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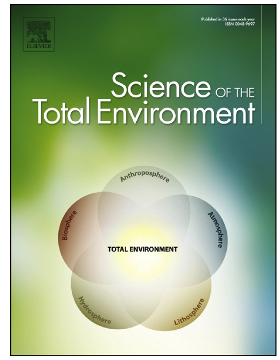

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A cold-health watch and warning system, applied to the province of Quebec (Canada)

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Abstract

Context: A number of studies have shown that cold has an important impact on human health. However, almost no studies focused on cold warning systems to prevent those health effects. For Nordic regions, like the province of Quebec in Canada, winter is long and usually very cold with an observed increase in mortality and hospitalizations throughout the season. However, there is no existing system specifically designed to follow in real-time this mortality increase throughout the season and to alert public health authorities prior to cold waves.

Objective: The aim is to establish a watch and warning system specifically for health impacts of cold, applied to different climatic regions of the province of Quebec.

Methodology: A methodology previously used to establish the health-heat warning system in Quebec is adapted to cold. The approach identifies cold weather indicators and establishes thresholds related to extreme over-mortality or over-hospitalization events in the province of Quebec, Canada.

Results and conclusion: The final health-related thresholds proposed are between (-15 °C, -23 °C) and (-20 °C, -29 °C) according to the climatic region for excesses of mortality, and between (-13 °C, -23 °C) and (-17 °C, -30 °C) for excesses of hospitalization. These results suggest that the system model has a high sensitivity and an acceptable number of false alarms. This could lead to the establishment of a cold-health watch and warning system with valid indicators and thresholds for each climatic region of Quebec. It can be seen as a complementary system to the existing one for heat warnings, in order to help the public health authorities to be well prepared during an extreme cold event.

Keywords: threshold, cold spell, mortality, hospitalization, alert, preparedness.

1. Introduction

Extreme cold events are increasingly investigated because of their serious impacts on human life and health, and have been shown to increase daily mortality and hospitalization [1]–[6]. In particular, in temperate and Nordic regions, mortality is generally higher during winter than the rest of the year [7], [8]. Indeed, for the province of Quebec, Canada, winter is usually very cold and longer than for usual temperate regions. However, unlike the summer season for which health professionals and public health officers can rely on health related heat warning systems in order to prevent excess mortality during heat waves, no such system has been developed in the climatic context of Canadian winters. Therefore, it is of interest to establish a cold-health watch and warning systems (C-HWWS) to mitigate the impacts of extreme cold events on health.

In spite of known impacts of cold on human health, most studies focus on their relationships/associations [1]-[6], while there has been very limited work on C-HWWS. To the best of our knowledge, only a few operational C-HWWS are documented and they are established in England [9] and in the former Yugoslav Republic of Macedonia [10]. However, their methodologies present a number of limitations and drawbacks. First, the methods are based only on mean daily temperature which may not be adapted for extreme events [2]. Furthermore, they do not include the cumulative effect of cold over several days, as the impact of cold can be lagged over long periods of time and remain important [3], [11]–[14]. Finally, they have been established for a temperate climate, which is very different from Nordic regions climate. Thus, it is of interest to create a more adapted C-HWWS taking into account these effects, especially in the context of increased variability of climate linked to climate change, including winter [15], [16].

Unlike C-HWWS, several approaches in the heat wave context are currently available and are used in several countries (e.g. [9], [17]–[24]). Several heat health watch and warning systems (H-HWWS) have already demonstrated their utility and effectiveness in reducing mortality from extreme heat events [25], [26]. In particular, a H-HWWS was established for Quebec in 2010 [17] and continues to be effective in reducing extreme heat-related mortality in the province [27]. The hypothesis behind the present project is that similar public health benefits may ensue from a C-HWWS.

The proposed approach for C-HWWS is inspired by the one used for H-HWWS in [17]. It is adapted for the cold context and improved with recent methodological developments. The main difference between heat and cold is in the magnitude and lags of the relationship with health indicators. For instance, important spikes of mortality are usually observed during some heat waves, which is not the case during cold spells [15], [16]. In addition, mortality and hospitalization response to an exposure to high ambient temperatures is relatively short (a few days), while the effects for cold temperatures are generally much longer [3], [11]–[14], in the order of weeks. Thus, it is more delicate to establish a C-HWWS than a heat-related one.

The C-HWWS is hereby established for four regions, defined from gathering the 18 smaller administrative health regions (*Région Socio-Sanitaires*, denoted RSS). Indeed, the province of Quebec stretches over a large area but has a small population (8.3 M inhabitants in 2018 with a density of 5.5/km^2) with a non-uniform spatial distribution. The weather conditions of each region are very different and the very sparse population in some of them hinders satisfactory statistical analyses. Hence, it is necessary to group RSS into climatically homogeneous classes representing a sufficiently high number of daily events adapted for the analysis.

Finally, the obtained cold system should be implemented in the existing real-time Surveillance and Prevention of the impacts of Extreme Meteorological Events on public health (SUPREME) system in Quebec [28], established by the *Institut national de santé publique de Quebec* (INSPQ) in 2010 for heat warning system. Note that two different types of threshold/indicators are proposed in the present study, corresponding to the two types of health event considered, i.e. over-mortality and over-hospitalization. Due to the large variability in impact level and lag structure between cold effects on mortality and hospitalization [29]–[32], over-mortality and over-hospitalization events do not always occur simultaneously and without the same amplitude. Hence, it is appropriate to attribute different thresholds for different health issues. In addition, having two types of threshold/indicators also allows better anticipation and management of the consequences of cold waves.

In the following, we present the methodology and the main results of its application for the province of Quebec. Additional results can be found in the supplementary materials. These results will help establish a C-HWWS specifically for the cold season in Quebec. Note that even though these thresholds and indicators are determined for Quebec, the methodology is general and can be applied to other Nordic regions or cities.

2. Data and definitions

The data considered are those of 16 RSS of the province of Quebec (Figure 1). Note that RSS17 and RSS18, located north of the 50th parallel, have not been included in the present analysis (as in previous studies, e.g. [17]) because of their low population size. The study period spans the coldest months of the year which are December 1st to March 31st [33] (see Table S1 in supplementary materials) for years 1994 to 2015 in the case of mortality (n = 2667), and years 1995-2014 for hospitalization due to incomplete data (n=2425). Note that the months December to March correspond to the date of the health events. Given the lag period in the definition of the indicators, the weather data for the days preceding December 1st (late November) are included when necessary.

