



**WORKING PAPER**

**N° 2026-9**

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TEPP – Theory and Evaluation of Public Policies - FR CNRS 2042

# Who Is Most at Risk? Uncovering the Determinants of Population Vulnerability to Heat Waves in France \*

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June 22, 2026

## Abstract

Heat waves are becoming more frequent in France, raising concerns about their public health impacts. Using Emergency Unit Territories as a spatial unit, we examine how exposure, sensitivity, and adaptive capacity shape vulnerability to extreme heat by collecting environmental, demographic, socioeconomic and health access data at the municipality level. Our results show that high temperatures and age significantly increase hospital admissions and emergency room visits, while wealth and vegetation mitigate health risks. Additional factors, such as high humidity, the share of foreigners, limited mobility, and greater distance to emergency services exacerbate heat-related vulnerability within a territory. These findings challenge assumptions about the primary drivers of heat vulnerability and highlight the importance of targeted policies, such as strengthening support networks for elderly individuals. Finally, projection exercises using the RCP4.5 scenario allow us to simulate the evolution of hospital admissions and the number of hospital beds needed to cope with the adverse effects of rising temperatures by the end of the century.

**Keywords:** Heat vulnerability ; Public health ; Risk ; Climate adaptation

**JEL classification:** I12; I18; Q54; R23

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\*We thank Grégoire Mercier, Karolina Griffiths, Yoann Morin, Philippe Tessier, Magali Dumontet and Morgane Plantier for helpful remarks.

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# 1 Introduction

A report published by the National Institute of Statistics and Economic Administration (INSEE) revealed that France had already crossed alarming temperature thresholds, with peaks reaching up to 40 degrees Celsius (INSEE, 2020). This points to more frequent, persistent, and intense heat waves, which, in turn, impose a substantial burden on public health, including hospital admissions and emergency room visits (ERV). An illustrative case is provided by Campbell et al. (2018), who estimate the health impacts of heat waves in 854 locations and highlight the major toll on health systems.

However, there still exists a significant gap in our understanding of the effect of heat waves on hospitalizations and ERV since most studies explore fatal health outcomes and do not consider the multifaceted nature of non-fatal morbidity. Moreover, most studies examining temperature-related nonfatal morbidity rely on an indirect approach: they analyze hospital admission patterns during periods of high temperature (Xu et al., 2020; Sharma et al., 2023). Nevertheless, this methodology cannot guarantee that the observed increase in hospitalizations or ERV is attributable to elevated temperatures or heat waves rather than to confounding factors. In addition, these studies either focus on specific periods, like the 2009 heat wave in Australia (Zhang et al., 2016) or specific cities, like Paris (Sabri et al., 2024). This is problematic since effective heat wave adaptation measures require nationwide coordination and explicit consideration of multiple heat wave occurrences during a single summer season. The latter is essential to avoid the overcrowding of hospital beds in areas heavily affected by high temperatures and where the local community is particularly sensitive to such conditions.<sup>1</sup>

Against this background, this paper uses an original dataset provided by *Santé Publique France*, which identifies heat as a cause of hospitalization or ERV, to examine the determinants of population vulnerability to heat waves across France. To this end, we proceed in multiple steps. First, we collect the number of hospitalizations and ERV attributed to heat in all hospitals across France. We then aggregate municipalities

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<sup>1</sup>During the COVID-19 crisis, a similar situation arose, with patients being transferred between areas due to the limited availability of hospital beds.

into Emergency Unit Territories (EUT), where each EUT comprises a core municipality hosting emergency services and a set of peripheral municipalities dependent on this core for urgent care. This spatial aggregation yields 564 population-weighted EUT. Second, we draw upon the existing literature to identify key determinants of population vulnerability to heat waves. These determinants relate to environmental, demographic, socioeconomic, and health access characteristics. For instance, age is a crucial factor in vulnerability since heat alters thermoregulation, which older adults have difficulty managing (Pascal et al., 2017, 2023). It also exacerbates existing health conditions, including cardiovascular, renal, cerebrovascular, and respiratory diseases. In addition, socioeconomic conditions shape vulnerability. People with higher income levels are less vulnerable to high temperatures than those with lower income, particularly in France (Vandendorren et al., 2004; Rey et al., 2009). Wealthier individuals tend to live in better homes equipped with air conditioning, have more access to healthcare and social services, and greater adaptive capacity to changing conditions. As a result, ethnic minority groups with lower socioeconomic status are more likely to be exposed to heat stress (Harlan et al., 2006).<sup>2</sup> The level of education also shapes how people respond and adapt to high temperatures, with higher levels of education associated with greater awareness of heat-related vulnerabilities and with a healthier lifestyle (Johnson et al., 2009). On the one hand, population density, particularly in urban areas, exacerbates the heat island effect, which plays a crucial role in intensifying extreme heat events, especially for poorer households (Grislain-Letrémy et al., 2025).<sup>3</sup> On the other hand, rural areas also remain vulnerable since hospitals, emergency centers, and essential medical services are scarcer and more dispersed. Finally, France’s population faces heightened vulnerability to heatwaves given that air conditioning coverage is limited, with only 25% of households equipped,<sup>4</sup> compared to 90% in the United States.

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<sup>2</sup>Although most of the research highlighting the different impacts of heat waves on different ethnic groups was conducted in the United States (O’Neill et al., 2003), similar findings might be expected in France given the presence of disadvantaged minorities.

<sup>3</sup>Urban areas, for instance, were the most affected by the 2003 European heat wave. However, although the impact of heat waves on cities is often emphasized due to the heat island effect, non-urban areas—characterized by high sensitivity and low adaptive capacity—are also highly vulnerable.

<sup>4</sup>For recent estimates, see: <https://batizoom.ademe.fr/indicateurs/>

Consequently, we identify environmental, demographic, socioeconomic, and health access variables as potential determinants of population vulnerability to high temperatures. Environmental covariates comprise: (i) average summer temperature, (ii) vegetative land cover, (iii) air quality metrics, and (iv) humidity levels. Demographic variables include: (i) population density, (ii) age composition, (iii) foreign-born population share, and (iv) educational attainment levels. Socioeconomic factors include: (i) housing amenities (air conditioning prevalence and number of rooms), (ii) mobility accessibility, and (iii) multidimensional deprivation indices. Finally, health access variables are proxied by (i) distance to emergency services and (ii) healthcare supply at the EUT level. Our sample comprises daily observations over the summer months (June-August) from 2012 to 2022. Next, we estimate the relationship between non-fatal morbidity (hospitalizations and ERV) and our municipality-level covariates within each EUT using Poisson pseudo-maximum likelihood (PPML) with EUT fixed effects. As a final step, we combine the estimated parameters with projected climate, environmental, economic, and demographic variables to conduct scenario-based assessments of the evolution of heat-related morbidity through the end of the century at the EUT level.

Our results indicate that areas with a higher concentration of individuals vulnerable to extreme heat are, unsurprisingly, those most exposed to high temperatures and heat waves during the summer months. Moreover, while age exacerbates vulnerability, higher income levels and greater vegetation coverage have a dampening effect. Supplementary analyses suggest that humidity exacerbates heat wave impacts on morbidity, whereas air pollution exhibits no statistically significant effect. Turning to the socioeconomic dimension, our analysis reveals elevated heat-related hospitalization rates among both foreign-born populations and individuals with higher educational attainment. While the former finding may be attributable to heightened vulnerability among immigrant communities, the latter likely reflects superior health literacy and increased healthcare utilization (Johnson et al., 2009). Finally, limited mobility alternatives (proxied by automobile dependence), social deprivation, and distance to emergency services amplify

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`part-des-logements-climatises`.

non-fatal morbidity.

This paper contributes to research examining the association between temperature variability and morbidity. The closest study is [Sabri et al. \(2024\)](#), who consider the effect of heat waves, environmental factors, and demographic variables on healthcare needs in Paris, proxied by information about hospital stays spanning from June to September over the years 2009 to 2019.<sup>5</sup> They consider various variables based on their implications for the population’s vulnerability to heat effects, such as the index of social disadvantage values, building ages, the percentage of residents above 75 years old, prevalence of air conditioning, and availability of elevators. They find that the age group over 75 is the most likely to be hospitalized following a heat wave. Using the same approach applied to 1814 Brazilian cities, [Xu et al. \(2020\)](#) found significant associations between temperature variability and hospitalisation across sex, age groups, and geographical regions during the period 2000–2015. Specifically, the hospitalisation risk associated with a 1°C increase in temperature variability on the current and previous day increases by 0.52%, and the vulnerability is particularly high for people aged 0–19 years, 60 years or older, and for lower-middle incomes.

