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Projecting the overall heat-related health burden and associated economic costs in a climate change context in Quebec, Canada

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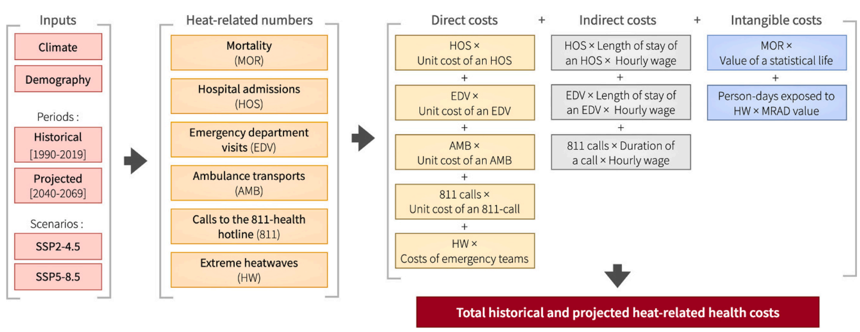
HIGHLIGHTS

- Heat-related health costs computed for 1990–2019 and 2040–2069 in Quebec, Canada.
- Considered costs were direct healthcare, indirect productivity and intangible costs.
- Annual historical costs were 15M$ (direct), 5M$ (indirect) and 3.6G$ (intangible).
- Total heat-related costs increased by 3X (SSP2–4.5) and 5X (SSP5–8.5) in 2050.
- Total costs were mainly driven by loss of life (~90–95%) and of well-being (~5–10%).

GRAPHICAL ABSTRACT



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ABSTRACT

Extreme heat represents a major health risk for the world's population, that is amplified by climate change. However, the health costs associated with these heat events have only been little studied. To stimulate the implementation of effective interventions against extreme heat, a more comprehensive economic valuation of these health impacts is crucial. In this study, a general framework for assessing historical and projected heat-related health costs is presented and then applied to the province of Quebec (Canada). First, heat-related mortality and morbidity, as well as the number of extreme heatwaves, were computed for a historical (~2000) and projected (~2050) period under two shared socioeconomic pathways (SSP). Then, these heat-related numbers were converted into 1) direct healthcare costs, 2) indirect productivity costs and 3) intangible societal costs, using the best available cost information. Results showed that historical heat-related health costs were respectively 15M$, 5M$ and 3.6G$ (in 2019 Canadian dollars) annually for the direct, indirect and intangible components in Quebec, Canada. Under a middle-of-the-road scenario (SSP2–4.5), there was a 3-fold increase in total costs due to climate and population change (10.9G$ annually), while under a pessimistic scenario (SSP5–8.5), the increase was 5-fold (17.4G$). Total costs were mostly driven by intangible impacts, such as loss of life (~90–95%) and of well-being during heatwaves (~5–10%). Given that heat-related health costs are already

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significant, and likely to increase substantially in the future, this study has demonstrated the vital need to reduce its burden now and in the future by adopting more measures to mitigate climate change and adapt to heat.

1. Introduction

Climate change is one of the greatest threats to human health in the 21st century (Haines et al., 2006; Watts et al., 2021). Among its numerous consequences, the increased frequency and intensity of extreme heat events have direct impacts on both mortality and morbidity (Campbell et al., 2018; Ebi et al., 2021; Song et al., 2017; Xu et al., 2016). Although many studies have projected the heat-related health burden under a changing climate (Cole et al., 2023; Huang et al., 2011; Sanderson et al., 2017), there is still only little research assessing the economic effects associated with these health impacts (Kousky, 2014; Schmitt et al., 2016; Wondmagegn et al., 2019). Estimating the costs of heat exposure is a key information that will help governmental and health authorities to better plan both mitigation and adaptation strategies to climate change (Austin et al., 2019; Huang et al., 2013).

The limited literature on heat-related health costs has some shortcomings that need to be acknowledged. On the one hand, many studies have only estimated the costs of historical extreme heat events of interest, leaving policymakers with no information on the future costs in the short-, medium- and long-term (Adélaïde et al., 2021; Beugin et al., 2023; Knowlton et al., 2011; Limaye et al., 2019; Wondmagegn et al., 2021a). On the other hand, most research projecting the health costs of heat exposure has analyzed a single health outcome such as mortality (Cheng et al., 2018; Díaz et al., 2019), hospital admissions (Crank et al., 2023; Hübler et al., 2008; Lin et al., 2012; Tong et al., 2021a, 2021b, 2022; Wondmagegn et al., 2021b), emergency department (ED) visits (Lay et al., 2018; Toloo et al., 2015; Tong et al., 2021c), or ambulance transports (Campbell et al., 2023), thus providing an incomplete and underestimated portrait of the overall expected heat-related health costs.

Economic valuation should include a wide variety of direct impacts such as mortality and various morbidity outcomes, as well as indirect and intangible effects (Schmitt et al., 2016). In this study, we proposed a general framework for a comprehensive economic assessment of the historical and projected heat-related health costs. Given the difficulty of accessing reliable healthcare and cost data for such analysis (Wondmagegn et al., 2019), we applied the framework to Quebec, a Canadian province of 8.5M inhabitants (~22% of Canada) for which such data was readily available. In addition, we base our work on previously developed heat-health exposure-response functions (Boudreault et al., 2024a), an ensemble of downscaled and bias-corrected climate models from the latest Coupled Model Intercomparison Project 6 (CMIP6) (Lavoie et al., 2024a), and regional demographic projections (Hebbern et al., 2023).

Briefly, heat-related mortality, morbidity, as well as number of extreme heatwaves, were computed in a historical (1990–2019) and projected (2040–2069) period under two shared socioeconomic pathways (SSP). These heat-related numbers were then converted into 1) direct healthcare costs, 2) indirect productivity costs of absenteeism due to medical care, and 3) intangible societal costs for loss of life and well-being, using the best available economic data from official agencies. To our knowledge, this is the first study to provide such a comprehensive portrait of all heat-related health costs at a provincial level.

