



HAL
open science

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

Mathilde Pascal, Véréne Wagner, Robin Lagarrigue, Delphine Casamatta, Jérôme Pouey, Nicolas Vincent, Guillaume Boulanger

► **To cite this version:**

Mathilde Pascal, Véréne Wagner, Robin Lagarrigue, Delphine Casamatta, Jérôme Pouey, et al.. A yearly measure of heat-related deaths in France, 2014–2023. *Discover Public Health*, 2024, 21 (1), pp.44. <10.1186/s12982-024-00164-3>. <hal-04669436>

HAL Id: hal-04669436

<https://hal.science/hal-04669436v1>

Submitted on 8 Aug 2024

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons CC BY 4.0 - Attribution - International License

1 **A yearly measure of heat-related deaths in France, 2014-2023.**

2

3 Mathilde Pascal¹, Véréne Wagner¹, Robin Lagarrigue¹, Delphine Casamatta¹, Jérôme Pouey¹, Nicolas
4 Vincent¹, Guillaume Boulanger¹

5

6 ¹Santé publique France

7 12 rue du val d'Osne

8 94 415 St Maurice

9 France

10 Mathilde.Pascal@santepubliquefrance.fr

11

12 **Author contribution statement:**

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

16

17 **Data availability**

18 The data that support the findings of this study are not openly available and are available from the
19 corresponding author upon reasonable request.

20 No human were involved in the study. Mortality data were collected from a national health database.

21

22

23

24

25

26

27

28

29 **Abstract**

30 Climate change's impact on health, specifically increasing temperatures, has become a prominent
31 field of study worldwide. Although its importance is growing, decision makers still have little knowledge
32 on the subject. Developing indicators to monitor spatial and temporal trends of health impacts due to
33 climate change is a vital advancement needed to encourage policy adaptations. This research
34 proposes an approach to producing annual estimates for heat-related mortality as an indicator to
35 support these policies. The first step was to develop temperature-mortality relationships for each of the
36 96 metropolitan French departments, for the summer months (June-September) between 2014 and
37 2022. Several approaches were tested to control for a possible influence of the COVID-19 pandemic
38 since 2020. The temperature-mortality relationships were used to compute the annual mortality
39 attributable to heat for the same years, and for 2023.

40 Heat-related risks were slightly higher after the pandemic; an increase from 19.8°C to 28.5°C was
41 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-
42 2022. Between 2014 and 2023, 37,825 deaths [IC95% 34,273 : 40,483] were attributable to heat. The
43 largest impacts were observed in 2022 (6,969 [6,277 : 7,445]), 2023 (5 167 [4 587 ; 5 551]), and 2019
44 (4,441 [4,086 : 4,717]).

45 The annual indicator of heat-related mortality documents the mortality impact of heat during the
46 summer and during extreme heat waves. It shows that the impact is increasing, despite major
47 prevention efforts. This call for a more ambitious, transformative adaptation to climate change.

48 **Keywords** : Heat wave, heat, climate change, mortality, indicators

49

50 **Statements and Declarations**

51 Competing interests: none

52 Funding: none

53

54

55

56

57

58

60 1. Introduction

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

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

79 Summer 2022 in continental France was emblematic of the challenges raised by rapid climate
80 change. High temperatures (close to the heat wave warning thresholds) were sustained during
81 several months, alternating with acute heat events (temperatures above the heat wave warning
82 thresholds). At the same time, record-breakings forest fires and droughts were observed in several
83 regions, while an increase in the number of COVID-19 cases was recorded. Two thousands and eight
84 hundred excess deaths were observed during heat waves in 2022, and the total summer excess
85 mortality was estimated to exceed 10,000 deaths according to the EuroMomo surveillance method [8].

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

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

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

99 **2. Method**

100 **2.1. Study areas and period**

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

105 **2.2. Mortality data**

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

108 **2.3. Temperature data**

109 Daily minimum and maximum temperatures measured for a station per department (reference station
110 of the heat warning system) were obtained from Météo-France. In each department, the daily mean
111 temperature was computed as the average between the minimum and the maximum temperatures.
112 The mean temperature was chosen based on several previous works which concluded that using
113 mean, minimum or maximum temperatures, and whether or not humidity was taken into account, had
114 very little influence on the performance and results of the models [3, 9].

115 **2.4. Data related to the COVID-19 pandemic**

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

- 118 - a binary "pandemic" indicator indicating the absence (summers 2014-2019) or presence
119 (summers 2020-2022) of the pandemic during the study period,
- 120 - the daily departmental incidence rate for COVID-19 [10].
- 121 - the departmental daily number of hospitalizations for COVID-19 [10],
- 122 - the departmental daily count of hospital deaths for COVID-19 [10].

123 **2.5. Temperature-mortality relationships**

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

127 Seasonality was modeled with a cubic natural-spline of day of year with four degrees of freedom per
128 season and an interaction term between this spline and year. The association with temperature was

129 modeled using non-linear distributed lag models [11], including 10-days of lag, with a cubic natural-
130 spline with two internal nodes placed at the 50 and 90 percentiles of the mean temperature distribution
131 (chosen based on the Akaike criteria). The association in the lag dimension was modeled using a
132 natural-spline with two equidistant internal nodes in the log scale to allow more flexibility in the first
133 part of the lag curve where more variability is expected.

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

- 135 - Model built over the period 2014-2019 (Model 2014-2019)
- 136 - Models built over the period 2014-2022 (2014-2022 Models/COVID-19 Indicators) 1) without
137 consideration of COVID-19, 2) with the pandemic indicator, 3) with the COVID-19 deaths
138 indicator, 4) with the COVID-19 hospitalizations indicator, or 5) with the COVID-19 incidence
139 rate indicator.
- 140 - Models stratified over the period without and with Covid (Model 2014-2019 and Model 2020-
141 2022). The 2020-2022 models were built 1) without consideration of any Covid indicator, 2)
142 with the COVID-19 death indicator, 3) with the COVID-19 hospitalizations indicator, or d) with
143 the COVID-19 incidence indicator.

