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PII: S0013-9351(24)01252-0
DOI: https://doi.org/10.1016/j.envres.2024.119347
Reference: YENRS 119347

To appear in: *Environmental Research*

Received Date: 27 February 2024
Revised Date: 30 May 2024
Accepted Date: 4 June 2024

Please cite this article as: Boudreault, J., Lavigne, É., Campagna, C., Chebana, F., Estimating the heat-related mortality and morbidity burden in the province of Quebec, Canada, *Environmental Research*, https://doi.org/10.1016/j.envres.2024.119347.

Estimating the heat-related mortality and morbidity burden in the province of Quebec, Canada

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Revised manuscript submitted to *Environmental Research.*

May 30, 2024

Abstract

Background: As climate change increases the frequency and intensity of extreme heat events, there is an urgent need to quantify the heat-related health burden. However, most past studies have focussed on a single health outcome (mainly mortality) or on specific heatwaves, thus providing limited knowledge of the total pressure heat exerts on health services.

Objectives: This study aims to quantify the heat-related mortality and morbidity burden for five different health outcomes including all-cause mortality, hospitalizations, emergency department (ED) visits, ambulance transports and calls to a health hotline, using the province of Quebec (Canada) as a case study.

Methods: A two-step statistical analysis was employed to estimate regional heat-health relationships using Distributed Lag Non-Linear Models (DLNM) and pooled estimates using a multivariate meta-regression. Heat burden was quantified by attributable fraction (AF) and attributable number (AN) for two temperature ranges: total heat (above the minimum mortality/morbidity temperature) and extreme heat (above the 95th percentile of temperature).

Results: Higher temperatures were associated with greater risk ratios for all the health outcomes studied, but at different levels. Significant AF ranging from 2–3% for the total heat effect and 0.4–1.0% for extreme heat effect were found for all health outcomes, except for hospitalizations that had an AF of 0.1% for both heat exposures. The estimated burden of all heat (and extreme heat) every summer across the province was 470 (200) deaths, 225

(170) hospitalizations, 36 000 (6 200) ED visits, 7 200 (1 500) ambulance transports and 15 000 (3 300) calls to a health hotline, all figures significant.

Discussion: This new knowledge on the total heat load will help public health authorities to target appropriate actions to reduce its burden now and in the future. The proposed state-of-the-art framework can easily be applied to other regions also experiencing the adverse effects of extreme heat.

Keywords : hot temperature, extreme heat events, health outcomes, distributed lag non-linear model, multivariate meta-regression, attributable fraction.

1. Introduction

It is well established that elevated ambient temperatures (i.e., heat) exacerbate health conditions, leading to increased mortality and morbidity (Basu, 2009; Campbell et al., 2018; Kovats & Hajat, 2008; Song et al., 2017). These heat-related health effects can translate into massive costs borne by the healthcare system and society in general (Callahan & Mankin, 2022; Wondmagegn et al., 2019). Because of climate change and population ageing, these impacts will become even more devastating in the future (Curtis et al., 2017; Huang et al., 2011; 2013). Therefore, there is an urgent need to understand and quantify the current heat load on health to reduce its effects now and in the future.

In the recent years, the quantification of the heat burden became increasingly important (e.g., Ballester et al., 2023; Burkart et al., 2021; Gasparrini et al., 2015; Vicedo-Cabrera et al., 2021; Zhao et al., 2021). However, previous studies on temperature-related health burden have focussed mainly on mortality, as recently reviewed by Cheng et al. (2019). The same emphasis on mortality has also been observed more generally in the heat-health literature (Campbell et al., 2018; Cole et al., 2023). Although heat-related mortality is a major concern, the burden on the healthcare system should also be measured in terms of morbidity indicators such as hospitalizations, emergency department (ED) visits and ambulance transports (Wondmagegn et al., 2019), among others. While studies estimating morbidity-health relationships exist (see Li et al. (2015) and Ye et al. (2012) for reviews), a more limited number of studies have taken a step further and quantified the morbidity burden associated with heat (e.g., Bai et al., 2016, 2018; Cheng et al., 2016; Lin et al., 2012; Liu et al., 2019; Wellenius et al., 2017; Wondmagegn, 2021a, 2021b; and Cheng et al. (2019) for a review). Finally, most of the aforementioned studies were limited to a single health outcome (i.e., either mortality or one morbidity variable), thus providing a limited portrait of the overall heat burden.

In addition, past research on the heat burden has sometimes focussed on specific episodes of extreme heat such as “official” heatwaves defined by public health authorities (e.g., Adélaïde et al., 2021; Bustinza et al., 2013; Fouillet et al., 2006; Knowlton et al., 2009; Limaye et al., 2019) or on the additional heatwave effect above average temperatures (e.g., Guo et al., 2018; Yin et al., 2018). While these studies are important, they only cover part of the total heat load. Indeed, heat can have adverse effects at temperatures below heatwave thresholds, as well as on singular days of hot temperature (i.e., non-consecutive) (Campbell et al., 2018; Song et al., 2017). Moreover, there exists many different definitions of heatwaves (e.g., using different temperature thresholds, single or multiple day average, etc.), in addition to the “official” heatwaves, that can all lead to diverging results when quantifying the heat burden (e.g., Cheng et al., 2018; Kanti et al., 2022; Kent et al., 2014; Xu et al., 2016).

In this study, a detailed analysis of the total heat burden of 5 health outcomes, including both mortality and morbidity (i.e., hospitalizations, ED visits, ambulance transports and calls to a health hotline) was performed, using the province of Quebec (Canada) as a case study. Heat-health exposure-response functions were developed using Distributed Lag Non-Linear Models (DLNM) and multivariate meta-regressions. They were then used to compute attributable fractions and numbers to both total and extreme heat. This study provides, for one of the first time, a comprehensive portrait of the overall heat burden on various mortality and morbidity indicators using a unified and state-of-the-art methodology.

