A heat-health watch and warning system with extended season and evolving thresholds.

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A heat-health watch and warning system with extended season and evolving thresholds

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Abstract

Background

Many countries have developed heat-health watch and warning systems (HHWWS) or early-warning systems in an attempt to mitigate the health consequences of extreme heat events. HHWWS usually focus on the four hottest months of the year and impose the same threshold over these months. However, according to climate projections, hot season is expected to extend and/or shift. Some studies demonstrated that health impacts of heat waves are more severe when the human body is not acclimatized to heat. In order to adapt those systems to potential heat waves occurring outside the hottest months of the season, this study proposes specific health-based monthly heat indicators and thresholds over an extended season from April to October in the northern hemisphere.

Methods

The proposed approach, an extension of the HHWWS methodology currently adopted in the province of Quebec, Canada, was developed in the Greater Montreal area (current population 4.3 million) based on historical health and meteorological data over the years. This approach consists of determining excess mortality episodes and then choosing indicators and thresholds that may involve excess mortality.

Results

We obtain thresholds for the maximum and minimum temperature couple (in °C) that range from (23 and 12, respectively) in April, to (32 and 21) in July and back to (25 and 13) in October. The resulting HHWWS is flexible, with health-related thresholds taking into account the seasonality as well as the monthly variability of temperatures in the threshold definition process for an extended summer season.

Conclusions

This adaptive system has the potential to prevent, by data-driven health alerts, heat-related mortality outside the typical July-August months of heat waves. The proposed methodology is general and can be applied or adapted to other regions and situations.

Keywords: Warning systems, heat wave, seasonality, health, climate, thresholds, methods, mortality.

1 Background

Heat waves are considered among the deadliest extreme weather events around the world (e.g. Mora, Dousset [1]). A significant number of deadly heat waves has been observed over the last three decades. The ones of Chicago and Pakistan in July 1995 generated a mortality toll estimated respectively at 670 and 523 deaths [2]. One of the most famed heat waves touched several European countries in August 2003, causing an excess close to 45,000 deaths in 12 European countries [4]. The one of Russia in July 2010 resulted in an increase of 11,000 deaths more than the previous year [5, 6]. In Quebec, during the five-day heat wave of July 2010, the excess daily mortality reached around 33% in the Greater Montreal area and four other public health regions [7]. In early July 2018, a six-day heat wave caused 30% excess mortality in the same geographical region, and 23% excess ambulance transportation [8].

The increase in the number and severity of heat wave events led several countries to establish their own heat-health watch and warning systems (HHWWS) or early warning systems [9]. These systems are usually based on meteorological indicators (generally maximum, minimum or mean temperatures, and in some cases the humidity level) or on air masses (in case of the synoptic systems), and a threshold above which a significant increase in mortality is expected [2, 10, 11]. As it is the case for the definition of heat waves, there is no universal threshold for warning systems, since they reflect local weather/climate conditions, as well as specificities of the local population [2]. Moreover, many of these thresholds are still not evidence-based on human heat-related health mortality or morbidity data [2].

In most developed countries, the existing HHWWSs are established with a single threshold for the whole summer season, usually the four or five hottest months [9, 11-16]. Spain is an exception with thresholds that vary in time throughout the year [9]. On the other hand, according to climate projections and due to climate change, the probability of heat waves occurring early or late in the season should increase [17, 18]). Ouarda and Charron [19] studied over 50 years of heat waves in six stations distributed across the Province of Québec and found a non-negligible trend of the intensity, magnitude, and duration of these events. Another study reported that the number of heat-wave days could increase by up to 13 days in the period 2021 to 2050 and even by up to 40 days in the period 2071 to 2100 in the Iberian Peninsula and the Mediterranean region [20]. Acclimatization is an essential element of the human adaptation mechanism to variations in environmental heat exposure. Several studies have shown that the degree of human heat acclimatization varies throughout the season, explaining why deadlier heat waves are often detected in June or July [21, 22, 24]. For instance, Lee et al., 2014 have demonstrated that, over 148 cities in the U.S., heat effects of increased temperatures were larger in the spring and early summer.

It is thus of public health importance to take into account human acclimatization through seasons and develop an early warning system where health-based thresholds could evolve over time, with a monthly resolution for instance.

The objective of the present study is to establish an extended data-driven HHWWS that evolves over the season, based on the meteorological and health data of each month (April to October in the studied case). To pursue this objective, the proposed methodology is an extension and generalisation of the HHWWS system currently in use in the province of Quebec, Canada [11]. The methodology consists in determining historical excess mortality episodes, then temperature thresholds are chosen by based on sensitivity and false alert criteria. Therefore, the proposed methodology is an adaption and extension of the method of Chebana et al. (2013). Unlike the latter, in the proposed HHWWS, each month has its own threshold (evolving). Hence, the proposed system allows taking into account the within-season variability in mortality response to temperature. In addition, the proposed HHWWS covers a larger part of the year to account for summer season extension due to climate change.

The paper is organized into five sections. Section 2 describes the data and the proposed method to establish the novel adaptive HHWWS. The obtained results are presented in Section 3 whereas the outcomes of the study are discussed in Section 4. Section 5 concludes the paper.

2 Methods

2.1 Data

The data used to establish indicators and thresholds include all-cause daily deaths and meteorological data from the Greater Montreal area (including public health regions of Montréal, Laval, Lanaudière, Laurentides and Montéregie; Figure 1). Health data are available from 1981 to 2015, for a total of 35 years of observations, and are provided by the National Institute of Public Health of Quebec (*Institut national de santé publique du Québec* INSPQ). The study period is restricted to the months of April to October included.

The meteorological data were available for the same period as per health data. Daily maximum and minimum temperatures (noted respectively Tmax and Tmin) are used and are collected from the DayMet database supported by the National Aeronautics and Space Administration (NASA) [25]. It produces estimates of several daily weather variables on a 1 km x 1 km gridded surface. The final temperature series are thus daily averages of all grid points inside the Greater Montreal area.

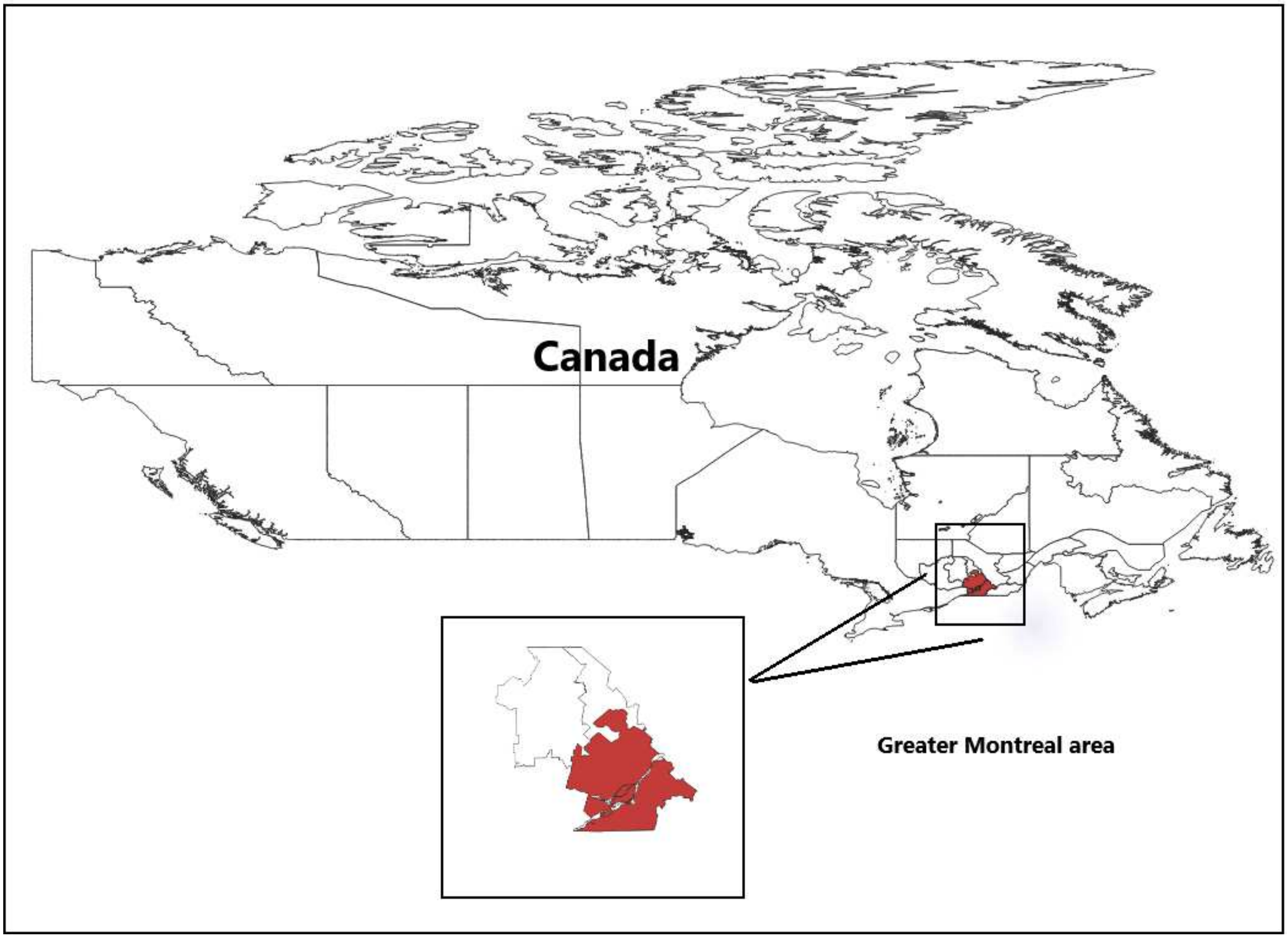


Figure 1: Study Area, Greater Montreal area, the area is identified with the color red

2.2 Methodology

Briefly, the purpose of this method is to estimate two indicators $I_{m,t}^{(Tmax)}$ and $I_{m,t}^{(Tmin)}$ for given months m and day t, as weighted averages of the associated variable over a number of days (lag), as well as their associated thresholds (S^{Tmax} and S^{Tmin}) such that $I_{m,t}^{(Tmax)} > S^{Tmax}$ & $I_{m,t}^{(Tmin)} > S^{Tmin}$. The proposed methodology to establish the warning system is inspired by that defined by Chebana et al (2013). However, the first and main contribution concerns the foundation of the system itself, namely the shape of the threshold and the period of coverage. Indeed, we defined a new system in which the maximum and minimum (Tmax, Tmin) thresholds temperatures are evolving according to the temporal scale (monthly) for a broader period of the year. This evolving character of the thresholds is based on the meteorological reality of each month instead of defining constant threshold over the entire season. Hence, the proposed system has the ability to adapt to the weather situations of each considered month. In addition, regarding the period of coverage, we were able to carry out a temporary extension of the system from both ends of the temporary space, from April to October in the case study. The aim is to integrate months of the intermediate seasons between winter and summer, in order for instance to take into account human non-acclimation over potential heat waves that could occur in these intermediate periods.

In terms of methodology, as a second contribution, we have introduced a rule to determine the preliminary threshold on the basis of the characteristics of the weather event under study (heat wave). In order to reduce subjectivity in available heat systems, we considered a new approach to calculate the expected excess mortality as well as lag selection (respectively with the spline and the DLNM model). The latter was proposed in the case of recent pollution and cold systems ([26]; [27]).

Lagged indicators are selected to take into account the possible delay (in days) between the heat wave and the impact on mortality. The basic method includes four steps as detailed below:

a) Compute excess mortality (EM) relatively to a baseline;
b) Identify heat-related excess mortality episodes;
c) Select the maximum lags for the indicators;
d) Choose the optimal thresholds and associated indicators.