2. Material and methods

This study received ethics approval from the Human Research Ethics Committee of the National Institute of Scientific Research (CER-22-693). The graphical abstract provides an overview of the methodology.

2.1. Study area

This study took place in Quebec (Canada), a province of 8.5M inhabitants (in 2019), representing ~22% of the Canadian population. Quebec is divided into 18 health regions (HR), a geographical division of public healthcare services in Canada relevant for decision makers (Fig. S1). The 3 northernmost HR (i.e., #10, #17, #18) were excluded from the current study due to their colder climate and small population (<1%) (Boudreault et al., 2024a). Due to provincial health jurisdictions, healthcare and cost data was not fully available in the other Canadian provinces, so this study only included Quebec. The summer period was defined as May to September, the months during which heat surveillance takes place in Quebec (Toutant et al., 2011).

2.2. Statistical analysis of the association between heat and health outcomes

Daily health data in each HR was provided by *Institut national de la santé publique du Québec* (INSPQ) for five all-cause health outcomes: mortality (1996–2019), hospital admissions (1996–2019), emergency department (ED) visits (2014–2019), ambulance transports (2014–2019) and calls to the 811-health hotline (2008–2019). Daily temperature data was obtained from Daymet at a 1 km × 1 km resolution (Thornton et al., 2022). Mean temperature was computed from the average of maximum and minimum daily temperatures, then aggregated in each HR by weighting temperature values with the number of residential units in each grid cell using geocoded addresses (Boudreault et al., 2024b). Distributed Lag Non-Linear Models (DLNM) were developed to capture the non-linear and lagged association over 8 days between mean temperature and every health outcome during summer for each HR (Gasparrini et al., 2010). The non-linear heat-health association was accounted by using a natural cubic spline with two internal knots placed at the 50th and 90th percentiles of each region's temperature distribution and two degrees of freedom (Vicedo-Cabrera et al., 2021). The lag effect was modelled with a natural cubic spline with two knots placed on the log scale from 0 to 7 days and two degrees of freedom. Then, meta-regression models were fitted on the reduced cumulative effect over 8 days to obtain Best Linear Unbiased Predictions (BLUP) of each heat-health associations in all HR (Gasparrini and Armstrong, 2013; Sera et al., 2019). Risk ratios were computed relative to the minimum mortality/morbidity temperature (MMT) value, obtained by scanning the temperature values from the 25th to the 98th percentile of each HR temperature distribution (Vicedo-Cabrera et al., 2021). The readers are referred to Boudreault et al. (2024a) for additional details on the fitting of DLNM and meta-regression, sensitivity analyses and resulting graphs of exposure-response functions.

2.3. Climate and demographic data

The EPSO-G6-R2 ensemble of 15 downscaled and bias-corrected global circulation models (GCM) of CMIP6, developed by the Ouranos consortium on regional climatology, was employed (Lavoie et al., 2024a). Two shared socioeconomic pathways (SSP) were considered: SSP2–4.5, a middle-of-the-road scenario, and SSP5–8.5, a pessimistic scenario in which emissions continue to rise through the century (IPCC, 2021). Daily mean temperature during 1990–2069 in each HR was computed from the average of daily minimum and maximum temperatures, then bias-corrected using the Hempel method to adjust remaining bias between population-weighted temperature data (used to develop exposure-response functions) and climate models values (Hempel et al., 2013; Vicedo-Cabrera et al., 2021). Demographic data by HR was provided by *Ministère de la santé et des services sociaux du Québec* (MSSS) for the 1996–2019 period (MSSS, 2022). Data for 1990–1995 was linearly extrapolated from the HR to Quebec ratio of population trend during the 1996–2000 period. Projected population by HR from 2020 to 2069 was provided by Statistics Canada for two demographic scenarios associated with SSP2 and SSP5, previously used for forecasting future temperature-related mortality burden in Canada (Hebbern et al., 2023). These scenarios were in line with Quebec's population forecasts for the 2020–2041 period (MSSS, 2022).

2.4. Attributable numbers to heat and number of extreme heatwaves

Climate and demographic data were then used with BLUP of exposure-response functions in each HR to compute attributable numbers (AN) for the historical (1990–2019) and projected (2040–2069) periods. AN to all heat and extreme heat were computed respectively by summing the individual contributions of all temperatures above the MMT (i.e., *all heat*) and above the 95th percentile of historical summer temperature by HR (i.e., *extreme heat*) (Boudreault et al., 2024a; Gasparrini and Leone, 2014; Steenland and Armstrong, 2006). The mean historical daily count of each health outcome was used to compute AN for both periods (Gasparrini et al., 2017; Vicedo-Cabrera et al., 2019). To supplement AN to all and extreme heat, number of extreme heatwaves (HW) at each reference weather station's location of HR were also computed (Fig. S1). HW were defined on the basis of official public health thresholds of 3-day weighted average values of maximum and minimum temperatures, respectively 33°C and 20°C for HR #6 and #13–#16, 31°C and 18°C for HR #2–#5, #7–#8 and #12, 31°C and 16°C for HR #1, #9 and #11 (Chebana et al., 2013; Lamothe et al., 2023). The person-days exposed to HW were computed by multiplying the duration of each heatwave by the population in the HR, in order to assess the loss of well-being due to extreme heat events (Adélaïde et al., 2021). To isolate the specific effect of climate and demographic changes, projections were made separately for 1) historical climate and demography (1990–2019), 2) projected climate (2040–2069), but with historical demography, and 3) both projected climate and demography in 2040–2069, as recommended in a recent review (Sanderson et al., 2017).

