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Health effects from heat waves in France: an economic evaluation

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Abstract

Background Scarcity of data on the health impacts and associated economic costs of heat waves may limit the will to invest in adaptation measures. We assessed the economic impact associated with mortality, morbidity, and loss of well-being during heat waves in France between 2015 and 2019.

Methods Health indicators monitored by the French national heat wave plan were used to estimate excess visits to emergency rooms and outpatient clinics and hospitalizations for heat-related causes. Total excess mortality and years of life loss were considered, as well as the size of the population that experienced restricted activity. A cost-of-illness and willingness-to-pay approach was used to account for associated costs.

Results Between 2015 and 2019, the economic impact of selected health effects of heat waves amounts to €25.5 billion, mainly in mortality (€23.2 billion), minor restricted activity days (€2.3 billion), and morbidity (€0.031 billion).

Conclusion A better understanding of the economic impacts of climate change on health is required to support concrete adaptation actions and to alert decision-makers to the urgency of the situation.

Keywords extreme heat; heat-related illness; mortality; economic assessment; climate change

1. Introduction

Extreme weather events are among the most direct consequences of climate change [1]. Assessing their economic impacts is challenging, and often the economic valuation only covers the direct consequences on infrastructures, with some additional consideration of the indirect socio-economic impacts. These costs were found to represent between \$94 and \$130 billion each year between 2000 and 2012 worldwide, but health impacts were reportedly seldom studied [2].

The number, frequency, and intensity of heat waves is evolving rapidly [1], making adaptation to heat a priority. However, although they are among the deadliest extreme events [3], they are under-represented in the total estimated economic burden of extreme weather events, partly due to their limited impact on infrastructures. Few studies have focused on estimating the economic burden associated with heat waves (see [4,5] for recent reviews). The August 2003 record-breaking heat wave led to about 70,000 deaths in Europe [6] and 15,000 in France [7]. The associated direct morbidity and mortality-related medical costs borne by the French national health insurance system were estimated at between €10 and €280 million [8], but this did not account for the health-related and intangible effects supported by the population. The scarcity of data on the actual health impacts and associated economic costs of heat waves, coupled with low heat-related risk perception among stakeholders, may limit the will to invest in adaptation.

To fill this gap, we performed the first overall assessment of the health-related economic burden of heat waves from 2015 to 2019 in France. We not only considered excess mortality and morbidity based on epidemiological data, which is standard, but also tackled two more rarely addressed issues. We evaluated loss of well-being of the exposed population and jointly assessed epidemiological and economic uncertainties. Our paper contributes to the literature on health effects observed during heat waves, and aims to make decision-makers aware of the urgency of prioritizing measures to prevent the adverse health consequences of climate change.

2. Methods

This study was conducted in the 96 metropolitan French departments for the period 2015-2019. Computations were made at the department level and then aggregated at national level. A negative number of excess cases was assumed to represent an absence of heat effect. Consequently, any negative health effect at the department level is set to 0 when computing the health impact and the economic evaluation at the national level. We used the definitions, databases, and indicators developed within the French national heat wave plan to assess the health burden of heat waves, as described below.

2.1. Heat wave definition and warning levels

Daily minimum and maximum temperatures were obtained from the French National Meteorological Service (Météo France). Heat waves were defined as periods when the average minimum and maximum temperatures over three consecutive days exceeded predefined departmental thresholds [9]. Within the heat prevention plan,

each department and each day is classified by Météo-France as green, yellow, orange, and red. Orange and red levels exceed the thresholds defined above (i.e. indicate heat waves), while the yellow level indicates an intermediate situation (e.g. slightly below the thresholds), and the green level absence of risk.

2.2. Estimation of health impacts from heat waves

2.2.1. Morbidity

Daily emergency department (ED) visits and outpatient clinic visits (SOS Médecins) were obtained for each department from the French syndromic surveillance system (SurSaUD®). The database provides detailed information such as age, sex, diagnosis, whether the visit led to hospitalization, and covers approximately 93% of ED visits and 95% of outpatient clinic visits in France. We selected visits involving at least one of the heat-related adverse effects: faintness, hyponatremia, hyperthermia, heat stroke, isolated fever, and/or dehydration [10,11]. Three age groups were considered (0-14, 15-64, 65 and older).

The morbidity impacts were computed strictly for the heat wave periods because of their immediate health impact in terms of adverse effects. We used quasi-Poisson models to assess the daily number of expected cases per age group in the absence of heat waves, and controlled for day of week, month, and year. The total numbers of ED and outpatient clinic visits recorded were also included as an offset to control for a possible confounding effect from variations in the volume of activity and coding quality over time. Morbidity data are highly dependent on the number of hospitals and SOS Médecins emergency care associations reporting daily data.

Excess morbidity during heat waves was estimated at the department level as the daily observed number of cases per age group minus the expected number of cases in the absence of heat waves. The standard 95% confidence interval (CI) of the model provided an estimation of the uncertainties surrounding the estimates. We also tested three alternative models as a robustness check, without significant differences in assessments (data available upon request). Two departments were excluded from the analysis due to data quality issues, and in some departments, analyses by age groups were limited by the very small number of cases.

2.2.2. Mortality

The heat wave periods were extended by three days to account for possible delayed effects [12]. We used yearly estimates of the all-cause excess mortality by age groups during heat waves (<https://geodes.santepubliquefrance.fr>) [13]. These estimates are based on the daily number of all-cause deaths (for age groups 0-14, 15-44, 45-64, 65-74, 75 and older) provided by the National Institute of Statistics and Economic Studies (INSEE) for a sample of 3,000 municipalities accounting for 80% of deaths in France, and extrapolated to provide estimates for the whole country. Excess mortality during heat waves is computed at the department level as observed mortality minus expected mortality, based on records from previous years, in the absence of heat waves.