Our contribution to the literature is threefold. First, we construct a comprehensive dataset of environmental, socioeconomic, demographic, and health access variables at the EUT level, enabling national-scale analysis. Second, we identify the determinants of heat-related morbidity across France. Third, we project population vulnerability to high temperatures through the end of the century, quantifying both the anticipated change in heat-related hospital admissions and the additional hospital bed capacity required to accommodate them.

The remainder of this paper is organized as follows. Section 2 characterizes Emergency Unit Territories and presents descriptive evidence on non-fatal morbidity. Section 3 develops the theoretical framework while section 4 describes the data and estimation strategy. Section 5 presents the main empirical results and section 6 provides scenario-

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<sup>5</sup>This detailed information concerns the purpose of hospitalization, the residential location, and hospitalization dates.

based projections of heat-related morbidity through the end of the century. Finally, section 7 concludes.

## 2 The Emergency Unit Territories

We define spatial units based on access to emergency healthcare, which we define as Emergency Unit Territories (EUT). Each EUT consists of a municipality hosting emergency services, referred to as the core municipality, and a set of surrounding municipalities that do not have such facilities. Hence, residents of these peripheral municipalities rely on the emergency services located in the core municipality to access urgent medical care. Accordingly, every French municipality belongs to an EUT: it is either the core municipality or a peripheral one associated with a core.

To construct these spatial units, we proceed in multiple steps. First, we identify municipalities that host emergency facilities using a dataset provided by the *Direction de la Recherche, des Études, de l'Évaluation et des Statistiques* (DRESS) of the French Ministry of Health. This dataset lists all municipalities equipped with either an emergency department (*Service d'Urgences Hospitalières*) or a Mobile Emergency and Resuscitation Service (*Service Mobile d'Urgence et de Réanimation*). These constitute the core municipalities of our EUT. Second, we assign all other French municipalities, those without emergency facilities, to one of these core municipalities. To match core and peripheral municipalities, we use another DREES dataset reporting the travel time between each municipality and the nearest emergency facility. Peripheral municipalities are therefore linked to a core municipality based on travel time rather than physical distance.<sup>6</sup> However, for a small number of municipalities, travel time information is unavailable. In these cases, we rely on the Territoires de Vie Santé, defined by DREES as territorial units that aggregate municipalities around a central hub providing essential health services and infrastructure.

Our classification identifies 35,793 municipalities grouped into 568 Emergency Unit

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<sup>6</sup>The boundaries of an EUT may go beyond departmental or regional borders, since the grouping is based on functional relationships between municipalities rather than administrative divisions.

Territories. Table 1 shows that, while each EUT includes on average 63 municipalities, the standard deviation is relatively large (49). The same pattern emerges for mean distance (6 km) and population (117,525), both exhibiting substantial standard deviations (11 km and 84,514, respectively). This reveals significant heterogeneity across EUT in France, reflecting the inclusion of both dense urban areas and sparsely populated rural areas with fewer emergency services.

**Table 1: Descriptive Statistics of Emergency Unit Territories**

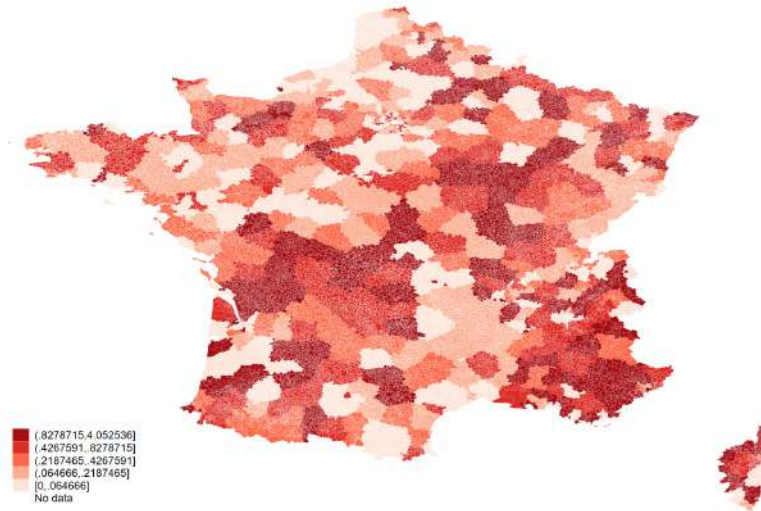
<b>Variable</b>	<b>Value</b>
Number of municipalities	35,793
Number of Emergency Unit Territories	568
Mean number of municipalities per EUT	63
Std. dev. of municipalities per EUT	49
Mean distance municipality-EUT (km)	6
Std. dev. distance municipality-EUT (km)	11
Mean population per EUT	117,525
Std. dev. population per EUT	84,514

Despite this heterogeneity, we assume that the EUT represents the appropriate analytical unit for examining the effects of high temperatures and heat waves on hospitalizations and ERV in France for two reasons. First, the EUT are specifically designed to group populations based on access to healthcare infrastructure, rather than relying on administrative boundaries. This distinction is particularly useful for analyzing hospital admissions during periods of high temperatures and heat waves, as healthcare utilization is driven by accessibility and proximity to services. Hence, since the EUT encapsulate real-world healthcare access patterns, they allow for a more nuanced understanding of hospital admissions triggered by heat-related illnesses, especially for vulnerable populations such as the elderly or those with chronic health conditions. By studying data at this scale, we are able to capture the localized effects of high temperatures and heat waves on healthcare demand without any distortion caused by aggregating data over larger and less homogeneous administrative regions. Second, heat wave impacts are inherently localized due to spatial variations in temperature and humidity. In this context, the EUT scale provides a valuable framework for integrating environmental and health

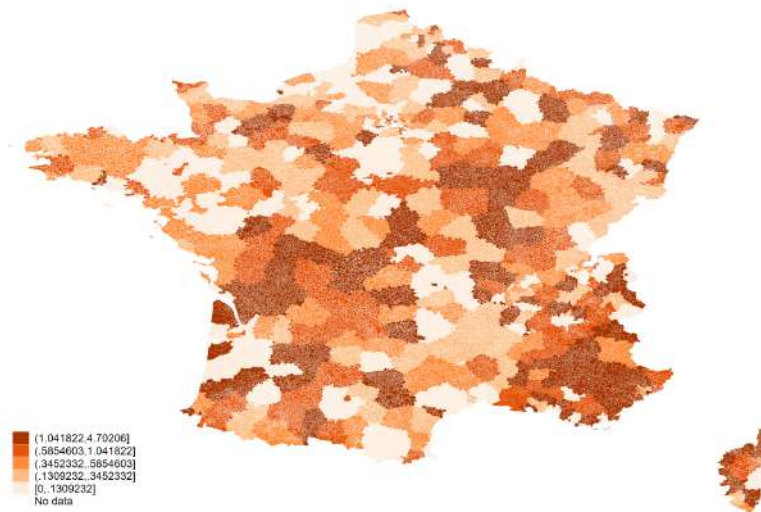
data since their boundaries align closely with geographical and climatic variation. In short, the EUT scale ensures that environmental and health data are analyzed within territories that share similar exposure to heat-related risks. Conducting research at the EUT scale ensures that our findings are directly relevant to policymakers and healthcare planners. For example, understanding how high temperatures and heat waves impact hospitalizations within a specific EUT can inform resource allocation decisions, such as increasing hospital capacity, deploying mobile medical units, or establishing cooling centers in the most affected areas. As a result, actionable insights derived from EUT-level research can contribute to more effective public health interventions and preparedness strategies.

We measure nonfatal morbidity at the EUT scale using two variables: the number of ERV and the number of ERV resulting in hospitalization due to heat-related causes. We obtain these measures from *Santé Publique France*, which reports establishment-level statistics (hospitals and emergency care facilities) disaggregated by municipal location which are then aggregated at the EUT level. Figures 1 and 2 show the average number of hospitalisations and ERV for 1000 inhabitants due to high temperatures and heat waves in the period 2012-2022. While these two metrics are highly correlated, they are not uniformly distributed at the EUT level, with areas more heavily impacted than others, such as the South East (Provence-Alpes-Côte d’Azur) and the South West (Poitou Charente and the North of Aquitaine) of France. Interestingly, high temperatures alone do not fully explain heat-related morbidity. Territories less affected by extreme heat, such as the center-east region (Bourgogne-Franche-Comté), also experience elevated hospitalization and emergency room visit rates. This pattern suggests that population vulnerability to heat waves is multifactorial, including socioeconomic and demographic dimensions alongside environmental ones. The empirical analysis conducted in this paper aims to highlight this multifaceted nature of heat vulnerability.

