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Authors:
Grégoire Rey[1,2,3], Anne Fouillet[1,2], Pierre Bessemoulin[4], Philippe Frayssinet[4], Anne Dufour[5], Eric Jougla[3], Denis Hémon[1,2]

[1]INSERM, U754, Villejuif, France
[2]Univ Paris-Sud, UMR-S754, IFR69, Villejuif, France
[3]INSERM, CépiDc, Centre d'Epidémiologie sur les Causes Médicales de Décès, Le Vésinet, France
[4]Meteo-France, Toulouse, France
[5]CNRM, Toulouse, France

Corresponding Author:
Grégoire REY
Inserm-CépiDc
44, Chemin de Ronde
F-78116 Le Vésinet Cedex, France
e-mail: Gregoire.Rey@inserm.fr
tel.: (+33) 1 34 80 24 32 fax: (+33) 1 34 80 24 29

ABSTRACT

Background Heat waves may become a serious threat to the health and safety of people who currently live in temperate climates. It was therefore of interest to investigate whether more deprived populations are more vulnerable to heat waves. **Methods** In order to address the question on a fine geographical scale, the spatial heterogeneity of the excess mortality in France associated with the European heat wave of August 2003 was analysed. A deprivation index and a heat exposure index were used jointly to describe the heterogeneity on the *Canton* scale (3706 spatial units). **Results** During the heat wave period, the heat exposure index explained 68% of the extra-Poisson spatial variability of the heat wave mortality ratios. The heat exposure index was greater in the most urbanized areas. For the three upper quintiles of heat exposure in the densely populated Paris area, excess mortality rates were two-fold higher in the most deprived *Cantons* (about 20 excess deaths/100 000 people/day) than in the least deprived *Cantons* (about 10 excess deaths/100 000 people/day). No such interaction was observed for the rest of France, which was less exposed to heat and less heterogeneous in terms of deprivation. **Conclusion** Although a marked increase in mortality was associated with heat wave exposure for all degrees of deprivation, deprivation appears to be a vulnerability factor with respect to heat-wave-associated mortality.

Keywords: Heat Wave, Mortality, Vulnerability, Ecological study, Deprivation

Abbreviations:

HEI: heat exposure index

HW-MR: heat wave mortality ratio

SEMR: standardized excess mortality rate

UUC: urban unit category

INTRODUCTION

In the context of climate change, an increased frequency of extreme weather events is expected, with little uncertainty, within decades.[1] During summer 2003, very high temperatures were recorded over the whole of Western Europe.[2] In France, from 3rd to 15th August, the heat wave was associated with an excess mortality of nearly 14 000 deaths.[3] It is therefore important to determine whether more deprived populations are more vulnerable to heat waves.

Case-control studies have been used by various authors to compare the subjects who died during a heat wave and/or were considered to have died because of the heat to survivors of the same heat wave.[4-6] However, except for some very specific variables such as the presence of air conditioning or living on the top floor, such studies did not enable vulnerability to heat to be distinguished from that associated with general mortality.

In a temporal analysis of the time course of mortality in seven US cities, a greater increase in heat-related mortality was observed for low socio-economic level subjects compared to high socio-economic level subjects,[7] but, in a study of the 2003 heat wave in Barcelona, no such association was observed.[8]

A study of the incidence of heat related deaths in St Louis during the 1980 heat wave described a six-fold risk difference between the areas of the first and the last quartiles of socio-economic level, [9] while case-crossover studies on four cities in Italy and on three Latin American cities, and a temporal study in Sao Paulo, did not find any association between the socio-economic level of the various areas considered and heat associated mortality.[10-12]

However, none of those studies took precise account of the spatial heterogeneity of heat exposure or the potentially confounding urban heat island effect.

Although indicators of the *temporal* association between temperature and mortality have been proposed by several authors,[13-20] few indicators of heat exposure describing the *spatial* heterogeneity of the mortality associated with heat waves have been constructed.[21, 22] Ozone concentration, which was particularly high during the 2003 heat wave,[23] is also suspected to play a role with respect to short-term mortality.[24]

In that context, the objective of this study was to generate new quantitative information on the respective contributions of heat exposure and socio-economic disparities in the explanation of the excess mortality related to heat waves. An ecological analysis of the spatial heterogeneity of the August 2003 heat-wave-related mortality in France was used to address the question.

