Exposure to extreme-heat in the United States: drivers, historic patterns, and mortality

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Introduction

Climate change risks are a function of both the nature of physical hazards related to climate and the vulnerability of society and ecosystems to those hazards [1]. Recognition of the importance of assessing human exposure and vulnerability to climate-related hazards is growing as evidenced by the treatment of risk and vulnerability in the IPCC Special Report on Extremes [1], the recent Working Group II report of the IPCC Fifth Assessment Report [2], and the third National Climate Assessment [3]. Vulnerability itself can be viewed as a function of the exposure and sensitivity of society to hazards and its capacity to adapt [1]. These three aspects of vulnerability change over time, influencing the magnitude of the risk from extreme events. Recent work [e.g., 4] attempts to characterize patterns of future exposure to climate-hazards (extreme heat) and decompose the degree to which population and climate change contribute. Here we expand upon this work by examining historical patterns of exposure to extreme heat in the United States, and assessing the relative importance of shifting climate and population in driving these changes. Furthermore, we use this analysis in conjunction with historical heat-related mortality data to assess the relationship between exposure to extreme heat and adverse health outcomes over space. We hypothesize that the relative contributions of population and climate change to exposure, as well as the relationship between exposure and mortality, vary significantly over space.

Extreme heat is currently responsible for more deaths in the United States than any other weather-related event [5, 6], and its frequency and intensity is expected to increase over the course of this century [7, 8]. The physical effects of extreme heat on human populations are well-documented [9-11], and certain demographic and socioeconomic factors heighten vulnerability to heat-related health problems, such as age, income, and level of education [9, 11]. Understanding how climate and population shifts combine to drive changes in exposure to extreme heat events is a key component of understanding vulnerability and, subsequently, to adequate planning and mitigation for future events [12]. There is no universally agreed upon definition of extreme heat, but it has been found that alternative temperature and humidity metrics lead to similar outcomes in studies of heat-related mortality [13]. Additionally, excess mortality related to extreme heat events can be effectively described as the independent effect of individual days' temperature rather than as a function of multi-day heat waves [14]. A similar multiplicity of approaches exists in regards to quantifying exposure and/or vulnerability, and a number of studies have attempted to estimate future changes in heat-related mortality that can be attributed to climate change at the city [15], state [16], and national [17] scale. However, most attempts to quantify future climate-driven changes in mortality lack consideration of population change [18], thus effectively ignoring a potential crucial component of exposure and vulnerability. As such, it is not surprising that the recently completed third National Climate Assessment identifies as a key research goal "understanding how climate uncertainties combine with socioeconomic and ecological uncertainties and improve ways to communicate the combined outcomes" [19]. In this work we focus on systematically quantifying historic exposure to extreme heat in the United States as a function of both climate and population change. The work is a step toward understanding how patterns of exposure emerge as a result of the interaction between changes in population structure and regional climate, which will have implications for how we think about potential adaptation and mitigation strategies.

Data

Meteorological data, including maximum and minimum daily temperature and relative humidity, are from the University of Idaho Gridded Surface Meteorological Data [METDATA, 20]. METDATA are produced at 4km resolution for the contiguous United States using spatially explicit climate and terrain data from the PRISM historical dataset and the NASA North American Land Data Assimilation System (NLDAS-2), and have been validated against observed station data. In this work we will use daily temperature and humidity measurements from METDATA, which are available for the period 1979-2014.

Data on heat-related mortality are from the CDC National Center for Health Statistics [NCHS, 21]. Prior to 1989 mortality data include exact dates, geographic identifiers, and International Statistical Classification of Diseases and Related Health Problems (ICD) code. For the period 1990-2011 data include geographic identifiers (county-only), year, month, and day of the week (no exact dates), and IDC code. For purposes of this work we will aggregate mortality data to the county level by year and month.

Population data, including counts, urban/rural status, and age structure are from the US Census Bureau. Our analysis requires population data at the county-level and organized on a raster grid. Block-level data are used to interpolate population counts and characteristics to the METDATA 4km grid, while county-level data come from the 1980-2010 decadal censuses as well as the intercensal estimates.