For each period studied, the method provides five estimates corresponding to the number of preceding years (from one to five) considered, and summarized using the mean, minimum, and maximum values. We thereby obtained a range of possible values, although not equivalent to a 95% CI. Results are expressed in numbers of excess deaths per age group. We also derived an estimation of the associated years of life lost (YLL) computed as the number of excess deaths in each age group multiplied by the average remaining life expectancy by age group and sex (see supplementary Figure 1 and supplementary Table 1 for details).

2.2.3 Loss of well-being

We approached loss of well-being through activity restriction associated with the red heat wave level (cancellation of various events, warnings to avoid travel and to reduce all physical activities). From a medical perspective, the temperatures during “red” days are likely to lead to symptoms such as fatigue, cramps, faintness, decreased alertness and cognitive function, even in young and healthy people. We considered the situation analogous to a Minor Restricted Activity Day (MRAD), i.e. “when individuals reduce most usual daily activities and replace them with less-strenuous activities or rest, but do not miss work or school” [14]. We defined the exposed population as those resident in the departments throughout the red alert days, because data on tourists by day and department were not available.

2.3. Monetary estimates: central values

The overall health burden of heat waves was considered from a societal perspective and expressed through monetary estimates of effects from morbidity, mortality, and loss of well-being in euros 2017, based on the French national consumer price index.

2.3.1. Morbidity

Morbidity costs were estimated using a “cost-of-illness” (COI) approach that included direct medical costs (ED visits, outpatient clinic visits and hospitalizations), indirect costs (loss of production), and intangible components. We used the French generic cost of an ED visit without hospitalization: €151 [15]. The cost of an outpatient clinic visit was assessed based on the French national health insurance system fees, which depend on the times of day/night and days of the visit. We calculated an average visit cost weighted by the distributions of times and days of consultation during heat waves. We assumed that the hourly distribution of outpatient clinic visits attributable to the heat wave was similar to the hourly distribution of the total visits. We obtained an average cost of €48 per outpatient clinic consultation. We added a €5 additional fee for pediatric consultations (0 to 6 years) to cover the observed pediatric fraction (33%) of the excess visits during heat waves. Some ED and outpatient clinic visits were followed by hospitalization, but no details of the causes were available. We therefore arbitrarily selected the cost of hospitalization for respiratory disease (heat being a known risk factor for respiratory hospitalization [16,17]). We chose a value of €3,866, the total cost of an average hospital stay for a respiratory system condition in France [18].

Production losses were calculated using the average French gross daily salary of €104.24 [19] for adults aged 15 to 64; this was also applied to children under 15, assuming that one parent would have to take leave from work to take care of his / her child. In total, production losses were assessed for 71.5% of the patients. We assumed that one working day was lost for each ED and outpatient clinic visit not followed by hospitalization. For patients who were hospitalized, we considered a number of lost working days equal to twice the average length of hospitalization, to account for the home rest period [20, 21]. We used an average length of hospitalization of 6.7 days (average length of respiratory hospitalizations in France in 2017 [22]), *i.e.* loss of production for 13.4 days.

To account for the intangible components related to morbidity, we used Willingness-To-Pay (WTP) for reducing the risk of emergency room visits and hospitalization. Since the literature offered no heat-wave-specific WTP, we felt that the most appropriate substitute would be WTP estimated in the air pollution context [16, 17, 23]. We chose a WTP to avoid an ED visit of €267 from Ready et al. [21] and a WTP to avoid hospitalization of €1,454, the arithmetic mean of the WTP values of €469 from Ready et al. [21] and €2,440 from Chilton et al. [24]. Although there is no clear consensus on the best way to jointly account for direct, indirect, and intangible components, we followed various studies [25-27] by grouping them together.

2.3.2. Mortality

We faced two main difficulties in valuing mortality effects, an essential but delicate exercise. First, no monetary expression of mortality meets with consensus among economists. Although it is common to use Value of a Statistical Life (VSL) and Value of a Life Year (VoLY), the choices are continually evolving with methodological developments [28]. Second, to our knowledge, there is no heat-wave-specific VSL or VoLY. To address the first challenge, we limit the arbitrariness of a choice between valuing excess deaths via VSL or via YLL with VoLY by using both, as derived from stated preference methods. In the absence of heat-wave-specific data, we rely on values from the air pollution context, when available. For the VSL, we chose €3.17 million, as recommended for French public policies [29]. This is based on a previous study from the Organization for Economic Co-operation and Development that proposes a VSL to be used in the evaluation of environmental, transport, and health policies [30]. For the VoLY, we chose €82,000, the arithmetic mean of the VoLY of €42,000 recommended by Desaignes et al. [31] for air pollution policies in the European Union and the €122,000 recommended by Quinet [29] in France.

In addition, as recently recommended by Hammitt et al. [28], we assessed the mortality impact for each year as an annual risk shared by the population living in departments experiencing heat waves, and expressed it in monetary terms per year and exposed inhabitant:

$$\frac{\text{Number of excess deaths per year}}{\text{Number of inhabitants in the departments with heat waves}} \cdot \text{VSL}$$

2.3.3. Loss of well-being

We used a stated preference approach to assess the WTP to avoid a MRAD during red-alert periods. In the absence of heat-wave-specific WTP, we selected the central value proposed by Ready et al. [21] of €43 for a MRAD.

2.4. Accounting for uncertainties

Both the estimates of health impacts and the choice of economic values involved uncertainty, which we accounted for using two approaches. The first approach considered the uncertainties for health outcomes separately from the uncertainties for economic values. For morbidity, the uncertainty comes from the 95% CI around the central estimate; for mortality, it comes from the minimum and maximum values. No health uncertainty is associated with loss of well-being, which is based on observed numbers of red days and population exposed. For the estimates of the unit economic values, we applied a $\pm 33\%$ range around the economic estimate as a rule of thumb previously recommended [32], to mimic a one-standard-deviation change around the mean for a Normal distribution. We obtained a range of monetary valuations (low, central, and high) for each health outcome and each year, providing a range of magnitude for the monetary health benefits associated with heat waves. The second approach combined the uncertainties related to the health impact estimates and the economic values through an integrated approach based on Monte Carlo simulations [33].

