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Short Report

Differences in heat-related mortality across four ecological regions with diverse urban, rural, and remote populations in British Columbia, Canada

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ABSTRACT

Temperature–mortality analyses are challenging in rural and remote communities with small populations, but this information is needed for climate change and emergency planning. The geographic health areas of British Columbia, Canada were aggregated into four ecoregions delineated by microclimatic conditions. Time series models were used to estimate the effect of maximum apparent temperature on daily non-traumatic mortality. The population of the coldest ecoregion was most sensitive to hot weather, while the population of the hottest ecoregion was least sensitive. The effects were consistently strongest in decedents aged less than 75 years. A province-wide total of 815 deaths was attributed to hot weather over the 25-year study period, with 735 deaths in the most populous ecoregion. The framework described could be adapted to other climatically variable regions with urban, rural, and remote populations.

1. Introduction

From a population perspective, the relationship between summertime temperatures and mortality can be described as a “hockey stick” (Armstrong, 2006). Mortality is relatively low at milder temperatures, and it starts to slope upward when the effects of warm weather first become apparent in the population, reaching highest mortality during the hottest days of the year. Herein this slope is referred to as the “temperature–mortality slope”, and the temperature at which it starts is referred to as the “inflection temperature”. Although imperfect, this model provides a useful framework for describing how temperature affects mortality within a population, and for comparing effects between populations. Indeed, several studies report that the inflection temperatures and the temperature–mortality slopes vary widely between locations (Anderson and Bell, 2009; Chestnut et al., 1998; Curriero et al., 2002; Kalkstein and Davis, 1989; Loughnan et al., 2010; Michelozzi et al., 2006). This is partially due to differences in population density, residential heating and cooling, demographics, and weather-related behaviors, and partially due to differences in climatic factors (Anderson and Bell, 2009; Chestnut et al., 1998; Curriero et al., 2002). In general, inflection temperatures are lower in cooler climates, and higher in warmer climates (Anderson and Bell, 2009; Baccini et al., 2008; Chestnut et al., 1998; Curriero et al., 2002; Medina-Ramón and Schwartz, 2007).

Much of the epidemiologic research on heat-related mortality has been conducted in urban areas, where the number of deaths attributable to hot weather can be very high. The results of such work allow public health authorities to evaluate the expected impacts of climate change (McGeehin and Mirabelli, 2001), and to plan strategies for population adaptation and emergency response (Haines et al., 2006). Less research has been done in rural and remote areas (Loughnan et al., 2010; Sheridan and Dolney, 2003) where populations are often too small to conduct statistically robust analyses. Even so, public health authorities in such areas require information about the population response to hot weather to support the same adaptation and emergency planning conducted in urban environments. Countries such as Canada are characterized by vast areas with small populations, and they need methods to evaluate and compare heat-related mortality across urban, rural and remote regions. Ecoregions are delineated using a worldwide classification system that groups similar macroclimates (Bailey, 1998), making these geographic areas an appropriate basis for studying the health effects of climatic factors. Here we describe a framework for using ecoregions to examine differences in patterns of heat-related mortality across the Canadian province of British Columbia (BC), which had a 2012 population of 4.6 million people distributed over one million square kilometers (Fig. 1). Until an unprecedented hot weather event in 2009 (Kosatsky et al., 2012)

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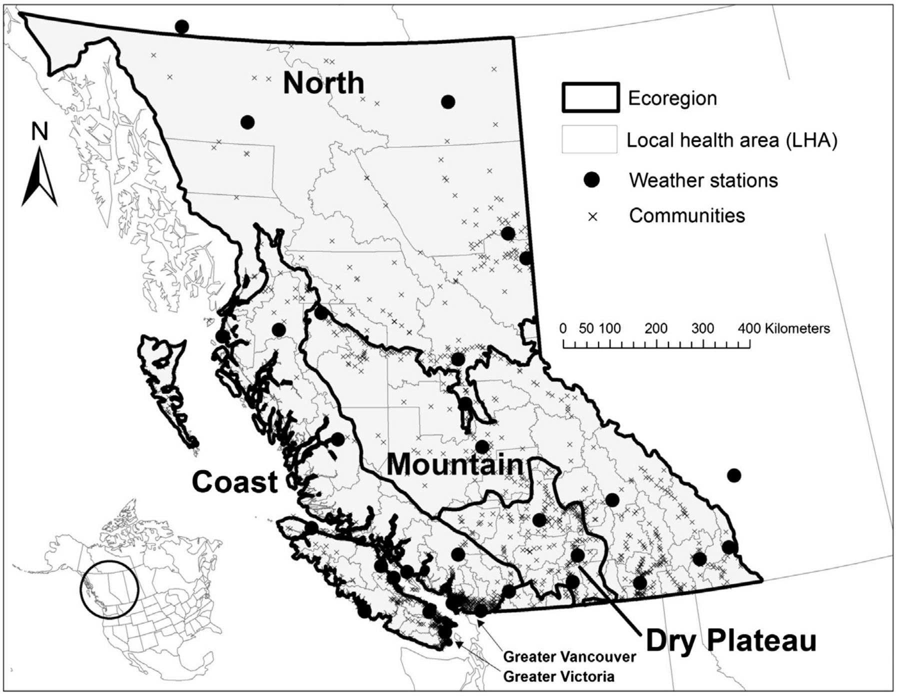