**Figure 1: Average Number of hospitalisations by EUT per 1000 inhabitants (2012-2022)**



**Figure 2: Average Number of emergency room visits at the EUT scale per 1000 inhabitants (2012-2022)**



### 3 Theoretical framework

Our approach draws on a broad literature on vulnerability, which is defined in the context of climate change as “*the degree to which a system is susceptible to, or unable to*

*cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate change and variation to which a system is exposed, its sensitivity, and its adaptive capacity*” (Watson et al., 2001). Following McCarthy (2001), the literature generally assumes that vulnerability depends on three main factors : (i) exposure, which refers to “*the nature and degree to which a system is exposed to significant climatic variations*”. (ii) sensitivity, which is “*the degree to which a system is affected, either adversely or beneficially, by climate-related stimuli*”, and (iii) adaptive capacity, that is “*the ability of a system to adjust to climate change*”. Therefore, vulnerability can be measured as: exposure + sensitivity - adaptive capacity (Szagri et al., 2023).

For our purposes, we refine these definitions as follows. First, we define vulnerability as the degree to which high temperatures and heat waves affect health. At the individual level, vulnerability can be measured by the severity of symptoms caused by extreme heat. At the territorial level, it can be quantified by the number of people affected. As described in section 2, we consider two metrics to capture population vulnerability: hospital admissions and ERV, both explained by heat-related symptoms. Second, from an empirical perspective, *exposure* can be seen as the intensity of a shock or the severity of the hazard. Since our objective is to identify factors that explain why, in the specific context of high temperatures and heat waves, a specific territory acce greater health consequences compared to another one, factors such as humidity, air quality, population density, and the proportion of vegetated surfaces are key variables. Third, we consider *sensitivity* as a dimension of vulnerability that reflects individual characteristics that can explain the extent of health deterioration following a shock. This includes factors such as advanced age and socioeconomic variables like social isolation or being a foreigner. Finally, *adaptive capacity* can be defined as the ability of individuals to access tools or resources that help them mitigate the effects of high temperatures. This includes access to air conditioning, medical infrastructure, or the flexibility to adjust work schedules based on temperature conditions.

This theoretical framework, though broadly endorsed, proves difficult to translate

into an explicit empirical methodology. Many variables appear to simultaneously influence *sensitivity*, *exposure*, and *adaptive capacity*. Consider, for example, an individual's income: it is an inherent characteristic categorized under sensitivity by Szagri et al. (2023). However, one could also argue that a wealthy person is more likely to live in a less densely populated area, such as a house surrounded by a shaded garden, which mitigates the hazard and reduces *exposure* to extreme temperatures. Moreover, wealthier households are more likely to have air conditioning, thus enhancing their *adaptive capacity*. The same complexity applies to social isolation: a person living alone, a characteristic linked to *sensitivity*, is more likely to live in a smaller apartment, which can increase *exposure*. Furthermore, in the event of health issues, social isolation reduces the likelihood of receiving immediate first aid from nearby friends or family members when mild symptoms appear, thereby limiting *adaptive capacity*.

Therefore, while the theoretical framework of vulnerability proves useful for guiding our analysis and interpreting our results, it appears essential to complement it with a more pragmatic framework that aligns with our empirical approach. Specifically, the variables representing exposure, sensitivity, and adaptive capacity can be categorized into several sets based on the characteristics of the territories: environmental, socioeconomic, demographic and health access variables.

## 4 Data and Empirical setup

### 4.1 Data and Stylized facts

We use four categories of datasets to assess the factors driving population vulnerability to high temperatures and heat waves.

- **The environmental data.** We use temperature as a measure of exposure to extreme heat, measured at the land surface during the summer period (average temperature of every summer (June, July, and August, in °C) from 2012 to 2022. After extracting data via the Historical Weather API, which allows us to query daily average temperatures for specific geographic coordinates at a given date range, we

consider the average temperature of the land surface over the entire EUT area. Second, vegetalization measures the percentage of vegetative cover in a territory, and is collected from the Corine Land Cover database, which is available in the French government’s website.<sup>7</sup> For air quality metrics, we rely on [Real et al. \(2022\)](#) to collect annual data on air pollution for each municipality.<sup>8</sup> We aggregate these pollutants from the municipality to the EUT level using population-weighted averages. Humidity data are collected at the monthly level from the Historical Weather API. Each EUT core municipality is matched to the nearest grid point where humidity is measured.

- **The demographic data.** We consider three demographic dimensions along which the EUT vary: (i) age distribution, measured by mean population age, the share of children under 14 (%), the share of elderly aged 60 and above (%), and the youth dependency ratio (population aged 0-14 relative to population aged 15-59, %),<sup>9</sup> (ii) the share of the foreign population within the territory and (iii) the percentage of individuals aged 25 and older with a higher education qualification.
- **The socioeconomic data.** To assess socioeconomic conditions, we first examine wealth and income levels within the EUT. While wealth is measured by average housing prices in current euros—real estate being the primary form of household wealth in France—income is assessed through municipal GDP. Second, we consider household characteristics, including the proportion of single-person households. In addition, we consider the average number of rooms per residence. Finally, we in-

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<sup>7</sup>The following types of areas are classified as vegetated: urban green spaces, orchards and small fruit plantations, olive groves, grasslands and other permanent agricultural grass surfaces, agroforestry areas, broad-leaved forests, coniferous forests, mixed forests, natural grasslands and pastures, heathlands and scrubs, sclerophyllous vegetation, transitional woodland and shrub vegetation, and sparse vegetation.

<sup>8</sup>We consider six pollutants: NO<sub>2</sub> (Nitrogen Dioxide), O<sub>3</sub> (Ozone), SOMO35 (Sum of Ozone Means Over 35 ppb), AOT40 (Accumulated Ozone exposure over a Threshold of 40 ppb), PM<sub>10</sub> (Particulate Matter  $\leq 10 \mu\text{m}$ ), and PM<sub>2.5</sub> (Particulate Matter  $\leq 2.5 \mu\text{m}$ ). SOMO35 and AOT40 are cumulative exposure metrics for ozone, with SOMO35 focused on health impacts and AOT40 on vegetation damage.

<sup>9</sup>All demographic data are obtained from the INSEE database. In particular, we use the base “Population municipale des communes - France entière” that contains the data of the municipal population census in the French communes, and the database “Couples - Familles- Ménages” that provides data on the characteristics of households (age, marital status, socio-professional category, etc).

clude a composite indicator of social disadvantage, the Deprivation Index, where higher scores indicate higher levels of deprivation.<sup>10</sup>

- **The Health access data.** To measure healthcare access at the EUT level, we use two proxies: (i) geographic distance, defined as the mean distance between peripheral municipalities and the core municipality where emergency services are located, and (ii) the Localized Potential Accessibility (LPA) indicator for general practitioners, measured as the number of consultations/visits accessible per age-standardized inhabitant.

Table 9 in the appendix presents descriptive statistics of our dataset. Some EUT recorded zero ERV and hospitalizations attributable to heat exposure throughout the sample period. This pattern likely reflects geographical heterogeneity in climate exposure, particularly in mountainous regions where cooler temperatures prevail year-round, thereby mitigating heat-related health risks. Consistent with this interpretation, the variables measuring heat-days and heat waves similarly exhibit minimum values of zero across several territories, confirming substantial spatial variation in thermal stress exposure.

## 4.2 Empirical setup

We identify the environmental, socioeconomic, demographic, and health access characteristics that shape population vulnerability to temperature-induced morbidity. The two metrics considered to capture the nonfatal morbidity of high temperatures and heat waves will alternatively appear on the left-hand side of the following equation:

$$y_{it} = \alpha_i + \gamma T_{it} + \beta X_{it} + \varepsilon_{it}; \quad (1)$$

where  $y_{it}$  denotes heat-related hospitalizations or ERV (per 1000 inhabitants) in EUT  $i$  at time  $t$ . The variable  $T_{it}$  captures exposure to high temperatures or heat waves,

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<sup>10</sup>This index is derived from the first principal component of a weighted principal component analysis based on four key variables: the unemployment rate, the proportion of manual laborers, the proportion of high school graduates, and the median income.

while  $X_{it}$  is a vector of environmental, socioeconomic, demographic, and health access controls. The term  $\alpha_i$  represents EUT-specific fixed effects that absorb all time-invariant unobserved heterogeneity across spatial units, and  $\varepsilon_{it}$  is an idiosyncratic error term.

To account for potential over-dispersion and unobserved heterogeneity across spatial units, we use the Poisson pseudo-maximum likelihood (PPML) estimator with high-dimensional fixed effects at the EUT level. This allows one to control for time-invariant confounders, mitigating omitted variable bias. Furthermore, the inclusion of robust standard errors clustered at the EUT level makes it possible to address potential heteroskedasticity and intra-cluster correlation, ensuring valid inference. Finally, the PPML framework accommodates the presence of zeros in the dependent variable without requiring log-transformations, which is advantageous given the count nature of hospitalization data. Eq. (1) becomes:

$$E[y_{it} | T_{it}, X_{it}, \alpha_i] = \exp(\alpha_i + \gamma T_{it} + \beta X_{it}); \quad (2)$$

Given the exponential functional form of eq. (2), direct interpretation of the coefficients  $\gamma$  and  $\beta$  is inappropriate. Instead, one must compute incidence rate ratios (IRR), whereby the interpretation follows a multiplicative rather than additive framework. To limit multicollinearity issues arising from highly correlated covariates capturing similar dimensions (e.g. alternative measures of income or wealth), we do not include all controls simultaneously but introduce them in separate specifications. For expositional clarity, constant terms are omitted from the reported results. Finally, we conduct Moran's I tests to assess spatial autocorrelation; in all cases, the null hypothesis of no spatial autocorrelation is not rejected, suggesting that standard econometric methods are sufficient.

