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1 **Analyzing effect modifiers of the temperature-mortality relationship in the Paris Region to**
2 **identify social and environmental levers for more effective adaptation to heat**

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16 original draft preparation, Writing - reviewing and editing. **GF:** Data curation, Methodology, Formal
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19 Data curation, Writing - reviewing and editing. **JL:** Writing - reviewing and editing. **JMA:** Writing -
20 reviewing and editing. **EC:** Writing - reviewing and editing. **AR:** Writing - reviewing and editing. **VW:**
21 Methodology, Writing - reviewing and editing. **AL:** Data curation, Writing - reviewing and editing,
22 Supervision.

23

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Abstract

Adaptation to heat is a major challenge for the Paris region (France). Based on fine-scale data for the 1,287 municipalities of the region over 2000-2017, we analyzed (time-series design) the temperature-mortality relationship by territories (urban, suburban, rural), age (15-64 and ≥ 65) and sex, and explored how it was modified by vegetation and socio-economic indicators. Heat was associated with an increased mortality risk for all territories, age groups, sex, and mortality causes. Women aged 65 and over residing in the most deprived municipalities had a relative risk (RR) of death at 29.4°C (compared to 16.6°C) of 4.2 [3.8:4.5], while the RR was 3.4 [3.2:3.7] for women living in less deprived municipalities.

Actions to reduce such sex and social inequities should be central in heat adaptation policy.

Keywords: mortality, temperature, heat, climate, sex inequities, social inequities, vegetation

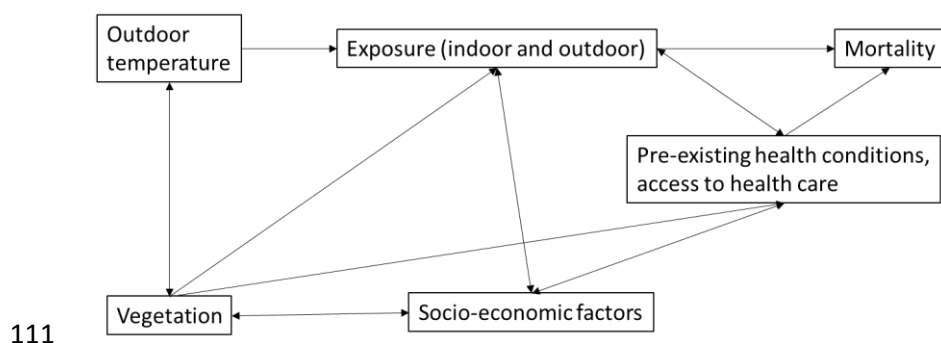
60 1. Introduction

61 Heat and heat extremes are more than ever a public health priority in Western Europe (IPCC 2022,
62 Rousi, Kornhuber et al. 2022). In France, the intensity of recent heat waves has been fueled by
63 climate change. For example, the likelihood of observing the extreme temperatures recorded in 2019
64 (World weather attribution 2019) or in 2022 (Météo-France 2023) in France would have been very low
65 without human influence on the climate. Between 2014 and 2022, more than 32,000 excess deaths in
66 France were due to heat, 28% of which occurred during heat waves (Pascal, Wagner et al. 2023). The
67 largest impacts were observed in the warmest years: 2022 (6,969 [6,277:7,445] deaths attributable to
68 heat) and 2019 (4,441 [4,086:4,717] deaths attributable to heat).

69 Heat is of particular concern in the Paris region, where more than 12 million inhabitants are exposed to
70 rapidly changing temperatures. Urban areas cover 27% of the region, agricultural land (mainly cereals)
71 49%, and natural areas (forests, water) 24%. The city of Paris is one of the most densely populated
72 cities in Europe, with more than 20,600 inhabitants per square kilometer on average, and up to 41,500
73 inhabitants per square kilometer in some neighborhoods. The urban heat island (UHI) effect can reach
74 up to 6 to 8°C between the moist urbanized and central areas and the outskirts of the region
75 (Lemonsu and Masson 2002, Orlando, Mosconi et al. 2021)(Madelin and Dupuis 2020). The Paris
76 region is also characterized by large economic inequities (Sagot 2019).

77 In the city of Paris, the fraction of mortality due to extreme heat has increased since the 2000s
78 (Pascal, Wagner et al. 2023). However, few studies have examined the individual, social and
79 environmental risk factors associated with heat-related health risks in the whole Paris region. A case-
80 control study focusing on the 2003 heat wave and restricted to urban areas reported an increased risk
81 for people with pre-existing health conditions (e.g. mental disorders, neurological or cardiovascular
82 diseases, cancer...), for manual workers, for people living in poorly insulated buildings, and for people
83 with a bedroom under the roof (Vandentorren, Bretin et al. 2006). The average minimum temperature
84 observed during the days before deaths, used as a proxy of the UHI, was also associated with an
85 increased mortality risk in 2003 (Laaidi, Zeghnoun et al. 2012). An ecological study over the period
86 1990-2015 and covering the whole region found that the risk of heat-related mortality was higher in
87 municipalities that lacked green spaces or had a high proportion of impervious surfaces (Pascal, Gorla
88 et al. 2021).

89 In terms of prevention, current adaptation to heat is mainly based on communication of appropriate
 90 behavior all-through summer (e.g. how to stay hydrated, how to reduce indoor temperatures, how to
 91 recognize heat stroke), and on short-term measures triggered by heat warnings (e.g. increasing
 92 staffing in hospitals, cancelling sports events, shifting working hours). People who feel vulnerable to
 93 heat can also contact the municipal authorities to benefit from at-home visits during warnings. In 2022,
 94 of the 2.1 million inhabitants of the city of Paris, only 10,000 people registered themselves as
 95 vulnerable to heat (Ville de Paris 2023). Several municipalities of the region have also launched
 96 programs to increase vegetation and shade in public spaces. However, long-term adaptation
 97 strategies to simultaneously reduce the three dimensions of heat vulnerability (exposure, individual
 98 susceptibility and adaptive capacity), proposed by Ellena, Breil et. al. (Ellena, Breil et al. 2020), are still
 99 needed. The nexus between heat, vegetation, socio-economic status and health is of particular
 100 interest in this context. Figure 1 schematizes the complex interactions between those factors. Through
 101 shadow and evapotranspiration, vegetation has a direct influence on outdoor temperature (Shashua-
 102 Bar, Pearlmutter et al. 2009), which in turn affects vegetation (Kabano, Lindley et al. 2021). Outdoor
 103 temperature is classically used as a proxy of indoor and outdoor temperature exposure in
 104 epidemiological studies. It is consistently associated with mortality. Actual exposure depends on
 105 individual behaviors, on health conditions (for instance affecting mobility or behavioral capacities), on
 106 socio-economic status (for instance through occupational exposure, or access to air conditioning), and
 107 on vegetation (for instance, providing access to fresh areas). Vegetation is also beneficial to social
 108 link, physical and mental health, reducing the overall vulnerability of the population to environmental
 109 hazards such as heat (Yang, Zhao et al. 2021). Those interdependencies may additionally depend on
 110 the type of territory, from rural to urban, but also on gender and age.



112 **Figure 1 – Schematization of the links between temperature, vegetation, socio-economic status**
 113 **and health**

114 To identify levers for adaptation, we investigated the temperature-mortality relationship by type of
115 territory, age and sex, and explored how it was modified by vegetation and socio-economic indicators.