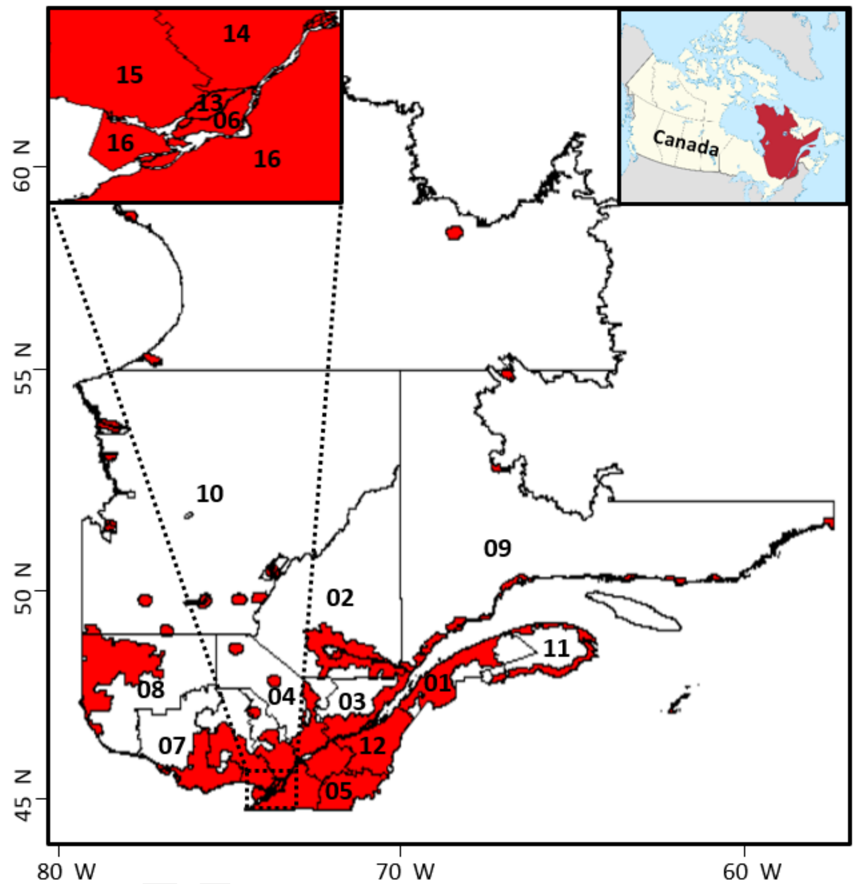

Figure 1: The 16 administrative health regions (RSS) of Quebec located south of the 50th parallel. The red region represents the ecumene areas of the province.

Health data considered in the present study are the daily all-cause mortality and the daily all-cause hospitalization data for each RSSs of Quebec. They were provided by INSPQ. All-cause health data are included to ensure enough cases for proper threshold estimation, since the number of observations is not large enough especially for the mortality, whereas the daily mortality is below 10 persons in several RSSs. Considering the confounding effects on the system of winter-related influenza cases, a sensitivity analyse is carried out after obtaining the final results. The ICD-10 and ICD-9 codes (described in Table S2) were used to eliminate diseases and deaths related to influenza and viral pneumonia in all-cause health data. This code list consist of classified diseases and medical problems, published by the World Health Organization (WHO) [34].

For each meteorological variable, grid points or meteorological stations inside the ecumene zone of each RSS are averaged to obtain a single time series per RSS. The considered variables include daily temperatures (max, min, mean), wind speed (max, min, mean) and vapor pressure. Note that vapor pressure is converted to the more convenient relative humidity through standard formulas [35]. All these data are used for RSS clustering. However, for determining cold indicators and thresholds, only temperature data are used. In the context of climate change, no significant trend in overall winter temperature can be found during the study period (Figure S1). Meteorological data series, except wind speed, are extracted from the *DayMet* database. It corresponds to an interpolated/extrapolated data on a spatial grid with a resolution of 1 km^2 covering most of North-America [36], [37]. The *DayMet* calendar is based on a standard 365-day calendar year where the February 29th is included for leap years, while December 31th is discarded from leap years. Hence, here we considered the same way. For those years, no cold spell were observed on December 31th. Wind speed data is not available in DayMet and is thus extracted from the data provided by meteorological stations maintained by *Environment and Climate Change Canada* (ECCC).

3. Methods

This section presents the methods used for the three main parts of the study. The first part is to cluster Quebec's RSSs into larger groups, the second part is to determine the corresponding indicator and thresholds for each group of RSSs, and the last part is evaluate the potential confounder effects.

3.1 RSS clustering

In order to obtain groups of climatically homogeneous RSSs for the winter period, a hierarchical agglomerative clustering (HAC) is performed on the daily climatic variables of the 16 RSSs of Quebec (temperatures, wind speed and vapor pressure). The HAC method iteratively aggregates the most similar values for a given criterion as described by Saporta [38]. The distance used is the standardized Euclidean distance and the aggregation criterion follows Ward's method [39].

3.2 Threshold and indicator estimation

The second part is to estimate temperature indicators and thresholds for each class of RSSs determined in the previous section. The methodology proposed is an adaptation of the H-HWWS one [17] and its recent improvement [40] to the specific context of cold. In the proposed warning system, alerts will be triggered when both indicators (based on Tmax and Tmin) below the corresponding thresholds. In summary, the considered method contains four main steps:

1) Choose appropriate lags for cold indicators;
2) Compute the over-health (OH, includes over-mortality and over-hospitalization) series from the daily mortality and hospitalization data;

3) Determine the cold-related historical episodes of OH;

4) Choose the appropriate indicators and corresponding thresholds.

3.2.1 Appropriate lags for weather indicators

The first step aims at choosing objectively the maximum lag value for cold indicators. Cold indicators S_t are defined as a linear combination of *Tmax* and *Tmin* on some consecutive days. For a maximum lag value $=L$, the indicators are expressed as:

$$S_t = \sum_{l=0}^{L} \alpha_l X_{t-l} \quad (1)$$

where X_t are the forecast temperatures of *Tmax* and *Tmin* at day t, and α_l are the weightings such that:

$$\begin{cases} \alpha_i \geq \alpha_j, for\ i < j < L \\ \displaystyle\sum_{l=0}^{L} \alpha_l = 1 \end{cases}$$

The first constraint ensures that the temperature of the day closer to the target day has more contribution than the previous days, as the importance of forecast for meteorological data decreases with time. The second constraint ensures that the sum of the weightings of an indicator is equal to 1, which is useful for interpretation.

In the case of H-HWWS [9], [17]–[23], it is generally chosen *a priori* as $L = 2$. To adapt in case of cold, the value L can be chosen by examining the lag-response relationship between temperature and the health issue of interest. It is estimated by a distributed lag non-linear model (DLNM) [41], [42], which expresses a non-linear relationship between the exposure and the response while accounting for lag effects. In this study, a quasi-Poisson DLNM is used, with penalized splines on both temperature variables and lags from 0 to 14 days. The day of the season and the long-term trend are also added in the model as unmeasured confounders, calculated by smooth spline functions, with 4 degrees of freedom for the day of the season and 1 degree of freedom per decade for the long-term trend, as in [43].