Fig. 1. Study Area. A map of British Columbia, showing the four ecoregions along with the 89 local health areas (LHAs) and the 31 weather stations (29 in BC, one in the Yukon Territories to the north, and one in Alberta to the east) used in the analyses. The locations of recognized communities are shown to indicate the distribution of the population, and the areas of the two major metropolitan areas are marked. The small area to the south of the Coast and Dry Plateau ecoregions is part of the Mountain ecoregion, where the American Cascade Range stretches across the Canadian border.

there was little public health concern about significant heat-related mortality in BC, where the climate is predominately temperate. As of the summer of 2012, only the population around metropolitan Vancouver was protected by a coordinated heat health warning system (Henderson and Kosatsky, 2012).

2. Methods

2.1. Identification of ecoregions

Spatial data for the ecoregions of North America were obtained from the US Environmental Protection Agency (1997). At the coarsest level (Level I) there are 11 ecoregions in Canada, and at the finest level (Level III) these are subdivided into 68 smaller areas. We used information from all three levels to identify four study areas described throughout as the Coast, Dry Plateau, Mountain, and North ecoregions (Fig. 1). Health care in BC is administered via 89 geographic units called local health areas (LHAs). Each LHA was assigned to an ecoregion according to the distribution of its 2001 census population. Dissemination areas (DAs) are the smallest census geography in Canada, each having a population of 400–700 residents. We assigned the population of all 7469 DAs in BC to their geographic center, and then used all DAs within each LHA to calculate the population-weighted center of that LHA. Finally, each LHA was assigned to the ecoregion that contained its population-weighted center.

2.2. Exposure assessment

The study used summertime (June through August) data from 31 Environment Canada weather stations that had ≥90% complete hourly records of temperature, relative humidity, and wind speed spanning the 1986–2010 study period. Of these, 29 were in BC and two were in other provinces, near to the BC border (Fig. 1). Only 16 of the stations ran 24 h per day during the entire study period, and the remainder ran during daytime hours only throughout some or all of the 25 years. As such, analyses were limited to the daytime hours of 07:00–17:00, and daily minimum temperatures were not considered.

Some meteorological data were missing from most stations due to short-term interruptions and longer-term station failures. We used deterministic imputation by regression (Gelman and Hill, 2007) to recreate complete hourly temperature, relative humidity, and wind speed records for each station. For missing hourly records within a day, all available hourly values in the same day were used to build the regression model. In cases where fewer than 50% of the hourly records were available for the regression, an average of hourly temperature values from the two nearest meteorological stations was used instead. The temperature, relative humidity, and wind speed were used to calculate the maximum apparent temperature (AT_{max}) at each station on each day (Steadman, 1994).

To assign each LHA to a representative weather station, its population-weighted center was manually matched to one of the stations, based primarily on proximity and secondarily on geographic similarity. To reflect demographic changes between 1986–2010, we downloaded the annual estimated population of each LHA from BC Stats (2011), and used those values to weight how much each LHA contributed to the daily overall temperature for its ecoregion on a year-by-year basis.

2.3. Statistical analyses

Information on all provincial deaths was provided by the BC Vital Statistics Agency. These anonymous data included the date of death, primary cause of death (coded according to the ICD-10), age, sex, and residential LHA for each decedent. The daily count of non-traumatic deaths was calculated for each ecoregion by summing the deaths in its contributing LHAs.