MATERIAL AND METHODS

Population data

Mainland France has a population of nearly 60 million and is administratively divided into 22 "*Regions*", 96 "*Departements"*, 3,706 "*Cantons*" and 36,600 "*Communes*". The populations by *Canton*, age and gender were extrapolated from the 1999 census data, provided by the National Institute of Statistics and Economical Studies (INSEE), and adjusted for estimates of the marginal change in population by *Departement*, age and gender.

Urban Unit Category (UUC)

The urban unit category (UUC) concept developed by INSEE and based on the continuity of buildings was used to define the degree of urbanization of the *Cantons*. An urban unit is a group of *Communes* with a population of at least 2,000 in which no residence is separated from the next by more than 200 metres. If a *Commune* is not part of an urban unit, it is considered rural. There are five urban unit categories (UUC) of *Commune*: Rural (less than 2,000 people), Quasi-rural (population from 2,000 to 9,999), Quasi-urban (population from 10,000 to 99,999), Urban (population from 100,000 to 1,999,999) and Paris-and-suburbs (Paris Urban Unit).

Mortality

Mortality data

The mortality data were derived from the Inserm (National Institute for Medical Research) national database. The *Canton* of residence of each dead subject was used as the spatial location to be linked with exposure variables and socio-economic data. In this study, only subjects aged more than 55 years were considered. They accounted for more than 95% of the excess mortality during the 2003 heat wave.[21]

Mortality indicators

A non-heat-wave-exposed reference period was defined as the months of July and August of years 2000 to 2002. In each *Canton* "i", the Heat Wave Mortality Ratio ($HW\text{-}MR_i$) was calculated as the ratio of the number of deaths from 3rd to 15th August 2003 (O_i), to the expected number of deaths in the same *Canton* given its 2003 population and the age- and gender-specific mortality rates of that *Canton* during the reference period (E_i).

The Standardized Excess Mortality Rate (SEMR) was used to characterize the *absolute* increase in mortality rate by population unit in each *Canton*, adjusted for the *Canton* population structure by age and gender. SEMR were calculated as the difference between the age- and gender-standardized mortality rates observed during the 2003 heat wave period and during the reference period.

Smoothing mortality

To map spatial variations in mortality over small spatial units, a Bayesian spatial smoothing Poisson model (BYM) was used to take into account both local over-dispersion and between-neighbour autocorrelation.[25] The neighbourhood of a given canton was defined as the cantons sharing common borders with it.

Deprivation index

The FDep99 deprivation index, previously built in order to analyse socioeconomic spatial mortality differentials over the whole country,[26] was used to characterize each *Canton*.

Exposure to heat

Meteorological data

Daily maximum (T_x) and minimum (T_n) temperatures for the months of July and August 2000 to 2003 were obtained from Météo-France. The data were derived from a grid of 4145 points (10-km step).

Daily temperature indicators were averaged over the heat wave period (3rd to 15th August 2003). Reference temperatures (T_x^{ref} and T_n^{ref}) were defined as the average of the temperatures observed during the reference period. From those temperatures, relative maximum (T_x^{rel}) and minimum (T_n^{rel}) temperatures were calculated for each *Canton* as the difference between the observed temperatures (T_x and T_n) and the corresponding local reference temperatures.

A recent study has identified key variables for the prediction of daily mortality rates in France as a function of daily temperature.[13] Those variables are the moving average of the mean of the minimum and maximum temperatures for the last 10 days (MA), and the number of cumulative degrees of the maximum temperature above a cut-off point over the last 10 days, set to 0 if the maximum temperature was below the cut-off point (Accum).

With regard to the averaged temperature over the whole of mainland France, the optimal cut-off point, obtained by maximization of the likelihood of the observations was 27°C,[13] which was 2°C more than the average reference temperature over the whole country. In order to take into account the adaptation of population to their local climate, local cut-off points for each *Canton* were defined as:

- equal to 27°C if the maximum reference temperature of the *Canton* was less than or equal to 25°C,
- 2°C higher than the maximum reference temperature of the *Canton* if that temperature was greater than 25°C.

Ozone concentration data were derived from the 10-km resolution MOCAGE chemistry-transport model developed by Météo-France.[27] The 24-hour mean ozone (O_3) concentration (µg/m^3) from 3rd to 15th August 2003 was computed.

