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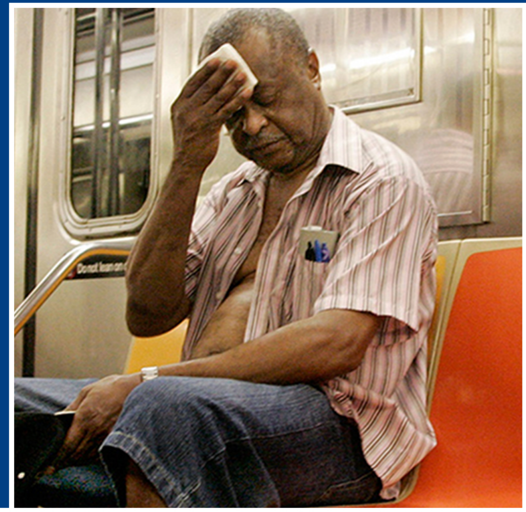

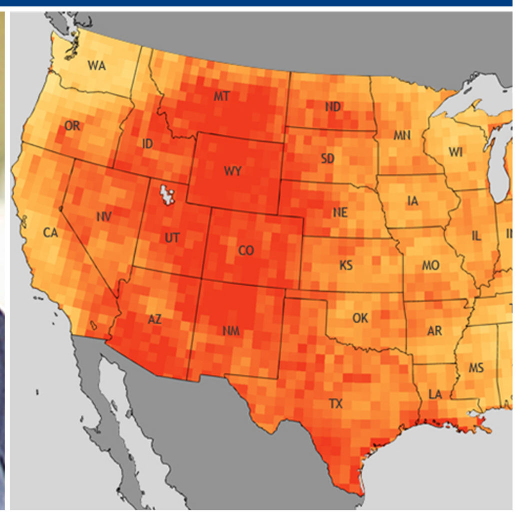

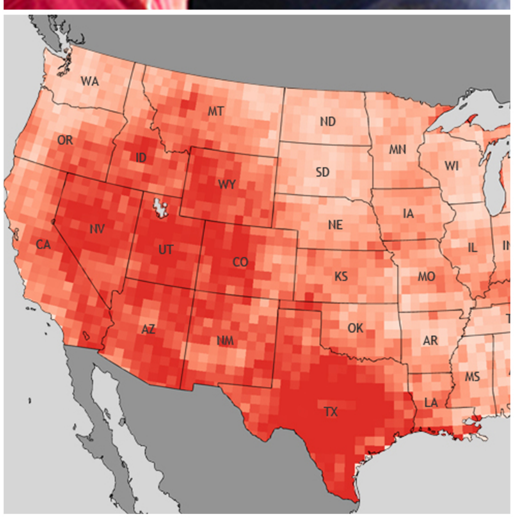

Mapping the Vulnerability of Human Health to Extreme Heat in the United States

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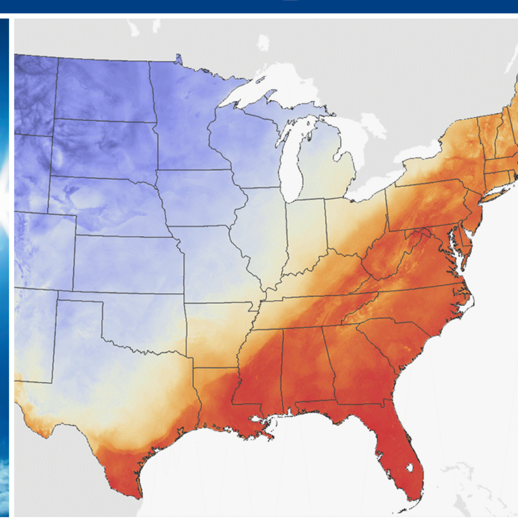

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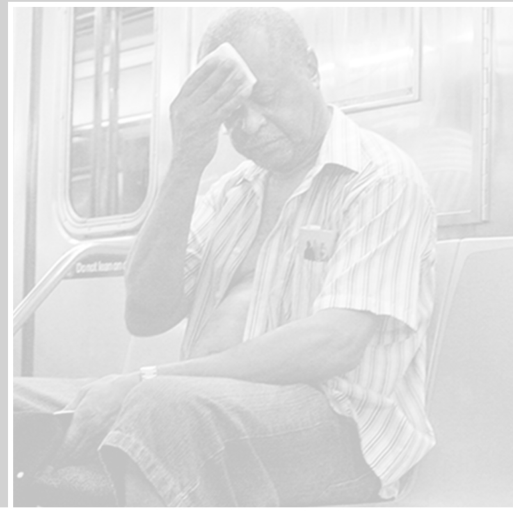

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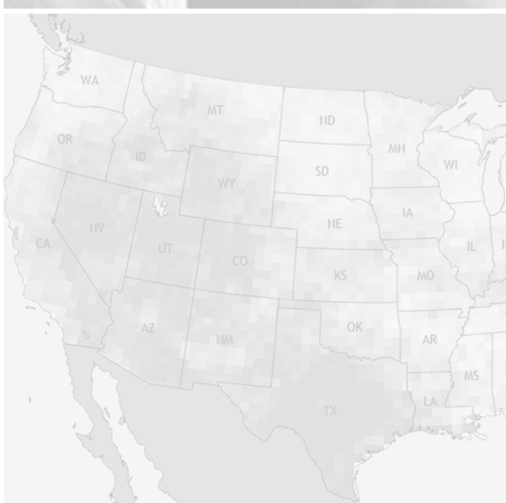

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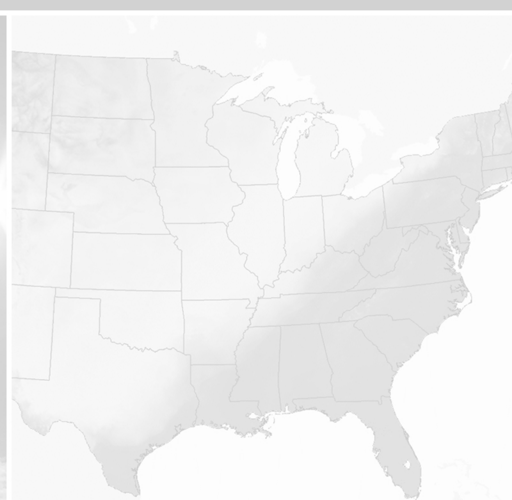

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EPA/600/R-18/212F
August 2018

Mapping the Vulnerability of Human Health to Extreme Heat in the United States

by

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Abstract

Spatial analyses of vulnerable locations and populations – such as people in urban areas susceptible to heat waves – have led to the utilization of maps to depict the vulnerability of populations to weather extremes. The U.S. Environmental Protection Agency is exploring challenges associated with mapping the vulnerability of human health to hazards associated with extreme heat, especially the lack of agreement regarding methodologies and analytic approaches that have, at times, been based on convenience or familiarity as opposed to efficacy or comparability. One-on-one interviews were conducted with a group of 11 subject matter experts (SMEs) from government and academia. The interviews addressed issues related to vulnerability mapping, including methodologies; accessibility and usability of data; issues of timeframe and geographic scale; addressing uncertainty; and using maps as communication and visualization tools. Following their interviews, the SMEs gathered in a workshop and a report was prepared that summarized their responses and identified approaches for conducting assessments of vulnerability and creating and using maps. This report was designed to inform state and local health departments, community planners, emergency preparedness professionals, and other stakeholders, as they prepare maps that convey useful knowledge on exposure to extreme heat while helping to identify and implement effective adaptation strategies. This report is submitted in fulfillment of contract number EP-C-14-001 under the sponsorship of the U.S. Environmental Protection Agency. This project covers the period from February 2016 through its completion in August 2018.

Foreword

The U.S. Environmental Protection Agency (EPA) is charged by Congress with protecting the Nation's land, air, and water resources. Under the mandate of national environmental laws, the Agency strives to formulate and implement actions that create a balance between human activities and protecting the public health and the environment. To meet its mandate, EPA's research program provides data and technical support for solving environmental problems and building a science knowledge base necessary to manage ecological resources wisely, understand how pollutants and other environmental stressors affect human health, and prevent or reduce environmental risks in the future.

The National Center for Environmental Assessment (NCEA) is located within the Office of Research and Development (ORD). NCEA is the EPA’s center for conducting assessments with the goal of identifying and reducing risks from pollutants and other environmental stressors that threaten human health and the environment. NCEA collaborates with both public and private sector partners to develop assessment methodologies that reduce the costs of adaptation while characterizing emerging risks.

NCEA includes an Immediate Office of the Director and four divisions, with staff located in Washington, DC; Cincinnati, OH; and Research Triangle Park, NC. NCEA includes a diverse team of biologists, chemists, ecologists, economists, engineers, epidemiologists, geneticists, statisticians, and toxicologists. NCEA's products — its guidance documents, criteria documents, risk assessments, models, and databases — are the result of dedicated scientists who follow projects throughout a process of internal and external peer review and a response to public comments to insure high quality science products.

The accompanying report is based on an elicitation of the knowledge and experience of subject matter experts from within government and academia. These experts completed one-on-one interviews focused on the methodology and data requirements associated with the assessment of vulnerability of certain populations to extreme heat. The overall goal of the report is to understand the health impacts associated with exposures to high ambient temperatures. The process for developing vulnerability maps includes the characterization and the location of specific populations of concern. The true value of vulnerability maps is to identify targeted areas for risk reduction to enhance adaptive capacity and improve resilience.

Tina Bahadori, Sc.D.
Director
National Center for Environmental Assessment

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Acronyms and Abbreviations

ACS	American Community Survey
BenMapCE	Benefits Mapping and Analysis Program—Community Edition
CBG	census block group
CDC	Centers for Disease Control and Prevention
CHVI	cumulative heat vulnerability index
EJ	environmental justice
EPA	U.S. Environmental Protection Agency
ERG	Eastern Research Group
FEMA	Federal Emergency Management Agency
GEMSS	Geospatial Emergency Management Support System
GIS	geographic information systems
HSIP	Homeland Security Infrastructure Program
ICLUS	Integrated Climate and Land-Use Scenarios
IPCC	Intergovernmental Panel on Climate Change
LDRM	local disaster risk management
NCAR	National Center for Atmospheric Research
NCEA	National Center for Environmental Assessment
PCA	principal component analyses
SME	subject matter expert
SoVI	Social Vulnerability Index
SSP	Socioeconomic Pathway
USGCRP	U.S. Global Change Research Program

Acknowledgments

The lead author for this report is Janet L. Gamble, PhD from the Office of Research and Development in NCEA-Washington in the Exposure Analysis and Risk Characterization Group. Michael Schmeltz, DrPH, a postdoctoral fellow of the Association of Schools and Programs of Public Health at the EPA (from September 2015 through May 2017) is a coauthor. The EPA also contracted with ICF to provide support for the expert elicitation and a workshop with the technical working group. ICF staff who contributed to the project and this report included: Brad Hurley, Jennifer Hsieh, Gabrielle Jette, and Hannah Wagner.

The eleven Subject Matter Experts (SMEs) who participated in the expert elicitation one-on-one interviews and the subsequent workshop of the Technical Working Group (see Appendix C. Subject Matter Expert Biographies for short biographical sketches of the SMEs) included:

- Susan Cutter, University of South Carolina
- Kristie L. Ebi, University of Washington
- Sharon Harlan, Northeastern University
- David Hondula, Arizona State University
- Nesreen Khashan, U.S. Census Bureau
- George Luber, Centers for Disease Control and Prevention
- Arie Manangan, Centers for Disease Control and Prevention
- Andrew Monaghan, UCAR
- Benjamin L. Preston, RAND Corporation
- Colleen Reid, University of Colorado, Boulder
- Jan Semenza, European Center for Disease Prevention and Control

An internal review was completed by Philip Morefield (NCEA-Washington Exposure Analysis and Risk Characterization Group) and Alexandra Dichter (EPA Region 1). An external review draft was prepared in response to the internal review. An expert peer review by letter was conducted by the Eastern Research Group (ERG) led by Laurie Waite. Three reviewers responded to ERG’s request, including: Wen-Chiing Chuang, PhD; Eric Delmelle, PhD; and Mark L. Wilson, ScD.

Executive Summary

ES.1 Background and Motivation

There has been limited guidance with respect to establishing methodologies to map the vulnerability of certain populations to the human health impacts associated with exposures to extreme heat. This report has two objectives: (1) to complete a review of the scientific literature that explores methods and data used to assess and map health outcomes related to temperature extremes in the United States, and (2) to prepare a report based on an expert elicitation process designed to assess how experts describe their experience in using vulnerability assessments and the maps drawn from those assessments.

The central focus for the use of vulnerability mapping is based on understanding how populations are and will experience health impacts. Definitions of population vulnerability differ somewhat across disciplines. For our purposes, we consider vulnerability as it relates to the causal mechanisms that identify vulnerable populations (e.g., exposures to extreme heat) or which incorporate ideas of coping, adaptive capacity, resilience, mitigation, and recovery (Blaikie et al., 2014; IPCC, 2014). Based on their disciplinary perspectives, researchers may incorporate an array of exposure variables to estimate risk. For instance, to assess populations vulnerable to heat, a sociologist may identify populations living below the poverty line as being the most vulnerable while a geographer may define vulnerable populations as only those who live in urban heat islands where exposure to heat waves determines vulnerability (Cutter et al., 2003; Füssel and Klein, 2006; Füssel, 2007).

Ultimately, this report is designed to develop and apply vulnerability assessments as a means by which to prepare and implement appropriate adaptations. Understanding how exposures overlap with the geographic distribution of populations of concern is critical for identifying and setting in motion effective response strategies (USGCRP, 2016).

Spatial analyses of vulnerable locations (e.g., urban heat islands) have given rise to vulnerability maps which use geographic information systems (GIS) to assess the exposure, sensitivity, and adaptive capacity of people and places (Lane et al., 2013; Preston et al., 2011). At their core, vulnerability maps are communication devices. They are used to educate the public and to assist planners, public health officials, first responders, and other end users in crafting and putting into place adaptation policies and investments. As a tool in spatial analysis, vulnerability maps can be used to identify areas with populations facing risks from impacts of high ambient temperatures and to explore components of vulnerability. Information from these maps can then be applied to guide adaptation and resilience-building efforts.

The intended audience of this report includes researchers; local or state public health, community planning, or environmental agency officials; concerned and interested citizens; and other stakeholders who wish to undertake (or understand) map-based assessments of human health vulnerabilities to heat waves in the United States.

ES.2 Approach

The EPA initiated this project with a review of the literature. Using online databases (Web of Science, MEDLINE/PubMed, Science Direct, Scopus, and Google Scholar), the authors identified scholarly articles, government reports, and projects concerning vulnerability mapping published between January 2008 and October 2015. The keywords “vulnerability mapping” and “extreme heat” were used as inclusion criteria for articles, reports, and projects in combination with other terms, including: spatial analysis, GIS, health, illness, disease, disorder, disaster, mortality, morbidity, hospitalization, emergency, preparedness, adaptation, vulnerability assessment, exposure, sensitivity, and risk. References and citations were inspected manually to make sure all relevant articles were included. Eligibility criteria included papers that used spatial analysis in examining vulnerability and had an appropriate health risk measure (e.g. incidence of disease, hospitalization, or mortality) as an outcome. Included also were papers that spatially analyzed vulnerability through the identification of a vulnerable population based on geographic, socioeconomic, and demographic characteristics usually described as a vulnerability index. Papers were restricted to geographic locations within the United States, though some additional examples of exposures which were not well covered by papers in the United States, were included in the review. Titles and abstracts were screened for relevance and full texts were obtained for further assessment if papers met inclusion criteria. Articles without full text, in a language other than English, or without sufficient details about data, methods, maps, and analytical techniques were excluded.

The initial search tagged 2,118 papers. Using the criteria described above, a subset of 38 studies from the United States was selected for a more detailed review. For this report, the focus was narrowed to include health impacts associated with exposures to heat waves. The literature review informed the overall project by identifying some of the questions and content that was desired for the experts to consider.

Following the literature review, EPA implemented an expert elicitation process. A Technical Working Group of eleven Subject Matter Experts (SMEs) from government and academia was convened (see Appendix C. Subject Matter Expert Biographies for SME names, affiliations, and biographic sketches). Experts were chosen by EPA based on their contribution to relevant literature, along with recommendations from peers and experts in the field. In April 2016, EPA conducted one-on-one interviews by telephone with each of these experts to elicit their perspectives on vulnerability assessments and the development and use of vulnerability maps. Interviewers took detailed notes during each call. Their inputs were used to develop an initial draft report that organized and summarized their responses. In August 2016, the SMEs participated in a workshop in Washington, DC, during which they reviewed and commented on the initial draft manuscript and elaborated on their viewpoints regarding the conduct of vulnerability assessments. To elaborate and inform the SME inputs, a Glossary is included to define and summarize important concepts related to vulnerability mapping.

An abbreviated overview of the questions posed to the SMEs in their one-on-one interviews is as follows (the complete interview questions appear in Appendix B. Questions for the Subject Matter Expert Interviews):

1. What are the most promising methodologies for mapping the vulnerability of human health to heat-related impacts and what are their key benefits and limitations?

2. What are the most significant data considerations and limitations in mapping vulnerability and what are the best data sources for mapping?

3. What issues are in play for identifying and assessing vulnerability indicators, including those related to socioeconomic, political, demographic, biophysical, and other relevant factors? How do vulnerability assessments address issues with respect to compatible time frames and geographic scales?

4. What methodological challenges are common in vulnerability mapping, especially those due to a lack of standardized methods or data gaps or other study design considerations and limitations?

5. Are there caveats that people should keep in mind when utilizing vulnerability maps?

6. How can uncertainty, model complexity, generalizability, and comparability be addressed across a range of methods and data?

ES.3 Summary Findings

A series of "take away" messages from the expert elicitation were compiled. These messages were not comprehensive nor were they based on consensus, rather, they reflected summaries of the extensive input from the SME one-on-one interviews and the discussion that took place at the workshop of the Technical Working Group.

- **With respect to stakeholders.** There are issues with respect to adequate capacity, funding, and expertise that are common across all scientific endeavors. Vulnerability assessments and mapping exercises require experts from multiple disciplines and demand significant time investments. The level of expertise required to best inform and assist end users was characterized. One fundamental error in mapping exercises is underestimating the value of input from potential stakeholders. Securing participation of stakeholders from the outset is key.

- **Revising map inputs.** Maps provide a starting point for discussion. Iterative revisions of maps with stakeholder input along the way is a best practice. Stakeholders may include those who serve as data repositories, those with technical expertise, local residents, public health and community planners, first responders, and other end users.

- **An iterative approach.** From a policy perspective, the identification of risk and population vulnerabilities is at the core of assessment and mapping. To that end, one may think of map making as an iterative process whereby one compiles an initial mapped realization, rethinks, gets input, and generates a revised version.

- **With respect to data availability.** It is important to try to obtain all potentially helpful data, even if it is not entirely a good fit. When a variable you wish to measure is not available at the spatial scale or timeframe of interest (or not available at all), you may use a proxy variable in its place that provides a good representation of the desired variable.

- **There is no one method for mapping vulnerability.** Common mapping methodologies include participatory vulnerability assessments (which use people's personal experience, local knowledge, and risk perceptions), map overlays, cluster analyses, machine learning, time-activity patterns, and hazard mapping. In the end, maps should be grounded in theory about existing health disparities and knowledge of physiological impacts.

- **With respect to qualitative data.** The unique and important value of qualitative data is included where possible, to integrate or incorporate qualitative with quantitative measures.

- **Understanding uncertainty and clarifying assumptions are important for map making.** Transparency related to sources of uncertainty and methodological assumptions help to validate and compile data sets based on compatible spatial and temporal characteristics.