First, we proceed to the division of the database into a monthly basis. Then, the previous steps are applied to each month considered independently. Note that each month is treated partially alone in particular to obtain its own threshold. However, the final proposed system is a unique system for the whole period, i.e. includes all the months. The performance evaluation of the entire system which makes the connection between the months. More precisely, it is about the evaluation of the system as a whole (with criteria given below) and not each month separately. Note that during the realization of the analysis, we did not distinguish the data associated to known heat waves from other data, i.e. we used all available data, as it is the case in the literature (e.g., Casanueva et al. 2019, Chebana et al. 2013). These allow to verify the capacity of our approach to really detect heat events, this could not influence the final result of the system, since the idea of the method is to discriminate conditions leading to high levels of over-mortality compared to business-as-usual conditions. Moreover, Since the results are binary over the threshold (either dangerous or not), the results cannot be dominated by a single heat wave since, in this scenario, this heat wave would only be one of the episodes.

a) Excess Mortality Computation

Excess mortality is defined as the relative difference between observed deaths and baseline of expected deaths over a period of time. Formally, it is calculated as [26, 28]:

$$EM_t = \frac{OD_t - ED_t}{ED_t} * 100 \quad (1)$$

where OD_t is the number of observed deaths and ED_t is the estimated number of expected deaths on day *t*. The approach used here is the same as in Masselot, Chebana [26], the expected death is calculated by natural cubic splines with eight degrees of freedom per year for a total of 35 years. Note that the degree of freedom value is for the whole year, in order to account for the trend before the computation of EM for each month. Considering splines allow for a more flexible representation of seasonal variations and the long-term trend of mortality [26, 29]. The latter gave satisfactory results as shown in Figure 2 in results section below.

b) Identification of Heat-related Excess Mortality Episodes

Once EM_t is computed, the following step is to determine EM episodes, i.e. successive days that should be detected by the warning system. These days are those for which the EM value exceeds a predefined mortality threshold (noted S_{EM}). S_{EM} is chosen through careful examination of the curve of extreme values of EM_t compared to that of total values of EM_t as in Masselot et al. (2019). In addition, Tmax and Tmin of the same day have to be above preliminary temperature thresholds. This last condition ensures that the identified episode is likely heat-related (since the EM episode corresponds to the T episode). In the present study, preliminarily temperatures considered were: the 90th percentile for April, 95th for May, 92.5th for June-August, 95th for September, and 92.5th for October, corresponding the range of percentiles in the literature for the definition of a heat wave [30, 31]. The selection of these percentiles is obtained by computing the associated number of heat waves that should have occurred. By choosing the value of the different percentiles cited above as thresholds in the application of the heat wave definition. Note that the choice of these percentile values to determine the preliminary temperature is based on one of the characteristics of the phenomenon for each month individually, because its do not have the same reality or meteorological characteristic. in order to do this, we count the number of heat waves that should have occurred by choosing them as a priori alert thresholds for the triggering of heat wave days. For choosing, we used the criterion of heat wave rarity, i.e. the relative minimum number of heat waves that could possibly be generated by the value of the preliminary temperature. This allows us to distinguish heat-related mortality episodes from artifacts and to do not put all months on the same level, because it do not have the same weather reality or characteristic.

As Chiu, Chebana [32] indicated that the extreme peaks tend to occur in clusters, we combine consecutive EM exceedance days into one episode. In the present study, two EM peaks or "episodes" separated by less than 3 days are considered as a single episode (here, a heat wave).

c) Selection of the Maximum Lags for Temperature Indicators

The indicator used in the HHWWS consists of a weighted mean of lagged temperature. Using lagged temperature allows to take into account the effect that could occur after the hot day. It is denoted by $I_{m,t}^{(k)}$ for all $k \in \{Tmax, Tmin\}$, and is defined as follows:

$$I_{m,t}^{(k)} = \sum_{j=0}^{l} \alpha_{j\_k} X_{m,t-j}^{(k)} \qquad (2)$$

Where $X_{m,t-j}^{(k)}$ are the values of the daily temperature (Tmax or Tmin, in the present case) for month *m* and lagged at day *t* minus the associated lag *j*, and α_{j_k} are weights such that $\alpha_{0\_k} \geq \alpha_{1\_k} \geq \cdots \geq \alpha_{l\_k}$ (condition 1) and $\Sigma_j \alpha_{j\_k} = 1$ (condition 2). The first condition ensures that the weighting assigned to each day decreases with the horizon, ensuring that the system, once implemented, will account for the decreasing accuracy of temperature forecasts with the horizon. Note that the weighting decreases with the time horizon means that the accuracy of forecasts decreases with the number of the considered days (e.g. Lorenz 1982). The second condition defines a weighted average for the indicators to be on the same scale as their respective temperature variables.

The purpose of the present step consists in determining the maximum lag l of indicators in equation (2). This is chosen by examining the lag response relationship between extreme temperature and mortality estimated using a distributed lag non-linear model (DLNM [33]. The temperature dimensions of the DLNM surface is modelled through a penalized spline (Gasparrini et al. 2017) and the lag dimension through a natural spline with three knots. Unmeasured confounders are included as a natural spline of time with four degrees of freedom for the day of the season and one degree of freedom per decade for interannual trend as in Gasparrini, Guo [35]. The measured confounders used is relative humidity. A quasi-Poisson family is used to account for over-dispersion as in Gasparrini, Armstrong [33].

d) Selection of the best health-based temperature thresholds and associated indicators

The objective of this final step is to determine the optimal thresholds S^{Tmax} and S^{Tmin}, as well as indicator weights α_{j_k}. They are chosen based on the comparison between detected alerts (modeled episodes) and actual EM episodes. Thus, for given weighting and threshold values, the estimated heat waves episodes are such that $I_{m.t}^{(Tmax)} > S^{Tmax}$ & $I_{m,t}^{(Tmin)} > S^{Tmin}$.

As in Chebana, Martel [11], the quality of each weighting and thresholds combination is assessed using the following criteria: i) sensitivity, which is the probability of detections being actual EM episodes; ii) number of false alerts (FA) which are estimated EM that are not actual EM episodes. The best modelled system is the one with high sensitivity, the minimum number of false alerts.

3 Results

In this section, we present the obtained results of the data of Greater Montreal area and then we consider a sensitivity analysis.

3.1 Results of the proposed methodology

The following results are obtained by following the above four steps of the presented methodology.

a) Excess mortality

Step 1 of the methodology seeks to estimate EM as a function of the expected deaths through equation (1). Figure 2 below shows the interest of using the spline approach to quantify the expected deaths. Descriptive statistics of the estimated daily excess mortality are presented in Table 1 (all the EM series are presented as figures in the next steps).

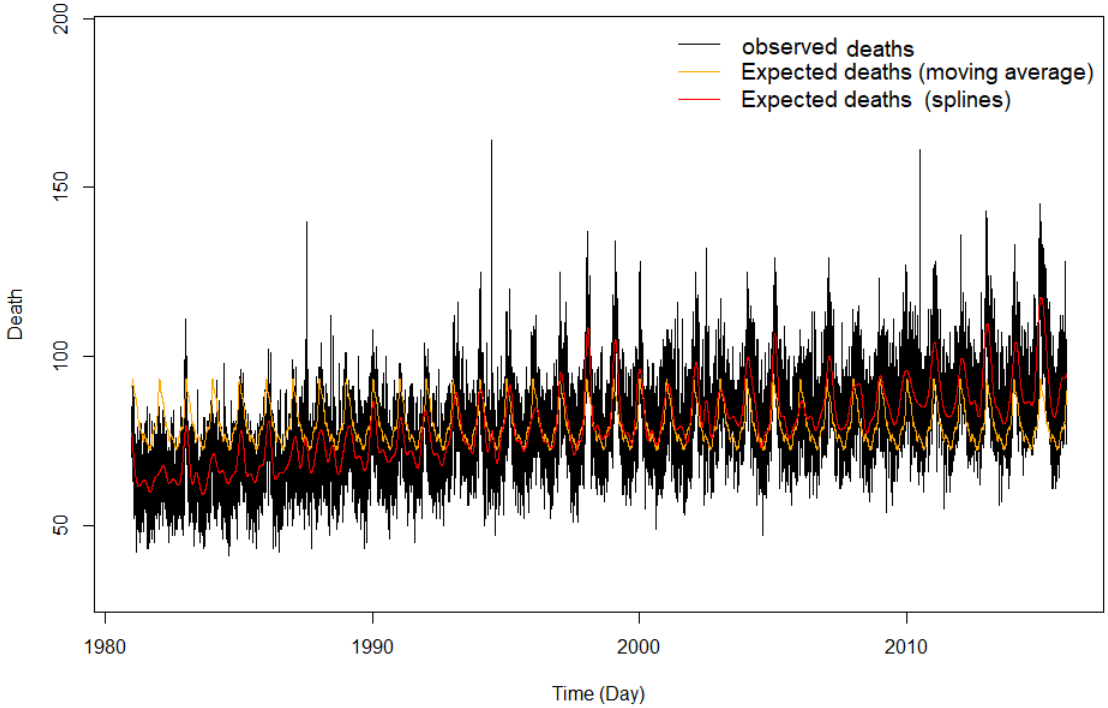


Figure 2 : Daily observed deaths with the expected death estimate using the moving average (orange) and splines (red) for data from May to September

The results of Table 1 indicate that months not belonging to the warmest period (April, May, September and October) have roughly the same standard deviation of EM (with a difference of the standard deviation intra-season around 0.4), while the standard deviations of summer months are slightly higher (with an average difference around 0.8). This more important standard deviation of the summer months is probably related to the important EM maxima witnessed during this period (e.g., historical deadly heat waves). As for the summer season, June recorded the highest EM value (111.2%), it even exceeded that of the heat wave period of July 2010 (88.3%, which corresponds to the maximum value of the excess mortality compared to July).

Table 1. Descriptive statistics and standard deviation of the estimated daily excess mortality for the different months throughout the study period (%)

Month	Minimum	Mean	Maximum	Standard deviation
April	-38.1	0.4	44.8	11.7
May	-35.1	-0.1	40.3	12.2
June	-33.8	0.2	111.2	13.4
July	-35.7	0.6	88.3	14.2
August	-36.3	-1.0	40.9	12.3
September	-35.1	-0.5	40.9	12.1
October	-34.3	2.2	48.9	11.8

b) Heat-related excess mortality episodes

Before identification of the episodes, the present sub-step aims at choosing the EM threshold above which a day is included within an episode. Figure 3 shows the number of EM episodes obtained for different S_{EM} values for each month. Note that for the sake of clarity, from there all results are presented in three seasons (spring: April and May, summer: June, July and August, autumn: September and October). Regarding April and May, Figure 3a shows that for values of S_{EM} higher than 35%, the number of heat-related EM episodes and the total number (unconstrained) of episodes are equal to zero for both months. Thus, we consider respectively the S_{EM} equal to 10% and 30% as EM thresholds of April and May, which corresponds to one episode for each one.

Figure 3b indicates that the EM episodes associated with threshold values above 45% are almost all related to heat for July. We therefore choose S_{EM} equal to 50% for June, and 40% for July and August with one, four and one episode respectively.

For the autumn months, Figure 3c, the outcomes are similar to the results of the spring months. We then choose the values of 30% and 10% as preliminary thresholds for September and October, which corresponds to two and one episode respectively.

