Estimation of the mortality attributable to heat in France between 2014 and 2022

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Abstract

Heat waves are associated with large excess mortality in France, but the extent of the total-heat related mortality is unknown. We estimated the fraction of mortality attributable to heat in France during summers 2014 to 2022, to complement the estimations of all-cause excess mortality during heat waves.

Temperature-mortality relationships were developed for each of the 96 metropolitan French departments, for June-September, between 2014–2022. Several approaches were tested to control for a possible influence of the COVID-19 pandemic since 2020 (models including COVID-19 indicators, stratified models before/after the pandemic). The fraction of mortality attributable to heat was computed during summer and during heat waves.

Taking COVID-19 into account did not improved the models. Relative risks (RR) tended to be slightly higher after the pandemic; an increase from 19.8°C to 28.5°C was associated with a RR of 1.25 [CI 95% 1.21 :1.30] in 2004–2019, and 1.31 [1.24 :1.38] in 2020–2022. Between 2014 and 2022, 32,658 deaths [IC95% 29,612 : 34,975] were attributable to heat, 28% of these occurred during heat waves. The largest impacts are observed in 2022 (6,969 [6,277 : 7,445]), and 2019 (4,441 [4,086 : 4,717]).

Results suggest that a specific focus on heat waves is justified from an operational point of view; they represent 28% of the heat-related mortality impact concentrated on only 6% of summer days. However, this reactive adaptation during heat waves must be complemented by structural adaptation to reduce the risk throughout the summer.

1. Introduction

High temperatures have been identified by the Intergovernmental Panel on Climate Change as one of the climate risks of greatest concern in Europe, due to their effects on human health and ecosystems (Pörtner 2022). Exposure to heat (understood relatively as a high temperature compared to the usual climate) has multiple effects on health, resulting in increased morbidity and mortality. This influence of heat on mortality is non-linear, and is characterized by a strong increase in risks, for the most extreme temperatures (Gasparrini et al. 2015). It is also rapid, since the highest risk of mortality is observed less than 24 hours after exposure, and can be expected within 0 to 10 days (Pascal et al. 2018).

Between 1970 and 2022, more than 42,000 excess all-cause deaths were observed during heat waves in France, including nearly 11,000 between 2015 and 2022 (Pascal, Lagarrigue, et al. 2021). Outside of heat waves, non-extreme temperatures are also associated with an increased risk of death. Between 2000 and 2010, in 18 French cities, 13,855 deaths were attributed to heat, representing 1.2% [1.1 : 1.2] of total mortality in these cities. Approximately 29% of this heat-attributable mortality was associated with extreme temperatures (Pascal et al. 2018).

Summer 2022 in continental France was emblematic of the challenges raised by rapid climate change. High temperatures (close to the heat wave warning thresholds) were sustained during several months,
alternating with acute heat waves (above the heat wave warning thresholds). At the same time, record-breaking forest fires and drought were observed in several regions, while an increase in the number of COVID-19 cases was recorded. 2,800 excess deaths were observed during heat waves in 2022, and the total summer excess mortality was estimated to exceed 10,000 deaths according to the EuroMomo surveillance system (Santé publique France 2022).

This paper presents an approach to assess the total heat-related mortality in France, taking into account the COVID-19 pandemic, in order to complete the assessments specifically targeting the estimation of all-cause excess mortality during heat wave periods.

2. Method

2.1. Study areas and period

The study covers 96 departments of France, excluding overseas territories (considering the strong differences in climate and demography in those territories). Departments are the smallest geographical units currently used by the French heat warning system. The study period covers the summers (June-September) 2014 to 2022.

2.2. Mortality data

Annual population and daily mortality (total mortality, all ages and 75 years and older) was obtained for each department from the National Institute of Statistics and Economic Studies (INSEE). Mortality data per causes were not available for the most recent years (2017–2022), and therefore not investigated.

2.3. Temperature data

Daily minimum and maximum temperatures measured at each departmental station of the heat warning system were obtained from Météo-France (one station per department). Mean temperature was computed as the average between the minimum and maximum temperatures.