For morbidity, values were sampled from a Normal approximation of the quasi-Poisson distribution whose central value is the central estimate of the models, and the standard deviation is derived from the 95% CI. For mortality, values were equiprobably sampled from 4 estimates considering 2 to 5 years. Expected mortality was not assessed on a 1-year basis due to the large number of missing data (as heat waves are increasingly frequent, it was often impossible to assess mortality in the absence of heat waves based on only one year's data). Epidemiological uncertainty associated with loss of well-being was not assessed, as explained above. For each unit economic value, we used a triangular distribution defined in terms of a central value, a maximum and a minimum (here based on the $\pm 33\%$ range around the central value), standard practice when knowledge of the variable is more subjective than objective. Once defined, we generated 10,000 Monte Carlo samples from these probability distributions, which provided a probabilized distribution of the economic assessment of the heat-wave-related morbidity and mortality impacts each year.

3. Results

Table 1 summarizes the economic impacts, detailed below. Losses of well-being were only observed in 2019 following the triggering of the red alert, and represent €2.3 billion that year. Mortality effects account for the largest share, but the valuation differs depending on the metric used. Valuations based on VSL are around two to three times higher than those based on VoLY, partly because almost two-thirds of deaths occurred after the age of 75 and thus with low loss of life expectancy. Morbidity accounts for a very small share (around 0.1%) of the total. Overall, the largest impacts were observed in 2019 (partly due to the loss of well-being) and the smallest in 2016 and 2017.

Table 1 – Summary of health-related economic impacts from 2015-2019 heat waves in France

Year	Morbidity (in million € ₂₀₁₇)	Mortality (in billion € ₂₀₁₇) based on ...		Loss of well- being (in billion € ₂₀₁₇)	Total (in billion € ₂₀₁₇) based on ...	
		... excess deaths	... YLL		... excess deaths	... YLL
2015	7.95 [5.97-10.15]	5.71 [4.19-7.34]	1.65 [1.21-2.12]	0	5.72 [4.20-7.35]	1.66 [1.22-2.13]
2016	1.58 [1.12-2.12]	1.65 [1.23-2.08]	0.60 [.44-.75]	0	1.65 [1.23-2.08]	0.60 [.45-.75]
2017	4.76 [3.37-6.39]	3.33 [2.37-4.39]	1.34 [1.00-1.69]	0	3.34 [2.38-4.39]	1.35 [1.00-1.70]
2018	8.21 [5.72-11.14]	5.94 [3.62-8.06]	2.22 [1.35-3.00]	0	5.95 [3.63-8.06]	2.22 [1.36-3.01]
2019	12.40 [8.52-16.85]	6.31 [3.51-8.80]	2.47 [1.59-3.30]	2.32 [1.72-2.92]	8.64 [5.72-11.29]	4.80 [3.71-5.86]

Notes: Figures were obtained from the integrated uncertainty approach, intervals in brackets are based on the Percentile 2.5 (P_{2.5}) and P_{97.5} of the underlying Monte Carlo distributions.

3.1. Economic estimate of the impact of heat waves on morbidity

Between 2015 and 2019, 8,990[6,883-11,209] excess ED visits and 3,363 [2,708-4,024] excess outpatient clinic visits not followed by hospitalization were observed during heat waves. 4,654 [3,320-6,105] visits were followed by hospitalization (Table 2). The figure for ED visits not followed by hospitalization is €4.290 million [3.277-5.355], and for ED visits followed by hospitalization €24.495 million [17.458-32.299]. There were €0.361 million [0.287-0.435] outpatient clinic visits not followed by hospitalization and €1.506 million [0.882-2.181] visits followed by hospitalization (see Table 2, and supplementary Tables 2 and 3 for details). ED visits followed by hospitalization represented 80% of the morbidity costs, and ED visits not followed by hospitalization 14%. The largest health impacts and the highest costs were observed in 2019, representing 36% of the total morbidity costs observed over the period.

3.2. Economic estimate of the impact of heat waves on mortality

Between 2015 and 2019, 7,309 [5,018-10,105] excess deaths were observed during heat waves, representing 102,108 YLL [67,005-147,931]. In absolute numbers, the largest impacts were observed in 2015, 2018, and 2019, and when expressed in an excess death rate per 100,000 exposed inhabitants, in 2015 (5.37 [4.21-6.54]) and 2019 (6.88 [4.18-10.34]). Mortality by age group is detailed in Supplementary Table 4. Estimates for children are to be interpreted with caution due to the small number of cases. The total economic valuation of excess mortality was estimated at €23 billion using the VSL approach and €8.3 billion using the VoLY approach (Table 3). Under the VSL approach, the estimated economic impact of mortality during heat waves ranged from €68 per capita in 2017 to €218 per capita in 2019.

Table 2 – Morbidity impacts and associated costs during heat waves in France 2015-2019

