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Spatiotemporal analysis of regional socio-economic vulnerability change associated with heat risks in Canada

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ABSTRACT

Excess mortality can be caused by extreme hot weather events, which are increasing in severity and frequency in Canada due to climate change. Individual and social vulnerability factors influence the mortality risk associated with a given heat exposure. We constructed heat vulnerability indices using census data from 2006 to 2011 in Canada, developed a novel design to compare spatiotemporal changes of heat vulnerability, and identified locations that may be increasingly vulnerable to heat. The results suggest that 1) urban areas in Canada are particularly vulnerable to heat, 2) suburban areas and satellite cities around major metropolitan areas show the greatest increases in vulnerability, and 3) heat vulnerability changes are driven primarily by changes in the density of older ages and infants. Our approach is applicable to heat vulnerability analyses in other countries.

1. Introduction

Climate change is influencing the severity and frequency of heat waves in cities throughout the world (IPCC, 2009; IPCC, 2011; Meehi & Tebaldi, 2004; Murray & Ebi, 2012; Reid et al., 2009), which can in turn lead to increasing heat-related morbidity and mortality, especially during extreme heat events (Basu, 2009). Extreme heat events and the associated excess mortality are worldwide phenomena that are occurring in the tropics (Yan, 2000), subtropics (Huang, Kan, & Kovats, 2010), and temperate climate zones, including Western Europe in 2003 (Filleul et al., 2006) and major cities in Canada in 2009 and 2010 (Bustinza, Lebel, Gosselin, Bélanger, & Chebana, 2013; Kosatsky, Henderson, & Pollock, 2012). In order to address related public health impacts, previous studies have estimated either the spatial or temporal variability of heat-related illness/mortality (Anderson & Bell, 2010; Eisenman et al., 2016; Hattis, Ogneva-Himmelberger, & Ratick, 2012; Henderson, Wan, & Kosatsky, 2013; Hondula et al., 2012; Jones et al., 1982; Kovach, Konrad, & Fuhrmann, 2015; Laaidi et al., 2012; Rosenthal, Kinney, & Metzger, 2014; Son et al., 2012a, 2012b; Vaneckova, Beggs, & Jacobson, 2010), and developed indices to locate the heat-vulnerable populations (Reid et al., 2009, 2012; Rinner et al., 2010; Vescovi, Rebetez, & Rong, 2005).

Although previous studies have developed approaches for heat health vulnerability assessments (Chan, Goggins, Kim, & Griffiths, 2012; Hondula et al., 2012; Rinner et al., 2010; Tomlinson, Chapman, Thornes, & Baker, 2011), most research only isolated either the spatial or the temporal vulnerability to investigate heat risk trends (Anderson & Bell, 2010; Hattis et al., 2012; Hondula et al., 2012; Tomlinson et al., 2011) but did not attempt to estimate spatio-temporally changing vulnerability for health planning based on historical datasets. Doing so will allow targeted adaptation efforts in not only the areas that are vulnerable now, but also in those areas where vulnerability is likely to rise. It is important to combine both spatial and temporal trends to investigate how changing populations in communities may influence heat vulnerability in the future (Sheridan & Dixon, 2016), and ultimately combine the resulting information with climate projections (also stated in Health Canada guideline for extreme heat and health vulnerability assessment) to facilitate extreme heat adaptation (Goldberg, 2007; Gosling, McGregor, & Lowe, 2009; Huang et al., 2011; Jackson et al., 2010; Jeong et al., 2016). While ambient temperature largely determines the heat exposure of a population, vulnerability defines how that population is affected by the exposure, which during extreme heat events may lead to substantial excess mortality (Ho, Knudby, Walker, & Henderson, 2017; Toloo, FitzGerald, & Tong, 2014). The relationship

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between heat exposure, vulnerability and risk is complicated by both short- and long-term acclimatization, as evidenced by latitudinal gradients in the temperature-mortality relationship (Henderson et al., 2013, Anderson and Bell, 2010), and also by societal responses to heat such as heat emergency warning systems (Kalkstein & Sheridan, 2007; Toloo et al., 2013, 2014; Tong, Conalonieri, Ebi, & Olsen, 2016). Nevertheless, quantifying spatiotemporal change in vulnerability and identifying the spatial clusters based on temporal vulnerability change could help estimating heat-related mortality or morbidity during future extreme heat events (Chow, Chuang, & Gober, 2012), especially because socio-economic vulnerability factors are substantially more important than environmental exposure levels in determining the local spatial distribution of health risk (Adger, 2006; Füssel & Klein, 2006; INVS, 2004; Toloo et al., 2013), and heat exposure is largely constrained by urban morphology and land cover (Gago, Roldan, Pacheco-Torres, & Ordoñez, 2013). Most heat-related mortality does not occur in the general population, but rather in specific population groups that have elevated vulnerability due to a variety of personal, socio-economic, infrastructural or environmental factors (Reid et al., 2009; Tomlinson et al., 2011; Yardley, Sigal, & Kenny, 2011). Understanding the spatiotemporal pattern of this vulnerability is therefore key to heat-related public health planning and to climate change adaptations (Ford et al., 2010). Personal vulnerability factors may include pre-existing health conditions, personal heat-adaptation habits as well as demographic characteristics such as age, gender, race, income, and educational attainment (Uejio et al., 2011; Yardley et al., 2011). Infrastructural and environmental factors include characteristics of the built and natural environment where a person resides, such as the amount of green-space, impervious surface, and microclimate characteristics (Aminipouri, Knudby, & Ho, 2016; Brown & Walker, 2008; Harlan, Brazel, Prashad, Stefanov, & Larsen, 2006; Kim & Ryu, 2015; Uejio et al., 2011; Wilhelmi & Hayden, 2010). While infrastructural and environmental factors influence vulnerability to heat, standardized data on their status and trend across large regions are rarely available, severely complicating their integration into health planning. On the other hand, information on several personal vulnerability factors is often available in the form of socio-economic data from a national census. While these data do not describe vulnerability at an individual level, they do portray both spatial and temporal trends in community-level vulnerability. Because these data primarily contain socio-economic information, and to emphasize that they are only available at the community-level, we henceforth collectively refer to them as describing socio-economic vulnerability factors. It is important to note here that such community-level variables (e.g. the average income in a census district) only represented community vulnerability, and in nature difference to the individual vulnerability such as corresponding personal characteristics (e.g. the income of a person living in that census district) and thus do not act exclusively to represent unavailable personal-level data (Diez Roux, 2004).