3.2.2 Over-health (OH) series

The second step is to evaluate the OH series, the ratios that represent the relative difference in the number of deaths or hospitalizations from the average number of deaths or hospitalizations that can be normally expected. The calculation formulas of OH for mortality and hospitalization are exactly the same. In case of mortality, for time *t*, OH is expressed as [41]:

$$OH_t = \frac{OD_t - ExpD_t}{ExpD_t} * 100 \quad (\%) \tag{2}$$

where OD_t is the observed number of daily deaths, and $ExpD_t$ is the expected number of daily deaths without influence of cold. For mortality, ExpD is calculated using natural cubic splines with 8 degrees of freedom per year. It accounts for the seasonal and long-term trends of daily mortality. For hospitalizations, strong weekend and holiday effects are observed. To evaluate the expected number of daily hospitalizations (ExpH), a day of week indicator and 12 indicators for each day between the 23rd of December and the 3rd of January are further added to account for week-end and holiday effects. Note that the ExpD and ExpH series are calculated with data of the whole year, to avoid boundary effects. Then they are truncated to only keep the winter months (December to March).

3.2.3 Cold-related historical episodes of OH

The purpose of this step is to determine the historical episodes of OH extremes that can be linked to cold. All episodes identified correspond to a high level of OH (denoted

OHT) and an extreme weather event. Because of the lack of a definition of extreme cold, preliminary maximum and minimum temperature thresholds (denoted Tmax_P and Tmin_P) for 'cold spell' need to be defined. In addition, considering the cumulative effect of cold, the 3-day means of temperature series are used in this step, in other words, to determine the Tmax_P and Tmin_P and the final thresholds. Same as the ExpD, the 3-day means is applied on whole temperature series and then truncated by the winter period of each year, in order to minimize the loss of information. To ensure that extracted extremes correspond to cold and not to other causes such as influenza, we add the constraint that the 3-day means of Tmin and Tmax are below their 5th percentile over the winter period of these years.

In summary, all episodes *i* of OH determined in this study should meet the following three conditions : 1) OH_i > OHT; 2) $Tmax_i$ < Tmax_P and 3) $Tmin_i$ < Tmin_P. Missing either condition will not be considered an episode.

3.2.4 Final indicators and thresholds estimation

The last step consists in finding the optimal indicator weights α_l, $l = 0,\ldots, L$, in equation (1) and the corresponding final cold thresholds. Hence, a sequence of candidate combinations of indicators and thresholds is performed and checked manually to find the one leading to the best trade-off between high sensitivity and low number of false alarms (FA). The latter is equivalent to false positive or type 1 error. The sensitivity is the probability of correctly predicting the actual episodes determined in step 3. Typically, a threshold/indicator corresponding to high sensitivity and fewer FAs is preferred. In public health practice however, it is considered more important to correctly predict episodes than to avoid FAs, i.e. certain number of FAs is acceptable if the sensitivity is close enough to 1.

For practical reasons, two different types of optimal combination of threshold/indicator are defined in the present study. First, the theoretical optimal threshold/indicator (denoted TO), which represents the overall best performances among all combinations based only on optimizing the sensitivity and FA criteria. In other words, TO has the highest possible sensitivity and the lowest possible number of FAs. However, the optimal TO indicators can be inappropriate in practice or for interpretation purposes. In particular, they may contain very negligible weight values, such as $\alpha_l = 0.1$, which means that the temperature of the corresponding day has a very small effect on the threshold. In addition, due to the uncertainty of the temperature forecast when the system will be activated in practice, accounting for days with negligible weights is less useful for a warning system. Therefore, the second type of optimal threshold/indicator is defined, called the final choice (denoted FC). The latter consists in choosing larger weights with performances close to that of TO. Hence, FC combines theoretical and practical aspects, and it represents the threshold/indicator proposed in the present study.

3.3 Confounders control

Finally, to evaluate the potential confounding variables such as influenza and viral pneumonia (and notably syncytial respiratory virus), a sensitivity analysis is performed to isolate the direct effect of cold. For example, in winter, influenza may be a leading cause of mortality/morbidity and can thus affect the present analysis [44], [45]. In Quebec, 417 deaths with influenza on average per year were observed over the 2011-2016 period, with a rate of 5.2/1 000 000 person per year [46]. This sensitivity analysis is applied only on hospitalizations in the present study, in which influenza and viral pneumonia usually bring more changes on the daily numbers.

4. Results

The results of the grouping of RSSs is presented first followed by the obtained indicators and thresholds. To avoid repetition, only results for class 1, corresponding to the Montreal region (the most populated area in Quebec), are presented in details. The results of the remaining classes are briefly presented and detailed in the supplementary material. A sensitivity analysis is performed in the last section, to ensure that the obtained results are not affected by the other confounding variables.

4.1 Clustering of RSSs based on climatic variables

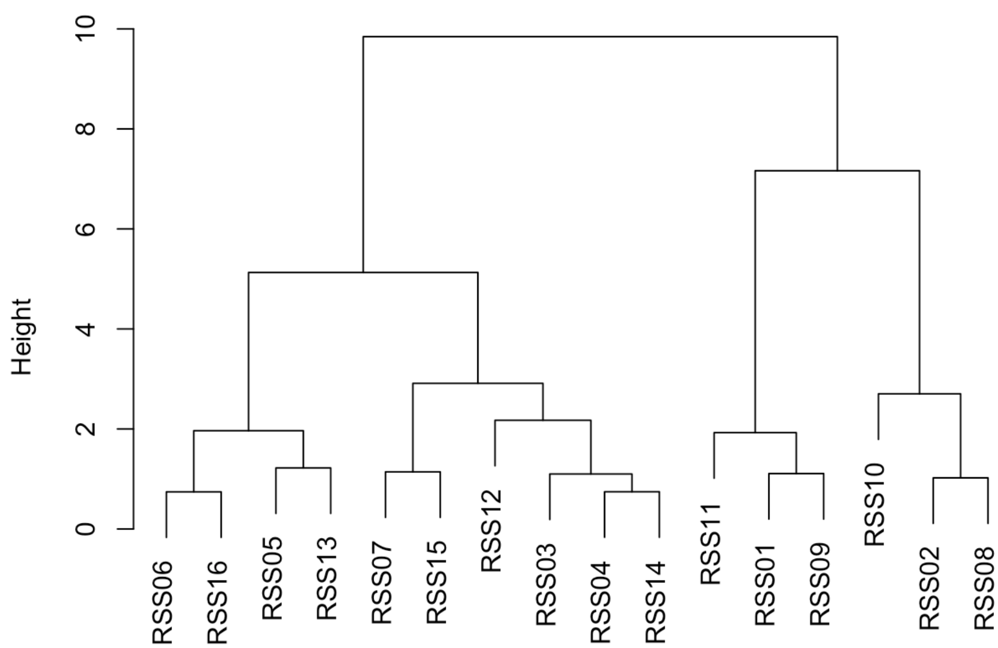

Figure 2: Dendrogram of the 16 RSSs of the province of Quebec for the winter period.

Figure 2 shows the dendrogram obtained through HAC. By considering the large gap in the height, 4 classes of RSSs are obtained (Figure 3a). A visual comparison with the

Quebec climate map based on the average temperature for the winter period of 1981-2010 (Figure 3b) shows that the obtained classes follow the distribution of temperature across the province. This Quebec climate map was obtained from the Ouranos consortium, based on [47] methodology.