Analysis

This work will is based on two primary research questions, (1) how has population exposure to extreme heat in the U.S. changed and what are the relative contributions of population and climate change to shifts in exposure, and (2) what is the relationship between exposure to extreme heat and heat-related morbidity/mortality? In both cases we are considering the contiguous United States and will assess spatial variation in outcomes. To assess exposure and its relationship to morbidity/mortality we require a definition of extreme heat. In this work we will test multiple measures, however for purposes of illustration will adopt the metric from Jones et al. (2014), a daytime high temperature above 35° C.

To address question one we consider three 10-year periods (1980-1989, 1990-1999, and 2000-2009) and the observed change occurring between each 10-year period (denoted here as 1985-1995 and 1995-2005). For each period we will produce 4km gridded distributions of the average number of annual days above 35° C and the population, including age structure[1]. Exposure to temperatures in excess of 35° C is calculated by multiplying the population in each grid cell (total and disaggregated by age) by the average number of observed annual days above 35° C for that cell. As such, exposure is expressed in person-days. We will produce a spatially explicit distribution of exposure for each period (total population and age specific), and from those we will calculate change between periods (e.g., change between observed exposure in 1985 and 1995). In addition to distributions, we aggregate person-days from grid cells to states, census divisions and regions, and the national-level.

To assess the relative contribution of population and climate change to exposure over each period we will consider four additional historic scenarios. To assess the impact of climate on changes in exposure we will assess exposure under a hypothetical scenario in which population remains constant between periods. For example, we hold the observed average population distribution over the first period (1980-1990) constant but expose that population to the average observed number of annual days above 35° C for the second period (1990-2000). If we compare this distribution to that of the first period we isolate the portion of the change in exposure that resulted from a shifting climate. We refer

[1] We use 10-year periods to limit the impact of single year meteorological anomalies. Population averages are constructed as the mean of the observed census counts (by age) for the decadal census at the beginning and end of the period.

to this as the climate effect. To assess its opposite, the population effect, we do the reverse – hold observed climate data constant in the initial period and exposing the population from the subsequent period. Prior work [4] indicates that a third effect is present when this type of analysis is applied, the interaction effect. This effect can be characterized as the change in exposure that results from spatially explicit changes in population and climate that occur simultaneously. We will calculate each of these three effects for the periods 1985-1995 and 1995-2005.

It has been found that multiple forces contribute to the population effect, including aggregate national population growth, regional population redistribution (e.g., migration), and changes is local/urban spatial distribution [4]. To further decompose the population effect we consider two additional scenarios in which climate it held constant. In the first we hold the spatial distribution of the population in the base-period constant and scale the population in each grid cell by the observed change in the aggregate national-level population. From this scenario we can extract the importance of aggregate population change relative to population redistribution and changes in local spatial structure. In the second scenario projection we allow for broad-scale migration/redistribution between census divisions, but hold the base-year spatial distribution within each census division constant. From this scenario we separate the effect of broad scale redistributions from that of changes in local/small-scale spatial structure.

To address question two we will begin by interpolating observed climate data to the county-level. Using county-level census data (including intercensal estimates) will recalculate observed exposure at the county level, however in this case on a monthly basis. For example, for each year and month for which we have temperature data we will expose the population (total and by age) at the county level to the observed number of days above 35° C corresponding to that county. The result will be a monthly time-series record of exposure to temperatures above 35° C at the county-level for the period 1979-2010 with age-specific detail. We will use this data, in conjunction with mortality data that have been similar aggregated, in a multivariate regression analysis accounting for spatial and temporal autocorrelation, climate factors and other factors, to identify the relationship between mortality and exposure [e.g., 22].

Results from prior work and preliminary results

Previous related work, presented at the 2014 PAA annual meeting and currently under review for publication, found that, under the SRES A2 scenario [23], exposure to extreme heat will increase some four- to six-fold nationally by the mid 21st century. Furthermore, it was found that changes in population were as important as changes in climate in driving this outcome. Aggregate population growth, as well as redistribution of the population across larger US regions, strongly affected outcomes while smaller-scale spatial patterns of population change had smaller effects. The relative importance of population and climate as drivers of exposure varied across regions of the country [4].   One purpose of our current work is to provide a baseline against which to measure these projected results. The figures below illustrate some of the key findings from our previous work.