## 5 Results

### 5.1 Baseline results

Table 2 presents the baseline specification, incorporating the variables that exhibit the strongest statistical significance across the different dimensions under consideration (see section 4.1).

Variables across all four dimensions are significantly associated with non-fatal morbidity related to high temperatures. Specifically, we find that morbidity is positively associated with temperature and age, while the relationship with wealth and vegetation turns out to be negative. Interestingly, these relationships are similar, in terms of sign and significance, regardless of the metric used to assess morbidity, hospitalizations or ERV. Given the log-linear specification of the model, coefficients cannot be interpreted directly; incidence rate ratios (IRRs), obtained by exponentiating the estimated coefficients, provide meaningful effect sizes. For temperature, the IRR of 1.0749 ( $p < 0.001$ ) implies that a  $1^{\circ}\text{C}$  increase in average summer temperature is associated with a 7.5% rise in hospitalization incidence rates, controlling for territorial fixed effects. To illustrate the magnitude of these associations, note that the average summer temperature and hospitalization rate in our sample are  $20.06^{\circ}\text{C}$  and 0.46 per thousand inhabitants, respectively. In a summer where the average temperature reaches  $21^{\circ}\text{C}$ , the expected hospitalization rate would be approximately 0.5 per thousand inhabitants, *ceteris paribus*.

The remaining covariates exhibit similar signs and significance levels to those in the baseline specification. The coefficient on log real estate prices, which serves as a proxy for wealth, is -1.03 (IRR = 0.36). Hence, a 1% increase in prices is associated with a 1.03% decrease in the expected number of hospitalizations. Regarding the vegetation coverage variable, the latter is measured as a proportion (0-1), with a mean of 0.41 and a standard deviation of 0.25. The PPML estimate suggests a large negative association: a 1 percentage-point (pp) increase in urban vegetation is associated with an approximately 8.5% reduction in expected hospitalizations. Interpreting the association at the scale of one standard deviation yields an even larger magnitude. While the negative sign is

consistent with the literature on urban heat mitigation and environmental health, the magnitude likely reflects structural differences across areas (high density urban areas *versus* low density rural areas) captured by vegetation coverage, suggesting that the coefficient should be interpreted as a reduced-form association rather than a pure causal effect. Finally, the share of elderly population (60+) is positively associated with hospitalizations (IRR = 1.594): a 1 pp increase in this share is associated with a higher expected hospitalization rate of about 6–7%.

Given that extreme temperatures frequently coincide with heat wave events, we include two additional variables capturing this meteorological phenomenon: (i) the total number of heat wave days based on Météo France criteria over the summer period,<sup>11</sup> and (ii) the number of heat wave episodes (independent of length) over the same period. Table 2 suggests that these heat wave metrics are positively and significantly associated with hospitalization counts. Specifically, each additional heat wave day is associated with an approximately 0.27% higher hospitalization rate (IRR = 1.0027,  $p < 0.001$ ), consistent with the notion that repeated heat stress may have cumulative health implications (e.g., 10 extra heat wave days correspond to a 2.7% difference). Moreover, an additional heat wave episode is associated with a 5.8% higher hospitalization incidence (IRR = 1.0579,  $p < 0.001$ ), a pattern consistent with a non-linear or threshold relationship and with the heightened risk posed by prolonged and intense heat events rather than isolated hot days.

All in all, these results provide initial evidence of the importance of considering environmental, socioeconomic and demographic factors when assessing the associations between high temperatures and non-fatal morbidity.

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<sup>11</sup>According to Météo-France, a heatwave is defined when the national thermal indicator reaches  $\geq 25.3^{\circ}\text{C}$  for at least one day and remains  $\geq 23.4^{\circ}\text{C}$  for at least three consecutive days. The episode ends when the indicator falls below  $23.4^{\circ}\text{C}$  for two consecutive days or below  $22.4^{\circ}\text{C}$  for a single day.

**Table 2: Baseline Model and Alternative Heat Measures**

	Baseline Model		Alternative Measures	
	(1) Hosp.	(2) ERV	(3) Hosp.	(4) Hosp.
Vegetalization	-19.21* (9.91)	-20.60** (8.35)	-21.69** (10.08)	-21.74** (9.91)
Elderly Population	6.39*** (1.94)	7.20*** (1.68)	8.04*** (1.89)	7.18*** (1.89)
Wealth	-1.02*** (0.31)	-1.07*** (0.27)	-1.12*** (0.31)	-1.01*** (0.31)
Temperature	0.07*** (0.01)	0.08*** (0.01)		
Heat-days			0.0027*** (0.00)	
Heatwaves				0.06*** (0.01)
N	5390	5434	5390	5390

Fixed effect: yes. Estimator: Poisson Pseudo-Maximum Likelihood (PPML).

Robust standard errors in parentheses. Statistical significance: \*10% \*\* 5% \*\*\*1%.

## 5.2 Environmental factors

We consider the role of humidity and air quality as additional climatic stressors (see table 3). The latter are commonly hypothesized to be associated with greater heat vulnerability, particularly among individuals with respiratory or cardiovascular conditions (Barreca, 2012). When introduced as a continuous variable, relative humidity exhibits a positive but modest association with hospitalizations. This limited magnitude is consistent with the climatic context of metropolitan France, where extreme humidity levels remain relatively rare. However, focusing on high-humidity episodes (defined as the top quartile of observations – Column 2) reveals a substantially stronger and statistically significant association, highlighting the non-linear nature of humidity-related health risks. The interaction between temperature and high humidity further reinforces this interpretation. The positive and significant interaction term indicates that heat-related health associations are stronger under humid conditions. This pattern is consistent with physiological mechanisms: high humidity is associated with reduced efficiency of perspiration, impaired thermoregulation and increased heat stress. Finally, restricting the sample to

high-humidity observations (Column 4) shows that the association with age is no longer significant, while the temperature coefficient increases.

Regarding air quality, we find no statistically significant association between pollution levels and hospitalizations in the overall sample. This result may be explained by the fact that episodes of high pollution generally occur in winter, while heat waves occur in summer. Furthermore, when the focus is restricted to densely populated urban areas, a limited number of pollutants exhibit positive and marginally significant associations with hospitalization rates. In contrast, a wider range of gaseous pollutants demonstrates robust positive and statistically significant associations with ERV, even when considering the full sample.

Our results suggest that while high humidity is associated with broadly higher vulnerability across the entire population and attenuated age-specific differentials, pollution may be more strongly associated with acute health episodes rather than with general hospitalization incidence. Overall, these findings point to the combined role of temperature and humidity as a key correlate of health vulnerability during climatic stress events.

**Table 3: Humidity and Air Quality**

	Humidity				Air Quality					
	(1) Hosp.	(2) Hosp.	(3) Hosp.	(4) Hosp.	(5) Hosp.	(6) Hosp.	(7) Hosp.	(8) Hosp.	(9) Hosp.	(10) Hosp.
Vegetalization	-19.93*	-18.64*	-18.51*	-14.72	-27.49***	-28.23***	-23.43***	-23.33***	-23.53***	-23.41***
	(12.10)	(9.85)	(9.87)	(12.65)	(8.59)	(8.60)	(8.39)	(8.40)	(8.38)	(8.40)
Elderly Pop.	6.73***	6.10***	6.11***	3.61	0.15***	0.15***	0.15***	0.15***	0.15***	0.15***
	(2.13)	(1.92)	(1.92)	(2.64)	(0.04)	(0.04)	(0.04)	(0.04)	(0.04)	(0.04)
Wealth	-1.07***	-1.02***	-1.02***	-0.80*	-1.04***	-1.04***	-1.00***	-1.01***	-1.02***	-1.02***
	(0.35)	(0.31)	(0.31)	(0.43)	(0.28)	(0.28)	(0.28)	(0.28)	(0.28)	(0.28)
Temperature	0.10***	0.09***	0.08***	0.11***	0.09***	0.09***	0.08***	0.08***	0.08***	0.08***
	(0.02)	(0.01)	(0.01)	(0.02)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
Humidity	0.01*									
	(0.01)									
High humidity		0.10**								
		(0.04)								
Temp. x high hum.			0.01**							
			(0.00)							
NO2					0.08					
					(0.06)					
NO2xTemp.						0.00*				
						(0.00)				
AOT40							0.06*			
							(0.03)			
AOT40xTemp.								0.00		
								(0.00)		
Somo35									0.07*	
									(0.04)	
Somo35xTemp.										0.00
										(0.00)
N	4585	5390	5390	1864	5434	5434	5434	5434	5434	5434
Sample	all	all	all	High hum.	all	all	all	all	all	all

Estimator: Poisson PMLH, with EUT Fixed effect. Statistical significance: \*10% \*\* 5% \*\*\*1%.