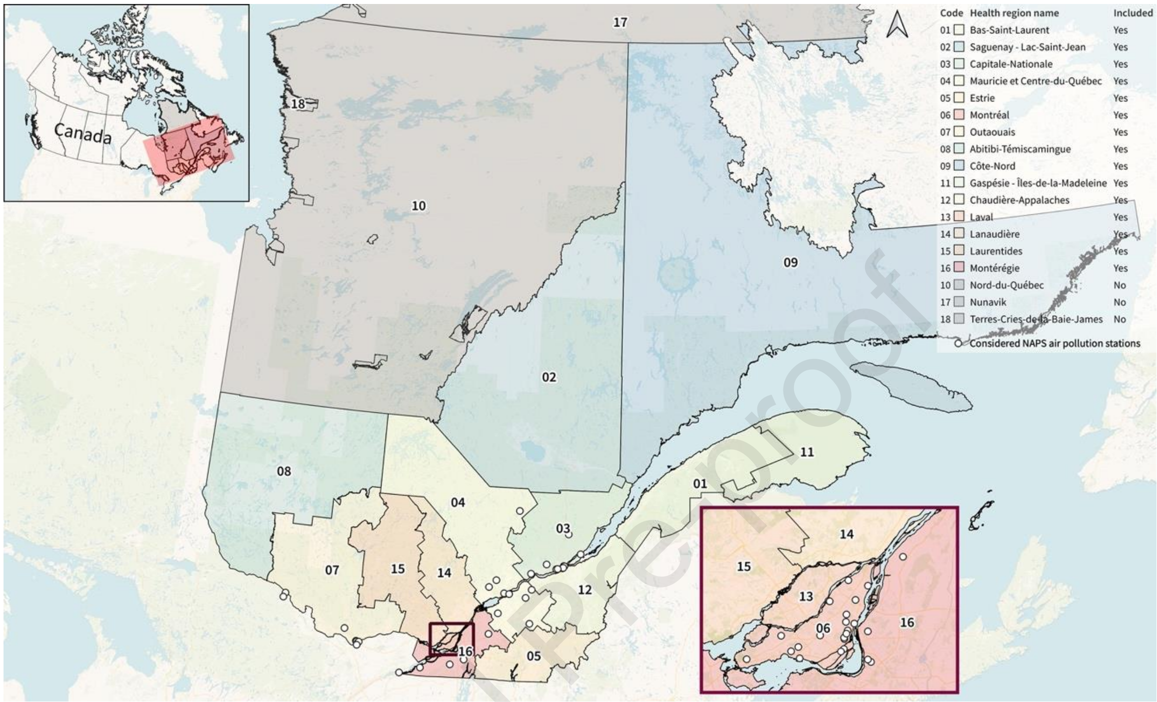
2. Material and methods

2.1. Study design and health outcomes

A time series ecological study in the 15 southernmost health regions (HR) in the province of Quebec, Canada, was performed (Fig. 1). Quebec has a population of approximately 8.5M inhabitants and is the second most populous province of Canada, with 23% of the Canadian population. Given the diversity of socioeconomic and climate conditions across its HR, Quebec is a good candidate for this study. In addition, Quebec's health data was readily available for multiple health outcomes, which was not systematically the case for the other provinces of Canada. Finally, most heat burden studies performed in Quebec have focussed on heatwaves only (e.g., Bustinza et al., 2013; Lebel et al., 2017, 2019). This project received ethics approval from the Human Research Ethics Committee of the National Institute of Scientific Research (CER-22-693).

The HR spatial resolution was chosen because of its relevance for decision makers (i.e., each HR has its own public health team and director). Also, it represents a finer resolution of previously developed "climate regions" for heat-health studies in Quebec, that are combinations of multiple HR (e.g., Chebana et al., 2013; Tupinier Martin et al., 2024). As in previous studies, the northernmost HR #10, #17 and #18 were excluded due to their low population (i.e., <1% of Quebec population) and their colder climate. Associations between daily mortality or morbidity and ambient temperature in each HR during the months of May to September were evaluated.

Fig. 1. Map of the studied health regions (HR) in the province of Quebec (Canada) and location of the considered air pollution stations of the National Air Pollution Surveillance (NAPS) program. HR #10, #17 and #18 were excluded from the present study.



Health data was made available by the *Institut national de santé publique du Québec* (INSPQ) at the HR level, based on 2021 administrative boundaries for all years of data. Studied health outcomes were the daily cases of all-cause: 1) mortality, 2) hospitalizations, 3) ED visits, 4) ambulance transports and 5) *Info-Santé* 811 calls (a free hotline service for non-urgent health issues). All-cause indicators were selected instead of cause-specific (e.g., cardiovascular diseases) as they are more readily available indicators tracked by public health authorities in Québec through the health surveillance system of extreme weather events called *SUPREME* (Toutant et al., 2011), although they may include some non-heat-related conditions. Mortality and hospitalization data were available from 1996, ED visits and ambulance transports from 2014 and 811 calls from 2008. All health outcomes were considered until 2019, prior to the COVID-19 pandemic.

2.2. Weather, air pollution and regional data

Daily maximum and minimum temperature and water vapour pressure data at 1 km × 1 km over North America were extracted from NASA's Daymet database for the 1996–2019 period (Thornton et al., 2022). Mean temperature was computed from the average of daily maximum and minimum temperatures. Relative humidity, dew point and humidex were computed from vapour pressure and mean temperature using *MetPy* in Python (May et al., 2022). Humidex is a well-known index of perceived temperature, derived from temperature and dew point, widely used for heat surveillance in Canada (Smoyer-Tomic & Rainham, 2001). Pixel values of weather data were aggregated at the HR level by weighting each pixel with the number of units located in each pixel using the *AQgéobâti* database (Adresses Québec, 2023), resulting in population-weighted weather times series for each HR. AQgéobâti provides the geocoded information of each residential address in Quebec, along with the number of units (e.g., single-family home = 1 unit, duplex = 2 units, etc.). The number of units was used as a proxy for the population, as population data at the address level was not available.

Hourly air pollution data was extracted at the stations of the National Air Pollution Surveillance (NAPS) program of Environment and Climate Change Canada (ECCC). All stations in the province of Quebec were included, in addition to those within 10 km of Quebec's border to supplement the database (e.g., Ottawa stations, located ~5 km from HR #7, were considered to be within this HR). NAPS hourly data was aggregated to daily mean values. Then, a spatial aggregation of daily data from all stations within the HR boundaries was performed to get a unique time series of air pollutants for each HR, as commonly done in similar studies (Boudreault et al., 2024; Lavigne et al., 2023; Masselot et al., 2019).

Resulting air pollution time series were complete (with less than 2% of daily missing values) for ozone concentration (O_3) in HR #3, #4, #6, #7 and #16 from 1996 to 2019 and particulate matter ($PM_{2.5}$) for the 5 same HR, but only from 2003 to 2019. There were approximately 5 to 15 stations used for the spatial aggregation in each of these five HR with complete O_3 and $PM_{2.5}$ data (Figure 1). Other air pollutants (PM_{10}, NO_2, SO_2 and CO) were not available in sufficient regions/years to be included. Remaining missing values in O_3 and $PM_{2.5}$ time series in these 5 HR were linearly interpolated. While including air pollution as a confounding effect in heat-mortality relationships is debatable (Buckley et al., 2014; Reid et al., 2012), its inclusion was considered as a sensitivity analysis to see if the heat-health relationships change when air pollution is added in the models (e.g., Gasparrini et al., 2015; Guo et al., 2014).

HR-level information was considered to explain the heterogeneity that can exist across regions in the multivariate meta-regression (presented in section 2.3), including the percentage of elderly population (65+), the percentage of women, the material and social deprivation index (MSDI), the natural logarithm of population density, the normalized difference vegetation index (NDVI) and the historical summer temperature (Lavigne et al., 2023; Wang et al., 2021). Demographic data was provided by the *Ministère de la Santé et des Services Sociaux* (MSSS) du Québec from 1996 to 2019 (MSSS, 2022). The MSDI for its social and material components was available every census year (1996, 2001, 2006, 2011, 2016 and 2021) from INSPQ (INSPQ, 2024). NDVI values during the hottest summer day without cloud interference in each region (i.e., varying spatially) were computed from 2013 Landsat-8 data by the *Centre d'enseignement et de recherche en foresterie de Sainte-Foy* and provided by INSPQ (CERFO, 2022) and provided by INSPQ.

