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Research

A yearly measure of heat-related deaths in France, 2014–2023

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Abstract
Climate change's impact on health, specifically increasing temperatures, has become a prominent field of study worldwide. Although its importance is growing, decision makers still have little knowledge on the subject. Developing indicators to monitor spatial and temporal trends of health impacts due to climate change is a vital advancement needed to encourage policy adaptations. This research proposes an approach to producing annual estimates for heat-related mortality as an indicator to support these policies. The first step was to develop temperature-mortality relationships for each of the 96 metropolitan French departments, for the summer months (June–September) between 2014 and 2022. Several approaches were tested to control for a possible influence of the COVID-19 pandemic since 2020. The temperature-mortality relationships were used to compute the annual mortality attributable to heat for the same years, and for 2023. Heat-related risks were slighly higher after the pandemic; an increase from 19.8 °C to 28.5 °C was associated with a relative risk 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 2023, 37,825 deaths [IC 95% 34,273: 40,483] were attributable to heat. The largest impacts were observed in 2022 (6,969 [6277: 7445]), 2023 (5167 [4587; 5551]), and 2019 (4441 [4086: 4717]). The annual indicator of heat-related mortality documents the mortality impact of heat during the summer and during extreme heat waves. It shows that the impact is increasing, despite major prevention efforts. This call for a more ambitious, transformative adaptation to climate change.

Keywords Heat wave · Heat · Climate change · Mortality · Indicators

1 Introduction

The Intergovernmental Panel on Climate Change (IPCC) has identified high temperatures as one of the most significant climate risks in Europe, due to its impacts on human health and ecosystems [1]. Exposure to heat (defined as a higher temperature compared to the usual climate) has a multitude of effects on health, resulting in increased morbidity and mortality. The impact of heat on mortality is non-linear, with a strong increase in risks at the highest temperatures [2]. It is also rapid, with the highest risk of mortality observed within 24 h of exposure and continuing for up to 10 days [3]. Environmental, social and individual risk factors can exacerbate heat-related mortality risk. Significant health impacts are observed everywhere, but heat raises specific challenges in dense urban setting, with the urban heat island resulting in over-exposure of large populations [4].

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Between 1970 and 2022, more than 42,000 excess all-cause deaths (computed by comparing the observed mortality to a reference mortality) were observed during heat waves in France, including nearly 11,000 excess deaths between 2015 and 2022 [5]. However, it is not known how much of this estimated excess mortality during heat waves is attributable to the heat itself. Epidemiological studies in French cities found, consistently with the literature [6], a J-shape relationship between heat and mortality [3, 4, 7]. Between 2000 and 2010, in 18 French cities, 13,855 deaths were attributed to heat, representing 1.2% [1.1: 1.2] of the total mortality in these cities. Approximately 29% of this mortality attributable to heat was due to the most extreme temperatures observed during heat waves, and 71% was due to usual summer heat [3].

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 events (temperatures above the heat wave warning thresholds). At the same time, record-breakings forest fires and droughts were observed in several regions, while an increase in the number of COVID-19 cases was recorded. Two thousands and eight hundred 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 method [8].

Despite the considerable knowledge now established in the scientific literature, decision-makers may have limited understanding of the magnitude of the mortality impacts of heat, or of their changes over time and space. Developing a simple indicator to monitor annually the mortality impact of heat is an asset to support adaptation.

We propose an approach for producing such estimates in France. First, we build temperature-mortality relationships for each department, based on historical data (2014–2022). Departments were chosen as the smallest geographical units currently used by the French heat warning system. They are an administrative sub-level of the government and state administrations. As an illustration, supplementary Figure S1 maps the number of heat waves days per department during summer 2023.

These temperature-mortality relationships were used to compute an indicator of annual mortality attributable to heat for the same years (2014–2022). They will also be used to annually complete the heat-related mortality indicator data serie, for the next five years (here we present the annual estimates for 2023).

2 Method

2.1 Study areas and period

The study covers the 96 departments of continental France, excluding overseas territories (considering the strong differences in climate and demography in those territories). The study period covers the summers (June–September) 2014–2022 for the building of the temperature-mortality relationships, and 2014–2023 for the computation of the heat-related mortality.

2.2 Mortality data

Annual population and daily mortality (total mortality, all ages and 75 years and older) data were obtained for each department from the National Institute of Statistics and Economic Studies (INSEE).

2.3 Temperature data

Daily minimum and maximum temperatures measured for a station per department (reference station of the heat warning system) were obtained from Météo-France. In each department, the daily mean temperature was computed as the average between the minimum and the maximum temperatures. 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 [3, 9].