Panel A: Elderly Population. Panel B: Mean Age. Humidity = relative humidity by Historical Weather API.

High humidity = top 25% highest humidity observations.

### 5.3 Population composition

Table 4 explores the relationship between demographic structure and hospitalization outcomes, examining the associations between age distribution, foreign population shares, and educational attainment.<sup>12</sup> Column (1) shows that mean age is positively and significantly associated with hospitalizations, suggesting that territories with older populations tend to exhibit higher hospitalization rates. This result is consistent with the positive and significant coefficient obtained for the share of elderly population (aged 60+) in Column (2), confirming age as a key vulnerability correlate.<sup>13</sup> In contrast, the share of young population (aged 0–14) is negatively associated with hospitalizations in Column (3), a result that may appear counterintuitive given the physiological vulnerability of very young children to environmental stressors. However, this negative association is likely driven by compositional and household-level factors rather than by direct health effects on children. First, the age group considered (0–14) extends beyond early childhood, while health vulnerability is primarily concentrated among infants and very young children. Second, children typically co-reside with working-age adults, who constitute the least health-sensitive share of the population. The inclusion of the working-age population share in Column (4) supports this interpretation, as it exhibits a strong and negative association with hospitalizations, consistent with a “prime-age resilience” pattern. Finally, the youth dependency ratio (Column 5) does not display a statistically significant association, suggesting that a higher proportion of children relative to adults is not associated with increased hospitalization rates.

While the positive association between education and hospitalizations (Column 6), as well as ERV (not shown), likely captures differential healthcare-seeking behavior, more educated individuals being more likely to seek medical care rather than being more physiologically vulnerable, the proportion of foreigners emerges as a significant and positive correlate of hospitalizations, consistent with existing literature highlighting

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<sup>12</sup>To avoid multicollinearity issues, we exclude wealth when including the share of foreigners and the level of education.

<sup>13</sup>The coefficient obtained for the share of elderly population is a recall of the baseline result, shown for comparison.

the heightened vulnerability of immigrant populations. This elevated association may reflect not only lower average income or substandard housing conditions (factors already accounted for by other variables) but also weaker social support networks and potential language barriers that may reduce the effectiveness of public health communications. Accordingly, being foreign-born appears as an independent vulnerability correlate.

Taken together, these results suggest that demographic vulnerability is primarily associated with population ageing, while the presence of children does not appear to constitute an independent risk factor once household composition and age structure are taken into account; the share of foreign-born residents, however, emerges as a distinct and significant vulnerability correlate.

**Table 4: Population Composition**

	Age Distribution					Socio-Cultural	
	(1) Hosp.	(2) Hosp.	(3) Hosp.	(4) Hosp.	(5) Hosp.	(6) Hosp.	(7) Hosp.
Vegetalization	-19.68** (9.90)	-19.21* (9.91)	-32.78*** (9.25)	-20.35** (10.20)	-36.21*** (9.51)	5.97 (11.45)	0.72 (10.29)
Wealth	-1.02*** (0.32)	-1.02*** (0.31)	-0.75** (0.30)	-0.97*** (0.32)	-0.60* (0.31)		
Temperature	0.07*** (0.01)	0.07*** (0.01)	0.09*** (0.01)	0.08*** (0.01)	0.10*** (0.01)	0.07*** (0.01)	0.08*** (0.01)
Mean Age	0.14*** (0.04)						
Elderly Pop.		6.39*** (1.94)				-0.13 (2.75)	4.2** (0.77)
Young Pop.			-15.30*** (4.46)				
Working-Age Pop.				-6.37*** (2.37)			
Young Depend.					-0.86 (2.42)		
Education						5.18** (2.3)	
Foreigner							9.35** (4.38)
N	5390	5390	5390	5390	5390	5390	5390

Estimator: Poisson PMLH, with EUT Fixed effect. Statistical significance: \*10% \*\*5% \*\*\*1%.

Elderly Pop. = aged 60+ (%). Young Pop. = aged 0-14 (%). Working-Age Pop. = aged 15-59 (%).

Young Depend. = aged 0-14 / aged 15-59. Education = share of high-school graduates. Foreigner = share of foreign-born.

## 5.4 Socioeconomic Vulnerability

To assess how socioeconomic conditions are associated with heat vulnerability, we include measures of housing quality (rooms per dwelling), mobility constraints and deprivation. While mobility constraints are proxied by the share of households without car ownership (“no mobility”), representing limited access to private transportation, deprivation is measured as the first principal component of median income, share of high-school graduates, share of manual workers, and unemployment rate, with lower values indicating higher poverty.<sup>14</sup>

Table 5 shows that, contrary to expectations, the proxy for adaptive capacity (rooms per dwelling) does not yield significant associations at the territorial level, possibly reflecting aggregation limitations. In terms of mobility constraints, we find a similar result when considering the full sample (Column 2), likely due to the aggregation at the territorial level: in urban areas such as Paris, lacking a car is common and does not necessarily reflect limited adaptive capacity. Conversely, in rural areas where public transport options are scarce, car ownership is closely associated with mobility and access to services, including healthcare. Hence, splitting the sample between rural and urban territories reveals that in rural areas (Columns 3 and 5), the absence of mobility is significantly associated with higher vulnerability, as indicated by the positive and statistically significant coefficient for emergency room visits (ERV), though not for hospitalizations (Hosp.). These findings highlight the importance of considering spatial heterogeneity when assessing the role of mobility in climate-related health vulnerability.

Finally, while Column (6) shows that individuals in wealthier areas tend to exhibit lower hospitalization rates, paradoxically, the deprivation index also exhibits a negative and significant coefficient (Column 7), running counter to the established literature linking poverty to heat vulnerability via greater exposure (inadequate housing insulation) and lower adaptive capacity (limited resources to access cooling or medical care). This counterintuitive result aligns with sociological insights suggesting that poorer pop-

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<sup>14</sup>We exclude wealth from specifications including rooms-per-dwelling or deprivation due to high collinearity among these socioeconomic indicators.

ulations may be less likely to seek medical care for various reasons, resulting in fewer recorded hospital admissions. To explore this further, the sample is split into the poorest 25% and richest 25% based on deprivation levels (Columns 3 and 4). Among the poorest, typical vulnerability correlates such as age remain significantly associated with hospitalizations, while among the richest, these associations lose significance, with temperature (exposure) being the only robust correlate. This pattern suggests that wealthier populations tend to exhibit lower overall vulnerability, consistent with better access to quality healthcare and other protective resources.

**Table 5: Sociodemographic characteristics**

	<b>Housing</b>	<b>Mobility constraints</b>				<b>Deprivation index</b>			
	(1) Hosp.	(2) Hosp.	(3) Hosp.	(4) ERV	(5) ERV	(6) Hosp.	(7) Hosp.	(8) Hosp.	(9) Hosp.
Vegetalization	-10.97 (10.24)	-9.06 (9.26)	-18.07* (9.31)	-10.07 (7.60)	-25.54*** (7.94)	-19.21* (9.91)	-9.16 (9.36)	-19.21* (9.91)	54.40 (39.37)
Elderly Population	4.01** (1.91)	3.65* (2.09)	-5.57 (5.34)	4.39** (1.80)	-6.55** (3.32)	6.39*** (1.94)	3.21* (1.88)	6.39*** (1.94)	5.08 (4.22)
Temperature	0.08*** (0.01)	0.08*** (0.01)	0.12*** (0.02)	0.09*** (0.01)	0.12*** (0.02)	0.07*** (0.01)	0.07*** (0.01)	0.07*** (0.01)	0.12*** (0.02)
Wealth						-1.02*** (0.31)		-1.02*** (0.31)	-0.03 (0.66)
Rooms-per-dwelling	0.51 (1.12)								
No mobility		-2.85 (3.47)	7.85 (4.87)	-2.47 (3.22)	9.77*** (3.12)				
Deprivation							-2.98** (1.48)		
N	5390	5390	1038	5434	1049	5390	5291	5390	1395
Sample	all	all	rural	all	rural	all	all	Poorer 25%	Richer 25%

Estimator: Poisson PMLH, with EUT Fixed effect. Statistical significance: \*10% \*\* 5% \*\*\*1%.