Health outcomes	Year	Cases			Economic evaluation (in thousand € ₂₀₁₇)		
		Total number of visits for selected causes	Expected number of visits in the absence of heat wave [95% CI]	Excess number of visits attributed to heat wave [95% CI]	... low 95% CI	... central 95% CI	... high 95% CI
ED visits not followed by hospitalization	2015	7,825	5,941 [5,488-6,387]	1,884 [1,450-2,337]	606 [466-751]	904 [696-1,121]	1,202 [925-1,490]
	2016	1,770	1,515 [1,416-1,616]	274 [196-360]	89 [64-117]	133 [95-174]	176 [126-232]
	2017	7,001	5,549 [5,182-5,912]	1,474 [1,147-1,826]	477 [371-590]	711 [553-881]	946 [736-1,172]
	2018	9,831	8,134 [7,613-8,648]	1,729 [1,256-2,229]	550 [398-710]	821 [594-1,060]	1,091 [790-1,410]
	2019	14,279	10,654 [9,822-11,483]	3,629 [2,834-4,457]	1,154 [898-1,420]	1,722 [1,340-2,119]	2,290 [1,782-2,818]
Outpatient clinic visits not followed by hospitalization	2015	1,780	1,001 [851-1,150]	779 [630-929]	56 [44-67]	82 [65-99]	109 [87-131]
	2016	342	232 [204-262]	121 [98-146]	8 [6-10]	12 [10-15]	16 [13-20]
	2017	1,473	898 [786-1,010]	585 [482-689]	45 [36-52]	66 [54-78]	87 [71-103]
	2018	1,890	1,180 [1,041-1,319]	711 [574-849]	51 [41-61]	75 [60-91]	100 [80-120]
	2019	2,953	1,786 [1,542-2,030]	1,167 [924-1,411]	85 [66-104]	125 [97-153]	166 [129-203]
ED visits followed by hospitalization	2015	4,340	3,372 [3,061-3,680]	1,005 [744-1,286]	3,757 [2,750-4,858]	5,607 [4,104-7,251]	7,458 [5,458-9,644]
	2016	955	768 [703-833]	211 [161-263]	786 [596-986]	1,173 [889-1,472]	1,561 [1,183-1,958]
	2017	3,304	2,821 [2,594-3,048]	569 [407-757]	2,145 [1,515-2,882]	3,202 [2,261-4,300]	4,259 [3,007-5,720]
	2018	5,218	4,209 [3,874-4,545]	1,072 [781-1,379]	3,985 [2,873-5,186]	5,948 [4,288-7,741]	7,911 [5,703-10,295]
	2019	6,891	5,407 [4,871-5,941]	1,534 [1,071-2,044]	5,738 [3,963-7,728]	8,564 [5,915-11,534]	11,391 [7,868-15,341]
Outpatient clinic visits followed by hospitalization	2015	151	89 [54-128]	67 [33-97]	254 [122-376]	380 [182-560]	505 [242-746]
	2016	24	16 [8-21]	11 [10-16]	42 [37-60]	62 [55-90]	83 [73-120]
	2017	104	64 [43-86]	47 [27-63]	183 [105-249]	272 [156-371]	362 [207-494]
	2018	142	93 [60-119]	56 [37-83]	213 [139-319]	318 [208-477]	423 [276-634]
	2019	184	110 [69-155]	82 [49-117]	318 [188-457]	474 [281-682]	631 [374-907]

Notes: All intervals in brackets are standard 95% confidence interval (CI) of the underlying epidemiological models. Excess numbers attributed to heat wave is not exactly equal to total numbers minus expected numbers due to negative number of excess cases

Table 3 - Economic evaluation of excess mortality during 2015-2019 heat waves in France

Year	Exposed population	Health impacts		Economic evaluation of excess deaths (in billion € ₂₀₁₇)...			Economic evaluation per exposed inhabitant (in € ₂₀₁₇)...			Economic evaluation of YLL (in billion € ₂₀₁₇)...			
		Number of excess deaths [min-max]	Excess death rate (per 100 000 exposed inhabitants)	Number of YLL [min-max]	... low [min-max]	... central [min-max]	... high [min-max]	... low [min-max]	... central [min-max]	... high [min-max]	... low [min-max]	... central [min-max]	... high [min-max]
2015	33,181,549	1,782 [1,396-2,169]	5.37 [4.21-6.54]	19,844 [14,443-25,628]	3.8 [3.0-4.6]	5.6 [4.4-6.9]	7.5 [5.9-9.1]	114 [89-139]	170 [133-207]	226 [177-276]	1.1 [0.8-1.4]	1.6 [1.2-2.1]	2.2 [1.6-2.8]
2016	20,452,269	516 [376-677]	2.52 [1.84-3.31]	7,261 [5,020-10,036]	1.1 [0.80-1.4]	1.6 [1.2-2.1]	2.2 [1.6-2.9]	54 [39-70]	80 [58-105]	106 [78-140]	0.40 [0.3-0.6]	0.60 [0.4-0.8]	0.8 [0.55-1.1]
2017	46,436,803	991 [596-1,532]	2.13 [1.28-3.3]	15,679 [9,705-24,720]	2.1 [1.3-3.3]	3.1 [1.9-4.9]	4.2 [2.5-6.5]	45 [27-70]	68 [41-105]	90 [54-139]	0.9 [0.5-1.4]	1.3 [0.8-2.0]	1.7 [1.1-2.7]
2018	47,965,437	1,988 [1,416-2,674]	4.14 [2.95-5.57]	28,547 [19,093-40,367]	4.2 [3.0-5.7]	6.3 [4.5-8.5]	8.4 [6.0-11.3]	88 [63-118]	131 [94-177]	175 [124-235]	1.6 [1.0-2.2]	2.3 [1.6-3.3]	3.1 [2.1-4.4]
2019	29,531,532	2,032 [1,234-3,053]	6.88 [4.18-10.34]	30,777 [18,744-47,181]	4.3 [2.6-6.5]	6.4 [3.9-9.7]	8.6 [5.2-12.9]	146 [89-220]	218 [132-328]	290 [176-436]	1.7 [1.0-2.6]	2.5 [1.5-3.9]	3.4 [2.0-5.1]

Notes: All intervals in brackets are the minimum and maximum estimates of the underlying models used to estimate excess deaths and YLL.

3.3. Economic estimate of the impact of heat waves on well-being

The red alert was only observed for two days in 2019, affecting almost 27 million French citizens and economically estimated at €2.3 billion [1.5-3.1].

3.4. Accounting for uncertainties

Uncertainties of an epidemiological nature are shown as 95% CI for morbidity (Table 2) and as min-max values for mortality (Table 3). Uncertainties of an economic nature are shown as low and high estimates (Tables 2 and 3), and associated with the range of health outcomes to provide a separate treatment of uncertainties.

Figure 1 represents a more thorough treatment of uncertainty, considered jointly thanks to Monte Carlo simulations. For each year, the probabilized distribution of the total economic assessment is plotted based on combined morbidity, mortality (measured by excess deaths), and well-being impacts, although mortality effects obviously dominate. Years 2015, 2018 and 2019 have the highest total (health) impacts.