2.5. Heat-related health costs

Heat-related numbers were converted to health costs using the cost-of-illness approach and then summarized in three categories: 1) direct healthcare costs, 2) indirect productivity loss to seek medical care, and 3) intangible societal costs (Schmitt et al., 2016; Wondmagegn et al., 2019). To obtain comparable figures for the historical and projected periods, all costs were expressed in 2019 Canadian dollars ($), without considering past healthcare costs or making assumptions on future healthcare expenditures (Lay et al., 2018; Limaye et al., 2019). When cost metrics were not in $2019, they were converted using the consumer price index of the Bank of Canada (Bank of Canada, 2024). Direct costs were computed by multiplying AN to all heat (or extreme heat) with the unit cost (UC) of each health outcome (Knowlton et al., 2011; Limaye et al., 2019). In addition, the costs of emergency teams when HW thresholds are met were also considered (Larrivée et al., 2015). Indirect costs were computed by converting AN to the total duration using Length of Stay (LoS), then multiplied by the mean hourly wage in Quebec (Knowlton et al., 2011; Limaye et al., 2019). Finally, intangible costs were estimated using the Value of a Statistical Life (VSL) multiplied by the AN of heat-related mortality (Limaye et al., 2019; Liu et al., 2019), and loss of well-being using the Minor Restricted Activity Day (MRAD) willingness-to-pay for each person-day exposed to HW (Adélaïde et al., 2021). All economic metrics used are listed in Table A1, along with the relevant references.

A Monte Carlo simulation was performed to assess the uncertainty in estimated costs. The simulation algorithm consisted of five steps: 1) selecting randomly 30 years in either the historical or projected period across all simulated years of the 15 GCMs (i.e., 450 years); 2) deriving AN during these years by sampling random coefficients of BLUP for each health outcome, assuming a multivariate-normal distribution of these coefficients as commonly done to assess the uncertainty of exposure-response functions for climate projections (e.g., Gasparrini et al., 2017; Vicedo-Cabrera et al., 2021); 3) computing the number of HW as well as the population exposed to HW during these 30 years; 4) simulating UC, LoS, VSL, MRAD and hourly wage based on uncertainties and distributions provided in Table A1; and 5) aggregating the direct, indirect, intangible and total costs of all heat and extreme heat as an average annual cost over these 30 years. For the economic metrics with no uncertainties provided, a triangular distribution with ±33% around the central value was assumed (Adélaïde et al., 2021). This process was replicated 15,000 times for each period (historical and projected) and combination of climate and demographic scenarios (i.e., SSP2–4.5 and SSP5–8.5). Empirical 95% confidence intervals (eCI) were then computed based on these simulations. Dunn's tests were performed to assess a statistically significance difference between the simulated costs in the different periods and scenarios, adjusted with the Bonferroni method for multiple comparisons.

3. Results

3.1. Climate and demographic evolution

The average summer temperature during May to September months in Quebec (Canada) was approximately 15.5°C during the historical period. Based on an ensemble of bias-corrected and downscaled climate models from CMIP6, mean temperature was projected to increase to ~18°C (+2.5°C) under SSP2–4.5 and to ~19°C (+3.5°C) under SSP5–8.5 over the 2040–2069 period (Fig. 1a). Overall, the ensemble of climate models well represented the observed temperatures in Quebec (black line) during the historical period. In terms of demography, Quebec's population grew from 7M inhabitants in 1990 to 8.5M in 2020 (Fig. 1b). Under SSP2, projections showed that it could reach 9.5M in 2050 and 10.3M in 2070. Under SSP5, for which a higher demographic growth is expected, Quebec's population could reach 10.5M in 2050 and 13M in 2070.

3.2. Heat-related numbers

During the historical period (1990–2019), heat (i.e., all temperatures above MMT) resulted in AN of roughly 410 deaths, 200 hospital admissions, 31,900 ED visits, 6100 ambulance transports and 13,300 calls to the 811-health hotline every summer in Quebec (Table 1). These AN were lower when considering only extreme heat (i.e., temperatures above the 95th percentile of historical summer temperature) with AN of approximately 160 deaths, 150 hospital admissions, 5500 ED visits, 1300 ambulance transports and 2600 calls to the 811-health hotline. There were roughly 3.1 HW and 6.9M person-days exposed to HW every summer in Quebec during that period. Under SSP2–4.5, mortality increased by 118%, hospital admissions by 230%, and the other morbidity outcomes by 50–65% in the projected period (i.e., 2040–2069) compared to the historical period, only because of climate change (i.e., without considering any other socioeconomic change or adaptation). In addition, there was roughly 4X more HW and person-days exposed to these HW in the projected period. When also considering demographic change based on SSP, there was a 3-fold increase in heat-related mortality, 4-fold increase in hospital admissions, 2-fold increase in ED visits, ambulance transports and 811 calls, and 5-fold increase in person-days exposed to HW. The increases in AN to extreme heat were even greater: 230–300% without considering demographic change, and 280–400% when considered. Under SSP5–8.5 (Table S1), increases in AN reached up to 7-fold for all heat and 9-fold for extreme heat.