Deprivation = first principal component of median income, share of high-school graduates, share of manual workers, and unemployment rate. Lower index values indicate higher levels of poverty.

## 5.5 Healthcare factors

Given the concentration of medical deserts along France’s “diagonale du vide”, which stretches from the northeastern Ardennes (Belgian border) to the southwestern Atlantic coast (Spanish border), residents of these areas may face heightened vulnerability to extreme heat events, holding other factors constant. Against this background, we introduce two proxy variables for healthcare access: accessibility (geographic access) and health supply (service availability). The latter is captured through the Local Potential Accessibility (LPA) indicator, which measures general practitioner supply and demand by combining practitioner activity volumes with age-adjusted service utilization rates.

Table 6 highlights the role of healthcare access in its association with health outcomes. On the one hand, we find that the distance to the nearest emergency center is negatively associated with both hospitalizations and ERV, suggesting higher utilization in territories located closer to emergency facilities. This result is consistent with urban environments being both more exposed to heat stress (due to urban heat island effects) and characterized by lower access costs to emergency care, which is associated with greater healthcare use in response to acute shocks. On the other hand, when hospitalizations are normalized by healthcare supply (i.e. expressed per unit of medical capacity – Column 5), the qualitative results remain unchanged. This suggests that the estimated associations mainly reflect healthcare demand patterns rather than mechanical congestion or saturation effects on the supply side. In contrast, directly controlling for LPA reveals a negative and statistically significant association between medical supply and hospitalizations: territories with better access to healthcare tend to exhibit fewer hospital admissions (Column 6). This result is consistent with a substitution pattern, whereby improved access to primary care may facilitate preventive monitoring and early treatment, potentially reducing the need for hospital care, particularly emergency admissions. Subsample analyses by levels of healthcare accessibility further clarify these patterns. In territories with limited healthcare supply (Column 7), age is associated with a stronger vulnerability gradient, highlighting the elevated vulnerability of elderly populations in contexts of restricted access to care and lower adaptive capacity. In these

contexts, individual wealth ceases to display a significant protective association, likely because structural healthcare limitations may outweigh private adaptive resources. Conversely, in areas with abundant healthcare supply (Column 8), most vulnerability correlates (including age, vegetalization, and environmental exposure) lose their statistical significance, while wealth remains the sole significant correlate. This pattern suggests that adequate healthcare supply is associated with attenuated age- and environment-related health risks, while higher-income households may retain additional margins of adaptation through superior housing quality, air conditioning, and preventive behaviors.

From a policy perspective, these findings underscore the potential role of healthcare accessibility and supply in territorial resilience. A well-developed and accessible medical infrastructure is associated with lower vulnerability to climate-related health shocks and attenuated socioeconomic and demographic inequalities in health outcomes. Strengthening local healthcare provision thus emerges as a potentially important adaptation policy, which may contribute to reducing the health burden associated with climate-related shocks.

**Table 6: Healthcare Factors**

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Hosp.	Hosp.	ERV	ERV	Hosp./LPA	Hosp.	Hosp.	Hosp.
Vegetalization	-19.21*			-20.60**	-68.27***	6.55	32.70***	-24.15
	(9.91)			(8.35)	(12.33)	(11.33)	(12.27)	(33.69)
Elderly Population	6.39***	8.15***	7.20***	9.01***	30.37***	-1.25	9.86**	-2.57
	(1.94)	(0.99)	(1.68)	(0.88)	(2.50)	(2.26)	(4.95)	(8.46)
Wealth	-1.02***	-0.88***	-1.07***	-0.92***	-2.40***	-0.23	0.47	-5.52***
	(0.31)	(0.17)	(0.27)	(0.16)	(0.47)	(0.37)	(0.72)	(1.75)
Temperature	0.07***	0.08***	0.08***	0.09***	0.17***	0.04***	0.04*	0.04
	(0.01)	(0.01)	(0.01)	(0.01)	(0.02)	(0.01)	(0.02)	(0.03)
Distance		-0.33***		-0.33***				
		(0.13)		(0.13)				
LPA						-0.01***		
						(0.00)		
N	5390	6116	5434	6116	5390	5390	1205	976
Sample	all	all	all	all	all	all	Low 25%	High 25%

Estimator: Poisson, with EUT Fixed effect. Statistical significance: \*10% \*\* 5% \*\*\*1%.

Distance = average distance to emergency center. LPA = local potential accessibility.

## 5.6 Extension – Nonlinear Specifications

Many studies have shown that temperature has non-linear associations with heat-related morbidity. For instance, [Martinez-Solanas and Basagana \(2019\)](#) show that while cold temperatures were associated with increased risk of cardiovascular, cerebrovascular and respiratory hospital admissions, hot temperatures were only associated with higher hospital admissions for respiratory causes. Furthermore, [Zhao et al. \(2019\)](#) find that the risk of hospitalization is stronger for heatwaves characterized by high daily temperatures ( $\geq 90$ th percentile) in all parts of Brazil except the north. To allow for nonlinear temperature associations while mitigating multicollinearity, we mean-center all temperature variables prior to estimation. For each temperature indicator  $Z_{it}$ , the centered variable is defined as  $Z_{it}^c = Z_{it} - \bar{Z}$ , where  $\bar{Z}$  denotes the sample mean, with the quadratic term constructed as  $(Z_{it}^c)^2$ .<sup>15</sup> All models are estimated via PPML with territorial fixed effects and standard errors clustered at the territorial level (see table 7).

The results indicate a statistically significant and concave relationship between summer temperature and hospital admissions (Column 1). While the coefficient on centered summer temperature is positive and highly significant, the coefficient on its squared term is negative and significant, pointing to diminishing marginal associations at higher temperatures. The implied turning point is given by  $-\beta_1/(2\beta_2)$ , which corresponds to approximately 4.8°C above the sample mean. Given an average summer temperature of about 20.1°C, this implies a threshold of roughly 24.9°C beyond which additional temperature increases are associated with a declining marginal association with hospital admissions.

A similar nonlinear pattern is observed when using the number of heat wave days. Both the linear and quadratic terms are statistically significant, yielding a turning point at around 96 heat wave days per year. This suggests that while additional heat wave exposure is initially associated with higher hospital admissions, the marginal association weakens at very high levels of exposure, potentially consistent with behavioral adaptation

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<sup>15</sup>This transformation reduces correlation between linear and squared terms, improving both numerical stability and coefficient interpretability, without affecting the estimated marginal effects or turning points.

or saturation effects. In contrast, for the number of heat wave episodes, the quadratic term is not statistically significant, indicating an approximately linear association over the observed range.

Several mechanisms could account for the concave relationship between heat exposure and hospital admissions. First, behavioral adaptation may play a role: as temperatures reach very high levels or heat wave episodes become more frequent, individuals may adjust their behavior by reducing outdoor activity, increasing hydration, or seeking cooler environments, which may be associated with attenuated marginal health risks. Second, institutional and collective adaptation may also be relevant, as repeated exposure to extreme heat may be associated with improved public health responses, such as heat warning systems, targeted interventions for vulnerable populations, and better coordination of emergency services. Third, physiological and reporting saturation patterns may emerge at high levels of exposure, whereby the most vulnerable individuals are already affected at lower temperature thresholds, reducing the marginal increase in hospital admissions at higher temperatures. Finally, infrastructural factors, such as increased access to air conditioning, improved housing insulation, or urban greening, may be associated with attenuated marginal health risks of extreme heat in highly exposed territories. Taken together, these patterns are consistent with diminishing marginal associations between temperature and heatwave exposure and health outcomes.

**Table 7: Nonlinear Heat Effects**

	(1)	(2)	(3)
	Hosp.	Hosp.	Hosp.
Vegetalization	-21.97** (10.31)	-21.93** (10.03)	-22.00** (9.89)
Elderly Population	5.97*** (1.93)	7.81*** (1.89)	7.11*** (1.90)
Wealth	-0.97*** (0.31)	-1.11*** (0.31)	-1.02*** (0.31)
Temperature (rebased)	0.08*** (0.01)		
Temperature square	-0.01*** (0.00)		
Heat-days (rebased)		0.00*** (0.00)	
Heat-days square		-0.00*** (0.00)	
Heatwaves (rebased)			0.06*** (0.01)
Heatwaves square			-0.00 (0.00)
_cons	19.84*** (7.03)	20.95*** (6.88)	20.05*** (6.82)
N	5390	5390	5390

-  
Estimator: Poisson PMLH, with EUT Fixed effect  
Statistical significance: \*10% \*\* 5% \*\*\*1%.

## 6 Projection Analysis

The empirical framework developed in the previous section allows us to characterize how territorial vulnerability to high temperatures and heat waves is shaped by environmental, socioeconomic, demographic, and health access factors. Building on these estimates, we conduct a scenario-based projection analysis to assess how heat-related morbidity outcomes may evolve over time across EUT under the RCP4.5 scenario of climate change.