4. Discussion

Between 2015 and 2019, we estimate that the selected health impacts of heat waves amount to €25.5 billion, the majority through mortality (€23.2 billion) and the remainder through minor restricted activity days (€2.3 billion) and morbidity (€0.031 billion). These results highlight a significant economic burden on the French health system and the population. Climate change was identified as a contributor to most of the heat waves included in our analysis, increasing either their probability of occurrence (especially for departments previously not affected [7]) or their intensity. The late heat wave of September 2016 was even identified as virtually impossible in the absence of climate change, like the record-breaking September 2020 one. Therefore, this economic evaluation adds further evidence of the overall economic burden associated with climate change and underlines the urgent need for concrete adaptation actions.

Monte Carlo simulations offer a way to combine uncertainties associated with methodological choices in epidemiological modeling and economic evaluation. When the simulated mean and 95% CI are compared with the economic evaluations (in Tables 2 and 3, central, min, and max values), the absolute average difference (over the 5 years) for the central value is 3.03 % using the VSL approach and 2.44% using the VoLY approach. The average 95% CI interval ranges are smaller for the Monte Carlo simulations, by about 24% in the VoLY approach and 5% in the VSL approach. Overall, jointly accounting for uncertainty provides a better (and narrower) representation of the distribution of the economic impacts.

The values we found may appear low in comparison to other public health issues. For example, Chanel et al. [34] estimated the economic impact of avoiding 48,283 premature deaths from chronic exposure to fine particles (PM_{2.5}) at €145 billion for France. Heat waves are rare events happening on a few days per year - therefore with

a much smaller impact - but the expected rise in temperatures and in the number of heat waves should sharply increase the associated economic burden.

Our study is subject to inherent uncertainties linked to the choice and modeling of health impacts, as well as to the economic values we used, often derived from air pollution studies in the absence of heat-wave-specific values. First, we assumed the entire excess deaths and health care utilization calculated to be attributable to the heat waves. An alternative would have been to model the fraction of mortality and morbidity attributable to each heat wave, but such models also involve high uncertainty, given the rarity of heat waves, the strong non-linearity of the temperature-mortality relationship, and its sensitivity to contextual factors (e.g. adverse effect prevention campaigns, summer months when heat waves occur). Models were previously shown to be unable to capture all heat wave mortality impacts, especially during the most extreme events [13, 35]. The capacity to model morbidity has seldom been studied in the literature.

The mortality estimates we used were extrapolated from a sample of municipalities, as it takes approximately 5 years to obtain a complete mortality database in France. Comparison of observed and extrapolated data for the 2015 heat wave showed that this extrapolation provided a reliable order of magnitude of total mortality impact in France (data not shown). Our morbidity data came from a sample of hospitals. Extrapolating these to the whole country yields €30.8 million in excess ED visits and €1.96 million in excess outpatient clinic visits.

Second, regarding economic values, we implicitly assumed that life expectancy at death for excess heat-wave-related deaths was similar to that observed for all causes of death, in the absence of relevant data. Clearly, a different life expectancy value would change the share of mortality in the total economic assessment, especially in the extreme case of only one YLL per death. Less importantly, losses of production were only included for the 0-64 age group, although the French employed population aged 65 to 69 was estimated at 7.8% in 2019 [36].

Only certain health impacts were explored here, not all possible adverse outcomes. A growing literature links heat with a wide range of adverse health outcomes (cardiorespiratory effects [37], mental health [38], pregnancy outcome [39], occupational health, and productivity loss [40]). However, lack of epidemiological data prevented us from including more health outcomes. Finally, our focus on heat waves certainly underestimates the total burden of heat-related health impacts: high temperatures, even when not classified as heat waves, impact health too.

In the literature, we only found 15 studies investigating the economic impacts of adverse health outcomes due to heat waves, 8 at single-country level and 5 for the European Union. They varied widely in their approach to heat wave definition, type of health indicators used, computation of excess cases, thus limiting comparability. Most of the studies only included direct impacts in the economic valuation: mortality [41-50], hospital admissions or outpatient visits (emergency room visits, hospitalizations, outpatient consultations, etc.) [41-43, 47-49, 51-55] or the loss of production associated with morbidity [41, 43, 48, 53]. Twelve studies built a model to obtain the number of hospital admissions or outpatient visits associated with heat waves [41-49, 51, 53, 55], while the

others did not specify their method of calculation [50, 52, 54]. All the studies found the estimated health costs of heat waves to be significant.

Further research on the health impacts of heat waves is required, together with their economic evaluation, to better understand the non-linear effect of extreme temperatures and events with no historical precedent. Efforts should be made to obtain robust fractions attributable to mortality and morbidity, to assess the risk of onset or exacerbation of chronic heat-related diseases during heat waves and to estimate heat-wave-specific monetary values. Attempts to predict the magnitude of future heat waves would also be welcome. Stronger actions to prevent adverse health consequences, could help avoid some health and economic impacts during heat waves, such as deaths. Such actions are all the more important in the context of adaptation to current climate change, with increased frequency, duration, and intensity of heat waves predicted by 2050 [56]. Since 2000, heat-related worldwide mortality has already increased by more than 50% among people over 65 [57]. Allocating more resources in the short term would reduce longer-term health spending. More generally, a better understanding of the economic impacts of climate change on health is required to support the implementation of concrete adaptation actions and to alert decision-makers to the urgency of the situation.