A single year of NDVI value (i.e., 2013) was used for the whole study period, shown to be equivalent than using multiple yearly values in such studies (Pascal et al., 2021). Finally, historical temperature from the past 20 years during summer (May to September) by HR was computed from Daymet mean temperature values.

2.3. Statistical analysis

A two-stage statistical analysis was performed. First, a quasi-Poisson model was fitted in each HR to assess the association between daily fluctuations in temperature and daily mortality or morbidity. The Distributed Lag Non-Linear Model (DLNM) was employed to account for both the non-linear relationship between mean temperature and the health outcome, as well as the delayed (lagged) temperature effect (Armstrong, 2006; Gasparrini et al., 2010). Models were fitted with a lag period of 8 days (i.e., lag 0 to lag 7) before the observed mortality or morbidity (Boudreault et al., 2023; Wang et al., 2021), using a natural cubic spline with 2 knots placed on the log scale from 0 to 7 days. The non-linear heat-health association was accounted by using a natural spline with two internal knots placed at the 50th and 90th percentiles of each HR's temperature distribution (Vicedo-Cabrera et al., 2021). Day of week and holidays were considered as factors in the model. Seasonal and long-term trends were also adjusted with a natural spline of day of year with 4 degrees of freedom by year and a factor variable for each year (Vicedo-Cabrera et al., 2021). Daily relative humidity up to 7 days prior to the observed mortality/morbidity was also controlled with a linear effect.

Second, the region-specific estimates obtained from the first step were pooled using multivariate meta-regression models (Gasparrini & Armstrong, 2013; Sera et al., 2019).

This pooling procedure allowed to decrease uncertainty around region-specific heat-health associations by deriving Best Linear Unbiased Predictions (BLUP). In this study, the Risk Ratio (RR) of heat-related health outcomes were reported to the Minimum Mortality/Morbidity Temperature (MMT), the temperature at which the lowest health effect is observed. This was done by scanning temperature values from the 25th and 98th percentiles of temperatures in each HR (Vicedo-Cabrera et al., 2021), excluding potentially colder temperatures from the MMT value (i.e., if the function is decreasing for colder temperature, the MMT will refer to the 25th percentile of temperature). Sensitivity analyses were performed to validate the obtained MMT values (see last paragraph of this section).

Meta-regression was fitted with a forward stepwise approach using health region information. Briefly, the meta-regression was first fitted with no predictors. Then, each of the regional predictors (described in section 2.2) was tested in the model, but only the predictor minimizing the Akaike Information Criteria (AIC) was added to the model. This process was repeated until the AIC did not decrease anymore. Heterogeneity in the meta-regression was assessed using the I^2 statistic and Cochran's Q-test (Lavigne et al., 2023). All analyses were performed using the R software (version 4.3.0) with the packages *dlnm* and *mixmeta*.

Apart from the main analysis, supplementary analyses included: 1- changing the definition of summer season to the three hottest months of summer (June–August) instead of May–September; 2- considering the 5th or the 10th percentile of temperature as the lower bound for searching the MMT value (instead of the 25th percentile); 3- changing the temperature exposure variable to minimum temperature, maximum temperature, mean humidex and mean dew point, as recommended for temperature-related burden studies (Cheng et al., 2019); and 4- adding controls for daily mean concentration of O_3 and $PM_{2.5}$ (up to 7 days prior to observed mortality/morbidity) in regional estimates for which air pollution data was available for potential changes in the obtained heat-health relationships.

2.4. Heat burden quantification

To quantify the heat burden, attributable fraction (AF) and attributable number (AN) were computed using the BLUP of the reduced exposure-response functions obtained from meta-regression for each HR (Gasparrini et al., 2015; Vicedo-Cabrera et al., 2021). AF was computed from $AF_t = (RR_t - 1)/RR_t$, where RR_t is the risk ratio at a given temperature value *t*. AN was computed from $AN_t = AF_t \times n_t$, where n_t is the mortality/morbidity count at temperature *t* (Steenland & Armstrong, 2006). AF_t and AN_t for all temperature values were aggregated across the desired heat range (e.g., all heat or extreme heat only). To account for the uncertainty in the BLUP, 95% confidence intervals (CI) of AF/AN were derived from 1000 simulations of AN/AF computed by sampling the coefficients of the exposure-response curve, assuming a multivariate normal distribution (Vicedo-Cabreba et al., 2021). Two temperature ranges were considered to quantify the heat burden: 1) *all heat*, which refers to all the temperature effect above the MMT, and 2) *extreme heat*, which refers to the effect of extremely hot temperature only, defined as the temperatures above the 95th percentile of the summer temperature distribution by HR during the 1996–2019 period (Liu et al., 2019; Tupinier Martin et al., 2024; Wang et al., 2021).

To supplement results obtained using the regional BLUP, two other attribution methods were also considered. First, the complete bidimensional functions from regional DLNM were also used (referred to as the "*regional DLNM*" method). The *attrdl* function described in Gasparrini & Leone (2014) was employed and, again, 95% CI were computed from 1000 simulations of the coefficients. Second, the pooled cumulative exposure-response function over the whole province (i.e., all HR) obtained from the meta-regression was also used (referred to as the "*pooled estimate*" method). The AF/AN computation from the pooled estimate (and its uncertainty) was similar as the one described above for the regional BLUP.

3. Results

Descriptive statistics of health outcomes, weather and air pollution data are first presented (section 3.1). Then, results of the regional and pooled exposure-response curves are shown (section 3.2). Finally, the heat-related health burden is presented for the whole province of Quebec (section 3.3), as well as its temporal and spatial variability (section 3.4).

3.1. Descriptive statistics

During May to September, there were every year approximately 23k deaths, 263k hospitalizations, 1.5M ED visits, 265k ambulance transports and 662k calls to the 811-health hotline in the province of Quebec (Table 1). HR #6 (Montréal), #16 (Montérégie) and #3 (Capitale nationale) had the highest observed health outcomes during the study period, with respectively 20–26%, 13–16% and 8–11% of the grand total across the province. HR #8 (Abitibi-Témiscamingue), #9 (Côte-Nord) and #11 (Gaspésie — Îles-de-la-Madeleine) were the HR with the fewest cases of health outcomes (i.e., <3%). Indeed, these more rural HR had less population and hence, experienced less of the total mortality and morbidity. Information about socio-economic variables by HR (i.e., regional information) can be found in Table S1.

Table 1. Descriptive statistics of the studied health outcomes for each health region (HR) and the total for the province of Quebec. All values are the total count during May to September period, averaged across all available years of data. The percentage in parentheses is the proportion over the total for the whole province. ED = Emergency department.