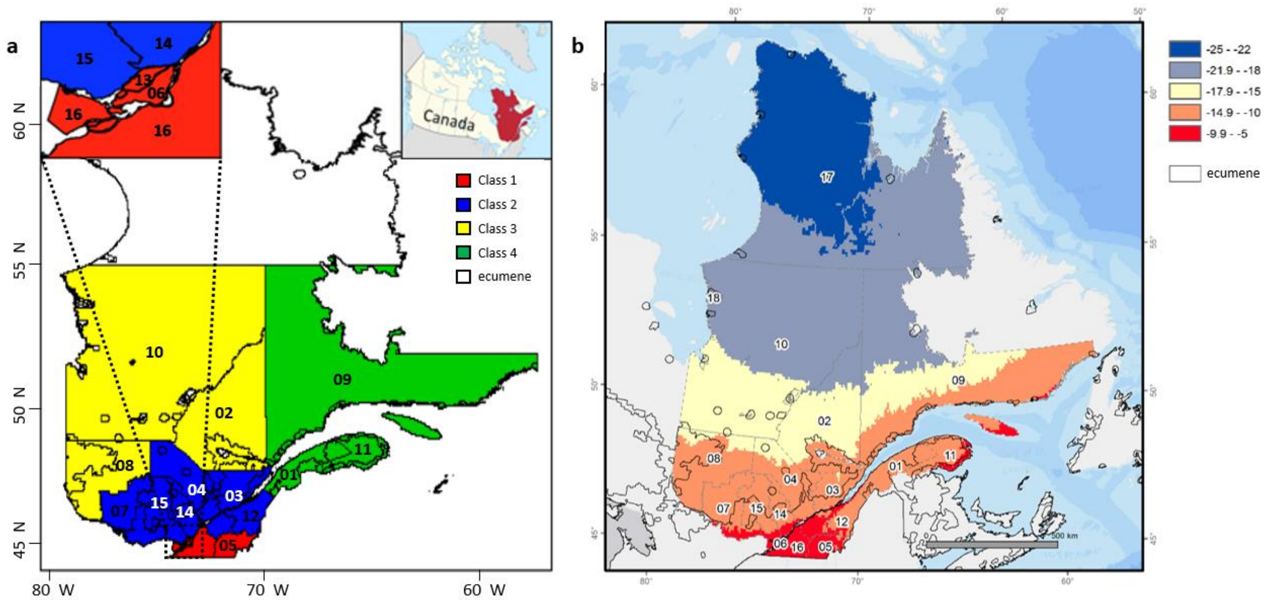

Figure 3: a) Grouping of the 16 RSSs of the province of Quebec for the winter period, used in the present study. Colors indicate different classes. The white region represents the 2 RSSs north of the 50th parallel which were excluded in the analysis. **b)** Quebec climatic map based on the average temperature of 1981-2010 (January, February and March only) [47].

The final clustering (Figure 3a) is geographically homogeneous and shows good agreement with the climatic map (Figure 3b). The only exception is class 4 (north-east in Figure 3a) which seems to have an average temperature level similar to class 3. This result is also confirmed by comparing the descriptive statistics of each class (Table 1). Indeed, with this summary, class 1 has a higher temperature, while class 3 is the coldest and driest. This is consistent with the actual situation, since class 1 is located in the southern part of the province and includes the largest city in the province, Montreal. On the other hand, class 3 is located in the northern area of the province. Class 4 contains the

3 RSSs located east of the province, i.e. around the St-Laurence river estuary as well as next to the Atlantic Ocean. This class is thus more humid and more windy than the others, which explains the little disagreement between Figures 3a and 3b. Finally, class 2 is located in the middle of the province and, as such, it is a mid-point value in temperature and humidity, while being the least windy among these 4 classes.

Table 1: Summary of the average value of the variables used in classification, plus the average of the daily mortality-hospitalization during winter for each class. RH is relative humidity, WS is wind speed.

Class	RH (%)	Tmax (°C)	Tmin (°C)	WS max (km/h)	WS min (km/h)	Daily mortality	Daily hospitalization
1	71	-2	-11	22	4	87	1449
2	68	-4	-14	20	3	62	1107
3	64	-7	-19	22	4	10	223
4	72	-5	-14	32	8	10	198

4.2 Results of cold indicators and thresholds for climatic class 1

This section presents the detailed results for the determination of cold indicators and thresholds for climatic class 1 (red zone in Figure 3a), which contains the Montreal region, the largest urban area in the province.