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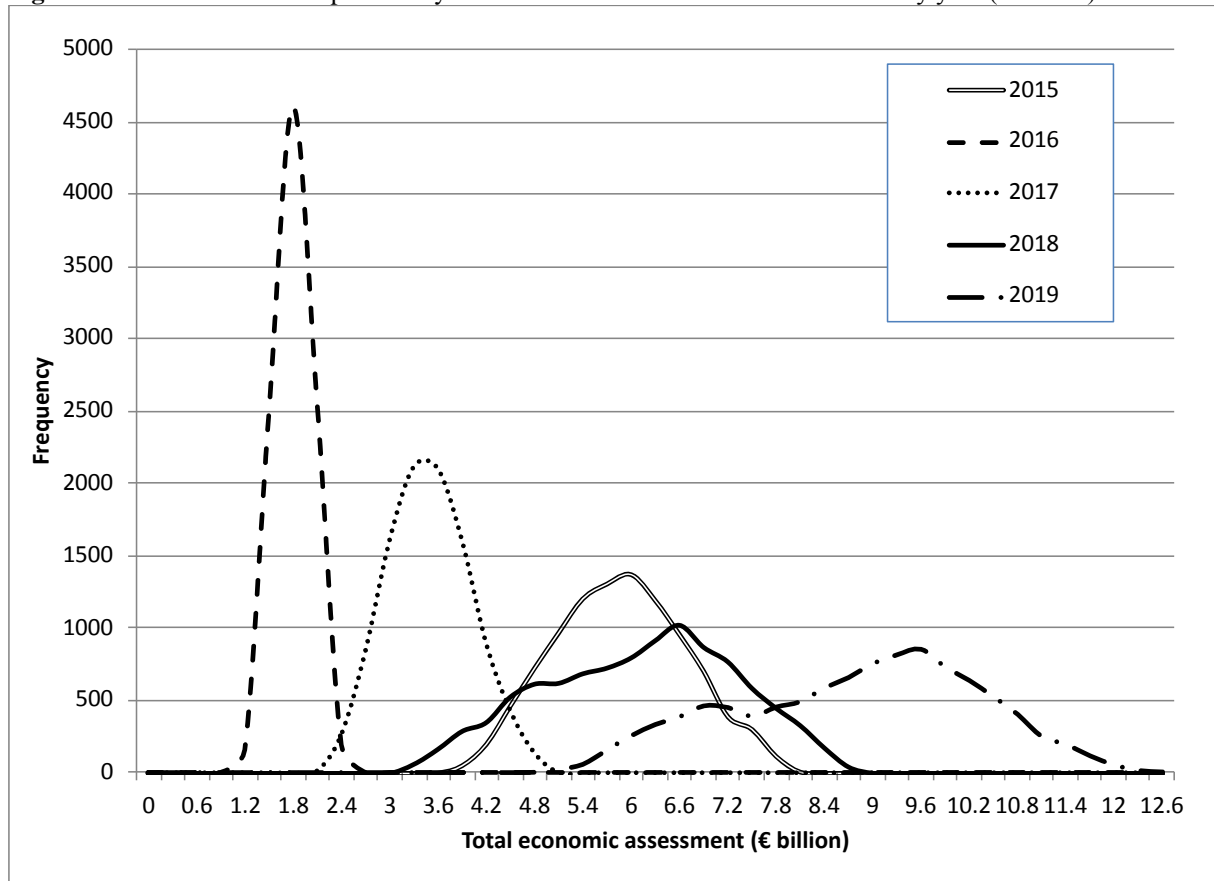
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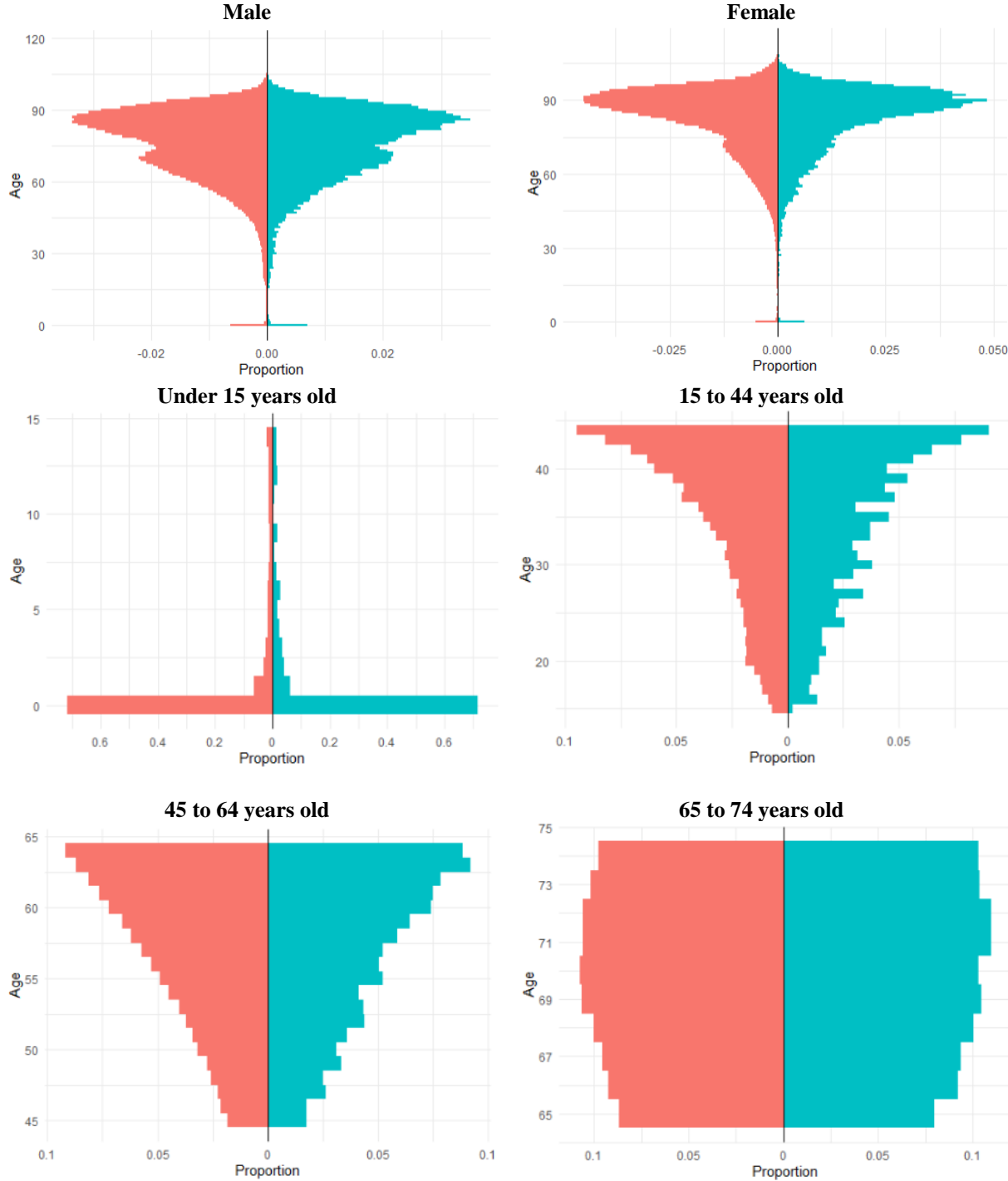
Fig. 1 Monte Carlo simulated probability distribution of total economic assessment by year (€ billion)