HR	Mortality	Hospitalizations	ED visits	Amb. transports	811 calls
1	735 (3.2%)	8 264 (3.1%)	60 782 (3.9%)	7 580 (2.9%)	16 523 (2.5%)
2	883 (3.9%)	11 887 (4.5%)	73 260 (4.7%)	9 133 (3.4%)	26 460 (4%)
3	2 110 (9.3%)	22 104 (8.4%)	162 564 (10.5%)	26 359 (9.9%)	60 008 (9.1%)
4	1 673 (7.4%)	18 517 (7.1%)	110 657 (7.2%)	18 581 (7%)	51 836 (7.8%)
5	1 320 (5.8%)	16 188 (6.2%)	94 105 (6.1%)	15 023 (5.7%)	45 488 (6.9%)
6	5 871 (25.9%)	59 807 (22.8%)	312 656 (20.2%)	68 247 (25.7%)	144 264 (21.8%)
7	938 (4.1%)	9 139 (3.5%)	71 055 (4.6%)	10 505 (4%)	34 328 (5.2%)
8	380 (1.7%)	5 066 (1.9%)	45 297 (2.9%)	3 142 (1.2%)	10 080 (1.5%)
9	275 (1.2%)	4 545 (1.7%)	47 447 (3.1%)	3 247 (1.2%)	6 147 (0.9%)
11	334 (1.5%)	4 482 (1.7%)	45 051 (2.9%)	3 948 (1.5%)	5 955 (0.9%)
12	1 236 (5.4%)	15 089 (5.7%)	110 144 (7.1%)	13 158 (5%)	32 986 (5%)
13	994 (4.4%)	12 332 (4.7%)	53 714 (3.5%)	12 381 (4.7%)	33 709 (5.1%)
14	1 157 (5.1%)	14 931 (5.7%)	71 666 (4.6%)	15 211 (5.7%)	42 677 (6.4%)
15	1 426 (6.3%)	18 542 (7.1%)	90 935 (5.9%)	16 962 (6.4%)	47 059 (7.1%)
16	3 352 (14.8%)	41 665 (15.9%)	197 621 (12.8%)	41 987 (15.8%)	104 448 (15.8%)
Total	22 684	262 558	1 546 954	265 464	661 968

Mean temperature values during summer were higher in southernmost HR #6 (Montréal), #13 (Laval) and #16 (Montérégie) with a mean value during summer of ~18ºC, while northernmost HR #1 (Saguenay-Lac-Saint-Jean), #9 (Côte-Nord) and #11 (Gaspésie — Îles-de-la-Madeleine) were colder with mean summer temperature below 14ºC (Table 2). Generally, maximum temperature was 4–6ºC higher than mean temperature, while minimum temperature and mean dew point were 4–6ºC lower. Mean humidex was approximately 5–6 units higher than mean temperature. Its standard deviation of 7–8 units was higher than for other temperature metrics that had a standard deviation of 4–5ºC. Mean relative humidity during summer ranged from 65% to 75% (with a standard deviation of approximately 10%) for all HR. Finally, mean daily O_3 and $PM_{2.5}$ concentration during summer (in HR where air pollution data was available) ranged respectively from 22 to 27 ppb and from 6 to 9 μg/m^3.

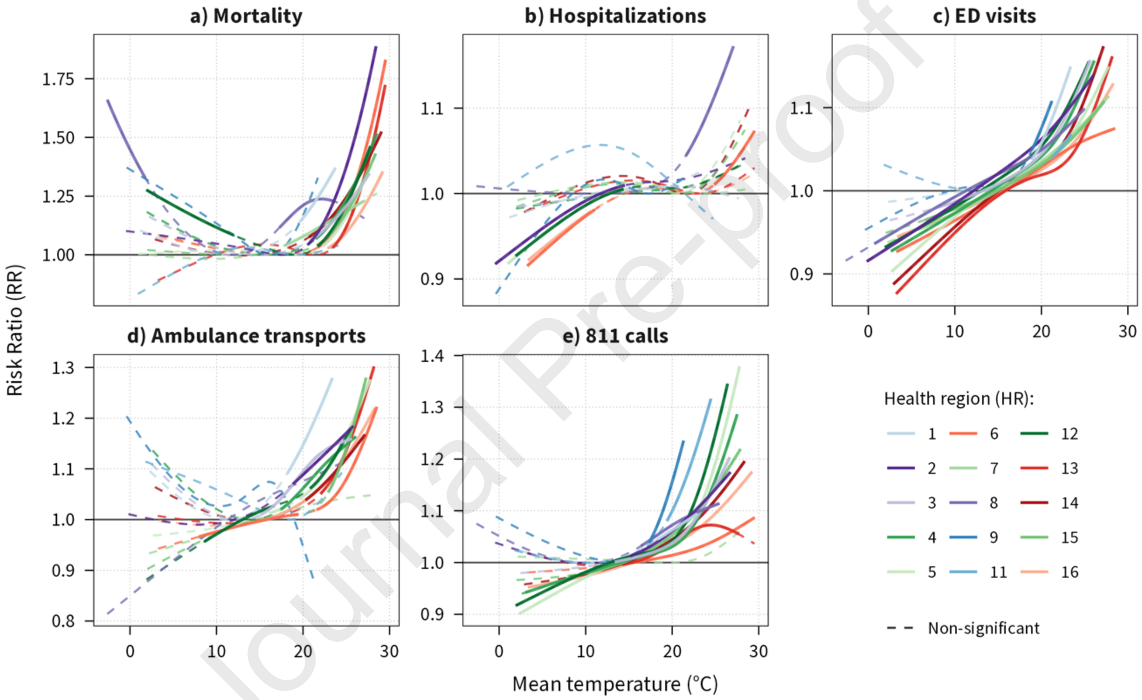
Table 2. Descriptive statistics of weather and air pollution variables for each health region (HR). All values are the mean daily values during May to September from 1996 to 2019, except for $PM_{2.5}$ that was only available from 2003 to 2019. O_3 and $PM_{2.5}$ were only available for five HR. Standard deviation is indicated in parentheses.

HR	**Tmean** ºC	**Tmin** ºC	**Tmax** ºC	**Dew point** ºC	**Humidex**	**Rel. Hum.** %	**Mean O_3** ppb	**Mean $PM_{2.5}$** μg/m^3
1	13.8 (4.2)	8.6 (4.0)	18.9 (4.9)	8.5 (4.1)	18.0 (7.0)	71.0 (8.2)	-	-
2	14.8 (4.7)	8.9 (4.9)	20.8 (5.5)	8.5 (5.2)	19.2 (7.9)	66.6 (11.4)	-	-
3	16.0 (4.5)	10.4 (4.7)	21.6 (5.2)	10.3 (4.7)	21.5 (7.6)	69.4 (9.8)	22.4 (7.8)	7.7 (4.8)
4	16.7 (4.5)	11.1 (4.8)	22.4 (5.0)	10.9 (5.0)	22.7 (7.7)	69.1 (9.7)	25.1 (8.4)	7.8 (5.0)
5	16.6 (4.6)	10.9 (4.9)	22.4 (5.0)	10.8 (5.0)	22.5 (7.8)	68.9 (9.5)	-	-
6	18.2 (4.6)	12.9 (4.7)	23.5 (5.0)	12.7 (4.7)	25.4 (7.7)	70.9 (8.7)	23.6 (8.9)	9.0 (5.5)
7	17.3 (4.6)	11.3 (4.9)	23.4 (5.2)	11.0 (5.1)	23.4 (7.7)	67.3 (10.7)	25.5 (9.2)	6.2 (4.6)
8	14.3 (5.1)	8.0 (5.2)	20.6 (5.8)	7.4 (5.7)	18.0 (8.4)	64.4 (12.0)	-	-
9	12.3 (4.1)	7.7 (4.1)	16.9 (4.5)	7.6 (4.1)	15.9 (7.0)	73.6 (7.8)	-	-
11	13.8 (4.5)	9.1 (4.5)	18.4 (5.0)	9.1 (4.5)	18.4 (7.7)	73.6 (7.9)	-	-
12	15.8 (4.6)	10.0 (4.8)	21.6 (5.2)	10.0 (4.9)	21.1 (7.7)	68.8 (9.9)	-	-
13	18.2 (4.6)	12.9 (4.7)	23.5 (5.0)	12.7 (4.8)	25.4 (7.7)	70.9 (8.9)	-	-
14	17.4 (4.6)	11.7 (4.8)	23.2 (5.1)	11.5 (4.9)	23.8 (7.7)	69.0 (9.8)	-	-
15	17.1 (4.6)	11.3 (4.9)	22.9 (5.1)	11.2 (4.9)	23.3 (7.7)	68.9 (9.7)	-	-
16	18.1 (4.5)	12.5 (4.7)	23.6 (5.0)	12.4 (4.8)	25.0 (7.7)	69.9 (9.2)	26.7 (9.1)	7.8 (5.0)