## 6.1 Methodology

first use the parameters estimated in the empirical analysis to simulate future outcomes, setting temperature exposure to its projected level in 2089.<sup>16</sup> For each territory  $i$ , the expected level of heat-related hospital admissions is computed as:

$$E[y_{iT} | T_{iT}, X_{iT}, \alpha_i] = \exp\left(\hat{\alpha}_i + \hat{\gamma}T_{iT} + \hat{\beta}X_{iT}\right); \quad (3)$$

where  $T$  denotes the projection horizon (year 2089). The coefficients  $\hat{\gamma}$  and  $\hat{\beta}$  are held constant and correspond to the estimates obtained in the baseline specification (table 2). Projected temperature exposure  $T_{iT}$  is drawn from the TRACC-2023 scenario produced by Météo France (see [Soubeyrou et al. \(2025\)](#)), which assumes a nationwide temperature increase exceeding  $+4^\circ\text{C}$  by the end of the century. This scenario provides spatially detailed projections across the entire French territory and serves as the climatic backbone of our prospective analysis.

To ensure internal consistency, we also project future values of the control variables,  $X_{iT}$ , corresponding to the three key structural determinants of vulnerability shown in table 2: vegetalization, the share of elderly population, and wealth. Future trajectories for territorial wealth are based on projections of GDP per capita growth up to 2090 provided by [Mikou et al. \(2025\)](#), under an RCP4.5 scenario. Demographic projections for the elderly population rely on INSEE’s prospective demographic scenarios derived from the Omphale model ([Algava and Blanpain, 2021](#)). These projections, originally available at the departmental level up to 2070, are interpolated to the EUT scale until 2090, allowing us to capture spatial heterogeneity in population ageing. Finally, future vegetalization rates are projected by applying, for each territory, the average annual rate of land artificialization observed over the past decade (2012-2022). This approach preserves existing spatial contrasts between urban and rural areas while generating forward-looking trajectories consistent with current land-use dynamics. The values obtained for all projected variables are presented in the appendix (table 10).

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<sup>16</sup>The year 2089 represents the furthest projection horizon available in the ALADIN63.CNRM-CM5 model developed by Météo France (as of January 2026).

## 6.2 Key Assumptions, Limitations, and Contributions

This scenario-based analysis relies on a standard structural stability assumption: the relationships estimated in the current period, captured by coefficients  $\hat{\gamma}$  and  $\hat{\beta}$ , are assumed to remain valid up to 2090. As in much of the reduced-form climate–health literature, the exercise therefore abstracts from potential structural changes arising from climate adaptation, medical progress, public health policies (notably those affecting healthcare supply), or behavioral adjustments by households and local authorities.

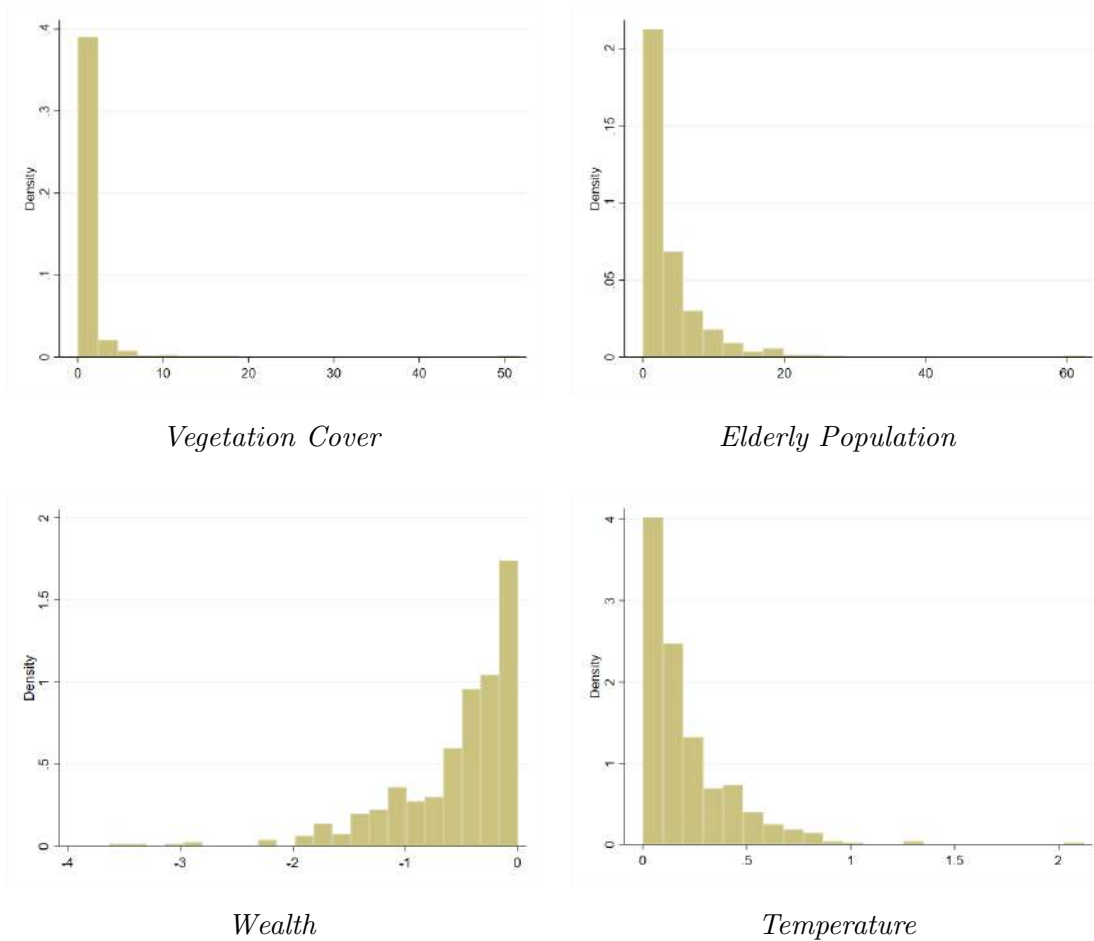
Moreover, the projections are inherently conditional. They depend on a specific high-warming climate scenario (TRACC-2023, +4°C) and on particular trajectories for the control variables. As a result, the outcomes should not be interpreted as forecasts in a strict sense, but rather as internally consistent scenario-based simulations. Finally, coherence across the different projection exercises is constrained both by data availability and, more fundamentally, by the difficulty of jointly modeling interactions and endogeneity between climate, demographic, economic, and land-use dynamics over long horizons.

Despite these limitations which are common to prospective exercises of this nature, our approach provides several contributions to the literature on climate-related health impacts. First, it delivers a spatially explicit, forward-looking mapping of vulnerability to heat-related morbidity, highlighting territories where existing structural characteristics are likely to amplify future temperature shocks. Second, by combining climatic projections with socioeconomic, demographic, and environmental dynamics at a fine spatial scale, the analysis sheds light on the mechanisms through which climate change translates into heterogeneous health outcomes across territories. Finally, these results offer a policy-relevant framework for territorially targeted adaptation strategies, helping to identify priority areas where preventive interventions and investments in resilience may yield the highest returns.

### 6.3 Results

To disentangle the contribution of each determinant, we first vary the four baseline variables one at a time, temperature, vegetalization, the share of elderly population, and wealth, *ceteris paribus*. The results are reported in Figure 8 and are expressed as deviations from current predicted values. More precisely, we compute the difference between the number of heat-related hospitalizations predicted using present-day values of the exogenous variables and those obtained when a single variable is set to its projected future level.

**Table 8: Contribution of Each Determinant to Projected Changes in Hospitalization Rates (per 1,000 inhabitants)**



The top-left panel illustrates the association between changes in vegetalization and the number of heat-related hospitalizations per 1,000 inhabitants. Although vegetalization is associated with a protective pattern against heat-related health risks, given the assumed decline in vegetal cover over time, the projected association implies an increase in hospitalization rates. This association remains limited in magnitude: for the vast majority of territories, the reduction in vegetalization is associated with an increase of fewer than five additional hospitalizations per 1,000 inhabitants during the summer. The left panel of the second row shows the association between changes in wealth and hospitalization rates. Since territorial wealth is projected to increase under RCP4.5 and higher income is associated with greater heat resilience, this economic development is projected to be associated with fewer heat-related hospitalizations. Nevertheless, the magnitude of this protective association remains modest, as rising incomes are associated with fewer than two cases per 1,000 inhabitants in the vast majority of territories.