2.4. Data related to the COVID-19 pandemic

Four indicator were considered to investigate the possible influence of the COVID-19 pandemic on the temperature-mortality relationship:

- a binary "pandemic" indicator indicating the absence (summers 2014–2019) or presence (summers 2020–2022) of the pandemic during the study period,
- the daily departmental incidence rate for COVID-19 (République française 2022).
- the departmental daily number of hospitalizations for COVID-19 (République française 2022),
- the departmental daily count of hospital deaths for COVID-19 (République française 2022).
2.5. Temperature-mortality relationships

In each department, temperature-mortality relationships were built for mean temperature. The mean temperature was chosen based on several previous works which concluded that using mean, minimum or maximum temperatures, and whether or not humidity was taken into account, had very little influence on the performance and results of the models (Schaeffer et al. 2016; Pascal et al. 2018).

The temperature-mortality relationship was studied using a generalized linear model with a Poisson distribution of mortality taking into account the over-dispersion of the data. The model included average temperature, day of the week, seasonality and long-term trend.

Seasonality was modeled with a cubic natural-spline of day of year with four degrees of freedom per season and an interaction term between this spline and year. The association with temperature was modeled using non-linear distributed lag models (Gasparrini, Armstrong, and Kenward 2010), including 10-days of lag, with a cubic natural-spline with two internal nodes placed at the 50 and 90 percentiles of the mean temperature distribution (chosen based on the Akaike criteria). The association in the lag dimension was modeled using a natural-spline with two equidistant internal nodes in the log scale to allow more flexibility in the first part of the lag curve where more variability is expected.

To account for the possible influence of the COVID-19 pandemic, several models were tested:

- Models built over the period 2014–2022 (2014–2022 Models/COVID-19 Indicators) 1) without consideration of COVID-19, 2) with the pandemic indicator, 3) with the COVID-19 deaths indicator, 4) with the COVID-19 hospitalizations indicator, or 5) with the COVID-19 incidence rate indicator.
- Models stratified over the period without and with Covid (Model 2014–2019 and Model 2020–2022). The 2020–2022 models were built 1) without consideration of any Covid indicator, 2) with the COVID-19 death indicator, 3) with the COVID-19 hospitalizations indicator, or d) with the COVID-19 incidence indicator.

In a preliminary phase, several lags were tested for the COVID-19 hospitalizations and incidence indicators, and a period of 0–14 days before the day of temperature exposure was selected based on the Akaike criteria.

For each model, the estimated department-specific overall cumulative exposure–responses were combined using a random-effects model and a re-centered temperature-mortality relationship was then produced for each department following the methodology developed by Gasparrini et. al. (Gasparrini, Armstrong, and Kenward 2012; Gasparrini and Armstrong 2013).

2.6. Mortality attributable to temperatures

The re-centered temperature-mortality relationship were used to calculate the number of deaths attributable to temperature, according to the methodology described by Gasparrini et. al (Gasparrini and
Leone 2014).

The 50th percentile of the summer temperature distribution was chosen as a reference to identity hot days. The number of heat-related deaths (deaths attributable to temperatures during hot days) was calculated annually from the 1st June to the 15th September (corresponding to the operation of the French heat warning system) and during heat waves. Heat waves correspond to days when the 3-day moving average of minimum and maximum temperatures exceed departmental alert thresholds, as defined in the interministerial instruction for health management of heat waves. The thresholds applied were the alert thresholds used in 2022.

Two attributable fractions are calculated:

1) fraction attributable to heat from June 1 to September 15 = number of heat-attributable deaths / number of total deaths from June 1 to September 15.

2) fraction attributable to heat on hot days = number of deaths heat-attributable deaths / number of total deaths on hot days.

The first illustrates the weight of heat on mortality for the entire surveillance period and will be influenced by the number of hot days observed each year. The second highlights the importance of heat only on hot days.

2.7. Comparison with other estimates

Excess mortality during heat waves is estimated annually by Sante publique France (Wagner et al. 2018), based on the comparison between observed and expected mortality. Those data were extracted for each department from the public database geodes.santepubliquefrance.fr for 2014–2022.

The European climate change and health observatory proposes an estimation of the annual number of heat-related deaths per millions inhabitants per country, based on an approach develop for the Lancet climate countdown (van Daalen et al. 2022). Annual estimates for France were extracted for 2014–2022, and transformed into annual number of heat-related deaths based on the annual French population provided by INSEE.

3. Results

The analyses included 1,437,755 all-cause deaths, of which 964,330 (67%) involved persons aged 75 years and over. The annual number of deaths, all ages, and 75 years and older, has increased between 2014 and 2022 in all regions, while the proportion of deaths over 75 years old remained stable. At the departmental level, the average daily number of deaths varies from 2 to 59 depending on the department.