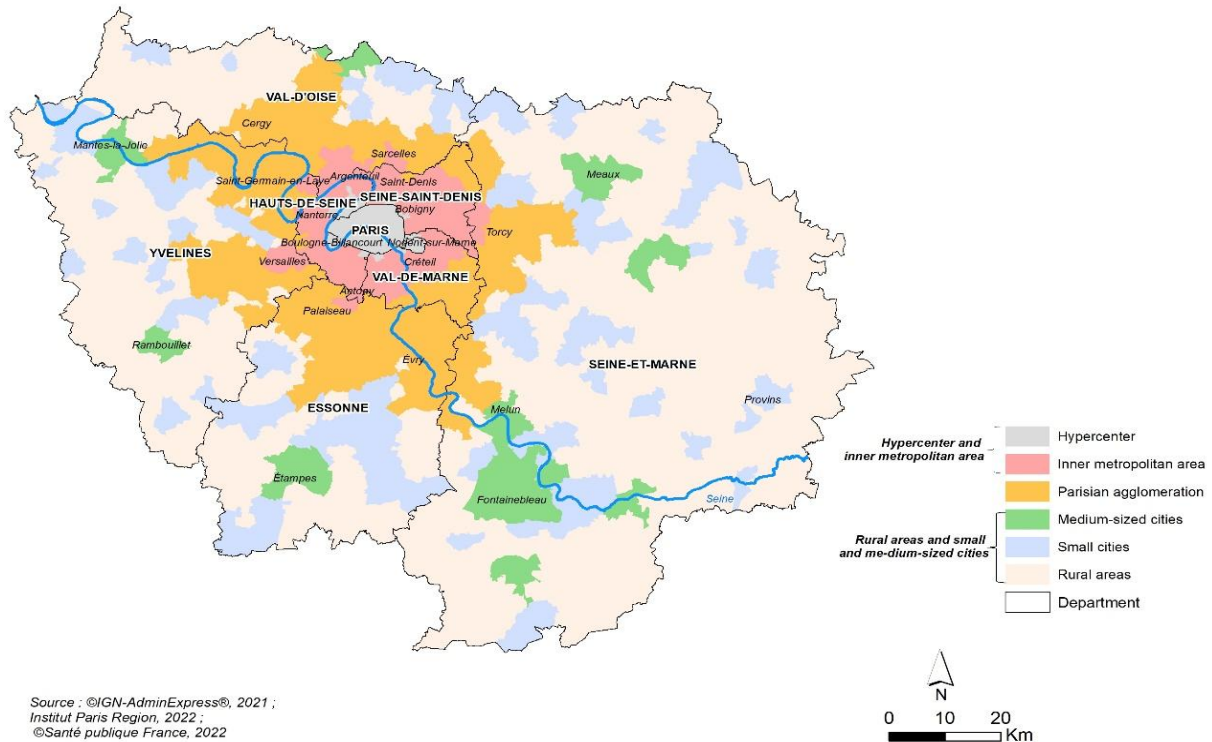
116 **2. Method**

117 **2.1. Study area and study period**

118 The region is divided into eight administrative departments comprising 1,287 municipalities (using the
119 2019 geographical reference of the National Institute for Statistics and Economic Studies (Insee)). The
120 most central departments (Paris, Hauts de Seine, Seine-Saint-Denis and Val-de-Marne) are also the
121 most urbanised and densely populated. The other departments (Val-d'Oise, Yvelines, Essonne, Seine-
122 et-Marne) are less densely populated and more rural. The regional planning authority (Institut Paris
123 Region) further classifies the departments and municipalities into six territorial sub-divisions, from rural
124 areas to the densest part of Paris. This territorial division based on land use is more interesting for
125 studying the influence of heat on health than other administrative divisions. In order to ensure
126 sufficient statistical power for the epidemiological analyses, these six territorial sub-divisions were
127 merged into three larger territories representing 1) rural, small and medium-sized municipalities, 2) the
128 Paris agglomeration, 3) the inner metropolitan area and the hyper-centre (Figure 2).

129 Analyses focused on the summer months (April-September) of the period 2000-2017. More recent
130 years could not be included in the analyses due to unavailability of mortality data by causes.

Territorial division of the Region of Paris, 2022
based on population density, urban attractiveness and building continuity



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 Institut Paris Region, 2022 ;
 ©Santé publique France, 2022

131

132 **Figure 2 – Territorial sub-division of the Paris region used to stratify the analysis**

133 **2.2. Mortality and population data**

134 Daily death counts for all-causes, cardiovascular (ICD-10 I00-I99), cardiac (I00-I52) and respiratory
 135 (J00-J99) causes were collected for each municipality (CépiDC data), by sex and age (15-64 years
 136 and ≥ 65 years).

137 Cardiovascular and respiratory mortality are the most frequently investigated causes in the literature
 138 (Cheng, Xu et al. 2019). Cardiovascular mortality is a broad category of diseases, engaging different
 139 physiological systems in response to heat. We decided to include also cardiac causes to capture
 140 possible differences for this subset of cardiovascular diseases. Due to the small number of cases, it
 141 was not possible to include other categories of cardiovascular mortality such as cerebrovascular
 142 mortality for instance.

143 For each municipality, annual total and 200-m gridded population data were provided by Insee for the
 144 1999 and 2006-2017 censuses. Linear interpolations were used to estimate the population for years
 145 between censuses.

146 **2.3. Temperature data**

147 Daily gridded minimum (Tmin), maximum (Tmax) and mean (Tmean) temperatures were produced by
148 spatially interpolating temperatures recorded by Météo-France weather stations. The interpolation took
149 into account the influence of altitude and urbanisation (Koukoku-Arnaud and Brion 2018, Le Roy,
150 Lemonsu et al. 2020) (Lemonsu, Alessandrini et al. 2024). The horizontal resolution for these gridded-
151 temperatures was 1.25 km across the whole region.

152 Two additional indicators derived from microclimatic modelling carried out over the same period 2000-
153 2017 (with a horizontal resolution of 1 km) were considered: the daily mean radiant temperature (MRT)
154 and the daily mean universal thermal climate index (UTCI) (method described in Supplementary mate-
155 rial).

156 For each municipality, daily temperature indicators were estimated by combining the gridded-
157 temperature at a 1.25 or 1 km resolution with the 200-gridded population data. The values for each
158 temperature grid intersecting the surface of the municipality were weighted and averaged according to
159 the population at 200 m. (Forceville, Lemonsu et al. 2024). This approach provides an estimate of the
160 average exposure in each municipality, giving more importance to inhabited areas.

161 Supplementary Figure S1 illustrates the geographical variations of each indicator for a selected day
162 (the 7th of July 2015).

163 **2.3. Vegetation data**

164 Three complementary indicators were considered to assess the level of greening of each municipality
165 and investigate if this modified the temperature-mortality relationship. Here, the objective was not to
166 capture the daily influence of vegetation on temperature (this being already captured in the fine-scale
167 temperature data), but to investigate the broader possible influences of vegetation.

168 The first indicator, based on land-use, estimated the proportion of artificialized areas within each
169 municipality. It was calculated for 2006, 2012 and 2018, as the proportion of the municipal area
170 classified in items 11 to 13 (11.Urban fabric, 12.Commercial and transport units, 13. Mines, landfills
171 and construction sites) in the Corine Land Cover database (European Copernicus programme), as
172 described in Pascal et. al (Pascal, Goria et al. 2021). It indicates the possible presence of permeable
173 soil and vegetation.

174 The second indicator was the annual mean summer (June-August) Normalised Difference Vegetation
175 Index (NDVI). It was estimated for each municipality as a surface-weighted average of Landsat data
176 on a 30-metre resolution grid (Hough, Rolland et al. 2023). It indicates the presence of vegetation
177 without information on the type of vegetation.

178 The third indicator was the proportion of the municipality covered by tree canopy. It was computed as
179 a surface-weighted average of the density of the urban canopy estimated for 2015 (between March-
180 October) from Sentinel 2, Landsat 8 data on a 20m resolution grid (Copernicus 2015). It indicates the
181 presence of trees.

182 Maps of each vegetation indicators for the year 2015 are presented on Supplementary Figure S2.

183 **2.4. Socio-economic data**

184 For each municipality, the median income (in €), % of high school graduates, % of unemployment, %
185 of manual workers and % of social housing were obtained from Insee. The median income, % of high
186 school graduates, % of unemployment, % of manual workers were used to calculate the French Depri-
187 vation Index (FDep) according to the method described by Rey et al.(Rey, Jouglu et al. 2009). The
188 FDep is a composite indicator of social disadvantage that was specifically designed for use in health
189 studies in France. We also considered the median income and the percentage of social housing as
190 two additional indicators of social inequities. The median income exhibits larger variations in the Paris
191 Region than in other regions of France. Housing is also a strong driver of social inequities in the region
192 (Sagot 2019). Social housing rents are regulated and, on average, two to three times lower than regu-
193 lar rents (Ministère de la transition écologique et de la cohésion des territoires 2023). The majority of
194 social housing residents are from low-income households.