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 [10].
- The departmental daily number of hospitalizations for COVID-19 [10],
- The departmental daily count of hospital deaths for COVID-19 [10].

2.5 Temperature-mortality relationships

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 [11], 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:

- Model built over the period 2014–2019 (Model 2014–2019)
- 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 (4) 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 the linear unbiased prediction (BLUP) of the temperature-mortality relationship was than produced for each department following the methodology developed by Gasparrini et al. [12, 13]. The approach of BLUP makes a trade-off between the department-specific relationship and the pooled relationship, and could thus provide more accurate estimates, especially for departments with relatively less daily death cases.

2.6 Mortality attributable to heat

The department—specific associations defined by the BLUPs were used to calculate the number of deaths attributable to heat, according to the methodology described by Gasparrini et al. [14]. Specifically, the daily number of attributable (NA) deaths was calculated for each department as follows:

$$\mathrm{NA} = \frac{(RR_{\Delta} - 1)}{RR_{\Delta}} \times \mathrm{N}$$

where RR_{Δ} is the relative risk for the change in temperature exposure Δ and N is is the number of deaths observed.

The number of heat-related deaths 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 by summing the daily mortality contributions when the temperature on a specific day was higher than the department-specific reference temperature. This reference value corresponds to the 50th percentile of the summer temperature distribution. Heat waves correspond to days when the 3-day moving average of minimum and maximum temperatures exceed departmental alert thresholds [5], as defined in the interministerial instruction for health management of heat waves. The thresholds applied were the thresholds used in 2022.

The attributable fractions was calculated as the number of heat-attributable deaths / number of total deaths from June 1 to September 15.

Another indicator computed the ratio between the fraction attributable to heat during heat waves and the fraction attributable to heat all through summer.

Empirical 95% confidence intervals were estimated from Monte Carlo simulations of the coefficients defining the BLUPs, assuming a multivariate normal distribution. These correspond to the 2.5th and 97.5th percentiles of the empirical distribution.

2.7 Comparison with other estimates of mortality impacts during heat waves

Excess mortality during heat waves is estimated annually by Sante publique France [15], based on the comparison between observed and expected mortality. Until 2022, the expected mortality was estimated based on a comparison with historical data from the 5 previous years. Since 2023, the expected mortality is estimated using the Euromomo [16, 17] adapted to a daily basis (tests showed that Euromomo based on weekly data tended to underestimate the impacts of heatwaves lasting less than one week) [18]. These data were extracted for each department from the public database geodes.santepubliquefrance.fr for 2014–2023.

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 [19]. 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 1,602,441 all-cause deaths, of which 1,077,040 (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 2023 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.

Figure 1a plots the 50th percentile used to define heat in each department, showing a North–South gradient. In all departments, average temperatures were higher in 2022 and 2023 compare to the previous years (Fig. 1b).

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 (Supplementary Table S1). 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 slighly 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 only presented for the stratified model, without any COVID-19 indicator. This model was preferred

