AN ANALYSIS OF POTENTIAL HEAT-RELATED MORTALITY INCREASES IN U.S. CITIES UNDER A BUSINESS-AS-USUAL CLIMATE CHANGE SCENARIO

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Abstract

Heat is the leading cause of weather-related deaths in the United States, responsible for more than 3,400 fatalities between 1999 and 2003. As climate change is projected to raise average mean temperatures over North America by approximately 6.3°-11°F within this century, heatwaves are likely to increase in magnitude and duration in portions of the U.S. where they already occur. This analysis attempts to quantify the projected increase in heat-related mortality due to climate change for 21 U.S. cities by determining the sensitivity of the population of each city to extreme heat events and applying that sensitivity to a projection of mid-century climate conditions. A method to account for acclimatization was also employed, as it is likely that the population will partially adjust to the increased warmth. The findings indicate that for most of the cities studied, climate change is projected to more than double the average number of summertime heat-related deaths, with the greatest increases occurring in mid-latitude major cities where summer climate variability is greatest.

Introduction

Heat ranks among the top weather-related killers in the United States, responsible for more deaths than hurricanes, lightning, tornadoes and floods combined.[1] Between 1999 and 2003, extreme heat killed more than 3,442 people.[2] This may be a conservative estimate, considering that many heat-related deaths are missed by medical examiners; a recent study estimates that heat kills approximately 1,500 people in the U.S. during an average summer.[3] In addition, the Centers for Disease Control (CDC) found in one study that heat-related deaths are under-estimated by as much as 54%.[4]

According to the most recent assessment by the Intergovernmental Panel on Climate Change (IPCC), hot days, hot nights and heatwaves have become more frequent in recent years.[5] As climate change is projected to raise average mean temperatures over North America by approximately 6.3°–11°F within this century,[6] heatwaves are likely to continue to increase in magnitude and duration in portions of the U.S. where they already occur.[7] For example, in California, the number of heat wave days is expected to double in cities like Los Angeles and Sacramento, and the length of the "heat wave season," the period when dangerous heat waves can occur, will increase by about 20 percent by the middle of the next century.[8]

According to the IPCC's most recent report, there are serious implications of this increase; "Without increased investments in countermeasures, hot temperatures and extreme weather are likely to cause increased adverse health impacts from heat-related mortality. . . ."[9]

Extreme heat events affect certain segments of the population more intensely with the elderly being the most vulnerable. Thus, in North America, the aging Baby Boomer generation will bear the greatest brunt of increased heat-related mortality, according to the IPCC, which states that "the population over the age of 65 will increase slowly to 2010, and then grow dramatically as the Baby Boomers join the ranks of the elderly—the segment of the population most at risk of dying in heatwaves."[10]

Other vulnerable groups include the very young, obese individuals, people using medications with diuretic effects, those isolated from social contacts, the mentally ill, those without air conditioning, and outdoor workers.[11] Socio-economic conditions such as education level and poverty also increase risk.[12] One way in which this latter factor operates was demonstrated by a study of the 1995 Chicago heatwave, which found that concern about the cost of utility bills influenced individuals to limit air conditioning use.[13] Another contributor is poor housing conditions (including lack of air conditioning) and cramped living spaces, both of which have been identified as significant risk factors.[14]

This analysis attempts to quantify the projected increase in heat-related mortality in selected United States cities due to climate change in the absence of a significant policy response, and presents estimates of excess deaths that will be attributed to heat.

Summary of Methodology
For readability, the methodology has been summarized and technical terms defined. The full technical methodology appears in the Appendix.

The following factors were considered for this analysis:
- The current sensitivity to extreme heat events for the population of each city studied;
- The meteorological conditions that trigger heat-related mortality;
- The effect of behavioral changes on heat-related mortality; and
- How climate change might alter meteorological conditions by mid-century.

The sensitivity of each city's population to extreme heat and the meteorological conditions causing heat-related deaths was determined by evaluating past temperatures and other meteorological data with historical mortality data covering the period 1975-2004. Meteorological data were compiled by and obtained from the National Oceanographic and Atmospheric Administration's National Climate Data Center. Mortality data were drawn from the National Center for Health Statistics. The meteorological and mortality records also explained how mortality changes in response to temperature, enabling the determination of a "threshold" temperature for each city, above which mortality increases significantly. For the sake of simplicity, the sensitivity to heat events is referred to as the "heat-mortality relationship," and the threshold days are referred to as "Increased Mortality Days."

