The Mortality Impact of the August 2003 Heat Wave in France

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Paper prepared for presentation at the 2006 Population of America Association Meeting, Los Angeles, March 30-April 1st.

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In August 2003 Western Europe suffered from a deadly heat wave. An estimated 15,000 people died in France from the direct effect of the heat wave. Applying an indirect estimation technique to the monthly number of deaths by sex, age and place of residence for the period 1997-2003, a method that can easily be reproduced in other contexts, we estimate the number of years that would have remained to those who died from the heat wave had they been spared. The paper also evaluates the role of the 2003 heat wave "harvesting" effect in explaining the deficit of deaths recorded in 2004 (estimated at 25,500 out of a total expected 533,000 deaths).

In August 2003, France suffered from an unprecedented heat wave with temperatures reaching the high 30s in Celsius degrees for a record of fifteen successive days and little difference between day- and night-time. Consequences were deadly for the population: an estimated 15,000 of the total 56,500 deaths recorded during that month have been attributed to the direct effect of the heat wave (Hémon and Jougla, 2003). The crisis had a major socio-political impact with the calling into question of the responsibility of the highest authorities, leading to the resignation of the Minister of Health and the transfer of a number of high-ranking officials in that ministry, as well as the organisation of the French health care system and the responsibility of individual families. The outrage was such that major resources were promised by the government to prevent such a crisis to occur again in the future (Abenhaïm 2003).

A better understanding of the crisis was regarded as the first step to designing effective preventive measures and numerous reports were requested from specialised agencies though there is a paucity of scientific articles based on the analysis of basic demographic data. This paper specifically aims at describing the demographic characteristics of the victims of the August 2003 heat wave in France and at measuring its long term mortality impact. One aspect of the debate in the literature centred around the question of whether those who died were particularly vulnerable persons who were expected to live only a few more days or weeks independently from the heat wave or whether the heat wave killed randomly among the general population. Considering that this issue has not yet been properly addressed, an additional purpose of this paper is to estimate to which extent the unusually low mortality recorded in 2004 is the result of an harvesting effect of the August 2003 crisis.

After providing some background on the French heat wave of August 2003 and demonstrating how unusual this episode has been in the demographic history of the past thirty years, the paper describes the specific hypotheses investigated in the analyses as well as the data and methods used. It then presents the results of the statistical analyses and ends with a discussion of the findings.

Background

Summer 2003 reached record high temperatures for an unusual number of days in all of Western Europe. Large excess mortality has been attributed to the heat wave in a number of countries, including in addition to France, Italy, Spain, England and Wales, Belgium, Germany, Portugal, The Netherlands and Switzeland for a total approximating 45,000 to 50,000 deaths, depending on the method of estimation (Fischer, Brunekreef and Lebret, 2003; Garssen, Harmsen and de Beer, 2005; Grize et al., 2005; Johnson et al., 2005; Kosatsky, 2005; Kovats, Wolf and Menne, 2004; Nogueira et al., 2005; Pirard, 2003; Simon et al., 2005). In addition to being one of the hardest hit countries, second only to Italy where the heat wave killed 20,000 people according to the latest estimate (Istituto nazionale di statistica, 2005), France was characterized by a crisis much more concentrated in time than in some other countries. In Italy for instance, the victims were killed over a four months period, from June to September, with only half of all excess deaths in August. By contrast, in France, the 15,000 victims died over a two weeks period. This abruptness partly explains the lack of immediate public health response. The unpreparedness is also understandable considering the very unusual character of the episode. Indeed, neither France, nor any other developed country, has ever experienced a heat wave related mortality crisis on such a scale over the past fifty years (for the United States, see for instance Greenough *et al.*, 2001, and Semenza *et al.*, 1996).

Historical comparison

The August 2003 heat wave was clearly unusually intense. A recent study ordered by the French Government to determine temperature thresholds at which to trigger a health alert and activate a hot weather response plan found that, in Paris for instance[1], the best indicator was a succession of three days with all minima above 20 Celsius degrees and all maxima above 35 Celsius degrees (Invs, 2004). When looking back since January 1st, 1880, the first day of operation of the Paris meteorological station up to the present, one found a total of only six qualifying episodes but while the August 2003 episode lasted for an entire ten days, the next longest one (which took place in 1957) lasted for six days. In the Paris metropolitan area, the most severely hit region in 2003, temperatures reached a high of 35 Celsius degrees during day-time starting on August 3 and they remained above that level until August 14 when they declined below 30. Throughout this period, the lowest temperatures recorded at night never fell below 20, preventing a complete physiological recuperation to occur.