The total number of COVID-19 cases during the study period varied from 1,650,299 in 2020, to 8,010,271 in 2021 and 3,380,724 in 2022.
Average departmental mean temperatures over the entire period ranged from 18°C in the North to 26°C in the South (Fig. 1-a). In all departments, average temperatures were higher in 2022 (Fig. 1-b)

### 3.1 Temperature-mortality relationships

The 2014–2022 models without detailed COVID-19 indicators (deaths, hospitalizations, or incidence) were better, according to the Akaike criteria, than models incorporating those indicators. The same was true for models restricted to the period 2020–2022. All models tested show a similar "J-shaped" relationship, reflecting an increase in the risk of death with higher temperatures, for all-age mortality and for those aged 75 years and over (Fig. 2).

Figure 3 details the relative risks (RR) for the different models. The models using different COVID-19 indicators led to similar RR. In the stratified models, the RR tended to be slightly high for the period 2020–2022. For instance, an increase from 19.8°C (P50) to 28.5°C (P99.5) was associated with a RR of 1.25 [1.21 :1.30] in 2004–2019, compared to 1.31 [1.24 :1.39] in 2020–2022 (model without any COVID-19 indicator).

### 3.2 Mortality attributable to temperature

As all models gave very similar results in terms of the shape of the relationship and RR, the mortality attributable to temperature is presented for the stratified model, without any COVID-19 indicator. This model was preferred over the 2014–2022 model, as it allows to take into account a possible systemic influence of COVID-19 on the temperature-mortality relationship (influence on behaviors, medical management, socioeconomic vulnerability...).

Between 2014 and 2022, 32,658 all-age deaths [IC95% 29,612 : 34,975] were attributable to heat, and 28% of these deaths occurred during heat waves. 23,080 [21,076 : 24,556] deaths of persons aged 75 years and older were attributable to heat during this period (28% during heat waves).

The largest impacts were observed in 2022 (6,969 [6,277 : 7,445] excess deaths of which 29% during heat waves), and 2019 (4,441 [4,086 : 4,717] excess deaths of which 42% during heat waves). The impact was also greater than 4,000 deaths in 2018 and 2020. The contribution of heat waves to the total heat-related mortality was logically small in years with few heat waves, such as 2014, 2016, and 2021 (Table 1).
Table 1
– Annual mean summer temperatures, number of heat waves, and heat-related mortality during summer and during heat waves

<table>
<thead>
<tr>
<th></th>
<th>Mean summer temperature (°C)</th>
<th>Number of départements with at least an heat wave</th>
<th>Cumulated number of heat wave days across all départements</th>
<th>Heat-related mortality</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<td></td>
<td></td>
<td></td>
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<tr>
<td><strong>During summer (1st June – 15th September)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2014</td>
<td>19.1</td>
<td>5</td>
<td>30</td>
<td>1,103 [923 : 1,259]</td>
</tr>
<tr>
<td>2015</td>
<td>20.3</td>
<td>50</td>
<td>688</td>
<td>3,795 [3,477 : 4,059]</td>
</tr>
<tr>
<td>2019</td>
<td>20.6</td>
<td>86</td>
<td>1,055</td>
<td>4,441 [4,086 : 4,717]</td>
</tr>
<tr>
<td>2021</td>
<td>19.9</td>
<td>9</td>
<td>63</td>
<td>1,927 [1,673 :2,137]</td>
</tr>
<tr>
<td>2022</td>
<td>22.0</td>
<td>69</td>
<td>981</td>
<td>6,969 [6,277 :7,445]</td>
</tr>
</tbody>
</table>

Depending on the department and the year, up to 9.4% of the total summer mortality was attributable to heat. This attributable fraction was on average higher than 2.7% in 2015, 2018, 2019 and 2020, and higher than 4.1% in 2022. When the attributable fraction is calculated only on hot days (with a temperature above the 50th percentile), it averaged above 5% in 2015, 2019, 2020, and 2022 (Fig. 4).

The contribution of heat waves to the total heat-related mortality varies by year and department from 0 to 99% in Hérault in 2018 (corresponding to a summer in which hot days coincided almost completely with
3.3 Comparison with other estimates

The stratified model indicates that 9,018 deaths occurred during heat waves between 2014–2022. Over the same period, the reports of excess mortality during heat waves totalled 10,642 excess deaths (Table 2). In 2017 and 2019, the estimates of heat-related mortality during heat wave exceed the estimates of the total excess mortality during heat waves. However, estimates from the two approaches are largely consistent and overlapping (Table 2).