One way that individuals respond to the most intense extreme heat events is by modifying their behavior to limit their exposure and risk. Responses include limiting outdoor daytime activities, increasing liquids intake, and purchasing and installing air conditioners. This behavior response, known as *acclimatization*, is likely to become the norm as extreme heat events become more intense, frequent, and lengthy. Previous research has estimated acclimatization by assuming that people will respond to heat under climate change conditions as they do today during the very hottest summers.[15] That metric was adopted for this analysis, which determined acclimatization for each location by identifying the five hottest summers encountered during the 30-year study period for each city, and examining heat-mortality relationships during only those periods. These "analog" summers appear to best replicate the summers projected under the climate change scenarios.

A new heat-mortality relationship was measured for those hottest summers using the meteorological variables listed in the appendix (maximum apparent temperature, minimum apparent temperature, a hot consecutive day variable and a time of season variable; refer to appendix for detailed explanation). As expected, in most cases, the new "acclimatized" relationships were weaker and yielded heat-related excess deaths that are smaller than the results produced without this acclimatization procedure. Only the acclimatized results of the analysis are presented here.

Mid-twenty-first century meteorological projections were modeled with the Max Planck Institute's ECHAM5 model in response to a future climate scenario that assumed no major policies to reduce climate change pollution and relatively slow economic growth. The same meteorological variables listed above were extracted from the ECHAM5 model. The ECHAM5 model is one of the models routinely used by laboratories performing climate projections for use by the Intergovernmental Panel on Climate Change (IPCC). The emissions scenario used, the IPCC's "A2," is one of several developed by the IPCC to reflect a "business-as-usual" path for climate change pollution. The A2 scenario assumes a slower rate of economic and technological growth than the IPCC's other business-as-usual scenario, the "A1" scenario. Those assume more rapid economic development and thus produce higher emissions of greenhouse gases, contributing a more upward pressure on temperatures. Use of an A1 scenario would likely have resulted in higher temperatures and thus higher heat-related mortality.

In order to clearly demonstrate the effect of a warming climate on heat-related deaths, population changes were not accounted for in the mid-century projections. The resulting data shows heat-related deaths assuming the population of each city stays the same. If a city gains population, mortality will be higher than the results shown in this analysis. If a city loses population, mortality would be lower.

Cumulative estimates of heat-related deaths were derived by assuming a linear increase in annual summertime heat-related deaths from current levels to mid-century levels and adding together the resulting mortality estimates. In actuality, heat-related deaths are not likely to linearly increase from year to year, but will fluctuate significantly with the annual variability of the summer climate. Assuming a linear increase is however, the fairest way of providing this estimate in the absence of knowing precisely how each city's climate will unfold from year to year.

Such analyses are best accomplished with large cities and metropolitan areas, where there are a sizable number of daily deaths. All the cities in this study were large enough to yield numbers that are meaningful except for Manchester, New Hampshire. For this locale, the developed weather/mortality relationships are for the Boston metropolitan area, a rather short distance away. It is feasible to assume that the populous in cities with similar climates respond similarly to excessive heat events, so using Boston as a surrogate for Manchester is quite valid. Heat-related deaths were then scaled down from Boston to a population that was equivalent to Manchester's.

Results
Results of the analysis are presented in two separate tables. Data are for summertime experiences, not annual. The first table addresses Increased Mortality Days. For each city the following data are presented: the Threshold Temperature at which mortality significantly increases; the current average number of Increased Mortality Days (or days during which the

Threshold Temperature is exceeded); the number of Increased Mortality Days projected for mid-century; and the increase between the current and projected number of such days.

The second table refers to actual heat-related deaths. For each city the following data are presented: the average number of heat-related deaths currently experienced during summertime; the average number of heat-related deaths projected for mid-century on the basis of the climate model; the increase between those two numbers (which reflects the specific effect of climate change) and the estimate of cumulative heat-related deaths projected to occur by mid-century.