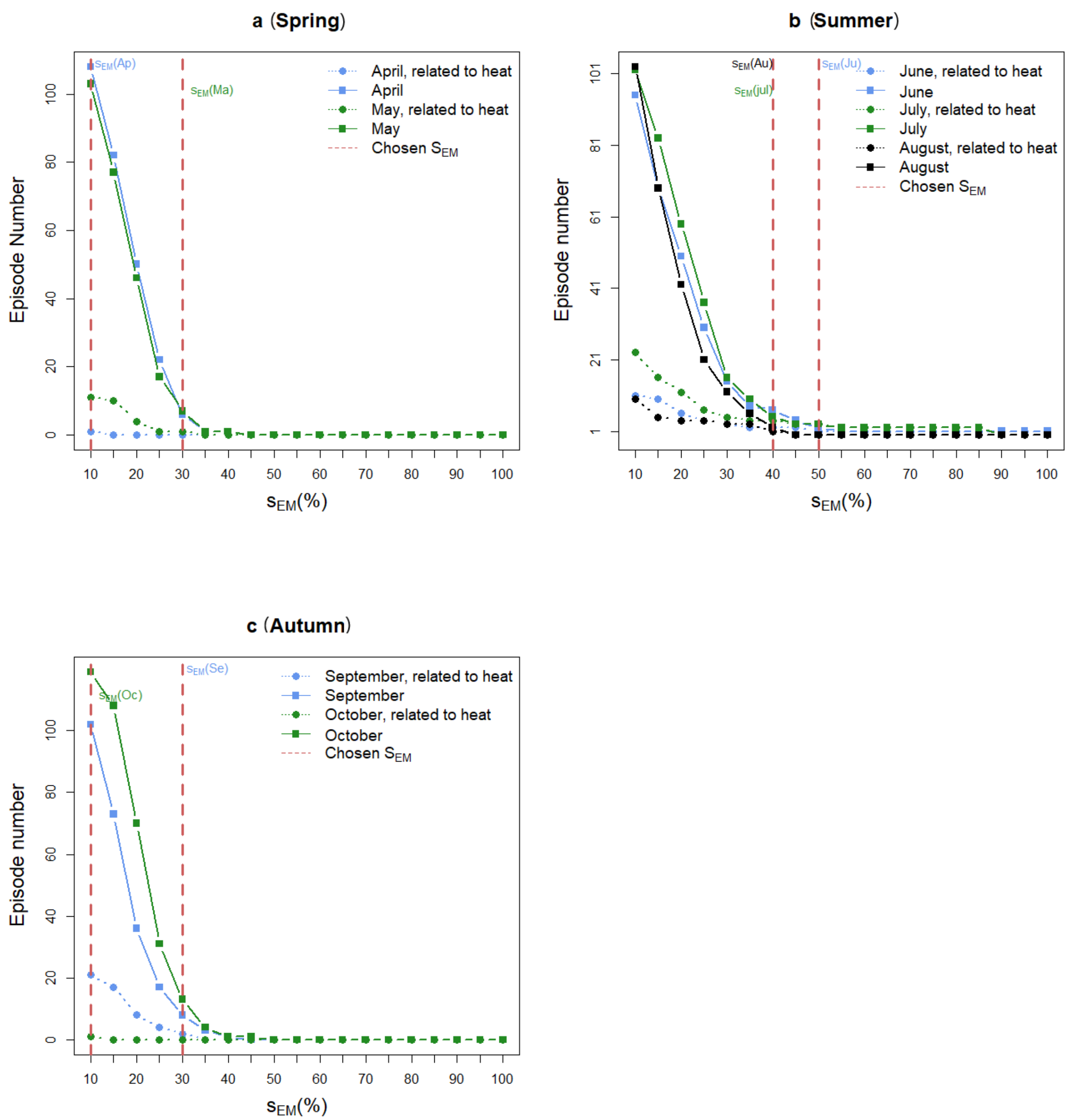
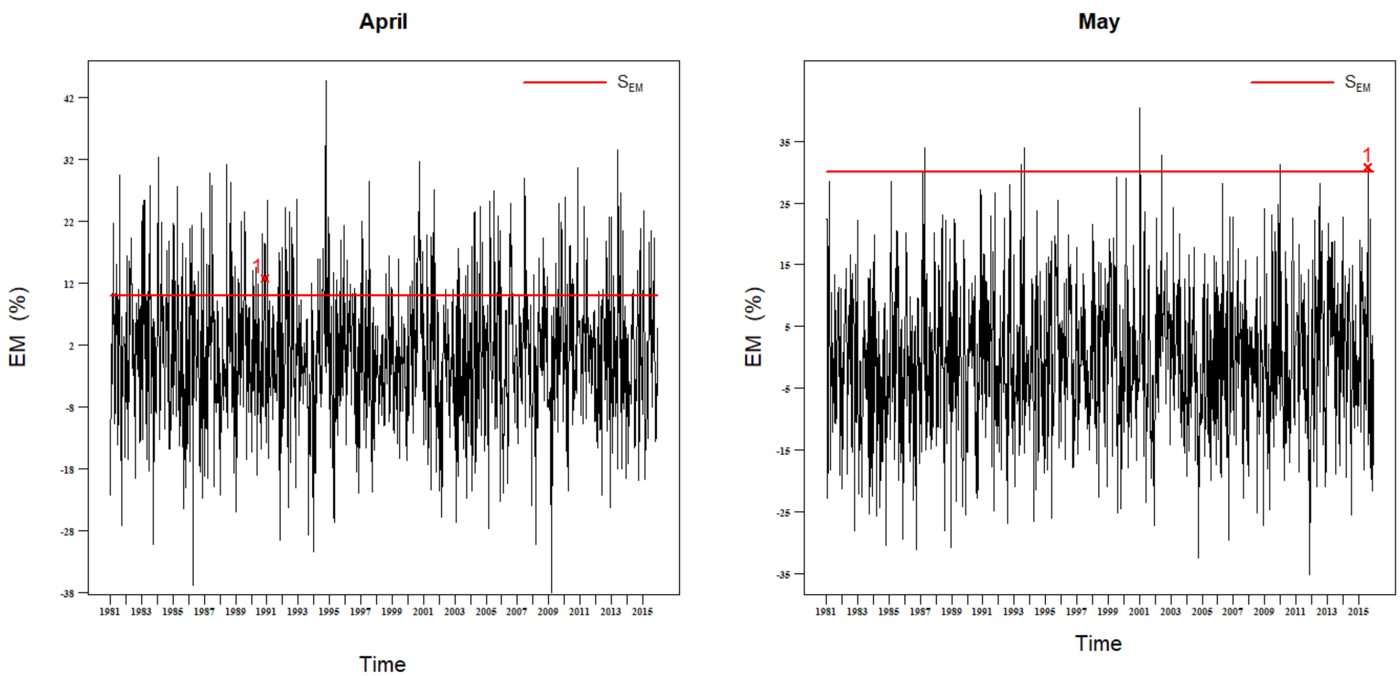


Figure 3: **Number of excess mortality (EM) episodes related to heat (dotted lines) and total number of EM episodes (full lines) according to threshold values of EM (S_{EM}) between 10 and 100%, for each month combined in season, with the chosen S_{EM} for the different months.**

Figure 4 shows the computed EM series along with the EM episodes identified through the S_{EM} thresholds obtained in the previous step. The highest number of EM episodes observed is in the months of July (4 EM episodes) and the lowest is recorded during all other months with 1 episode, except September which counts 2.



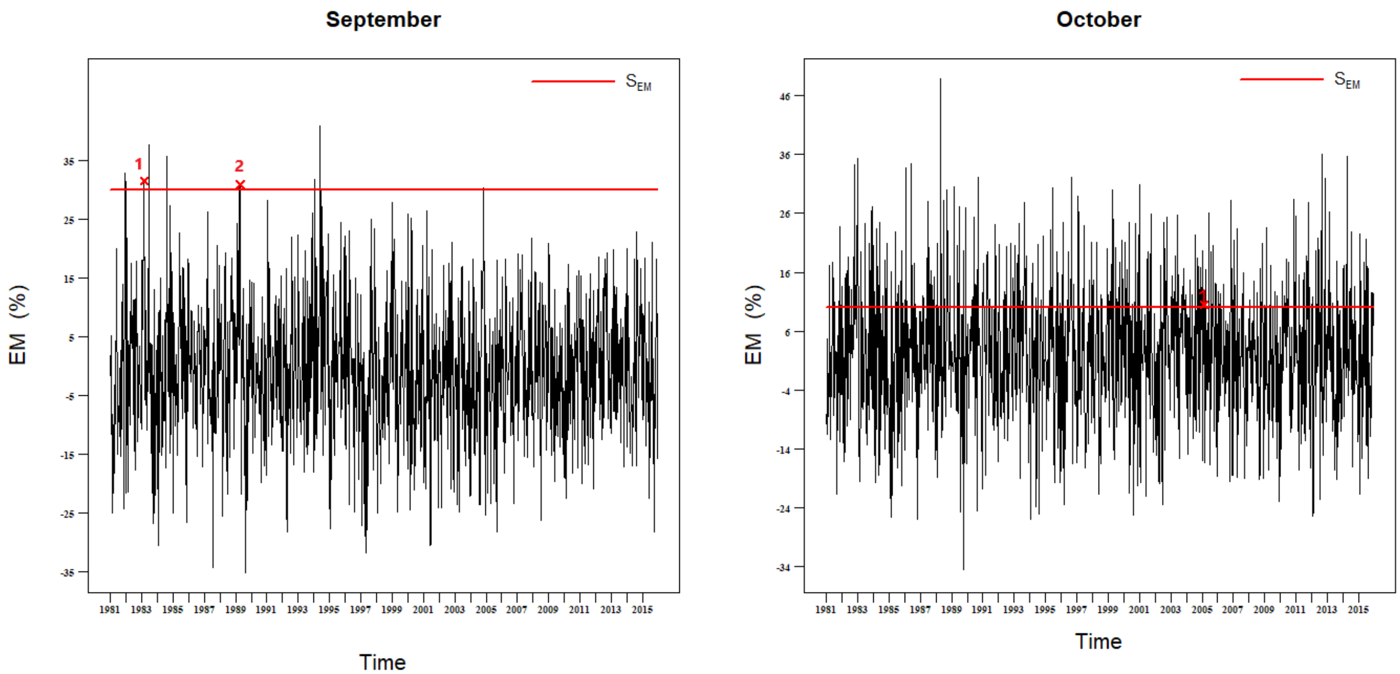


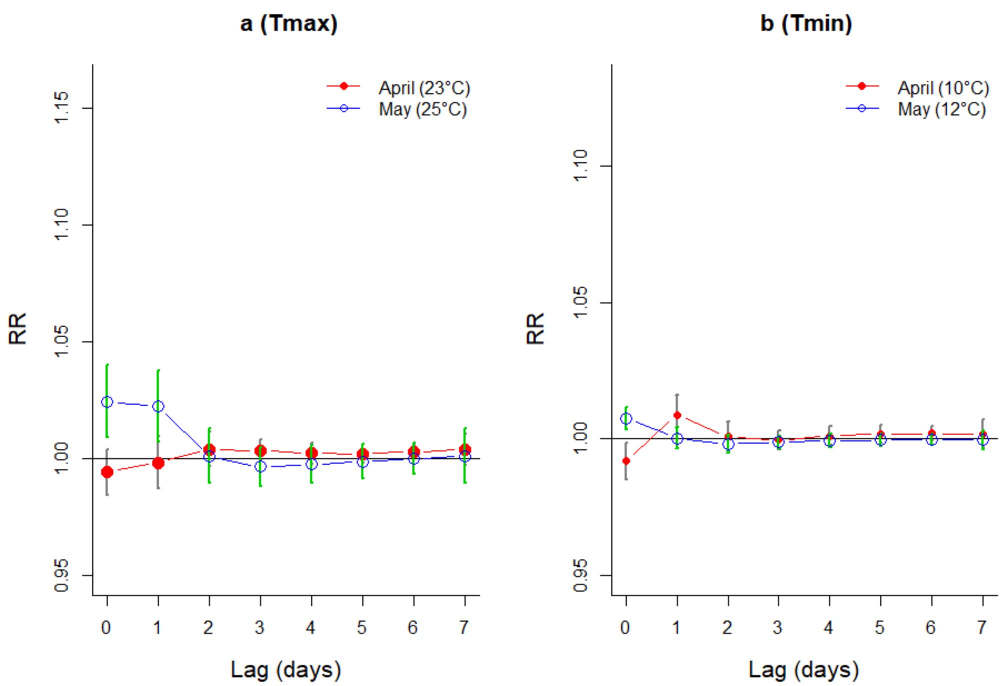
Figure 4: **Daily excess mortality (EM) estimation with the identification of EM episodes (numbering) and S_{EM} threshold indicator (horizontal segments) according to each period of the month.**

c) Selection of lags for the indicators

Figure 5 shows slices of the DLNM surface at each preliminary temperature threshold determined in section 2.2. For spring months, Figure 5a shows that RR are significantly higher than 1 only for lags 0 and 1 for May. In April, the RR trend is different with a negative association for the smallest lags, probably due to late cold days. We therefore choose l=1 for the Tmax indicator in April and May. Regarding Tmin, Figure 5b illustrates that the lag-response relationship for May reaches its highest RR for lag 0 and then remains stable around RR values not significantly different from 1. In April it is at lag 1. The maximum lag for the Tmin indicator is then chosen at l=1 for both May and April.

For Tmax, Figure 5c shows that the RRs for all summer months are strongly significant with a lag 0, but remains significant at lag 1. We observe the same thing at lag 0 and at lag 1 the RR stays around 1 for Tmin (Figure 5d). Thus, we choose an indicator based on lag 1 for Tmax and Tmin of all summer months.

For Autumn months, Figure 5e suggests for Tmax a lag 0 with RR values significantly higher than 1 for September and then decreases to 1, but it is non-negligible at lag 1. October RR for Tmax is consistently around 1 for all lags. Although the RR of Tmin (Figure 5f) for the two months are close to 1 for lags 1, we choose a lag value equal to 1 for the Tmax and Tmin.