4.2.1 Appropriate lag for cold indicators related to health variables

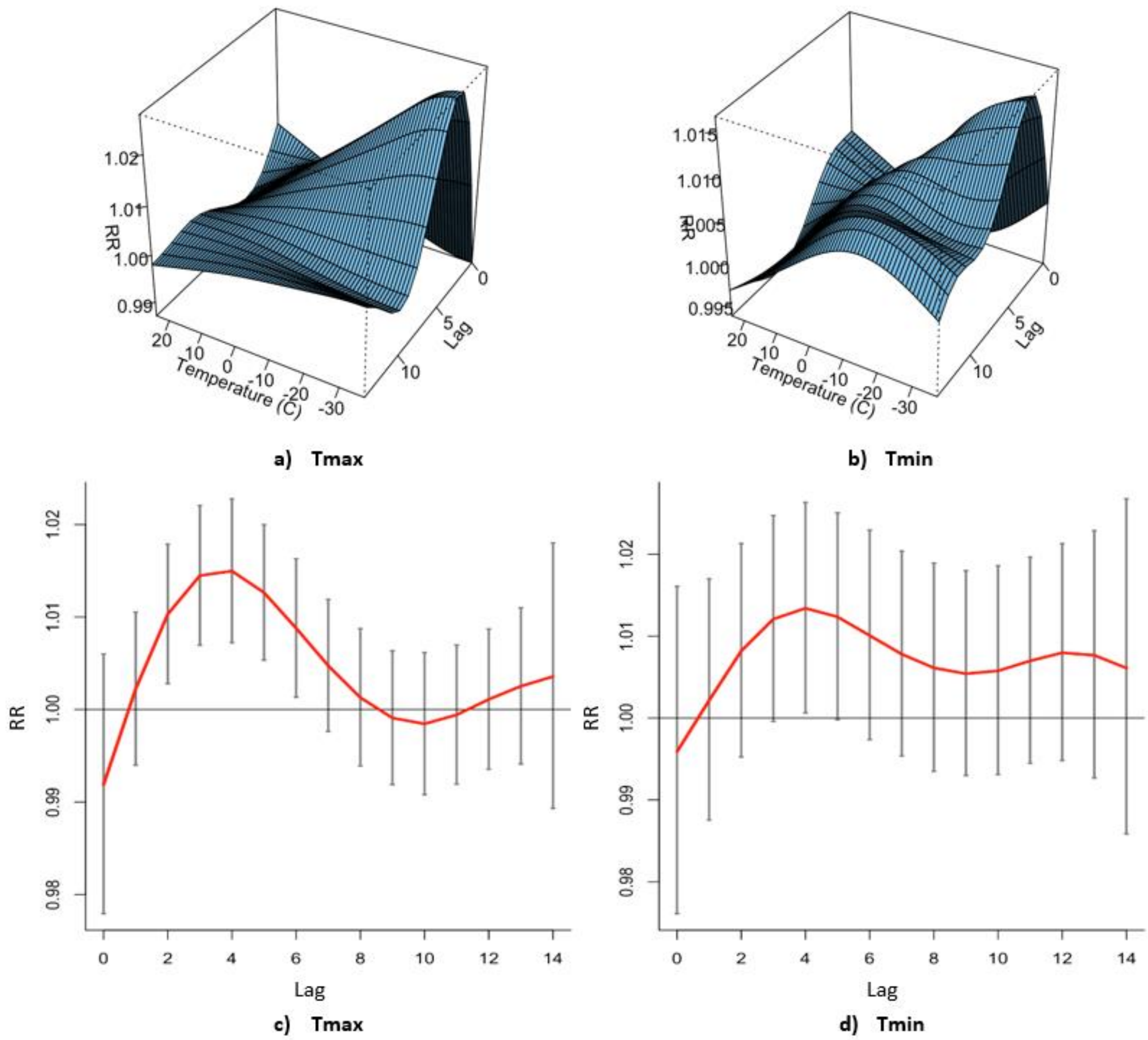

Figure 4: a) DLNM surfaces between Tmax and daily mortality. **b)** DLNM surfaces between Tmin and daily mortality. Lag-response relationships between daily mortality and *Tmax* **(c)** and *Tmin* **(d)** for winter period of class 1, at *Tmax=-12 °C* and *Tmin=-23 °C,* grey bars show 95% confidence intervals.

First, the lag value *L* is chosen by examining the lag-response relationship between temperature and the health variables, which is estimated by DLNM [40]–[42], as described in section 3.2.1. Figures 4a and 4b show the surface of relative risk (RR) along explanatory variables (daily Tmax and Tmin) and lags compared with the point of the overall minimum mortality. Figures 4c and 4d show slices of the obtained DLNM surface at the 5th percentile of the temperature distribution, i.e. corresponding to *Tmax = -12 °C, Tmin= - 23 °C.*

For Tmax, RR increases for lags between 0 (same day) and 4 days, then rapidly decreases until l=10 days with again a slight increase. According to the 95% confidence intervals, RR values are significantly different from 1 for $2 \leq l \leq 6$, with a peak at l=4. For Tmin, the behaviour of RR is similar to that of Tmax, except that it decreases again when l>12. However, the 95% confidence intervals of RR are larger and do not include 1 only for l=4. Indeed, the choice of the lag can be up to 6 day for Tmax. Yet, since the accuracy of temperature forecast rapidly decreases over the days, the reliability of weather forecasts in the short-term is greater than in the medium-term for a warning system. For similarity in terms of performance, a lag of 4 days is finally chosen for both Tmax and Tmin indicators. The results for hospitalization data do not differ from 1 for all $l>0$ (supplementary material, Figure S2). To avoid underestimating cold impacts on hospitalization, a lag of L=4 is also used in the case of daily hospitalization for both Tmax and Tmin indicators.

4.2.2 Cold-related historical episodes of OH

ExpD (or ExpH for hospitalization) is needed to compute the OH series as described in equation (2). The final expected number ExpD (ExpH) is represented in Figure S3 (Supplementary materials). However, as the OH levels are different in case of mortality and hospitalization, the choice of OHT is also different for each case. The final OHT and corresponding episodes are separately described below.

Mortality episodes

For mortality data, the choice of OHT is based on the total exceedance function and the cold-related exceedance function as in [40]. These two exceedance functions are illustrated in Figure 5.

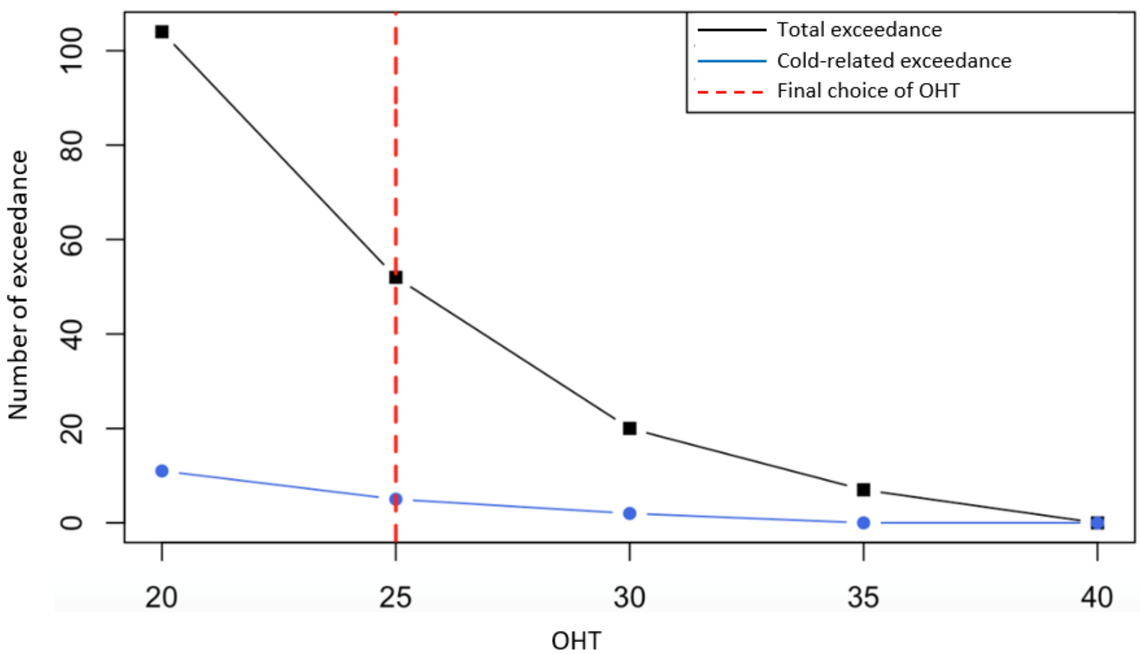

Figure 5: Total exceedance function and the cold-related exceedance function.

OHT must reach a trade-off between enough OH extremes and high enough values of OH. Therefore, it is appropriate to choose the OHT in the range 25% - 30% in the present case. However, according to Figure 5, only 2 episodes are detected with OHT = 30% which means that some important episodes may be missed. Hence, we choose OHT=25% for class 1. This threshold detects 4 OH episodes as presented in Table S3. These detected episodes in OH series and the associated 3-day mean temperatures are shown in Figure 6. Note that several important peaks are not detected in Figure 6c, since their 3-day mean temperatures are not below the thresholds of preliminary temperature Tmax_P and Tmin_P. In other words, they are not a cold spell according to the definition adopted in this study, despite having a high OH. Potential causes of high OH episodes that are unrelated to cold include influenza and viral pneumonia.