195 Maps of each socio-economic indicators for the year 2015 are presented on Supplementary Figure S3.

196 **2.5. Statistical analysis**

197 **2.5.1. General approach**

198 Time-series analyses using non-linear distributed lag models (DLNMs) were used to consider the non-
199 linear relationship between temperature and mortality, as well as the delayed effects of temperature
200 (Gasparrini, Armstrong et al. 2010, Gasparrini, Scheipl et al. 2017, Gasparrini 2022, Song, Gasparrini
201 et al. 2023).

202 Daily mortality rates at the municipality level were modelled using a quasi-Poisson regression to
203 account for over-dispersion:

$$204 \log[E(Y_{ij})] = \alpha + \beta_1 \text{dow}_j + \beta_2 \text{bh}_j + \text{ns}(\text{time}_j) + \text{ns}(\text{day}_j) * \text{year} + f(\text{Tmean}_{ij,l}) + \beta_3 \text{prop75}_i + \beta_4 \text{FDep}_i + \beta_5 \\ 205 \text{NDVI}_i$$

206 where Y_{ij} is the number of deaths in small area i in the day j . The annual population size of each
207 municipality was included as an offset to account for the difference in population size between
208 municipalities. Controlling factors such as FDep (FDep_i), the percentage of people aged 75 and over
209 (prop75), NDVI , day of the week (dow_j), bank holidays (bh_j), seasonality, and long-term trends were
210 also included in the models. The function $f(\text{Tmean}_{ij,l})$ specifies the cross-basis that describes the
211 association of mortality and daily mean temperature Tmean_{ij} and its lag structure and is characterised
212 by two dimensions:

213 -the exposure-response dimension, modelled using a quadratic B-spline with two internal
214 nodes located at the 50th and 95th percentiles of the temperature indicator distribution, based
215 on the Akaike criteria;

216 -the lagged-response dimension, fitted using a natural spline with two internal nodes, placed at
217 equally spaced values in the log-scale to allow for more flexibility in the first lags where more
218 variability is expected. Individual lags were investigated up to 10 days.

219 To capture seasonality, a natural spline of day of the season, defined as a count in days increasing
220 from April to September, with 3 degrees of freedom per summer was used ($\text{ns}(\text{day})$). An interaction
221 between this spline function and the year indicator was specified to allow the seasonal trend to change
222 across the years. The long-term mortality trend was controlled by a natural spline of time with one
223 degree of freedom every 10 years ($\text{ns}(\text{time})$).

224 A sensitivity analysis included a spatial component in the model to account for residual spatial
225 autocorrelation and heterogeneity. It was modeled with a Markov random field smoother using a
226 conditional autoregressive model with a normally distributed conditional autoregressive prior to deal
227 with the neighbourhood correlations according to whether municipalities shared a common boundary
228 (Chien, Guo et al. 2016, Pascal, Gorla et al. 2021).

229 This modelling philosophy was used to develop several models summarized in supplementary material
230 Figure S4, and detailed below. To ensure sufficient statistical power, those models were developed
231 only when at least 5,000 deaths were recorded during the study period, as proposed by Masselot et al.
232 (Masselot, Mistry et al. 2023).

233 All analyses were performed using R software with the *dlnm* and *mgcv* packages (Gasparrini 2011,
234 Wood 2017), and the script developed for small-scale analysis (Gasparrini 2022).

235 **2.5.2. Selection of the temperature indicator**

236 Initially, models for all-causes, cardiovascular, cardiac and respiratory mortality were built for the entire
237 region, using various temperature indicators. Those models were stratified by age-group, under the
238 assumption that the most relevant temperature indicator could depend, among other things, on
239 physical activity and physiology, and that age would be a structuring parameter in this case.

240 The most significant temperature indicator, as determined by Akaike's criteria, was then used in all the
241 analyses described below.

242 **2.5.3. Mortality risks by causes, age, sex and territorial sub-division**

243 We investigated the temperature-mortality relationship by causes, age, sex, and type of territory,
244 based on the previously selected temperature indicator. We used stratified models, based on the
245 assumption that age and sex were key parameters for the constituent of vulnerability to heat (the
246 individual susceptibility to heat, the ability to cope with heat, and the ability to adapt). We additionally
247 stratified by type of territory, considering that the exposure patterns and the social mechanisms
248 implied in vulnerability could vary between rural and urban settings.

249 **2.5.4. Effect-modification by vegetation and socio-economic indicators**

250 Here, we investigated how socio-economic or vegetation indicators modified the temperature-mortality
251 relationship. We build on the models previously developed, and added a linear interaction between the
252 effect modifier (vegetation or socio-economic indicator) and the temperature term. The results
253 compared the temperature-mortality relationship in municipalities with a low level of the studied
254 indicator (5th percentile) versus municipalities with a high level (95th percentile).

255 Again, these models were stratified by age, sex, and territorial sub-division.

256

257

258 **3. Results**

259 The study area comprised 1,287 municipalities with a total population of approximately 9.8 million
 260 individuals aged 15 and over. From 2000 to 2017, there were 140,047 deaths among individuals aged
 261 15-64 and 465,180 deaths among those aged 65 years and over (Table 1). The number of deaths due
 262 to cardiovascular, cardiac, and respiratory mortality was insufficient to develop models by territorial
 263 sub-division for the age group 15-64.

264 **Table 1 – Population (2017) and mortality data (2000-2017) by causes, sex, age-group, and**
 265 **territorial subdivision**

		Men				Women			
		Rural areas, small and medium-sized cities	Parisian agglomeration	Hypercenter and inner metropolitan area	Total	Rural areas, small and medium-sized cities	Parisian agglomeration	Hypercenter and inner metropolitan area	Total
Population	15-64	486,903	1,075,217	2,341,468	3,903,588	498,165	1,115,865	2,492,749	4,106,779
	65+	109,326	204,512	446,199	760,037	138,403	266,499	620,230	1,025,132
All-cause mortality	15-64	13,188	23,678	54,078	90,944	6,354	12,183	28,306	46,843
	65+	30,972	52,366	127,245	210,583	35,934	60,884	158,847	255,665
Cardiovascular mortality	15-64	<i>1,875*</i>	<i>3,495</i>	<i>7,107</i>	<i>12,477</i>	<i>604</i>	<i>1,158</i>	<i>2,439</i>	<i>4,201</i>
	65+	8,060	13,276	31,468	52,804	10,489	17,227	43,822	71,538
Cardiac mortality	15-64	<i>1,387</i>	<i>2,547</i>	<i>5,101</i>	<i>9,035</i>	<i>372</i>	<i>697</i>	<i>1,507</i>	<i>2,576</i>
	65+	5,804	9,262	22,260	37,326	7,339	12,035	30,408	49,782
Respiratory mortality	15-64	<i>302</i>	<i>569</i>	<i>1,241</i>	<i>2,112</i>	<i>123</i>	<i>243</i>	<i>572</i>	<i>938</i>
	65+	<i>2,310</i>	<i>3,735</i>	<i>8,866</i>	<i>14,911</i>	<i>2,342</i>	<i>3,774</i>	<i>9,836</i>	<i>15,952</i>

266 **values in italics indicate numbers that are too small for modelling purposes (<5,000)*

267 The mean daily temperature, averaged over extended summers (April-September) for the period
 268 2000-2017 varied between 16.1°C in rural areas and small to medium-sized cities, and 17.4°C in the
 269 hyper-centre and inner metropolitan area. Warmer minimum temperatures were observed in the

270 densest urban areas, while maximum temperature were more heterogeneous through the region (see
271 Figure S1 for an illustration).

272 The percentage of artificialized area was significantly lower in rural, small, and medium-sized cities
273 (9.9%) compared to other areas. However, the distribution of NDVI and the percentage of surface
274 lacking tree canopy were similar between rural areas, small and medium-sized cities, and the Parisian
275 agglomeration (e.g. 0.57 and 0.55 for NDVI, respectively). Figure 3 and Figure S2 indicate a lack of
276 vegetation in the hyper-centre and inner metropolitan area compared to other areas.