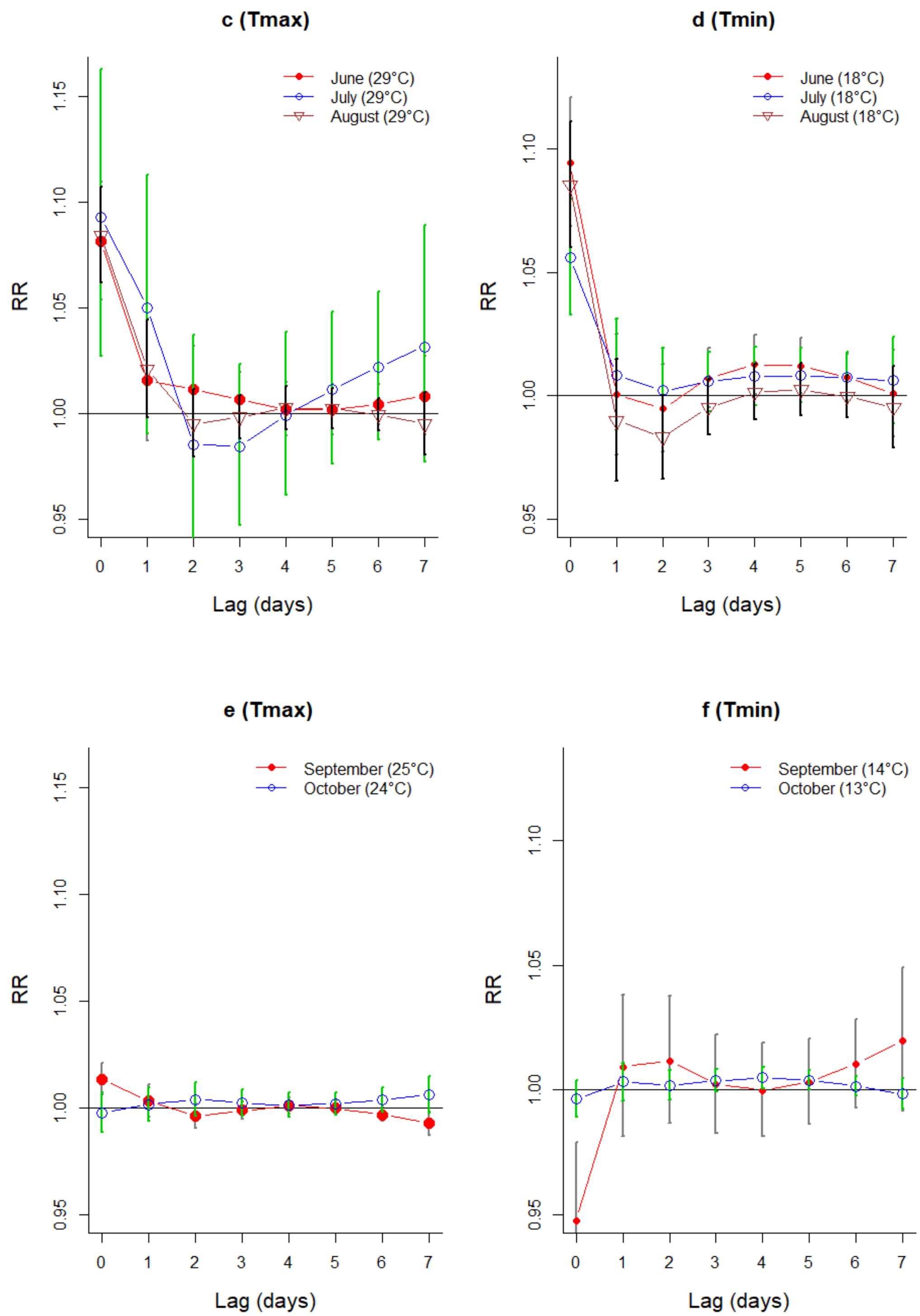


Figure 5: **Lag-response relationship between mortality and Tmax (a, c , e) and Tmin (b , d , f) at preliminary temperature values. Vertical bars represent the 95% confidence interval.**

d) Thresholds and Indicators of the System

Table 2 summarizes the results of the chosen temperature threshold values and indicator weights related to the different months. It shows that the Tmax indicator weights are mainly assigned to the first day of all months except for May, June, and August. For Tmin, weights found are based on two days. As expected, temperature thresholds increase up to July and decrease afterward. The criterion of performance indicates that the resulting system has a sensitivity of 100% and less than one false alert per year. These performance results are almost similar to those of the current system for which corresponds to class 1 in Chebana, Martel [11]. Note that as indicated in methodology, the corresponding values of performance evaluation (sensitivity and false alert) are not for the month, but for all the system.

Table 2: Indicator weights, thresholds, sensitivity and number of false alert (FA) per year for the various months

Month	Indicator weights				Thresholds (°C)		Sensitivity(%)	FA/year
	α_{0_Tmax}	α_{1_Tmax}	α_{0_Tmin}	α_{1_Tmin}	S^{Tmax}	S^{Tmin}		
April	1.0	0.0	0.8	0.2	23	12	100.0	0.1
May	0.5	0.5	1.0	0.0	27	13		
June	0.8	0.2	0.6	0.4	32	20		
July	1.0	0.0	0.7	0.3	32	21		
August	0.6	0.4	0.5	0.5	31	19		
September	1.0	0.0	0.6	0.4	28	19		
October	1.0	0.0	1.0	0.0	25	13		

3.2 Sensitivity Analysis

The selected lag to identify the final temperature thresholds are mainly based on estimated lag-response relationship of the DLNM. In addition, the constraint imposed on the weights (same or different weights for the construction of each indicator). Even though these choices lead to 100%

of sensitivity and 0.1 of FA, a sensitivity analysis is hereby performed to evaluate the sensitivity of model performances to the choice of two parameters: the maximum lag of the equation (2) and same/different weights for the two indicators (Tmax and Tmin). In particular, sensitivity to the choice of lag is evaluated by running the methodology using lag 2 (three days) as was the case in previous studies [11, 36]. Figure 6 shows the receiver operating characteristic (ROC) curve that relates sensitivity of the HHWWS to its number of false episodes per year, for each of the following designs. The first case is the system with lag equal to 1 and with the weighting constrained to be the same for both indicators. The second case uses a lag 2 and the weighting of indicators that differs. Finally, the third case also uses a lag 2, but with the same weighting of indicators. Note that the ideal ROC curve is the one that passes through the upper left corner of sensitivity =1 and false episode = 0.

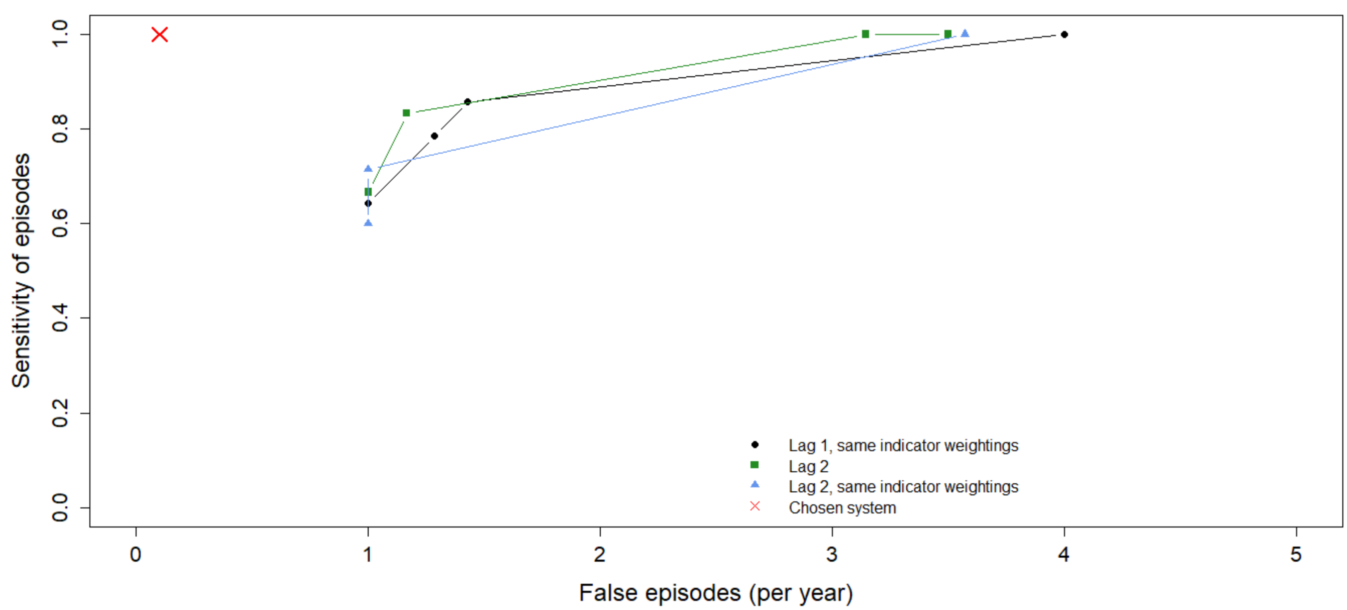


Figure 6: **Receiver operating characteristic (ROC) curves for different lag values used to develop the HHWWS, with the red cross represents the resulting system.**

Figure 6 indicates that the performance of the HHWWS is lower using $l = 1$ (case 1) with equal weights for both indicators compared to the cases with $l = 2$ (cases 2 and 3). Case 2 HHWWS shows a ROC curve close to the upper left corner. However, it remains less performant when compared to the obtained system in terms of the number of false episodes. This is consistent with the results show in Figure 5 that $l = 1$ is the lag that is somewhat significant compared to $l= 2$. Therefore, the choice of a system with $l = 1$ and different indicator weights is optimal.

4 Discussion

This study proposes for the first time a data-based heat-health watch and warning systems (HHWWS) that can adapt the mortality-related temperature thresholds to the months of the seasons and heat waves detection over an extended season based on the characteristics of each month, especially with adaptive and evolving threshold. To carry out our study, we used meteorological and health data. however, the health data are all-cause deaths without distinction of accidental deaths. because this allows us to have relevant/credible thresholds. It has even been already addressed in the study by Chebana et al. (2013) on practically the same data set. In this paper, both all-cause and non-accidental deaths were studied with little differences between the two cases. The scientific literature on this aspect has focused on the summer season and often more specifically on the hottest four months of the year [30]. Most authors use a single threshold for the whole summer season and with an excess mortality threshold at 60% [9, 11-13]).

The proposed approach for the definition of these thresholds is an extension and a generalization of the approach currently used in Quebec [11], especially the evolving aspect of the threshold. These improvements include the determination of a rule to filter out potential deaths related to heat, the formulation of the indicator, as well as the determination of lags to be considered in the construction of the indicators.

It should be noted that among the 4 EM episodes in July, we found two that were detected in the study of Giroux, Chebana [37]. One among the EM episodes is related to the 2010 heat wave that occurred in Quebec. This could confirm that the choice of monthly resolution also allows for a good characterization of the heat wave following each specific period. As a result, the model is able to distinguish between true positive and false positive. Previously published health-related heat thresholds [11, 37] for the same geographical area (Greater Montreal area) is shown in Table 3 in order to compare them with the present results (Table 2). Having split the system in monthly intervals did not shown aberrant results compared to a system taking into account the hole extended summer.

The threshold values of Tmax and Tmin obtained in the present study applied to months April-October vary from 23 to 32 for Tmax and from 12 to 21 for Tmin. The average Tmin threshold for the summer months is similar to those currently used by the national HHWWS in the same area of interest (Table 3). The one of Tmax has a difference of 1 °C. Even if we look at the monthly thresholds for June, July and August this proximity stay ranges from minus 1 to 2 °C for the threshold of Tmax and minus or plus 1 the threshold of Tmin. Nevertheless, they have the same performance, therefore the median threshold of May-September of present study could be more anticipatory with a threshold of (32,21) versus (33,20).

Table 3: Indicator weights, thresholds currently in use and the present study in the Greater Montreal area.