3.2. Regional and pooled cumulative exposure-response curves

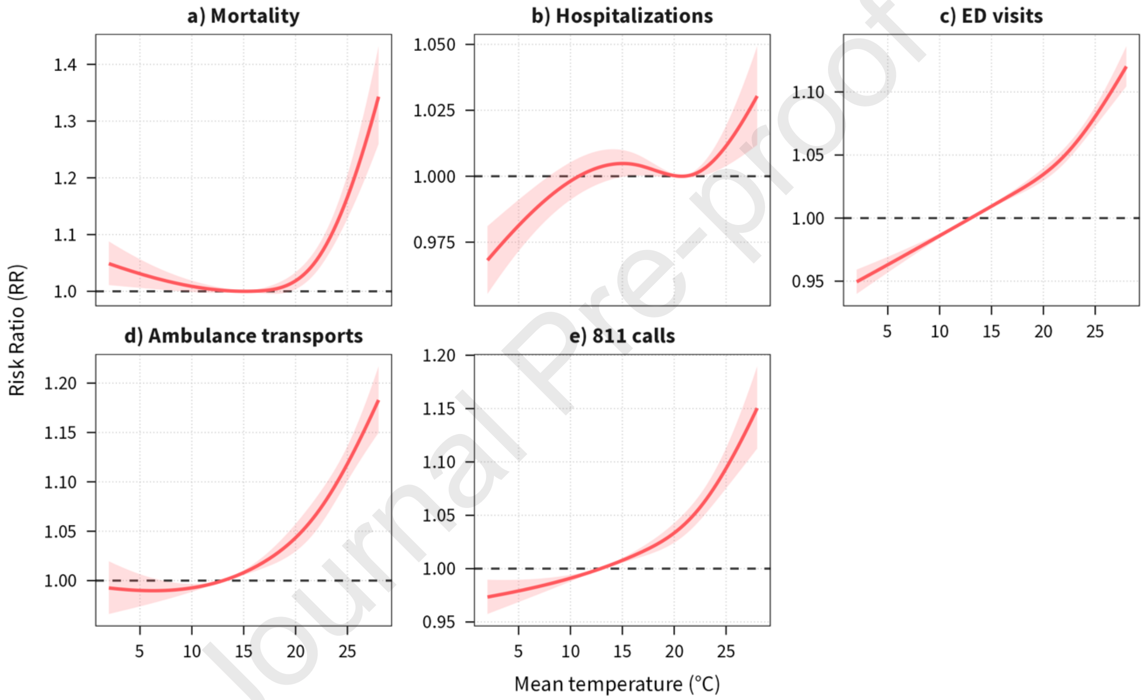
Estimated cumulative exposure-response curves over 8 days from DLNM for the 15 HR and 5 health outcomes are presented in Fig. 2. Overall, all health outcomes appeared to increase with higher temperatures, but there was considerable variability between HR and across the different health outcomes. Notably, curves in light blue (i.e., HR #11) were the most variables with generally a different shape than the others. An important point is that some of these relationships were not significant for some parts of the curves (as noted with dashed lines on the figure), particularly for hospitalizations.

Fig. 2. Cumulative exposure-response functions over 8 days in each health region (HR) from regional DLNM for a) mortality, b) hospitalizations, c) ED visits, d) ambulance transports and e) 811 calls. Dashed lines indicate non-significant parts of the curves, while solid lines indicate significant parts. Colours are set according to climate classification from red (warmer HRs) to green to purple to blue (colder HRs).



These regional estimates from DLNM were then combined in a multivariate meta-regression model using regional information, resulting in BLUP for each HR (Fig. S1) and pooled cumulative exposure-response curves for the whole province of Quebec (Fig. 3). Mortality exhibited a U-shaped relationship, with an MMT at around 15ºC. The exposure-response curve for hospitalizations had a wiggly shape (~), with a potential protective effect below 7ºC. However, a significant increase in hospitalizations was noted after 22ºC. ED visits, ambulance transports and 811 calls increased consistently with higher temperatures, with different inflection points. The MMT for these three health outcomes was thus assigned to ~13ºC (i.e., corresponding the 25th percentile of the summer temperature distribution, recall section 2.3).

Fig. 3. Pooled cumulative exposure-response functions over 8 days in the province of Quebec for a) mortality, b) hospitalizations, c) ED visits, d) ambulance transports and e) 811 calls. Light red region indicates the 95% confidence interval in the risk ratio.



As seen on Fig. 2, there was some heterogeneity in the regional curves to develop these pooled effects, but also when looking at Q-Cochran test and I^2 statistics (Table S2). For example, the Q-Cochran test was only significant for 811 calls, while the I^2 statistic was <5% for hospitalizations, ED visits and ambulance transports. Thus, results from meta-regression should be interpreted with caution, especially for these three health outcomes. In addition, it was found that for all health outcomes, none of the meta-predictors significantly minimized the overall AIC in the meta-regression (Table S2). Hence, none of the meta-predictors was included in the model.

Supplementary analyses for the pooled exposure-response curves showed that considering summer to span only from June to August led to similar trends at high temperatures (Fig. S2). For most of the studied health outcomes, the effect of colder temperature had wider CI. MMT values were consistent for mortality and hospitalizations, but slightly higher (i.e., ~5ºC higher) for the other health outcomes (e.g., ED visits, ambulance transports and 811 calls) when using only June to August data. When testing lower percentiles for searching the MMT value (i.e., 5th and 10th), lower MMT values (i.e., ~5ºC lower) were found for all health outcomes, except for mortality (Fig. S3). Exposure-response curves with other temperature metrics showed similar shapes than when using mean temperature (Fig. S4). Finally, adjusting models for O_3 and $PM_{2.5}$ (in HR for which air pollution data was available) did not change the shape of the pooled cumulative curve for most health outcomes, only slightly for hospitalizations when both O_3 and $PM_{2.5}$ were controlled for (Fig. S5).