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

147 For each model, the estimated department-specific overall cumulative exposure–responses were
148 combined using a random-effects model and the linear unbiased prediction (BLUP) of the
149 temperature-mortality relationship was than produced for each department following the methodology
150 developed by Gasparrini et. al. [12, 13]. The approach of BLUP makes a trade-off between the
151 department-specific relationship and the pooled relationship, and could thus provide more accurate
152 estimates, especially for departments with relatively less daily death cases.

153 **1.6. Mortality attributable to heat**

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

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

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

160 The number of heat-related deaths was calculated annually from the 1st June to the 15th September
161 (corresponding to the operation of the French heat warning system) and during heat waves by
162 summing the daily mortality contributions when the temperature on a specific day was higher than the

163 department-specific reference temperature. This reference value corresponds to the 50th percentile of
164 the summer temperature distribution. Heat waves correspond to days when the 3-day moving average
165 of minimum and maximum temperatures exceed departmental alert thresholds [5], as defined in the
166 interministerial instruction for health management of heat waves. The thresholds applied were the
167 thresholds used in 2022.

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

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

172 Empirical 95% confidence intervals were estimated from Monte Carlo simulations of the coefficients
173 defining the BLUPs, assuming a multivariate normal distribution. These correspond to the 2.5th and
174 97.5th percentiles of the empirical distribution.

175 **1.7. Comparison with other estimates of mortality impacts during heat waves**

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

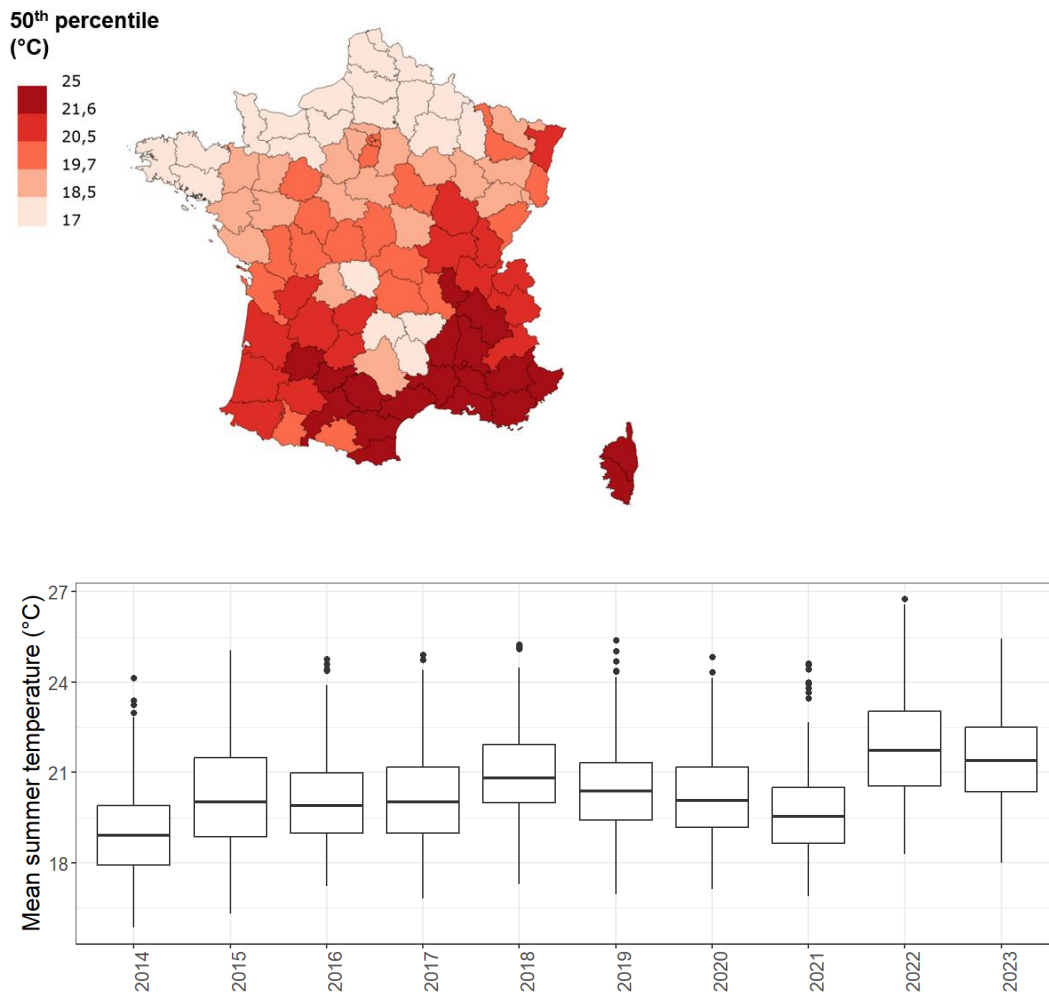
183 The European climate change and health observatory proposes an estimation of the annual number of
184 heat-related deaths per millions inhabitants per country, based on an approach develop for the Lancet
185 climate countdown [19]. Annual estimates for France were extracted for 2014-2022, and transformed
186 into annual number of heat-related deaths based on the annual French population provided by INSEE.

187 **2. Results**

188 The analyses included 1,602,441 all-cause deaths, of which 1,077,040 (67%) involved persons aged
189 75 years and over. The annual number of deaths, all ages, and 75 years and older, has increased
190 between 2014 and 2023 in all regions, while the proportion of deaths over 75 years old remained
191 stable. At the departmental level, the average daily number of deaths varies from 2 to 59 depending
192 on the department.