Building the index of the spatial heterogeneity of heat exposure

The spatial variation of the ratio between the mortality observed during the heat wave and that observed during the reference period in the same *Canton* (HW-MR) was modelled using a log linear Poisson model of the following form:

$$\mathrm{Log}\left[E(O_i)\right] = \mathrm{Log}\left(E_i\right) + \alpha + \sum_{k \in S} \beta_k \cdot MI_{k,i} ,$$

In which "i" is a canton, O_i is the observed number of deaths, E_i is the Expected number of deaths, $MI_{i,k}$ is one of the meteorological indicator included in the set S, the union of the following groups of exposure indicators:

- Basic group: T_x, T_n, T_x x T_n, Accum, T_x x Accum and MA,
- Relative temperature group: T_x^{rel}, T_n^{rel} and T_x^{rel} x T_n^{rel},

- Ozone group: O_3 , $O_3 \times T_x$, $O_3 \times T_n$ and O_3 x Accum.

Then, the Heat Exposure Index (HEI) was defined as the estimate of the expected value of the HW-MR, as follows:

$$HEI_i = \exp\left(\hat{\alpha} + \sum_{k \in S} \hat{\beta}_k \cdot MI_{k,i}\right),$$

In which $\hat{\alpha}$ and the $\hat{\beta}_k$ are the estimated parameters deduced from the model.

Sensitivity analysis

Although the HEI used in the main analysis took into account the three groups of indicators, as a sensitivity analysis, the same associations were also calculated after excluding the relative temperature group, ozone group and both those groups from the calculation of the HEI.

The HEI was also calculated with different cut-off points defining Accum, ranging from T_x^{ref} to T_x^{ref} + 6°C. Although the remaining overdispersion was not very sensitive to this choice, the T_x^{ref} + 2°C cut-off point corresponded to the lower values.

The ozone group was also calculated by considering successively the number of hours during which ozone concentration was higher than 120µg/m^3 and higher than 180µg/m^3 rather than the 24-hour mean concentration. The results remained unchanged.

Statistical software

The main analysis, data management and mapping were done with SAS 9.1. The BYM models were computed by using the package "spdep" in R, and WinBUGS.

RESULTS

Spatial distribution of the mortality

The spatial variability of the smoothed heat wave mortality ratios (HW-MR) was quite large, ranging from 1 to 4 (figure 1). The greatest increase in the mortality was observed in the Ile-de-France *Region*, which includes the Paris area, and in a large band running from the north-east to the south-west of that *Region*.

Figure 1 here

Building the Heat Exposure Index

The scatter plot of HW-MR by heat exposure index (HEI), aggregated at the *Departement* level (figure 2), shows that the estimated HEI correlates quite well with the spatial variations in HW-MR. The spatial variations in HEI explained 68% of the extra-Poisson variability of the HW-MR, ranging from a value close to 1.0 in the *Departements* where the HW-MR was close to 1.0 to a value close to 3.5 in the *Departements* where the HW-MR was close to 3.5.

Figure 2 here

Deprivation

The average FDep99 index decreased progressively from high values in rural areas (+ 0.49) to much lower values in Paris-and-suburbs (- 1.16) (table 1). In parallel the difference in averaged FDep99 index between the upper and lower quintiles of FDep99 was much larger in Paris-and-suburbs (100%) than in rural areas (40%).

Variations in exposure to heat with UUC and deprivation

The average values of the heat exposure index (HEI) and the heat wave mortality ratios (HW-MR) were both close to 1.65 for the rural, quasi-rural, quasi-urban and urban areas (table 1). In contrast, the average values of the HEI and HW-MR were, on average, two-fold greater for Paris-and-suburbs (about 3.2).

As expected on the basis of the 'heat island effect', the HEI adjusted for the 22 *Regions* was greater in urban UUC (1.10) and Paris-and-suburbs (1.35) than in rural (1.00), quasi-rural (0.99) and quasi-urban (1.00) areas (table 1).

The local variations in HEI were *positively* associated with the FDep99 index in rural UUC, and *negatively* associated in urban UUC and Paris-and-suburbs (table 1). However, the amplitude of those associations was small.

The results were similar when the HEI were calculated without including the relative temperature or ozone concentration groups.