All analyses were completed in the R Development Core Team (2010). We started with exploratory analyses to identify the inflection AT_{max} in each ecoregion. First, the daily mortality count was plotted against the same-day average of AT_{max} over the whole time series, and locally weighted smoothing (LOESS) with an estimate at every 0.1 deg was used to fit the trend. Next, the fitted LOESS values were extracted, and the temperature at which the trend changed to increasing was recorded. Finally, these inflection points were entered into quasi-Poisson time-series models with distributed lagged intervals (Gasparrini, 2011) to estimate the linear effects of AT_{max} on mortality, adjusted for day-of-week, month, and year to control for short- and long-term trends. The rate ratio (RR) was the measure of the effect. These models assumed that AT_{max} could affect mortality on the day of or the day after its occurrence (up to a 1-day lagged interval). Primary analyses were conducted to compare inflections and slopes across the four ecoregions, and secondary analyses were conducted to examine how different lagged intervals (up to 1-day vs. up to 1-week), time periods (1986–1998 vs. 1998–2010), and age categories (<75 years vs. ≥ 75 years) modified those slopes. The hottest recorded temperatures in BC have occurred over the past decade, and the time periods were chosen to compare the relatively hotter and cooler years.

To estimate the absolute heat-related mortality in each ecoregion we compared expected mortality with (1) observed mortality and (2) mortality predicted by the fitted models. We started by identifying all dates between 1986–2010 that had AT_{max} values greater than the 95th percentiles of the entire distribution for the ecoregion. The expected mortality for each date was estimated by entering the day-of-week, month, year, and inflection AT_{max} into the fitted model for the ecoregion. First, the difference between the expected and observed mortality was calculated and summed. Second, the difference between the expected and predicted mortality was calculated and summed. The predicted mortality for each date was estimated by entering the day-of-week, month, year, and observed AT_{max} into the fitted model. The ecoregion-specific mortality ratios were calculated by dividing the sums of observed and predicted mortality but the sum of expected mortality.

3. Results

3.1. Differences between ecoregions

Mean summertime (June through August) population-weighted AT_{max} was lowest in the North (18.6 °C), highest in the Dry Plateau (24.2 °C), and intermediate in the Coast and Mountain ecoregions (19.9 °C and 21.0 °C, respectively), with similar differences between the 75th percentiles and maximum values. The 1986–1998 75th percentiles were greater than the 1998–2010 75th percentiles in the Coast, Dry Plateau, and Mountain ecoregions, but not in the North (Table 1). There were clear differences between the inflection temperatures and temperature–mortality slopes across the ecoregions (Fig. 2). The Dry Plateau was the hottest of the ecoregions, and it had the highest inflection temperature at 22.2 °C, and a marginal 4% increase in mortality at 30 °C. The North was the coolest of the ecoregions, and it had the lowest inflection temperature at 14.1 °C, and a steep 19% increase in mortality at 30 °C (Fig. 2).

3.2. Differences by lagged interval, time period, and age category

Changes to the temperature–mortality slopes under different modeling conditions were assessed by comparing differences in the RR estimates at an AT_{max} of 30 °C (Table 2). When the lagged interval of the temperature effect was extended from up to 1-day to up to 1-week, the slope remained stable for the North ecoregion, but was lessened for the other ecoregions. When analyses were divided into the 1986–1998 (relatively cooler) and 1998–2010 (relatively hotter) periods, the slopes remained stable for the Dry Plateau and North ecoregions, and were increased during the later period for the Coast and Mountain ecoregions. The effect of temperature was markedly higher for those aged less than 75 years in the Dry Plateau, Mountain, and North ecoregions, but not in the Coast ecoregion.

3.3. Attributable mortality

The observed ecoregion-specific mortality ratios (95% confidence intervals) for days with AT_{max} over the 95th percentile ranged from 1.00 (0.95–1.06) in the Dry Plateau to 1.14 (1.02–1.26) in the North (Table 3). The absolute heat-related mortality estimates suggested that the model for the Coast under-predicted mortality by 25% (549 predicted, 735 observed), while the model for the Dry Plateau over-predicted mortality by more than 600% (52 predicted, 7 observed). The under- and over-predictions were more moderate for the North and Mountain ecoregions, respectively (Table 3).