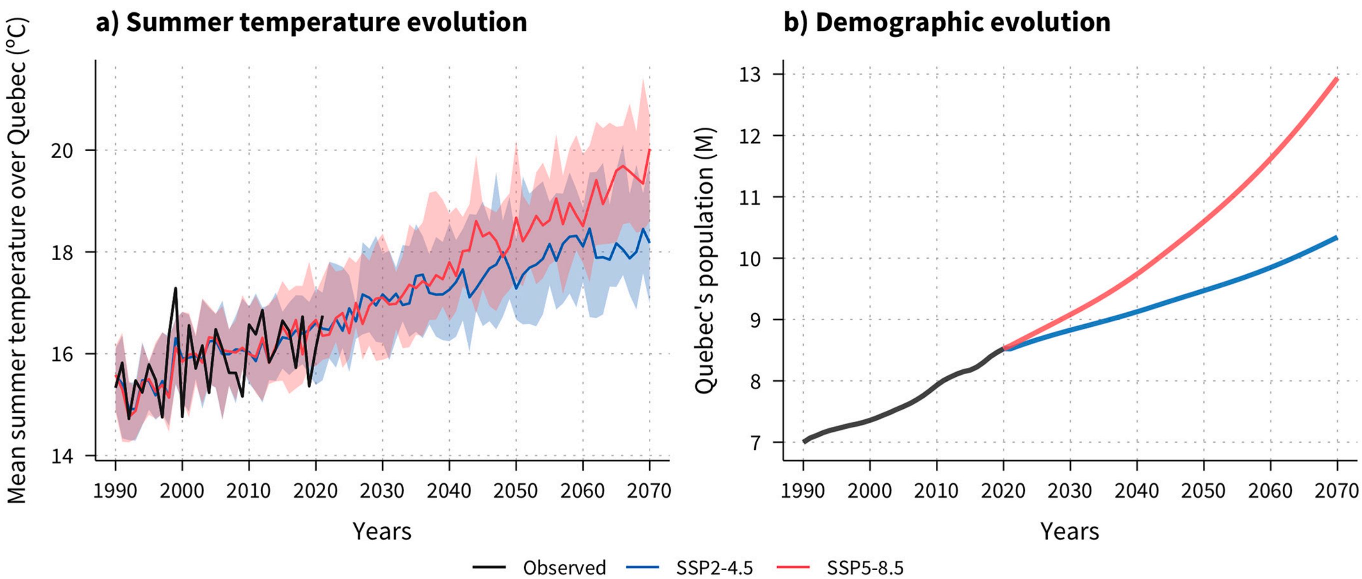

Fig. 1. Evolution of (a) mean summer temperature (May to September) and (b) demography across Quebec based on SSP2–4.5 and SSP5–8.5 scenarios over the 1990–2070 period. The ribbon corresponds to the 10th and 90th percentiles of the climate models ensemble.

Table 1
Attributable numbers (AN) to all and extreme heat every summer in Quebec for mortality (MOR), hospital admissions (HOS), ED visits (EDV), ambulance transports (AMB) and calls to the 811-health hotline (811), as well as number of extreme heatwaves (HW) across the 15 health regions of Quebec and person-days exposed to HW during the historical (1990–2019) and projected (2040–2069) periods under SSP2–4.5. The median of all climate models is presented. Refer to Table S1 for results under SSP5–8.5.

			All heat		Extreme heat	
	Climate	Demography	Number	Increase (%)	Number	Increase (%)
	Historical	Historical	414	Ref.	159	Ref.
AN of MOR	Projected	Historical	900	118 %	548	246 %
	Projected	Projected	1140	176 %	702	343 %
	Historical	Historical	198	Ref.	146	Ref.
AN of HOS	Projected	Historical	654	230 %	576	295 %
	Projected	Projected	822	315 %	728	399 %
	Historical	Historical	31,895	Ref.	5475	Ref.
AN of EDV	Projected	Historical	48,880	53 %	17,997	229 %
	Projected	Projected	56,972	79 %	20,800	280 %
	Historical	Historical	6132	Ref.	1256	Ref.
AN of AMB	Projected	Historical	10,029	64 %	4118	228 %
	Projected	Projected	12,322	101 %	5144	310 %
	Historical	Historical	13,305	Ref.	2631	Ref.
AN of 811	Projected	Historical	21,413	61 %	8617	228 %
	Projected	Projected	26,393	98 %	10,465	298 %
	Historical	Historical	3.1	Ref.		
Number of HW	Projected	Historical	13.2	322 %	Same as for all heat.	
	Projected	Projected	13.2	322 %		
	Historical	Historical	6.9	Ref.		
Person-days (M) exposed to HW	Projected	Historical	27.4	299 %	Same as for all heat.	
	Projected	Projected	34.5	402 %		

3.3. *Health costs of heat exposure*

The historical annual health costs attributable to all heat were estimated to be respectively 14.8M$, 5.3M$ and 3.6G$ (in 2019 Canadian dollars) for the direct, indirect and intangible components, of which 5.3M$, 1.5M$ and 1.5G$ were respectively attributable to extreme heat only (Table 2). Under SSP2–4.5, all costs doubled in 2050 compared to the historical period with increases of 85% to 135% only because of climate change (i.e., keeping demography fixed as of 1990–2019). Higher increases of 250–290% were noted for health costs attributable to extreme heat. Demographic growth added an extra load on the health burden with increases of 120% to 200% for all heat, and of 320% to 400% for extreme heat. Under SSP5–8.5 (Table S2), the total health costs of all heat increased from 3.7G$ in the historical period to 11.7G$ in the projected (2040–2069) period only because of climate change, and to 17.4G$ when considered both evolving climate and demographic. All costs categories were 3X to 4X higher compared to the historical period. The total health costs attributable to extreme heat in 2050 was multiplied by >8X with both climate and demographic changes under SSP5–8.5, for a grand total of 12.6G$. Roughly, SSP5–8.5 doubled the heat-related health costs in 2050 compared to SSP2–4.5.

3.4. *Uncertainties in estimated costs*

Monte Carlo simulations demonstrated the uncertainties in the historical and projected health costs arising from the epidemiological models, economic metrics and climate projections, as illustrated by the heights of the boxplots in Fig. 2. Uncertainty was smaller during the

Table 2
Yearly direct, indirect, intangible and total health costs (in Canadian M$2019) attributable to all and extreme heat in the historical (1990–2019) and projected (2040–2069) periods under SSP2–4.5. The median of all climate models is presented. Empirical 95% confidence intervals (eCI) based on Monte Carlo simulations are shown in parentheses. Refer to Table S2 for results under SSP5–8.5.

			All heat		Extreme heat	
	Climate	Demography	Cost in M$2019 (95%eCI)	Increase %	Cost in M$2019 (95%eCI)	Increase %
Direct healthcare costs	Historical	Historical	14.8 (11.6–19.2)	Ref.	5.3 (3.5–7.7)	Ref.
	Projected	Historical	32.1 (27.9–46.6)	116 %	20.2 (17.5–34.0)	279 %
	Projected	Projected	36.4 (31.2–52.9)	145 %	22.3 (19.1–37.7)	319 %
Indirect productivity costs	Historical	Historical	5.3 (2.0–11.1)	Ref.	1.5 (0.7–2.7)	Ref.
	Projected	Historical	9.8 (4.8–20.3)	84 %	5.2 (3.2–10.7)	254 %
	Projected	Projected	11.6 (5.9–24.0)	119 %	6.3 (3.9–12.8)	331 %
Intangible societal costs	Historical	Historical	3589 (1815–5505)	Ref.	1466 (744–2372)	Ref.
	Projected	Historical	8432 (5076–14,115)	135 %	5687 (3460–9944)	288 %
	Projected	Projected	10,837 (6483–17,823)	202 %	7257 (4388–12,529)	395 %
Total costs	Historical	Historical	3609 (1836–5527)	Ref.	1473 (749–2380)	Ref.
	Projected	Historical	8474 (5120–14,166)	135 %	5712 (3485–9981)	288 %
	Projected	Projected	10,885 (6538–17,878)	202 %	7286 (4418–12,569)	395 %