Table 1 Here

Variations in the association between HEI and excess mortality by deprivation

The multiplicative interaction of the association of HW-MR with heat exposure and the FDep99 index was significantly greater than one in the quasi-urban and Paris-and-suburbs areas (table 2). The results were not modified by introducing a spatial autocorrelation structure of the observations using a BYM model. When the relative temperature and the ozone groups of meteorological variables were excluded from the HEI, the multiplicative interaction observed for the quasi-urban UUC became non-significant while that observed in the Paris-and-suburbs area remained unchanged.

Table 2 here

For all the UUC and both the highest and lowest quintile of the FDep99 index, the standardized excess mortality rate (SEMR) increased markedly with heat exposure (table 3). In Paris-and-suburbs, the SEMR difference between the fifth and the first quintiles of FDep99 was positive and statistically significant, for the three highest quintiles of the heat exposure index (HEI) only. This additive interaction between HEI and FDep99 on mortality was of high amplitude: for the three highest quintiles of the HEI, the excess mortality for the fifth quintile of deprivation (around 20 excess deaths/100,000 people/day) was twice that of the first quintile (around 10 excess deaths/100,000 people/day).

For almost all the other UUC and quintiles of HEI, the difference was very close to zero.

It is noteworthy that the Paris-and-suburbs UUC was simultaneously the UUC which was the most exposed to heat and the most heterogeneous in terms of deprivation (table 1). No other UUC had such a small deprived quintile and was exposed to such a high level of heat as the *Cantons* that were located in the last three quintiles of the heat exposure index for Paris-and-suburbs.

The difference in SEMR between the fifth and first FDep99 quintiles persisted for Paris-and- suburbs when the relative temperature and ozone concentration groups were excluded from the HEI.

Table 3 here

DISCUSSION

A heat exposure index was defined in order to describe the geographic heterogeneity of the excess mortality observed during the August 2003 heat wave in France on the *Canton* scale (3706 spatial units over the whole country).

The heat exposure index explained 68% of the extra-Poisson spatial variability of the heat wave mortality ratios (HW-MR) by *Canton* during the heat wave. It was much greater in the most urbanized areas. This finding reflected both an urban heat island effect and the fact that the most urbanized French *Region*, which includes not only Paris but also less densely urbanized *Cantons* in the Paris area, was the most exposed to the heat wave.

For the three most exposed quintiles in the Paris area, excess mortality rates from 3rd to 15th August 2003 were two-fold higher in the most deprived *Cantons* than in the least deprived *Cantons*. No such additive interaction between heat exposure and deprivation was observed for the other urban unit categories, which were less exposed to heat and less heterogeneous in terms of deprivation.

Heat Exposure Index (HEI)

The HEI used in this study was based on temperature and ozone exposure variables. Some studies have suggested other variables, such as the altitude gradient of temperature or synoptic air masses, for the characterization of heat exposure,[28, 29] but country-wide data are not available.

Precise evaluation of the respective contributions of temperature and ozone variables in the description of the excess mortality is clearly of interest but was not the subject of this study. From a descriptive point of view, the temperature variables used in the present study essentially explained the spatial heterogeneity of excess mortality. The HEI may be considered a reasonable estimate of exposure suitable for evaluating the spatial interaction between exposure and deprivation with respect to mortality.

Considering the place of death as that of residence may have led to erroneous estimation of exposure to heat for the subjects who died during their holidays, particularly since August is the most popular vacation period in France. However, 96% of the deaths during the 2003 heat wave in France occurred in the victims' *Region* of residence.

The urban heat island effect gave rise to a 10% increase in HEI in the urban UUC and a 35% increase in Paris-and-suburbs, compared to the more rural UUC. Those findings are not sufficient to explain the extremely high heat exposure and excess mortality observed in Paris-and-suburbs, which were also related to hot weather over all of the Ile-de-France area.

Densely populated urban areas have often been reported to be the main zones at risk during heat waves [30-34] and specific measures are being taken to attenuate the risk (more green spaces, air conditioning, etc.) [20, 35]. However, rural zones are also subject to marked heat exposure. High excess mortality occurred in all UUC during the 2003 heat wave.