3.3. Heat burden in the province of Quebec

AF and AN for all health outcomes derived from regional BLUP were computed across the whole province (Table 3). Supplementary analyses (e.g., with other temperature metrics, air pollution controls, etc.) were not pursued in this section as pooled exposure-response curves presented in section 3.2 did not differ significantly in these analyses. Approximately 2–3% of summer mortality, ED visits, ambulance transports and 811 calls were attributable to heat, but only 0.1% for hospitalization. Less than 1% of each health outcome was attributable to extreme heat (i.e., temperatures above the 95th percentile). AF/AN to heat and extreme heat were all statistically significant. In terms of AN, 471 and 203 deaths every summer were attributable respectively to all heat and extreme heat exposures, 226 and 170 hospitalizations, 36 273 and 6 228 ED visits, 7 177 and 1 517 ambulance transports, and 15 058 and 3 3306 calls to the 811-health hotline (Table 3). Differences between all heat and extreme heat exposures were greater for ED visits, ambulance transport and 811 calls (with factors of 4X–6X for all heat *vs.* extreme heat), while for deaths and hospitalizations, the difference was much smaller (1.5X–2.5X).

Table 3. Attributable number (AN) and fraction (AF) in the province of Quebec computed from regional BLUP for all heat and extreme heat exposures. AN are presented as the yearly number of cases every summer across the studied period. ED = Emergency department.

	All heat		**Extreme heat**	
	AN	**AF**	**AN**	**AF**
Mortality	471 (251 – 693)	2.1% (1.1–3.1)	203 (138 – 267)	0.9% (0.6–1.2)
Hospitalizations	226 (138 – 318)	0.1% (0.1–0.1)	170 (118 – 226)	0.1% (0.0–0.1)
ED visits	36 273 (32 328 – 40 060)	2.3% (2.1–2.6)	6 228 (5 589 – 6 870)	0.4% (0.4–0.4)
Ambulance transports	7 177 (4 594 – 9 592)	2.7% (1.7–3.6)	1 517 (1 326 – 1 700)	0.6% (0.5–0.6)
811 calls	15 058 (9 270 – 20 990)	2.3% (1.4–3.2)	3 306 (2 413 – 4 206)	0.5% (0.4–0.6)

Comparison of results using regional DLNM, regional BLUP and pooled estimates generally showed consistent values (within the same CI) for AN (Fig S6a) and AF (Fig S7a) for the total heat exposure. However, higher AN/AF for hospitalizations were found when using regional DLNM, but these values were not statistically significant anymore. For extreme heat exposure, AN (Fig. S6b) and AF (Fig. S7b) from pooled estimates yielded much lower values (1.5-2.0X smaller) than from regional DLNM and BLUP that were consistent. CI were generally wider with regional DLNM than with BLUP, except for mortality and 811 calls. Numerical values of AN/AF computed from the regional DLNM and pooled estimates are available in Table S3.

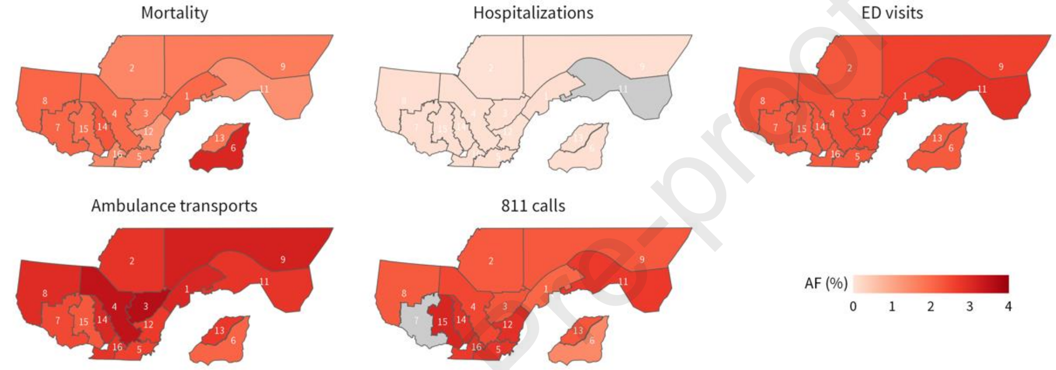
3.4. Temporal and spatial variability of the heat burden

AN were also computed separately for each year of observations (Fig. 4 and Table S4 for numerical results of the last 10 years of data). Years with higher AN were respectively 2001, 2002, 2005, 2010 and 2018. For mortality, almost half the heat related AN was due to extreme heat (i.e., the 5% hottest days). This proportion was even higher for hospitalizations. For all health outcomes (except 811 calls), there were linear increasing trends in AN to total and extreme heat over the studied period. During summer of 2018 (during which all health outcomes data was available), approximately 480 deaths, 400 hospitalizations, 14 000 ED visits, 3 600 ambulance transports and 5 800 calls to the 811-health hotline were attributable to extreme heat (Table S4).

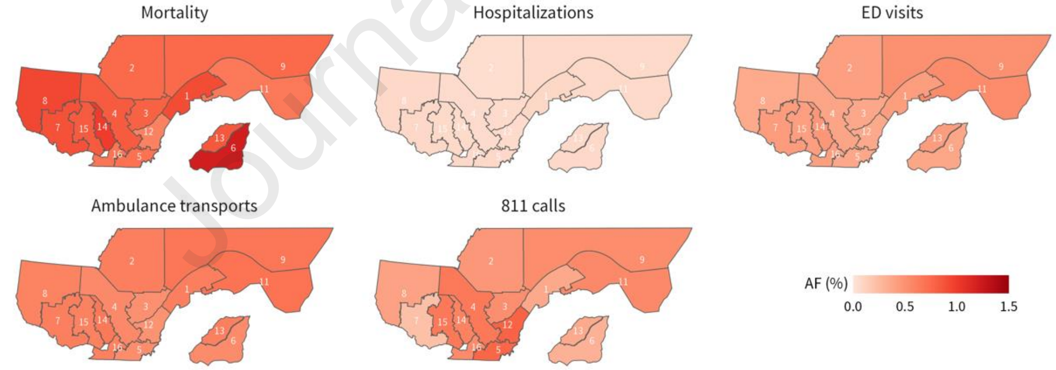
Fig. 4. Attributable numbers (AN) to all heat and extreme heat exposures during 1996–2019 based on regional BLUP across Quebec. Error bars represent the 95% CI. Dotted lines are linear trends over the studied period. Grey regions are years with major heatwaves. Data was not available for 1996–2013 for EDV and AMB, and 1996–2007 for 811 calls. MOR = Mortality. HOS = Hospitalizations. EDV = Emergency department visits. AMB = Ambulance transports. 811 = Health hotline calls.

AF were also computed separately by HR (Fig. 5 and Table S5 for numerical results of AF and AN). Significant AF due to all heat ranged from 1.5–3.0% for mortality, 0.1-0.1% for hospitalizations, 2.0–3.0% for ED visits, 2.0%–3.5% for ambulance transports and 1.5–3.0% for 811 calls (Fig. 5). These AF were all <1.5% when looking only at extreme heat exposure. AF to all heat exposure in HR #11 for hospitalizations and in HR #7 for 811 calls was not significant. The example of the HR with the highest population (Montreal, #6) showed statistically significant AN of 180 (71) deaths, 53 (41) hospitalizations, 6 995 (1 171) ED visits, 1 415 (368) ambulance transports and 2 157 (446) calls to the 811 due to all heat (and extreme heat) every summer in average (Table S5).