Geographical area	Season	Lag	Indicator weights α_0		α_1		α_2	Thresholds (°C) S^{Tmax}	S^{Tmin}	Performance results Sensitivit (%)	FA/ year
Greater Montreal area[2] [11]	May-September	2	0.4		0.4		0.2	33	20	100	0.12
The present study (median result)	May-September	1	0.8	0.7*	0.2	0.3*	n.a	32	21	100	0.10

[2]: Excludes Laurentides, *: represents α0 and α1 of Tmin, n.a: there is no α_2 in the case of the present study

In addition to the validations that have been made through the measurements of performance, sensitivity and number of false alarms, we also have observations for the month of May 2020 (provided by Environment and Natural Resources Canada) in which there is a heat wave that is produced in part of the area. This allows us to further demonstrate the reliability of the thresholds for May resulting from the proposed systems. If we want for the rest of the months it can be further verified with climatic scenarios.

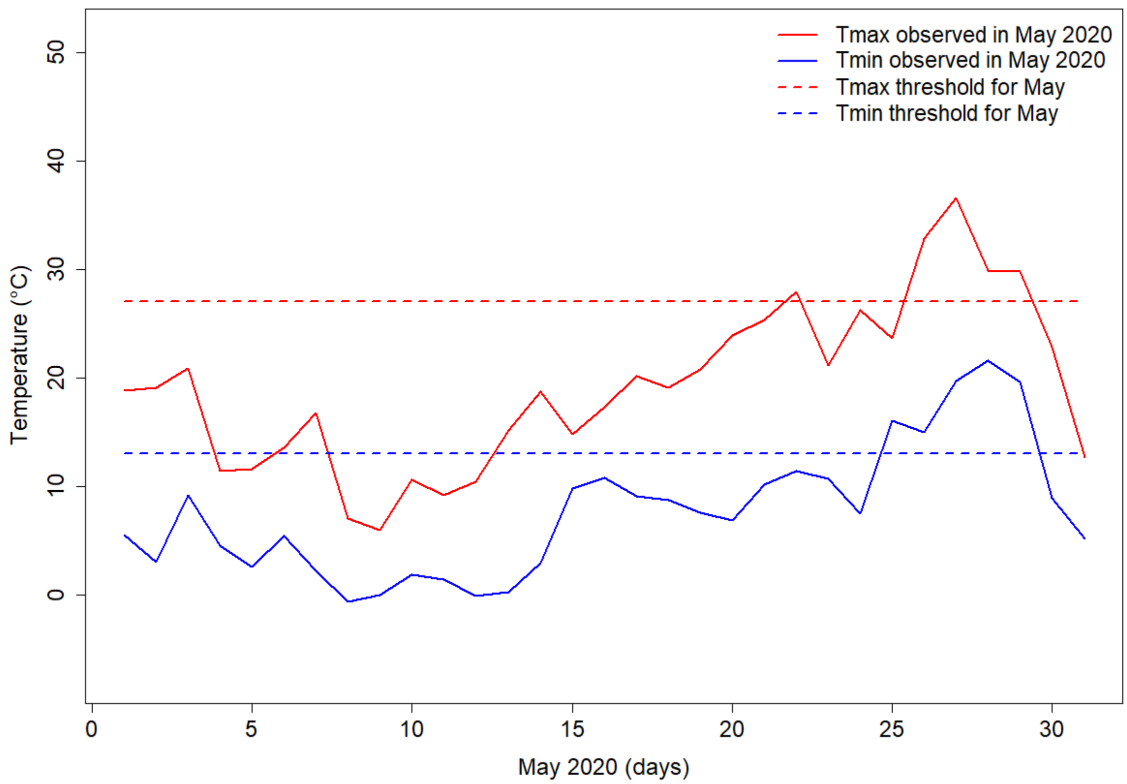


Figure 7: Comparison between the observations of May 2020 and the thresholds of proposed systems for May

Figure 8 presents the thresholds of the current and previous studies. This one illustrates well the staggered form of the thresholds for the coolest months at the most. We note that the Tmax threshold of June coincides with that of July and idem between August and September for the Tmin thresholds. This can be explained by the border effect between the different in question.

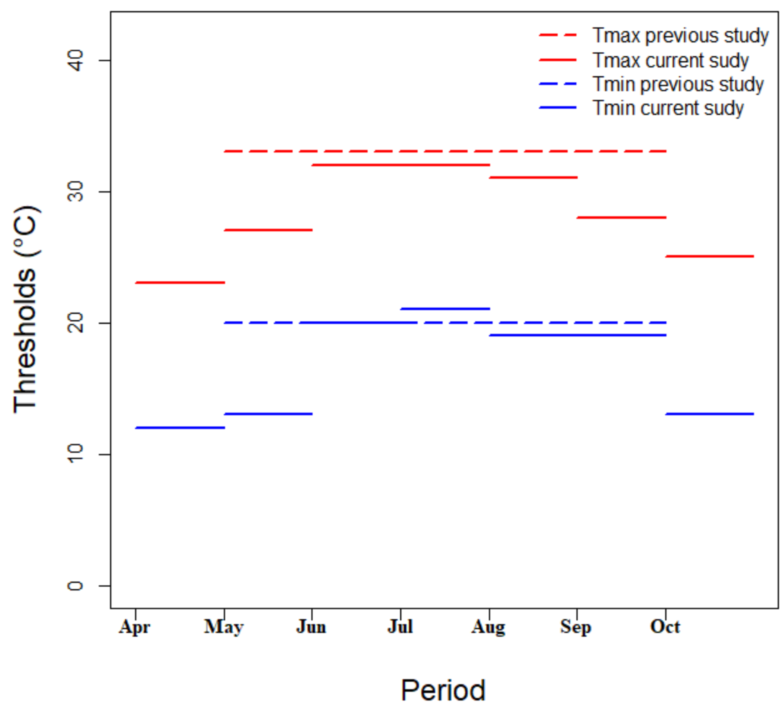


Figure 8: **Thresholds of previous study for the study Area from May to September and the thresholds of present study following months April-October**

The present system has some limits. The proposed approach to establishing an HHWWS with an evolving threshold is still subjective concerning the criterion of determining a threshold for excess mortality, since it is graphically-based. However, the foundation of this step is based on the characteristics of the phenomenon to be studied (heat wave) and its link with the health outcome (mortality). Other points of improvement could concern meteorological indicators (Tmax and Tmin) to be used, it could be interesting to test other indicators such as Wet-Bulb/ WBGT, Excess Heat Indices, UTCI, diurnal temperature range [38-40]. Another limitation of this study is do not consider the humidity as climate index. Humidity has a role to play in the effects of heat on human health and we have thought of integrating it in the model but unfortunately we could not consider it as a weather indicator for the determination of thresholds, because humidity is not observed and its forecasts are much less reliable than temperature. Moreover, it was found to be difficult to predict accurately some variables, such as dew point (Agence de la santé et des services sociaux de Montréal 2007). The role of humidity on mortality remains hence unclear in epidemiological studies (Armstrong et al.2019). Note that directly adding humidity in the model implies increasing the number of indicators, which will undoubtedly lead to a significantly more complex model for rare events, which will have impacts on the quality of the estimates. Therefore, we decided to not include it directly as a weather variable, but it is considered as a confounding variable in the DLNM. Except that it was found that it does not lead to any differences compared to the case in which it is not considered.

Humidity will hence probably be included in another level of development (e.g. in the construction of climate indices). We note that with the current warning system in place, humidity was used in the construction of an index to validate thresholds locally. However, it could be interesting in the construction of climate indices (eg, UTCI as in Jendritzky et al. (2012)). Another point could also be the edge effect, leading to a smooth threshold. This model ought to be updated frequently to insure the inclusion of take into account the changing climate variables. We can also see from Figure 4 with the data available on the months of April and October that it is not obvious to determine the EM threshold. However, this does not have too much influence on the statistical power of the final meteorological thresholds to identify excess mortality for the medium and long term.

5 Conclusions

In this paper, we developed a HHWWS that has adjusted thresholds for each month, taking into account the human acclimatization through seasons. This novel system covers an extended season over the year and can help public health authorities in preparing for heat waves, especially in the context of climate change. The proposed methodology is general and can be applied or adapted to other regions.

The proposed methodology is inspired by that of the current system, consists to determine meteorological threshold values (maximum and minimum temperatures) that could significantly increase mortality through the evaluation of the heat-mortality relation. The thresholds obtained start in April with 23°C for Tmax and 12°C for Tmin, to reach 32°C and 21°C in July, then back down to 25°C and 13°C in October. The final recommended thresholds per month and lags are summarised in Figure 9. The system could also be improved by considering other health outcomes such as hospital admissions.

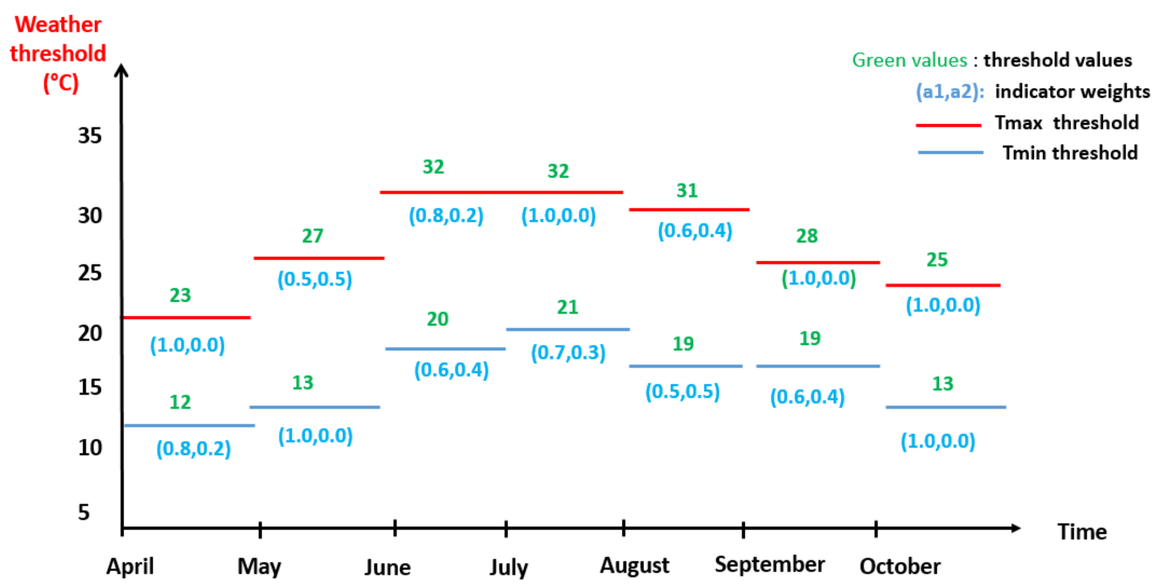


Figure 9: Final recommended thresholds per month and lag is always 2 except when a2 is equal to zero lag becomes 1

List of abbreviations

DLNM: Distributed lag non-linear model

EM: Excess mortality

FA: False alerts

HHWWS: Heat-health watch and warning systems

RR: Relative risk

S_{EM}: Predefined exceeds mortality threshold

Tmax: Maximum temperature

Tmin: Minimum temperature

UTCI : Indice universel du climat thermique

WBGT: Wet-bulb globe temperature

Declarations

Ethics approval and consent to participate

Spatially and temporally aggregated data (number per day over an entire region) are used, so no ethical considerations are needed.

Consent for publication

Not applicable.

Availability of data and materials

The meteorological data generated and/or analysed during the current study are available in the DayMet database repository, [https://daymet.ornl.gov/getdata]. The health data are available from the authors on reasonable request.

Competing interests

There are no competing interests to declare.

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Authors' Contributions

MAI: conclusive analysis, methodology, software, writing—original draft, visualization; FC: conceptualization, methodology, writing—review and editing, supervision, funding acquisition; PM.: validation, software, writing—review and editing; CC: conceptualization, validation, writing—review and editing, funding acquisition; ÉL: validation, writing—review and editing; PG: validation, writing—review and editing; TO: writing—review and editing. All authors have read and approved the manuscript.

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References

1. Mora, C., et al., *Global risk of deadly heat.* Nature climate change, 2017. **7**(7): p. 501-506.
2. WMO, W., *Heat waves and health: guidance on warning-system development.* World Meteorological Organization and World Health Organization. http://www. who. int/globalchange/publications/heatwaveshealth-guidance/en. Accessed, 2015. **12**.