Figure 1 includes (a) the projected change in the spatial distribution of the population under the A2 scenario produced using the National Center for Atmospheric Research downscaling model [24], (b) the corresponding change in the average annual number of days above 35° C projected using the eleven-member ensemble of climate models from the North American Regional Climate Change Assessment Program [NARCCAP, 25], and (c) the projected change in exposure that results.

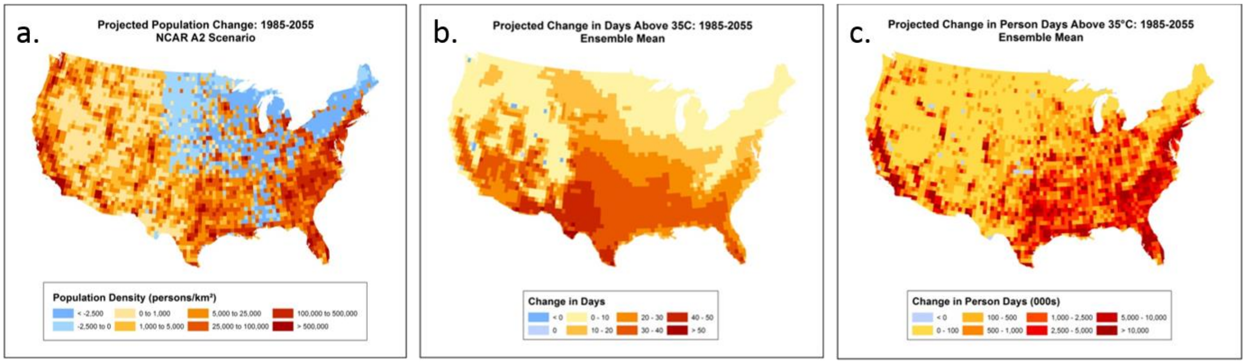

Figure 1. Projected change in the (a) spatial population distribution under the NCAR A2-scenario, (b) mean annual number of days above 35°C, and (c) annual exposure in person-days; 1971-2000 through 2041-2070.

From these data we were able to describe spatial characteristics of the projected change in exposure at multiple scales. To decompose exposure into the climate and population effects we held one element constant (population or climate), and allowed the other to evolve. Figure 2 illustrates the relative contribution of the climate, population, and interaction effects at the national level while Figure 3 does the same at the level of the US Census Division. The population effect was further decomposed and it was found that aggregate population change (57%) and broad-scale migration/redistribution of the population across Census Divisions (34%) accounted for most population-driven change, while changes in local spatial patterns (9%) were responsible for considerably less.