- **Targeting areas for risk reduction.** The real value of vulnerability maps is to identify targeted areas for risk reduction to enhance adaptive capacity or improve resilience. Vulnerability maps provide a quasi-scientific and apolitical way of identifying vulnerable areas and allow end users to determine the most susceptible communities in which to invest resources.

- **Interactions with other factors.** Existing environmental, health, behavioral, institutional, and experiential characteristics put some populations at greater risk to health effects associated with exposures to extreme heat. Such exposures interact with an array of other factors to exacerbate or ameliorate health impacts for certain people and places.

Introduction

The EPA has begun to identify and define methodologies for developing maps and mapping tools that allow for an assessment of the health impacts of extreme heat on vulnerable populations. Maps can serve as powerful tools for analysis and communication: they reveal complex spatial and temporal patterns that would be difficult to interpret through text alone and allow local stakeholders to visualize areas of vulnerability within the context of places they know. Maps can also be influential in decisions to target resources to vulnerable populations (de Sherbinin, 2014).

EPA is exploring key challenges associated with vulnerability mapping, especially the lack of consensus regarding mapping methodologies and analytic approaches that have, at times, been based on convenience or familiarity as opposed to efficacy or comparability. This report utilizes the input of SMEs derived from their one-on-one interviews and discussions at the SME Technical Working Group workshop. The objective is to develop an overview of vulnerability mapping, including:

- Research to identify and evaluate mapping methodologies for understanding vulnerabilities to extreme heat at a range of spatial extents (e.g., local, regional, and national) and to the interaction with other demographic, socioeconomic, and environmental stressors;
- A sample of applications that support information integration for standardizing and mapping spatial data drawn from large health, demographic, land use/land cover, meteorological data, and other relevant data sources;
- Making the connection between vulnerability mapping and approaches for adaptation, especially addressing opportunities for improved risk communication and targeting emergency response;
- Determining how uncertainty, model complexity, generalizability, and comparability can be addressed across a range of mapping methodologies; and,
- A Literature Review which was prepared as background for the expert elicitation process.

There are many definitions but no agreement across disciplines, on how the concept of vulnerability is applied in the literature, including in mapping studies. It would be useful to review why maps are a good tool to understand vulnerable populations. Researchers will sometimes map hazards, exposures or sensitivity, and, less frequently, health outcomes. The goal is usually to improve the ability to manage the risks that weather poses for populations according to their geographic location and socioeconomic or demographic characteristics.

Some divergent views expressed at the workshop are noted in this report, but there was broad support among experts at the workshop for vulnerability maps as a useful tool in assessing population vulnerability and associated adaptation responses. Fruitful discussions addressed pros and cons regarding: how future projections are compared to current situations; the most relevant timeframes and geographic resolution and extent; and whether or when it is appropriate to consider characteristics of the place or link outcomes more strongly to health disparities across populations regardless of place. There were also important discussions reflecting the environmental justice literature about multiple and overlapping environmental and social stressors that have cumulative impacts on vulnerable populations.

1.1 Methodology for Expert Interviews

As one of the first steps in this project, EPA convened a Technical Working Group of 11 SMEs from government and academia (see list of SMEs with short biographical sketches in Appendix C. Subject Matter Expert Biographies. During April 2016, EPA conducted one-on-one interviews with each of the experts to elicit their opinions and perspectives on the development and use of vulnerability maps for visualizing heat-related human health impacts. EPA developed a set of questions for these interviews (see Appendix B. Questions for the Subject Matter Expert Interviews for the interview questions) which focused on the following topics:

1. Mapping methodologies, including GIS tools, to visualize the vulnerability of human populations in certain locations to the impacts on health associated with exposures to heat.
2. The accessibility and applicability of spatially resolved climate, environmental, and health data.
3. What issues are in play in the process of identifying and assessing vulnerability indicators, including those related to key socioeconomic, political, demographic, biophysical, and other relevant factors?
4. Description of how vulnerability assessments address the issues of compatible time frames and geographic scales, especially when incorporating historical trends, projections, and scenarios.
5. Methodological challenges associated with vulnerability mapping, especially those challenges in mapping that are due to a lack of standardized methods or data gaps or other data limitations and uncertainty related to modeling approaches or other research design considerations.
6. Recommended practices for vulnerability mapping that contribute to identifying, planning, and helping to implement adaptation strategies for vulnerable people in vulnerable places.

A detailed interview transcript was prepared for each SME. Their inputs were used to develop an initial draft report that organized and summarized their responses. There was no effort to reach consensus, rather we sought to faithfully convey the richness of the SME responses to our questions. The SMEs were invited to a workshop in Washington, DC in August 2016 during which they reviewed the initial draft document and expanded their suggestions regarding the conduct of vulnerability assessments and the creation of vulnerability maps. (see the Appendix C. Subject Matter Expert Biographies for short biographical sketches of each of the SMEs).

Overarching Considerations for Mapping the Vulnerability of Populations to Extreme Heat in the United States

This chapter discusses a series of overarching considerations that are in play in the process of mapping heat-related impacts on vulnerable populations. To develop vulnerability maps, one needs to examine the purpose for which such maps are prepared. These factors include: mapping extreme heat hazards; mapping those elements that demonstrate and communicate the vulnerability of people and places; the process by which stakeholders are engaged; and guidance on how to effectively communicate uncertainty. The main source material for this and subsequent chapters is drawn from the expert elicitation process that was received through one-on-one interviews with subject matter experts (SMEs) and the discussions at the SME workshop. As such, some assertions made here are based on discussions rather than specific citations, except where indicated.

2.1 Purpose and Focus

Before undertaking a vulnerability assessment or developing a map of vulnerable populations, the questions that we seek to address are framed. These questions guide the vulnerability assessment process:

- **Defining vulnerability:** What are the elements of vulnerability—exposure, sensitivity, and adaptive capacity—associated with temperature-related health impacts on vulnerable populations?
- **Place, time, and data:** What geographic locations and temporal scales are assessed? How do data availability and analytic techniques influence research design?
- **Participatory-based research and engagement:** Who are the intended audiences? stakeholders? and end users? and how can they be engaged to participate in developing and applying vulnerability maps?
- **Qualitative data:** How can qualitative data from people's experience, local knowledge, and risk perceptions be incorporated in vulnerability assessments?
- **Communication:** What opportunities exist for improved risk communication and for directing the prepositioning, placement, or implementation of emergency or other timely responses designed to improve community resilience to the health impacts associated with heat waves?
- **Uncertainty and complexity:** How can uncertainty, model complexity, generalizability, and comparability be addressed across a range of mapping methodologies and available data sources?

Throughout the assessment process, efforts were made to examine vulnerability, spatial and time scales, and health outcomes. Each of these determinants of vulnerability should be incorporated from the outset, as inconsistent definitions may hinder the interpretation and development of maps. **See the Glossary for**

terminology used in this report.

An approach to assessing risk can be characterized by risk-based framing which clearly defines what is at risk and its implications with respect to vulnerability. By carrying out analyses to identify what risky outcomes are possible or may not be ruled out, one can direct end users to distinguish between two questions regarding "What is most likely to happen?" and "How bad could it be?"

It is important that objectives are well articulated so that the choices related to the assessment of vulnerability are clear. Initial thoughts about these objectives help us to better manage risk and uncertainty, as it is evident that an array of stressors may interact with one another to either increase or decrease vulnerability. Vulnerability mapping can be a useful tool for educating and assisting public health officials and other community planners by effectively communicating spatial information.

2.2 Communicating Vulnerability

It is important that researchers reach out across multiple disciplines to build interdisciplinary networks to retrieve information needed to assess vulnerability and to disseminate knowledge gained through vulnerability assessments and their associated maps.

People are drawn to maps and the information about the places and vulnerabilities they convey. But maps must not be too complicated (e.g., they should avoid presenting a large number of variables simultaneously) and the process by which they are produced should be readily apparent. A major issue is how vulnerability maps are used and if, in fact, they will be used. It is imperative that map makers be able to explain the map content to the target audience quickly and clearly.

Clear visualization of the data is key. One can do extensive analyses, but if you do not have an effective map (i.e., one that can be interpreted by targeted users) then the information your analysis seeks to convey is lost. The number and complexity of the elements demonstrated by the map should be limited to improve message clarity. If they see a map of vulnerability in their community, will this modify their responses? Or will people conclude that it is some other place or population that is vulnerable?

The scales of time and space involved in assessments of future vulnerability to extreme heat also require careful communication to target audiences. People are accustomed to adjusting their behavior based on local weather maps, short-term weather forecasts, or the effects of recent extreme weather events, But, stakeholders may have a harder time imagining how to respond to projected vulnerabilities unless those vulnerabilities are communicated in ways that feel tangible.

Throughout this report maps are displayed that help characterize the kind of information on vulnerability that can be visualized through mapping. Figure 1 displays the vulnerability of heat-related illness in Georgia prepared by the Centers for Disease Control and Prevention (CDC). The top map provides a measure of composite vulnerability for the Atlanta area and the remaining six maps demonstrate six state-wide vulnerability factors for Georgia.

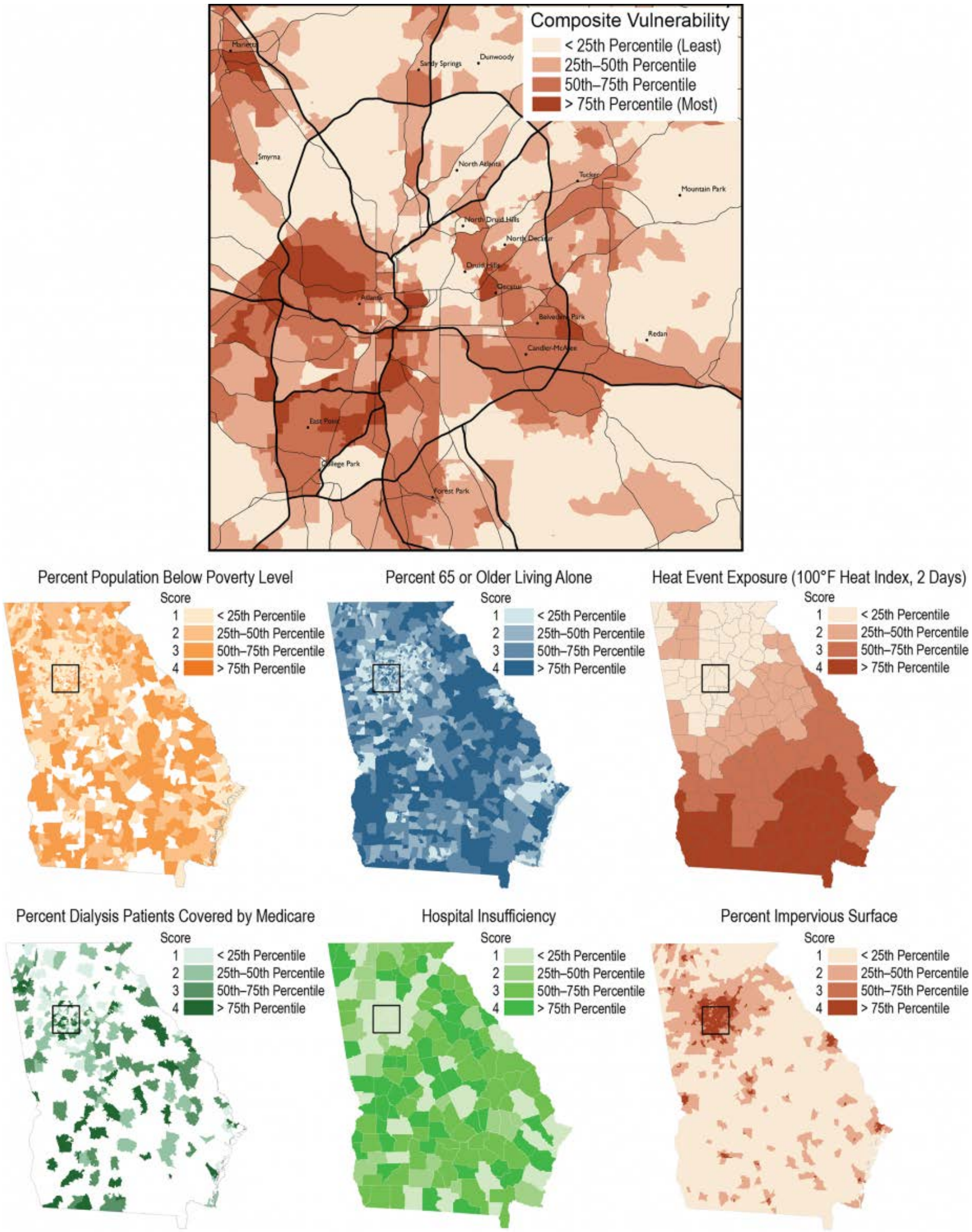

Figure 1. Vulnerability to heat-related illness in Georgia as it extends beyond urban zones.

The CDC conducted a case study of heat-related vulnerability in Georgia using data from 2002-2008. Vulnerability to heat related illness in Georgia extends beyond urban zones. The map on the top shows a composite measure of social vulnerability for the Atlanta Metropolitan Area (darker colors indicate greater vulnerability). The six state-wide maps show the following six vulnerability factors:

1. Percent population below the poverty level,
2. Percent aged 65 and older living alone,
3. Heat event exposure with Heat Index over 100°F for 2 consecutive days,
4. Percent dialysis patient on Medicare,
5. Hospital insufficiency based upon accessibility of hospital infrastructure, and

6. Percent impervious surface.

Areas in rural southern Georgia experienced more hazardous heat events, had less access to health care and had a higher percentage of people living alone. These types of studies allow researchers to use geographic information systems (GIS) to identify vulnerable communities, which can aid in the development of public health interventions and other adaptation strategies.

Source: Manangan et al. (2014).

2.3 Target Audiences

In communicating vulnerability, it is important to identify intended audiences. The temporal scale of the vulnerability assessment will help define the audience by addressing whether one intends to build near-term capacity or assess long-term projections. It is often a combination of both.

In many cases vulnerability is determined by a priori knowledge from past events and the results of epidemiological studies. The goal is to develop meaningful maps that the targeted audience may use to develop and implement adaptation strategies.

Determining the target audience will shape how the research, analysis, and maps are developed. For instance, is the audience elderly; or composed of immigrants with English as a second language; a community board meeting at the local high school; or the mayor's office or local planning agency? Identifying the audience for the vulnerability map allows researchers to improve messaging and promote risk communication that will be used by the intended audience.

The audience for this report is local or state public health, community planning, or environmental agencies who are deciding whether to use vulnerability mapping to characterize their discrete areas of responsibility. For example, decision makers at the state level tend to gravitate toward the underlying data that went into the map overlays, as those maps depict vulnerability by simply layering vulnerable factors on each other. This kind of map encourages people to talk about what factors are important to them, and highlights regional differences, as any given location may experience a range of heat-related hazards and demonstrate variations in vulnerability across both place and population.

2.4 Considerations Regarding Uncertainty

It is important to find ways to reduce uncertainty in vulnerability assessments. For example, when you use methodologies such as factor analysis, you need to be able to go back and conduct a sensitivity analysis—a process for revealing which assumptions have the greatest influence on the results (Tate, 2012)—that deconstructs the information conveyed by each vulnerability factor. Often, there are limited geographically explicit data for health impacts at fine resolutions. In addition, the number and type of uncertainties may compound across each step of assessment modeling.

Uncertainty also accrues when estimating future vulnerability. One option to reduce uncertainty is to develop maps that address the current situation and then as things change, adjust and update them accordingly. Web-based dynamical maps may be relevant in this regard. Focusing on who is vulnerable now and what they are vulnerable to could improve the quality of maps in the present while increasing public interest in future-oriented maps.

2.5 Participatory Approach

All too often, there is a lack of engagement and participation by stakeholders in vulnerability mapping. Preston et al. (2011) and Wolf et al. (2015) have identified this as a key missing element. While it may be easier to do the analysis without community stakeholder engagement, it is probably less useful and ultimately less likely to be adopted when implementing adaptation strategies. The value of stakeholder engagement in planning is well established (see, for example, Frazier, 2009); stakeholders can provide valuable on-the-ground perspective to aid in vulnerability assessments and buy-in for assessment findings and subsequent action to reduce vulnerabilities is likely to be enhanced when stakeholders are involved early in the assessment process.

Applying a participatory approach such as community-based participatory research methods for vulnerability mapping is critical. Stakeholder participation may not always be necessary to complete the analysis, but in terms of the acceptance and the utility of the results it is beneficial to have state, county, and other local partners involved early and often. Invariably, their reaction to a vulnerability map is not as good if they are seeing it for the first time without any opportunity to contribute to the statistical analysis and the map realization from the outset.

Stakeholder involvement also encourages dialogue. Often stakeholders need education and capacity building to help them understand how to take advantage of new technologies and information, such as the visualization through maps of vulnerable populations.

Academics often explore novel ideas using complex statistical analyses and may want to obtain data from local managers to improve their studies. However, in many cases, local government and other public health and community planners have no incentive to be involved in another institution's assessment activity. But, it is particularly important to encourage reciprocity in the transfer of data and knowledge. Stakeholder involvement is central to the transfer and utilization of data.

When engaging stakeholders, it is useful to find ways to capture and apply their knowledge. It is important to include people's experience, local knowledge, and risk perception in assessments of vulnerability. These qualitative measures provide access to a more nuanced view of what affects a person's life and how they experience weather-related hazards. While, qualitative data are more common in the developing world, a qualitative approach has applicability in the United States as well. There are many places where there is inadequate quantitative data, while valuable local knowledge is available. Stakeholder knowledge is central in this regard.

A community-based participatory approach calls for interdisciplinary engagement. Involving interdisciplinary teams in the field to interview people and to learn more about the micro-mechanisms that make people and places vulnerable is key. Ethnographic research, field work, document analyses, in-depth interviews, social surveys, and ecological surveys may be used to complement the secondary data sources on which researchers commonly rely. In addition, using mixed quantitative and qualitative methods and data sources is essential to completing an effective and comprehensive vulnerability assessment.

2.6 Considering Specific Risks

For hazards such as extreme heat, one may not necessarily have good information about acute exposures at an individual level. Additionally, methods that seem best for those hazards have shorter causal pathways, because there is a better chance to represent them at the temporal scale at which the hazard occurs. There are differences in confidence levels depending on the type of hazard or exposure being analyzed. For example, representing where extreme heat will occur can be characterized with high confidence.

In terms of human health, extreme events like heat waves, flooding, storms, and wildfires contribute to acute health impacts. These differ from slower-moving changes such as sea level rise or drought. Longer-term variability may not result in large mortality and morbidity changes but can have chronic and cumulative impacts on both physical and mental health. Chronic health effects can manifest in many ways, including those that occur because of heat-related illness and death.

The advantage of a hazard mapping approach is that you are starting with an explicit definition of areas exposed to or at risk to hazards (e.g., weather maps). Such examples are well defined and are sometimes "sanctioned or official." While specific aspects of weather-related hazards can differ, knowing which factors to examine is essential for determining risk. In addition to environmental hazards, factors related to individual characteristics—including age, health status, and socioeconomic and other demographic variables—also need to be considered when assessing the human health impacts from exposure to ambient temperature extremes.

Figure 2 displays the national geographic distribution of a cumulative heat vulnerability index with evidence of spatial clustering as prepared by Reid et al. (2009). Four factors explained more than 75% of total variance with inner cities showing the greatest vulnerability to heat.