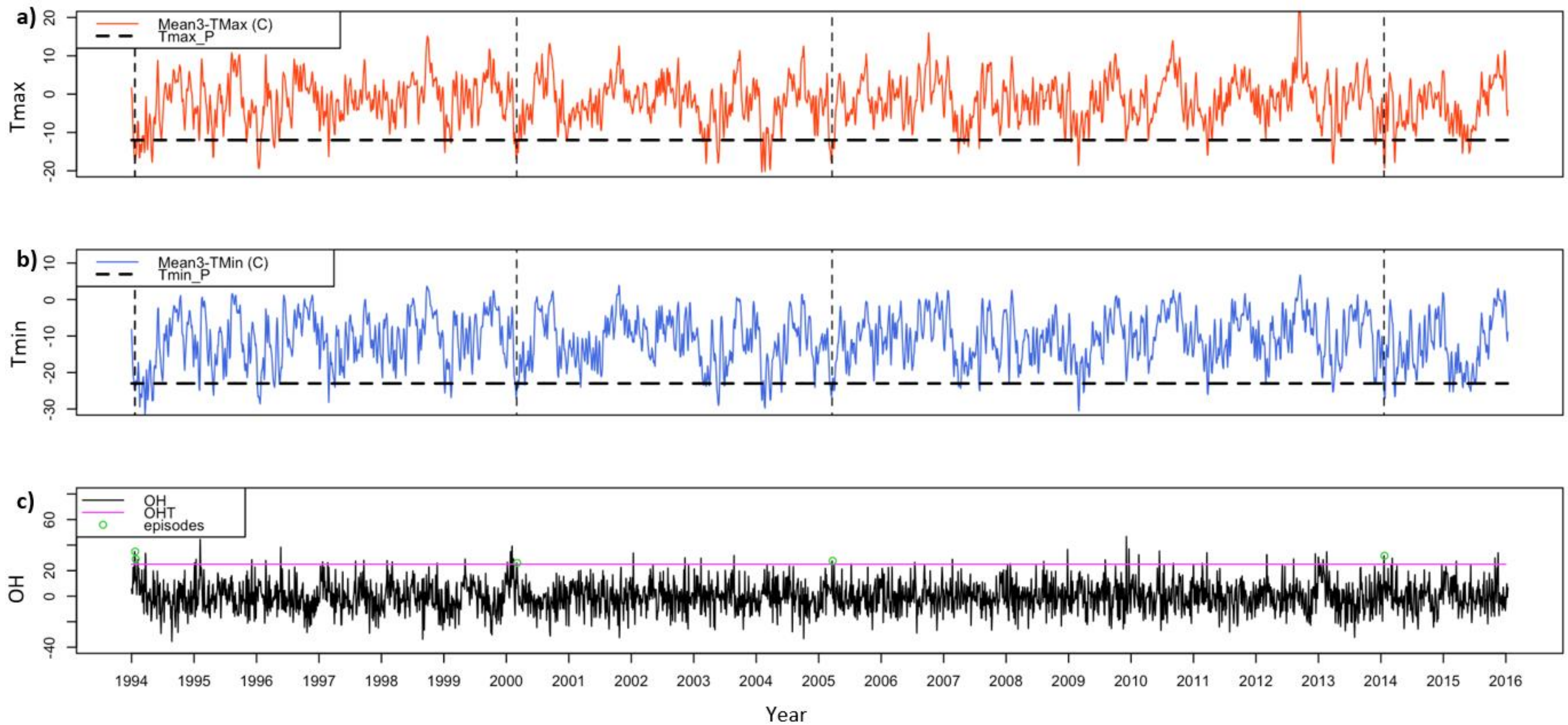

Figure 6: Temperature series and over-mortality (OH) series for class 1. **a)** *Tmax* series and preliminary threshold *Tmax_P*. **b)** *Tmin* series and preliminary threshold *Tmin_P*. **c)** OH series and the detected episodes with OHT=25%. The vertical dashed lines identify each OH episode.

Hospitalized morbidity episodes

For hospitalization data, OH series and corresponding 3-day mean temperatures are presented in Figure 7. The level of OH obtained (Figure 7c) is much lower than that of mortality data (Figure 6). By applying the same methodology as for mortality, an OHT=7% is chosen in the case of hospitalization. Although this value may appear to be low, it is quite significant for over-hospitalization. In fact, the average number of daily hospitalization is almost 20 times the daily mortality. A 7% increase of OH would put tremendous pressure on local hospitals. This threshold detects five episodes of OH as presented in Table S4. By comparing the episodes identified in the case of mortality and hospitalization, we observe that the 24th of January 2005 is the only common episode for mortality and hospitalization. However, the most important hospitalization peak (3rd and 7-8th of January 1996) is not found as a mortality peak.