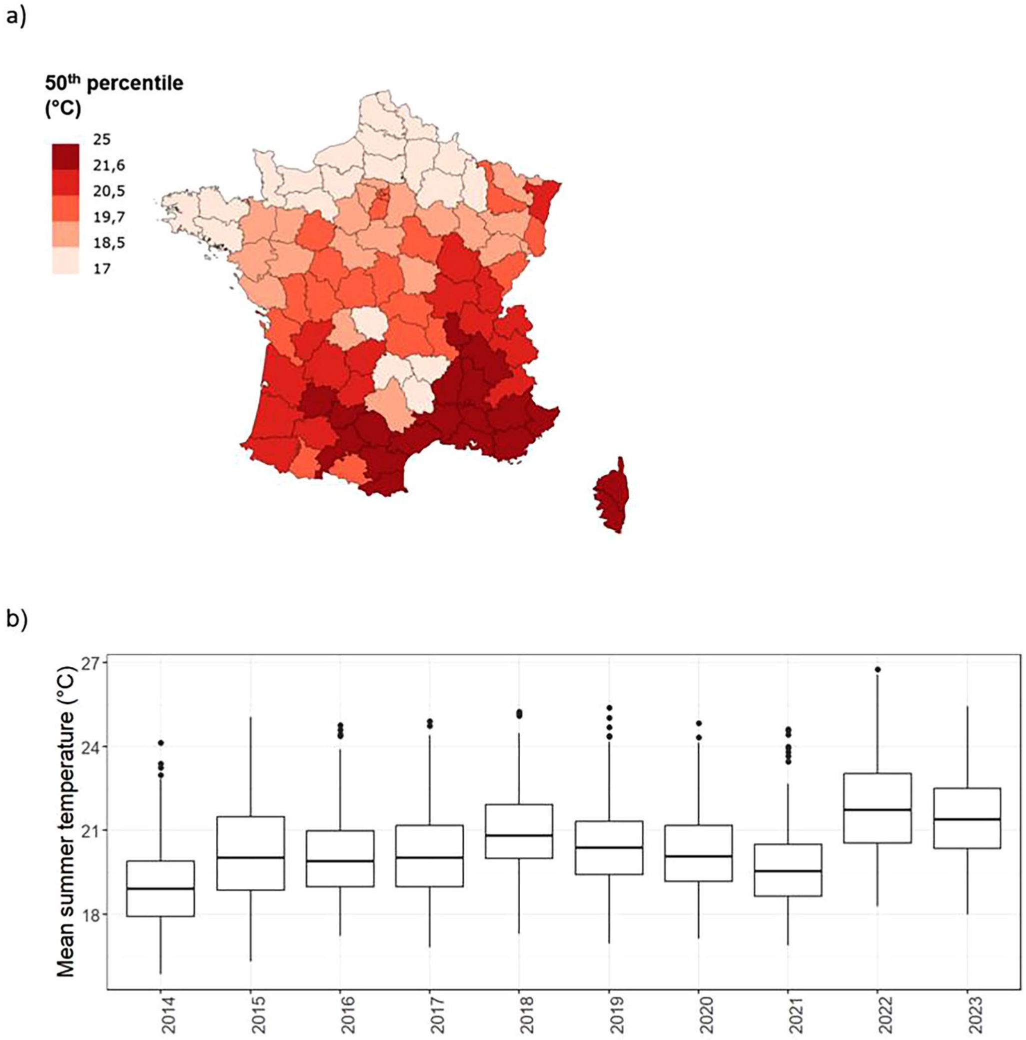

Fig. 1 Departmental mean temperature—**a**) 2014–2022 50th percentile, **b)** summer mean per year

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 2023, 37,825 all-age deaths [IC 95% 34,273: 40,483] were attributable to heat, and 28% of these deaths occured during heat waves. 26,852 [24,604: 28,465] deaths of persons aged 75 years and older were attributable to heat during this period (29% during heat waves).

In all departments, the total number of °C cumulated above the percentile 50 was the highest in 2022, 2023 and 2019 (Fig. 4). Logically, this also lead to the largest mortality impacts observed in 2022 (6969 [6277: 7445] excess deaths of which 29% occurred during heat waves), 2023 (5167 [4 587; 5551] excess deaths, 29% during heat waves) and 2019 (4441 [4086: 4717] excess deaths, 42% during heat waves). The impact was also greater than 4000 heat-related 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).

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 equal to 2.7% in 2015, 2018, 2019 and 2020, 3.3% in 2023 and 4.1% in 2022. (Fig. 4).

The contribution of heat waves to the total heat-related mortality varied by year and department from 0 to 99% in Hérault in 2018 (corresponding to a summer in which hot days coincided almost completely with heat wave periods).