Furthermore, although conceptual frameworks for estimating vulnerability from climate change exist (Adger, Arnell, & Tompkins, 2005; Ford et al., 2010; Füssel & Klein, 2006; Füssel, 2007; Moser & Ekstrom, 2010), they do not allow systematic quantification of changes in heat vulnerability or risk (Toloo et al., 2014; Tong et al., 2016), for example, Vescovi et al. (2005) assumed that socioeconomic vulnerability in Quebec would not change through time. How and to what extent population distributions and redistributions (defined as "population dynamics" in this paper) influence heat vulnerability is thus unknown, and the application of statistical models that use demographic trends to quantify vulnerability and risk change is needed in order to develop policy and strategies for climate change adaptation (Berrang-Ford, Ford, & Paterson, 2011; Ford et al., 2010). Several previous studies attempted to quantify relative heat risks spatially, such as Tomlinson et al. (2011) for Birmingham, UK; Buscail, Upegui, and Viel (2012) for Rennes, France; Ho, Knudby, and Huang (2015) and Aminipouri et al. (2016) for Vancouver, Canada; Rinner et al. (2010) for Toronto, Canada; Laverdière, Mélissa Généreux, and Morais (2015) and Vescovi et al. (2005) for Southern Quebec, Canada, and Scherer et al. (2014) for Berlin, Germany, but none of them were applied to a large region, nor to understand both the spatial and temporal dynamics. It is also important to develop a model that can compare the relative spatial difference through years, in order to incorporate with national health guidelines for extreme heat adaptation and heat vulnerability assessment.

In this study, 1) we estimate the temporal change in socio-economic vulnerability associated with heat risk in Canada, from 2006 to 2011, by combining community vulnerability data in a heat vulnerability index (Reid et al., 2009; Tomlinson et al., 2011; Buscail et al., 2012), and 2) we use Moran's I to identify local clusters based on the results above, in order to locate extended areas with high temporal change. This combines existing methods to develop a simple technique that can be used to assess the spatiotemporal change of socioeconomic vulnerability related to heat risk in a national extent. Our study demonstrates current heat vulnerability trends in Canada, and may be used to target heat risk mitigation strategies in the most vulnerable areas in both the short term responses (e.g. disaster risk management, public health planning) and the long term (e.g. urban planning, regional development) (Cutter, Mitchell, & Scott, 2000; Schwarz et al., 2011). The approach is easily adapted to any other country that has the necessary census data, and is following the Health Canada guideline for a complete extreme heat and health vulnerability assessment, for fulfilling the research gap to describe trends expected to influence heat-related health outcomes for assessing future risks.

2. Study area

Our study area includes all 10 Canadian provinces (British Columbia, Alberta, Manitoba, Saskatchewan, Ontario, Quebec, Newfoundland and Labrador, New Brunswick, Nova Scotia, and Prince Edward Island) (Fig. 1), an area with 33.4 million people or 99.7% of the Canadian population in 2011 (Geographic Research, 2015b). In southern Ontario and Quebec, the number of extremely hot days ($>=30\,^{\circ}$C) at late 1990s was more than that of the summer normal since 1948 (Smoyer-Tomic, Kuhn, & Hudson, 2003), and similar trends have been observed in later years (Kosatsky, King, & Henry, 2005, pp. 167–171; Jeong et al., 2016). During these extreme hot summer days, elevated temperature has significantly increased mortality in afflicted locations (Bustinza et al., 2013; Henderson et al., 2013; Kosatsky et al., 2005, pp. 167–171; Kosatsky et al., 2012; Smoyer-Tomic, Rainham, & Hewko, 2000). For example, mortality increased by 40% for six consecutive days during the 2009 Vancouver extreme heat event (Kosatsky et al., 2012), and the number of non-traumatic deaths in Montreal on one extremely hot day in June 1994 exceeded twice the monthly mean death rate (Kosatsky et al., 2005, pp. 167–171). Heat-related mortality has also been demonstrated from cooler parts of Canada, including northern British Columbia (Henderson et al., 2013); as a result we have included all 10 Canadian provinces in our study. The three Canadian territories (Nunavut, Yukon, Northwest Territories) were excluded because the population in these regions is not known to experience adverse health effects from extreme heat.

3. Data and methods

3.1. Heat vulnerability index

In order to quantify the relative change of vulnerability, we used a heat vulnerability index from Ho et al. (2015) that combines census data in a multi-criteria analysis (Reid et al., 2009; Tomlinson et al., 2011; Buscail et al., 2012). Multi-criteria analysis (MCA) is a statistical model that allows users to semi-quantitatively combine data layers in an estimation by assigning weights that represent the importance of each layer, typically based on results of meta-analysis or expert