Fig. 5. Attributable fraction (AF) in each health region (HR) computed from regional BLUP for a) all heat and b) extreme heat exposures. Non statistically significant AF are in grey. Refer to Table S5 for numeric results of AF (and AN).



a) All heat



b) Extreme heat

4. Discussion

This study considered a two-stage statistical analysis with DLNM and multivariate meta-regression to estimate the heat burden for five health outcomes, including both mortality and morbidity, in the province of Quebec (Canada). While there was some notable variability and heterogeneity in the regional exposure-response functions (recall Fig. 2 and

Table S2), the pooled estimates showed that all studied health outcomes had higher RR at hotter temperatures, but at different levels. ED visits, ambulance transports and 811 calls did not exhibit the classical U- or J-shape relationship as observed with mortality, but rather monotonic increases in RR with higher temperatures. These less familiar relationships highlighted the need to correctly assign the MMT value, which will ultimately affect the calculation of the heat burden. MMT values were slightly higher when focussing on the three hottest months of summer (Fig. S2), but lower when using lower percentiles of temperature (e.g., 5th or 10th) to extract MMT values (Fig. S3). Thus, the reference MMT values used for these three health outcomes should be seen as conservative in our study. Further work is therefore recommended to that end for morbidity variables, as well as explaining the mechanisms between lower temperatures and these health impacts, that was out-of-scope for the current study focussing on heat. For mortality and hospitalizations, MMT values were consistent in the main and supplementary analyses.

Exposure-response functions obtained from BLUP were then used to compute the health burden associated with exposure to all heat (i.e., temperatures above the MMT) and extreme heat (i.e., temperatures above the 95th percentile) for the whole province, across years and regions. Results from BLUP were compared to regional DLNM (without meta-regression adjustment) and pooled estimates across the province. For the total heat exposure, the associated burden had consistent results for the three tested methods, except for hospitalizations when using regional DLNM (i.e., non-significant AN/AF). For extreme heat, both regional methods (BLUP and DLNM) had higher values (1.5-2X) than pooled estimates for the whole province, which could be due to a poorer representation of extreme temperatures in a unique pooled estimate for the whole province compared to regional estimates (recall Fig. S6 and Fig. S7). To the best of our knowledge, this study is one of the first to provide such a detailed portrait of the heat burden at a national scale combining multiple health outcomes, employing a robust and state-of-the-art methodology, as well as testing for different summer definitions, temperature exposures, air pollution adjustments and methods for the heat burden quantification.

In terms of mortality, the burden for the whole province was equivalent to AF of 2.1% of all summer mortality, representing AN of ~470 deaths each summer. When only the 5% hottest days of summer were analyzed, AF and AN were respectively of 0.9% and ~200 deaths. In Montreal (Canada), Benmarhnia et al. (2014) found 62 deaths each summer attributable to heat during June to August months (years 1990–2007), while we found 180 deaths during the May–September period (years 1996–2019) for this location (recall Table S5). In Canada, Hebbern et al. (2023) found AF of 0.41% of annual mortality due to heat during the 2010–2019 period. In the multi-city multi-country study of Gasparrini et al (2015), the AF in Canada was 0.54% for all heat (0.68% in Montreal only) and 0.26% for extreme heat (above the 97.5th percentile), again reported over annual mortality. These last two results are consistent with ours, given that our AF were reported over summer mortality only.

During the heatwaves of 2010 and 2018 in Quebec, public health authorities reported respectively an excess of 280 (Bustinza et al., 2013) and 210 (Lebel et al., 2019) deaths across the province. We found that 462 and 480 deaths were associated to extreme heat during these two years, respectively (recall Fig. 4 and Table S4). In addition, there was almost no significant impact on mortality during 2011–2015 official heatwaves in Quebec

(Lebel et al., 2017), while we have found significant AN due to heat and extreme heat during all those years. These differences are mainly due to the definition of heatwaves used in the aforementioned studies (i.e., three consecutive days above thresholds), whereas extreme heat was defined as all days with temperatures above the 95th percentile in our study. Globally, the review of Cheng et al. (2019) reported that AF to heat were <2.0% for mortality (when only summer months were analyzed), which is consistent with our findings for the province of Quebec (i.e., AF of ~2.0%).

The AF for hospitalizations was found to be 0.1% (to both all heat and extreme heat exposures), representing AN of ~225 hospitalizations to heat and ~170 to extreme heat every summer across the province. In Ontario (Canada), Bai et al. (2016, 2018) found that 1.4% of hypertension, 11.2% of diabetes, 1.2% of coronary heart disease and 1.8% of stroke hospitalizations were due to heat. These AF are much higher than our results, but focussed on specific diseases that are known to be temperature-related (e.g., Liu et al., 2022; Phung et al., 2016). Indeed, focussing on all-cause hospitalizations could dilute the heat-hospitalization relationship, making the heat effect harder to detect. Studying cause-specific morbidity (or mortality) is left for future research. Furthermore, as our AF was computed over all hospitalizations, the obtained value will be lower than if it were calculated only for cause-specific hospitalizations as in Bai et al. (2016, 2018). Around the world, the study of Lin et al. (2012) found that ~100 hospitalizations for respiratory causes were attributable to extreme heat each year in the state of New York (~20M hab.). Wondmagegn et al. (2021a) found that ~500 hospitalizations were attributable to heat every year in Adelaide, an Australian city of ~1.3M inhabitants. Finally, Liu et al. (2019) noted that 0.8% of hospitalizations in the 0–19 age group were related to moderate heat in the

Minneapolis/St. Paul region (USA), while AF for other age groups were not statistically significant.

The heat burden on ED, ambulance services and health hotline was considerable in our study with AN of respectively 36 000, 7 000 and 15 000 cases due to heat every summer in Quebec, representing AF of 2.0–3.0%. During the 2010 heatwave in Quebec, Bustinza et al. (2013) noted an excess of 3 400 ED visits. While no ED data was available in 2010 in our study, we found ~14 000 ED visits associated with extreme heat in 2018, a comparable year to 2010 in terms of heatwave intensity. Kegel et al. (2021) studied the relationship between ED visits and summer temperatures in two hospitals of Montreal (Canada) and found that higher temperatures were associated with a higher number of patients in ED (same as in our study), but they did not report any AF nor AN. There was no other burden quantification study found in the literature for these morbidity variables in Quebec or Canada. Around the world, Wondmagegn et al. (2021b) found that ~290 ED visits were heatwave-related every year in Adelaide while Wellenius et al. (2017) estimated ~7 200 ED visits attributable to heat in 15 locations of New England, USA (2.7 M hab.). Cheng et al. (2016) reported AF of 2.2% for extreme heat-related ambulance transports in the city of Huainan (China) while Li et al. (2021) found AF of 11.7% to high temperatures for ambulance calls in 11 Chinese cities. In its review of temperature-related health burden, Cheng et al. (2019) reported that AF to heat was <1.4% for all-cause morbidity globally (though without differentiating by health outcomes), whereas higher figures were reported in our study (i.e., AF of 2–3% for ED visits, ambulance transports and calls to a health hotline).