193 The total number of COVID-19 cases during the study period varied from 1,650,299 in 2020, to
194 8,010,271 in 2021 and 3,380,724 in 2022.

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

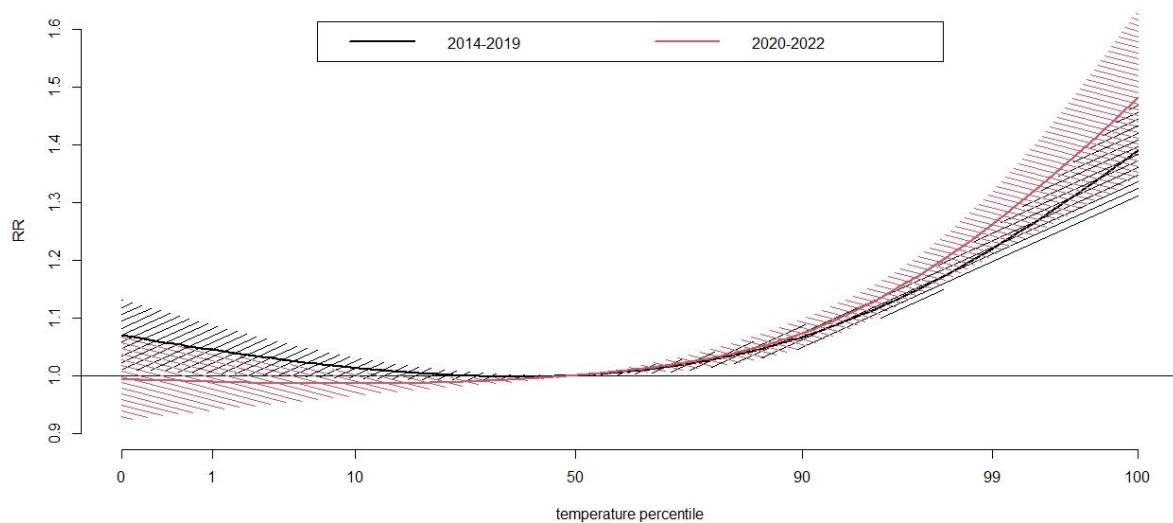


198 **Figure 1 – Departmental mean temperature - a) 2014-2022 50th percentile, b) summer mean per**
 199 **year**

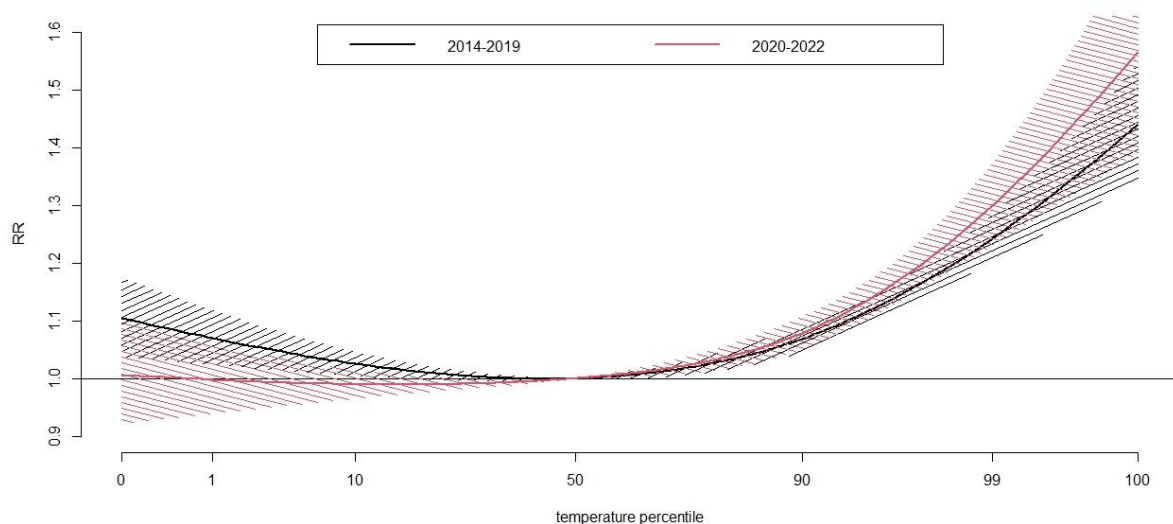
200 **3.1 Temperature-mortality relationships**

201 The 2014-2022 models without detailed COVID-19 indicators (deaths, hospitalizations, or incidence)
 202 were better, according to the Akaike criteria, than models incorporating those indicators
 203 (Supplementary Table S1). The same was true for models restricted to the period 2020-2022. All
 204 models tested show a similar "J-shaped" relationship, reflecting an increase in the risk of death with
 205 higher temperatures, for all-age mortality and for those aged 75 years and over (Figure 2).

206 Figure 3 details the relative risks (RR) for the different models. The models using different COVID-19
 207 indicators led to similar RR. In the stratified models, the RR tended to be slightly high for the period
 208 2020-2022. For instance, an increase from 19.8°C (P50) to 28.5°C (P99.5) was associated with a RR
 209 of 1.25 [1.21 :1.30] in 2004-2019, compared to 1.31 [1.24 :1.39] in 2020-2022 (model without any
 210 COVID-19 indicator).