Increased Mortality Days

As expected, the results show consistent increases during the summer season in the number of Increased Mortality Days, defined as those days above the threshold temperature when significant excess mortality occurs. Individual city results closely reflect findings in the scientific literature, with the most dramatic changes experienced in the mid-latitudes.

The number of Increased Mortality Days for all the cities combined increases two and a half times, going from a total of 113 per summer to 283. Of the 21 cities studied, only two—Raleigh and Miami—showed no discernable increase in mortality due to extreme heat events. Thus, the results for these two cities are zero, since there is no apparent effect of heat on mortality. This is consistent with other work that shows little heat/health response in warm, subtropical cities.[16]

Increases in Summertime Increased Mortality Days due to Global Warming				
City	Threshold Temperature for Increased Mortality Days	Average Number of Increased Mortality Days per Summer		
		Current Days	Mid-century Days	Additional Days Due to Global Warming
Albuquerque	91	2	7	5
Baltimore	101	6	16	10
Charleston	102*	4	21	17
Chicago	103	10	17	7
Columbus	103	8	17	9
Detroit	102	5	16	11
Houston	110	5	12	7
Las Vegas	112	1	3	2
Little Rock	104*	8	16	8
Los Angeles	100	7	16	9
Manchester	100	4	10	6
Miami	n/a	0	0	0
Minneapolis	104	8	16	8
New York	100	15	22	7
Philadelphia	100	12	21	9
Pittsburgh	100	2	12	10
Portland, ME	87	2	15	13
Portland, OR	88*	2	11	9
Raleigh	n/a	0	0	n/a
Richmond	100*	7	20	13
Washington, DC	100*	5	15	10
Total:		**113**	**283**	**170**

Table 1: Increases in Summertime Increased Mortality Days due to Climate change. Note that Threshold Temperature is the "apparent" temperature which considers temperature and humidity. The * denotes cities where the threshold temperature was set at the highest 20 percent of summer days, since an apparent "jump" in mortality was not found. Please refer to the full methodology in the Appendix.

Heat-related Deaths

The increase in Increased Mortality Days contributes to a similar increase in mortality. For all the cities studied, the number of heat-related deaths estimated for a mid-century summer is projected to more than double, going from 908 heat-related deaths per summer to 1,873. Climate change is projected to more than double the average number of summertime heat-related deaths in most of the cities studied.

| City | Average Heat-related Deaths per Summer | | | Cumulative |
	Current Deaths	Mid-century Deaths	Additional Deaths Due to Global Warming	Deaths Due to Global Warming (Current to Mid-century)
Albuquerque	3	23	20	480
Baltimore	48	141	93	2,232
Charleston	9	21	12	288
Chicago	110	243	133	3,192
Columbus	11	29	18	432
Detroit	50	134	84	2,016
Houston	24	32	8	192
Las Vegas	26	87	61	1,464
Little Rock	11	20	9	216
Los Angeles	35	110	75	1,800
Manchester	13	31	18	432
Miami	0	0	0	0
Minneapolis	32	67	35	840
New York	381	528	147	3,528
Philadelphia	72	234	162	3,888
Pittsburgh	39	49	10	240
Portland, ME	2	4	2	48
Portland, OR	16	30	14	336
Raleigh	0	0	0	0
Richmond	21	83	62	1,488
Washington, DC	5	7	2	48
Total:	908	1,873	965	23,160

Increases in Summertime Heat-Related Deaths due to Global Warming

Table 2: Increases in Summertime Heat-Related Deaths due to Climate change.

Study Characteristics and Limitations
The inherent limitations of localized modeling, the difficulties involved in projecting highly localized climate conditions and the variety of factors that influence actual and recorded heat-related mortality make estimating future mortality challenging and can lead to under- or over-estimates. The study was designed and the data and models were selected to produce the most accurate possible projections. We have tried to remain conservative in our approach to this study, which would minimize the chance of overinflating the mortality projections.

Secondary factors in heat-wave mortality include societal changes made to adapt to rising temperatures, changes in the size of vulnerable populations and the impact of air pollution. These influences are not reflected in this analysis.