4. Discussion

Many people live in rural and remote areas where heat-related mortality is challenging to study due to small, sparsely distributed populations. We have described a framework for examining underlying temperature–mortality relationships within such populations using geographic areas defined by ecoregions, which are delineated by macroclimatic conditions. We have applied this framework in one Canadian province with diverse microclimates and widely dispersed urban, rural, and remote populations. We believe that the framework could be usefully applied across Canada, and in other global areas with analogous microclimates and population distributions, including northern Europe, northern Asia, the northern United States, and possibly parts of the southern hemisphere. It may also be valuable in other areas with different

Table 1
Summary maximum apparent temperature (AT_{max}) and demographic information for the four ecoregions.

Ecoregion	Mean AT_{max} (°C)	1996–1998 75th percentile AT_{max} (°C)	1998–2010 75th percentile AT_{max} (°C)	Max AT_{max} (°C)	Inflection AT_{max} (°C)	Population in 1986/2010 (thousands)[a]	Aged ≥75 years in 1986/2010 (%)[a]	Average daily mortality in 1986/2010[a]	Average age at death in 1986/2010[a]
Coast	19.9	22.1	22.8	35.5	18.4	2,252/3,565	4.5/6.6	42/60	72/74
Dry Plateau	24.2	27.5	28.4	38.4	22.2	376/582	4.7/8.5	7/14	71/74
Mountain	21.0	23.8	24.8	33.5	16.2	525/615	3.0/6.8	4/6	68/71
North	18.6	21.9	21.7	33.1	14.1	203/215	1.3/4.3	2/3	60/66

[a] Values for the 1986 and 2010 populations, percent of populations aged ≥75 years, daily average mortalities, and average ages at death are presented to give readers a sense of how these areas changed over the study period, and are not intended to imply linear increases between the years.