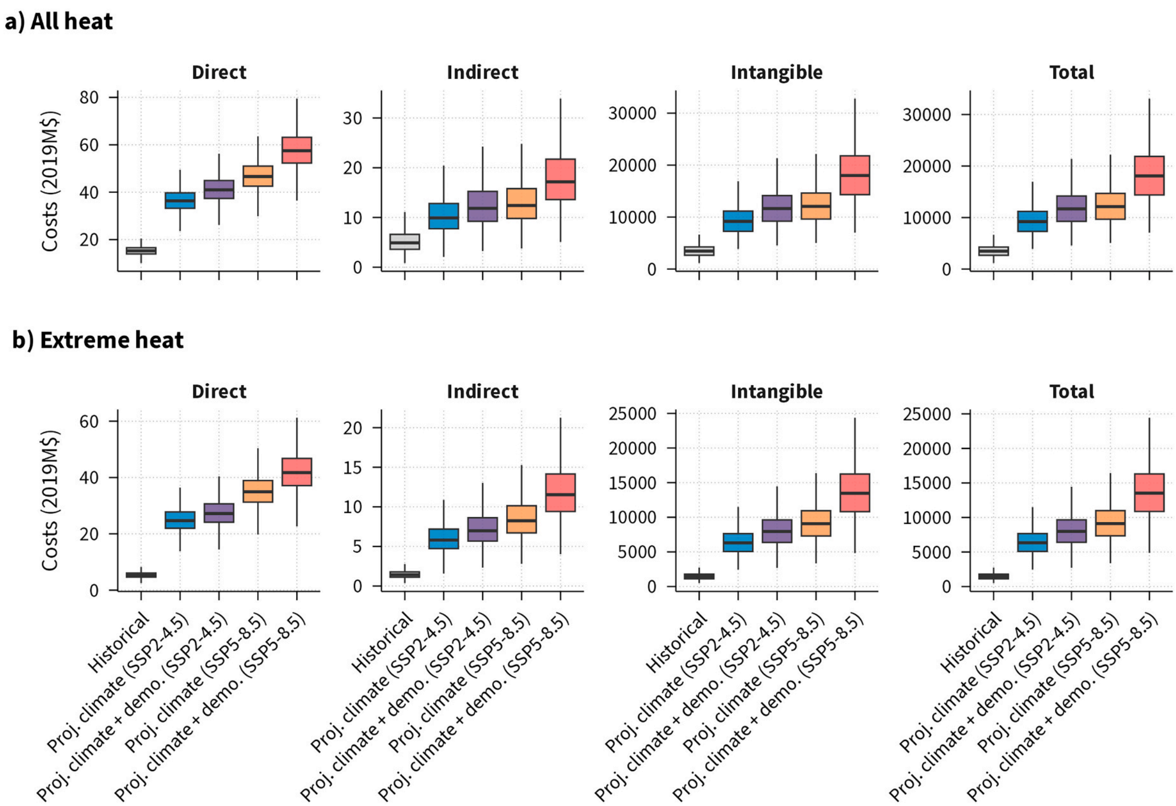

Fig. 2. Results of Monte Carlo simulations for historical (1990–2019) and projected (2040–2069) yearly heat-related health costs for direct, indirect, intangible and total components for a) all heat and b) extreme heat. Refer to Table 2 (for SSP2–4.5) and Table S2 (SSP5–8.5) for numeric results of the 95% empirical confidence intervals.

historical period, for which climate conditions are known, while climate scenarios added additional uncertainty during the projected period. This was particularly marked under the high-emission high-population scenario (i.e., SSP5–8.5) (Fig. 2). These Monte Carlo simulations also allowed to derive 95% empirical confidence intervals (eCI) of estimated costs (Table 2 for SSP2–4.5 and Table S2 for SSP5–8.5). For example, the eCI of the total health costs of all heat was 1.8–5.3G$ during the historical period, increasing during the projected period to 6.5–17.9G$ under SSP2–4.5 and 10.1–27.8G$ under SSP5–8.5, when considering both climate and demographic changes. Finally, the differences between all periods/scenarios were all statistically significant at a 5% level for all cost categories based on the Dunn's test (Fig. S2).

3.5. Breakdown of health costs

Historical direct healthcare costs of all heat were mostly driven by ED visits, followed by hospital admissions, ambulance transports and emergency teams during HW (Fig. 3). In all projected scenarios (i.e., SSP2–4.5 and SSP5–8.5), the share of emergency teams doubled from ~15% to ~30%, becoming the second most important direct cost. This can be linked to the higher number of heatwaves and more frequent deployments of emergency teams during the projected period. For the indirect costs, the share was ~75% for ED visits loss of productivity, followed by hospital admissions with ~25%. A higher share of loss of productivity due to hospital admissions was noted in the projected period (i.e., 2040–2069). For the intangible component, mortality costs