277 The percentage of social housing varied across different areas, with rural areas and small to medium-
278 sized cities having a lower percentage (2.9%) compared to the hyper-centre and inner metropolitan
279 area (25%). The median income in the hyper-centre and inner metropolitan area was generally lower,
280 with larger differences between municipalities compared to other areas. Social deprivation was also
281 more heterogeneous in the hyper-centre and inner metropolitan area, as shown in Figure 3 and Figure
282 S3.

283 Mean temperature was strongly correlated with all other temperature indicators (Supplementary Figure
284 S5). Supplementary Figure S6 details the correlation between mean summer temperature indicators,
285 and vegetation and socio-economic indicators. Mean temperature showed a correlation with % of
286 social housing (0.47), NDVI (-0.47), and artificialized areas (0.62) over the entire region. However, it
287 did not show any correlation with lack of tree canopy (0.08). In urban areas, minimum temperature
288 was correlated with NDVI and artificialized area.

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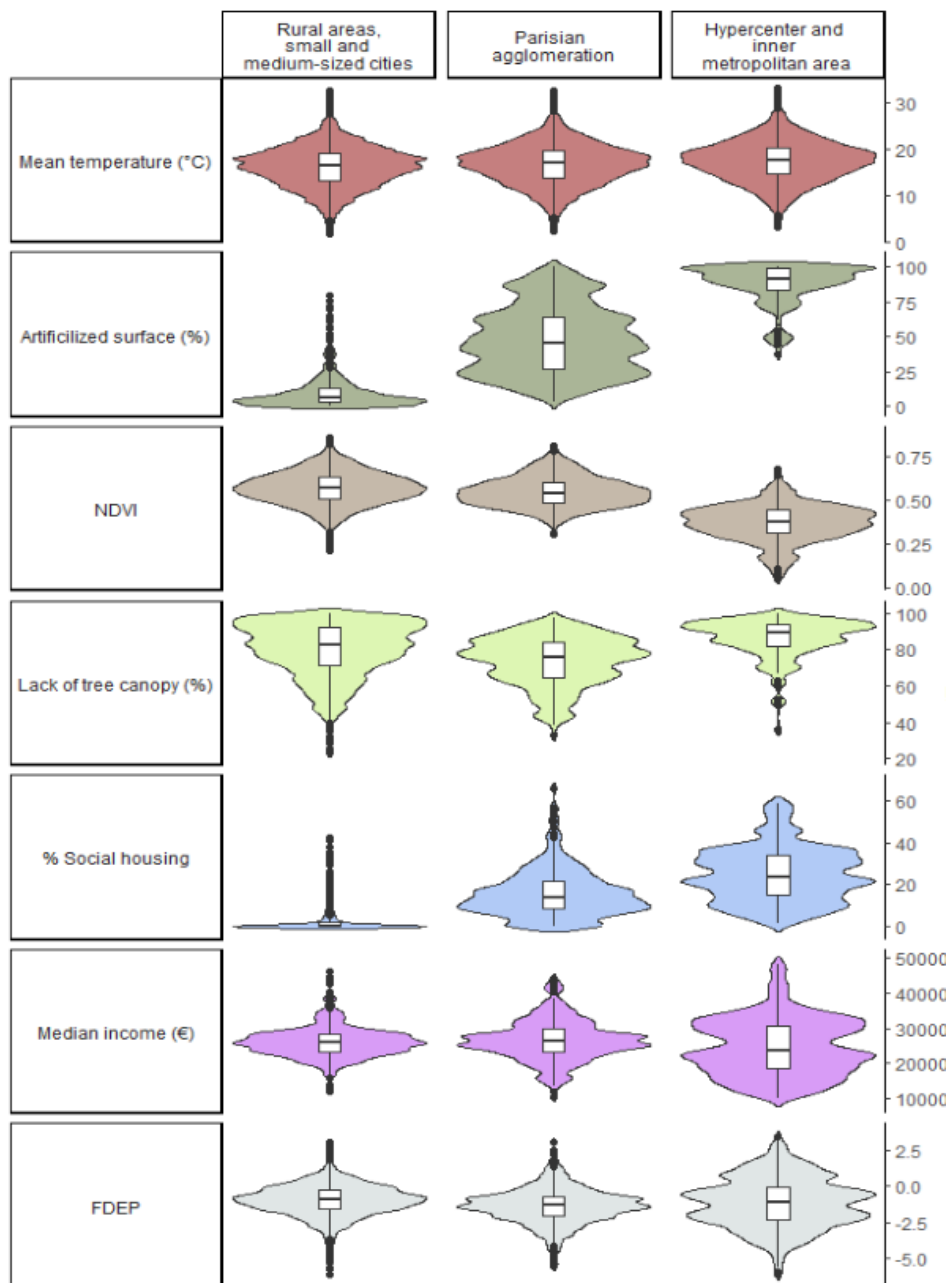
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299 **Figure 3 – Distribution of the environmental and socio-economic indicators by territorial sub-**
300 **division (for FDep, a higher value indicates a higher social deprivation)**



301

302 3.2. Selection of the temperature indicator

303 These analyses were limited to the entire region. For all temperature indicators, a similar J-shaped
304 mortality response was found, with a significant increase in relative risks (RR) at extreme

305 temperatures (supplementary material Figure S7). Table 2 displays RR for each indicator for all-cause
 306 mortality, for high temperature percentiles. Supplementary material Table S1 provides details for
 307 cardiovascular, cardiac, and respiratory mortality.

308 Supplementary Figure S8 provides information on the response by lag for selected temperature
 309 percentiles. The impact of minimum daily temperature was limited to the first 48 hours after exposure
 310 and lasted a maximum of 6 days at percentile 99.9, while the effect of maximum daily temperature
 311 persisted for 4 to 10 days.

312 Mean daily temperature was identified as the best indicator for modelling all causes of mortality, for
 313 both age groups, based on the Akaike criteria. However, the Akaike criteria showed that all indicators
 314 were very similar (see supplementary material Table S2). Therefore, mean daily temperature was
 315 used for the analyses presented below.

316 **Table 2 – Relative risks (RR) (0-10 lags) and 95% confidence intervals for all-cause mortality by**
 317 **age group, for selected percentiles of each daily temperature indicators calculated over the**
 318 **whole region**

	Age	P95 vs P50	P99 vs P50	P99.5 vs P50	P99.9 vs P50
Mean daily temperature		23.2°C vs 16.6°C	26.3 °C vs 16.6°C	27.3°C vs 16.6°C	29.4°C vs 16.6°C
	15-64	0.97 [0.93:1.00]	1.12 [1.06:1.17]*	1.27 [1.21:1.34]	1.95 [1.79:2.13]
	65+	0.93 [0.91:0.94]	1.21 [1.18:1.24]	1.53 [1.49:1.57]	3.23 [3.10:3.37]
Maximal daily temperature		30.7°C vs 21.8°C	34.6°C vs 21.8°C	36.2°C vs 21.8°C	39.1 °C vs 21.8°C
	15-64	0.99 [0.95:1.03]	1.22 [1.15:1.30]	1.52 [1.43:1.63]	2.77 [2.39:3.21]
	65+	0.96 [0.94:0.99]	1.45 [1.40:1.49]	2.20 [2.13:2.28]	6.95 [6.48:7.45]
Minimal daily temperature		17.3°C vs 11.3°C	19.3°C vs 11.3°C	20.1°C vs 11.3°C	21.7 °C vs 11.3°C
	15-64	0.94 [0.91:0.97]	1.02 [0.97:1.06]	1.11 [1.06:1.17]	1.54 [1.44:1.65]
	65+	0.89 [0.87:0.90]	1.01 [0.99:1.04]	1.18 [1.15:1.20]	1.95 [1.89:2.02]
Mean daily radiant temperature		34.8°C vs 25.9°C	37.9°C vs 25.9°C	39.0°C vs 25.9°C	40.5°C vs 25.9°C
	15-64	0.99 [0.94:1.04]	1.29 [1.21:1.37]	1.58 [1.45:1.73]	2.34 [1.97:2.78]
	65+	1.13 [1.10:1.16]	1.81 [1.75:1.87]	2.50 [2.39:2.61]	4.48 [4.12:4.87]

Mean daily UTCI	26.2°C vs 17.6°C	29.7°C vs 17.6°C	31.1°C vs 17.6°C	33.3°C vs 17.6°C
15-64	0.97 [0.93:1.01]	1.21 [1.14:1.27]	1.49 [1.40:1.59]	2.54 [2.24:2.89]
65+	0.96 [0.94:0.98]	1.47 [1.43:1.51]	2.17 [2.10:2.24]	5.64 [5.30:6.00]

319 * significant RR are presented in bold

320 3.3. Mortality risks by causes, age, sex and territorial sub-divisions

321 These models examined the association between heat and all-cause mortality by age, sex and type of
322 territories using the mean daily temperature. The results showed that heat was consistently associated
323 with an increased risk of all-cause mortality, and that small changes in temperature resulted in large
324 changes in RR (Table 3). The increase in RR was steeper for people aged 65 years and over.

