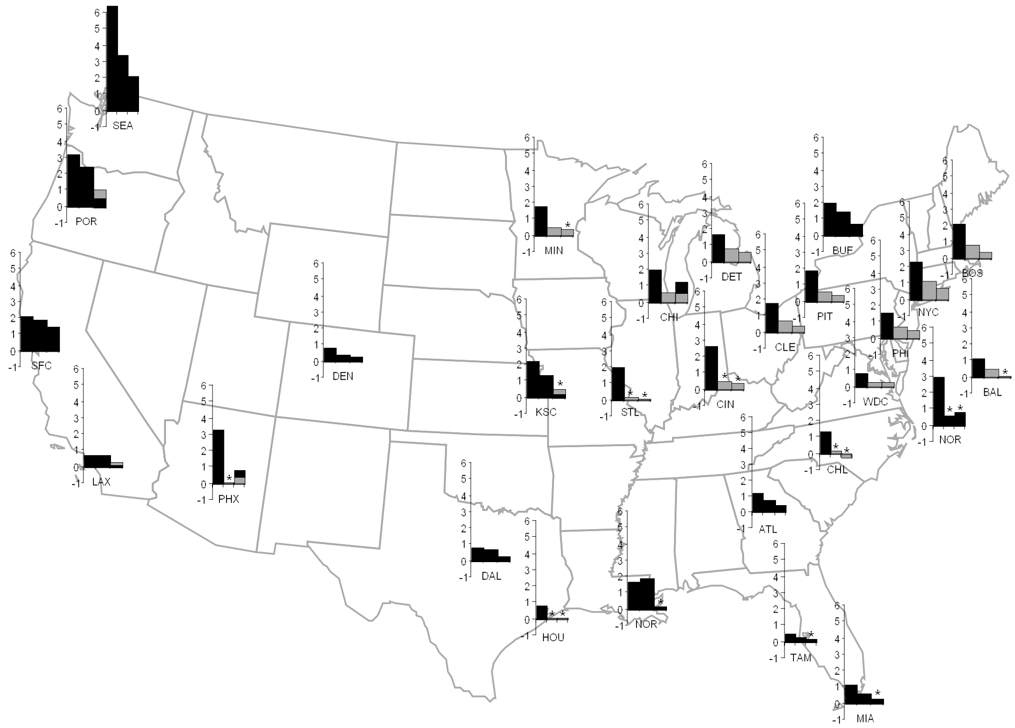

Figure 3a. The average daily mortality anomaly above the 1960s–70s Threshold apparent temperature during each "decade" for all 28 MSAs. The bars are ordered by "decade" ("1964–1966 and 1973–1979," "1980–1989," and "1990–1998" successively) for each city. Decades indicated by gray bars are statistically different from decades plotted with black bars and asterisks (*) above bars indicate that the average mortality anomaly for that decade is not statistically different from zero. In the decade of the 1990s, some bars have two colors. In these cases, the color of the top half of the bar represents the association between the nineties and the sixties/seventies and the color in the lower half of the bar represents the comparison between the nineties and the eighties.

Figure 3b. Same as in Figure 3a, except that the Threshold Apparent Temperature is determined seperately for each "decade."

Figure 4. Annual average excess deaths (for days that exceed the Threshold apparent temperature determined for each “decade”) for each MSA, by decade. For each MSA, the first bar represents the “decade” of the 1960s-70s, the middle bar the eighties, and the third bar the nineties. Deaths have been age-standardized relative to a normal population to allow for direct comparisons over time and between cities.

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