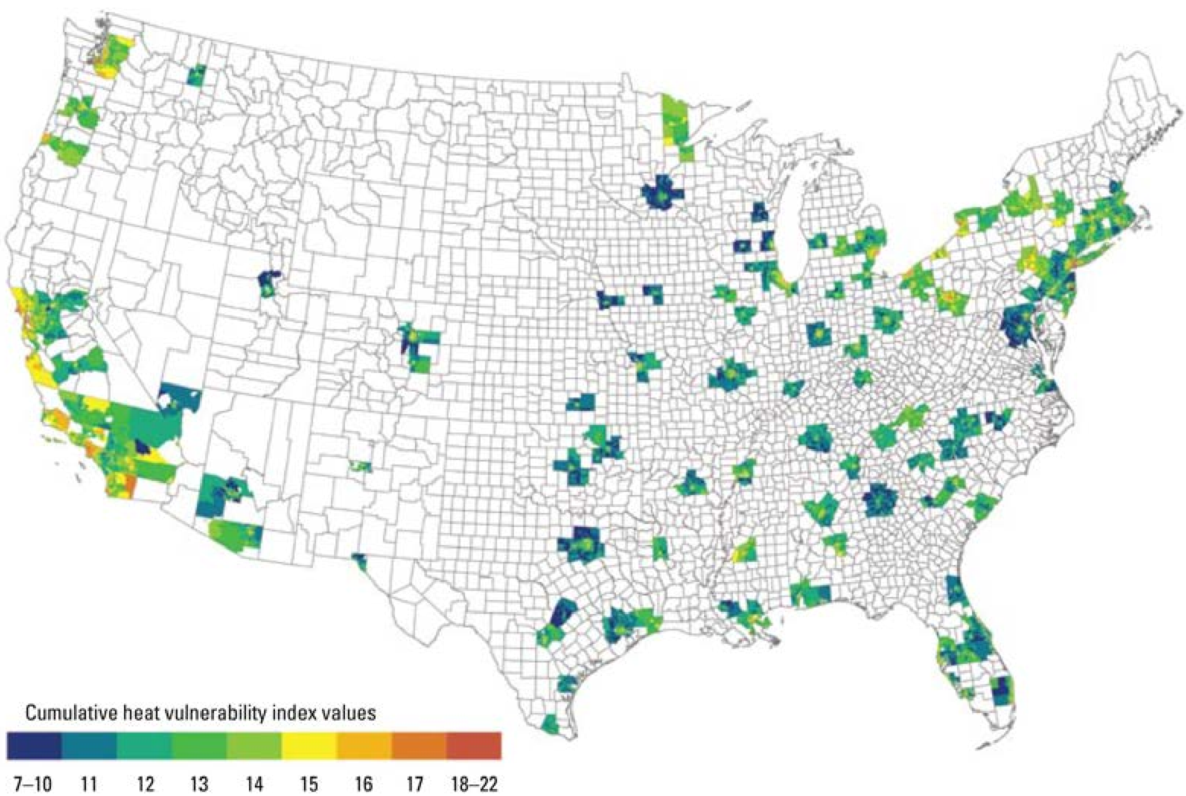

Figure 2. Contiguous U.S. map of cumulative heat wave vulnerability index by census tract.

This figure shows the national geographic distribution of the cumulative vulnerability index, with evidence of spatial clustering. NOTE: areas shaded in white are not included in the 50 cities which are the focus of this map. Overall, higher vulnerability was seen in the Northeast and along the Pacific Coast, with some pockets of higher vulnerability in the Southeast and along the U.S.−Mexico border. Thirteen census tracts had the highest cumulative heat vulnerability index values (21 or 22). Eight of these are in the San Francisco Bay Area (San Francisco County and Alameda County); two are in Cuyahoga County, OH; one is in Pierce County, WA; and one is in Los Angeles County, CA. All of these census tracts are above the mean for all four factors. No census tract reached the highest vulnerability category for all four factors.

Four factors explained >75% of the total variance in the original 10 vulnerability variables: (a) social/environmental vulnerability (combined education/poverty/race/green space), (b) social isolation, (c) air conditioning prevalence, and (d) proportion elderly/diabetes. Substantial spatial variability of heat vulnerability nationally was found, with generally higher vulnerability in the Northeast and Pacific Coast and the lowest in the Southeast. In urban areas, inner cities showed the highest vulnerability to heat.

Source: Reid et al. (2009).

2.7 Other Stressors Contributing to Vulnerability

For socioeconomic factors, issues such as governance and other community and infrastructure factors are important to incorporate in the assessment. Research is needed that considers factors that may not be apparent. Clearly, as exposure to ambient heat is a contributing factor for morbidity and mortality endpoints, such factors may not necessarily be the most important.

Figure 3 displays a map of Philadelphia in 2015 with high populations of older adults and people living below poverty levels who are not within easy walking distance of a cooling center.

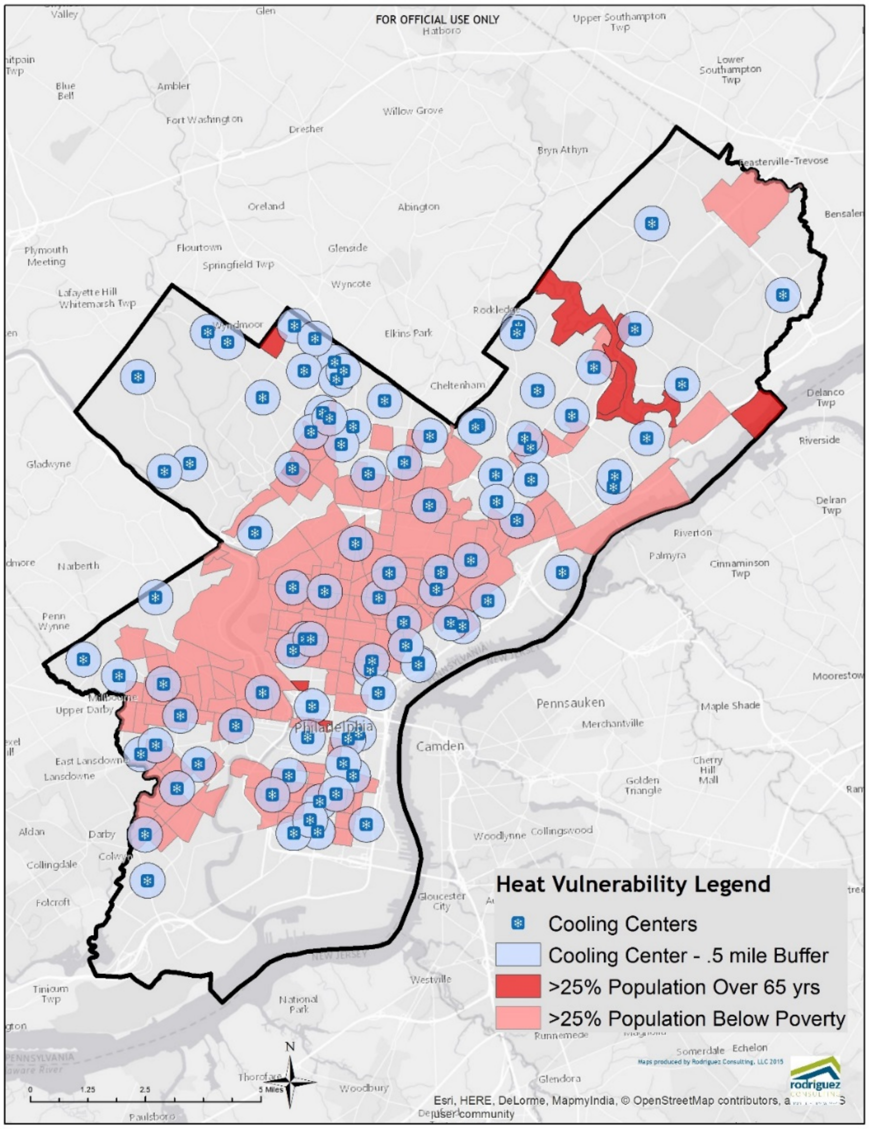

Figure 3. Philadelphia heat vulnerability in 2015.

The map shows areas in Philadelphia with high populations of older adults and people living below poverty level who are not within easy walking distance of a cooling center. Note that this in itself is not necessarily an indicator of vulnerability: for example, individuals living in air-conditioned homes would not need access to a cooling center (as long as electricity is available), and the list of cooling centers does not include privately-owned but publicly-accessible air-conditioned spaces such as movie theaters and malls.

Source: City of Philadelphia (2015).

Data

Access to high-quality data at appropriate spatial and temporal extent and resolution are essential for developing vulnerability maps. In the United States, meteorological data are generally more complete and available than health data. While there have been some recent enhancements to improve data access, including data portals and a movement toward cloud computing and web technologies, solutions to encourage consistent health data collection at finer resolutions and to improve accessibility to these data are needed. Developing collaborations and partnerships will improve data accessibility and support interdisciplinary research.

3.1 Accessibility and Applicability of Data

One of the greatest challenges for mapping human health vulnerability to potential temperature extremes is accessing appropriate data. Determining the right data to use can be difficult when there is uncertainty about the attribution of impacts. For example, increases in heat morbidity and mortality could be attributed to weather variability or could be associated with inadequate use of air conditioning or both.

In the United States, meteorological data are reasonably available, but appropriate and accessible health data can be limited. Barriers to accessing appropriate data include lack of data collection or surveillance, incompatible data structures or formats, lack of access to data due to legal or privacy concerns, and lack of stakeholder partners to improve data accessibility. Demographic data may also have limitations or restrictions.

Climate scientists often use data formats not common to other fields. For example, data from National Centers for Environmental Information (formerly NCDC, National Climatic Data Centers) are formatted as “hypercubes” of data. For most health scientists and geographers, that data format is not generally accessible. While there are scripts and software packages that can be used to extract the data, it can still be challenging as complex and computationally intensive data from different resolutions or extents must be compiled.

Some parts of the federal government are developing data portals and tools to improve data access and usability, such as the data portal developed by the U.S. Global Change Research Program (USGCRP), U.S. Climate Resilience Toolkit (https://toolkit.climate.gov/) and the emergency response mapping applications developed by the Census Bureau, such as OntheMap for Emergency Management (http://onthemap.ces.census.gov/em/).

While these tools address some barriers, their utility can be limited by other considerations that affect the field more broadly—such as not having data available at fine enough resolution. In addition, some otherwise useful data sets have access restrictions. For example, the Department of Homeland Security has the Homeland Security Infrastructure Program (HSIP), which compiles geospatial data from federal agencies, commercial vendors, and state and local partners. HSIP contains useful data and is available to federal partners, while states have only limited access to the HSIP data.

3.2 Urban vs. Rural: A Data Bias

It is important to determine the appropriate geographic resolution for the analysis. Some data are available only for larger cities and not for rural areas, such as the air conditioning prevalence data available through the American Community Survey (ACS). There are fewer studies conducted on rural populations, sometimes because smaller populations in rural areas limit the statistical power of epidemiological studies. Certain types of health information may be more limited in rural or sparsely populated areas due to privacy considerations. This limited data availability for rural areas may affect our understanding of how vulnerability may differ in rural versus urban areas, as well as the ability to set into motion adaptations in rural areas.

The issue of neglected rural areas results from a data bias, as most of the data we can use for vulnerability mapping is in densely populated areas. Stakeholders in rural communities may have to rely on qualitative information regarding vulnerability if “statistical sampling” cannot provide adequate data for assessing the vulnerability of rural communities. It may also be an environmental justice (EJ) issue if we include under-served communities like Native American peoples or other marginalized groups in rural areas or in areas where little secondary data is collected.

Figure 4 displays the results of the Reid et al (2009) analysis of four urban areas and their relative vulnerability to heat related mortality. Four factors explained >75% of the total variance in the original 10 vulnerability variables. There is substantial spatial variability of heat vulnerability nationally, with generally higher vulnerability in the Northeast and Pacific Coast and the lowest in the Southeast. In urban areas, inner cities showed the highest vulnerability to heat.

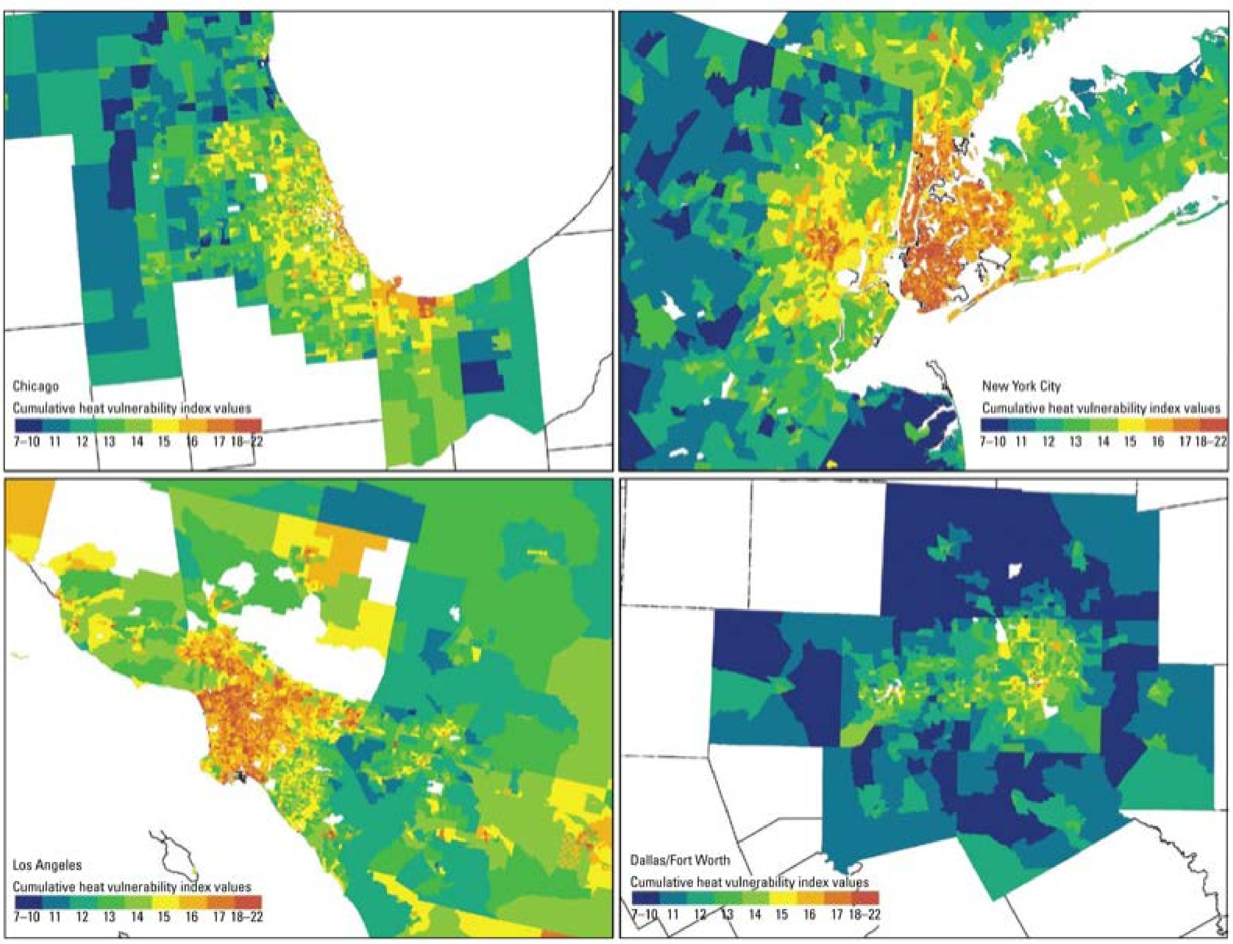

Figure 4. Mean cumulative heat vulnerability maps by census tract for 4 U.S. cities.

Four factors explained >75% of the total variance in the original 10 vulnerability variables: (a) social/environmental vulnerability (combined education/poverty/race/green space), (b) social isolation, (c) air conditioning prevalence, and (d) proportion elderly/diabetes. There is substantial spatial variability of heat vulnerability nationally, with generally higher vulnerability in the Northeast and Pacific Coast and the lowest in the Southeast. In urban areas, inner cities showed the highest vulnerability to heat.

Source: Reid et al. (2009).

3.3 Quantitative vs. Qualitative Data

Involving interdisciplinary teams out in the field to interview people and to learn more about the micro-mechanisms that make people and places vulnerable can be useful. Field work is often missing from vulnerability assessments and may be an important data gap. Ethnographic research, document analyses, in-depth interviews, social surveys, and ecological surveys should be used more frequently to complement the secondary data sources on which researchers commonly rely.

The use of qualitative data and how it can be incorporated in an analysis of quantitative data needs to be considered. We also need to address how data sources dictate research design and engage stakeholder groups, as together these can shape or inform a complex integrated assessment.

For example, Eric Klinenberg conducted a sociological study of the 1995 Chicago heat wave (Klinenberg, 2002, 2015). His book identified important markers of population vulnerability that were often missed in traditional epidemiological analyses of heat waves that relied solely on secondary data sources. Some of the qualitative data sources that his investigation identified, such as data on the incidence of violent crime, are difficult to access especially in studies that focus across multiple jurisdictions. Another study, by Mary Haden and colleagues (Hayden, Brenkert-Smith, and Wilhelmi, 2011) surveyed participants from 359 households across three U.S. Census block groups in Phoenix, Arizona, to ascertain their knowledge, attitudes, and practices during extreme heat events, along with factors that facilitated or hindered efforts to reduce their vulnerability to extreme heat.

3.4 Scale: Spatial and Temporal Resolution and Extent

Incompatibility between the extent or resolution of temperature data and other relevant variables is challenging. While heat exposure is an important stressor, it is not a major determinant of social vulnerability. As you resolve the data to a fine resolution, the relative influence of extreme weather on human health outcomes is diminished compared with other socioeconomic and demographic factors. There is a general lack of geographically explicit data for weather-related health effects and a lack of health data at fine resolutions.

For example, census tract-level information is relatively coarse and the demographics may not match the tract level boundaries, so demographic data must be manipulated to fit the desired spatial extent and resolution. Some types of emergent events cannot be integrated with other data because of incompatible resolution (e.g., county-level data would not be appropriate or useful for an event defined by a few city blocks). In cases such as these, the smallest geographic reporting units of the data need to be significantly smaller than the area of the emergent event.

Most researchers can only access health data at the county level, and sometimes these data are 5–10 years old. More fine-resolution data can sometimes become available through partnerships with stakeholders, but extensive preliminary paperwork may be required to obtain data release. Access to health data can also be restricted by privacy considerations. One example is the limited data available for assessing heat-related morbidity. If there are low counts of hospitalizations in a given geographic area, the data may be suppressed due to confidentiality restrictions that protect individual privacy in those cases where small numbers might allow the identification of individuals.

Temporal extent is also important. Socioeconomic and demographic projections may not be available for determining future vulnerability. It remains a challenge for researchers to acquire data with adequate temporal coverage at a fine spatial resolution for time-series analyses. As a result, most vulnerability analyses yield maps presented as static snapshots in time, rather than portraying changes in vulnerability over time and across space.

Some researchers have concluded that better projections of socioeconomic and demographic factors are needed to help reduce risk even if they are highly uncertain. Others believe that focusing on the current situation and developing current vulnerability maps and interventions to address needs should be paramount. Map updates or revisions can then be made as the situation evolves, rather than attempting to map uncertain future projections. These alternative approaches are a source of debate, but clearly, maps of both current and future vulnerability are potentially useful.

In addition to the time frame, the spatial resolution of heat-related data can be a particularly important issue. Analysts often use remote sensing data, though these data may omit the hottest places or those where the complete thermal environment (including, not only, temperature but also humidity, radiation, and wind speed) is most dangerous.