325 Significant RR for women aged 15-64 were only observed in the hyper-centre and inner metropolitan
326 area, while significant RR for men were also observed in rural, small and medium-size cities, and in
327 the Parisian agglomeration. For men aged 15-64 living in the hyper-centre and inner metropolitan
328 area, at a mean temperature of 29.4°C (99.9th percentile) the RR was 2.17 [1.93:2.45]. The RR for
329 women of the same age group in the same area was 1.76 [1.48:2.08].

330 By contrast, for people aged 65 and over, larger RR were observed for women in all areas, and the
331 difference with men increased with temperature. In this age group, the larger RR for women were
332 observed in the rural, small and medium-size cities. At a mean temperature of 29.4°C (99.9th
333 percentile), the relative risk (RR) for men aged 65 years and over living in rural areas, small and
334 medium-sized cities was 1.89 [1.39:2.57]. The RR for women of the same age group in the same area
335 was 3.94 [3.09:5.01]. The RR for men aged 65 and over living in the hyper-centre and inner
336 metropolitan area was 2.44 [2.26:2.64], while the RR for women of the same age group in the same
337 area was 3.44 [3.24:3.66]. Similar patterns were observed for cardiovascular, cardiac and respiratory
338 mortality in people aged 65 years old and over. The largest RR were observed for respiratory
339 mortality: in the hyper-centre and inner metropolitan area, a temperature of 26.3°C was associated
340 with a RR of 1.39 [1.14:1.70] in men aged 65 and over, and a RR of 1.55 [1.29:1.87] in women aged
341 65 and over. At a temperature of 29.4°C, the RR were respectively 3.01 [2.29:3.96] and 4.12
342 [3.23:5.25].

343 RR stratified by territorial sub-division and age are presented in Supplementary material Table S3 and
 344 S4.

345

346 **Table 3 – Relative risk (RR) (0-10 lags) and 95% confidence interval for selected percentiles of**
 347 **mean temperature, all-cause mortality, by age and sex and territorial sub-division - RR in**
 348 **reference to P50 (16.6°C)**

		All-cause mortality					
		Men			Women		
Age		P99 26.3 °C	P99.5 27.3°C	P99.5 27.3°C	P99 26.3 °C	P99.5 27.3°C	P99.5 27.3°C
Rural areas, small and medium- sized cities	15-64	1.17 [0.98:1.39]	1.27 [1.02 :1.57]	1.59 [1.01:2.51]	1.06 [0.82:1.38]	1.17 [0.85:1.61]	1.57 [0.78:3.13]
	65 +	1.13 [1.00:1.27]	1.28 [1.11:1.47]	1.89 [1.39:2.57]	1.47 [1.33:1.63]	1.87 [1.67:2.11]	3.94 [3.09:5.01]
Parisian agglomeration	15-64	1.03 [0.91:1.17]	1.14 [1.00:1.31]	1.64 [1.26:2.15]	0.98 [0.83:1.17]	1.07 [0.89:1.30]	1.45 [0.99:2.14]
	65 +	1.18 [1.09:1.29]	1.40 [1.28:1.54]	2.41 [2.03:2.87]	1.29 [1.19:1.40]	1.68 [1.54:1.82]	3.90 [3.37:4.51]
Hyper-centre and inner metropolitan area	15-64	1.12 [1.04:1.21]	1.29 [1.19:1.40]	2.17 [1.93:2.45]	1.05 [0.94:1.18]	1.17 [1.05:1.31]	1.76 [1.48:2.08]
	65 +	1.07 [1.01:1.12]	1.27 [1.20:1.34]	2.44 [2.26:2.64]	1.13 [1.08:1.19]	1.43 [1.37:1.50]	3.44 [3.24:3.66]
		Mortality by causes, 65 years old and over					
		Men			Women		
Causes		P99 26.3 °C	P99.5 27.3°C	P99.5 27.3°C	P99 26.3 °C	P99.5 27.3°C	P99.5 27.3°C
Rural areas, small and medium- sized cities	Cardiovascular	1.04 [0.83:1.31]	1.22 [0.93:1.61]	2.01 [1.11:3.63]	1.45 [1.21:1.76]	1.79 [1.44 :2.23]	3.35 [2.13:5.27]
	Cardiac	1.06 [0.81:1.39]	1.16 [0.83:1.63]	1.51 [0.73:3.15]	1.56 [1.24:1.95]	1.98 [1.52 :2.58]	4.06 [2.35:6.99]
Parisian agglomeration	Cardiovascular	1.18 [1.00:1.40]	1.35 [1.13:1.63]	2.04 [1.44:2.92]	1.25 [1.08:1.44]	1.51 [1.29 :1.77]	2.78 [2.11 :3.67]
	Cardiac	1.18 [0.97:1.44]	1.37 [1.10:1.70]	2.16 [1.42 :3.27]	1.28 [1.07:1.53]	1.50 [1.24 :1.81]	2.45 [1.74 :3.46]
Hypercenter and inner metropolitan area	Cardiovascular	0.98 [0.88:1.10]	1.13 [1.01:1.26]	1.90 [1.61:2.23]	1.13 [1.03:1.23]	1.36 [1.24 :1.49]	2.68 [2.36:3.04]
	Cardiac	0.98	1.14	2.08	1.18	1.45	3.02

		[0.86:1.11]	[1.00:1.30]	[1.72:2.51]	[1.06 :1.31]	[1.30 :1.62]	[2.60:3.51]
	Respiratory	1.39	1.66	3.01	1.55	1.94	4.12
		[1.14:1.70]	[1.35:2.03]	[2.29:3.96]	[1.29:1.87]	[1.60:2.35]	[3.23:5.25]

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350

351 **3.4. Effect modification by vegetation and socio-economic indicators, by age and sex, for the**
352 **whole region**

353 **a) Vegetation indicators**

354 In the entire region, people aged 15-64 residing in municipalities with more vegetation (as determined
355 by the percentage of artificialized areas, NDVI, or lack of tree canopy) had a lower risk of heat-related
356 mortality compared to those living in municipalities with less vegetation (Figure 4). The difference in
357 risk increased with temperature. However, this protective effect of vegetation was not observed among
358 individuals aged 65 years and above. For example, when the temperature was 29.4°C compared to
359 16.6°C, the RR for all-cause mortality in the 15-64 age group was 2.04 [1.83:2.29] in a municipality
360 with 98% of its surface area lacking tree canopy, compared to 1.31 [1.04:1.82] in a municipality with
361 51% of its surface area lacking tree canopy. In the 65 and over age group, the RR were 3.11
362 [2.95:3.27] and 3.13 [2.78:3.52], respectively.

363 **b) Socio-economic indicators**

364 For both age groups, the risk of mortality due to heat was higher in municipalities with higher levels of
365 deprivation (higher FDep), a higher percentage of social housing, or a lower median income (Figure
366 4). For example, among people aged 15-64 years old, the RR associated with a mean temperature of
367 29.4°C compared to 16.6°C was 2.08 [1.88:2.30] in a municipality with 34% social housing, compared
368 to 1.63 [1.38:1.93] in a municipality without social housing. For individuals aged 65 and over, the RR
369 were 3.38 [3.21:3.56] and 2.96 [2.76:3.19], respectively. However, when stratifying by sex, this effect
370 of socio-economic indicators was observed in women only. Women aged 65 and over residing in the
371 most deprived municipalities according to the FDep had an RR at 29.4°C of 4.16 [3.83:4.51],
372 compared to 3.44 [3.20:3.71] for women living in less deprived municipalities. For men, the RR were
373 respectively 2.55 [2.30:2.83] and 2.43 [2.20:2.68].