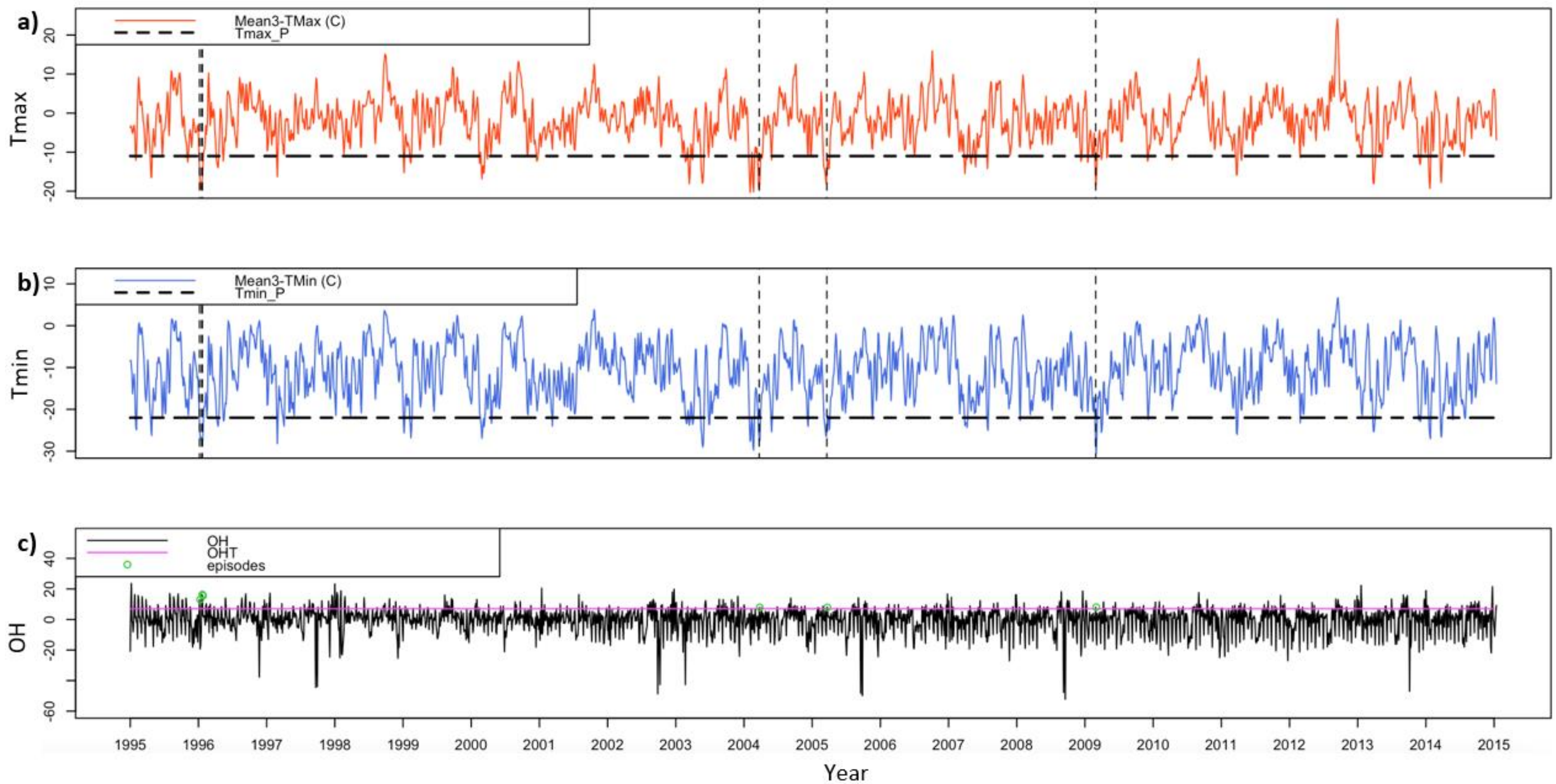

Figure 7: Three-day mean temperature series and over-hospitalization (OH) series for class 1. **a)** *Tmax* series and preliminary threshold *Tmax_P*. **b)** *Tmin* series and preliminary threshold *Tmin_P*. **c)** OH series and the detected episodes with OHT=7%. The vertical dashed lines indicate temperatures associated to each OH episode.

4.2.3 Final temperature indicators and thresholds

Given the large amount of results, we only present a limited significant part of the obtained threshold/indicator weight couples. We select the indicators and thresholds that enable the detection of most episodes (i.e. a high sensitivity), while resulting in the lowest possible number of FA.

For comparison purposes, two different types of results (corresponding to TO and FC described in section 3.2.4) are shown for each of the mortality and hospitalization dataset. The obtained results are summarised in Table 2.

Table 2 Results of optimal indicator weightings and thresholds for climatic class 1.

Data	Number of episodes	Results	Optimal weights					Thresholds (°C)	Sensitivity (%)	FA (per year)
			α0	α1	α2	α3	α4			
Mortality	4	TO	0.5	0.4	0.1	0	0	(-15,-20)	100	0.59
		FC	0.5	0.5	0	0	0	(-15,-23)	100	0.68
Hospitalization	5	TO	1	0	0	0	0	(-14,-24)	100	0.75
		FC	1	0	0	0	0	(-14,-24)	100	0.75

FA: False alarm. TO: theoretical optimal weights. FC: final choice (theoretical and practical).

For climatic class 1, the results of both TO and FC allow to predict all episodes of health events, which corresponds to 100% sensitivity. However, TO produces slightly less FA per year, in the case of mortality. The selected weights of FC are very similar to TO's weights, only with the small $\alpha_2 = 0.1$ shrunk to zero and compensated by α_1. This also leads to lower thresholds in the case of FC. The indicators based on the average of 2 days (FC) are therefore chosen, as they are much easier to implement in a real system (functioning on meteorological forecasts). For the hospitalization data, the TO and FC are identical with an indicator based on the same day only. The final threshold values are -15 °C for *Tmax* and -23 °C for *Tmin* for mortality, whereas for hospitalization, they are -

14 °C for *Tmax* and -24 °C for *Tmin.* The thresholds on mortality and hospitalization are thus consistent.

4.3 Results for other climatic classes

For the other 3 climatic classes of RSSs, the same process is applied as for class 1. The obtained results are summarised in Table 3.

Table 3 Results of optimal indicator weightings and thresholds for classes 2-4.

Class	Health issue	Number of episodes	Results	Optimal weights					Thresholds (°C)	Sensitivity (%)	FA (per year)
				α0	α1	α2	α3	α4			
2	Mortality	4	TO	0.6	0.1	0.1	0.1	0.1	(-14,-28)	100	0.50
			FC	0.5	0.5	0	0	0	(-16,-28)	100	0.68
	Hospitalization	7	TO	0.6	0.2	0.1	0.1	0	(-13,-24)	100	1.00
			FC	0.7	0.3	0	0	0	(-13,-26)	100	1.10
3	Mortality	5	TO	0.8	0.1	0.1	0	0	(-20,-31)	67	0.95
			FC	0.7	0.3	0	0	0	(-20,-29)	67	1.05
	Hospitalization	6	TO	0.7	0.3	0	0	0	(-17,-30)	100	1.30
			FC	0.7	0.3	0	0	0	(-17,-30)	100	1.30
4	Mortality	4	TO	0.7	0.1	0.1	0.1	0	(-14,-23)	100	1.18
			FC	0.5	0.5	0	0	0	(-15,-23)	100	1.27
	Hospitalization	5	TO	1	0	0	0	0	(-13,-23)	100	1.95
			FC	1	0	0	0	0	(-13,-23)	100	1.95

FA: False alarm. TO: theoretical optimal weights. FC: final choice (theoretical and practical).

As in class 1, FC does not always exactly match TO since some negligible weights α (0.1) appear for the three classes. However, the loss of performance compared to TO is always negligible. Indeed, the sensitivity is always 100% (except class 3), which means that they both are able to predict all health event episodes. The difference is that FC always produces slightly more FAs per year.

Similar to class 1, the thresholds of FC are generally lower than TO, except in the case of mortality in class 3. In addition, the thresholds for hospitalization are generally higher, and thus less restrictive, than those of mortality. This seems reasonable since mortality generally responds to more extreme conditions than hospitalizations.

Finally, by summarizing all the proposed FC threshold/indicators, we always observe a sensitivity of 100%, with the only exception of class 3. In addition, we observe higher numbers of FA in classes 3 and 4 than in classes 1 and 2. This can be explained in the situation of Quebec by the fact that the populations of each RSS in classes 3 and 4 are very small, which decreases the signal visibility in the data. In particular for class 4, the thresholds are higher than those of other classes, which seems inconsistent with its lower average temperature during winter. A possible explanation is that this region is the most humid and windy in Quebec resulting in lower perceived temperatures, which leads to a higher threshold on temperature in this region.

4.4 Sensitivity analysis

This section presents the results of sensitivity analysis on hospitalization data. The episodes found in case of all-cause hospitalization by eliminating influenza and viral pneumonia are summarized in Table S5 (supplementary materials). These results show that influenza and viral pneumonia do not affect the obtained results with the all-cause data. The final cold indicators and thresholds (Table S6) are exactly the same as presented in Tables 2 and 3. This conclusion is also expected because the constraint used in the method (Temperature < 5^{th} percentile) is already able to ensure that the determined episodes correspond to cold spells.