3.5 Representing Uncertainty in Data

There are several sources of uncertainty in data. In some cases, uncertainty can be caused by inconsistent data. While a source such as Census data is relatively consistent in the United States, state-level data quality and reporting may vary and it can be difficult to determine if there are true differences between states or local jurisdictions which dictate the appropriate analytic approach.

Another source of uncertainty is whether exposure data available at a larger spatial scale may be representative of the exposure at a smaller scale. Some techniques for vulnerability mapping use downscaling procedures to make predictions at smaller scales from larger scale data. Downscaling may introduce additional uncertainty; and caution should be taken when interpreting or applying downscaled results.

One suggestion to help reduce uncertainty is to conduct ground-truthing of data sets. For example, researchers addressing heat vulnerability have used an image of urban heat islands to represent exposure, yet it is unknown how representative these images are for urban surface and air temperatures, or actual personal heat exposure (outdoor vs indoor). The goal of ground-truthing is to take personal heat exposure measurements and get information on the indoor component of temperature exposure to reduce uncertainty about exposure to ambient temperature.

3.6 Data Types

3.6.1 Meteorological and Environmental Data

Weather data is often more abundant with higher spatial and temporal resolution than socioeconomic, demographic, or health data. Such data are available across larger geographic extents and over longer periods, and are continuous across time. Availability of weather data is not the limiting factor in vulnerability mapping, although there can be issues with applicability and comparability. While it may be relatively easy for some researchers to utilize weather data, it may be technically difficult for others.

Some useful, high-quality environmental data sets are available. For example, the U.S. Geological

Survey produces the GAP Land Cover data set which is available at high resolutions of 30 meters and provides relatively detailed information on ecological zones. FEMA provides floodplain data at a very high resolution and for multiple flood risk levels. However, other research areas such as vector-borne diseases lack the underlying ecological data needed to map vulnerability and may require the use of proxy data (e.g., tick population data over large geographic scales) rather than a measure of actual exposure.

3.6.2 Health Data

Compared to weather data, there is a general lack of geographically explicit data for heat-related health effects and a lack of health data at fine resolutions. While health data are better in the United States and other developed countries, the data are mainly available at coarse resolutions (such as county level). County and state health departments should have access to these data, but for those outside of local or state governments, data access can be time-consuming and difficult and may be limited by personally-identifiable information.

Developing relationships between collaborators for interdisciplinary studies is possible and beneficial for accessing health data, though not utilized often enough. It can take time to gain the trust of collaborators and a long process to get necessary approvals (including permissions from Institutional Review Boards). Even when health data sets are available, there can be reporting differences across state and local areas and changes in reporting requirements over time, making it hard to reliably assess historical trends. At times, it is hard to see trends in the data because of differences in reporting practices. While there may be reasonable resolution, both temporally and spatially, there is often limited consistency of data across space or time.

Sometimes it is possible to circumvent this issue. We find that available data may not always be exactly what researchers want, but it still may be informative and instructive. Other types of data relevant to health should also be considered—such as access to health insurance and available health care providers and accessibility of medical treatment. Medicare and Medicaid provide useful data, including health care infrastructure data for hospitals and nursing homes, which can be used for modeling the vulnerability of health care systems and their capacity for treating at-risk populations.

3.6.3 Population Data

Two commonly used sources of population data, including socioeconomic and demographic variables, are the U.S. Decennial Census and the American Community Survey (ACS). These data sets are considered the "gold standard." U.S. Census data contain poverty and some economic data available at the census block level, so there is high spatial resolution. In the ACS, many relevant variables are available, such as those pertaining to age, disability status, household income, educational attainment level, languages spoken at home, English language proficiency, access to automobiles, access to telephones and Internet connectivity, access to air conditioning, and age and type of residential construction.

There can be limitations with population data depending on the type of analysis. Census block variables are helpful, but only available once every 10 years. Additionally, some of these variables change or are discontinued from one census to the next and can limit the use of this data in time-series analyses. For example, geographic boundaries of Census blocks change over time based on population growth and urban development. To reveal temporal dimensions of vulnerability across space, researchers need to use geospatial techniques (e.g., the Longitudinal Tract Database developed at Brown University) to align historical Census information to more recent Census boundaries.

Researchers want a more robust time series to look at variability in stressors. The Census has changed substantially since 2010 and is now collecting less information. The federal government is focusing more on the ACS. This change needs to be evaluated going forward as it may make it more difficult to access or effectively use some Census data.

The Census Bureau's surveys and data on the U.S. population are robust, but users need to be aware of the margins of error associated with the data and rely on their best judgement when using census data. Hyper-granularity is highly sought after, but the Census Bureau's smallest unit often has a considerable margin of error. One of the ways to reduce such error is to use a 5-year data set like the ACS, though the user is giving up some timeliness or immediacy because the data are reported as a 5-year weighted moving average.

Household surveys are sometimes useful when trying to obtain fine-resolution data. But, while providing valuable information on factors associated with vulnerability, household surveys are expensive, time-consuming, and may be limited in scale. Census data may have to be used as a proxy for more specific or localized indicators when the desired data are not available. For example, block-level poverty may be an indicator of extreme heat sensitivity because lower-income households are less likely to have or to use air conditioners due to their cost. In addition, poverty could be increasing vulnerability through other pathways such as social isolation.

3.6.4 Time-Activity Data

One relatively new technique to help address uncertainties in exposure data uses time-activity patterns. Exposure is assessed at the respondent's home address and does not account for how much time people spend there as compared to other locations such as work or school. Actual person-level information, such as measures of personal heat exposure with wearable sensors, may be derived from this type of monitoring. While this is not practical for an entire population, it may help improve understanding of overall activity patterns across population groups. The U.S. Environmental Protection Agency (EPA) uses this type of data in air quality assessments, though it is not yet included in most weather-related hazard research. There are several recent publications in this area (Bernhard et al., 2015; Glass et al., 2015; Karner et al., 2015; Kuras et al., 2015).

3.6.5 Behavioral Data

One of the big challenges or key factors that affect health outcomes is behavior. We can map a floodplain and conclude that there is a greater risk of an adverse outcome there, but the adverse outcome is contingent on behavior (such as drivers putting themselves at risk by driving through flooded roadways). Behavioral data is complex and limited by privacy considerations and data formats. If part of the goal is to empower local and state health departments, these issues must be addressed. Analysts need the capacity to identify, retrieve, and analyze behavioral data.

Vulnerability Indicators

4.1 Developing Vulnerability Indices

A reasoned approach to developing and applying vulnerability indices is key. Work in this area has identified suitable indicators that can be used to create composite indices. From the perspective of a social vulnerability index, some likely index variables have been determined by field evidence from disaster response experiences. Finding individual variables to use as proxies for larger and/or more complex concepts is central to this approach. Circumstances change over time and will rely on available data and measures. Projecting into the future is also a challenge for employing demographic changes. You may be able to project population growth, but you are less likely to be able to project other population characteristics with reasonable certainty.

Vulnerability indicators can target effects from weather-related hazards such as extreme heat. Health impacts have different driving forces, and data requirements will vary for each vulnerability indicator. The most robust indicators will incorporate specific spatial and time scales. It is essential to address the consistency of data across time and space when developing indicators, as comparisons across locations are problematic.

Identifying and defining vulnerability indicators is challenging. For some types of weather-related hazards, epidemiologic studies are not sufficient to clearly and consistently identify vulnerable populations. When considering social vulnerability, definitions from EJ communities are helpful to describe those factors that measure vulnerability. These can include communities where people are most sensitive to health impacts because they are simultaneously affected by a number of other stressors. Vulnerable communities are often the first to experience the effects of temperature extremes because they have been pushed to marginal, precarious, or polluted landscapes in which they live, work, study, and play. Economic status, including income and other measures of wealth, is one of a number of factors that should be considered when deriving vulnerability indicators. Race or ethnicity are also consistent indicators of vulnerability.

Figure 5 illustrates the cumulative heat vulnerability index (CHVI) scores mapped for 2,081 census block groups (CBGs) in Maricopa County, AZ. Higher scores represent higher vulnerability.

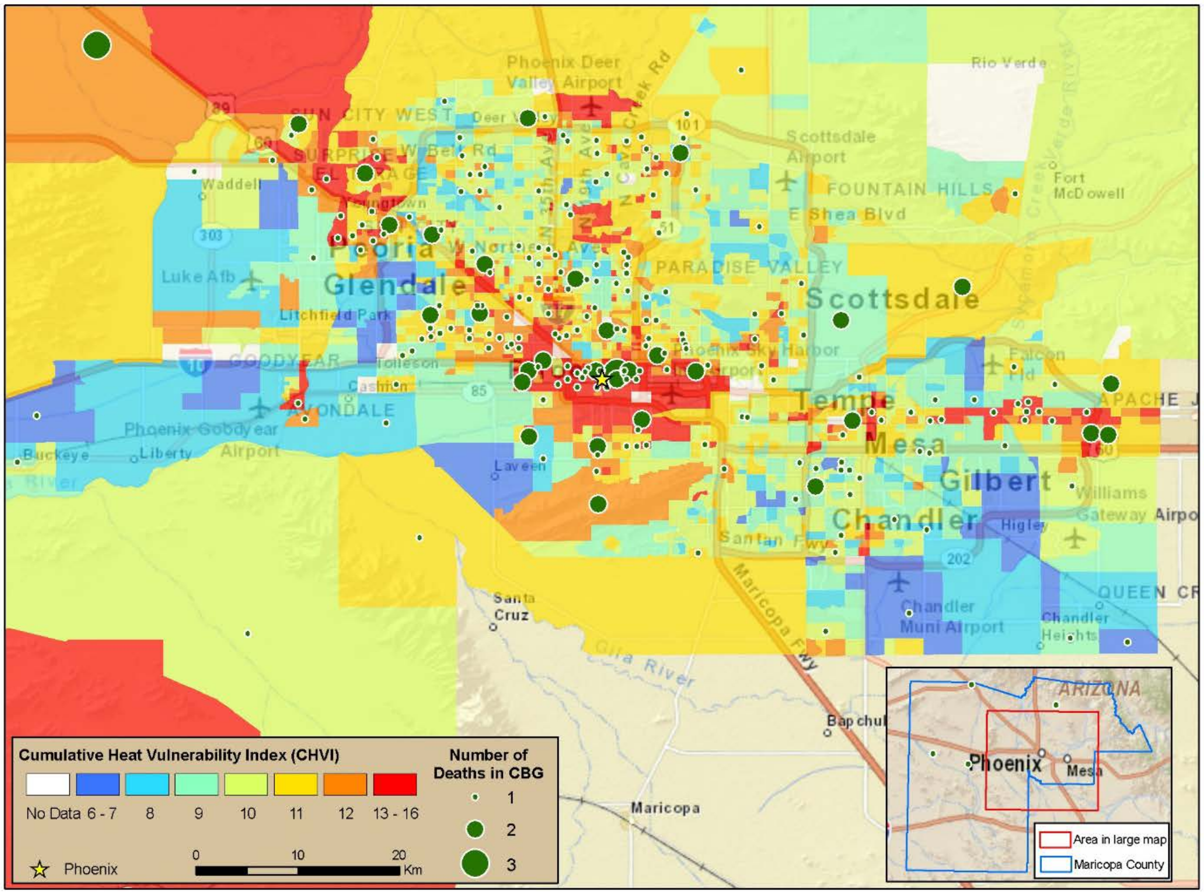

Figure 5. Cumulative heat vulnerability index (CHVI) scores mapped for 2,081 census block groups in Maricopa County, AZ.

The cumulative heat vulnerability index (CHVI) scores (using a method modified from Reid et al., 2009) mapped for 2,081 census block groups (CBGs) in Maricopa County, AZ. Higher scores represent higher vulnerability. The map inset in the lower right corner indicates the urbanized area of Maricopa County (red box) shown in the larger map. The county, which also contains a much larger area of uninhabited desert and sparse settlement, is outlined in blue. The urbanized area covers all the cities and all but one of the major towns in the county. Residences of only four people who died from heat exposure were located outside the urbanized area (green circles in inset).

Source: Harlan et al. (2013).

Analysts create vulnerability indices, using factor analyses or principal component analyses (PCA),[1] to understand and rank the explanatory strength of independent variables and to provide predictive capacity. PCA has the advantage of reducing data redundancy and multicollinearity (i.e., when two vulnerability variables are describing or quantifying the same underlying source

[1] For definitions of factor analysis, principal component analysis, and a discussion of the differences between them, see https://theanalysisfactor.com/the-fundamental-difference-between-principal-component-analysis-and-factor-analysis/

of vulnerability or are just statistically highly correlated) and providing dimensions of vulnerability to examine. Analysts can use PCA to create and combine independent factors that center on similar underlying concepts. PCA is commonly used by analysts when the impacts included in the assessment are multiple and complex.

Despite its advantages, PCA requires analysts to weigh a range of vulnerability factors to estimate explanatory coefficients. Several of the advantages of PCA can also be disadvantages. For instance, since PCA groups variables together to create factors, users are not able to separate out the magnitude of the impacts associated with individual variables. Also, since factors are aggregated, all data must be converted to a consistent spatial scale. Further, even though PCA can provide predictive skill, its predictive capacity may be limited and can lead to inaccurate conclusions about the actual causes of vulnerability. Other limitations of these analyses are related to:

1. **Mechanisms:** How well does census variability represent the processes related to vulnerability?
2. **Exposure:** How well is the exposure represented by an index?
3. **Data handling:** How do analysts weigh the explanatory capacity of one variable as compared to another?
4. **Geographic consistency:** Is it appropriate to incorporate the same variables across different locations?
5. **Accuracy:** Validation is important to ensure that no statistically significant variables (those with explanatory capacity) are missing from the index.

Ultimately, the usefulness of PCA is determined by the type of vulnerability, the available data, and how these indices can be compiled. There are significant uncertainties and analysts need to describe their assumptions and test maps with control data to validate map elements.

It is wise to do post-modeling interpretive work based on local knowledge of historical and current conditions to understand the risk-scape of exposures in specific places. Post-modeling work can help analysts to use maps to promote discussion and target areas for risk reduction or interventions that enhance adaptive capacity or improve resilience. Maps provide a science-based and apolitical way of identifying vulnerable areas for targeting resources. From a policy perspective, the identification of risk and population vulnerabilities is the value of social vulnerability indices and their associated vulnerability maps. Figure 6 illustrates the Cutter et al (2003) social vulnerability index tool applied to the U.S. by county. Vulnerability is characterized by quintile with those most vulnerable locations characterized as socially vulnerable.

Finally, there is a level of political sensitivity surrounding vulnerability mapping. Despite the apolitical nature of a vulnerability assessment produced by technical experts, end users could push back on maps for various reasons, such as, not wanting their communities to be labeled as vulnerable as such a characterization may have negative implications for property values.

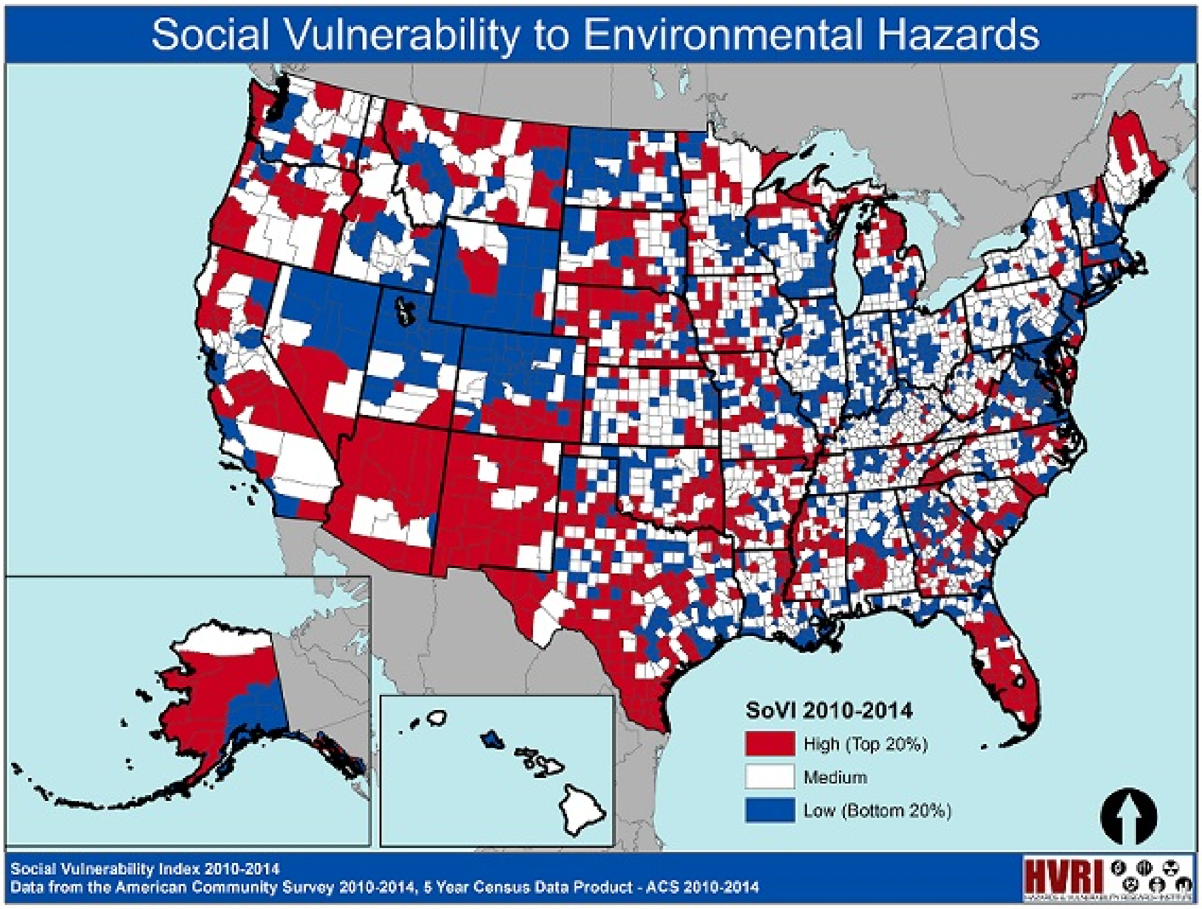

Figure 6. Social Vulnerability Index for the United States: 2010-2014.

The Social Vulnerability Index (SoVI®) 2010-14 measures the social vulnerability of U.S. counties to environmental hazards. The index is a comparative metric that facilitates the examination of the differences in social vulnerability across counties. SoVI® is a valuable tool for practitioners as it graphically illustrates the geographic variation in social vulnerability. The SoVI® index can determine the differential recovery from disasters using empirically-based data. It synthesizes 29 socioeconomic variables, which contribute to reductions in a community's ability to prepare for, respond to, and recover from hazards.

In SoVI® 2010-14, eight significant components explain 78% of the variance in the data. These components include wealth; race and social status; elderly residents; Hispanic ethnicity and residents without health insurance; special needs individuals; service industry employment; Native American populations; and gender. To compare the SoVI® scores at a national level, they are mapped using quantiles. Scores in the top 20% of the U.S. are more vulnerable counties (red) and scores in the bottom 20% of the U.S. indicate the least vulnerable counties (blue).

Source:

http://artsandsciences.sc.edu/geog/hvri/sites/sc.edu.geog.hvri/files/US_County_SoVI_2010_14_3_Class_2.jpg

4.2 Geographic Scale

Available data often determine the geographic scale of the analysis. While some researchers think it is necessary to focus on the smallest, most reliable resolution available, others suggest that it is more important to target the spatial resolution at which interventions are introduced. For example, if a city is going to design interventions for extreme heat events, then the heat vulnerability index should be done at the city level for areas that represent meaningful neighborhoods or spatial designations within that city.