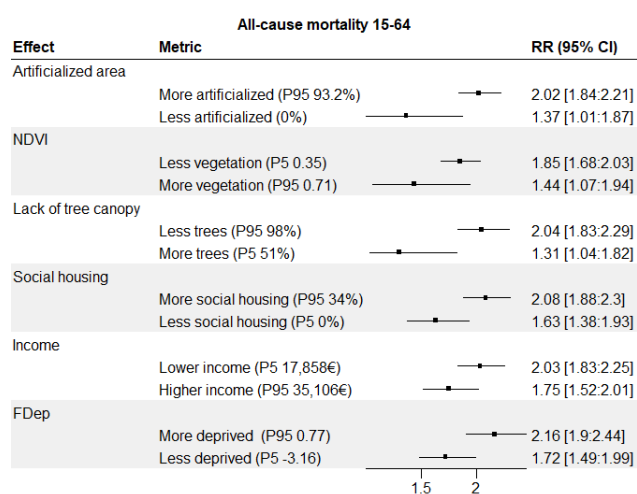
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Figure 4 - RR for all-cause mortality by vegetation and socio economic factors, for a mean temperature at P99.9 vs P50 (29.4°C, vs 16.6°C) by age-group and sex – entire region



Effect	Metric	Percentile	Whole population 65+			Men 65+			Women 65+		
			RR (95% CI)	RR (95% CI)	RR (95% CI)	RR (95% CI)	RR (95% CI)	RR (95% CI)	RR (95% CI)		
Artificialized area	More artificialized	P95 (93%)	3.23 [3.09:3.38]	2.55 [2.37:2.74]	3.69 [3.49:3.91]						
	Less artificialized	P5 (0%)	3.02 [2.64:3.46]	1.96 [1.56:2.46]	3.93 [3.32:4.65]						
NDVI	Less vegetation	P5 (0.35)	3.25 [3.11:3.4]	2.44 [2.27:2.62]	3.86 [3.64:4.09]						
	More vegetation	P95 (0.71)	3.42 [2.98:3.91]	2.11 [1.69:2.63]	4.69 [3.95:5.57]						
Tree canopy	Less trees	P95 (98%)	3.11 [2.95:3.27]	2.52 [2.31:2.74]	3.51 [3.28:3.76]						
	More trees	P5 (51%)	3.13 [2.78:3.52]	2.06 [1.69:2.51]	4.00 [3.45:4.63]						
% social housing	More social housing	P95 (34%)	3.38 [3.21:3.56]	2.53 [2.33:2.75]	4.01 [3.75:4.28]						
	Less social housing	P5 (0%)	2.96 [2.76:3.19]	2.41 [2.14:2.71]	3.31 [3.02:3.63]						
Income	Lower income	P5 (17,858 €)	3.31 [3.14:3.49]	2.50 [2.29:2.72]	3.89 [3.64:4.16]						
	Higher income	P95 (35,106 €)	3.12 [2.95:3.29]	2.46 [2.25:2.70]	3.56 [3.32:3.82]						
FDep	More deprived	P95 (0.77)	3.46 [3.25:3.69]	2.55 [2.30:2.83]	4.16 [3.83:4.51]						
	Less deprived	P5 (-3.16)	3.04 [2.86:3.22]	2.43 [2.20:2.68]	3.44 [3.20:3.71]						

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 386
 387
 388

3.5. Effect modification by vegetation and socio-economic indicators, by age and sex, and territorial sub-division
a) Vegetation indicators

389 When stratifying the analysis by territorial sub-division, the protective effect of vegetation indicators
390 disappeared for people aged 15-64 years old in all areas. For people aged 65 and over, vegetation
391 indicators did not modify the RR in rural areas, small and medium-sized cities. In the Parisian
392 agglomeration and in the hypercenter and inner metropolitan area, RR were higher in municipalities
393 with higher vegetation. For instance, in the Parisian agglomeration, the RR at 29.4°C was 2.85
394 [2.46:3.30] in municipalities with 89% of artificialized surfaces compared to 4.59 [3.56:5.92] in
395 municipalities with 49% of artificialized surfaces (Figure 4). Differences by sex were again observed: in
396 rural areas, small and medium size-cities, men living in municipalities with more vegetation tended to
397 have higher RR, but the opposite was observed for women. In the Parisian agglomeration, and in the
398 hypercenter and inner metropolitan area, women living in municipalities with more vegetation tended
399 to have higher RR (Supplementary material Table S5). Results by sex are however difficult to interpret
400 due to the large confidence intervals.

401 **b) Socio-economic indicators**

402 For both age groups, in the hypercenter, RR were higher in municipalities with more social housing.
403 For instance, for people 65 years old and over, in the hyper-center and inner metropolitan area, a
404 temperature at P99.9 was associated with an all-cause mortality RR of 3.35 [3.03:3.70] in
405 municipalities with 18% of social housing, compared to 2.87 [2.68:3.08] in municipalities with 6% social
406 housing (Figure 4). In rural areas, small and medium-sized cities, socio-economic indicators did not
407 modify the results by sex in people aged 65 years old and over. In the Parisian agglomeration, men
408 living in municipalities with more social housing, or with higher social deprivation, tended to have
409 larger RR, but the opposite was observed for women. In the hypercenter and inner metropolitan area,
410 no difference was observed for men, while women in municipalities with more social housing, or with
411 higher social deprivation, tended to have larger RR (Supplementary Table 5).

412 **3.6. Sensitivity analyses**

413 Results were not modified when including a spatial component in the model to account for spatial
414 autocorrelation and heterogeneity (data not shown).

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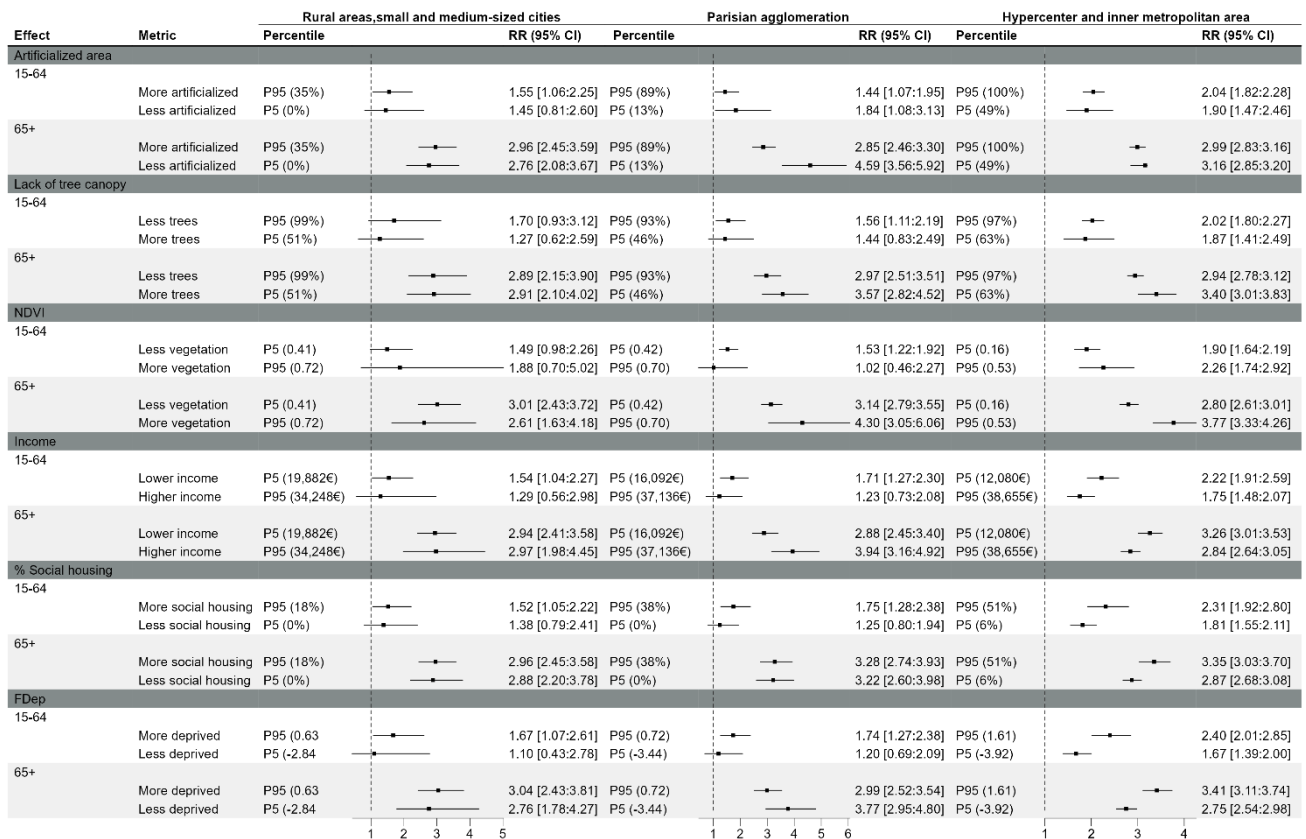
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422 **Figure 4 - Relative risk (RR) (0-10 lags) by age, all-cause mortality for a mean temperature at**
423 **P99.9 vs P50 (29.4°C, vs 16.6°C)**