5. Discussion

The World Meteorological Organization (WMO) recently issued guidelines for extreme cold events [48]. A recent meta-analysis also reviewed the criteria used by different authors for cold spells in several countries [2] and a recent paper studied the subject in Canada [49]. Generally, the existing thresholds for extreme cold events are determined by an absolute value or quantile of weather variables, with no known link to any health issue. The purpose of the method considered in the present study is to adjust such thresholds by combining the effects of OH events. Compared to thresholds directly defined by quantiles in guidelines, the threshold/indicator proposed here has a lower number of FA and possesses a very high sensitivity. Table 4 summarizes the obtained results. Note that the threshold directly defined by a quantile is a special case with an indicator $\alpha_0 = 1$. Furthermore, this is also the first study dealing specifically with a cold health warning system focused on hospitalization data in Quebec.

Table 4 Number of FA per year for thresholds proposed and directly defined by a quantile

	Class	FA per year with proposed thresholds	FA per year with a quantile
Hospitalization	1	0.75	1.35
	2	1.10	1.45
	3	1.30	1.55
	4	1.95	1.95
Mortality	1	0.68	1.23
	2	0.68	1.36
	3	1.05	1.50
	4	1.27	1.59

This study also confirms the need to propose different threshold/indicators according to different categories of health issues. The impact level and lag of extreme cold temperatures are very different on mortality and hospitalization, as shown in several studies [29]–[32]. The mortality peaks and hospitalization peaks therefore usually do not occur at the same time, as confirmed in the present study. Indeed, comparing the episodes found in the case of mortality and hospitalization (Table S3 and S4), one finds that few of them are simultaneous.

In terms of sensitivity, the method in the present study can correctly detect all episodes of OH, except for class 3, with a sensitivity of 67%. This value can be considered as statistically acceptable for this class since it has the lowest regional population size, the largest area and is the northernmost. Note that in the case of the Quebec H-HWWS study [17], similar sensitivity performances were obtained for almost the same class. In terms of the number of FAs, in this study more false alarms per year were produced compared with H-HWWS (less than 0.2 per year versus ≈1-2). In addition, the FAs have been grouped by 3 days (per episode) in this study, while they were counted for each day independently in the heat study. Indeed, the main difference between heat and cold studies is that the important spikes of OH during heat events generally present some extremely high values, which are significantly different from the average [17], whereas the signal is less obvious in the case of cold [15], [16]. Furthermore, the mortality and hospitalization response is short during heat waves, while it lasts generally much longer in the case of cold [3], [11]–[14]. In addition, given that influenza plays an important role in winter health analyzes [44], [45], a sensitivity analysis was performed by excluding these effects in the case of hospitalization. Finally we observe that the episodes identified in the present study are all linked to cold. Other factors such as air pollution, which is also seen as having an important impact on winter mortality, they are not included in the present study. Usually we do not observe any peaks of air pollution during winter in Quebec. Actually heating is mainly electric in Quebec with electricity provided by Hydro-Québec (public utility). In addition, air pollution does not seem to be a confounding factor in the relationship between temperature and mortality, as shown by several studies such as [50].

The method used here is an adaptation of the approach for H-HWWS. Differences mainly concern the lag selection for cold indicators, the definition of over-mortality as well as the definition and detection of over-mortality episodes. Indeed, in H-HWWS [17], the lag of indicators is predefined (without any technique) as $L=2$, since a stronger a priori can be obtained from the existing literature. In the case of cold, the optimal lag is less clear and thus required exploration, and as a result, is also more objectively selected. Note that, even though it is well known that the cold impacts on mortality and hospitalizations can be spread over weeks after the event [3], [11]–[14], the objective of the present study is to build a forecast system. Such a system will allow a quick reaction when weather services report unusual cold spells, and is not meant to explore the relationships between cold spells and health issues. This justifies the choice of a much shorter lag than those reported in previous studies. In other words, this system aims to prevent the peaks of OH observed in this study through various interventions in the mass media or for the homeless, for instance, and to support emergency room management.

In terms of OH, the expected number of daily deaths (ExpD) is hereby computed using natural splines, while the H-HWWS used the calendar mean of a moving average on the daily number of deaths, with a window of 15 days. Splines are more flexible and allow accounting for trends.

The method used here still presents a number of limitations. For example, the OH episodes found in the present study occur only in January or February, while data from December and March are also included. At the beginning and the end of the season, the levels of mortality as well as the temperature vary much more than in the middle of the season (January or February). A potential explanation is that temperature may not be the direct cause of high OH in December and March. Other factors could be more important such as the temperature variability (e.g. a sharp decrease or increase) [13]. Thus, a future improvement could focus on the effect of temperature variability on human health.

Another limitation is that the indicators in the present study are based only on temperature variables, while other weather variables, such as humidity and wind (or wind-chill) [51], may also be important to predict winter mortality. However, the forecasts of wind speed or humidity are much less reliable than temperature, which also increase the difficulty of integrating them to the warning system.

Furthermore, the present study was applied only to all-cause mortality/hospitalization, while other health issues could also be studied, such as those related to certain specific diseases like the cardio-respiratory ones [52]–[54]. However, multiple behavioral, physiological, environmental and pathophysiological mechanisms may have important impacts on occurrence of a specific disease. For instance, the cold effects on cardio-respiratory diseases are dependent to some extent on several other factors than weather. Different sex, age, race, type of work and lifestyle variables like smoking will impact incidence. Pre-existing medical conditions, most notably cardiovascular and respiratory, will bring a higher level of sensitivity to cold for hypertensive or asthmatic people, for instance [55]–[57].Their impacts cannot be summarized in the present study, in which the objective is to determine an inclusive and optimal threshold for these complex phenomena.

6. Conclusions

The present study proposes a starting point to establish a C-HWWS, by identifying cold indicators and thresholds in this context, based on a previous work on H-HWWS in the province of Quebec. Some improvements of the latter are proposed in order to better adapt to cold. In order to cover not only large cities but all regions of the province, a clustering of regions was performed for cold months. Results suggest that excesses of mortality can be expected when temperatures are below thresholds comprised between -15 °C and -20 °C for Tmax as well as -23 °C and -29 °C for Tmin according to the spatial classes. For a given class, the thresholds of hospitalization are usually higher than those of mortality, i.e. between -13 °C and -17 °C for Tmax and between -23 °C and -30 °C for Tmin. It appears that considering short-term indicators (lower than four-day lag) do not significantly reduce the performances of the system, as they are able to correctly predict important OH episodes related to cold with an acceptable number of FAs. They are also easier to interpret and apply compared to long-term ones. Finally, it also shows that confounding variables such as influenza seem not to affect the obtained results.

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Declaration of competing 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:

Credit Author Statement

Bixun Yan: Formal analysis, Methodology, Software, Writing - Original Draft

Fateh Chebana: Conceptualization, Methodology, Supervision, Writing - Review & Editing

Pierre Masselot: Methodology, Software, Writing - Review & Editing

Céline Campagna: Supervision, Validation, Writing - Review & Editing

Pierre Gosselin: Validation, Writing - Review & Editing

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Graphical abstract

Highlights

- This is the first developed health alert system dedicated to cold
- A number of new aspects are employed in the methodology
- The developed method is general and can be applied elsewhere