At the departmental level, the largest discrepancy between the two estimates was observed in 2020, in the Nord department, with an all-cause mortality estimated in the heat wave assessments of +353 deaths, vs. +199 attributable to heat as estimated by the model. The second largest difference was observed in Gironde department in 2022, with +182 excess all-cause deaths in the heat wave assessments, vs. +89 attributable to heat in the modeling.

Between 2014 and 2020, 23,762 deaths were attributable to heat in France using our models, vs 21,444 deaths based on the European climate change and health observatory indicator (Table 2). Estimates were largely consistent between the two sources after 2017.
Table 2
Comparison of the number of excess deaths during heat waves obtained by the model (attributable to heat), and by the heat wave assessments (all causes)

<table>
<thead>
<tr>
<th>Year</th>
<th>Heat-related mortality during heat waves [IC 95%]</th>
<th>Total excess mortality during heat waves [min; max]</th>
<th>Heat-related mortality during summer [IC 95%]</th>
<th>Estimated from the observatory indicator (Lancet Countdown in Europe 2022)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2015</td>
<td>1,161 [1,100:1,208]</td>
<td>1,739 [1,620:1,832]</td>
<td>3,795 [3,477:4,059]</td>
<td>3,135</td>
</tr>
<tr>
<td>2018</td>
<td>1,277 [1,191:1,350]</td>
<td>1,641 [1,071:2,164]</td>
<td>4,166 [3,716:4,520]</td>
<td>4,205</td>
</tr>
</tbody>
</table>

4. Discussion

4.1. Definition of heat and estimation of exposure

To compute heat-related mortality, epidemiological studies often use the temperature associated with the lowest risk of death (minimum mortality temperature (MMT)) to define heat (heat then corresponds to temperatures > MMT). However, we found that the MMT was very heterogeneous between departments (varying from percentile 0 to percentile 77 of the summer temperature distribution), and associated with large uncertainties. It is also difficult to communicate to non-epidemiologists. We preferred to estimate heat-related mortality based on the median of the summer temperature distribution (heat corresponds to temperatures > P50), as this definition of heat is easier to compare between departments, and to communicate to stakeholders. In the majority of the departments, the P50 fell within the confidence
interval of the MMT (data not showned). The European Observatory on Climate Change and Health observatory used the MMT, and find estimates consistent with ours.

In this study, we focus on the departmental level, which can mask sub-departmental contrasts in exposure and potentially in vulnerability and impacts. Although the departmental reference station of Météo-France is supposed to be representative of the exposure of the majority of the department's population, sub-departmental temperature variations can be significant, especially for coastal or mountainous departments or in areas experiencing a large urban heat island. Depending on the geographical distribution of heat each summer, this may lead to an under or overestimation of the impact compared to finer data.

The available information indicates the department of death, leading to the assumption that the heat exposure occurred in the same department. People who were exposed and died in two different departments are therefore incorrectly taken into account, but this represents a very small proportion of deaths, and has a very small impact on the results.

Finally, the study did not considered overseas departements due to their climatic and demographic specificities. Heat was also associated with an excess mortality in those territories, where specific prevention strategies should be developed (Pascal et al. 2022).

4.2. Influence of the COVID-19 pandemic

The different analyses suggest that the long-term trend and seasonality terms are sufficient to capture a possible influence of the COVID-19 pandemic. The results also suggest slightly higher RRrs for the highest percentiles over the period 2020–2022. In Portugal, a study estimated that the COVID-19 pandemic was responsible for at least a 50% increase in heat-related mortality in 2020 compared to what would have been expected without the pandemic, an impact that the authors explain by the disorganization of the health care system, and changes in people's behaviors (less use of health care) (Sousa et al. 2022). The state of health of the population, socio-medical care and social links are important factors of vulnerability or resilience to heat, and any event that significantly modifies them can lead to an aggravation of the impact of heat waves.

4.3. Air pollution

The modeling could not take into account ambient air pollution (departmental pollution indicators are not very meaningful). In the literature, several studies show a negative synergy between temperature and air pollution (Son, Liu, and Bell 2019; Scortichini et al. 2018; Pascal, Wagner, et al. 2021), with higher risks at equivalent temperatures when ozone or fine particle concentrations are higher. An interaction between heat and exposure to the smoke of forest fires may also increase the overall mortality impacts. Ad hoc studies should be conducted to investigate these interactions.