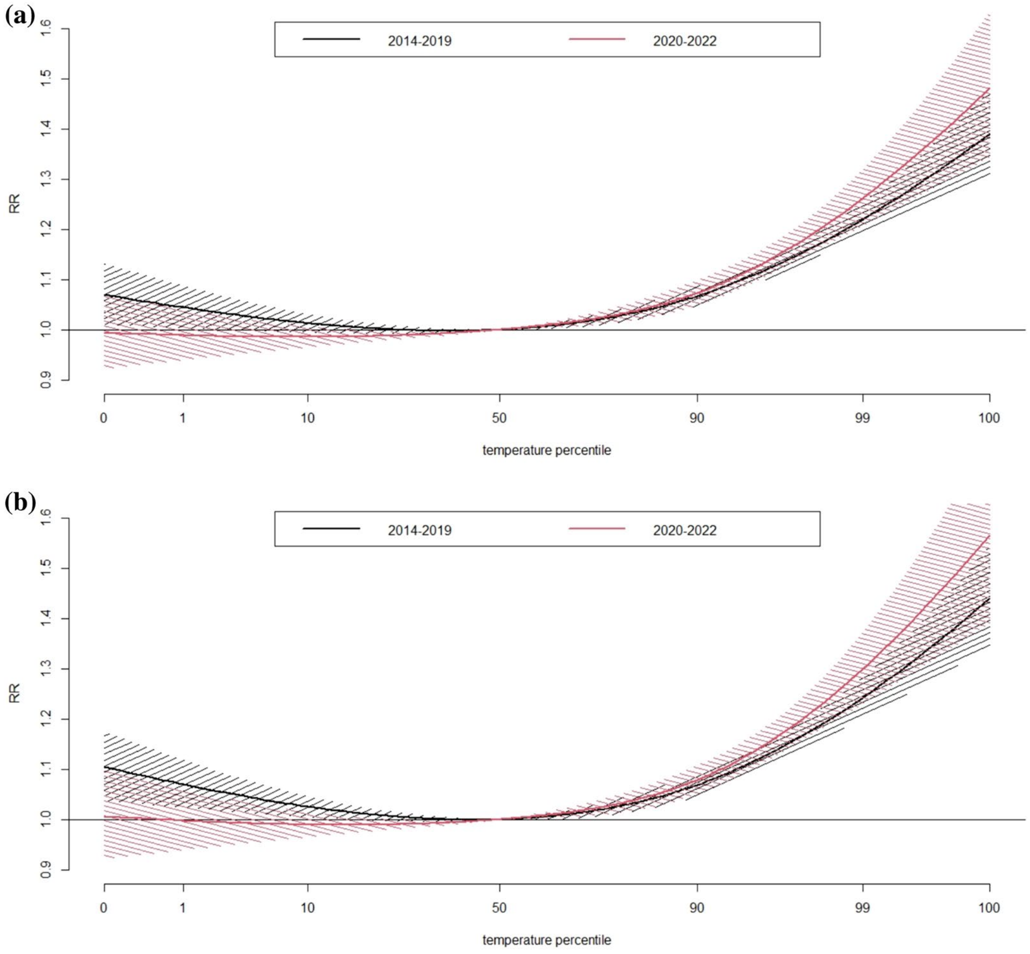

Fig. 2 Temperature-mortality relationship stratified by period (2014–2019 and 2020–2022), all ages (**a**) and over 75 years old (**b**), meta-analysis of the 96 departements, RR cumulated over 10 days and in reference to percentile 50

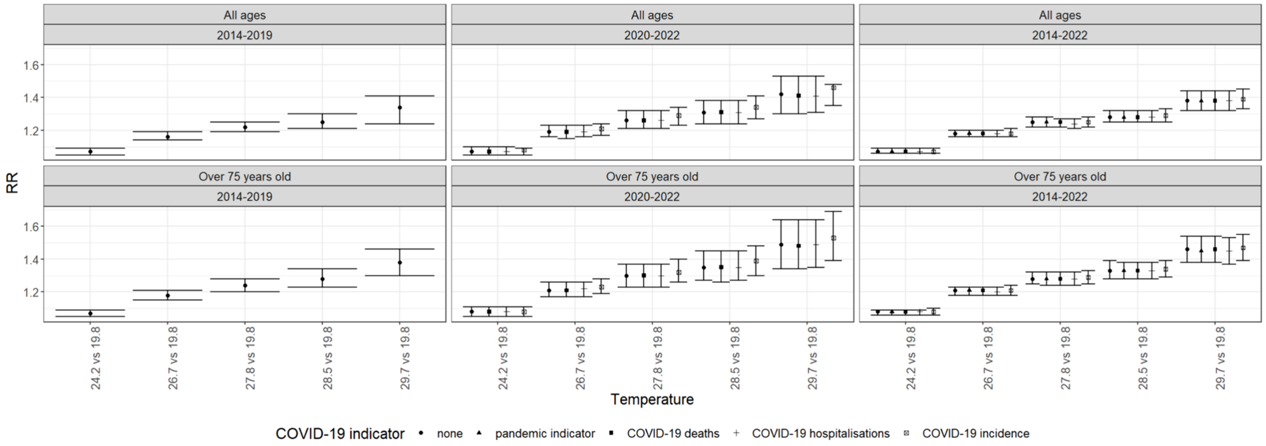

Fig. 3 Relative risk of mortality for several temperatures (°C) depending on the period, and the COVID-19 indicator—All ages and over 75 years old