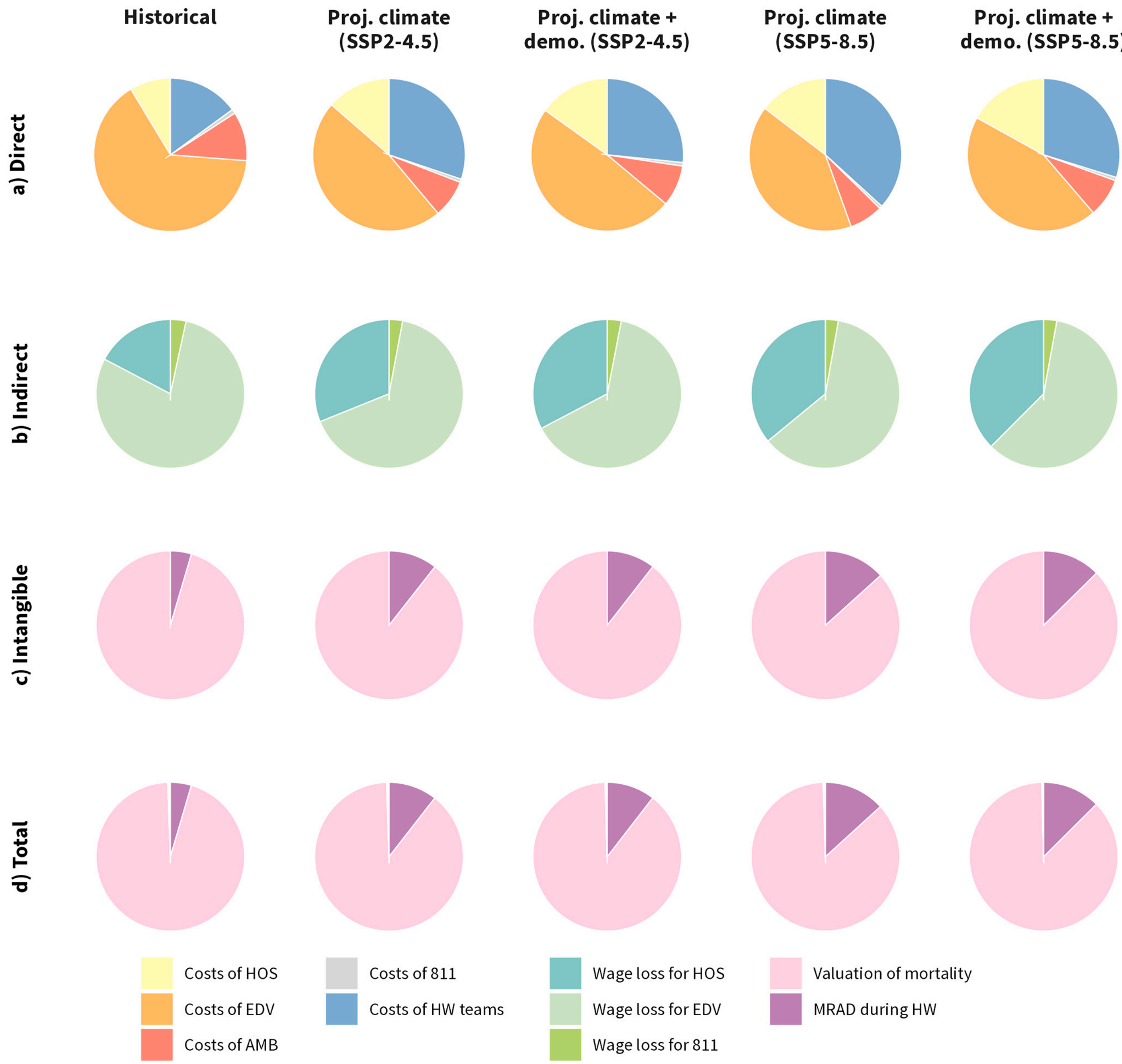

Fig. 3. Health costs breakdown of all heat by a) direct, b) indirect, c) intangible and d) total costs during the historical (1990–2019) and projected (2040–2069) periods based on SSP2–4.5 and SSP5–8.5 climate and demographic projections. Refer to Table S3 (for SSP2–4.5) and Table S4 (SSP5–8.5) for numerical results. AMB = Ambulance transports. EDV = Emergency department visits. HOS = Hospital admissions. HW = Extreme heatwaves. MRAD = Minor restricted activity day. 811 = Calls to the 811-health hotline.

were more important than loss of well-being in the historical period, but the share of well-being loss increased in 2050 with demographic growth, resulting in more people negatively affected by HW. Finally, the total costs were mostly driven by intangible loss of life (~90–95%) and of well-being (~5–10%) costs, and <1% for other costs. For extreme heat (Fig. S3), the portrait was a bit different with almost half the direct healthcare costs related to emergency teams, followed by ED visits and hospital admissions, in both historical and projected periods. The productivity costs were shared roughly by wage loss for ED visits (~50%) and hospital admissions (~50%). For intangible and total health costs, the same portrait as for all heat was noted. Refer to Table S3 (SSP2–4.5) and Table S4 (SSP5–8.5) for detailed heat-related health costs by outcome and their share over their category and the grand total.

4. Discussion

This study is among the first to evaluate the historical and projected heat-related health costs arising from multiple mortality and morbidity outcomes. Applied to the province of Quebec, Canada, total health costs attributable to all heat (i.e., temperatures above the MMT) were estimated at 3.6G$ annually during the 1990–2019 period. Considering both climate and demographic changes, these costs were projected to increase to 10.9G$ annually under SSP2–4.5 (a 3-fold increase) and to 17.4G$ under SSP5–8.5 (a 5-fold increase) during the projected 2040–2069 period. Costs attributable to extreme heat only (i.e., temperatures above the 95th percentile of historical summer temperature) had even greater increases in the projected period: 5-fold under SSP2–4.5 and 8.5-fold under SSP5–8.5. As in other international studies (Gasparrini et al., 2017; Vicedo-Cabrera et al., 2018), these projected numbers represent a "hypothetical future", as other changes will also occur such as biological acclimatization to heat and socioeconomic adaptation that may reduce the heat effect (Hondula et al., 2015). However, because hypotheses on adaptation are often simplistic and would add another layer of uncertainty to these projections (Sanderson et al., 2017), their inclusion was deemed out-of-scope for this initial attempt of assessing historical and projected heat-related health costs.