3. Semenza, J.C., et al., *Excess hospital admissions during the July 1995 heat wave in Chicago.* American journal of preventive medicine, 1999. **16**(4): p. 269-277.
4. Robine, J.-M., et al., *Death toll exceeded 70,000 in Europe during the summer of 2003.* Comptes rendus biologies, 2008. **331**(2): p. 171-178.
5. Rahmstorf, S. and D. Coumou, *Increase of extreme events in a warming world.* Proceedings of the National Academy of Sciences, 2011. **108**(44): p. 17905-17909.
6. Otto, F.E., et al., *Reconciling two approaches to attribution of the 2010 Russian heat wave.* Geophysical Research Letters, 2012. **39**(4).
7. Bustinza, R., et al., *Health impacts of the July 2010 heat wave in Quebec, Canada.* BMC public health, 2013. **13**(1): p. 56.
8. Germain, L., D. Marjolaine, and B. Ray. *Surveillance des impacts des vagues de chaleur extrême sur la santé au Québec à l'été 2018*. 2019; Available from: https://www.inspq.qc.ca/bise/surveillance-des-impacts-des-vagues-de-chaleur-extreme-sur-la-sante-au-quebec-l-ete-2018.
9. Casanueva, A., et al., *Overview of existing heat-health warning systems in Europe.* International journal of environmental research and public health, 2019. **16**(15): p. 2657.
10. World Health Organization 2009, *Improving public health responses to extreme weather/heat-waves– EuroHEAT. Technical summary, 2009*.
11. Chebana, F., et al., *A general and flexible methodology to define thresholds for heat health watch and warning systems, applied to the province of Québec (Canada).* International journal of biometeorology, 2013. **57**(4): p. 631-644.
12. Pascal, M., et al., *France's heat health watch warning system.* International journal of biometeorology, 2006. **50**(3): p. 144-153.
13. McLean, K.E., et al., *Establishing heat alert thresholds for the varied climatic regions of British Columbia, Canada.* International journal of environmental research and public health, 2018. **15**(9): p. 2048.
14. Nicholls, N., et al., *A simple heat alert system for Melbourne, Australia.* International Journal of Biometeorology, 2008. **52**(5): p. 375-384.
15. Lowe, D., K.L. Ebi, and B. Forsberg, *Heatwave early warning systems and adaptation advice to reduce human health consequences of heatwaves.* International journal of environmental research and public health, 2011. **8**(12): p. 4623-4648.
16. McGregor, G.R., et al., *Heatwaves and health: guidance on warning-system development*. 2015: WMOP.
17. Perkins, S., L. Alexander, and J. Nairn, *Increasing frequency, intensity and duration of observed global heatwaves and warm spells.* Geophysical Research Letters, 2012. **39**(20).
18. IPCC, *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)]*. 2012, Cambridge, UK,

and New York, NY, USA: Cambridge University Press.

19. Ouarda, T.B. and C. Charron, *Nonstationary Temperature-Duration-Frequency curves.* Scientific reports, 2018. **8**(1): p. 1-8.
20. Fischer, E.M. and C. Schär, *Consistent geographical patterns of changes in high-impact European heatwaves.* Nature Geoscience, 2010. **3**(6): p. 398-403.

21. Basu, R. and J.M. Samet, *Relation between elevated ambient temperature and mortality: a review of the epidemiologic evidence.* Epidemiologic reviews, 2002. **24**(2): p. 190-202.
22. Lee, M., et al., *Acclimatization across space and time in the effects of temperature on mortality: a time-series analysis.* Environmental Health, 2014. **13**(1): p. 89.
23. Dessai, S., *Heat stress and mortality in Lisbon part I. model construction and validation.* International Journal of Biometeorology, 2002. **47**(1): p. 6-12.
24. Gasparrini, A., et al., *Changes in susceptibility to heat during the summer: a multicountry analysis.* American journal of epidemiology, 2016. **183**(11): p. 1027-1036.
25. Thornton, P.E., S.W. Running, and M.A. White, *Generating surfaces of daily meteorological variables over large regions of complex terrain.* Journal of Hydrology, 1997. **190**(3-4): p. 214-251.
26. Masselot, P., et al., *Toward an Improved Air Pollution Warning System in Quebec.* International journal of environmental research and public health, 2019. **16**(12): p. 2095.
27. Yan, B., et al., *A cold-health watch and warning system, applied to the province of Quebec (Canada).* Science of The Total Environment, 2020. **741**: p. 140188.
28. Litvak, E., et al., *Programme de vigie et de prévention des effets de la chaleur accablante à Montréal.* Direction de santé publique Montréal, 2005.
29. Bhaskaran, K., et al., *Time series regression studies in environmental epidemiology.* International journal of epidemiology, 2013. **42**(4): p. 1187-1195.
30. Guo, Y., et al., *Heat wave and mortality: a multicountry, multicommunity study.* Environmental health perspectives, 2017. **125**(8): p. 087006.
31. Smith, T., B. Zaitchik, and J. Gohlke, *Heat waves in the United States: definitions, patterns and trends.* Climatic change, 2013. **118**(3-4): p. 811-825.
32. Chiu, Y., et al., *Mortality and morbidity peaks modeling: An extreme value theory approach.* Statistical methods in medical research, 2018. **27**(5): p. 1498-1512.
33. Gasparrini, A., B. Armstrong, and M.G. Kenward, *Distributed lag non-linear models.* Statistics in medicine, 2010. **29**(21): p. 2224-2234.
34. Gasparrini, A., et al., *Mortality risk attributable to high and low ambient temperature: a multicountry observational study.* The Lancet, 2015. **386**(9991): p. 369-375.
35. Gasparrini, A., et al., *Temporal variation in heat–mortality associations: a multicountry study.* Environmental health perspectives, 2015. **123**(11): p. 1200-1207.
36. Pascal, M., et al., *Definition of temperature thresholds: the example of the French heat wave warning system.* International journal of biometeorology, 2013. **57**(1): p. 21-29.
37. Giroux, J.-X., et al., *Indicateurs et valeurs-seuils météorologiques pour les systèmes de veille-avertissement canicule pour le Québec. Mise à jour de l'étude de 2010 et développement d'un logiciel de calcul pour les systèmes d'alerte*. 2017, INRS, Centre Eau Terre Environnement.
38. Willett, K.M. and S. Sherwood, *Exceedance of heat index thresholds for 15 regions under a warming climate using the wet-bulb globe temperature.* International Journal of Climatology, 2012. **32**(2): p. 161-177.
39. Nairn, J.R. and R.J. Fawcett, *The excess heat factor: a metric for heatwave intensity and its use in classifying heatwave severity.* International journal of environmental research and public health, 2015. **12**(1): p. 227-253.
40. Jendritzky, G., R. de Dear, and G. Havenith, *UTCI—why another thermal index?* International journal of biometeorology, 2012. **56**(3): p. 421-428.
41. Barnett, A.G., S. Tong, and A.C. Clements, *What measure of temperature is the best predictor of mortality?* Environmental research, 2010. **110**(6): p. 604-611.

42. Höppe, P., *The physiological equivalent temperature–a universal index for the biometeorological assessment of the thermal environment.* International journal of Biometeorology, 1999. **43**(2): p. 71-75.
43. Oleson, K., et al., *Interactions between urbanization, heat stress, and climate change.* Climatic Change, 2015. **129**(3-4): p. 525-541.
44. Spagnolo, J. and R. De Dear, *A field study of thermal comfort in outdoor and semi-outdoor environments in subtropical Sydney Australia.* Building and environment, 2003. **38**(5): p. 721-738.
45. Vaneckova, P., et al., *Do biometeorological indices improve modeling outcomes of heat-related mortality?* Journal of Applied Meteorology and Climatology, 2011. **50**(6): p. 1165-1176.
46. Besancenot, J.-P., *Vagues de chaleur et mortalité dans les grandes agglomérations urbaines.* Environnement, risques & santé, 2002. **1**(4): p. 229-40.
47. Bustinza, R., G. Lebel, and M. Dubé, *Surveillance des impacts sanitaires des vagues de chaleur extrême au Québec: bilan de la saison estivale 2013.* 2014.
48. Dousset, B., et al., *Evolution climatique et canicule en milieu urbain: apport de la télédétection à l'anticipation et à la gestion de l'impact sanitaire.* 2011.
49. Goddard, L., et al., *Current approaches to seasonal to interannual climate predictions.* International Journal of Climatology: A Journal of the Royal Meteorological Society, 2001. **21**(9): p. 1111-1152.
50. Gosselin, P. and D. Bélanger, *Recherche, impacts et adaptations de santé publique au nouveau climat du Québec.* Santé publique, 2010. **22**(3): p. 291-302.
51. Hajat, S., et al., *Impact of hot temperatures on death in London: a time series approach.* Journal of Epidemiology & Community Health, 2002. **56**(5): p. 367-372.
52. Hajat, S., et al., *Heat–health warning systems: a comparison of the predictive capacity of different approaches to identifying dangerously hot days.* American journal of public health, 2010. **100**(6): p. 1137-1144.
53. Hémon, D. and E. Jougla, *Surmortalité liée à la canicule d'août 2003: rapport d'étape.* 2003.
54. Honda, Y., et al., *Heat-related mortality risk model for climate change impact projection.* Environmental health and preventive medicine, 2014. **19**(1): p. 56-63.
55. Lee, J.Y. and H. Kim, *Projection of future temperature-related mortality due to climate and demographic changes.* Environment international, 2016. **94**: p. 489-494.
56. Li, T., R.M. Horton, and P.L. Kinney, *Projections of seasonal patterns in temperature-related deaths for Manhattan, New York.* Nature Climate Change, 2013. **3**(8): p. 717-721.
57. Lin, Y.-K., et al., *High-temperature indices associated with mortality and outpatient visits: characterizing the association with elevated temperature.* Science of the total environment, 2012. **427**: p. 41-49.
58. Masato, G., et al., *Improving the health forecasting alert system for cold weather and heat-waves in England: a proof-of-concept using temperature-mortality relationships.* PLoS One, 2015. **10**(10).
59. Masterton, J.M. and F. Richardson, *Humidex: a method of quantifying human discomfort due to excessive heat and humidity*. 1979: Environment Canada, Atmospheric Environment.
60. McMichael, A.J., et al., *International study of temperature, heat and urban mortality: the 'ISOTHURM'project.* International journal of epidemiology, 2008. **37**(5): p. 1121-1131.

61. Medina-Ramon, M. and J. Schwartz, *Temperature, temperature extremes, and mortality: a study of acclimatisation and effect modification in 50 US cities.* Occupational and environmental medicine, 2007. **64**(12): p. 827-833.
62. Naumann, G. and W.M. Vargas, *A study of intraseasonal temperature variability in southeastern South America.* Journal of climate, 2012. **25**(17): p. 5892-5903.
63. Patz, J., et al., *Health impact assessment of global climate change: expanding on comparative risk assessment approaches for policy making.* Annu. Rev. Public Health, 2008. **29**: p. 27-39.
64. Price, K., S. Perron, and N. King, *Implementation of the Montreal heat response plan during the 2010 heat wave.* Canadian Journal of Public Health, 2013. **104**(2): p. e96-e100.
65. Sheridan, S.C., C.C. Lee, and M.J. Allen, *The mortality response to absolute and relative temperature extremes.* International journal of environmental research and public health, 2019. **16**(9): p. 1493.
66. Sheridan, S.C. and L.S. Kalkstein, *Progress in heat watch–warning system technology.* Bulletin of the American Meteorological Society, 2004. **85**(12): p. 1931-1942.
67. Stocker, T.F., et al., *Climate change 2013: The physical science basis.* Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change, 2013. **1535**.
68. Sung, T.-I., et al., *Relationship between heat index and mortality of 6 major cities in Taiwan.* Science of the total environment, 2013. **442**: p. 275-281.
69. Toloo, G., et al., *Evaluating the effectiveness of heat warning systems: systematic review of epidemiological evidence.* International journal of public health, 2013. **58**(5): p. 667-681.
70. Toutant, S., et al., *An open source web application for the surveillance and prevention of the impacts on public health of extreme meteorological events: the SUPREME system.* International journal of health geographics, 2011. **10**(1): p. 39.
71. Valois, P., et al., *Développement d'un indice d'adaptation à la chaleur chez les personnes habitant dans les 10 villes les plus peuplées du Québec.* Québec: Université Laval, 2016.
72. Xu, Z., et al., *Heatwave and health events: A systematic evaluation of different temperature indicators, heatwave intensities and durations.* Science of The Total Environment, 2018. **630**: p. 679-689.
73. Yang, J., et al., *Heatwave and mortality in 31 major Chinese cities: definition, vulnerability and implications.* Science of The Total Environment, 2019. **649**: p. 695-702.