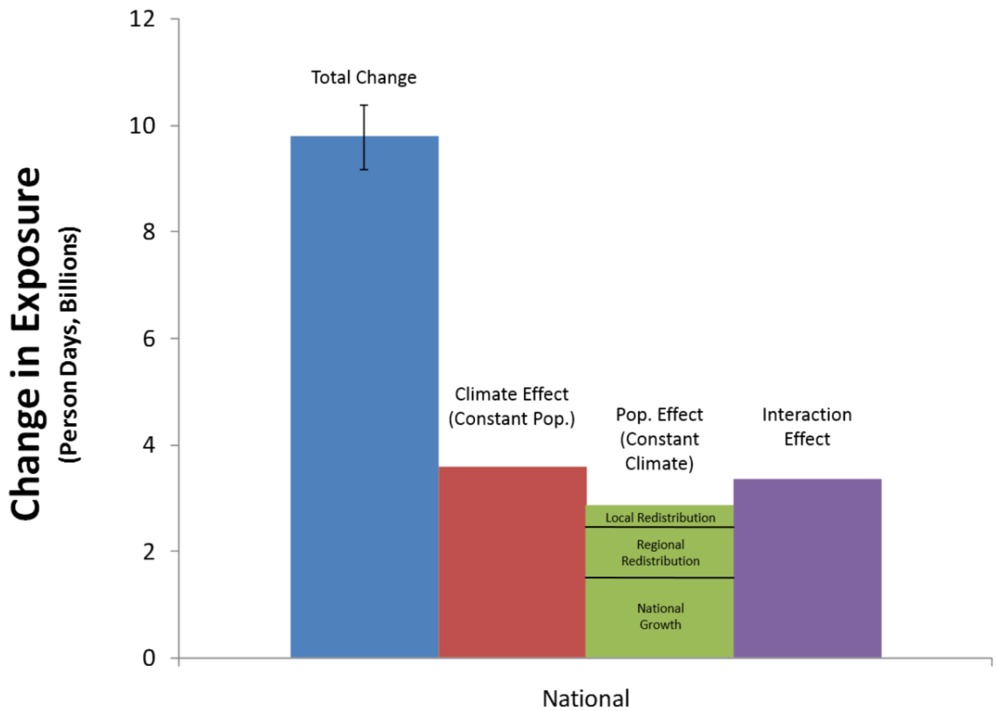

Figure 2. Decomposition of aggregate national-level projected change in exposure; error bar represents the standard deviation in projected exposure across the climate-model ensemble.

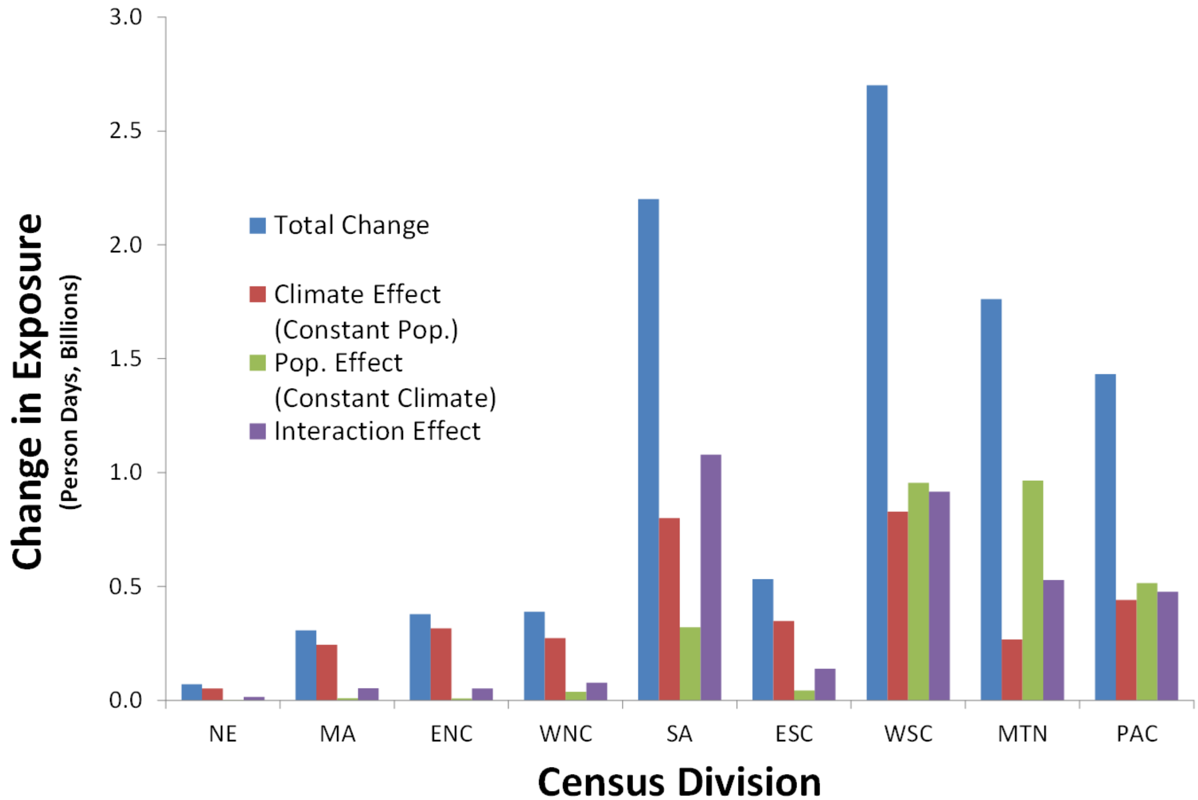

Figure 3. Decomposition of aggregate division-level change in exposure.