4.6. Comparison with other estimates
The estimates of the heat-related mortality during heat waves and the total excess mortality published in the annual heat wave reports were consistent. The observed differences were expected given the difference in method and scopes. Annual excess mortality report compared the observed mortality with and expected mortality based on historical data, without directly attributing deaths to heat, but assuming that heat is the main cause of the observed excesses. Compared to a model calculating a fraction attributable to heat, the balances may overestimate the impact of heat, but also capture unexpected or indirect impacts that are not taken into account by the modeling (e.g. unprecedented meteorological situation...). Large differences were observed particularly in Gironde in 2022 and in the North in 2020, and call for additional investigations. In 2022, it can be assumed that the duration, the intensity of the heat, and the co-exposure with the plumes of the forest fires led to exacerbated impacts in Gironde. In 2020, the COVID-19 pandemic may have led to increased vulnerability to heat, in an otherwise heat-unaccustomed department, and with a priori high social vulnerability to heat. In the United Kingdom, a comparison similar to that here also found significant differences in estimates of heat wave impacts in 2020, and hypothesized that COVID-19 amplified heat-related risks (Lo et al. 2022).

In 2022, during heat waves, the model estimated about 2,000 excess heat-related deaths vs. 2,800 excess all-cause deaths in annual assessment. For the same periods and departments, 894 Covid-19 deaths were recorded (Santé publique France 2022). Between the 1st June and the 15th September, 2022, 10,420 excess all-cause deaths were estimated in metropolitan France by the EuroMomo surveillance system and 5,735 Covid-19 deaths were recorded in hospitals and social and medico-social institutions (Santé publique France 2022). During the same period, about 6,800 excess heat-related deaths were estimated. These numbers suggest a partial overlap of heat-related deaths and COVID-19 deaths in 2022, but specific studies would be needed to investigate the synergies between COVID-19 and heat.

4.7. Implications for public health

The results highlight the importance of heat-related mortality in France, and the need to strengthen adaptation in a rapidly changing climate. Between 2014 and 2002, between 1,000 and 7,000 annual deaths were attributable to heat (at temperatures above the 50 percentile of the summer temperature distribution), depending on the weather context, despite extensive heat prevention. This impact corresponds to a small number of days per year, but in relative terms can represent up to 8% of summer mortality, and 11% of mortality on days when the temperature is above the 50th percentile. In comparison, particulate air pollution is responsible for 40,000 deaths per year in France (Medina and et. al. 2021), i.e. about 7% of annual mortality, for an exposure involving the entire population on all days of the year.

The results also underline that the impact of heat is not limited to the most extreme periods. Exposure of the population to heat outside of heat waves, associated with a lower but more frequent risk, contributes more to the total impact than extreme heat associated with a higher risk.

The focus of the alert on extreme heat waves is justified by their contribution to the total impact: on average, 6% of days account for 28% of the heat-related impact. The organization of a specific response during heat waves is also necessary given their potential for massive and rapid disorganization of the
health care system, as observed in 2003. However, this reactive adaptation during extreme events must be complemented by structural adaptation to reduce the risk throughout the summer.

The very high impact observed in 2022 compared to other years foreshadows the challenges to come: very high temperatures throughout the summer, with extreme peaks, and a risk aggravated by a pandemic and probably by air pollution generated by local fires. According to Météo-France, the heat waves of the summer of 2022 would have been "highly unlikely and much less intense without the effect of climate change" (Météo-France 2023).

Declarations

Author contribution statement:

Conceptualization; MP, VW, Data curation; RL, VW, Formal analysis; VW, MP; Methodology; all Supervision; MP Validation; GB, Writing – original draft; MP, Writing – review & editing. all

Competing interests: none

Funding: none

References


**Figures**
Figure 1

Summer (June-September) daily mean temperature per department – average over 2014-2022 and 2022

Figure 2

Temperature-mortality relationship stratified by period (2014-2019 and 2020-2022), all ages (left) and over 75 years old (right), meta-analysis of the 96 départements, RR cumulated over 10 days and in reference to percentile 50
Figure 3

Relative risk of mortality for several temperatures (°C) depending on the period, and the COVID-19 indicator – All ages and over 75 years old.

Figure 4

% of mortality attributable to heat during summer, and during warm days