Figure titles

Figure 1: Study Area, Greater Montreal area, the area is identified with the color red

Figure 2 : Daily observed deaths with the expected death estimate using the moving average (orange) and splines (red) for data from May to September

Figure 3: Number of excess mortality (EM) episodes related to heat (dotted lines) and total number of EM episodes (full lines) according to threshold values of EM (S_{EM}) between 10 and 100%, for each month combined in season, with the chosen S_{EM} for the different months.

Figure 4: Daily excess mortality (EM) estimation with the identification of EM episodes (numbering) and S_{EM} threshold indicator (horizontal segments) according to each period of the month.

Figure 5: Lag-response relationship between mortality and Tmax (a, c , e) and Tmin (b , d , f) at preliminary temperature values. Vertical bars represent the 95% confidence interval.

Figure 6: Receiver operating characteristic (ROC) curves for different lag values used to develop the HHWWS, with the red cross represents the resulting system.

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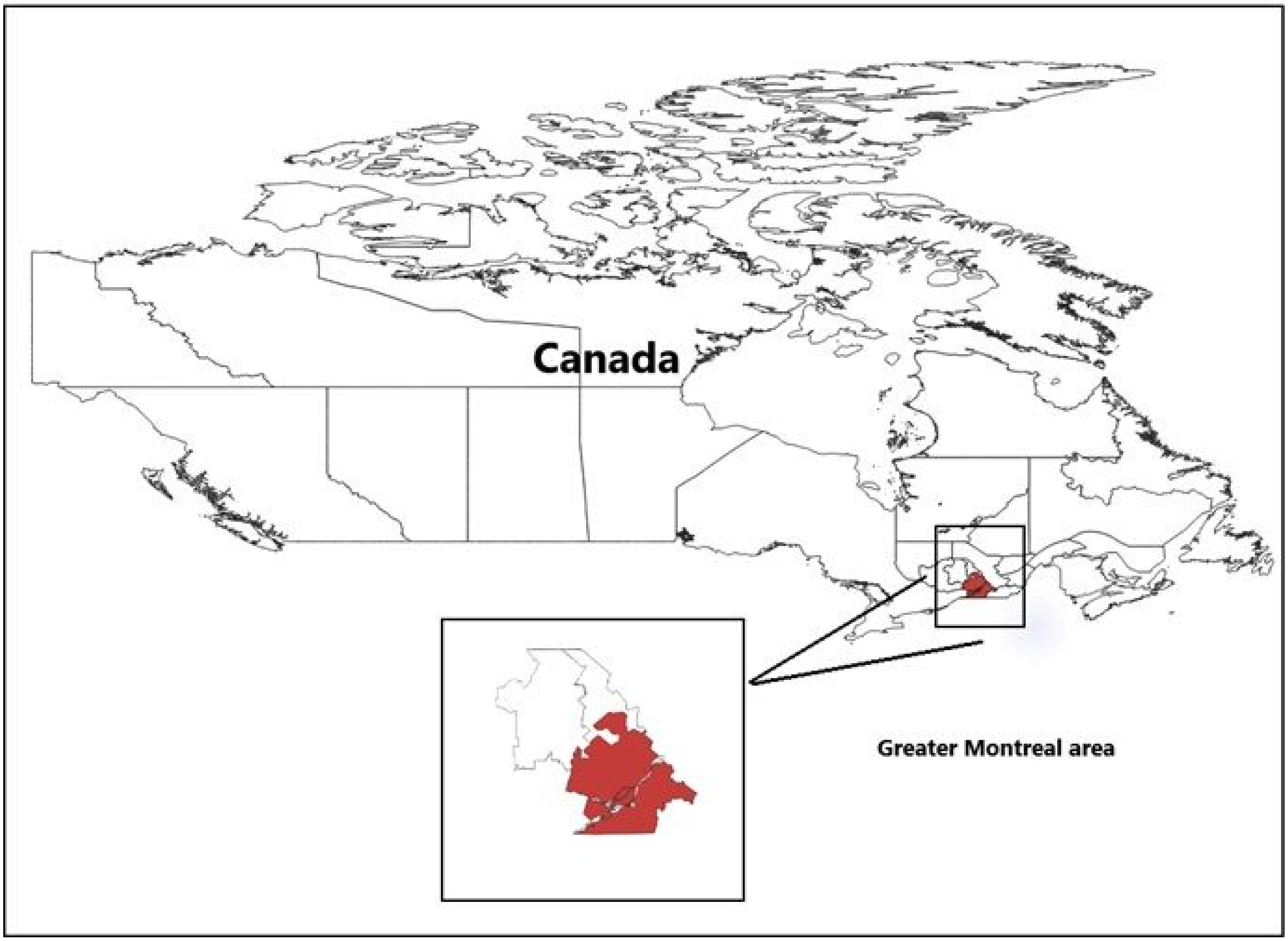
Figures



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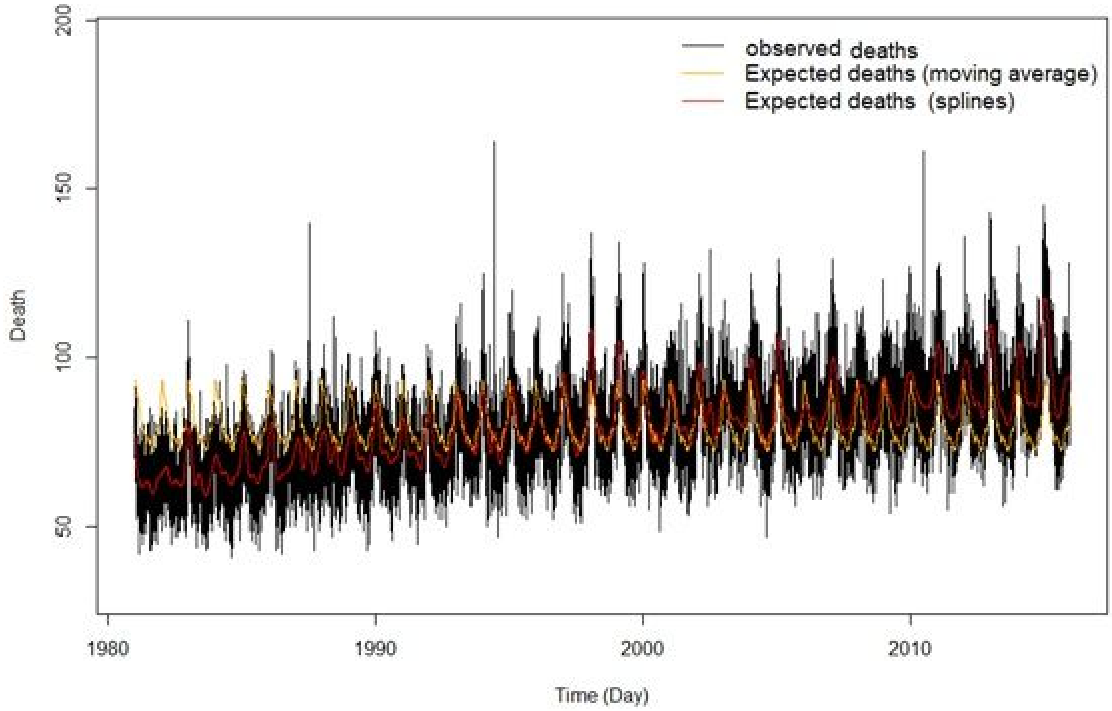

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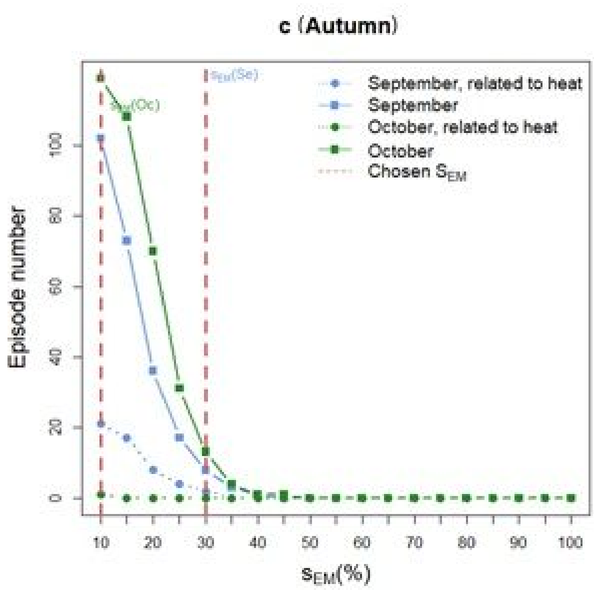

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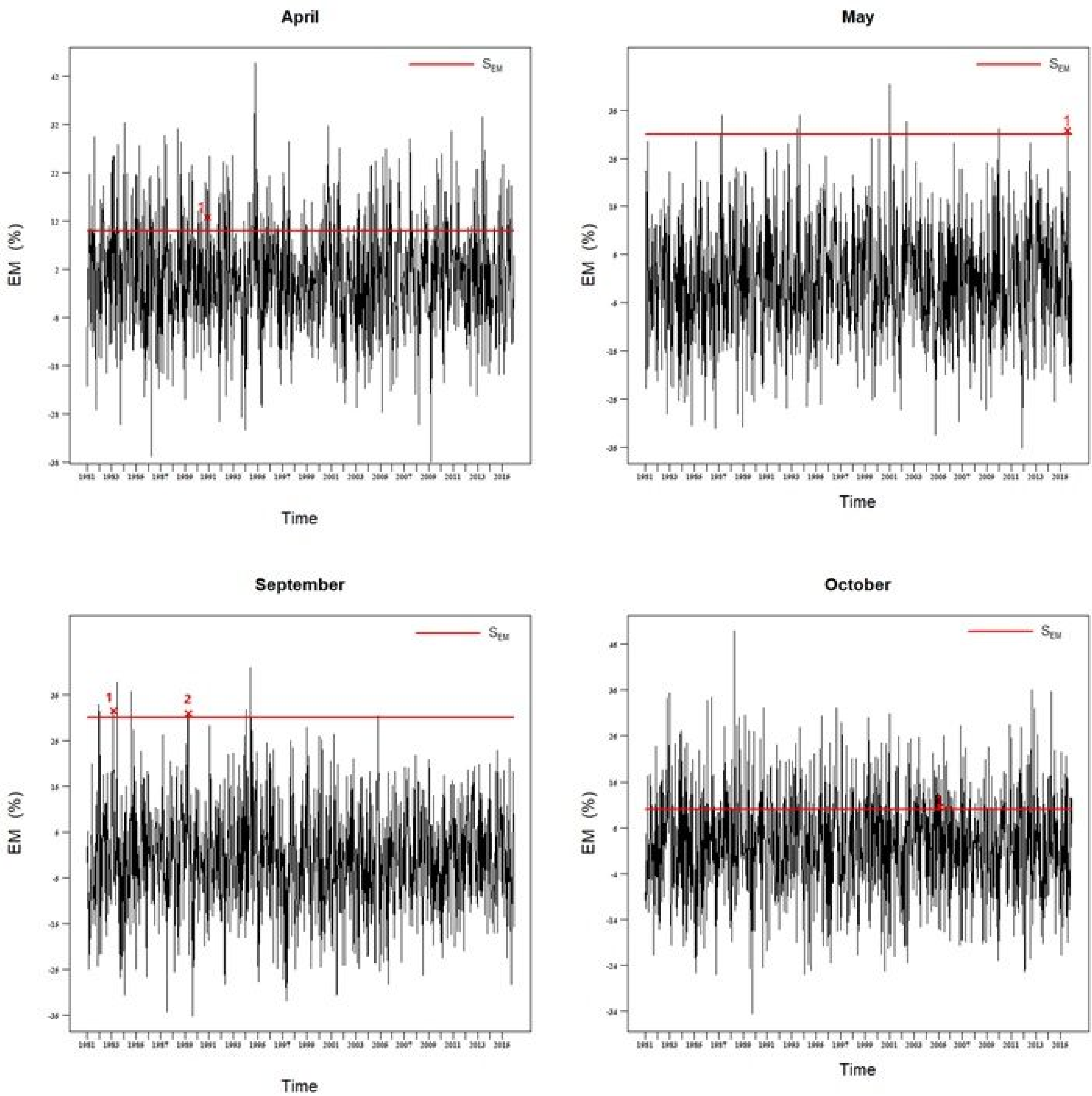