Social vulnerability indicators may be limited by inconsistent scales. Most health data are available by local, state, or regional administrative units. Areal units matter; using inconsistent scales can lead to contradictory or simply inexplicable results.

Social vulnerability indices are often utilized at the county level as counties are the first point of contact in disasters. Because most of disaster management is local, the county level resolution works best; the compromise being the lack of sub-county variability you may see in exposures and health outcomes. The rationale for decisions regarding resolution or extent should be apparent.

4.3 Types of Indicators

4.3.1 Vulnerability Indicators

Good quality data on extreme heat exposure are generally available. But data characterizing sociodemographic vulnerability are less so. The goal, from a health perspective, is to protect vulnerable populations. In the next few decades, vulnerability will be much more important than the hazard itself as a driver of the impacts of extreme events.

The most common vulnerability indicators include data on population and income (often from the U.S. Census and ACS), but these measures alone do not capture the range of identifiers or characteristics of vulnerable populations.

The most robust variables from the ACS include those related to a given population's sensitivity to heat exposure with respect to age (the very young or very old), disability status, educational attainment level, languages spoken at home and related English-language proficiency, access to automobiles and other modes of transportation, access to telephones and Internet connectivity, access to air conditioning, and the age and construction of residential and commercial structures.

Additional explanatory variables can be used as indicators, such as factors related to housing and the built environment, underlying health status such as chronic disease incidence, or social or community connections, derived from data about existing social networks. Environmental variables may also serve as indicators, such as vegetation cover and green space, particularly for heat- or flood-related vulnerability.

While the U.S. Census and ACS are good data sources, there is relatively less information available on the mechanism and process that confers vulnerability. Income is often thought of as a contributing factor to vulnerability, but income may only be important if mediated through some other mechanism. For instance, income is related to the presence of air conditioning, which is relevant to thermal stress or comfort. However, there are constraints on our ability to apply this relationship as an indicator of vulnerability: air conditioning use may change from day to day. It would be helpful to have better survey data, as there may be a wide range of air conditioner use. It may be possible to fill some data gaps through household survey data. County health departments may also help to provide additional data for the communities they serve.

We can leverage additional variables from the Census Bureau's Longitudinal Employer-Household Dynamics program (http://lehd.ces.census.gov/). These show workforce characteristics that give insight as to the status of a workforce within a disaster area, as well as the location of workers who live within a declared disaster zone. These types of variables demonstrate major industries impacted and potential economic loss in endangered or disaster-warned areas.

Assessing exposure is more straightforward and less difficult than assessing adaptive capacity. There are well-defined factors to consider with exposure assessment, such as a simple count of the number of people located in the exposed area.

There may be reasons to assign weights to individual indicators, as well as to individual components of vulnerability, in the process of developing an overall vulnerability score or ranking. For example, if one indicator showing extreme vulnerability is averaged with another indicator showing no vulnerability, the resulting score would indicate moderate vulnerability. But, in reality, one of the extremes might better represent overall vulnerability than the average value. Indicators may also be weighted according to stakeholders' or analysts' perceptions, such as confidence in the underlying data. For example, in a case where confidence in sensitivity and exposure data is higher than confidence in data on adaptive capacity, overall vulnerability scores or indices could place more weight on the sensitivity and exposure components of vulnerability. The impact of weighting decisions can be explored through sensitivity analysis.

Limitations of vulnerability indicators. While a range of different data sources are used in deriving vulnerability indicators, there are limitations to their application. Sometimes available epidemiological studies are not sufficient to determine which population groups are most vulnerable. It is possible that one factor is clearly an indicator in one place, but not an indicator in another place. In addition, the relationships between different indicators may not be well understood. We need to evaluate:

- Whether designations of vulnerability are universal,
- For which populations are there enough reliable data to conduct factor analyses,
- How will different vulnerability indicators for the same weather-related health outcome relate to one another, and
- Are indicators compatible and either synergistic, additive, or multiplicative when assessed across an array of explanatory factors?

By laying out a conceptual framework the overarching reason for creating a vulnerability index can be described. Articulating how we think the system works, before proceeding with data analyses, is key. There are also assumptions and decisions that go into deriving indices that can change the outcome of the measure. It is important to explain the decisions made at each step of its construction (e.g., why is it an additive rather than a weighted index).

4.3.2 Adaptive Capacity

Defining adaptive capacity. Resilience and adaptive capacity are related but distinct concepts. Most often, the term adaptive capacity is used to describe the capacity to mitigate hazards and to lessen or withstand harm.

Currently, there is an emphasis on resilience: the ability of a system and its component parts to anticipate, absorb, accommodate, or recover from the effects of a hazardous event in a timely and efficient manner, including through ensuring the preservation, restoration, or improvement of its essential structures and functions. Resilience is not the opposite of vulnerability: you can be very vulnerable but have considerable resilience that allows you to withstand and recover from adverse impacts.

To illustrate the differences among these terms, consider a community of older adults. Older adults are generally *sensitive* to extreme heat. However, if the older adults in a community live in air-conditioned spaces and remain indoors during extreme heat events, they will not be *exposed*. Their *adaptive capacity* is strong, as indicated by their access to and ability to afford air conditioning. Therefore, this community of older adults is not *vulnerable* to extreme heat events, as long as there is electricity available to operate their air conditioners and they can afford to keep them running. But that does not necessarily mean they are *resilient*. Resilience has more to do with their ability to return to good or improved health after exposure to an extreme heat event.

Data considerations for adaptive capacity. While the most desirable source of information is at the household level, and includes economic data related to poverty or income, education, and degree of integration across social systems, at a higher level we need more and better institutional research on the health care system, on community planning and governance, and on other social institutions that will determine or contribute to adaptive capacity and resilience. It is unlikely that adaptive capacity can be adequately or accurately determined at the individual or household level. Vulnerability assessments based on data at hand have been conducted, but data collection is time- and resource-intensive and may not be feasible.

Hospital location, accessibility, size, and available beds are good indicators of healthcare infrastructure and capacity for adaptation that contributes to our understanding of vulnerability. Yet, the spatial resolution and extent of these various measures may not be consistent and may mean that data at different scales will not support an integrated analysis.

Challenges with indicators of adaptive capacity. Adaptive capacity is not always measurable and depends in part on its definition. It has been suggested that most indicators of adaptive capacity are theoretical and conceptual rather than empirical. This does not mean that adaptive capacity cannot be assessed, but it makes it a more difficult undertaking. Getting the appropriate socioeconomic and demographic data can be challenging, although relatively easier than tracking the institutional and political determinants associated with adaptive capacity.

4.3.3 Cross-Sector Indicators

Evidence indicates that different vulnerability indicators for the same health outcome can be related statistically to one another. More research is needed—particularly across sectors. There are more direct pathways for hazard exposure and greater confidence in the resulting vulnerability map. Nonetheless, there remains a need for better understanding across sectors and with respect to indirect or complex pathways.

Mapping Methodologies and Challenges

There is no definitive method for mapping the vulnerability of health to exposures to extreme heat, as varying geographic and temporal scales, other environmental stressors, and health vulnerabilities may be best suited to a variety of approaches. Maps may be used to characterize different types or numbers of hazards or exposures. And, while a single-variable map may be useful for data exploration, one should consider how many map "layers" are available, understood, and applied.

5.1 Goals and Objectives

A number of questions are important to consider as analysts assess methodologies for mapping the vulnerability of heat-related health impacts:

- What are the goals and objectives of the vulnerability assessment?
- Who is the target audience and what do you want them to learn?
- What are the key benefits and limitations of various approaches?
- Are there types of heat-related stressors or impacts for which a specific methodology is most or least useful?
- Are there types of health vulnerabilities for which a specific methodology might be most or least useful?

5.2 General Considerations and Challenges

Everyone wants to obtain vulnerability measures that explain what can be done to improve conditions and lessen vulnerability. This desire for actionable outcomes affects the choice of methodology.

A key consideration is whether a given vulnerability mapping approach will reflect the causal pathways that link exposure and outcomes. For hazards such as heat waves and air quality changes, information about exposure at the individual level may not be available. Mapping methods may work best for those hazards that have shorter causal pathways, e.g., heat and air pollution exposures because they may represent pathways at the scale at which the hazard occurs. Sometimes it is not as essential to know the causal pathway as it is to know the relative explanatory capacity of a given vulnerability indicator.

Some general limitations and challenges to consider in evaluating methodologies include:

1. How well does the spatial resolution of Census data represent processes related to population vulnerability?
2. How well is a hazard or exposure represented by deriving or calculating a social vulnerability index?

3. How is the explanatory capacity of different vulnerability factors compared with respect to each other?
4. Does it make sense to use the same set of explanatory variables in two different locations?
5. How have recent efforts improved the ability to validate vulnerability indices (Harlan et al., 2013; Chuang and Gober, 2015; Reid et al., 2012)?

5.3 Map Content

The first consideration when determining the most appropriate mapping methodology is the content to be addressed. To some degree, analyses are constrained by available data, which might incline analysts to adopt an approach that includes the same standard set of indicator variables across a range of heat-related hazards and health outcomes. If the objective of the map is to visualize vulnerability associated with likely health impacts, maps should be grounded in social theory as it pertains to health disparities and knowledge about the physiological impacts of a specific hazard such as exposure to extreme heat.

This report does not provide comprehensive coverage of the technical aspects of map construction and has not addressed several relevant cartographic issues. Nonetheless, one way to interpret maps is to address options with “if/then” statements such as “if your map is looking at this variable, then this analytic approach will be the most useful.” It may be useful to provide end users with map examples and to rank them according to their relative difficulty or ease of preparation, interpretation, and application.

Participatory mapping is an interesting approach because what you are essentially asking is for stakeholders to develop maps according to their own understanding of the system. This is useful for data poor topics or complex issues where local knowledge adds value. Such an approach helps uncover new data and adds credibility and legitimacy to map making.

5.4 Map Boundaries

The appropriate spatial extent for a map may be determined by the geographic content of available data. Setting spatial boundaries is complicated by methodological issues such as trying to spatially cluster census tracts into socially similar areas of vulnerability. Institutional and social boundaries may not overlap with available physical or health outcomes data. Further, differences in resolution and mismatched data types and changes across time can pose challenges and introduce uncertainty in the interpretation of results.

5.5 Various Heat-Related Health Impacts

The variety of heat-related health impacts, as well as the lack of conceptual work on the different kinds of health outcomes that are caused by weather, are important considerations in mapping vulnerability. Many sudden or acute events such as heat waves, flooding, storms, and wildfires have acute health outcomes, which are different from slower-moving changes such as those related to sea level rise or drought. Stressors such as sea level rise or drought can be predicted and planned for over a longer time frame than more acute or emergent events such as heat waves. Figure 7 illustrates projected increases in the risk of very large wildfires by mid-century in the

U.S.

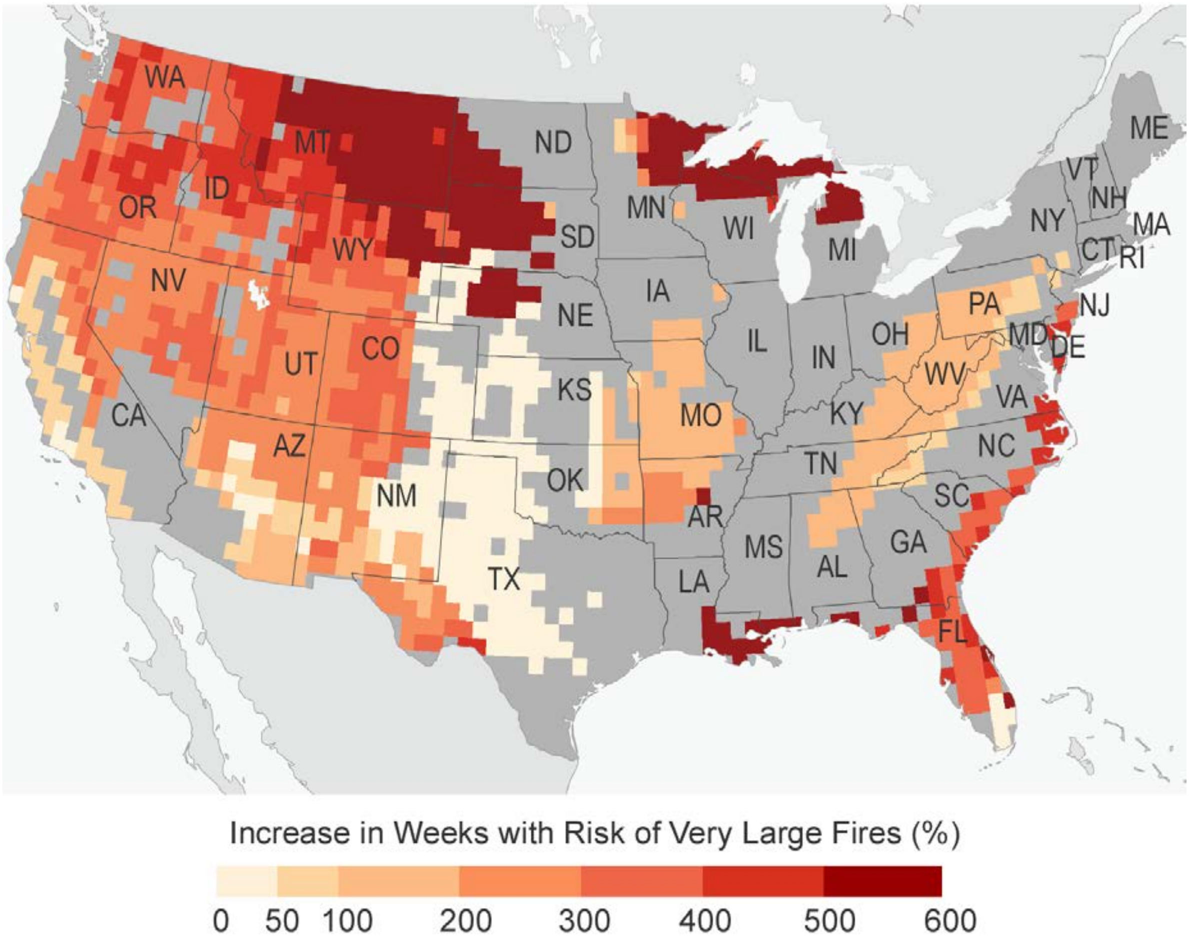

Figure 7. Projected increases in the risk of very large wildfires by mid-century.

Based on 17 climate model simulations for the continental United States using a higher emissions pathway (RCP8.5), the map shows projected percentage increases in weeks with risk of very large fires by mid-century (2041−2070) compared to the recent past (1971−2000). The darkest shades of red indicated that up to a six-fold increase in risk is projected for parts of the West. This area includes the Great Basin, Northern Rockies, and parts of Northern California. Gray represents areas within the continental United States where there is either no data or insufficient historical observations to build robust models. The potential for very large fire events is also expected to increase along the south Atlantic, the Gulf Coast, and the Great Lakes.

Source: Adapted from Barbero et al. (2015).

5.6 Issues Regarding Time and Space

Understanding how factors affecting vulnerability change across time and space is helpful for mapping vulnerability. This information targets adaptations in communities whose vulnerability may increase over time. Currently, it is not clear how vulnerability factors will change with the passage of time, nor is there data at an appropriate resolution to be used in that determination.

Establishing a baseline for the selected time frame is critical and goes back to issues surrounding data availability and accessibility.

Assessments are generally based on current or recent vulnerability. Research has tended to focus on how exposures will evolve over time, but there is less information on how the population itself might change in the future. Historical socioeconomic and demographic trends are under-reported compared with changes in exposure. Would we have known 100 years ago where elderly populations would be located today? Or would we have known there would be out-migrations from major cities?

Combining current socioeconomic data with weather data is confounding. There is a disconnect related to discounting future socioeconomic conditions. The other option is to think about how socioeconomic conditions will change in the future by building out future socioeconomic scenarios. While that may be the best way to look at future conditions, it is difficult to apply. More work is needed to establish a standardized methodology for addressing issues related to temporal scale.

Both current and future vulnerability merit consideration. The user of this report may find that the questions they seek to answer are situated in the current or near term or in a longer time frame. They will need to focus on the time scale that most closely coincides with their interests.

Challenges for this type of analysis include determining what scenarios should be used, and whether appropriate data products already exist (e.g., Socioeconomic Pathways [SSPs], Integrated Climate and Land-Use Scenarios [ICLUS]), or whether they would have to be derived from scratch (which is not a trivial undertaking).

Another option is to prepare vulnerability maps that address the current situation and then update them as circumstances change. Uncertainty related to future projections is an important consideration. Extreme weather events are already affecting human health, and there are adaptations that can be initiated. Mapping vulnerability can start now and adapt as things change over time.

Social vulnerability is multidimensional and dynamic and difficult to predict. Researchers may attempt to linearly extrapolate data, but population characteristics change in ways that may not be linear, so this may not be a viable approach. Existing tools are inadequate for addressing the issue of temporal scale. Someone might be able to do it with advanced modeling and simulations, and then in 10 years complete a hind cast to see how well they predicted—but that process is itself time and labor intensive.

5.7 Issues Regarding Time Frame in Mapping Vulnerabilities

Vulnerabilities that are particularly difficult to map include precipitation, droughts, and infectious diseases. As storm events can affect areas that extend beyond the immediate location of the precipitation (i.e., downstream) and may not be heterogeneous, analysts may find that mapping precipitation is complicated and may be prohibitive. Droughts are also difficult to assess, as their impacts may be indirect and the soil moisture levels used to characterize droughts are estimated across large areas—when in reality soil moisture can vary significantly over relatively small spatial extents.

The extent and nature of infectious diseases also can be very complex and uncertain. Further, as there is considerable uncertainty in each model step there is compounding uncertainty that cascades through the modeling process. Similarly, vector-borne illnesses are hard to map in part because incidents of illness are associated with where victims live, not necessarily with respect to the location where the illness was contracted.

Coastal flooding, sea level rise, and extreme heat are more readily mapped. Coastal flooding and sea level rise affect broad areas, and good quality elevation data is available for most coastal areas in the United States. We can map these exposures with high confidence.

Analysts also may be able to map exposures to heat with high confidence because they can obtain very refined, high-quality data on ambient temperatures (on daily or even hourly increments) in urban areas. However, hazards related to solar irradiance, wind speed, indoor temperatures, and humidity also play large roles in heat-related hazards and can complicate or simply confound the standardization of mapping methodologies.

5.8 Considerations Across Scales and Time Frames

Stressors such as sea level rise or drought can be predicted and planned for over a longer time frame than acute events, but acute events, such as heat waves, floods, and wildfires, need to be addressed by emergency service planning with build-out of more resilient infrastructure designed to reduce heat-related exposures. Vulnerability maps should be designed to accommodate and communicate information about both types of stressors—or if they focus only on gradual stressors they should at least acknowledge the presence of acute risks to encourage informed and adequate near-term response strategies.

There are a number of scale challenges, both spatial and temporal, that may be difficult to reconcile. Weather data typically have a fairly high spatial and temporal resolution, are available across large geographic extents, and are continuous over time. Therefore, it is easier to develop models based on historical data and then run those calibrated models into the future.

One of the biggest challenges of making long-term projections is that the socioeconomic data are dynamic. Political and planning timescales are on the order of a few years. And, one may not be able to assume that explanatory variables will remain the same with the passage of time. Projections assuming unchanging trends in population or development may grossly over- or underestimate vulnerability. Analyses using a range of assumptions about future socioeconomic conditions may most accurately capture the range of potential risks.

The American political system tends to have an election cycle time perspective. Policy decisions can fundamentally alter land use and development patterns in very short order, which in turn influence population distributions and movements. How we take those changes into account can be a useful intellectual—if not practical—exercise.

These considerations point to another significant challenge in mapping: how to communicate uncertainties in space, time, and other characteristics of the data. Researchers have developed ways to depict data uncertainty in maps, ranging from descriptions in map legends or captions; split or toggled maps that depict uncertainty data in a separate frame; maps that use integrated overlays of symbols, colors, or shading to indicate different types or degrees of uncertainty; and animations (MacEachren, Brewer, and Pickle, 1998). Each approach has advantages and disadvantages: narrative descriptions can provide nuance but may be easy for readers to overlook, split or toggled maps may be less cluttered than maps with integrated overlays, but require readers to look back and forth between two maps. Maps that integrate multiple overlays of symbols, colors, or patterns to indicate different types of uncertainty allow readers to visualize multiple uncertainties but may be confusing or take time to interpret. Animations may be very effective at communicating uncertainty but are limited to certain types of presentations.

5.9 Communication and Interpretation: Issues of Technical Capacity

Another consideration is how to accommodate different levels of technical skill or knowledge for map makers and users. Sometimes maps communicate simple information, but sometimes there is a need for technical expertise in interpreting the background information and evaluating the findings in addition to just viewing a static map. One may need to have a resource person who can interact with decision makers as they work through the technical details or nuances of the information displayed in a given map. Some methodologies are difficult to explain and present to decision makers. For example, local health departments may be limited in funding or staff and their knowledge and technical capacity may be inadequate or ill-suited to allow them to readily apply vulnerability maps.

5.10 Mapping Methodologies

5.10.1 Participatory Vulnerability Assessment

Participatory vulnerability assessment moves beyond readily available data and starts to bring in qualitative data on people's personal experience, local knowledge, and risk perception. This provides access to other types of knowledge, which lets analysts build a more nuanced view of what affects people's lives and how they experience different human health hazards. This methodology is most common in developing countries, due to a lack of geographic information systems (GIS) data but has been used in the United States.

Participatory approaches can be used to frame the question "here is what we have done and here are the results, what do you think?" Participatory mapping is interesting because what you are essentially asking is for stakeholders to generate the map from their own understanding of the system. This can be used for data poor topics or complex issues where local knowledge adds value. This method helps uncover new data and adds credibility and legitimacy to a map from an end user's perspective.

Qualitative data can be represented on maps in a variety of ways, such as through icons representing different levels of risk or exposure, or as visual representations of a qualitative scoring system (e.g., "high, medium, low"), e.g., expressed as colors on a map. Integrating qualitative and quantitative information on the same map requires caveats and explanations, although qualitative information is not necessarily less accurate or reliable than quantitative data.

The results of participatory vulnerability assessments are generally best for use related to broad-scale information/indicators, rather than for answering very geographically specific questions. Because of this limitation, analysts recommend looking less at where health impacts may be and more at the geographic extent of weather events and regional vulnerabilities.

Another limitation is the acceptance of participatory vulnerability assessments among the populations for which they are being conducted. For instance, San Francisco is currently conducting a geographically detailed assessment as part of its mitigation planning process. However, some neighborhoods express their concerns that such assessments may undermine property values if their community is designated a vulnerable location.

5.10.2 Map Overlays

Map overlays are a vulnerability mapping method based on *a priori* knowledge about certain health outcomes (see for example, Wang and Yarnal, 2012). A single variable map overlay is useful for data exploration. However, some suggest that the most useful maps are those that integrate data across a number of vulnerability indicators and health outcomes. Analysts must ensure that the viewer is not overwhelmed with too many elements in a single map. Bivariate maps, for example, display two variables (such as percentage of the population below poverty level, and percentage of the population over 65 years of age) on one map. Other solutions are possible for presenting a larger number of variables. For example, researchers recently published a paper on the potential for the spread of Zika virus in the United States looking at climate variability. In the paper, the authors considered the monthly suitability for Zika mosquitoes throughout the United States, then superimposed travel histories onto cities to look at the potential for the virus to be introduced in a given city. The authors also looked at other viruses transmitted by the same mosquito species to understand the habitat and historic spread pattern. All three of these elements (climate, travel, habitat/historic spread) were superimposed onto the same map to highlight the relative geographic likelihood of future Zika outbreaks (see Figure 8). It has been suggested that most people prefer no more than three types of information appear on a map, so the authors opted to put additional information in a separate map overlay.

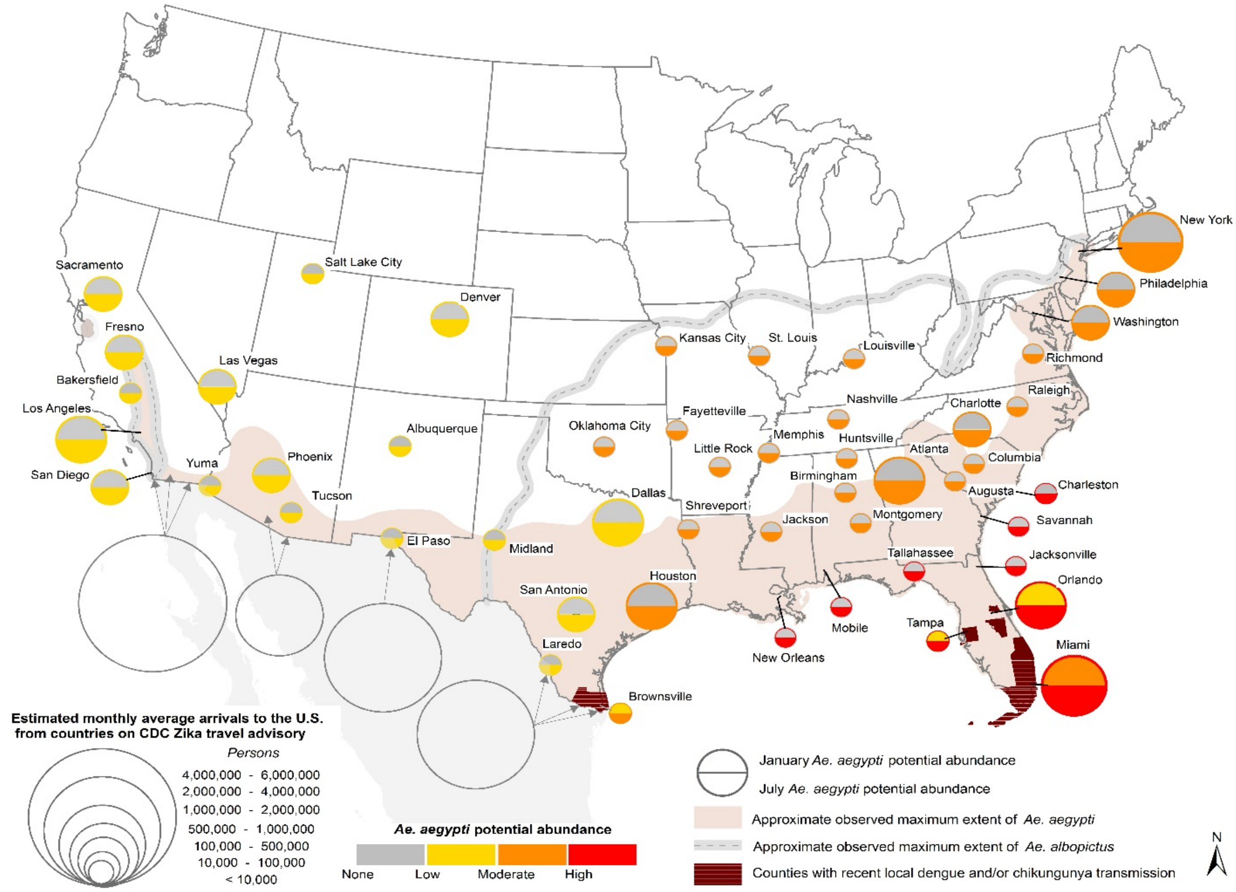

Figure 8. The occurrence and abundance of the Zika virus vector mosquito *Aedes aegypti* in the contiguous United States.

This U.S. map shows (1) *Aedes aegypti* potential abundance for Jan/July (colored circles), (2) approximate maximum known range of *Aedes aegypti* (shaded regions) and *Aedes albopictus* (gray dashed lines), and (3) monthly average number arrivals to the United States by air and land from countries on the CDC Zika travel advisory. While *Aedes aegypti* and *Aedes albopictus* are established across much of the southern United States, mosquito populations in many areas are only present seasonally. This seasonality varies according to local meteorological conditions, and thus can provide one measure of potential for Zika transmission. To better understand the risk for local Zika transmission in the United States, we simulated the potential abundance of adult *Aedes aegypti* mosquitoes across fifty cities using meteorologically-driven life cycle models and identified proxies of travel-related introduction and of human exposure to vectors to provide context for the model results.

Source: Monaghan et al. (2016).

There are several advantages to using a map overlay approach. Map overlays are straightforward to understand, and analysts can readily visualize the underlying data. For example, if an analyst was interested in poverty and the implications of heat waves, that analyst could create map layers that show where extreme heat is expected in relation to the location of households at or below the poverty line and households with affordable and reliable air conditioning. These layers show the intersection of location of a vulnerable population with respect to their particular exposures.

To successfully use a map overlay approach, analysts need extensive knowledge of the situation being analyzed, including what populations are adversely impacted. If one or more domains of data are unavailable, then a map overlay approach may not be applicable.

Another example of an appropriate use of map overlays is for an analysis of weather-related exposures incorporating the three elements of vulnerability: exposure, sensitivity, and adaptive capacity. For exposure, if analysts are interested in historical trends of days with temperatures of 95−99°F, they can use rasterized historical data interpolated to the county level. Sensitivity addresses socioeconomic and environmental risk factors associated with underlying morbidity and mortality. For instance, one may be interested in the number of patients with kidney disease, as they will be more at risk during heat waves. Socioeconomic status, poverty, and age (elderly or children) as well as sensitivity related to the environment (e.g., residence in urban heat islands or the lack of green space and the extent of impervious surfaces) also may be considered. The third piece is adaptive capacity, which refers to the ability of an individual, community, or organization to respond to an extreme event. For instance, analysts may look at information on hospitals in terms of accessibility (as measured by distance to the hospital, number of beds, facility size, specialized services and available trauma or intensive care units, etc.). Such a three-layer overlay analysis that maps each layer (kidney disease prevalence, socioeconomic status, and hospital location), is relatively easy to apply for most GIS tools.

5.10.3 Cluster Analysis

Conducting cluster analysis is analogous to developing vulnerability indices (see for example: Cutter et al., 2003; Clark et al., 1998; Reid et al., 2009). Users define areas with similar degrees of vulnerability, which helps analysts move away from a yes/no measure of vulnerability to an analysis of locations with similar challenges, opportunities, or assets. Users categorize data and investigate similarities across areas. This allows users to control various inputs and determine economic losses or negative health outcomes based on each of the inputs by using multivariate regression analysis to estimate coefficients once the indicator typologies are defined.

Cluster analyses can be used in the analysis of extreme events. For instance, analysts can investigate the impact of changes in population and economic development on exposure to extreme weather from an economic perspective. Users can take this approach and incorporate climate incidents, topography, and socioeconomic indicators (e.g., education, population, and income), and use clustering to develop such a typology and regress it against observed economic losses. Users can then predict losses from extreme weather based on a single aggregated explanatory factor.

5.10.4 Machine Learning

If users have data on outcomes and potential explanatory factors, they can use Bayesian networks or other machine learning methods to construct nodes and let models train themselves on a data set using machine learning algorithms (see for example, Holt et al., 2009). Such models tell users, based on their conceptualization, what driving forces are contributing to observed morbidity or mortality. Users can then diagnose the relative value of critical elements. Instead of starting with indicators, users start with outcomes and work backward to assess the influence of different indicators. Users can look at inferences associated with a variety of changes in temperature or precipitation. Users can also link it to GIS and map the influences on observed statistical relationships. By using machine learning approaches, users directly quantify the link between an outcome and the factors that contribute to its occurrence.

5.10.5 Time Activity Patterns

One newer mapping technique is information on time-activity patterns, which use actual spatial and temporal person-level data. The EPA uses this type of information in air quality assessments, but it has not been adopted to be part of most weather-related hazard research. With a few exceptions (Karner et al., 2015), analysts do not typically analyze people's activity patterns as doing so is complex, time-intensive, and expensive.

EPA's Consolidated Human Activity Database could be useful for gathering information on measuring personal heat exposure with wearable sensors (Bernhard et al., 2015). Yet this is not feasible for an entire population, but data samples may help analysts to better understand general activity patterns and develop and ultimately test related hypotheses.

5.10.6 Hazards Mapping

The advantage of the hazard mapping approach is that it is well defined and can be sanctioned or official, such as FEMA flooding maps. In addition, hazard mapping is a good point of entry because hazard maps are easy to understand and relatively easy to construct.

The disadvantage of hazard maps is that people may equate the existence of a hazard in a given location with consequences, even when that may not be the case. Exposure alone does not imply vulnerability. Vulnerability indicators can be mapped but developing meaningful relationships between exposure and social vulnerability indices can be challenging and a nontrivial source of uncertainty.

In addition, hazard maps may not account for factors with acute boundaries. For instance, urban heat islands may lead to increased heat in some areas, but heat is a relatively diffuse hazard. Also, the spatial pattern of the hazard does not tell analysts which areas or populations are at the greatest risk. To address these limitations, analysts need a better understanding of the epidemiology of hazards and how people "move" in their environment to determine their relative exposure.

Tools for Mapping the Vulnerability of Populations

6.1 Geographic Information Systems (GIS)-Based Tools

GIS tools can be used for activities such as determining adaptive capacity and identifying vulnerable populations and at-risk locations or vulnerable infrastructure. Relevant tools mentioned or discussed during interviews with SMEs are described below. Where available, information on monetary and technical requirements are provided. Different types of tools have been addressed, including: tools that incorporate data sets, tools that improve data accessibility, tools for visualization, and tools for analysis.

There are tools that are used to visualize data and help further define research questions associated with health impacts associated with extreme heat. This might be a useful starting point for people who do not have access to other tools. Tools such as ***Tableau*** (visualization of multidimensional data; https://www.tableau.com/solutions/topic/maps) help visualize data sets in a variety of ways, using basic map overlays. Data analytic tools give access to large data that can be introduced into one's own GIS application. Oftentimes, public health and planning entities have their own web service capabilities to retrieve and analyze data. Questions to consider, include:

- How can state and local government agencies be assisted to identify and access data?
- What is the penetration of ArcGIS or other common GIS tools in state and local government offices?
- What GIS-based tools are people already familiar with and routinely using?

If end users have already invested in a tool, we need to provide data and mapping input in a way that is seamless with and supportive of existing data sets and analytic approaches.

6.2 ArcGIS

ArcGIS is a desktop and online-based system used for creating maps, compiling geographic data, analyzing mapped information, and managing geographic information in a database.

ArcGIS can be used to map GIS layers without conducting any additional analyses. Such analyses help us to learn about the distribution of vulnerability factors and extreme weather hazards. To inform decision making in the health care community, information is produced that is useful to end users, not just academics. To do that, the distribution of factors that may impact vulnerability, such as demographic and socioeconomic factors, and the accessibility of healthcare services and infrastructure need to be assessed.

ArcGIS is a good approach, but it is an expensive analytic tool and requires an annual licensing agreement. In terms of technical requirements, state and local health departments often do not have the capacity or time to develop GIS mapping skills. They may have one or two epidemiologists on staff and perhaps they have some GIS skill, but they might not feel confident in developing a vulnerability index and associated vulnerability maps. See https://www.arcgis.com/features/.

6.3 Carto

Carto is a Web-based platform and set of applications that can be used to perform GIS, data analysis, and data visualization operations. See https://carto.com/.

While Carto has free plans, the paid plans offer privacy features and more data use capabilities. When using free software, users should be aware that data shared online may not be secure and may not ensure privacy especially if health data or other sensitive information is being used to develop vulnerability maps.

6.4 QGIS

QGIS is a free and open-source geographic information system that runs on Linux, Unix, Mac OSX, Windows, and Android. It supports a variety of vector, raster, and database formats and functionalities. See https://qgis.org/en/site/.

6.5 Social Vulnerability Index (SoVI)

The Social Vulnerability Index (SoVI) is an analytic tool that includes a GIS-based approach that is used to look at a range of hazards, some of which are sensitive to changes in weather patterns. Vulnerability is represented in a map format with shading to break vulnerability into tiers based on standard deviations or other statistical categorizations. The index, usually derived via factor analysis, is used extensively by academia and federal agencies. This tool gives the user information on preexisting social vulnerability in certain communities. With that information, GIS can be used to incorporate hazard information such as heat waves or overlay other environmental stressors to create bivariate maps. The bivariate map can use a color-coded matrix to identify areas with high social vulnerability and high levels of drought or any other bivariate combination of social vulnerability and weather-related risk. See http://artsandsciences.sc.edu/geog/hvri/sovi%C2%AE-0.

SoVI has been included in many state and county hazard mitigation plans and public health risk assessments and is used as a decision support tool in prioritizing and distributing U.S. Housing and Urban Development Community Development Block Grant Disaster Recovery Program funds.

6.6 Geospatial Emergency Management Support System (GEMSS)

The Geospatial Emergency Management Support System (GEMSS), a web-based mapping tool developed by the Texas Natural Resources Information System, a part of the Texas Water Development Board, integrates data collected during and after major disasters with real-time and existing geospatial data. GEMSS allows the data to be presented in a useful and compelling manner, without requiring specialized knowledge of GIS data or applications. GEMSS is designed as a public domain tool to support emergency response activities. See https://gemss2.tnris.org/.

6.7 OntheMap Emergency Management Tool

The Census Bureau's OntheMap Emergency Management tool offers an approach for mapping the vulnerability of human health to various extreme weather impacts by using an intuitive Google Maps API-based interface, integrating it with real-time data (updated every 4 hours) from federal agencies about current and past threats, and statistics from the U.S. Census Bureau about vulnerable communities, including the constituent workforce in impacted areas.

For disaster responders, this tool combines social, economic, housing, and workforce data with disaster area data in one tool. There is flexibility within this web application to assess local geographies so that state and local first responders can see the impacts within the jurisdictional boundaries they serve. Figure 9 provides screen shots of the OntheMap tool.

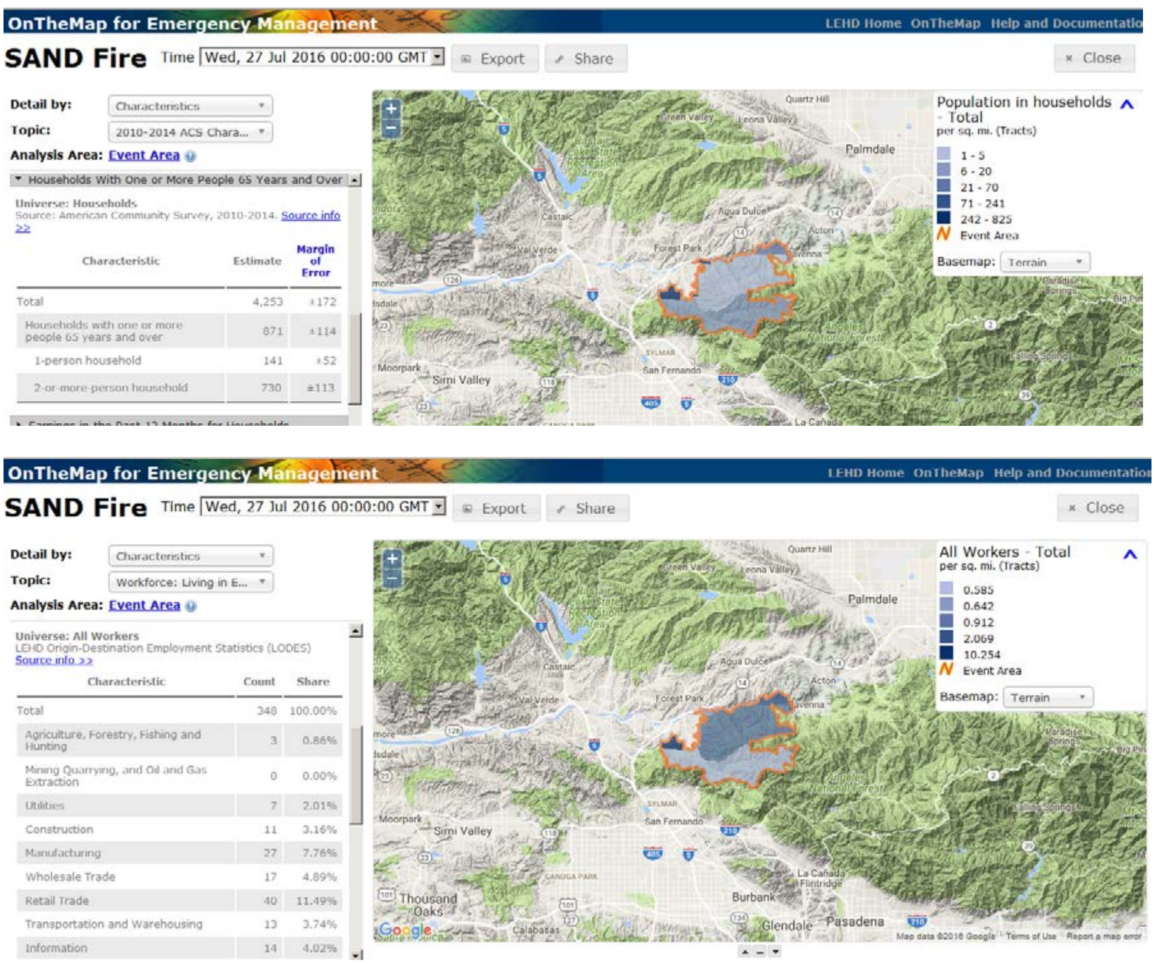

Figure 9. Screenshot from OntheMap Emergency Management displaying a wildfire emergency in Southern California on July 27, 2016.

To the left of the map is a pull-down menu where emergency responders can learn about the characteristics of the vulnerable populations residing in the wild fire area. Respondents can also use the pull-down menu to learn about characteristics of workers impacted by this wild fire (as shown in the second image).

The primary OntheMap tool allows for the rendering of all conventional geographies (states, counties, urban areas, census tracts, zip codes, etc.), while also allowing users the ability to derive custom geographies using more advanced tools. While the primary OntheMap tool takes more training to master than OntheMap Emergency Management, the Census Bureau routinely offers free data-access training as part of its Data Dissemination Branch to users nationwide.

OntheMap Emergency Management was meant to be used by members of the public and first responders in disaster situations. Recent enhancements, such as the 2014 addition of American Community Survey estimates, reflect this commitment. Future versions of OntheMap Emergency Management are slated to include enhanced reporting and expanded coverage of disaster types, including droughts, earthquakes, the impacts of rising sea levels, and heat waves

OntheMap Emergency Management contains a disaster data archive that goes back to 2010, which can serve as a useful resource for those who wish to use it as a tool to conduct disaster preparedness assessments. The limitations of OntheMap Emergency Management are that its geographic configurations are bound by specific events and the geographies that are impacted by them. Disaster preparedness teams can overcome this limitation by using the primary OntheMap tool, which allows use of workforce and demographic data for any geographic extent in the United States. Additionally, the smaller the geographic area of the disaster the larger the margin of error, so users need to be cautious in interpreting fine resolution data.

To visualize how OntheMap displays daily data and associated maps, see http://onthemap.ces.census.gov/em. From this website, one can access data and maps from 2010 forward. The website includes U.S. Census Bureau data for disasters, natural hazards, and extreme weather events. Note, that Figure 9 is an example of a screen shot that was generated for one day in 2016 that tracked a wildfire in southern California.

6.8 Other Tools

BioMod is a free, open-source ecological modeling package that uses ten different modeling approaches to model empirical outcomes (such as a disease occurrence or mortality). It is hypothetically possible to use BioMod for vulnerability mapping given the right variables. BioMod is implemented as a freeware, open source package in the statistical software R, so users must be familiar with using R software to use BioMod. This tool allows for multiple modeling approaches at once (e.g., regression, decision tree) by feeding a set of potential explanatory variables into the tool. After the tool runs, each of the ten models derives the best fit for the selected explanatory variables. See http://www.will.chez-alice.fr/Software.html.

The CDC's 500 Cities project provides city- and Census tract-level estimates for chronic disease risk factors, health outcomes, and clinical preventive service use for the largest 500 cities in the United States. These data may be used to characterize the burden and geographic distribution of health-related variables in these jurisdictions. See https://www.cdc.gov/500cities/.

Tools are available for mapping environmental justice and social vulnerability, such as CalEnviroScreen (https://oehha.ca.gov/calenviroscreen), a mapping tool that uses environmental, health, and socioeconomic information to produce scores for each census tract in the state. It maps pollution burdens as well as the location of vulnerable populations. The U.S. EPA's EJSCREEN environmental justice screening and mapping tool offers a nationally consistent dataset and approach for combining environmental and demographic indicators into environmental justice indexes. See https://www.epa.gov/ejscreen.

The EPA has also developed a number of products that are intended to help map current and future vulnerabilities associated with environmental stressors. The ICLUS is a tool that explores future changes in populations, housing density, and the extent of impervious services. The population and land-use projections ICLUS produces are based on updated global socioeconomic scenarios (e.g., SSPs) and new global climate change model targets (e.g., Representative Concentration Pathways). The environmental Benefits Mapping and Analysis Program—Community Edition (BenMapCE) is another easy-to-use program that assists in estimating the number and economic value of health impacts associated with changes in air pollution that may be exacerbated by extreme heat. BenMapCE has been used in a number of climate assessments examining how changes in air pollution associated with heat waves may impact morbidity and mortality. These tools and others can be found in the U.S. Climate Resilience Toolkit which houses methods to help manage risks that impact human health. See https://toolkit.climate.gov/.

6.9 Future Directions

Researchers are increasingly posting data and analyses on the cloud and using WebGIS or similar applications for conducting analyses, which reduces both data acquisition and storage requirements. This allows investigators to readily access and leverage the work of other researchers.

The CDC Environmental Public Health Tracking Branch has a new mapping application and tool that is being prepared to incorporate census tract data.

Google maps also has an interactive map tool. But there is a somewhat worrisome constraint with cloud-based maps and Google in particular. Google provides open access to the data it uploads even those health data that require privacy protection. The CDC has not embraced putting information on the cloud and has previously expressed concern with those tools, such as Carto, that do. Nevertheless, the future is in mobile technologies with web-based animations that are interactive and engaging. Such dynamic maps may improve the mapping experience for developers and end users.

It may be useful to make the link between people who need the data and mapping outputs with those who have the requisite technical skills to access data and conduct statistical or spatial analyses. For instance, local public health departments might work with a nearby university where technical experts can be identified to assist with accessing data and using appropriate data analytic tools. Some of the most significant barriers to these types of collaborations are time and funding limitations and data sharing issues for health data that are restricted by the Health Insurance Portability and Accountability Act (HIPAA).

Recommendations for Mapping the Vulnerability of Populations to Extreme Heat in the United States

7.1 Goals and Objectives

Researchers need to identify feasible goals and objectives for vulnerability assessment and map-making. Hypotheses should be derived that frame useful vulnerability mapping practices. Making sure the purpose for data analytics and map making is well articulated will be important to informing the choices that are made for identifying and retrieving data and ultimately in the spatial analyses that produce maps of weather-related hazard exposure, risks, and vulnerability.

A number of questions are important to consider in assessing vulnerability:

- Why is the work being undertaken and what hypotheses guide the research approach?
- What are the expected outcomes?
- Who does the product inform?
- How will vulnerability assessments and associated maps allow us to be prepared to better manage health risks?
- What geographic regions and timescales are being assessed?
- What kinds of tools and what kinds of data will be important to identify, access, and use?
- How are the factors we intend to map identified by the vulnerability assessment?

The following sections focus on more detailed considerations with respect to vulnerability mapping, especially related to methodologies, data accessibility and availability, addressing uncertainty, mapping do's and don'ts, and the importance of engaging stakeholders.

7.2 Defining Methodologies

There is no definitive methodology for mapping the vulnerability of human health to weather extremes. It is important to use the methodology that best reflects the requirements of each project. It will depend on data availability and the knowledge of what defines vulnerability for a specific heat-related hazard in a given location and how to represent that vulnerability through maps.

Different geographic scales and environmental stressors require different approaches. It is not always known which methodology works best at a given resolution or extent. Therefore, there is a need to allow for local flexibility and tailoring for specific place-based considerations.

There is significant ambiguity with respect to the “best” methodology. For any given analysis, it may be worthwhile to consider a range of methods according to their strengths and weaknesses. This allows researchers to target the methodology that best addresses their particular needs.

Mapping health effects can be challenging. Validating variables that contribute to exposure, sensitivity, and adaptive capacity and are statistically related to specific health outcomes can be difficult. For example, compared to general vulnerability to heat waves, infectious disease vulnerability tends to be more complicated because cause and effect relationships are more complex or indirect. It simply may not be possible to determine causal links between weather and heat-related health effects.

The utility of simply mapping GIS layers without conducting any additional analyses can be helpful; it can facilitate learning about the distribution of risk factors and hazards. Preparing a single-variable map can be useful for data exploration especially for identifying measures of central tendency and variation across relevant variables (and requires less technical knowledge compared to other spatial analytical techniques).

7.3 Limitations of Vulnerability Assessments

To characterize which population groups are more vulnerable, one may evaluate the following:

- Is vulnerability well-defined (see Glossary)
- For which populations or locations are there enough reliable data to conduct the analyses?
- How do different social vulnerability indicators for the same health outcomes relate to one another?
- Are these indicators the same or of a similar construct?
- Are indicators compatible across spatial and temporal scales?
- Are indicators synergistic, additive, or multiplicative?

The usefulness of case studies. Case studies can help to inform choices with respect to selecting appropriate analytic methodologies. For instance, the response and recovery activities following Hurricane Sandy provided an example of effective adaptation planning and implementation. The post-Super Storm Sandy report on mental health impacts in New Jersey is available online:

http://www.state.nj.us/humanservices/dmhas/home/disaster/sandy.html

Case studies also help visualize products that are similar in nature to research questions the reader may have and can assist in determining data and methodological needs. If a certain methodology worked well in one area, it may be reasonable to reproduce it in a different location. Peer-to-peer learning can be useful to that end.

7.4 Data Accessibility and Applicability

While there are data availability and quality limitations, it is important to try to obtain all potentially helpful data, even if it is not entirely a good fit. It could still be used to inform mapping exercises. There is a consistent call for finding better data sources. To that end, one could envision a future where collection of primary data is the norm rather than the exception.

Most often, meteorological data have finer spatial and temporal resolution than that of socioeconomic, demographic, or health data. Weather data are also available across larger geographic extents and over longer periods and are often continuous across time. The spatial scale (including extent and resolution) at which the vulnerability analysis should be conducted is that at which public health interventions or other adaptations will be prepared and implemented.

7.5 The Use of Proxy Variables

When a variable you wish to measure is not available at the spatial scale or timeframe of interest (or not available at all), you may choose to use in its place a proxy variable that provides a good substitute for that variable. For example, one may be able to capture education as a proxy for income. It is not uncommon that the vulnerability data we use are proxies of something we want to quantify, rather than a direct measurement of it.

For certain hazards, there can be complex exposure pathways—especially if there is an ecological link. For instance, to evaluate Lyme disease you may need tick distribution data, but if no data are available you could use proxy measures such as soil moisture or geological soil type (e.g., sandy soils). Certain infectious diseases, including waterborne and vector-borne illnesses, have very complex exposure pathways and available data can be the limiting factor in assessing vulnerability.

7.6 Using Household Surveys

Household surveys can be used to identify and obtain fine-resolution data. Census data are the most practical at large geographic extents, especially for modeling socioeconomic and demographic factors that affect weather-related health outcomes. But, while providing valuable information on factors associated with vulnerability, household surveys are expensive, time-consuming, and may be geographically constrained.

7.7 Sources of Socioeconomic and Demographic Variables

Socioeconomic and demographic variables that can be derived from the U.S. Census and the American Community Survey are the “gold standard.” Census block variables are helpful but limited, as the time series data from the Census is conducted only once every 10 years. In the ACS, variables pertain to age, disability status, household income, educational attainment level, languages spoken at home and related English language proficiency, access to automobiles, access to telephones and Internet connectivity, access to air conditioning and age and type of residential and commercial construction. The decennial Census continues to evolve and has changed since 2010. At this juncture, the Census Bureau is focusing more time and resources on the American Community Survey, which allows for data to be released more frequently and consistently over time.

7.8 Addressing Uncertainty

There are significant uncertainties and assumptions involved in map making. Mapping assumptions should be transparent, and maps should be tested with external data to validate the spatial representation of the data.

A map is likely to be the "tip of the iceberg," with significant uncertainty lying just below the surface. There is uncertainty associated with individual data sets and additional uncertainty from combining a variety of data sources and doing complex statistical analyses.

Reducing uncertainty is key. For example, when using certain methodologies, such as factor analyses, you need to "circle back" and conduct a sensitivity analysis by deconstructing or disaggregating what can be learned from each factor. For instance, you might find that older individuals living alone are at risk and that poorer people are at risk, but if you look at the correlation of these two populations, you may find that they are not occurring in the same place and may not be statistically related. The statistical relationships between these variables may also vary across locales.

Furthermore, those aspects of uncertainty that may be related to unmeasured spatial variability need to be characterized. Researchers addressing heat vulnerability have used images of urban heat islands to represent exposure, yet it is not known how representative they are with respect to urban surface temperature patterns, urban air temperature, or actual personal heat exposure. It would be useful to ground truth these findings, measure exposure, and take personal measurements. In addition, there is an indoor component, which reduces certainty about the extent of exposures that occur from extreme ambient (outdoor) temperatures.

7.9 Mapping Do's and Don'ts

Maps need to be readily understood. It is important to display multiple map overlays without overwhelming the viewer. One question that arises is about how to accommodate different levels of technical skill or knowledge for both map makers and users. End users may need technical support, as they construct their own maps or interpret maps made by researchers. Part of the reason to engage stakeholders early and often is to reduce this disconnect and improve the functionality of the maps they prepare.

Fundamentally, maps are communication devices and models: a simplification or reduction of the data. For best results, using color schemes, language, and presentation formats that can be readily understood and interpreted is ideal. All too often maps are prepared that are hard to use due to poor visual presentation. Well-chosen and visually-appealing maps are an important goal. There have been efforts to focus on trying to understand desirable practices and what those practices look like. One should ask: "How do you produce a map that people can look at and readily apply?"

7.10 Mapping the Current Time Period

Because weather-related vulnerability analyses typically focus on future vulnerability, they may overlook current vulnerability. Rather than trying to map only future change, it is important to produce maps that address the current situation, and then, as things change, update them. Paying more attention to at-risk situations now will help inform adaptations to future conditions. Also, focusing on who is currently vulnerable and what they are vulnerable to could improve public interest and encourage involvement in the assessment process. Mapping “on the fly” encourages the development of maps displaying current temperature-related health impacts.

7.11 Utilizing a Participatory Approach

One fundamental error in mapping exercises is underestimating the value of input from potential stakeholders. Their insights are crucial and given that taking a participatory approach is advised, securing participation of stakeholders from the outset is key. It may not always be necessary to the analysis, but in terms of acceptance of the results it is beneficial to have local partners and other end users involved early and often.

Adopting best practices can result in a good map, but you may miss the mark if you do not include community knowledge and input. To inform decision making in the public health community, we need to produce information that is readily utilized in that community. The goal of the vulnerability assessment is to address issues surrounding potential adaptation strategies and not merely as an academic exercise. At present, guidance on how to incorporate community knowledge and other qualitative data is not adequately delineated.

Participatory vulnerability mapping allows us to move beyond readily available data and start introducing people’s experience, local knowledge, and risk perceptions. This helps build a more nuanced view of what effects people’s lives and how they experience different heat-related health hazards.

Incorporating stakeholder input encourages dialogue. Often stakeholders need education and capacity building, so they can know how to take advantage of new methodologies or maps. In addition to engaging stakeholders, it may be beneficial to entrain professional communicators to fine-tune maps and other visual representations of vulnerability.

7.12 Takeaway Messages from This Report

The following messages summarize key findings and observations that will be especially useful for researchers, analysts, and agency officials as they develop vulnerability maps.

- There are issues with respect to capacity, funding, and expertise that are common across all scientific endeavors. Establishing the level of expertise required to best assist end users is important.
- Where possible, we need to link or integrate qualitative and quantitative data to prepare the most informative maps.
- Vulnerability assessments and mapping exercises require experts from multiple disciplines and demand significant time investment. Anticipating those demands and preparing to make those investments are core values.
- Maps should be a starting point for discussion. Revising maps with stakeholder input is a best practice. Stakeholders may include those who serve as data repositories,

those with technical expertise, local residents, and public health and community planners.

- Researchers should characterize and reduce uncertainties, be transparent about the assumptions they are making, and test maps with external data to validate its spatial representation.
- People may have a sense of where they are currently vulnerable but have no understanding about how this may evolve with exposures to extreme heat. There is post-modeling and post-interpretive work yet to be provided after maps are developed.
- Simple maps spur discussion about necessary adaptive actions and help to demonstrate how response resources will be most effectively and efficiently implemented.
- The real value of vulnerability maps is to identify targeted areas for risk reduction or interventions to enhance adaptive capacity or improve resilience. Vulnerability maps provide a quasi-scientific and apolitical way of identifying vulnerable areas and allow end users to determine the most susceptible communities where resources can be invested.
- From a policy perspective, the identification of risk and population vulnerabilities is central to the assessment and mapping process. To that end, one may think of map making as an iterative process whereby you generate an initial realization, rethink, get input, and generate an updated version.
- Clearly, vulnerability mapping is not only an academic exercise. We are called on to think through take-home messages and provide recommendations to stakeholders and end users at not much cost to ourselves but at potentially large costs for them.
- Existing environmental, health, behavioral, institutional, and experiential characteristics put some populations at greater risk to health effects associated with exposures to extreme heat. Also, meteorological factors interact with non-climate factors, including land-use and land-cover change, environmental factors, and socioeconomic and demographic trends to exacerbate or ameliorate health impacts for some populations or in some places.
- It is important for vulnerability assessments to focus on populations and locations with multiple susceptibilities e.g., the very young or very old, those who are socially isolated or live in poverty, some racial groups and Indigenous peoples, those with limited English language proficiency, those with workplace exposures, or those with preexisting physical or mental health conditions that put them at greater risk.