References

1. Cardona, O.D. *et al.*Determinants of risk: exposure and vulnerability. In: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation*. *A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change*. (Cambridge University Press, 2012).
2. IPCC. *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.*(Cambridge University Press, 2014).
3. Luber, G. K. *et al.*Ch. 9: Human Health. In: *Climate Change Impacts in the United States: The Third National Climate Assessment*, 220-256. (U.S. Global Change Research Program, 2014).
4. Jones, B. *et al*. Future population exposure to U.S. heat extremes. Submitted to: *Nature Clim. Change* (August 2014).
5. Luber, G. &McGeehin, M. Climate change and extreme heat events. *Am. J. Prev. Med.* 35, 429-435 (2008).
6. CDC. *Climate Change and Extreme Heat Events.* Available at: http://www.cdc.gov/climateandhealth/pubs/ClimateChangeandExtremeHeatEvents.pdf (2012).
7. Duffy, P. B. & Tebaldi, C. Increasing prevalence of extreme summer temperatures in the U.S. *Clim. Change* **111**, 487-495 (2012).
8. Kharin, V. V., Zwiers, F. W., Zhang, X. &Wehner, M. Changes in temperature and precipitation extremes in the CMIP5 ensemble. *Clim. Change* **119**, 345-357 (2013).

9. Anderson, B. G., & Bell, M. L. Weather-related mortality: how heat, cold, and heat waves affect mortality in the United States. *Epidemiol.* **20**, 205-213 (2009).
10. Kovats, R. S. &Hajat, S. Heat stress and public health: a critical review. *Annu. Rev. Public Health*. **29**, 41-55 (2008).
11. McGeehin, M.A. &Mirabelli, M. The potential impacts of climate variability and change on temperature-related morbidity and mortality in the United States. *Environ. Health Perspect.* **109**, 185–189 (2001).
12. Moss, R. P. L. *et al.*Ch. 26: Decision Support: Connecting Science, Risk Perception, and Decisions. In: *Climate Change Impacts in the United States: The Third National Climate Assessment*, 620-647. (U.S. Global Change Research Program, 2014).
13. Barnett, A.G., Tong, S. & Clements, A.C.A. What measure of temperature is the best predictor of mortality? *Environ. Res.* **110,** 604-611 (2010).
14. Gasparrini, A. & Armstrong, B. The impact of heat waves on mortality. *Epidemiology* **22,** 68-73 (2012).
15. Knowlton, K. *et al*. Projecting heat-related mortality impacts under a changing climate in the New York City region. *Am. J. Public Health* **97**, 2028–2034 (2007).
16. Ostro, B., Rauch, S. & Green, S. Quantifying the health impacts of future changes in temperature in California. *Environ. Res.* **111,** 1258-1264 (2011).
17. Vorhees, S. A. *et al.*Climate Change-Related Temperature Impacts on Warm Season Heat Mortality: A Proof-of-Concept Methodology Using BenMAP. *Environ. Sci. Technol.* **45,** 1450-1457 (2011).
18. Bouwer, L. M. Projections of Future Extreme Weather Losses Under Changes in Climate and Exposure. *Risk Anal.* **33,** 915-930 (2013).
19. Corell, R. W. *et al.*Ch. 29: Research Needs for Climate and Global Change Assessments. In: *Climate Change Impacts in the United States: The Third National Climate Assessment*, 707-718. (U.S. Global Change Research Program, 2014).
20. Abatzoglou, J. T. Development of gridded surface meteorological data for ecological applications and modelling. *International Journal of Climatology* (2012).
21. Centers for Disease Control and Prevention, NCHs micro-data. http://www.cdc.gov/nchs/nvss/dvs_data_release.htm
22. Barreca, A. I. Climate change, humidity, and mortality in the United States. *J. Environ. Econ. Mgmt.***63,** 19-34 (2012).
23. Nakicenovic, N. *et al. Special report on emissions scenarios.A special report of working group III of the intergovernmental panel on climate change.* (Cambridge University Press, 2010).
24. Jones, B. & O'Neill, B. C. Historically grounded spatial population projections for the continental United States. *Environ. Res. Lett.* **8,** 044021 (2013).
25. Mearns, L. O. *et al.*A regional climate change assessment program for North America. *EOS* **90**, 311-312 (2009).