As discussed in the methodology, this analysis assumes that individuals can be expected to change their behavior in response to the expected increase in heatwave frequency and intensity. These changes include, for example, taking in more liquids and seeking shade or air conditioning. On average, the acclimatized results produced by this analysis are 28% lower than those that assumed no behavioral response. This is consistent with acclimatization studies of heat-related deaths in New York and Los Angeles, where acclimatization was shown to reduce mortality by 20%–25%.[17]

However, it is difficult to determine the exact degree to which individual behavior will change or how much change can realistically be made. If individuals continue to respond to heat exposure by purchasing air conditioners or avoiding the outdoors during heatwaves, mortality would be lower than the estimates produced here. However, there are limits to the potential for behavioral response. Those people living in poverty, who are among the most vulnerable to heat-waves, are limited in their ability to purchase air conditioners. Likewise, many individuals are required by their jobs to spend time outside, so individual options for reducing exposure may be limited.

Another behavioral change that could reduce mortality would be adaptation measures implemented by governments, such as early-warning and air-conditioning installation programs, or even city redesign. While limited adaptation by different levels of government is likely, a significant response is not assured, and the expectations of widespread adaptation in response to the threat of heatwaves might be reasonably limited.

Another factor in understating the actual outcome is the maturing of the baby boomer generation. As the IPCC stated in its 2007 report on the impacts of climate change on the United States, "Across North America, the population over the age of 65 will increase slowly to 2010, and then grow dramatically as the Baby Boomers join the ranks of the elderly—the segment of the population most at risk of dying in heatwaves."[18]

The study also leans toward conservative results because it assumes a relatively steady increase, with temperatures rising incrementally over the period of study. Actual warming is likely to be much more variable over the next several decades, with gradual increases punctuated by larger and more intense deviations from normal meteorological conditions. The climate projections for this analysis may not fully reflect the potential for these sudden temperature swings. Thus, the cities in this study may experience sudden intense heatwaves that go significantly beyond the "thresholds" developed for this analysis. This will possibly result in more heat-related mortality than the analysis projects.

Conclusion

One of the better-understood impacts of a climate change is the potential relationship between mortality and excessive heat. Previous research has established that increased deaths may be one of many results of higher temperatures, and this report brings this possibility into clearer focus.. This analysis strongly suggests that heat-related mortality will increase if the climate warms as indicated by the ECHAM5 A2 model.   These newer estimates corroborate those developed by the authors in earlier studies, and point to the need for growing awareness about the present and future dangers of heat. The study also indicates a need for the development of sophisticated intervention procedures to lessen the negative health outcomes associated with excessive heat events.

APPENDIX

Detailed Methodology

Estimates of heat-related mortality were developed for the 21 cities in the study. There is a large variability in city size, and climates are considerably different from city to city. Thus, heat/health responses were expected to range from very sensitive to no effect, depending upon the locale. Historically, cities in mid-latitudes with highly variable summer weather have been shown to be most sensitive to negative heat/health outcomes, while those in subtropical or tropical environments with little day to day variation in summer weather are considerably less sensitive.[19]

Daily mortality data were extracted from historical files provided by the National Center for Health Statistics.[20] A 30-year record of mortality data was used, extending from 1975 to 2004. These mortality data are adjusted to account for changes in the total population of the individual cities during the period of record.

Meteorological data for each of the cities were compiled by NOAA's National Climatic Data Center. Because of data limitations in the climate model (based upon grid cells rather than point data), we extracted the following meteorological data, and derived other variables to develop historical weather/mortality relationships for each city:

- Maximum apparent temperature (a value that is computed based upon temperature and dewpoint, which evaluates how conditions "feel" to a typical human. The algorithm for developing apparent temperature is drawn from widely-cited research.)[21]
- Minimum apparent temperature.
- Consecutive days with maximum apparent temperature at least one standard deviation above the mean.
- Time of season for each value, based on Julian date. Historically, more people die from heat-related causes early, rather than late, in the summer season because of acclimatization and the deaths of susceptible people early in the season ("mortality displacement.")[22]

The historical mortality and meteorological variables were evaluated to determine if there is a "meteorological threshold" beyond which mortality increases significantly. This was accomplished by finding that maximum apparent temperature beyond which we see a "jump" in mortality or an upward trend. Such a threshold was found for most of the 21 cities. For 5 of the cities, Charleston; Washington, D.C.; Little Rock; Portland, Oregon; and Richmond, the relationships were weaker, and it was difficult to discern an actual apparent temperature/mortality threshold. For these cities, we utilized the 20 percent of days with the highest maximum apparent temperature as our threshold. For 2 other cities, Raleigh and Miami, even this procedure produced no discernable increase in mortality above the threshold, and we thus assumed that heat does not impact mortality in these two cities. This is consistent with other work that shows little heat/health response in warm, subtropical cities, particularly cities like Miami.[23]