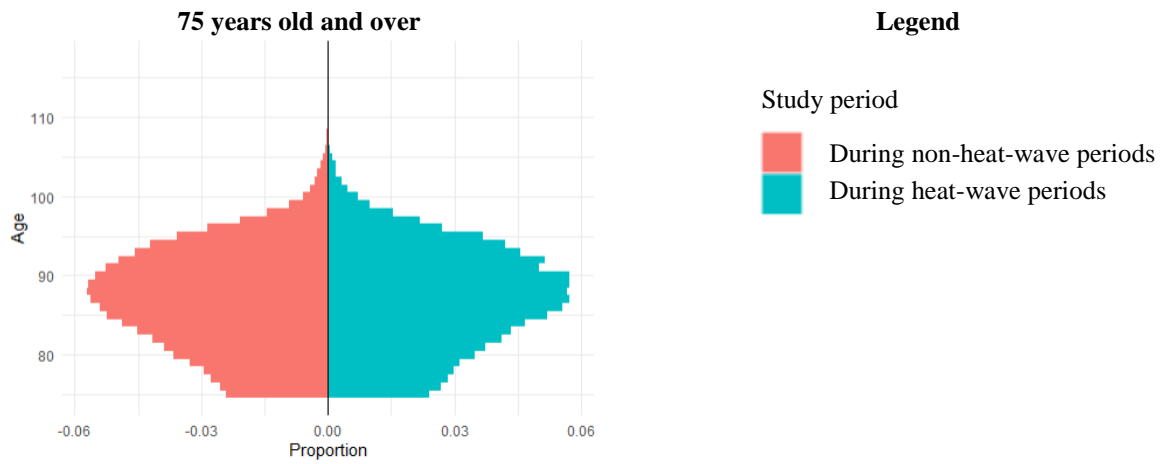


Supplementary Figure 1: Age distribution of heat-wave and non-heat-wave deaths from June 1 to September 15, 2015 to 2019

As excess mortality data were only available by age group (under 15, 15-44, 44-64, 65-74, 75+), it was impossible to estimate a precise number of YLLs for each excess death. Therefore, the age distribution of excess deaths within each age category was used to estimate YLL by age group. We assumed that the age distribution of heat-wave deaths is identical to the age distribution of non-heat-wave deaths.

The figures below show the age distribution of non-heat-wave and heat-wave deaths from 2015 to 2019 for each age category and for both sexes. These distributions were similar.





Supplementary Table 1: Weighted average number of years of life lost by age category

The table below shows the average number of YLLs by age category, weighted by age and sex distribution. The number of YLLs was calculated using the 2015 INSEE life tables from 0 to 104 years of age. Any person over 104 years of age at death was considered to have zero life expectancy.

Age categories	During non-heat-wave periods	During heat-wave periods
	Mean [Min-Max]	Mean [Min-Max]
Under 15	80.2 [65.4-85.2]	80.6 [65.4-85.2]
15 to 44	47.4 [36.7-70.6]	47.8 [36.7-69.6]
45 to 64	27.1 [19.9-41.2]	27.1 [19.9-41.2]
65 to 74	17.0 [12.7-23.1]	16.9 [12.7-23.1]
75 and older	6.4 [0-14.7]	6.4 [0-14.7]

Supplementary Table 2: Detail of the economic evaluation of excess ED visits during 2015-2019 heat waves in France (in thousand €₂₀₁₇)

Year	Direct medical costs			Loss of production			Loss of well-being		
	Low estimate 95% CI	Central estimate 95% CI	High estimate 95% CI	Low estimate 95% CI	Central estimate 95% CI	High estimate 95% CI	Low estimate 95% CI	Central estimate 95% CI	High estimate 95% CI
2015	191 [147-236]	284 [219-353]	378 [291-469]	78 [60-96]	116 [90-144]	1545 [119-191]	337 [259-418]	503 [387-624]	669 [515-830]
2016	28 [20-36]	41 [30-54]	55 [39-72]	12 [9-16]	18 [13-24]	24 [17-32]	49 [35-64]	73 [52-96]	97 [70-128]
2017	149 [116-185]	223 [173-276]	296 [230-367]	64 [49-79]	95 [73-118]	127 [98-157]	264 [205-327]	394 [306-488]	523 [407-648]
2018	175 [127-226]	261 [190-337]	347 [252-448]	66 [46-86]	98 [69-128]	130 [91-171]	309 [225-399]	462 [335-595]	614 [446-792]
2019	367 [287-451]	548 [428-673]	729 [569-895]	137 [104-172]	205 [155-256]	273 [206-340]	649 [507-797]	969 [757-1,190]	1,289 [1,006-1,583]
Total	910	1357	1,805	357	533	708	1,608	2,400	3,192
2015	2,603 [1,927-3,331]	3,885 [2,876-4,972]	5,167 [3,825-6,612]	1,747 [98-274]	260 [146-410]	347 [194-545]	979 [725-1,253]	1,461 [1,082-1,870]	1,943 [1,439-2,487]
2016	547 [417-681]	816 [622-1,017]	1,085 [828-1,352]	34 [22-49]	51 [33-73]	68 [44-97]	206 [157-256]	307 [234-382]	408 [311-509]
2017	1,474 [1,054-1,961]	2,200 [1,573-2,927]	2,926 [2,093-3,892]	117 [64-183]	175 [96-274]	232 [128-364]	554 [396-737]	827 [592-1,101]	1,100 [787-1,464]
2018	2,777 [2,023-3,572]	4,144 [3,019-5,331]	5,512 [4,016-7,091]	164 [89-271]	245 [133-405]	325 [177-538]	1,044 [761-1,343]	1,559 [1,136-2,005]	2,073 [1,510-2,667]
2019	3,973 [2,774-5,294]	5,930 [4,140-7,902]	7,887 [5,507-10,510]	270 [146-442]	404 [218-660]	537 [289-878]	1,494 [1,043-1,991]	2,230 [1,557-2,972]	2,966 [2,071-3,953]
Total	1,1374	16,976	22,578	760	1,135	1,509	4,278	6,385	8,491