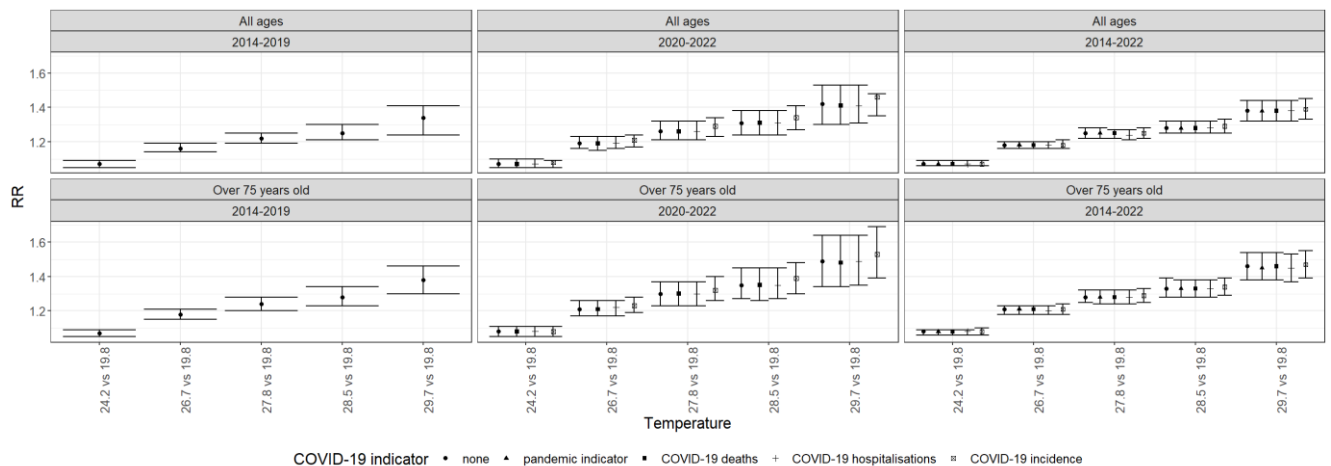


211



212

213 **Figure 2 – Temperature-mortality relationship stratified by period (2014-2019 and 2020-2022), all**
 214 **ages (left) and over 75 years old (right), meta-analysis of the 96 departements, RR cumulated**
 215 **over 10 days and in reference to percentile 50**



216

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

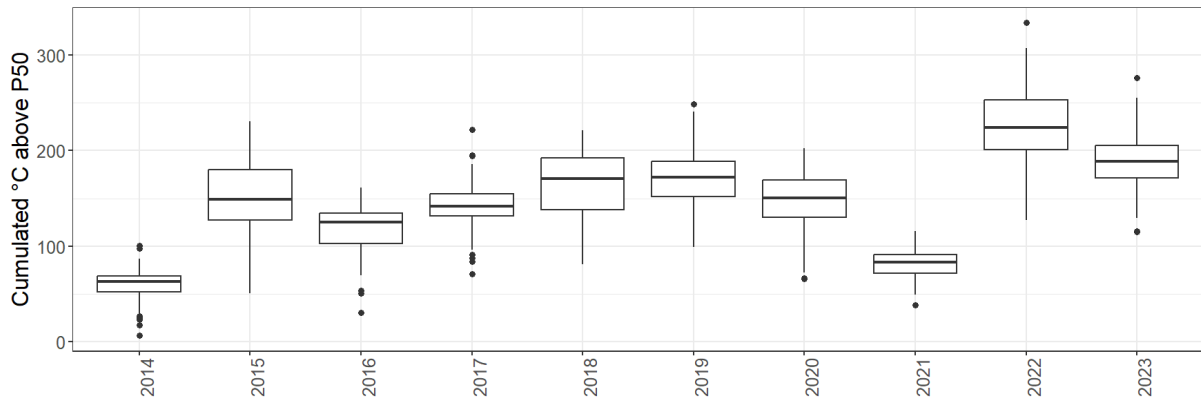
219 **3.2 Mortality attributable to temperature**

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

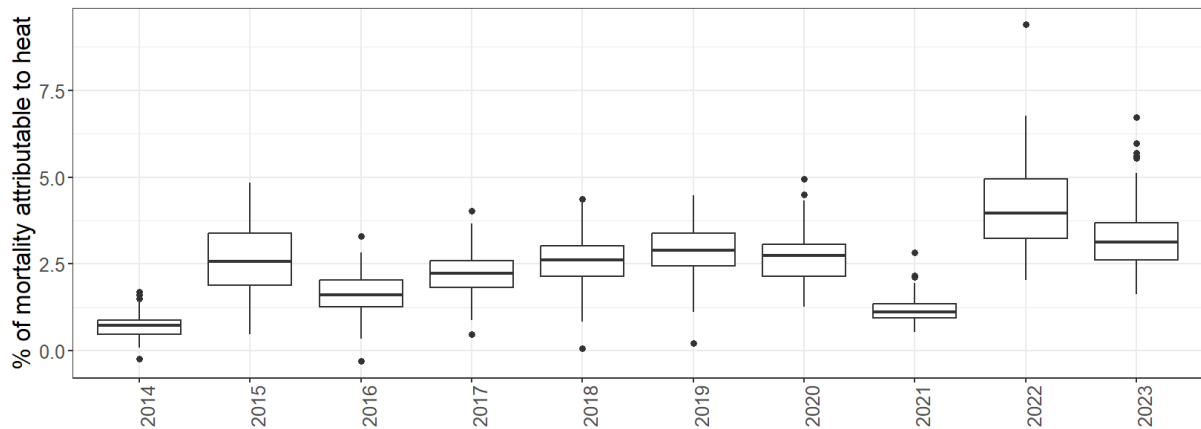
225 Between 2014 and 2023, 37,825 all-age deaths [IC95% 34,273 : 40,483] were attributable to heat, and
 226 28% of these deaths occurred during heat waves. 26,852 [24,604 : 28,465] deaths of persons aged 75
 227 years and older were attributable to heat during this period (29% during heat waves).