Variations in the association between HEI and excess mortality, by deprivation index

The multiplicative and additive interaction were both considered and found significantly positive in Paris-and-suburbs. Concerning the multiplicative approach, overdispersion was taken into account and the sensitivity to the inclusion of spatial autocorrelation (BYM model) was tested. However, the additive interaction was only considered under a marginal perspective, applying a Poisson variance to the death counts. The latter choice, implying a lost in the power of the analysis, was motivated by the large instability of additive Poisson models.

This study stands at an ecological level, which implies possible fallacies for individual associations' inferences. However, meteorological and air pollution data were computed at the finest possible scale. Therefore, confounding between exposure and socioeconomic level could have occurred if mortality and socioeconomic data were considered at a finer ecological level or at an individual level.

The geographic continuity of Paris-and-suburbs, in contrast to the scattering of the other UUC throughout France, may have conferred greater homogeneity on the relationship between heat exposure and increased mortality, and greater comparability of the socio-economic situations. In order to test that possibility, each of the 9 French urban centres with a population of 500 000 or more was considered separately. However, for those urban centres, no statistically significant interaction between HEI and FDep99 was observed for their association with increased mortality during the heat wave. The death counts, exposure levels and deprivation heterogeneities were systematically considerably less than those observed in Paris-and-suburbs.

In conclusion, although a marked increase in mortality related to heat wave exposure was observed for all *Canton* deprivation levels, the results point to the most deprived populations being more vulnerable to heat waves than the least deprived populations. This is specifically the case under extreme heat exposure when the spatial heterogeneity of deprivation is marked.

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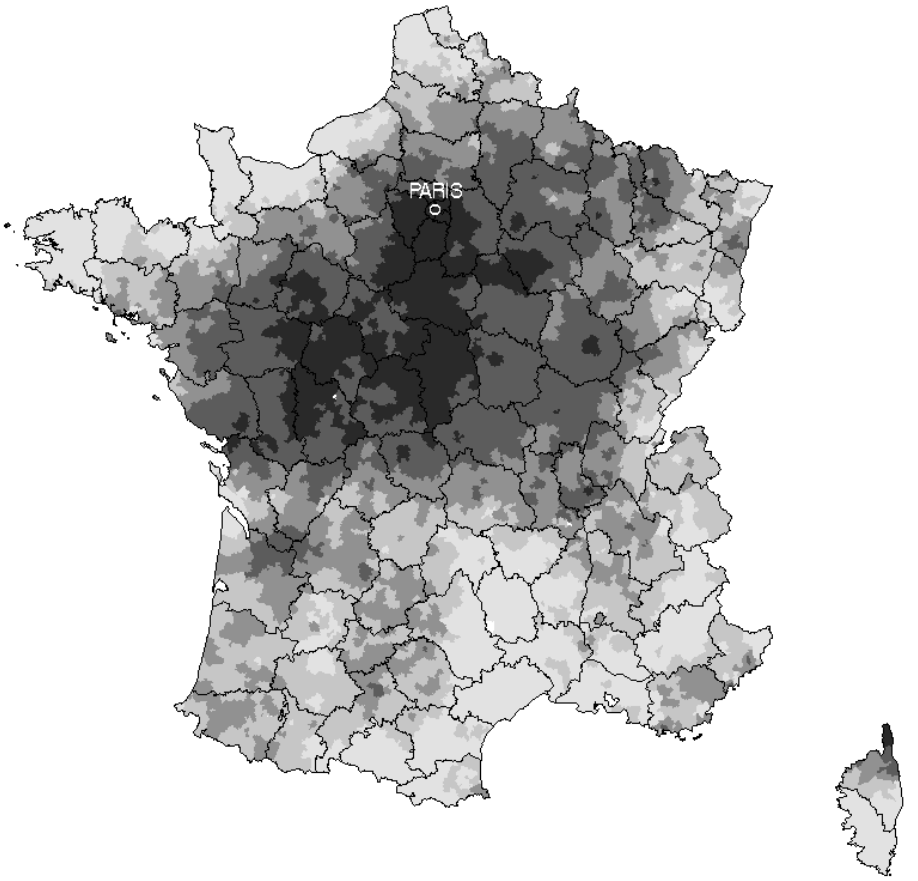
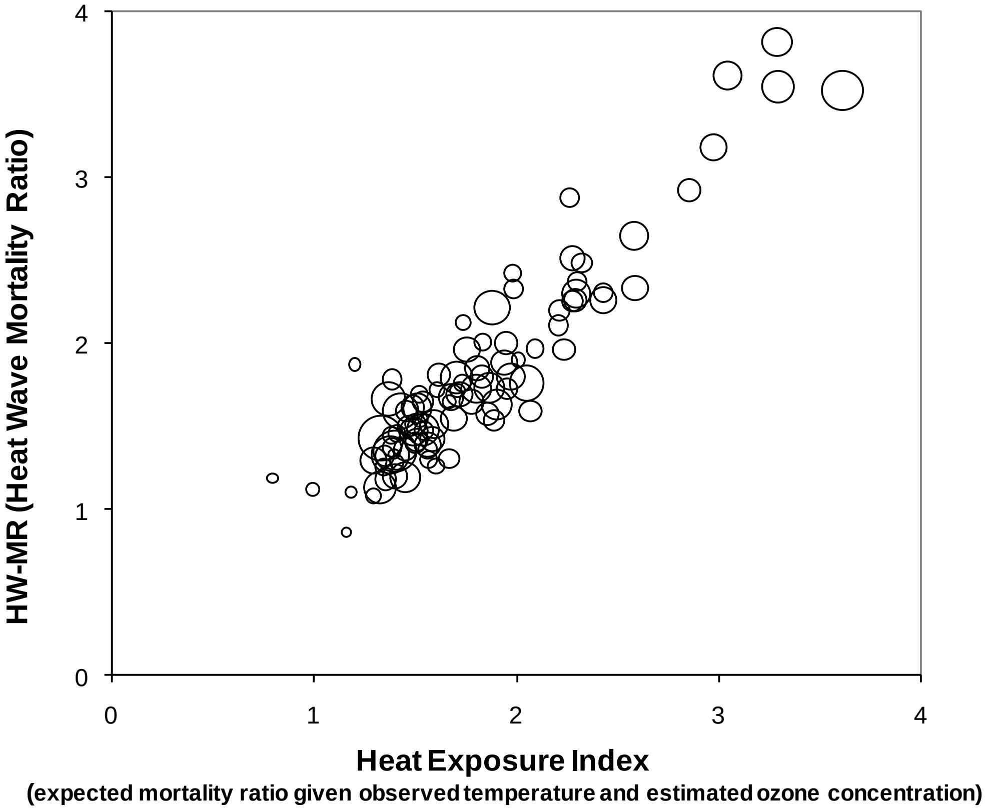
Figure 1: Smoothed heat wave mortality ratio (HW-MR) (BYM), by Canton France, 3rd to 15th August 2003