Supplementary Table 3: Detail of the economic evaluation of excess outpatient clinic visits during 2015-2019 heat waves in France (in thousand €₂₀₁₇)

	Direct medical costs			Loss of production			Loss of well-being			
	Year	Low estimate 95% CI	Central estimate 95% CI	High estimate 95% CI	Low estimate 95% CI	Central estimate 95% CI	High estimate 95% CI	Low estimate 95% CI	Central estimate 95% CI	High estimate 95% CI
Outpatient clinic visits not followed by hospitalization	2015	27 [22-32]	39 [31-46]	51 [41-61]	29 [23-35]	43 [34-52]	57 [45-69]	/	/	/
	2016	4 [3-5]	6 [5-7]	8 [6-10]	4 [3-5]	6 [5-8]	8 [6-10]	/	/	/
	2017	20 [16-24]	29 [24-34]	39 [32-45]	25 [20-29]	37 [30-43]	49 [40-57]	/	/	/
	2018	24 [20-29]	36 [29-42]	47 [38-56]	27 [21-32]	40 [32-48]	53 [42-64]	/	/	/
	2019	40 [32-48]	58 [46-71]	77 [61-93]	45 [34-56]	67 [51-83]	89 [68-110]	/	/	/
	Total	115	168	221	129	193	256	/	/	/
Outpatient clinic visits followed by hospitalization	2015	176 [87-255]	262 [129-380]	349 [172-505]	13 [3-27]	20 [5-40]	27 [7-53]	65 [32-94]	97 [48-141]	130 [64-188]
	2016	29 [26-42]	43 [39-63]	57 [52-83]	2 [0.7-3]	3 [1-4]	4 [1-5]	11 [10-16]	16 [15-23]	21 [19-31]
	2017	123 [71-165]	184 [106-247]	245 [141-328]	13 [7-22]	20 [11-33]	27 [15-44]	46 [26-61]	68 [39-92]	91 [52-122]
	2018	147 [97-218]	219 [145-325]	292 [193-432]	11 [6-21]	17 [9-31]	23 [12-41]	55 [36-81]	81 [54-121]	108 [72-161]
	2019	215 [129-307]	321 [192-458]	427 [255-609]	23 [12-36]	34 [18-54]	45 [24-72]	80 [48-114]	119 [71-170]	159 [95-226]
	Total	690	1,030	1,370	63	94	125	256	382	509

Supplementary Table 4: Excess mortality during 2015-2019 heat waves in France (by age groups)

	Year	Number of excess deaths [min-max]	Relative excess mortality (%)	Number of YLL [min-max]
All ages	2015	1,782 [1,396-2,169]	15.5	19,844 [14,443-25,628]
	2016	516 [376-677]	16.2	7,261 [5,020-10,036]
	2017	991 [596-1,532]	10.9	15,679 [9,705-24,720]
	2018	1,988 [1,416-2,674]	15.7	28,547 [19,093-40,367]
	2019	2,032 [1,234-3,053]	11.7	30,777 [18,744-47,181]
	Under 15 years old	2015	10 [4-13]	12.7
2016		4 [1-10]	14.3	322 [81-806]
2017		17 [12-25]	25.4	1,370 [967-2,015]
2018		36 [26-52]	29.8	2,902 [2,096-4,191]
2019		38 [22-59]	26.0	3,063 [1,773-4,755]
15 to 44 years old	2015	23 [9-45]	7.0	1,099 [430-2,151]
	2016	25 [19-34]	27.5	1,195 [908-1,625]
	2017	68 [41-112]	25.1	3,250 [1,960-5,354]
	2018	88 [49-138]	24.3	4,206 [2,342-6,596]
	2019	120 [74-181]	25.9	5,756 [3,537-8,652]
45 to 64 years old	2015	198 [144-266]	11.8	5,366 [3,902- 7,209]
	2016	63 [39-91]	13.2	1,707 [1,057-2,466]
	2017	141 [85-236]	10.7	3,821 [2,304-6,396]
	2018	221 [126-349]	12.4	5,989 [3,415-9,458]
	2019	249 [150-423]	10.9	6,748 [4,065-11,463]
65 to 74 years old	2015	252 [177-325]	15.1	4,259 [2,991-5,493]
	2016	126 [90-159]	23.3	2,129 [1,521-2,687]
	2017	223 [147-337]	16.0	3,769 [2,484-5,695]
	2018	470 [330-615]	22.7	7,943 [5,577-10,394]
	2019	460 [290-668]	16.2	7,774 [4,901-11,289]
75 years old and over	2015	1,299 [1,062-1,520]	16.7	8,314 [6,797-9,728]
	2016	298 [227-383]	14.6	1,907 [1,453-2,451]
	2017	542 [311-822]	8.9	3,469 [1,990-5,261]
	2018	1,173 [885-1,520]	14.1	7,507 [5,664-9,728]
	2019	1,165 [698-1,722]	10.0	7,456 [4,467-11,021]