228 In all departments, the total number of °C cumulated above the percentile 50 was the highest in 2022,
 229 2023 and 2019 (Figure 4). Logically, this also led to the largest mortality impacts observed in 2022
 230 (6,969 [6,277 : 7,445] excess deaths of which 29% occurred during heat waves), 2023 (5 167 [4 587 ;
 231 5 551] excess deaths, 29 % during heat waves) and 2019 (4,441 [4,086 : 4,717] excess deaths, 42%
 232 during heat waves). The impact was also greater than 4,000 heat-related deaths in 2018 and 2020.
 233 The contribution of heat waves to the total heat-related mortality was logically small in years with few
 234 heat waves, such as 2014, 2016, and 2021 (Table 1).

235 Depending on the department and the year, up to 9.4% of the total summer mortality was attributable
 236 to heat. This attributable fraction was on average equal to 2.7% in 2015, 2018, 2019 and 2020, 3.3 %
 237 in 2023 and 4.1% in 2022. (Figure 4).



238



239

240 **Figure 4 – Annual distribution of the number of °C cumulated above the percentile 50 and of**
 241 **the fraction of mortality attributable to heat during summer**

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

245 **3.3. Comparison with the heat-related mortality indicator of the European environment agency**

246 Between 2014 and 2020, 23,762 deaths were attributable to heat in France using our models, vs
 247 21,444 deaths based on the European climate change and health observatory indicator from the
 248 Lancet Countdown (Table 1).

249 **3.4. Comparison with the excess mortality during heat waves**

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

255 At the departmental level, the largest discrepancy between the two estimates was observed in 2020,
 256 in the Nord department, with an all-cause mortality estimated in the heat wave assessments of +353
 257 excess deaths, vs. +199 deaths attributable to heat. The second largest difference was observed in
 258 Gironde department in 2022, with +182 excess all-cause deaths in the heat wave assessments, vs.
 259 +89 deaths attributable to heat.

260 **Table 1 – Heat-related mortality during summer and during heat waves, and comparison with**
 261 **estimates from the Lancet countdown, and from Santé publique France’s excess mortality**
 262 **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	1,103 [923 : 1,259]	49 [37 :59]	473	No data
2015	3,795 [3,477 : 4,059]	1,161 [1,100 : 1,208]	3,135	1,739 [1,620 :1,832]
2016	2,573 [2,257 : 2,834]	249 [221 :271]	2,118	378 [327 : 441]
2017	3,354 [3,027 :3,630]	733 [684 :775]	2,769	474 [286 : 696]
2018	4,166 [3,716 :4,520]	1,277 [1,191 :1,350]	4,205	1,641 [1,071 : 2,164]
2019	4,441 [4,086 : 4,717]	1,879 [1,812 : 1,929]	4,721	1,462 [548 : 2,221]
2020	4,329 [3,919 :4,606]	1,531 [1,350 :1,636]	4,023	1,924 [1,484 : 2,387]
2021	1,927 [1,673 :2,137]	88 [63 :110]	Not available	239 [199 :296]
2022	6,969 [6,277 :7,445]	2,051 [1,791 : 2,214]		2,816 [1,989 : 3, 502]
2023	5 167 [4 587 ; 5 551]	1 523[1 242;1 677]		758

263 * published in the annual heat wave reported produced by Santé publique France. In 2023, the
264 method to compute excess mortality during summer changed and confidence intervals were not
265 provided with the new method

266 **4. Discussion**

267 **4.1. An actionable indicator of heat-related mortality**

268 Our approach allows us to propose a robust estimate of heat-related mortality in France, which can be
269 compared across time and space. We use a consistent modelling approach throughout all
270 departments. By using stable temperature-mortality relationships build over 2014-2022, we ensure
271 that the indicator reflects changes in observed mortality and temperature. Unless there are significant
272 changes between now and then (for example, higher temperatures than the current range), we plan to
273 updated the temperature-mortality relationships every 5 years.

274 Our results highlight the importance of heat-related mortality in France, and the need to strengthen
275 adaptation in a rapidly changing climate. Between 2014 and 2023, between 1,000 and 7,000 annual
276 deaths were attributable to heat (defined as temperature above the 50 percentile of the summer
277 temperature distribution), despite extensive heat prevention. This impact corresponds to a small
278 number of days per year, but in relative terms can represent up to 8% of summer mortality, and 11%
279 of the mortality during hot days (days when the temperature is above the 50th percentile of the
280 summer temperature distribution). In comparison, particulate air pollution is responsible for 40,000
281 deaths per year in France [21], i.e. about 7% of annual mortality, for an exposure involving the entire
282 population on all days of the year.

283 The results also underline that the impact of heat is not limited to the most extreme periods. The
284 population's exposure to heat outside of heat waves, which is associated with a lower but more
285 frequent risk, contributes more to the total impact than heat waves, which are associated with a higher
286 risk but are less frequent.

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

293 The very high impacts observed in 2022 and 2023 compared to other years foreshadows the
294 challenges to come: high temperatures throughout the summer, with extreme peaks, and a heat-
295 related risk aggravated by a pandemic and probably by air pollution generated by local fires.
296 According to Météo-France, the heat waves of the summer of 2022 would have been "highly unlikely
297 and much less intense without the effect of climate change" [22].

298

299 **4.2. Construction and update of the temperature-mortality relationship**

300 **Definition of heat**

301 To compute heat-related mortality, epidemiological studies often use the temperature associated with
302 the lowest risk of death (minimum mortality temperature (MMT)) to define heat (heat then corresponds
303 to temperatures >MMT). However, we found that the MMT was very heterogeneous between
304 departments (varying from percentile 0 to percentile 77 of the summer temperature distribution), and
305 associated with large uncertainties. It is also difficult to communicate the MMT to non-epidemiologists.
306 As an alternative to the MMT, we favoured the median of the summer temperature distribution. Heat
307 corresponds to temperatures above this median, a definition that is easier to compare between
308 departments, and to communicate to stakeholders. In the majority of the departments, the median
309 fell within the confidence interval of the MMT (data not shown). The European Observatory on
310 Climate Change and Health observatory used the MMT, and find estimates consistent with ours.

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

314 **Choice of the geographical scale**

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

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

326 Finally, the study did not consider overseas departments due to their climatic and demographic
327 specificities. Heat was also associated with an excess mortality in those territories, where specific
328 prevention strategies should be developed [24].

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

334 at departmental level guarantees the availability of data and therefore the sustainability of the indicator
335 over the coming years.

336 **Influence of the COVID-19 pandemic**

337 The different analyses suggest that the long-term trend and seasonality terms are sufficient to capture
338 a possible influence of the COVID-19 pandemic. The results also suggest slightly higher RRs for the
339 highest percentiles over the period 2020-2022. In Portugal, a study estimated that the COVID-19
340 pandemic was responsible for at least a 50% increase in heat-related mortality in 2020 compared to
341 what would have been expected without the pandemic, an impact that the authors explain by the
342 disorganization of the health care system, and changes in people's behaviors (less use of health care)
343 [25]. The state of health of the population, socio-medical care and social links are important factors of
344 vulnerability or resilience to heat, and any event that significantly modifies them can lead to an
345 aggravation of the impact of heat waves.

346 Finally, in this study, we compared the years before and after the pandemic, and considered data on
347 incidence and hospitalisations. However, several factors could have modified the influence of COVID-
348 19 on heat-related mortality during the different phases of the pandemics. Lockdowns were efficient to
349 reduce the transmission of COVID-19 [26], but they increased social isolation and limited access to
350 health care. Heat exposure was however limited during those periods, as the first lockdown ended on
351 the 2nd June 2020, while curfews were organized in May and June 2021. The harmful synergies
352 between COVID-19 and heat might have been much greater if the epidemic peaks had coincided
353 more closely with the summer months. The vaccination campaign, organized between December
354 2020 and January 2022, was associated with a decrease in the severity of the COVID-19 infections
355 and of the hospitalizations and deaths [26]. The influence of COVID-19 on heat-related mortality might
356 have decrease after the vaccination.

357

358 **Air pollution**

359 The modeling could not take into account ambient air pollution. The departmental scale is relatively
360 large, with a surface ranging from 105 km² to 10,000 km². This implies a great heterogeneity in air
361 pollution, and data to compute a meaningful daily air pollution indicator at this scale for all departments
362 and the whole study period was not available.

363 In the literature, several studies show a negative synergy between temperature and air pollution [6, 27,
364 28], with higher risks at equivalent temperatures when ozone or fine particle concentrations are higher.
365 An interaction between heat and exposure to the smoke of forest fires may also increase the overall
366 mortality impacts. *Ad hoc* studies should be conducted to investigate these interactions.

367 **4.3. Comparison with other estimates of the mortality impacts of heat**

368 Estimates of the mortality attributable to heat during heat waves and the total excess mortality
369 published in the annual heat wave reports were consistent. The observed differences were expected
370 given the difference in method and scopes. Annual excess mortality reports compared the observed
371 mortality with and expected mortality based on historical data, without directly attributing deaths to
372 heat, but assuming that heat was the main cause of the observed excesses. Compared to a model
373 calculating a fraction attributable to heat, the excess mortality may overestimate the impact of heat,
374 but also capture unexpected or indirect impacts that are not taken into account by the modeling (e.g.
375 unprecedented meteorological situation...). Large differences were observed particularly in the
376 department of Gironde in 2022 and in the department of North in 2020, and call for additional
377 investigations. In 2022, it can be assumed that the duration, the intensity of the heat, and the co-
378 exposure with the plumes of the forest fires led to exacerbated impacts in Gironde. In 2020, the
379 COVID-19 pandemic may have led to increased vulnerability to heat, in an otherwise heat-
380 unaccustomed department, and with a priori high social vulnerability to heat. In the United Kingdom, a
381 comparison similar to that here also found significant differences in estimates of heat wave impacts in
382 2020, and hypothesized that COVID-19 amplified heat-related risks [29].

383 In 2022, during heat waves, the model estimated about 2,000 heat-related deaths and the excess
384 mortality reports estimated about 2,800 excess all-cause deaths. For the same periods and
385 departments, 894 Covid-19 deaths were recorded [8]. Between the 1st June and the 15th September,
386 2022, 10,420 excess all-cause deaths were estimated in metropolitan France by the EuroMomo
387 surveillance system and 5,735 Covid-19 deaths were recorded in hospitals and social and medico-
388 social institutions [8]. During the same period, about 6,800 deaths were attributable to heat by our
389 models. These numbers suggest a partial overlap of heat-related deaths and COVID-19 deaths in
390 2022, but specific studies would be need to investigate the synergies between COVID-19 and heat.

391 Finally, our estimates for summer 2022 are also consistent with the recently published estimates of
392 heat-related mortality in Europe during summer 2022 [30]. This study estimated that between the 30rd
393 May and 4th September 2022, 4,807 [1,739 : 8,123] deaths were attributable to temperature in
394 France. They defined heat as temperatures above the MMT, and used temperature-mortality
395 relationships by age and sex. Between the 1st June and the 15th September 2022, we estimated that
396 6,969 [6,277 :7,445] deaths were attributable to heat, using all-ages all-sex temperature mortality
397 relationships, and defining heat in reference to the percentile 50. The consistency of these estimates
398 calls for greater investment in adapting to the heat in Europe.