Even though the above comparisons are interesting, they should be interpreted with caution, particularly for studies performed in other regions given the differences that exist in population size, demography, climate and health service management, among others (Gasparrini et al., 2015). In addition, in all studies cited above, there is not a single and universal temperature metrics used (e.g., mean, maximum, minimum temperature, heat index, etc.), no consistent definition of the total and extreme heat exposure (e.g., above different MMT values or percentiles such as 90th, 95th or 97.5th) and multiple heatwaves definitions (e.g., intensity, duration, temperature metrics), leading to even greater challenges in comparing the heat-related burden (Cheng et al., 2019). Thus, it highlights the need for more robust and comparable studies using a unified methodology that simultaneously quantify multiple health outcomes, as we have presented in this study and applied to Quebec, Canada.

By examining total and extreme heat exposures on a broader scaler than only during “official” heatwaves as was previously done in Quebec (e.g., Bustinza et al., 2013; Lebel et al., 2017; 2019), a new perspective on the heat load has been provided, which can be used to improve surveillance and protection activities by public health authorities. In addition, the variability of the heat burden between years (temporal) and health regions (spatial) was another insight that was revealed by our study. On the temporal side, years 2001, 2002, 2005, 2010 and 2018 were found to have the greatest health burden (recall Fig 4. and Table S4). The two last years (2010 and 2018) are also the ones during which recent major heatwaves occurred in Quebec. On the spatial side, the variability found in AF across health regions can be associated with different vulnerability factors such as demography, deprivation, built environment and adaptation to heat, among others (recall

Fig 5. and Table S5). These results can therefore help prioritize the most effective actions to reduce the heat burden locally and in a timely manner. However, as meta-regressions did not detect any significant predictors (recall Table S2), future work is therefore recommended to explore the vulnerability factors associated with heat in Quebec at a finer scale, as well as to better understand the heterogeneity that was found between HR across the different studied health outcomes.

Our study has several strengths. First, it used a well-known and state-of-the-art framework combining DLNM and meta-regression to derive the heat-related health burden. Second, 5 health outcomes (including both mortality and morbidity) were included, most of them only seldom studied in Quebec and Canada, but also in the literature more generally. Third, our study was performed for the 15 southernmost health regions of Quebec (i.e., 99% of Quebec's population of 8.5M inhabitants), a geographic scale representing a trade-off between statistical power and relevance for decision makers. Fourth, the computed AF and AN from regional BLUP were consistent compared to estimates from regional DLNM or pooled functions across the province, though some differences were also noted. Finally, supplementary analyses including a shorter definition of summer, different percentiles for the MMT value, four other temperature exposure variables and adjusting for air pollution, showed generally consistent results compared to the main analysis.

Some limitations must also be discussed. First, no stratification by sex/gender, age or cause of disease were performed. Our goal was to quantify the overall heat burden, not to assess the differences in heat-health relationships among population strata. This is left for further research, as well as the study of smaller geographical units that could be more suitable than the HR spatial scale for stratified analysis of some vulnerability factors such as built environment. Second, only 6 years of data was available for ED visits and ambulance transports (2014–2019), while longer time series (>10 years) were available for all other health outcomes. This limited the comparison of our results for ED visits and ambulance transports with the ones observed during the 2010 heatwave in Quebec. Third, the burden was only estimated for all heat (above the MMT) and extreme heat (above the 95th percentile) exposures, without studying, for example, the excess burden during heatwaves or the exposure to cold temperatures. Fourth, daily air pollution data was only fully available in 5 HR for the sensitivity analysis, while the low spatio-temporal resolution of air pollution data in Quebec prevented us from using population-weighted time series (as for weather data) in this analysis. Finally, while results were provided for other temperature exposure metrics, these analyses could be deepened in a future work.

5. Conclusion

By representing a state-of-the-art quantification of the heat burden, this study can serve as a reference for further studies in other parts of the world also experiencing the adverse effect of heat, drawing on the same detailed methodology and a comparable comprehensive database (i.e., several health outcomes in multiple regions combined with various temperature, air pollution and regional variables). Applied to the province of Quebec (Canada), all studied health outcomes had higher risk ratios at hotter temperatures, but at different levels. In terms of burden, heat translated into a massive load on the health system every summer in Quebec, with significant numbers of 470 (200) deaths, 225 (170) hospitalizations, 36 000 (6 200) ED visits, 7 200 (1 500) ambulance transports and 15 000

(3 300) calls to a health hotline due to heat (and extreme heat). Results also revealed a great deal of temporal (across years) and spatial (across health regions) variability. This new information will help public health authorities to target appropriate interventions depending on the health outcome, region and type of heat exposure, to reduce the heat-related health burden now and in the future.

Acknowledgments

The authors would like to thank Denis Hamel and Louis Rochette for their help with the health data extraction, Antoine Saint-Amand, Mathieu Tandonnet and Nathalie Gravel for their help with the spatial data extraction, Félix Lamothe, Magalie Canuel, Ray Bustinza and Annabel Ruf for their comments on this work, and Vaibhavi Mayya for her preliminary work on this project. The authors would also like to thank the editor, the associate editor and three anonymous reviewers for their comments that helped improve this manuscript.

Funding

The first author has received funding from the Natural Sciences and Engineering Research Council of Canada (Vanier Scholarship, #CGV-180821), the Canadian Institute of Health Research (Health System Impact Fellowship, #IF1-184093), Ouranos (Real-Décoste Excellence Scholarship, #RDX-317725) and the National Institute of Public Health of Quebec (no grant number).

Credit authorship contribution statement

Jérémie Boudreault: Conceptualization, Methodology, Data Curation, Formal analysis, Visualization, Software, Writing—Original Draft, Review and Editing, Funding

acquisition. **Éric Lavigne:** Conceptualization, Methodology, Software, Writing—Review and Editing. **Céline Campagna**: Conceptualization, Writing—Review & Editing, Supervision, Project administration, Funding acquisition. **Fateh Chebana**: Conceptualization, Writing—Review & Editing, Supervision, Project administration, Funding acquisition.

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.

Data availability

Authors do not have permission to share health data. Socioenvironmental data are freely available from the following organization: NASA for weather data, Environment and Climate Change Canada (ECCC) for air pollution data, Ministère de la Santé et des Services Sociaux (MSSS) for demographic data and Institut national de la santé publique du Québec (INSPQ) for socio-economic and built environment data. A code example to reproduce the conducted analyses with synthetic health data is available on the first author’s Github page (https://github.com/jeremieboudreault/paper_heat_burden_qc).

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Highlights :

- The heat-related burden of five health outcomes (HO) quantified in Quebec, Canada
- DLNM and meta-regression used to compute attributable fraction (AF) and number (AN)
- All HO showed increased risk ratios at higher temperatures, but at different levels
- AF to heat were 2–3% for all HO except for hospitalizations (0.1%), all significant
- Depending on the HO, AN to heat ranged from 100s to 10 000s each summer in Quebec

Declaration of interests

☒ 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.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: