Applied Geography 35 (2012) 23–31

Contents lists available at SciVerse ScienceDirect

Applied Geography

journal homepage: www.elsevier.com/locate/apgeog

Developing an applied extreme heat vulnerability index utilizing socioeconomic and environmental data

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Keywords:
Extreme heat
Urban heat island
Social vulnerability
Disaster preparation
Disaster mitigation
Heat-health vulnerability

ABSTRACT

Extreme heat is a leading cause of weather-related fatalities worldwide. Emphasis is currently being placed on the development of spatially specific vulnerability models, which are useful for decision support during extreme heat events (EHE). Research results concerning such spatially-explicit models lead efforts in preparation and mitigation of heat-related vulnerability and potential adaptation. The presented research analyzes the 1995 Chicago EHE in the context of a socio-environmental hazards approach, and fosters the development of an extreme heat vulnerability index (EHVI). The EHVI is a fused dataset consisting of census data and remotely sensed variables, which are examined in relation to geocoded mortality data. The presented analysis combines 25 well-known indicators of extreme heat-health risk into an applied index utilizing a principal components analysis. The developed EHVI presented a trend of higher rates of death in the highest risk zones to lower rates in lower zones of risk. The model explains nearly 80% of the total variance in the heat-health vulnerability variables utilized. This index could be utilized by city officials to assist in the mitigation of extreme heat events and is a further evolution of previously developed efforts. Our findings indicate extreme heat vulnerability models should likely be developed on a local level for a specific location, taking into account local variations in social and environmental vulnerability.

Introduction

Extreme heat is a leading cause of weather-related mortality in the United States (Patz et al., 2000). The summer of 2011 recorded the hottest temperatures in North America for 75 years, breaking many of the previously held modern record temperatures. One summer of excessive temperatures alone does not constitute overall concern; but when it is placed into context with recent climate models, which predict more intense and prolonged heat waves, it becomes a cause for greater concern. Coupling this with the fact that most communities in North America are poorly equipped to deal with excesses in temperature, the need for understanding the hazardous nature of extreme heat becomes paramount (Jackson & Shields, 2008).

Highlighting groups or populations that are especially susceptible (or vulnerable) to the effects of extreme heat is centrally important to communities as they develop contingency plans for a changing climate. Vulnerability, whether to extreme heat or something else, is a complex concept that is multidimensional in scope. It is typically defined as the inability, of a specific group or population, to appropriately respond or adapt to a specific harmful stressor (Andrew, Mitnitski, & Rockwood, 2008; Bankoff, 2001; Blaikie, Cannon, Davis, & Wisner, 1994). Vulnerability is oftentimes confused with risk, which is defined as the potential for a harmful or disadvantageous event. Since vulnerability is a multidimensional concept, its relationship to risk from natural hazards can be examined from multiple perspectives. Historically, it has been common to place explicit emphasis on the natural phenomena that are responsible for risk (Wisner, 2004). A natural output of this approach might specify the location where a hazard is likely to occur and draw a conclusion that persons in close proximity to the effected area are most "at-risk"; employing a hazard-first focus with disregard for underlying social aspects. An alternate approach is to examine the "social vulnerability" of an existing population (Bankoff, 2003; Cutter, Boruff, & Shirley, 2003; Cutter & Finch, 2008). Typically evidenced by socioeconomic status, social vulnerability implies that a population is at-risk due to social characteristics intrinsic and endogenous to the at-risk population. Social vulnerability implies that groups and populations are vulnerable due to a lack of resources enabling them to respond and

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0143-6228/$ – see front matter © 2012 Published by Elsevier Ltd.
doi:10.1016/j.apgeog.2012.04.006

adapt to a hypothetical hazard. Therefore, studies dealing with social vulnerability rarely highlight one specific hazard. A third more novel approach examining vulnerability is to mix the physical and social approaches, incorporating aspects of both, foster phenomena-specific vulnerability indexes (Harlan, Brazel, Prashad, Stefanov, & Larsen, 2006; Johnson & Wilson, 2009; Johnson, Wilson, & Luber, 2009). As one might expect, incorporating data from multiple perspectives potentially represents a richer more robust solution to elucidating vulnerability than by relying on a singular physical environmental or social dataset.

One of the greatest gaps in the current understanding of vulnerability to extreme heat is its specific intra-urban nature. Place is perhaps the most vital component in vulnerability as it is ubiquitous in an examination of most phenomena. In order to assist in the understanding of extreme heat-health risk and to further catalyze the development of models highlighting such risk, the research presented in this article demonstrates the development of an extreme heat vulnerability index (EHVI). The EHVI incorporates an approach utilizing well-recognized variables, both physical and social, which are known to contribute to extreme heat vulnerability. This effort is dissimilar to previous studies that have either examined variables (both environmental and social) to determine which are most indicative of heat-related health risk, or have sought to create an encompassing index without relating it to heat-related mortality or health outcomes (Harlan et al., 2006; Reid et al., 2009; Rinner et al., 2010; Uejio et al., 2011). This research seeks to fill this void and intends to be recognized as an evolution of heat-related vulnerability modeling in the context of previous findings. Moreover, this is the first significant spatial analysis of the Chicago 1995 extreme heat event, which includes a significant number of decedents ($n = 586$) in which to approximate vulnerability.

Background

Extreme heat, punctuated by heat waves or extreme heat events (EHE), is the primary cause of weather-related mortality in the United States (Luber & McGeehin, 2008; Wilhelmi & Hayden, 2010). Several communities have county wide heat warning systems, but determining variations in vulnerability within localized areas is a developing functionality that should significantly contribute to future mitigation plans of heat-related health concerns (Harlan et al., 2006; Kalkstein, 1991, Kalkstein & Greene, 1997; Kalkstein, Jamason, Greene, Libby, & Robinson, 1996; Wilhelmi & Hayden, 2010). Currently the most widely used method of spatially specific heat warnings is the Heat-Health Watch Warning System (HWWS), utilized by the National Weather Service (NWS) of the United State's National Oceanic and Atmospheric Administration (NOAA) (Kalkstein, 1991, Kalkstein et al., 1996). This system is currently employed by approximately 20 cities in the United States and focuses on atmospheric conditions which have previously contributed to heat-related mortality. The greatest limitation of this framework is the lack of spatial specificity when determining localized variations in risk, as it focuses on larger spatial entities such as city or county boundaries (Harlan et al., 2006; Johnson & Wilson, 2009; Johnson et al., 2009; Kalkstein, Greene, Mills, & Samenow, 2011; Smoyer, 1998; Smoyer-Tomic, Kuhn, & Hudson, 2003).

Numerous studies have attempted to address the lack of spatial specificity in heat warnings at the local level (Harlan et al., 2006; Johnson et al., 2009; Uejio et al., 2011; Wilhelmi & Hayden, 2010). These approaches are heavily influenced by advanced geospatial technologies such as remote sensing and geographic information systems. Utilizing these systems provides a robust modeling framework that places emphasis on the explicit spatial nature of natural hazards. Moreover, these techniques provide a foundation on which to fuse both social and environmental data sources in a way analogous to hybridization. Extreme heat, as with all natural hazards, is best understood by utilizing a social environmental approach due to the natural and latent complexities inherent in vulnerability (Huang et al., 2011; Miron, Montero, Criado-Alvarez, Diaz, & Linares, 2010; Pantavou, Theoharatos, Mavrakis, & Santamouris, 2011; Rinner et al., 2010; Wilhelmi & Hayden, 2010).

Thought to contribute to the health risks of extreme heat in urban settings, the urban heat island (UHI) is strongly related to the built environment (Dousset et al., 2011; Johnson & Wilson, 2009; Papanastasiou, Melas, Bartzanas, & Kittas, 2010; Stone, Hess, & Frumkin, 2010; Tan et al., 2010; Thorsson, Lindberg, Bjorklund, Holmer, & Rayner, 2011; Zhou & Shepherd, 2010). The UHI effect is generally described as the prevailing differences between the air and surface temperatures in the city contrasted to those temperatures in the adjacent rural hinterland. It is important to distinguish between two notably different types of UHI effect. The primary effect (historically observed first) is currently known as the canopy urban heat island (Lo & Quattrochi, 2003). This is the traditional view, where the entire urban area was though to exhibit a singular, and continuous, higher ambient air temperature than surrounding rural areas. The second type is the surface UHI that is observational through current satellite technologies registering thermal characteristics (land surface temperature, emissivity) (Wang, Zhu, & Wang, 2004; Weng, Lu, & Schubring, 2004). This is a measure of surface temperature and is not a direct metric of the sensible temperature of the environment. Important to note is that LST is not a measure of the air temperature but of the surface being imaged. The dichotomous interaction between the two (air temperature and LST) is an area of ongoing research within urban climatology. Strong evidence exists that there is a significantly positive relationship between the surface and ambient air temperature (Voogt & Oke, 2003; Weng & Quattrochi, 2006). However, intra-urban variations in temperature are much more apparent within the surface UHI due to the resolution of measurement with satellite remote sensing techniques and the spatial distribution of materials consistent with the built environment. These pockets of extremes in temperature within the UHI are termed micro-urban heat islands and are strongly related to the land cover present in the area of consideration (Aniello, Morgan, Busbey, & Newland, 1995; Dousset & Gourmelon, 2003; Smargiassi, Fournier, Griot, Baudouin, & Kosatsky, 2008). Considering this trait of the UHI effect, it is possible that certain areas of a city might experience episodes of extreme heat while other areas within the city, only a few hundred meters away, would not approach the same extreme heat threshold. Such a detailed local understanding could result in the delineation of smaller scale extreme heat alert procedures.

The social aspect of extreme heat-health risks is a complicated mix of socioeconomic and other demographic characteristics; not to mention individualized behaviors and adaptations (Basu, 2009; Curriero et al., 2002; Harlan et al., 2006; Johnson & Wilson, 2009; Uejio et al., 2011). The demographic disposition of individual neighborhoods within a city is readily observable through the U.S. Census Bureau's decadal census; although limitations exist for within decade projections. Primary population-based at-risk factors include: advanced age, lower levels of educational attainment, presence of children under 5, household income, and race. These same variables are present in many social vulnerability indices and without argue constitute a societal concern irrespective of the phenomena that is considered a hazard.

Entertaining both the social and environmental aspects of the health risks correlated with extreme heat exposure warrants the consideration of developing a heat specific vulnerability index. Many sociologists are familiar with the "SoVI" or the social