Once the thresholds are established, regressions between the variables listed above and mortality are developed for all days with apparent temperatures beyond the thresholds. The resulting algorithms (all significant to the .05 level or better; for variable inclusion, each variable must exceed a level of .20 or better) are then utilized to determine the historical heat-related mortality

totals. Using Baltimore as an example, the threshold temperature for the city is 101°F, indicating that daily mortality increases significantly when the apparent temperature is at 101° or greater. In an average summer, 6 days exceed the threshold in Baltimore. For all of these days during the period 1975 to 2004, a regression equation was developed between standardized mortality and the meteorological variables listed above. The resulting algorithm for Baltimore is:

excess mort = 0.13 + 1.27DIS - 0.06Jul + 0.66ATmax,

where DIS is day in sequence (consecutive days with maximum apparent temperature at least one standard deviation above the mean), Jul is the Julian date number for the year (June 1=152, June 2=153, etc.), and ATmax is the maximum apparent temperature. This is an intuitive algorithm, as mortality rises by 1.27 deaths with each added consecutive day, it goes down by 0.06 deaths with each day later in the year, and it goes up by 0.66 death for each added degree of maximum apparent temperature.   Utilizing this algorithm during the 30-year study period of 1975-2004, the average daily excess death total (heat related deaths) for days above the threshold is 8. Multiplying this by the average of 6 days that are above the threshold annually in Baltimore gives us an average summer season heat mortality total of 48 deaths. Of course, the number of heat-related deaths varies considerably from one year to the next, but the 30 year summer average is 48. These values are compiled in Table 2 for all the cities.

The algorithms for all the cities, along with their threshold temperatures, are utilized to develop estimates of heat-related mortality using a climate change model developed by the Max Planck Institute in Germany, ECHAM5. This well-established model is one of the baseline models for the IPCC, and most important, uses the same variables employed in this study.[24] The $C0_2$ scenario we selected is the A2 model from the IPCC Standard Reference Emissions Scenarios list. The A2 scenario envisions population growth to 15 billion by the year 2100 and rather slow economic and technological development. The A2 scenario is one of the standards used by the latest IPCC report, and is described in detail within the *IPCC Special Report on Emissions Scenarios*.[25]   Although it assumes a slow technological development, it contains provisions for robust agricultural development; thus, temperature increases for A2 models are generally less steep than the A1 counterparts.[26] (For further details, please refer to the *IPCC Special Report*.)

Climate change scenarios for each of the cities in Table 1 were extracted from the ECHAM5 model for the 20 year period of 2046-2065. The thresholds in Table 1 and the developed algorithms for each city were utilized with these scenarios to estimate heat-related mortality for each of the cities for the 20-year period centered on 2055, based on the ECHAM5 A2 assumptions. The impact of acclimatization was determined by utilizing a procedure we deem superior to the "analog city" approach used in our previous studies.[27] The new acclimatization procedure assumes that people will most likely respond to heat under climate change conditions as they do today during the very hottest summers.[28] Thus, instead of choosing analog cities, which typically possess different demographics and urban structure than the target city, we have selected "analog summers" within the same city, which were the five hottest summers encountered during the 30-year study period. These analog summers best replicate the projected summers seen under the climate change scenarios. For each of the selected cities, the hottest summers were determined based on mean summer apparent temperature values, and a new acclimatization algorithm was developed for days during these hottest summers that equaled or exceeded the apparent temperature thresholds in Table 1. In most cases, the new "acclimatized" algorithms, based on the five hottest summers, should be weaker and yield heat-related mortality numbers that are smaller than the unacclimatized algorithms, such as the one listed above for

Baltimore. This is expected, as people respond less dramatically to heat during more consistently warm temperatures. However, it is also expected that, using the ECHAM5 scenario, the increased frequency of extremely hot days will more than compensate for the lesser daily impact of hot weather, yielding higher heat-related mortality totals than present for most cities even if acclimatization does occur.

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