399

400

401

402

- 403 [1] H.-O. Pörtner, D.C. Roberts, H. Adams, I. Adelekan, C. Adler, R. Adrian, P. Aldunce, E. Ali, R.
404 Ara Begum, B. Bednar-Friedl, R. Bezner Kerr, R. Biesbroek, J. Birkmann, K. Bowen, M.A.
405 Caretta, J. Carnicer, E. Castellanos, T.S. Cheong, W. Chow, G. Cissé, S. Clayton, A. Constable,
406 S. Cooley, M.J. Costello, M. Craig, W. Cramer, R. Dawson, D. Dodman, J. Efitre, M.
407 Garschagen, E.A. Gilmore, B. Glavovic, D. Gutzler, M. Haasnoot, S. Harper, T. Hasegawa, B.
408 Hayward, J.A. Hicke, Y. Hirabayashi, C. Huang, K. Kalaba, W. Kiessling, A. Kitoh, R. Lasco, J.
409 Lawrence, M.F. Lemos, R. Lempert, C. Lennard, D. Ley, T. Lissner, Q. Liu, E. Liwenga, S. Lluch-
410 Cota, S. Löschke, S. Lucatello, Y. Luo, B. Mackey, K. Mintenbeck, A. Mirzabaev, V. Möller, M.
411 Moncassim Vale, M.D. Morecroft, L. Mortsch, A. Mukherji, T. Mustonen, M. Mycoo, J. Nalau,
412 M. New, A. Okem (South Africa), J.P. Ometto, B. O'Neill, R. Pandey, C. Parmesan, M. Pelling,
413 P.F. Pinho, J. Pinnegar, E.S. Poloczanska, A. Prakash, B. Preston, M.-F. Racault, D. Reckien, A.
414 Revi, S.K. Rose, E.L.F. Schipper, D.N. Schmidt, D. Schoeman, R. Shaw, N.P. Simpson, C. Singh,
415 W. Solecki, L. Stringer, E. Totin, C.H. Trisos, Y. Trisurat, M. van Aalst, D. Viner, M. Wairu, R.
416 Warren, P. Wester, D. Wrathall, and Z. Zaiton Ibrahim, "Technical Summary. [H.-O. Pörtner,
417 D.C. Roberts, E.S. Poloczanska, K. Mintenbeck, M. Tignor, A. Alegría, M. Craig, S. Langsdorf, S.
418 Löschke, V. Möller, A. Okem (eds.)]," in *Climate Change 2022: Impacts, Adaptation, and*
419 *Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the*
420 *Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S.*
421 *Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem,*
422 *B. Rama (eds.)]. Cambridge University Press, 2022.*
- 423 [2] A. Gasparrini *et al.*, "Mortality risk attributable to high and low ambient temperature: A
424 multicountry observational study," *The Lancet*, Article vol. 386, no. 9991, pp. 369-375, 2015,
425 doi: 10.1016/S0140-6736(14)62114-0.
- 426 [3] M. Pascal, V. Wagner, M. Corso, K. Laaidi, A. Ung, and P. Beaudreau, "Heat and cold related-
427 mortality in 18 French cities," *Environment International*, Article vol. 121, pp. 189-198, 2018,
428 doi: 10.1016/j.envint.2018.08.049.
- 429 [4] G. Forceville *et al.*, "Spatial contrasts and temporal changes in fine-scale heat exposure and
430 vulnerability in the Paris region," *Science of the Total Environment*, Article vol. 906, 2024, Art
431 no. 167476, doi: 10.1016/j.scitotenv.2023.167476.
- 432 [5] M. Pascal *et al.*, "Evolving heat waves characteristics challenge heat warning systems and
433 prevention plans," (in Anglais), *International Journal of Biometeorology*, vol. 65, no. 10, pp.
434 1683-1694, 2021. [Online]. Available:
435 https://www.ncbi.nlm.nih.gov/pmc/articles/PMC8019079/pdf/484_2021_Article_2123.pdf.
- 436 [6] J. Y. Son, J. C. Liu, and M. L. Bell, "Temperature-related mortality: A systematic review and
437 investigation of effect modifiers," *Environmental Research Letters*, Review vol. 14, no. 7,
438 2019, Art no. 073004, doi: 10.1088/1748-9326/ab1cdb.
- 439 [7] M. Pascal *et al.*, "Greening is a promising but likely insufficient adaptation strategy to limit
440 the health impacts of extreme heat," *Environment International*, Article vol. 151, 2021, Art
441 no. 106441, doi: 10.1016/j.envint.2021.106441.
- 442 [8] Santé publique France, "Bulletin de santé publique canicule. Bilan été 2022.," Saint Maurice,
443 France, 2022. [Online]. Available: [https://www.santepubliquefrance.fr/determinants-de-
444 sante/climat/fortes-chaieurs-canicule/documents/bulletin-national/bulletin-de-sante-
445 publique-canicule.-bilan-ete-2022](https://www.santepubliquefrance.fr/determinants-de-sante/climat/fortes-chaieurs-canicule/documents/bulletin-national/bulletin-de-sante-publique-canicule.-bilan-ete-2022)
- 446 [9] L. Schaeffer, P. de Crouy-Chanel, V. Wagner, J. Desplat, and M. Pascal, "How to estimate
447 exposure when studying the temperature-mortality relationship? A case study of the Paris
448 area," *International Journal of Biometeorology*, vol. 60, no. 1, pp. 73-83, 2016/01/01 2016,
449 doi: 10.1007/s00484-015-1006-x.
- 450 [10] République française. "Synthèse des indicateurs de suivi de l'épidémie COVID-19."
451 [https://www.data.gouv.fr/fr/datasets/synthese-des-indicateurs-de-suivi-de-lepidemie-covid-
452 19/#description](https://www.data.gouv.fr/fr/datasets/synthese-des-indicateurs-de-suivi-de-lepidemie-covid-19/#description) (accessed).
- 453 [11] A. Gasparrini, B. Armstrong, and M. G. Kenward, "Distributed lag non-linear models," (in
454 eng), *Statistics in medicine*, vol. 29, no. 21, pp. 2224-34, Sep 20 2010, doi: 10.1002/sim.3940.