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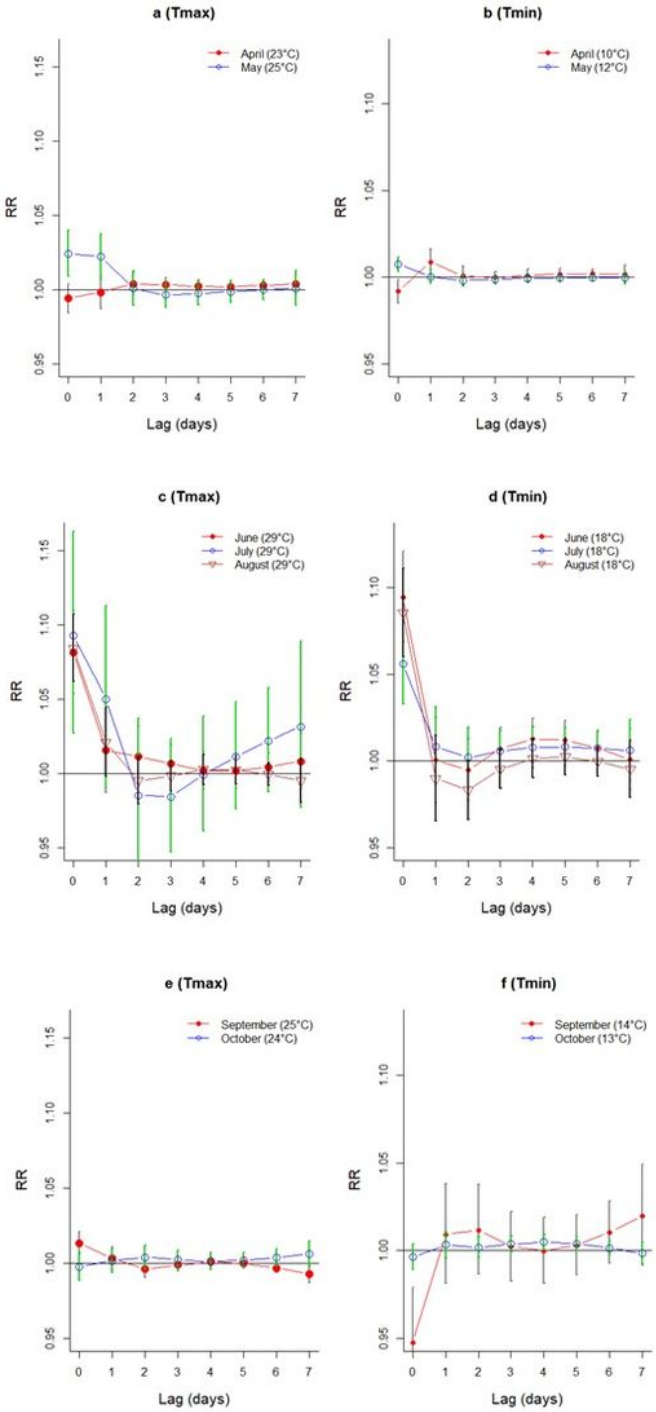

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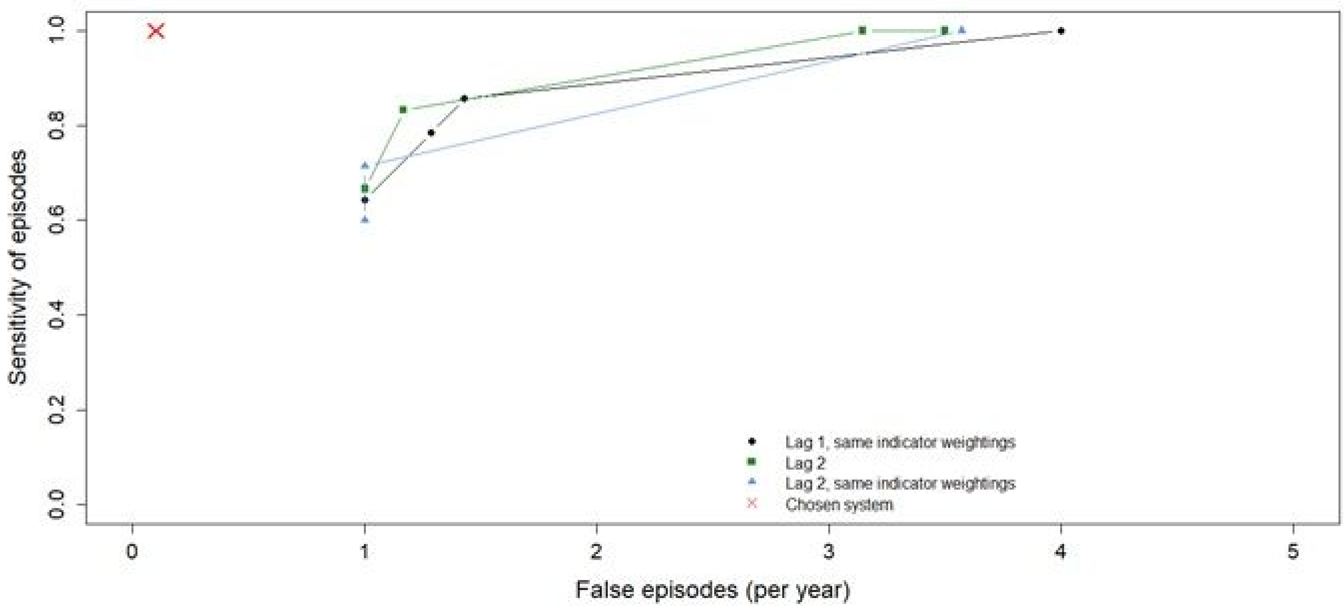

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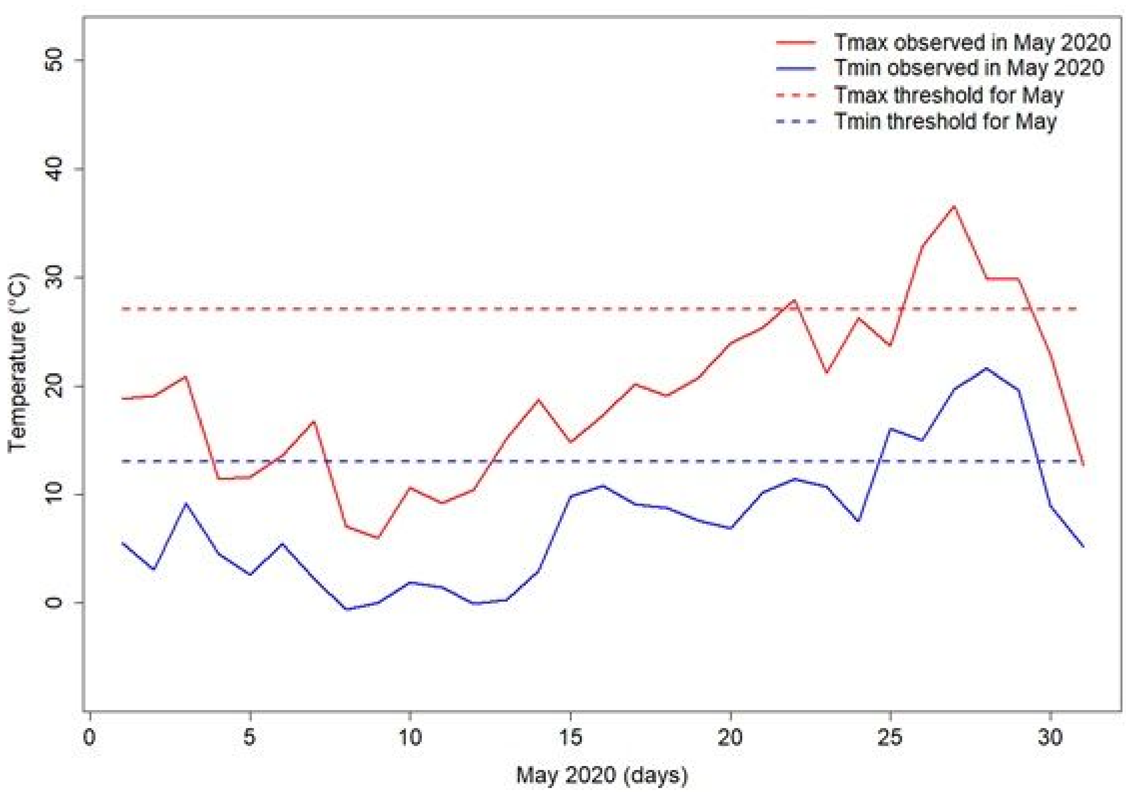

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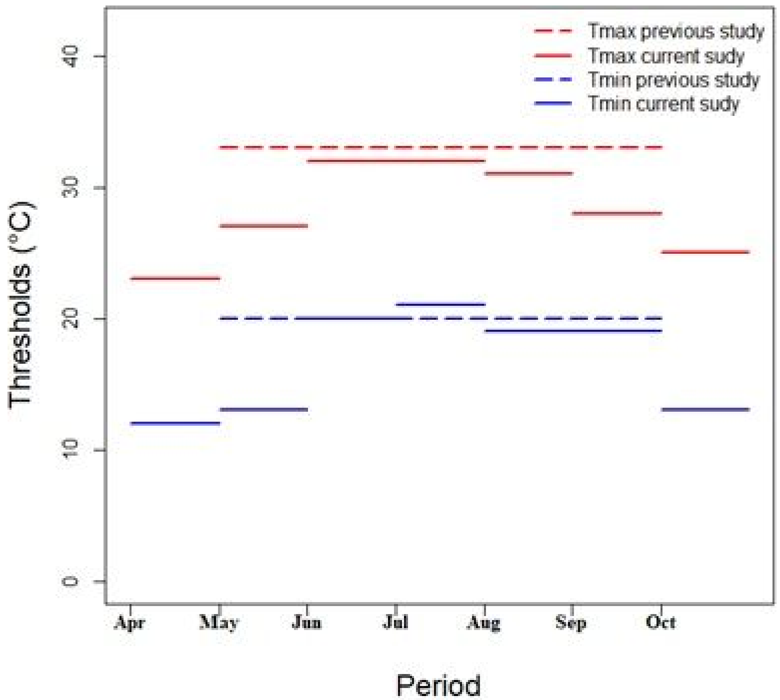

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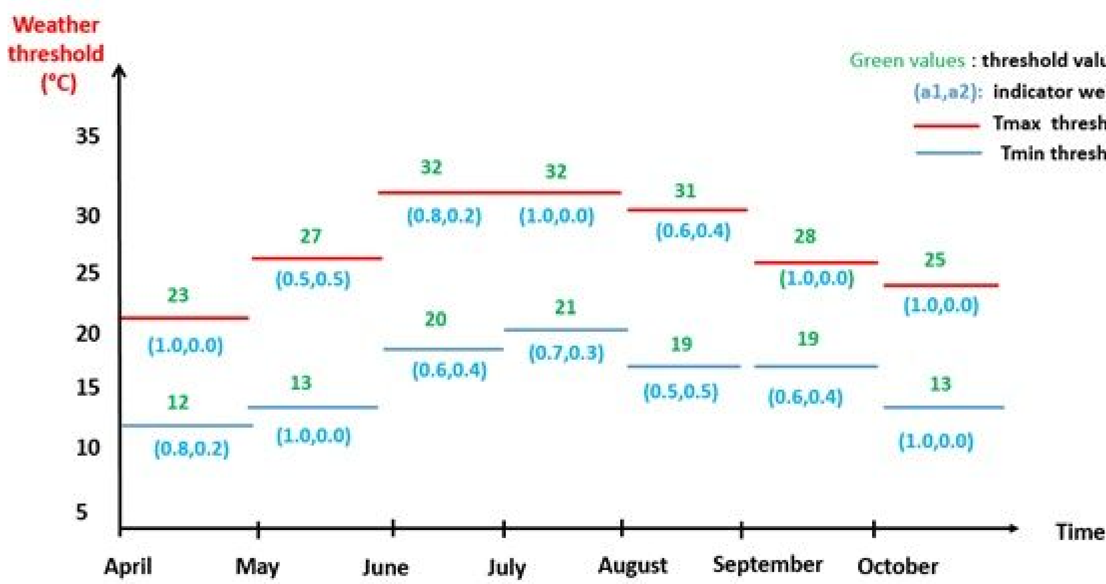

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Supplementary Files