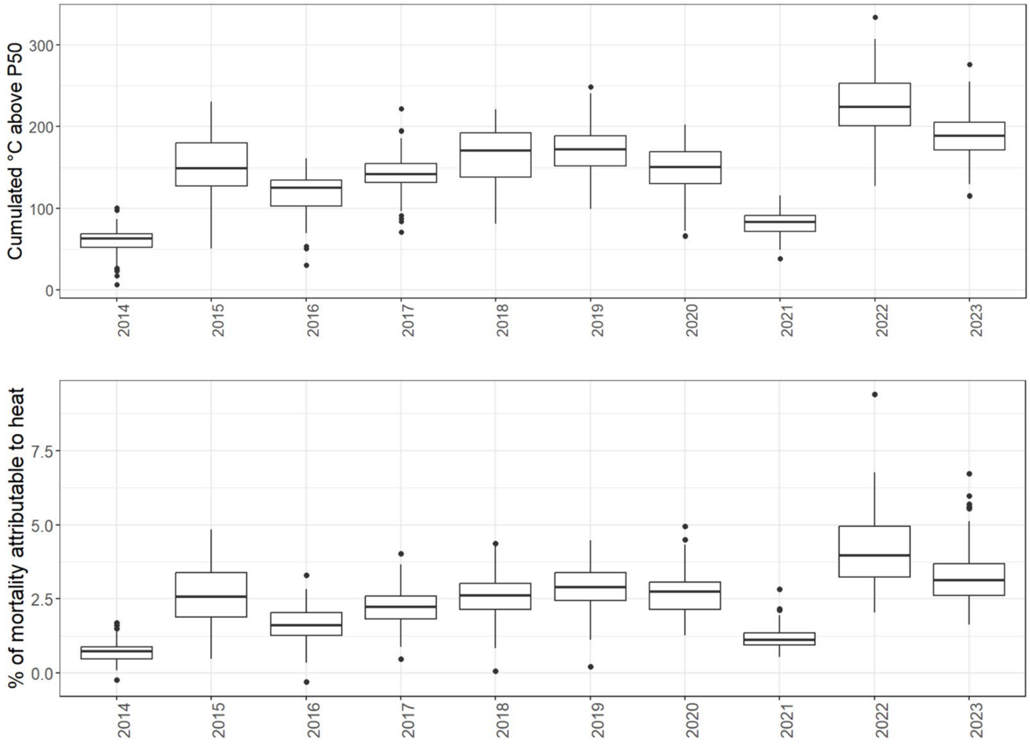

Fig. 4 Annual distribution of the number of °C cumulated above the percentile 50 and of the fraction of mortality attribuable to heat during summer

3.3 Comparison with the heat-related mortality indicator of the European environment agency

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 from the Lancet Countdown (Table 1).

3.4 Comparison with the excess mortality during heat waves

The stratified model estimated that 10,541deaths occurred during heat waves between 2014 and 2023. Over the same period, the reports of excess mortality during heat waves totalled 11,431 excess deaths (Table 1). In 2017 and 2019, the estimates of heat-related mortality during heat wave exceeds the estimates of the total excess mortality during heat waves. However, estimates from the two approaches were largely consistent and overlapping (Table 1).

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 excess deaths, vs. + 199 deaths attributable to heat. The second largest difference was observed in Gironde department in 2022, with + 182 excess all-cause deaths in the heat wave assessments, vs. + 89 deaths attributable to heat.

4 Discussion

4.1 An actionable indicator of heat-related mortality

Our approach allows us to propose a robust estimate of heat-related mortality in France, which can be compared across time and space. We use a consistent modelling approach throughout all departments. By using stable temperature-mortality relationships build over 2014–2022, we ensure that the indicator reflects changes in observed mortality

Table 1 Heat-related mortality during summer and during heat waves, and comparison with estimates from the Lancet countdown, and from Santé publique France's excess mortality reports

	Heat-related mortality		Comparison with other estimates	
	During summer (1st June–15th September)	During heat waves	Heat-related mortality estimated from the European observatory indicator (Lancet countdown) [20]	Total excess mortality during heat waves [min; max]* (Santé publique France annual reports)
2014	1103 [923: 1259]	49 [37:59]	473	No data
2015	3795 [3477: 4059]	1161 [1100: 1208]	3135	1739 [1620:1832]
2016	2573 [2257: 2834]	249 [221:271]	2118	378 [327: 441]
2017	3354 [3027: 3630]	733 [684:775]	2769	474 [286: 696]
2018	4166 [3716: 4520]	1277 [1191:1350]	4205	1641 [1071: 2164]
2019	4441 [4086: 4717]	1879 [1812: 1929]	4721	1462 [548: 2221]
2020	4329 [3919: 4606]	1531 [1350:1636]	4023	1924 [1484: 2387]
2021	1927 [1673: 2137]	88 [63:110]	Not available	239 [199:296]
2022	6969 [6277: 7445]	2051 [1791: 2214]		2816 [1989: 3502]
2023	5 167 [4 587: 5 551]	1523[1242;1677]		758

*Published in the annual heat wave reported produced by Santé publique France. In 2023, the method to compute excess mortality during summer changed and confidence intervals were not provided with the new method and temperature. Unless there are significant changes between now and then (for example, higher temperatures than the current range), we plan to updated the temperature-mortality relationships every 5 years.