424

425 **4. Discussion**

426 **4.1. Summary of the main findings**

427 This study confirms that heat is associated with an increased risk of mortality in the Paris region. It is
428 the first study in the Paris region to differentiate risks by age, sex, and territorial sub-division. Mortality
429 risks were of a similar order of magnitude between all territories. However, for the highest temperature
430 percentiles, the risks became larger in the hypercenter and inner metropolitan area.

431 The study suggested that women aged 65 and over are at higher risk than any other population of the
432 region. The results also found that vegetation had a protective effect in the 15-64 age group only. For
433 those aged 65 and over, sex and socio-economic factors appeared to be a major determinant of heat-
434 related mortality.

435

436 **4.2. Heat-related risks by territorial sub-division**

437 Heat is usually considered as a risk in urban areas. There have been limited studies on its impact in
438 rural areas, and almost none in developed countries or Europe (Odame, Li et al. 2018). The literature
439 suggests that heat-related risks in rural areas are similar in magnitude to those in urban settings
440 (Odame, Li et al. 2018). In the Paris Region, similar heat-related risks were observed in rural areas,
441 small and medium-sized cities, and in the densest urban areas of the region, for all causes and all age
442 groups. Differences only appeared at very high temperature percentiles, when the RR were higher in
443 the hypercenter and inner metropolitan area confirming the importance of short-term adaptation of
444 these territories. Our results indicate the need for a stronger adaptation to heat in rural areas, small
445 and medium-sized cities in the Paris region. In addition, in the coming years, rural areas may warm
446 faster than urban areas, potentially resulting in higher mortality burden in those areas (Lemonsu,
447 Kounkou-Arnaud et al. 2013, Le Roy, Lemonsu et al. 2020, Michau Y, Lemonsu A et al. 2024).

448 To go further in analysing the differences between urban, suburban and rural territories, it would be
449 relevant to reproduce similar analyses in other regions, and combine the results in a meta-regression.

450 **4.3. Heat-related risks by causes of deaths**

451 Our study showed that heat increased all-cause, cardiovascular, cardiac and respiratory mortality,
452 consistently with current knowledge (Cheng, Xu et al. 2019). The literature reports significant adverse
453 impacts of heat on cardiovascular (Gasparrini, Armstrong et al. 2012, Cheng, Xu et al. 2019, Alahmad,
454 Khraishah et al. 2023), ischemic (Gasparrini, Armstrong et al. 2012, Alahmad, Khraishah et al. 2023,
455 Zhang, Breitner et al. 2023), cerebrovascular (Gasparrini, Armstrong et al. 2012, Conti, Valente et al.
456 2022, Alahmad, Khraishah et al. 2023), and respiratory (Gasparrini, Armstrong et al. 2012, Cheng, Xu
457 et al. 2019, Zafeiratou, Samoli et al. 2023) mortality mortality during heat waves, or during warm days.

458 Other causes of mortality such as renal mortality, diabetes, injuries, and mental health related-
459 mortality including suicides can also be affected by heat and heat waves (Gasparrini, Armstrong et al.

460 2012) (Conti, Valente et al. 2022), and should be included in future analyses if sufficient number of
461 cases were available. Other health impacts such as emergency room visits, hospital admissions, or
462 sleep disturbance should also be explored to have a better understanding of the overall heat-health
463 impacts.

464 Finally, this study focused on the short-term impacts of temperature only, but long-term impacts could
465 also result in impaired health (Zafeiratou, Samoli et al. 2021).

466 **4.3. Heat-related risks by age and sex**

467 At moderate temperatures, the risks for younger men were larger than those for older men. This may
468 indicate a risk linked with occupational exposure or physical activity in men. It is also possible that risk
469 perceptions and adoption of protective behaviours are lower among young men.

470 In the older age group, by contrast, RR were larger for women compared to men. The literature reports
471 differences in heat-related mortality risk between men and women, but with few insights on the
472 possible drivers. A literature review focusing on 13 European studies published between 2000 and
473 2016 reported that the majority (8 studies) found higher mortality risks in elderly women (van Steen,
474 Ntarladima et al. 2019). Similar results were reported in more recent studies, for instance with higher
475 risks in women reported in Belgium (all ages) (Demoury, Aerts et al. 2022). Slightly higher RR were
476 reported for men younger than 65 years old in the Czech republic, similar RR between men and
477 women between 64 and 84 years old, and higher RR for women older than 84 years old (Vésier and
478 Urban 2023). In the Netherlands, the RR were higher for men in the youngest age group (<65), and
479 higher for women in older age groups (Folkerts, Bröde et al. 2022).

480 Sex and gender can influence physiological, behavioural and social risk factors (Folkerts, Bröde et al.
481 2022). A review of sex differences in thermoregulation for young fit women involved in physical
482 activities concluded that, despite physiological differences, there was no evidence that women have
483 an inherent susceptibility to heat-related illnesses (Yanovich, Ketko et al. 2020). Elderly women may
484 be more susceptible to heat due to hormonal changes after the menopause, but the knowledge on this
485 remains scarce (van Steen, Ntarladima et al. 2019).

486 Age can also partly explain the differences, as women are over-represented in the eldest age groups.
487 In 2020, in the Paris region, among women aged 65 and over, 51% were aged 65-74 years old, 41%

488 75-89 years old, and 8% were 90 and over. Among men aged 65 and over, 58% were aged 65-74
489 years old, 38% 75-89 years old, and 4% were 90 and over (Insee 2020). However, based on their
490 literature review, van Steen *et. al.* concluded that age alone cannot explain all the differences in heat-
491 related risks observed between men and women (van Steen, Ntarladima et al. 2019).

492 In France, gender is a significant factor in driving inequities. In 2018, women earned on average 20-
493 25% less than men. Among retired individuals, women's income was 29% lower than men's, and up to
494 53% lower in the poorest socioeconomic category (Insee 2021). In the city of Paris, women aged 50
495 years and over earn on average 32% less than men in the same age group. Additionally, the poverty
496 rate has increased more rapidly among women, particularly those aged 75 years and older (Insee
497 2021). Women aged 75 and over are more likely to experience isolation than men (Observatoire des
498 inégalités 2019). Women aged 85 years and over are also more likely to live in nursing homes (11%
499 compared to 7% of men), to experience social isolation at home (55% compared to 24% of men), and
500 to live with relatives less often than men (34% compared to 69% of men) (Insee 2022). Reducing sex
501 inequities and social isolation could be key to reduce the heat impacts in women.