HW−MR: 0.75 − 1.20; 1.20 − 1.35; 1.35 − 1.54; 1.54 − 1.96; 1.96 − 5.00

HW-MR: heat wave mortality ratio is defined as the ratio of number of deaths from 3rd to 15th August, 2003, to the expected number of deaths in the same *Canton* given its 2003 population and the age- and gender-specific mortality rates of the *Canton* during the reference period (July and August of 2000-2002)

Figure 2: Scatter plot of heat wave mortality ratios (HW-MR) and HEI, on the *Departement* scale, France, 3rd to 15th August, 2003



Ordinates: Observed value of the Heat Wave Mortality Ratio (HW-MR = ratio of the number of deaths observed in a given area during the 2003 heat wave to the expected value calculated from the 2003 population of the area and the age and gender specific mortality rates observed in the same area in the non-heat-wave-exposed reference period, 2000-2002.
Abscissae: Heat Exposure Index derived from the Poisson regression of the Heat Wave Mortality ratio by *Canton* (HW-MR), with exposure variables as covariates. It provides the estimate of the HW-MR based on the value observed for those exposure covariates.

Table 1: Exposure differentials and heat wave mortality ratios (HW-MR) by urban unit category and their associations with the deprivation index

Urban Unit Category	Rural	Quasi-rural	Quasi-urban	Urban	Paris-and-suburbs
Number of *Cantons*	1,921	495	603	452	235
Population 55 years and over	3,963,675	1,761,097	3,489,292	4,478,146	2,169,228
Deprivation index					
- Mean (% ≥ overall mean)[1]	0.49 (66%)	0.34 (60%)	0.32 (56%)	-0.06 (37%)	-1.16 (9%)
- D5-D1[2]	40%	51%	48%	62%	100%
Heat Wave Mortality Ratio					
HW-MR, average value[3]	1.62	1.64	1.66	1.78	3.34
Heat Exposure Index[4]					
- HEI, average value[5]	1.68	1.63	1.63	1.69	3.12
- HEI, region adjusted[6]	1.00 [Ref.]	0.99	1.00	1.10*	1.35*
- HEI_{D5} / HEI_{D1}[7]	1.08*	1.00	1.03*	0.96*	0.93*

D5: fifth quintile of deprivation; D1: first quintile of deprivation
[1]: Mean of the deprivation index, weighted by population (percentage of populations of *Cantons* for which deprivation is higher than or equal to the overall mean deprivation)
[2]: Difference between the average deprivation in the first and fifth quintiles (basis: 100 for Paris)
[3]: Ratio of the total number of death observed during the heat wave period (August 3rd to 15th, 2003) and the total number of expected death
[4]: Deducted from a log-linear Poisson model relating HW-MR with temperature and ozone variables
[5]: Exponential of the population-weighted average of the log HEI
[6]: Calculated by analysis of variance of log HEI adjusted for the 22 *Regions*
[7]: Calculated by multiplying the linear association between deprivation and log HEI by the difference between the average deprivation in the first and fifth quintiles, adjusted for the 22 *Regions*
*: Statistically different from 1 at the 5% level

Table 2: Multiplicative variations in the association between heat exposure index (HEI) and heat wave mortality ratio (HW-MR) by deprivation France, 3rd to 15th August 2003

Urban Unit Category	Rural	Quasi-rural	Quasi-urban	Urban	Paris-and-suburbs
Ratio of the association HEI – HW-MR[1] between D5 and D1 [95% CI]	1.01 [0.88;1.16]	0.97 [0.81;1.17]	1.18 [1.02;1.36]	0.99 [0.86;1.15]	1.16 [1.08;1.24]

D5: fifth quintile of deprivation; D1: first quintile of deprivation

[1]: Exponential of the interaction coefficient between HEI and deprivation, multiplied by D5 - D1, derived from a Poisson model of HW-MR with over-dispersion

Table 3: Variation in the age- and gender-standardized excess mortality rate (SEMR) between the first (D1) and the fifth (D5) quintile of deprivation, by quintile of Heat Exposure index (HEI). France, 3rd to 15th August 2003

Heat exposure index quintiles	Standardized excess mortality rates	Urban Unit Category				
		Rural	Quasi-rural	Quasi-urban	Urban	Paris-and-suburbs
HEI 1st quintile	$SEMR_{D5}$ (1)	1.4	2.9	3.4	1.9	11.7
	$SEMR_{D1}$ (2)	1.5	0.6	0.8	2.3	10.1
	(1) - (2)	-0.1	2.3	2.5	-0.4	1.7
HEI 2nd quintile	$SEMR_{D5}$ (1)	2.8	4.1	4.2	4.2	9.7
	$SEMR_{D1}$ (2)	3.9	3.9	2.4	2.2	10.8
	(1) - (2)	-1.1	0.2	1.8	2.0	-1.1
HEI 3rd quintile	$SEMR_{D5}$ (1)	4.9	4.2	3.5	3.1	19.0
	$SEMR_{D1}$ (2)	4.5	4.8	3.7	3.9	9.4
	(1) - (2)	0.3	-0.7	-0.2	-0.8	9.6*
HEI 4th quintile	$SEMR_{D5}$ (1)	5.6	4.4	5.2	9.2	23.0
	$SEMR_{D1}$ (2)	6.8	2.4	3.8	7.4	12.4
	(1) - (2)	-1.1	2.0	1.4	1.8	10.6*
HEI 5th quintile	$SEMR_{D5}$ (1)	7.3	7.7	10.5	12.4	22.3
	$SEMR_{D1}$ (2)	7.1	9.4	8.4	7.1	12.0
	(1) - (2)	0.1	-1.8	2.1	5.3*	10.3*

D5: fifth quintile of deprivation; D1: first quintile of deprivation
SEMR: standardized excess mortality rate (number of excess deaths /100,000/day) standardized by age and gender

*: The difference between the SEMR of the Cantons of the most deprived quintile and the SEMR of the Cantons of the least deprived quintile is statistically different from 0 at the 5% level