Our results highlight the importance of heat-related mortality in France, and the need to strengthen adaptation in a rapidly changing climate. Between 2014 and 2023, between 1000 and 7000 annual deaths were attributable to heat (defined as temperature above the 50 percentile of the summer temperature distribution), 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 the mortality during hot days (days when the temperature is above the 50th percentile of the summer temperature distribution). In comparison, particulate air pollution is responsible for 40,000 deaths per year in France [21], 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. The population's exposure to heat outside of heat waves, which is associated with a lower but more frequent risk, contributes more to the total impact than heat waves, which are associated with a higher risk but are less frequent.

The focus of the warning system on extreme heat waves is justified by their contribution to the total impact: on average, 6% of the summer days account for 28% of the heat-related mortality 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 impacts observed in 2022 and 2023 compared to other years foreshadows the challenges to come: high temperatures throughout the summer, with extreme peaks, and a heat-related 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" [22].

4.2 Construction and update of the temperature-mortality relationship

4.2.1 Definition of heat

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 the MMT to non-epidemiologists. As an alternative to the MMT, we favoured the median of the summer temperature distribution. Heat corresponds to temperatures above this median, a definition that is easier to compare between departments, and to communicate to stakeholders. In the majority of the departments, the median falled within the confidence intervall of the MMT (data not showned). The European Observatory on Climate Change and Health observatory used the MMT, and find estimates consistent with ours.

The use of the MMT has also recently been challenged on the ground of limited evidence of a causal relationship between heat and mortality for moderate temperatures [23]. An interdisciplinary analysis of the current evidence on heat and mortality would be highly valuable to orientate future choices.

4.2.2 Choice of the geographical scale

In this study, we focused 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.

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 wih an excess mortality in those territories, where specific prevention strategies should be developed [24].

Overall, the department is a good compromise for producing actionable indicators, as several policies, including the response during heat waves, is organized at that scale. It is also one of the scales for planning the response to climate change via climate plans. More detailed data can be invaluable in developing highly targeted adaptation policies on a local scale. However, such fine-scale data is currently very expensive to produce, and does not exist for all regions, or over long periods. Working at departmental level guarantees the availability of data and therefore the sustainability of the indicator over the coming years.

4.2.3 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 RRs 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) [25]. 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.

Finally, in this study, we compared the years before and after the pandemic, and considered data on incidence and hospitalisations. However, several factors could have modified the influence of COVID-19 on heat-related mortality during the different phases of the pandemics. Lockdowns were efficient to reduce the transmission of COVID-19 [26], but they increased social isolation and limited access to health care. Heat exposure was however limited during those periods, as the first lockdown ended on the 2nd June 2020, while curfews were organized in May and June 2021. The harmful synergies between COVID-19 and heat might have been much greater if the epidemic peaks had coincided more closely with the summer months. The vaccination campaign, organized between December 2020 and January 2022, was associated with a decrease in the severity of the COVID-19 infections and of the hospitalizations and deaths [26]. The influence of COVID-19 on heat-related mortality might have decrease after the vaccination.

4.2.4 Air pollution

The modeling could not take into account ambient air pollution. The departmental scale is relatively large, with a surface ranging from 105 km^2 to 10,000 km^2. This implies a great heterogeneity in air pollution, and data to compute a meaningful daily air pollution indicator at this scale for all departments and the whole study period was not available.

In the literature, several studies show a negative synergy between temperature and air pollution [6, 27, 28], 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.

4.3 Comparison with other estimates of the mortality impacts of heat

Estimates of the mortality attributable to heat 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 reports compared the observed mortality with and expected mortality based on historical data, without directly attributing deaths to heat, but assuming that heat was the main cause of the observed excesses. Compared to a model calculating a fraction attributable to heat, the excess mortality 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 the department of Gironde in 2022 and in the department of 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 [29].

In 2022, during heat waves, the model estimated about 2000 heat-related deaths and the excess mortality reports estimated about 2800 excess all-cause deaths. For the same periods and departments, 894 Covid-19 deaths were recorded

[8]. 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 5735 Covid-19 deaths were recorded in hospitals and social and medico-social institutions [8]. During the same period, about 6800 deaths were attributable to heat by our models. These numbers suggest a partial overlap of heat-related deaths and COVID-19 deaths in 2022, but specific studies would be need to investigate the synergies between COVID-19 and heat.

Finally, our estimates for summer 2022 are also consistent with the recently published estimates of heat-related mortality in Europe during summer 2022 [30]. This study estimated that between the 30rd May and 4th September 2022, 4807 [1739: 8123] deaths were attributable to temperature in France. They defined heat as temperatures above the MMT, and used temperature-mortality relationships by age and sex. Between the 1st June and the 15th September 2022, we estimated that 6969 [6277:7445] deaths were attributable to heat, using all-ages all-sex temperature mortality relationships, and defining heat in reference to the percentile 50. The consistency of these estimates calls for greater investment in adapting to the heat in Europe.