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Appendix A. End User Checklist for Developing Vulnerability Maps

- What is the question/problem you are aiming to answer by developing a vulnerability map of human health impacts associated with exposures to high ambient temperatures?
  - Hazard/vulnerable population; health outcome; place, time, and scale.
- Who are the stakeholders involved in developing the vulnerability map?
  - Government agency (Fed/State/Local); nongovernmental organization, community groups; technical developers; academic institutions.
  - If multiple stakeholders will use the map, should it be modified for the specific needs or capacities of each group, or is one map adequate for all stakeholders?
  - At what stage and how are stakeholders being engaged in the process?
- What level of technical expertise is needed to produce and interpret vulnerability maps?
  - Consider: data & data management; methodological and analytical needs; tools.
- What data are needed to produce the vulnerability map?
  - Literature review of current research and knowledge to assess data needs.
  - Are data readily available for location, time, and scale desired?
    - Secondary data sources: U.S. Census; meteorological data and land use/land cover data
    - Health outcome data: hospitalization; mortality and disease incidence.
  - What partnerships can be pursed to better access needed data?
    - State or local health departments; local hospitals or health clinics; academic institutions.
  - Will data need to be collected, if so, what type?
    - Household/individual surveys; focus groups; environmental measurements.
- What vulnerability or adaptive capacity indicators are already being employed for vulnerability mapping?
  - Are indicator indices available or will they need to be developed based on available data?
  - Are the vulnerability or adaptive capacity indicators and underlying data chosen valid and accurate in describing the explanatory capacity of the health vulnerability being assessed?
  - Does the appropriate scale identified in the original questions/problem statement match the availability and usefulness of chosen indicators from the perspective of a potential intervention or adaptation?
- What types of methodologies and tools will be used to analyze data and develop the vulnerability map?
  - Overlays; cluster analyses/indices; hazard mapping;
  - ArcGIS; OntheMap; Carto; other?

- Will the final design of the map, including color scheme, language, and presentation format be accurately and adequately characterized?
  - Will it have significance for and appeal to stakeholders and end users?

Appendix B. Questions for the Subject Matter Expert Interviews

Question 1. Mapping methodologies, including geographic information systems (GIS) tools, to visualize the vulnerability of human populations in certain locations to climate-related impacts on health.

1. In your opinion, what is the most promising methodology or methodologies for mapping the vulnerability of human health to various climate change impacts? (For example, one common methodology involves developing map overlays of areas with differing exposure to hazards on top of identified locations of vulnerable populations; another common methodology involves constructing a vulnerability index using principal component analysis or factor analysis.)
    a. For each methodology you highlight as promising, what are the key benefits and limitations of the approach?
    b. Are there certain types of stressors (e.g., extreme heat, sea level rise, flooding, tropical storms, wildfire, drought) or impacts for which a certain methodology is most or least applicable?
    c. Are there certain types of health vulnerabilities (e.g., heat related morbidity and mortality) for which a certain methodology might be most or least appropriate?
2. Are you aware of any updates to these methodologies or new methods under development?
3. What GIS-based analytic tools (e.g., mapping or other visualization tools) do you recommend for mapping human health vulnerabilities to impacts of weather extremes? Please include extensions, add-ons, or additional modules that may be dependent upon other free or commercial software.
    a. What are their advantages and their limitations?
    b. Are there any promising new tools that you know are currently under development?

Question 2. The accessibility and applicability of spatially resolved climate, health, environmental, and vulnerability data.

1. What do you see as the most significant data limitations in mapping the vulnerability of human health and well-being to impacts of extreme weather events?
2. What are the critical limitations of the currently available climate data or model output?
    a. What have you found to be the best data sources for vulnerability mapping?
    b. Can you identify ways to address limitations, such as ways to reduce uncertainty or data gaps or other data limitations related to data availability and applicability?
    c. What are the most effective ways to reconcile the scale of meteorological data with that of human health and other factors?

Question 3. What issues are in play in the process of identifying and assessing vulnerability indicators, including those related to key socioeconomic, political, demographic, biophysical, and other relevant factors?

1. What are the most robust indicators for assessing a given population's sensitivity to extreme weather (e.g., socioeconomic, political, demographic, biophysical, and other indicators of vulnerability)?
    a. What have you found to be the best sources of data for these indicators?
    b. What is the most appropriate geographic scales for mapping these indicators?
    c. Are there any major limitations associated with vulnerability indicators?
2. What have you found to be the best indicators for characterizing adaptive capacity as it relates to weather impacts on human health?
3. What have you found to be the best sources of data for these indicators?
4. Are there any major limitations or caveats associated with analyzing vulnerability indicators?

Question 4. Describe how vulnerability assessments address the issues of compatible time frames and geographic scales, especially when incorporating historical climate trends, climate projections, and socioeconomic scenarios.

1. What are some key variables/indicators/data that capture the dynamic aspects of the variation of vulnerability over time and space that can be used in vulnerability mapping?
2. What are the key challenges in addressing the issues of time frame and geographic scale when associated with vulnerability mapping?

Question 5. Describe methodological challenges associated with vulnerability mapping, especially those challenges in mapping that are due to a lack of standardized methods or data gaps or other data limitations and uncertainty related to modeling approaches or other study design considerations.

1. Are there key challenges associated with vulnerability mapping that you have not already identified? Preston et al. (2011) identify four categories of key challenges associated with vulnerability mapping, including those related to goals and objectives, assessment framing, methodological approaches, and participation and communication.

Question 6. Delineate best practices for vulnerability mapping that contribute to identifying, planning, and helping to implement adaptation strategies for vulnerable people in vulnerable places.

1. What are some best practices to consider in using maps to identify current and future vulnerable populations? (You may wish to focus on specific hazards, regions, or populations).
    a. Are there important caveats that people should keep in mind when using maps in vulnerability analyses?
    b. Can you provide any examples of vulnerability maps that have been used effectively to inform adaptation planning and implementation? What about those examples makes them stand out as particularly effective?

c. Do you have recommendations on how a best-practices guidance document should be organized?

d. How can we accommodate different levels of technical skill or knowledge among end users of these best practices?

2. Are there any other areas of discussion we should address as we work to prepare a collection of best practices and guidance for mapping vulnerability of human health to exposure to extreme heat?

Appendix C. Subject Matter Expert Biographies

Susan Cutter, PhD, University of South Carolina. Dr. Cutter is a Carolina Distinguished Professor of Geography at the University of South Carolina, where she directs the Hazards and Vulnerability Research Institute. Her primary research interests relate to disaster vulnerability/resilience science: what makes people and the places where they live vulnerable to extreme events and how vulnerability and resilience are measured, monitored, and assessed.

Kristie L. Ebi, PhD, University of Washington. Dr. Ebi is a Professor in the Departments of Global Health and Environmental and Occupational Health Sciences, University of Washington. She conducts research on the impacts of and adaptation to climate change, including on extreme events, thermal stress, foodborne safety and security, waterborne diseases, and vector-borne diseases. Her work focuses on understanding sources of vulnerability and designing adaptation policies and measures to reduce the risks of climate change in a multi-stressor environment.

Sharon Harlan, PhD, Northeastern University. Dr. Harlan is a Professor with joint appointments in Northeastern University's Department of Health Sciences, Department of Sociology and Anthropology, and the Social Science Environmental Health Research Institute. Her research explores the human impacts of climate change that are dependent upon people's positions in social hierarchies, places in built environments of unequal quality, and policies that improve or impede human adaptive capabilities.

David Hondula, PhD, Arizona State University. Dr. Hondula is an Assistant Professor of Climatology and Atmospheric Science in ASU's School of Geographical Sciences and Urban Planning. He is also an affiliate of the Center for Policy Informatics, an Honors Faculty Advisor for ASU's Barrett Honors College, a Senior Sustainability Scientist at the Julie Ann Wrigley Global Institute of Sustainability, and a Faculty Affiliate of the Maricopa County Department of Public Health. His research examines the societal impacts of weather and climate with an emphasis on extreme weather and health. Recent projects include statistical analysis of health and environmental data sets to improve understanding of the impact of high temperatures on human morbidity and mortality, especially within urban areas. Dr. Hondula is also engaged in quantitative and qualitative field work to learn how individuals experience and cope with extreme heat.

Nesreen Khashan, M.A., U.S. Census Bureau. Ms. Khashan is a Data Dissemination Specialist with the U.S. Census Bureau. As a data dissemination specialist, she provides presentations and trainings to the public on how to access and understand Census Bureau statistics. For more than 4 years, Nesreen has served in this role for the state of Maryland and the Metro DC area. Her public affairs, journalism, and education backgrounds have informed how she approaches data; as a shorthand for viewing our greater societies, and as tools for rending compelling and relevant stories about our current lives. Nesreen also served as a Partnership Specialist for the Census Bureau during the 2010 Census, conducting outreach about the importance of enumeration, and serving as a cultural specialist of Arab and Muslim communities during the campaign.

George Luber, PhD, Centers for Disease Control & Prevention. Dr. Luber is an epidemiologist and the Associate Director for Climate Change in the Division of Environmental Hazards and Health Effects at the National Center for Environmental Health, Centers for Disease Control and Prevention. His research interests in environmental health are broad and include the health impacts of environmental change and biodiversity loss, harmful algal blooms, and the health effects of climate change. Most recently, his work has focused on the epidemiology and prevention of heat-related illness and death, the application of remote sensing techniques to modeling vulnerability to heat stress in urban environments, and climate change adaptation planning.

Arie Manangan, M.A., Centers for Disease Control & Prevention. Mr. Manangan is a health scientist with the CDC's Climate and Health Program, which is located within the Division of Environmental Hazards and Health Effects. He has a Master's degree in Geography, specializing in Geographic Information Systems and health geography and mapping. As a member of the science team, he provides technical expertise in spatial analysis and GIS. He has been with the CDC since 2001, working in several programs including the Geospatial Research and Analysis Services Program and Viral Special Pathogens Branch.

Andrew Monaghan, PhD, UCAR. Dr. Monaghan is an Atmospheric Scientist at the National Center for Atmospheric Research (NCAR) in Boulder, CO. He is a guest researcher with the U.S. Centers for Disease Control and Prevention and a coleader of the NCAR Weather, Climate, and Health Program. His research interests include a broad range of interdisciplinary regional climate topics, with an emphasis on the use of model-based techniques to study climate-sensitive health and disease issues.

Benjamin L. Preston, PhD, RAND Corporation. Dr. Preston is a senior policy researcher at the RAND Corporation, and director of RAND's Infrastructure Resilience and Environmental Policy Program. Prior to joining RAND, he served as the Deputy Director of the Climate Change Science Institute at Oak Ridge National Laboratory. While working at ORNL, he engaged in research on vulnerability and resilience of U.S. energy systems to climate variability and change as well as opportunities and constraints associated with climate risk management. Previously, he served as a research scientist in Australia with the CSIRO's Division of Marine and Atmospheric Research and as a Senior Research Fellow at the Pew Center on Global Change.

Colleen Reid, PhD, University of Colorado at Boulder. Dr. Reid is an assistant professor in Geography at the University of Colorado where she conducts research focused on the health effects of climate change. Her work has included epidemiological analyses of exposure to air pollution from northern California wildfires and a national neighborhood-level spatial map of vulnerability to extreme heat that can be used in preparing for future heat waves. She applies epidemiologic approaches to environmental hazards, with the aim of furthering understanding of population vulnerability vis-à-vis climate hazards and, ultimately, using this knowledge to increase environmental protection and influence health policy.

Jan Semenza, PhD, European Center for Disease Prevention and Control. Dr. Semenza directs the work on environmental and social determinants of infectious diseases at the European Centre for Disease Prevention and Control in Stockholm, Sweden. He has also served as an Epidemic Intelligence Service Officer at the U.S. Centers for Disease Control and Prevention and has worked with the World Health Organization and conducted public health projects in Uzbekistan, Sudan, Egypt, Denmark, Brazil, and Haiti. Earlier in his career, Professor Semenza was a faculty member at UC Berkeley, UC Irvine, Oregon Health and Science University, and at Portland State University where he taught in the Oregon Masters' Program of Public Health.

Glossary

Included below is a Glossary of terms and concepts used in this report. These definitions were originally developed for the Intergovernmental Panel on Climate Change (IPCC) report entitled: Managing the Risk of Extreme Events and Disasters to Advance Climate Change Adaptation (IPCC, 2012). The selection of this source for definitions reflects the advice of the subject matter experts that informed this report. In some instances, the Glossary of terms from the IPCC Fourth Assessment Report, Working Group 2 (IPCC, 2007) is provided as an alternative definition. Finally, definitions of various scale elements (such as extent, resolution, and grain) were derived from a paper in Dungan et al. (2002) and modified to address revisions suggested by a peer reviewer.

A

Adaptation assessment

The practice of identifying options to adapt to extreme weather and evaluating them in terms of criteria such as availability, benefits, costs, effectiveness, efficiency, and feasibility.

Adaptive capacity

The combination of the strengths, attributes, and resources available to an individual, community, society, or organization that can be used to prepare for and undertake actions to reduce adverse impacts, moderate harm, or exploit beneficial opportunities.

C

Capacity

The combination of all the strengths, attributes, and resources available to an individual, community, society, or organization, which can be used to achieve established goals.

Climate

Climate in a narrow sense is usually defined as the average weather, or more rigorously, as the statistical description in terms of the mean and variability of relevant quantities over a period of time ranging from months to years or longer. The relevant quantities are most often surface weather variables such as temperature, precipitation, and wind.

Confidence

Confidence in the validity of a finding, based on the type, amount, quality, and consistency of evidence and on the degree of agreement. Confidence is expressed qualitatively.

Consequences

The magnitude of damage that would result from exposure to a hazard such as extreme heat.

Coping

The use of available skills, resources, and opportunities to address, manage, and overcome adverse conditions, such as exposure to extreme events, with the aim of achieving basic functioning in the near term.

Coping capacity

The ability of people, organizations, and systems, using available skills, resources, and opportunities, to address, manage, and overcome adverse or extreme conditions.

D

Disaster management

Social processes for designing, implementing, and evaluating strategies, policies, and measures that promote and improve disaster preparedness, response, and recovery practices at different organizational and societal levels.

Disaster risk

Severe alterations in the normal functioning of a community or a society due to hazardous physical events interacting with vulnerable social conditions, leading to widespread adverse human, material, economic, or environmental effects that require immediate emergency response to satisfy critical human needs and that may require external support for recovery.

Disaster Risk Reduction

Denotes both a policy goal or objective, and the strategic and instrumental measures employed for anticipating future disaster risk; reducing existing exposure, hazard, or vulnerability; and improving resilience.

E

Exposure

The presence (location) of people, livelihoods, environmental services and resources, infrastructure, or economic, social, or cultural assets in places that could be adversely affected by physical events and which, thereby, are subject to potential future harm, loss, or damage. Exposure refers to the inventory of elements in an area in which hazard events may occur. Hence, if population and economic resources were not located in (i.e., exposed to) potentially dangerous settings, no problem of disaster risk would exist. While the literature and common usage often mistakenly conflate exposure and vulnerability, they are distinct. Exposure is a necessary, but not sufficient, determinant of risk. It is possible to be exposed but not vulnerable (for example by living in a floodplain but having sufficient means to modify building structure and behavior to mitigate potential loss). However, to be vulnerable to an extreme event, it is necessary to also be exposed.

Extent

See definition for *scale*.

H

Hazard

The potential occurrence of a natural or human-induced physical event that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, and environmental resources. Physical events become hazards where social elements (or environmental resources that support human welfare and security) are exposed to their potentially adverse impacts and exist under conditions that could predispose them to such effects. Hazard is used to denote a threat or potential for adverse effects. At times, hazard has been ascribed the same meaning as risk; currently, it is widely accepted that it is a component of risk and not risk itself.

I

Impacts

The term impacts is used to refer to the effects on natural and human systems of extreme weather events. Impacts generally refer to effects on lives, livelihoods, health, ecosystems, economies, societies, cultures, services, and infrastructure due to the interaction of exposure to extreme heat and the vulnerability of an exposed society or system. Impacts are also referred to as consequences or outcomes.

L

Likelihood

A probabilistic estimate of the occurrence of a single event or of an outcome, such as an exposure to an extreme weather event, an observed trend, or projected changes in ambient temperature. Likelihood may be based on statistical or modeling analyses, elicitation of expert views, or other quantitative analyses.

Local disaster risk management (LDRM)

The process in which local actors (citizens, communities, government, nonprofit organizations, institutions, and businesses) engage in and have ownership of the identification, analysis, evaluation, monitoring, and treatment of disaster risk, through measures that reduce or anticipate hazard, exposure, or vulnerability; transfer risk; improve disaster response and recovery; and promote an overall increase in capacities. Local disaster risk management (LDRM) normally requires coordination with and support from external actors at the regional, national, or international levels. Community-based disaster risk management is a subset of LDRM where community members and organizations are in the center of decision making.

M

Mitigation (of disaster risk and disaster)

The lessening of the potential adverse impacts of physical hazards (such as extreme heat) through actions that reduce hazard, exposure, and vulnerability.

P

Probability

See Likelihood.

R

Resilience

The ability of a system and its component parts to anticipate, absorb, accommodate, or recover from the effects of a hazardous event in a timely and efficient manner, including through ensuring the preservation, restoration, or improvement of its essential structures and functions.

Resolution

A measure of the level of precision. “Grain” is also used to describe resolution. With respect to time, social scientists rarely use a resolution of less than an hour to describe the time frame of an observation. Regarding space, social scientists use a variety of resolutions ranging from a meter or less to coarser measurements. When an analysis involves large quantities of data, measurements normally use a larger aggregation of individual units (i.e., a coarser resolution) than when analyzing individual details.

Risk

The product of the probability that some event (or sequence) will occur and the adverse consequences of that event. EQUATION: Risk = Probability × Consequence. For instance, the risk a community faces from flooding from a nearby river might be calculated based on the likelihood that the river floods the town, inflicting casualties among inhabitants and disrupting the community’s economic livelihood. This likelihood is multiplied by the value people place on those casualties and that economic disruption. The equation provides a quantitative representation of the qualitative definition of disaster risk. All three factors—hazard, exposure, and vulnerability—contribute to impacts or ‘consequences.’ Hazard and vulnerability can both contribute to the ‘probability’: the former to the likelihood of a physical event (e.g., the river flooding the town) and the latter to the likelihood of the consequence resulting from the event (e.g., casualties and economic disruption).

S

Scale

In mapping, scale is the ratio or proportion between a distance on a map and the actual distance on the ground, such as 1:10,000 (indicating that one unit of measurement on the map represents 10,000 of the same units on the ground). Scales may also be used to indicate temporal extent, such as a day, a week, a year, a decade, a century, or a millennium.

Scenario

A plausible and often simplified description of how the future may develop based on a coherent and internally consistent set of assumptions about driving forces and key relationships. Scenarios may be derived from projections but are often based on additional information from other sources, sometimes combined with a narrative storyline.

Sensitivity

The degree to which a system is affected, either adversely or beneficially, by weather extremes or other meteorological changes. The effect may be direct (e.g., a change in human morbidity and mortality in response to a change in the mean, range, or variability of temperature) or indirect (e.g., damages caused by an increase in the frequency of heat waves).

Stakeholder

A person or an organization that has a legitimate interest in a project or entity or would be affected by a given action or policy (IPCC, 2007).

U

Uncertainty

An expression of the degree to which a value or relationship is unknown. Uncertainty can result from lack of information or from disagreement about what is known or even knowable. Uncertainty may originate from many sources, such as quantifiable errors in the data, ambiguously defined concepts or terminology, or uncertain projections of human behavior. Uncertainty can be represented by quantitative measures, for example, a range of values calculated by various models, or by qualitative statements, such as reflecting the judgment of experts.

V

Vulnerability

The propensity or predisposition to be adversely affected. Such predisposition constitutes an internal characteristic of the affected element. In the field of disaster risk, this includes the characteristics of a person or group and their situation that influences their capacity to anticipate, cope with, resist, and recover from the adverse effects of physical events. Vulnerability is related to predisposition, susceptibilities, fragilities, weaknesses, deficiencies, or lack of capacities that favor adverse effects on exposed elements. Vulnerability has been described as the degree to which a system is susceptible to, and unable to cope with, adverse effects of extreme events. Vulnerability is a function of the character and magnitude of weather extremes to which a system is exposed, its sensitivity, and its adaptive capacity.

Notes

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