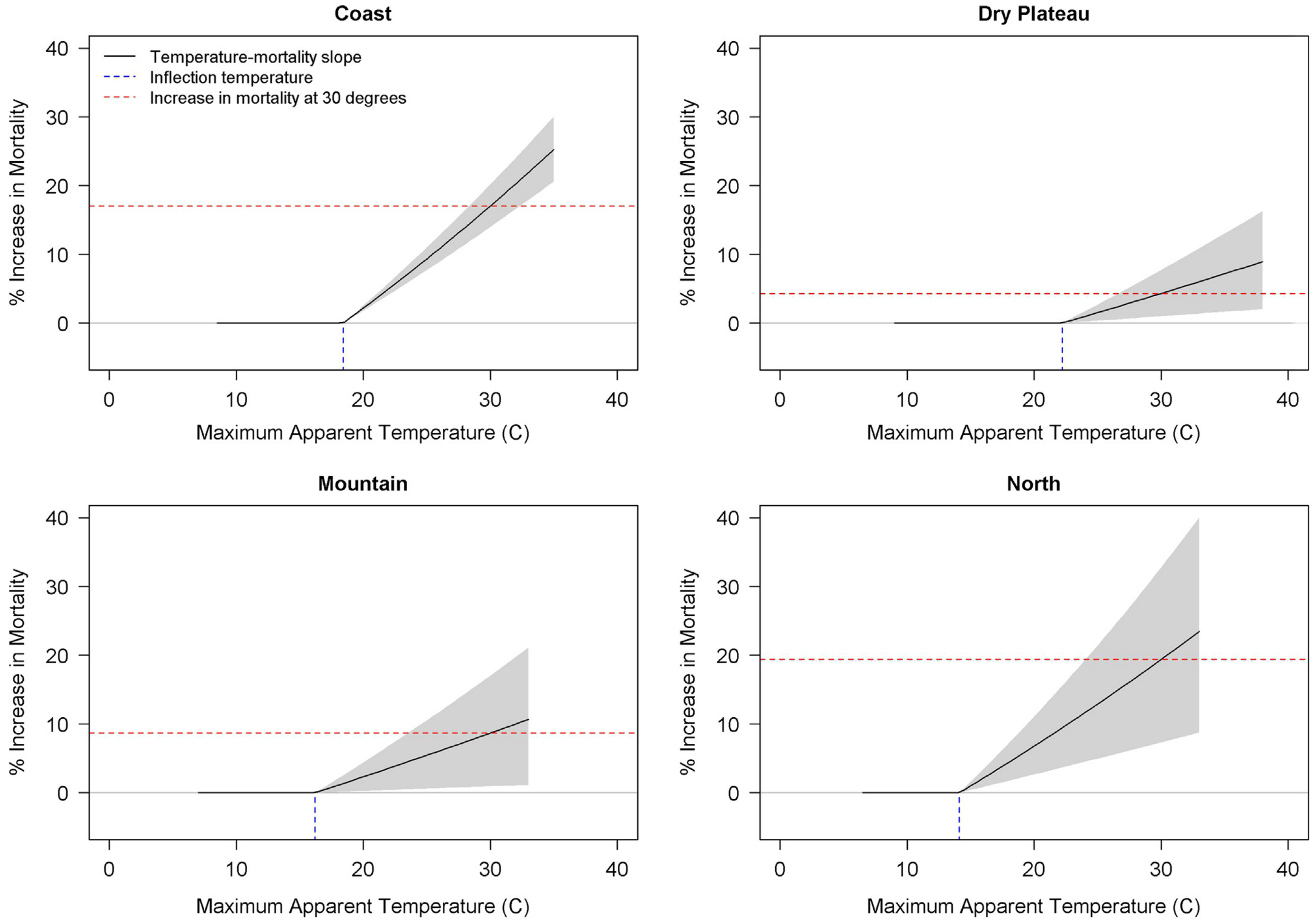

Fig. 2. Comparison of the Four Ecoregions. The inflection temperatures and temperature–mortality slopes for the four ecoregions. The thick lines indicate the inflection temperatures, while the dashed lines indicate the percent increase in mortality at a maximum apparent temperature of 30 °C, showing how the slopes vary between ecoregions. The gray areas show the confidence around the estimates, which decreases as temperatures increase from the baseline inflection point.

Table 2
Comparison of percent increases in mortality at a maximum apparent temperature (AT_{max}) of 30 °C under different scenarios. The first column highlights the base model, which included all ages during the 1986–2010 period, and allowed for up to a 1-day lagged interval between temperature and mortality. This is compared with the results from models allowing for up to a 1-week lagged interval, separating the 1986–1998 (relatively cooler) and 1998–2010 (relatively hotter) periods, and splitting decedents into those aged < 75 years and those aged ≥75 years.

Held constant from base models	All ages, 1986–2010		All ages, 1-day lag		1986–2010, 1-day lag	
Varied for comparison with base models	**1-day lag (base model)**	**1-week lag**	**1986–1998**	**1998–2010**	**< 75 years**	**≥75 years**
	% Increase in mortality (95% confidence interval) at AT_{max} of 30 °C					
Coast	17 (14, 20)[a]	14 (9,19)[a]	16 (12,21)[a]	19 (14,22)[a]	16 (10,20)[a]	18 (14,22)[a]
Dry plateau	4 (1,8)[a]	2 (−3,7)	5 (1,10)[a]	4 (−1,8)	11 (6,17)[a]	0 (−5,4)
Mountain	9 (1,17)[a]	5 (−9,18)	7 (−4,20)	11 (1,22)[a]	11 (0,23)[a]	7 (−4,18)
North	19 (7,33)[a]	19 (2,38)[a]	19 (1,39)[a]	19 (4,37)[a]	29 (12,48)[a]	6 (−11,26)

[a] Indicates a statistically significant result with a *p*-value less than 0.05.

Table 3
Absolute mortality and ecorgeiont-specific mortality ratios (MRs) for all summertime days from 1986–2010 with maximum apparent temperatures (AT_{max}) greater than the 95th percentile (i.e. all hot days).

Ecoregion	Total deaths	95th percentile AT_{max} (°C)	Observed/expected deaths	Observed/expected MR (95% CI)	Predicted/expected deaths	Predicted/expected MR (95% CI)
Coast	121,354	26.8	735	1.12 (1.09–1.15)	549	1.09 (1.06–1.11)
Dry plateau	23,151	32.8	7	1.00 (0.95–1.06)	52	1.04 (0.99–1.10)
Mountain	11,894	28.6	29	1.05 (0.97–1.13)	34	1.06 (0.97–1.14)
North	6,129	26.9	44	1.14 (1.02–1.26)	31	1.10 (0.98–1.21)

population distributions, but similar variability in macroclimatic conditions. In BC we found that AT_{max} was significantly associated with mortality in all ecoregions, but that the patterns varied considerably between them. The temperature–mortality slope was steepest in the North, where summers are typically mild and hot days are rare. On the other hand, summers are consistently hot in the Dry Plateau, and the shallow temperature–mortality slope suggests that the population is well-adapted to heat. Furthermore, disagreement between observed and predicted heat-related mortality in the Dry Plateau suggests that the model overestimated the actual impact. The absolute mortality attributable to hot weather was highest in the most populous Coast ecoregion, but the relative mortality attributable to hot weather was highest the least populous North ecoregion.