Author contributions MP and VW designed the study and wrote the main manuscript text. RL and VW prepared the data and VW performed the stastical analyses. RL, DC, JP, NV and GB contributed to the design, methods and interpretation of the results. All authors reviewed the manuscript.

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Data availability The data that support the findings of this study are not openly available and are available from the corresponding author upon reasonable request. No human were involved in the study. Mortality data were collected from a national health database.

Declarations

Competing interests The authors declare no competing interests.

References

1. Pörtner H-O, Roberts DC, Adams H, Adelekan I, Adler C, Adrian R, Aldunce P, Ali E, Ara Begum R, Bednar-Friedl B, Bezner Kerr R, Biesbroek R, Birkmann J, Bowen K, Caretta MA, Carnicer J, Castellanos E, Cheong TS, Chow W, Cissé G, Clayton S, Constable A, Cooley S, Costello MJ, Craig M, Cramer W, Dawson R, Dodman D, Efitre J, Garschagen M, Gilmore EA, Glavovic B, Gutzler D, Haasnoot M, Harper S, Hasegawa T, Hayward B, Hicke JA, Hirabayashi Y, Huang C, Kalaba K, Kiessling W, Kitoh A, Lasco R, Lawrence J, Lemos MF, Lempert R, Lennard C, Ley D, Lissner T, Liu Q, Liwenga E, Lluch-Cota S, Löschke S, Lucatello S, Luo Y, Mackey B, Mintenbeck K, Mirzabaev A, Möller V, Moncassim Vale M, Morecroft MD, Mortsch L, Mukherji A, Mustonen T, Mycoo M, Nalau J, New M, Okem A, Ometto JP, O'Neill B, Pandey R, Parmesan C, Pelling M, Pinho PF, Pinnegar J, Poloczanska ES, Prakash A, Preston B, Racault M-F, Reckien D, Revi A, Rose SK, Schipper ELF, Schmidt DN, Schoeman D, Shaw R, Simpson NP, Singh C, Solecki W, Stringer L, Totin E, Trisos CH, Trisurat Y, van Aalst M, Viner D, Wairu M, Warren R, Wester P, Wrathall D, Zaiton Ibrahim Z. Technical Summary. In: Pörtner H-O, Roberts DC, Poloczanska ES, Mintenbeck K, Tignor M, Alegría A, Craig M, Langsdorf S, Löschke S, Möller V, Okem A, editors. In climate change 2022: impacts, adaptation, and vulnerability. Contribution of working group ii to the sixth assessment report of the intergovernmental panel on climate change. Cambridge: Cambridge University Press; 2022.
2. Gasparrini A, et al. Mortality risk attributable to high and low ambient temperature: a multicountry observational study. Lancet. 2015;386(9991):369–75. https://doi.org/10.1016/S0140-6736(14)62114-0.
3. Pascal M, Wagner V, Corso M, Laaidi K, Ung A, Beaudeau P. Heat and cold related-mortality in 18 French cities. Environ Int. 2018;121:189–98. https://doi.org/10.1016/j.envint.2018.08.049.
4. Forceville G, et al. Spatial contrasts and temporal changes in fine-scale heat exposure and vulnerability in the Paris region. Sci Total Environ. 2024;906:167476. https://doi.org/10.1016/j.scitotenv.2023.167476.
5. Pascal M, et al. Evolving heat waves characteristics challenge heat warning systems and prevention plans. Int J Biometeorol. 2021;65(10):1683–94.
6. Son JY, Liu JC, Bell ML. Temperature-related mortality: a systematic review and investigation of effect modifiers. Environ Res Lett. 2019;14(7):073004. https://doi.org/10.1088/1748-9326/ab1cdb.