Our study reaffirmed the importance of mitigation strategies aimed at limiting greenhouse gases (GHG) emissions to further reduce the projected heat-related health burden (Romanello et al., 2023; Vicedo-Cabrera et al., 2018). Indeed, projected costs were approximately 2 times higher under SSP5–8.5 than SSP2–4.5. However, even under the more optimistic scenario, the heat-related health costs still significantly increased by 2050 and were amplified by a larger population exposed to heat. Therefore, this research also highlighted the need for better adaptation measures to heat such as increased greening, reduced heat urban islands or new alert systems, among others, to reduce the historical heat-related costs and the increasing costs in the future (Ebi et al., 2018; Huang et al., 2013). In addition, our results can be used to carry out cost-benefit analyses of such measures to stimulate their adoption, as already demonstrated for heat-health warning systems (e.g., Carmona et al., 2016; Chiabai et al., 2018; Ebi et al., 2004; Hunt et al., 2017; Williams et al., 2021).

Over the last decades, there have been a few reports in Canada that estimated some components of the heat-related health costs. NRTEE (2011) calculated heat-related mortality costs in Montreal of 0.6–0.8G$ in 2020 and 1.4–2.8G$ in 2050, which are comparable to our results of 3.4G$ in 2000 and 7.4G$ in 2050 for the whole province, given that Montreal is one fifth of Quebec's population. Larrivée et al. (2015) estimated the health costs associated with climate changed-induced heat at 32.4G$ (for mortality) and 372M$ (for morbidity) during the 2015–2064 period in Quebec using a discount rate of 4%. Performing a similar discounting, our costs for the 2015–2064 period would be ~50G$ for mortality and ~300M$ for healthcare costs, which is slightly higher for mortality but comparable for morbidity (although the morbidity outcomes studied were different in the two studies). Clark et al. (2021) estimated heat-related costs of 3.0–3.9G$ each year in 2050 for mortality and 138–167M$ for morbidity in Canada. While our climate change-related morbidity costs of 23M$ were comparable (assuming Quebec represents 22% of the Canadian population × 138M$ = 30M$), our mortality costs were much higher at 10.3G$ in 2050 versus 0.7G$ (22% × 3G$ = 0.7G$) in their study.

Comparing our results with studies published internationally is difficult due to the differences in studied population, health outcomes, projections parameters and health systems, among others. More importantly, most studies have only assessed historical costs of specific heatwaves or projected a single health outcome (see references in the introduction), making comparisons even more challenging. That being said, projections of heat-related health costs in the literature obtained similar orders of magnitude that ours. For example, Lay et al. (2018) found that ED visit costs for hyperthermia could triple by 2050 in USA. Hübler et al. (2008) found a 6-fold increase in heat-related hospital admission costs in 2071–2100 in Germany compared to their historical period. Gronlund et al. (2019) projected increases of 6X to 7X in the costs associated with extreme heat-related mortality, hospital admissions and ED visits in Michigan (USA). A recent review on heat-related healthcare costs noted that heat already poses a significant burden on healthcare and that this burden will substantially increase in the future (Wondmagegn et al., 2019), which is consistent with our results. To our knowledge, our study is the first to consider such a wide range of health outcomes to provide a complete picture of both historical and projected heat-related health costs, using the province of Quebec as a case study.

Our results showed that the heat-related health costs were mainly driven by intangible components such as loss of life (90–95% of the grand total) and loss of well-being (5–10%). Some previous studies have also highlighted that mortality effects account for the bulk of the health costs when several health outcomes are simultaneously analyzed (Adélaïde et al., 2021; Beugin et al., 2023; Clark et al., 2021; Knowlton et al., 2011; Larrivée et al., 2015; Limaye et al., 2019). On the other hand, the loss of well-being during HW has been less studied, but it could account for a significant proportion of the heat load, as also demonstrated in France (Adélaïde et al., 2021). The strong importance of mortality costs raises the question of the optimal valuation method using either the Value of a Statistical Life (VSL), an age-adjusted VSL or the Value of a Life Year (VoLY) (Chiabai et al., 2018). In our study, a central VSL of 8.2M$ was considered with lower and upper bounds of respectively 4.1M$ and 11.8M$, as used in other climate change and air pollution impact assessments in Canada (Beugin et al., 2023; Clark et al., 2021; Health Canada, 2021). Given that the older people are more likely to die during extreme heat events (Benmarhnia et al., 2015), an age-adjusted VSL or VoLY metric to value mortality would lead to a lower estimate than what was obtained here. Comparing different mortality valuation methods is left for future research as this would require age-adjusted exposure-response functions that were not available at the time this study was conducted. Such a study could also help understand the role of aging in projecting heat-related health costs (Cole et al., 2023).

Although intangible costs were the most important for the grand total, direct and indirect costs still represented annual costs of 15M$ and 5M$ respectively in the historical period, expected to rise to 36M$ and 12M$ under SSP2–4.5 and to 53M$ and 17M$ under SSP5–8.5, respectively. Compared to intangible effects that are borne by the society as a whole (Limaye et al., 2019), direct costs are assumed by the government, individuals or insurers. In the case of Quebec, which has universal health insurance, these costs are covered by the Ministry of Health's limited budget, and will contribute to the ever-increasing costs of the healthcare system (Wondmagegn et al., 2019). Furthermore, direct healthcare costs were probably underestimated in this study because 1) not all heat-related impacts were considered due to the lack of data (e.g., general practitioner consultations, community nursing visits, 911 emergency calls) and 2) the relationship between all-cause hospital admissions and heat was found to be weak with an historical attributable fraction of only 0.1% in Quebec (Boudreault et al., 2024a). Studying cause-specific hospitalizations could lead to higher direct costs, as shown by Bai et al. (2018) with heat-related hospitalization costs for coronary heart disease and stroke alone totalling 14.5M$ by year in Ontario, Canada. Regarding indirect costs, they only included the loss of productivity associated with medical consultations (i.e., absenteeism), while heat has much broader productivity and economic effects (Borg et al., 2021; Callahan and Mankin, 2022; García-León et al., 2021), that were out-of-scope for this study focussing on health impacts.