- 455 [12] A. Gasparrini, B. Armstrong, and M. G. Kenward, "Multivariate meta-analysis for non-linear
456 and other multi-parameter associations," (in eng), *Statistics in medicine*, vol. 31, no. 29, pp.
457 3821-39, Dec 20 2012, doi: 10.1002/sim.5471.
- 458 [13] A. Gasparrini and B. Armstrong, "Reducing and meta-analysing estimates from distributed lag
459 non-linear models," *BMC Medical Research Methodology*, Article vol. 13, no. 1, 2013, Art no.
460 1, doi: 10.1186/1471-2288-13-1.
- 461 [14] A. Gasparrini and M. Leone, "Attributable risk from distributed lag models," *BMC Medical
462 Research Methodology*, Article vol. 14, no. 1, 2014, Art no. 55, doi: 10.1186/1471-2288-14-
463 55.
- 464 [15] V. Wagner, A. Ung, C. Calmet, and M. Pascal, "Évolution des vagues de chaleur et de la
465 mortalité associée en France, 2004-2014," (in Français), *Bulletin épidémiologique
466 hebdomadaire*, no. 16-17, pp. 320-325, 2018.
- 467 [16] "Euromomo." <https://www.euromomo.eu/how-it-works/methods> (accessed 2024).
- 468 [17] A. Fouillet, "EuroMomo : la surveillance de la mortalité à l'échelle européenne," (in Français),
469 *Bulletin épidémiologique hebdomadaire*, no. 3-4, p. 81, 2014.
- 470 [18] "Canicule : dispositif d'alerte et de surveillance et dispositif de prévention de Santé publique
471 France," Santé publique France, Saint-Maurice, 2023.
- 472 [19] K. van Daalen *et al.*, "The 2022 Europe report of the Lancet Countdown on health
473 and climate change: towards a climate resilient future," *The Lancet Public Health*, vol. 7, no.
474 11, pp. e942-e965, 2022, doi: 10.1016/S2468-2667(22)00197-9.
- 475 [20] Lancet Countdown in Europe. "Heat-related mortality in Europe." [https://climate-
476 adapt.eea.europa.eu/en/observatory/++aq++metadata/indicators/heat-related-mortality-in-
477 europe?bs=0](https://climate-adapt.eea.europa.eu/en/observatory/++aq++metadata/indicators/heat-related-mortality-in-europe?bs=0) (accessed 2022).
- 478 [21] S. Medina and et. al., "Impact de pollution de l'air ambiant sur la mortalité en France
479 métropolitaine. Réduction en lien avec le confinement du printemps 2020 et nouvelles
480 données sur le poids total pour la période 2016-2019," Santé publique France, Saint-Maurice,
481 2021.
- 482 [22] Météo-France. "Eté 2022 : les épisodes de chaleur attribués au changement climatique."
483 [https://meteofrance.com/actualites-et-dossiers-0/ete-2022-les-episodes-de-chaleur-
484 attribues-au-changement-climatique](https://meteofrance.com/actualites-et-dossiers-0/ete-2022-les-episodes-de-chaleur-attribues-au-changement-climatique) (accessed).
- 485 [23] A. Bouchama, T. Mündel, and O. Laitano, "Beyond heatwaves: A nuanced view of
486 temperature-related mortality," *Temperature*, Review 2024, doi:
487 10.1080/23328940.2024.2310459.
- 488 [24] M. Pascal *et al.*, "Influence of temperature on mortality in the French overseas regions: a
489 pledge for adaptation to heat in tropical marine climates," *International Journal of
490 Biometeorology*, Article vol. 66, no. 6, pp. 1057-1065, 2022, doi: 10.1007/s00484-022-02257-
491 7.
- 492 [25] P. M. Sousa *et al.*, "Heat-related mortality amplified during the COVID-19 pandemic,"
493 *International Journal of Biometeorology*, vol. 66, no. 3, pp. 457-468, 2022/03/01 2022, doi:
494 10.1007/s00484-021-02192-z.
- 495 [26] I. Ganser, D. L. Buckeridge, J. Heffernan, M. Prague, and R. Thiébaud, "Estimating the
496 population effectiveness of interventions against COVID-19 in France: A modelling study,"
497 *Epidemics*, Article vol. 46, 2024, Art no. 100744, doi: 10.1016/j.epidem.2024.100744.
- 498 [27] M. Scortichini, M. De Sario, F. K. De'donato, M. Davoli, P. Michelozzi, and M. Stafoggia,
499 "Short-term effects of heat on mortality and effect modification by air pollution in 25 italian
500 cities," *International Journal of Environmental Research and Public Health*, Article vol. 15, no.
501 8, 2018, Art no. 1771, doi: 10.3390/ijerph15081771.
- 502 [28] M. Pascal, V. Wagner, A. Alari, M. Corso, and A. Le Tertre, "Extreme heat and acute air
503 pollution episodes: A need for joint public health warnings?," *Atmospheric Environment*,
504 Article vol. 249, 2021, Art no. 118249, doi: 10.1016/j.atmosenv.2021.118249.

- 505 [29] Y. T. E. Lo, D. M. Mitchell, R. Thompson, E. O'Connell, and A. Gasparrini, "Estimating heat-
506 related mortality in near real time for national heatwave plans," *Environmental Research*
507 *Letters*, Article vol. 17, no. 2, 2022, Art no. 024017, doi: 10.1088/1748-9326/ac4cf4.
- 508 [30] J. Ballester *et al.*, "Heat-related mortality in Europe during the summer of 2022," *Nature*
509 *Medicine*, vol. 29, no. 7, pp. 1857-1866, 2023/07/01 2023, doi: 10.1038/s41591-023-02419-z.

510