502 **4.4. Influence of vegetation and socio-economic indicators on the temperature-mortality** 503 **relationship**

504 When considering the entire region, municipalities with less artificialized surfaces, higher NDVI, higher
505 tree covering, lower number of social housing or higher incomes had lower all-cause and
506 cardiovascular mortality heat-related risks. When stratifying the results by territorial sub-division, we
507 found that artificialized areas and NDVI were no longer associated with a protective effect.

508 Several studies worldwide reported a protective influence of vegetation on the heat-related mortality. A
509 previous study in the Paris region, based from temperature recorded at monitoring stations, found
510 higher heat-related risks in in municipalities with less green spaces, less trees, and more impervious
511 soil (Pascal, Gorla et al. 2021). A meta-analysis based on six papers with substantial methodological
512 heterogeneity concluded that the heat-related mortality risk was about 5% higher in less green areas
513 (Schinasi, Benmarhnia et al. 2018). A recent study on heat-related cardiovascular mortality in Norway,
514 Germany and United Kingdom also reported higher risks for women, and for people living in dense
515 urban areas with low percentage of green spaces and high levels of particulate matter (PM_{2.5})(Zhang,

516 Breitner et al. 2023). Similar results were obtained for respiratory mortality in the same countries
517 (Zafeiratou, Samoli et al. 2023).

518 As previously mentioned, vegetation can modify temperature, but also exposure and individual
519 susceptibility to heat. Since we are using fine-scale temperature, part of the influence of vegetation on
520 temperature is already captured in the temperature term. Within dense urban areas, vegetation can
521 have an additional cooling effect that is not entirely captured by the temperature data, but with limited
522 geographical spread. This may result in a differentiated risk at a very fine-scale (e.g. neighborhoods,
523 streets), but cannot be observed when using mortality data at the municipality level. Efforts to collect
524 high resolution environmental and health data would be beneficial to further understanding the
525 benefits associated with greenspaces in urban areas.

526 Additionally, in this study we compared the heat-related risks between municipalities with high vs low
527 level of greening. But it may be that those actual differences in vegetation between municipalities are
528 not important enough to modify the heat-related risk (i.e., in dense urban area, the greenest
529 municipalities are not green enough), or that other risk factors are counterbalancing the benefits of
530 green spaces. For instance, a green space not used by the population may help to reduce the ambient
531 temperature locally, but would not contribute to improve the overall health of the population, nor offer
532 shelter to reduce exposure during extreme heat.

533 Greening cities has been proposed as a solution to adapt to climate change. Lungman et al. proposed
534 that in summer (June-August 2015), 71,25% of the heat-related mortality in Paris could have been
535 prevented by increasing the average tree cover density in the city from 5 to 30% (Lungman, Cirach et
536 al. 2023). However, a better understanding of the complex pathways between vegetation, heat and
537 health would be needed to design efficient adaptation policies based on vegetation. This in no way
538 detracts from the overall beneficial role of vegetation on health.

539 Results also underline the importance of socio-economic indicators, with larger RR observed in
540 municipalities with higher share of social housing, or with lower incomes. Socio-economic vulnerability
541 to heat is difficult to capture, that is why we retained three different socio-economic indicators. Those
542 who are deprived may have fewer resources to prepare, respond and adapt to heat. Deprivation is
543 considered to contribute to health inequalities in general due to multiple disadvantages such as
544 housing, education, environmental, working. In particular, housing condition has been reported as a

545 risk factor for higher heat-mortality risk(Gronlund, Berrocal et al. 2015). In 2013, in the Paris region,
546 9,3% of the population was experiencing housing difficulties, and the social inequities between home
547 owners and tenants, and especially social housing tenants were increasing(Insee 2017).

548 Finally, our study does not conclude on the best vegetation or socio-economic indicators to consider
549 when developing heat-adaptation policies. Results are being discussed with local stakeholders as part
550 of a wider debate on climate services (Lemonsu, Alessandrini et al. 2024). The discussions show the
551 importance of having a variety of indicators to respond to different contexts and to fuel rich cross-
552 sectoral discussions.

553 **4.5. Forces and limits**

554 This study assesses heat-related mortality in the Paris region over a 17-year period using fine-scale
555 data from an extensive temperature database. It aims to provide a more comprehensive
556 understanding of the impact of heat on mortality in the region.

557 One strength of the study is the used of fine-scale data to estimate exposure to vegetation and
558 temperature. For vegetation, the 20 m scale allows for a good accuracy when computing the ratio of
559 green surfaces.

560 The average surface of a municipality in the region is 9 km². Using a resolution of 1 km for the
561 temperature data, and a population-weighted average, allow accounting for sub-municipal variations
562 and giving more weight to inhabited areas. In densely populated areas, this is equivalent to a weighted
563 average based on surface area. In rural areas, this leads to slightly higher temperatures, as the natural
564 areas, which are often cooler but less frequented, weigh less (Forceville, Lemonsu et al. 2024).
565 Previous studies relied on temperature monitored by weather stations, which captured less
566 geographical variation (Pascal, Gorla et al. 2021).

567 This study did not explore directly the influence of other parameters such as wind speed or humidity.
568 Humidity has been identified as an important parameter for human thermoregulation, but, according to
569 previous studies, does not seem to play an important role in the Paris region (Schaeffer, de Crouy-
570 Chanel et al. 2016). This might be due to a climatological context where temperature and humidity are
571 largely correlated, and where high levels of humidity are rarely observed during heat waves
572 (supplementary Figure S9). Another hypothesis is that humidity has little influence on the mechanisms
573 leading to the majority of heat-related causes (Baldwin, Benmarhnia et al. 2023). Wind speed,

574 humidity and radiation were indirectly explored through the use of UTCI as a possible indicator. Based
575 on the Akaike criteria, UTCI has similar performances than mean, maximum or minimum temperature.
576 UTCI has been proposed to improve the modelling of heat-health related impacts in the built
577 environment(Leroyer, Bélair et al. 2018), but here it did not show added value compared to mean
578 temperature, which is easier to obtain and to communicate.

579 This study examines the impact of outdoor temperature on mortality. However, it is important to note
580 that individuals spend the majority of their time indoors, and indoor exposure is significantly influenced
581 by age and sex. In France, between 2003 and 2005, men aged 15-59 spent an average of 15 hours
582 per day indoors, while women spent 16 hours per day indoors. Men over 60 spent an average of 17
583 hours per day indoors, while women over 60 spent 19 hours per day indoors. During the summer,
584 people tend to spend less time indoors (Zeghnoun A and Dor F. 2010).

585 The study period stopped in 2017 due to the unavailability of mortality data by causes on the more
586 recent years. However, there has been a marked increase in temperatures and particularly in
587 extremes in the Paris region since 2015 (Forceville, Lemonsu et al. 2024). At the same time, there
588 have been a growing number of initiatives to prevent the associated health impacts and adapt to
589 climate change. It is therefore possible that the impact of heat on health and the modifying factors
590 have already changed in the Paris region. Repeating this type of studies at regular intervals would be
591 needed to capture these changes.

592 Air pollution was not included, due to the unavailability of data over the whole study area. Possible
593 synergies between air pollution (ozone and particulate matter (PM)) and heat were reported by
594 previous studies for all-cause mortality in multicentric studies including the city of Paris (Analitis, De'
595 Donato et al. 2018, Pascal, Wagner et al. 2021) Indication of a joint influence of heat and PM on
596 cardiovascular mortality was also reported (Analitis, De' Donato et al. 2018).

597 **4.6. Implications for public health**

598 The results indicate that heat vulnerability affects individuals of all ages, genders, and living
599 environments. While prevention and interventions often focus on densely populated urban areas and
600 the elderly, it is important to develop specific actions for rural areas and younger populations.

601 Interventions targeting the urban built environment have been effective in reducing heat-related
602 mortality, but should be complemented with measures to address social inequalities and isolation. An
603 experiment conducted in Italy demonstrated that interventions aimed at reducing social isolation
604 among elderly individuals (>80 years old) could decrease excess mortality during heat waves,
605 although not completely eliminate it (Orlando, Mosconi et al. 2021). Additionally, reducing lifelong
606 gender inequalities could also decrease the observed difference in risk between men and women. It is
607 important to note that no single action is sufficient, and coordinated interventions across multiple
608 domains are crucial for any effective adaptation policy.

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