This study has several strengths. First, it uses state-of-the-art and locally developed exposure-response functions to compute historical (1990–2019) and projected (2040–2069) heat-attributable numbers for various mortality and morbidity outcomes. Second, it considered a variety of direct healthcare, indirect productivity and intangible societal costs, thus providing a comprehensive picture of the health costs associated with two heat exposures (i.e., all heat and extreme heat). Third, costs were calculated for both periods with combinations of demographic and climate projections under two SSP, based on an ensemble of 15 bias-corrected and downscaled climate models from CMIP6. Finally, uncertainties in health costs were assessed using Monte Carlo simulations that considered the variability in exposure-response functions, economic metrics and climate models employed.

Limitations must also be acknowledged. First, all projections were made without socioeconomic changes other than demographic growth, excluding potential future adaptation to heat, rising healthcare costs and population aging, for example. Second, in the absence of stratified heat-health exposure-response functions, all economic metrics employed were averaged across all genders, age groups, causes of illness and regions, which may mask large differences in economic impacts (Merrill et al., 2008; Schmeltz et al., 2016), especially for mortality. Third, due to Canada's health jurisdictions, the studied health outcomes were only fully available in the province of Quebec. Therefore, the study region was limited to that province. Fourth, even though correction techniques were applied to the climate simulations, some residual bias may remain between observed and simulated data. However, such difference should not affect the users' needs to plan adaptation accordingly (Lavoie et al., 2024b). Finally, simulations (and resulting empirical 95% confidence intervals) were derived using a Monte Carlo technique, assuming for example a multivariate normal distribution of the parameters of the exposure-response functions as commonly done in environmental epidemiology studies. This method could be refined in a future study, as well as adapted to include the uncertainties of demographic projections that were not available at the time this study was conducted.

5. Conclusion

Heat-related health costs already represented a significant direct, indirect and intangible burden in Quebec, Canada. As a result of climate and demographic changes, but without considering other socioeconomic factors, this burden will significantly increase over the next 50 years by 3X under a middle-of-the-road scenario and by 5X under a pessimistic one. This new evidence underlines the importance of both climate change mitigation (i.e., reducing GHG emissions) and new measures to limit heat-related effects. In addition, this study can serve as a basis for investigating the role of adaptation in projecting health costs, as well as for eventual cost-benefit analyses of targeted adaptation interventions. Finally, the proposed robust and state-of-the-art methodology can be applied to other regions of the world that are also experiencing the devastating effects of extreme heat.

CRediT authorship contribution statement

Jérémie Boudreault: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Céline Campagna:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization. **Éric Lavigne:** Writing – review & editing, Software, Methodology, Conceptualization. **Fateh Chebana:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Economic metrics

Table A1

Overview of the economic metrics used in this study and corresponding references, along with their uncertainty and distributions used to compute Monte Carlo simulations. All values are expressed in 2019 Canadian dollars ($), unless otherwise specified. AMB = Ambulance transport. EDV = Emergency department visit. HOS = Hospital admission. HR = Health region. HW = Extreme heatwave. LoS = Length of Stay. MRAD = Minor restricted activity day. SD = Standard deviation. VSL = Value of a statistical life. 811 = Health hotline.

Metric	Central value	Uncertainty values	Distribution	References
Unit cost of an HOS	6500 $[a]	Lower value of 1750$ used in Quebec[b] and upper value of 11,500$ used in Ontario[c]	Uniform (lower to higher bounds)	[a]CIHI (2024a) [b]Ripoche et al. (2023) [c]Bai et al. (2018)
Unit costs of an EDV	303 $[d]	None found	Triangular (±33 % around central value)	[d]CIHI (2020)
Unit costs of an AMB	250 $[e]	Lower value of 125$ in Quebec[f] and upper value of 500$ in Canada[e]	Uniform (lower to higher bounds)	[e]CIHI (2016) [f] Québec (2024a)
Unit costs of an 811 call	10 $, the median nurse wage of 38.5$[g] × a mean duration of call of 0.25 h[h]	None found	Triangular (±33 % around central value)	[g]Canada (2024) [h]Québec (2024b)
Costs of HW emergency teams	3.2 M$ for a HW over 4–5 HR[i]	None found	Triangular (±33 % around central value)	[i]Larrivée et al. (2015)
LoS of an HOS	7.2 days[j]	None found	Triangular (±33 % around central value)	[j]CIHI (2023)
LoS of an EDV	4.9 hours[k]	90 % quantile of 19.6 h in Quebec[k]	Gamma (Mean = 4.9 and Q90 closest to 19.6)	[k]CIHI (2024b)
Duration of an 811 call	0.5 h, 0.25 h for the call duration[h] + waiting time of 0.25 h	Lower value of 0.25 h[h] and upper value of 0.75 h	Uniform (lower to higher bounds)	
Hourly wage	27 $/h[l]	None found	Triangular (±33 % around central value)	[l]ISQ (2024)
VSL	8.2 M$[m]	Lower value of 4.1 M$ used in Quebec[i] and upper value of 11.8 M$[m]	Uniform (lower to higher bounds)	[m]Boyd et al. (2020)
MRAD	33 $/person-day[n]	SD of 13$[n]	Normal (Mean = 33$, SD = 13 $)	[n]Health Canada (2021)

Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2024.178022.

Data availability

Authors do not have permission to share health data that was provided by *Institut national de la santé publique du Québec* (INSPQ). Weather data was obtained from Daymet of the NASA. Climate data was obtained from Ouranos using the Power Analytics and Visualization for Climate Science (PAVICS) platform. PAVICS is funded through Ouranos, the Computer Research Institute of Montreal, Environment and Climate Change Canada, CANARIE, the Fonds Vert, the Fonds d'électrification et de changements climatiques, the Canadian Foundation for Innovation and the Fonds de Recherche du Québec. Demographic data was obtained from the *Ministère de la Santé et des Services Sociaux du Québec* (MSSS) for the historical period and from Statistics Canada for the projected period. Economic metrics were all publicly available from the Canadian Institute for Health Information (CIHI), MSSS, *Institut de la Statistique du Québec* (ISQ), Statistics Canada or previously published literature. The codes to reproduce the analyses are available on the first author's Github page: https://github.com/jeremieboudreault/paper_heat_health_costs_qc.

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