7. Pascal M, et al. Greening is a promising but likely insufficient adaptation strategy to limit the health impacts of extreme heat. Environ Int. 2021;151:106441. https://doi.org/10.1016/j.envint.2021.106441.
8. Santé publique France, "Bulletin de santé publique canicule. Bilan été 2022." Saint Maurice, France, 2022. https://www.santepubliquefrance.fr/determinants-de-sante/climat/fortes-chaleurs-canicule/documents/bulletin-national/bulletin-de-sante-publique-canicule.-bilan-ete-2022.
9. Schaeffer L, de Crouy-Chanel P, Wagner V, Desplat J, Pascal M. How to estimate exposure when studying the temperature-mortality relationship? A case study of the Paris area. Int J Biometeorol. 2015;60(1):73–83. https://doi.org/10.1007/s00484-015-1006-x.
10. République française. "Synthèse des indicateurs de suivi de l'épidémie COVID-19." https://www.data.gouv.fr/fr/datasets/synthese-des-indicateurs-de-suivi-de-lepidemie-covid-19/#description. Accessed June 2024.
11. Gasparrini A, Armstrong B, Kenward MG. "Distributed lag non-linear models." Stat Med. 2010;29(21):2224–34. https://doi.org/10.1002/sim.3940.
12. Gasparrini A, Armstrong B, Kenward MG. "Multivariate meta-analysis for non-linear and other multi-parameter associations." Stat Med. 2012;31(29):3821–39. https://doi.org/10.1002/sim.5471.
13. Gasparrini A, Armstrong B. Reducing and meta-analysing estimates from distributed lag non-linear models. BMC Med Res Methodol. 2013;13(1):1. https://doi.org/10.1186/1471-2288-13-1.
14. Gasparrini A, Leone M. Attributable risk from distributed lag models. BMC Med Res Methodol. 2014;14(1):55. https://doi.org/10.1186/1471-2288-14-55.
15. Wagner V, Ung A, Calmet C, Pascal M. "Évolution des vagues de chaleur et de la mortalité associée en France, 2004–2014,." Bull Épidémiologique Hebdomadaire. 2018;16–17:320–5.
16. "Euromomo." https://www.euromomo.eu/how-it-works/methods. Accessed June 2024.
17. Fouillet A. "EuroMomo: la surveillance de la mortalité à l'échelle européenne." Bull Épidémiologique Hebdomadaire. 2014;3–4:81.
18. "Canicule: dispositif d'alerte et de surveillance et dispositif de prévention de Santé publique France." Santé publique France, Saint-Maurice. 2023.
19. van Daalen K, et al. The 2022 Europe report of the Lancet Countdown on health and climate change: towards a climate resilient future. Lancet Public Health. 2022;7(11):e942–65. https://doi.org/10.1016/S2468-2667(22)00197-9.
20. Lancet Countdown in Europe. "Heat-related mortality in Europe." https://climate-adapt.eea.europa.eu/en/observatory/++aq++metadata/indicators/heat-related-mortality-in-europe?bs=0. Accessed June 2024.
21. Medina S, et al. Impact de pollution de l'air ambiant sur la mortalité en France métropolitaine. Réduction en lien avec le confinement du printemps 2020 et nouvelles données sur le poids total pour la période 2016–2019. Saint-Maurice: Santé publique France; 2021.
22. Météo-France. "Eté 2022: les épisodes de chaleur attribués au changement climatique." https://meteofrance.com/actualites-et-dossiers-0/ete-2022-les-episodes-de-chaleur-attribues-au-changement-climatique. Accessed June 2024.
23. Bouchama A, Mündel T, Laitano O. Beyond heatwaves: a nuanced view of temperature-related mortality. Temp Rev. 2024. https://doi.org/10.1080/23328940.2024.2310459.
24. Pascal M, et al. Influence of temperature on mortality in the French overseas regions: a pledge for adaptation to heat in tropical marine climates. Int J Biometeorol. 2022;66(6):1057–65. https://doi.org/10.1007/s00484-022-02257-7.
25. Sousa PM, et al. Heat-related mortality amplified during the COVID-19 pandemic. Int J Biometeorol. 2022;66(3):457–68. https://doi.org/10.1007/s00484-021-02192-z.
26. Ganser I, Buckeridge DL, Heffernan J, Prague M, Thiébaut R. Estimating the population effectiveness of interventions against COVID-19 in France: a modelling study. Epidemics. 2024;46:100744. https://doi.org/10.1016/j.epidem.2024.100744.
27. Scortichini M, De Sario M, De'donato FK, Davoli M, Michelozzi P, Stafoggia M. Short-term effects of heat on mortality and effect modification by air pollution in 25 italian cities. Int J Environ Res Public Health. 2018;15(8):1771. https://doi.org/10.3390/ijerph15081771.
28. Pascal M, Wagner V, Alari A, Corso M, Le Tertre A. Extreme heat and acute air pollution episodes: a need for joint public health warnings? Atmospheric Environ. 2021;249:118249. https://doi.org/10.1016/j.atmosenv.2021.118249.
29. Lo YTE, Mitchell DM, Thompson R, O'Connell E, Gasparrini A. Estimating heat-related mortality in near real time for national heatwave plans. Environ Res Lett. 2022;17(2):024017. https://doi.org/10.1088/1748-9326/ac4cf4.
30. Ballester J, et al. Heat-related mortality in Europe during the summer of 2022. Nat Med. 2023;29(7):1857–66. https://doi.org/10.1038/s41591-023-02419-z.