Interpretation of these results is aided by consideration of the social context in each ecoregion, including anecdotal information on the use of air conditioning. The population of the Coast is dominated by the metropolitan areas of Vancouver and Victoria (Fig. 1), where the economy is driven by the business, government, and service sectors. Both cities grew rapidly over the study period. Air conditioning in private homes is rare, but increasing with the development of new housing stock. The population of the Dry Plateau is dominated by the city of Kelowna, which is a popular retirement destination owing to its situation on a large lake and its warm, dry climate. The Dry Plateau had the highest proportion of the population older than 75 years throughout the study period (Table 1), and most private homes have air conditioning. The Mountain and North ecoregions are predominantly comprised of small towns and hamlets, typically separated by tens or hundreds of kilometers. Air conditioning is rare in both ecoregions. The economy of the North is driven by resource extraction, and the region has the highest aboriginal population in BC, the highest smoking rates, and the shortest life expectancy. The economy in the mountain ecoregion is more dependent on tourism, and the population has a higher proportion of younger people who enjoy outdoor activity.

Our results are consistent with other studies reporting on heat-related mortality in cooler climates (Anderson and Bell, 2009; Baccini et al., 2008; Chestnut et al., 1998; Curriero et al., 2002; Medina-Ramón and Schwartz, 2007), and the spatial relationships are similar to those reported for nearby Washington State, which shares the same coastal, dry, and mountain areas (Jackson et al., 2010). The effects of hot weather were most consistent in the coolest North ecoregion, with similar impacts over the immediate (up to 1-day) and medium (up to 7-day) lagged intervals, and little difference between the 1986–1998 and 1998–2010 periods (Table 2).

Other reports suggest that hot weather has the biggest mortality impact on the most elderly (Chestnut et al., 1998; Huynen et al., 2001; Kovats and Kristie, 2006), but our results indicate that this is not true throughout BC. The Dry Plateau, Mountain, and North ecoregions all showed steep and significant effects for those aged <75 years and insignificant effects for those aged ≥ 75. Although the effects were similar in both age categories for the Coast, previous analysis of an extreme heat event in metropolitan Vancouver during the summer of 2009 indicated that persons aged 65–74 years were at 47% greater risk of mortality than those aged ≥ 85 years (Kosatsky et al., 2012). The age-related differences in risk may suggest that older populations are more protected from the heat, possibly because they are more likely to live in care facilities with air conditioning and/or caregivers who help to keep them cool.

The approach used here assumes that the population response to hot weather is primarily driven by the underlying climate, and not by more spatially-specific factors, such as demographic composition, socioeconomic conditions, or local heat islands. Although we know from the wider literature that these other factors do contribute to the population response (Anderson and Bell, 2009; Chestnut et al., 1998; Curriero et al., 2002), our methods were able to show meaningful differences between ecoregions without their consideration. The effects of temperature were not adjusted for the effects of air pollution in our models, because air pollutants such as particulate matter and ozone were not consistently measured throughout the study period. Finally, the Coast ecoregion had a much larger population and more statistical power than the others, due the inclusion of the metropolitan Vancouver and Victoria areas. Removing these LHAs from the analyses did not affect the inflection temperature or the temperature–mortality slope, but it did increase the confidence intervals around the estimates (not shown).

5. Conclusions

Although the absolute mortality attributable to hot weather was highest in the most densely populated ecoregion, the relative impact was highest in the most sparsely populated ecoregion. Public health authorities need a clear and consistent set of tools to evaluate how hot weather affects populations living in urban, rural and remote areas so that they can plan strategies for climate change adaptation and emergency response during extreme heat. We have described a rigorous and replicable method for evaluating temperature–mortality effects using climatically-delineated ecoregions as the unit of analysis, and we have identified some important differences between lagged intervals, time periods, and age groups in BC. This work will be used to encourage greater heat health emergency planning across the province, and as the foundation for more localized analyses.

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