The top-right panel focuses on population ageing. As France is expected to experience significant population ageing over the coming decades, this demographic channel is associated with a substantial projected increase in hospitalizations. In some territories, ageing alone is associated with an increase of up to 20 additional hospitalizations per 1,000 inhabitants during the summer, making it by far the most quantitatively important correlate among the variables considered. Finally, the bottom-right panel reports the association between higher summer temperatures and heat-related hospitalizations. Consistent with a warming scenario, rising temperatures are associated with higher heat-related hospitalizations. However, the magnitude of this association remains relatively modest: for all territories, the increase is below one additional hospitalization per 1,000 inhabitants. This association is therefore small when compared to that of demographic change. Taken together, these results suggest that the resilience gains associated with rising incomes are, on average, of similar magnitude to the erosion of resilience associated with higher temperatures. By contrast, population ageing emerges as the dominant correlate of projected future increases in heat-related morbidity.

When all projected changes are considered jointly, the overall association with vulner-

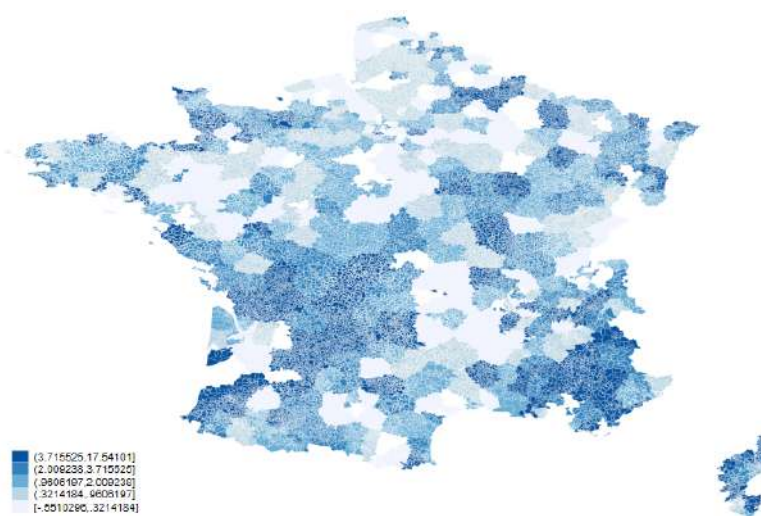
ability is unambiguously positive, as illustrated in Figures 3 and 4, which show projected hospitalization rates per 1,000 inhabitants and absolute changes in hospitalizations (a proxy for bed requirements), respectively.<sup>17</sup> These figures suggest that heat-related hospitalizations are projected to increase by an average of 3 cases per 1,000 inhabitants, corresponding to an additional projected demand of 234 hospital beds. However, this average masks considerable spatial variation. As a case in point, territories in southeastern and southwestern France are associated with substantially higher projected impacts than those in northern and western regions. Specifically, while many territories appear to require only a limited number of additional hospital beds, approximately half of them are projected to be associated with a need for more than 100 additional beds during the summer period. Although this figure may seem modest at first glance, it represents a substantial and highly concentrated projected demand over a short time horizon. Such a surge may be associated with significant stress on healthcare systems, potentially contributing to congestion and a deterioration in the functioning of health services.

These projections constitute a key finding of the paper. The projected increase in vulnerability does not appear to stem from climate change alone, but from the conjunction of climatic and socioeconomic trajectories. Demographic and social dynamics therefore appear to play a central role in the association between heat exposure and future health outcomes. Consequently, climate adaptation strategies may need to account for changes in population structure and territorial socioeconomic characteristics.

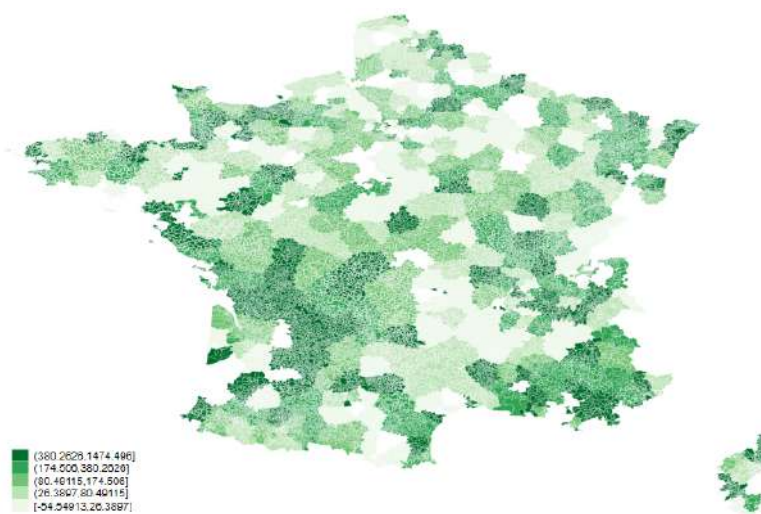
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<sup>17</sup>We winsorize the projections at the 90th percentile to maintain consistency with our main specification.

**Figure 3: Heat-Related Hospitalization Incidence by EUT under RCP4.5 (per 1,000 inhabitants, 2090)**



**Figure 4: Hospital Bed Requirements by EUT under RCP4.5 Scenario (2090)**



## 7 Conclusion

Heat waves are expected to become increasingly frequent in France. In this context, understanding their impact on public health is essential. This paper identifies which populations are most vulnerable to extreme heat by examining the environmental, demographic, socioeconomic, and health access factors that explain heat-related hospital admissions and emergency room visits. To this end, we aggregate municipal data at the Emergency Unit Territory (EUT) level, where each EUT comprises a core municipality providing health services and peripheral municipalities that rely on this core for health-care access. These units group municipalities based on functional ties to a central hub offering essential services, rather than administrative boundaries.

Our main findings reveal that the most heat-vulnerable populations are concentrated in areas experiencing the highest summer temperatures and number of heat waves. Beyond this environmental factor, age emerges as a major contributor to vulnerability. Age structure plays a critical role in territorial vulnerability: a higher share of elderly residents increases vulnerability, while a larger working-age population tends to enhance resilience. In contrast, regions with higher income levels and greater vegetation coverage tend to have more resilient populations. Further analysis reveals that high levels of humidity significantly exacerbate heat wave vulnerability, while air quality shows no significant effect. This finding likely reflects the fact that air pollution primarily impacts health during winter months rather than summer heat episodes. Regarding socioeconomic characteristics, both foreign-born residents and more educated populations exhibit higher heat-related hospitalization rates. While the former aligns with expectations given the generally lower socioeconomic status of immigrant populations, the latter may reflect behavioral differences rather than physiological vulnerability. More educated individuals may be more health-conscious and thus more likely to seek medical care for heat-related symptoms, while less educated populations may underutilize healthcare services even when experiencing heat stress. This interpretation is consistent with other sociodemographic indicators: both limited car access and the deprivation in-

dex show negative associations with hospitalization rates, suggesting that disadvantaged populations are less likely to reach hospitals despite experiencing heat stress. Finally, we find that health access, proxied by the distance to emergency services and the local potential accessibility, also affects population vulnerability to heat waves.

Projection exercises combining the estimated coefficients with projected values of key variables (temperature, vegetation cover, elderly population share, and wealth) under the RCP4.5 scenario reveal increases in both hospitalization rates and hospital bed requirements across all EUT. To mitigate the impact of heat waves on public health, policymakers should focus on strategies that address both climate change adaptation and socio-economic resilience. Urban planning policies should prioritize increasing green spaces and vegetation coverage, as these are associated with reduced heat vulnerability and provide cooling benefits in densely populated areas. Given the role of age in exacerbating heat-related health risks, strengthening support networks for elderly individuals is crucial. This could include community outreach programs, better access to health services, and targeted interventions. Moreover, urban density planning should ensure adequate space and air circulation, helping to prevent overheating, especially in high-density areas. Together, these measures can strengthen territorial resilience and reduce health risks as extreme heat events grow more frequent under climate change.

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## Appendix

**Table 9: Descriptive Statistics**

	mean	sd	min	max
Emergency Room Visit (per thousand inhab.)	0.63	0.81	0.00	7.35
Hospitalization (per thousand inhab.)	0.46	0.65	0.00	5.76
Vegetalization (pc)	0.41	0.25	0.0001	0.90
Elderly Population (pc)	0.28	0.06	0.13	0.54
Wealth (current euros)	179542.18	95307.55	62483.21	810378.69
Heat-days (days)	23.89	36.82	0.00	384.00
Heatwaves (waves)	2.30	1.87	0.00	10.00
Temperature (°C)	20.06	2.07	13.73	26.72
Observations	6116	6116	6116	6116

**Table 10: Projection Analysis : Calibration**

	2017-2022		2089		CACR
	mean	sd	mean	sd	
Vegetalization (pc)	0.41	0.25	0.38	0.26	-0.25
Elderly Population (pc)	0.29	0.06	0.50	0.13	0.79
Wealth (current euros)	12.04	0.46	13.15	0.45	1.63
Temperature (°C)	20.55	1.84	23.46	2.02	0.19

*Note:* CAGR is the compound annual growth rate of the mean (pc).

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