As indicated on Figure 1, which shows the number of deaths during the months of July and August over the past 30 years in France, other such episodes have occurred in the past but never with as strong an impact: in 1976 as in 1983, the number of extra deaths can be estimated at around 5,000 deaths[2]. In other Western countries, none of the Summer heat waves recorded over the past thirty years had killed more than 2,000 people before the 2003 episode (Institut national de veille sanitaire, 2003). The most documented one was undoubtedly the Chicago heat wave of 1995 to which fewer than 800 deaths were attributed (Klinenberg, 2003 ; Benbow, 1997).

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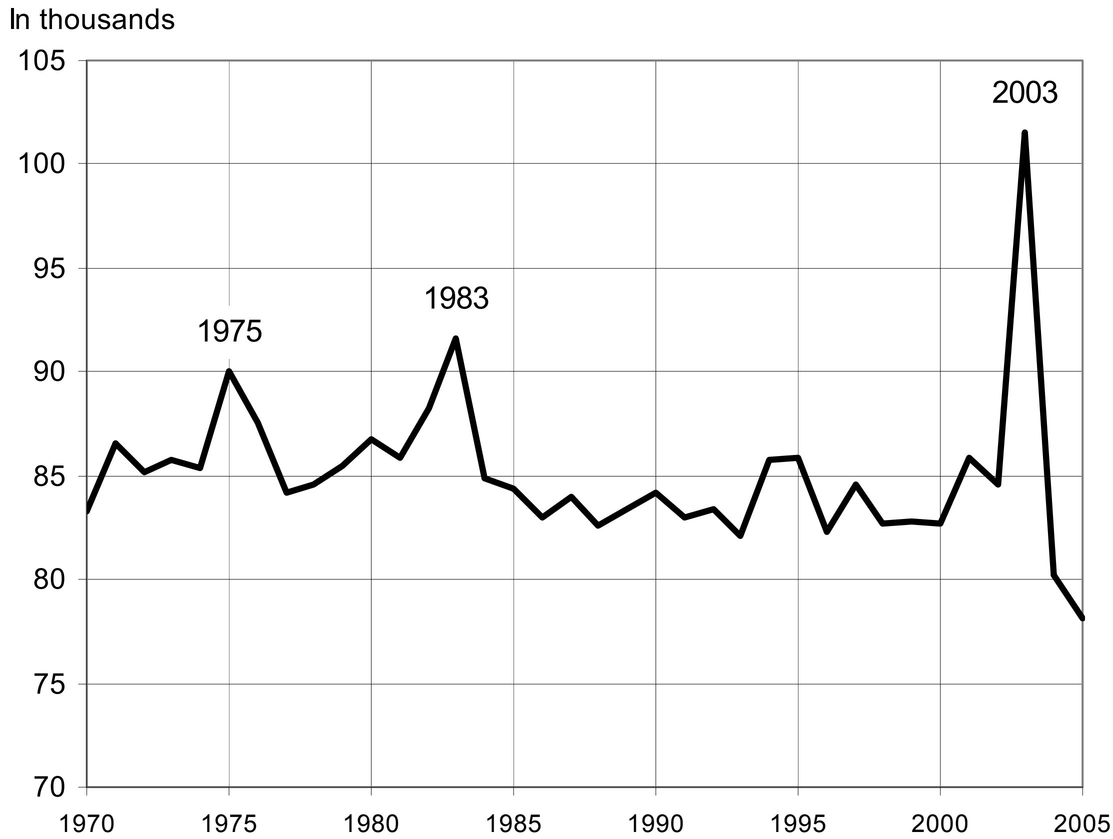
[1] The study also found that levels of minima and maxima temperatures showing an association with excess mortality vary from region to region.

[2] These numbers are estimated using the same methodology as the one leading to an estimated 15,000 excess deaths during the Summer 2003, i.e. by comparing the observed number of deaths in July and August of each given year by the mean number of deaths during the same months over the three preceding years. See also (Besancenot, 2002).

Figure 1. Number of deaths in July and August from 1970 to 2005. France

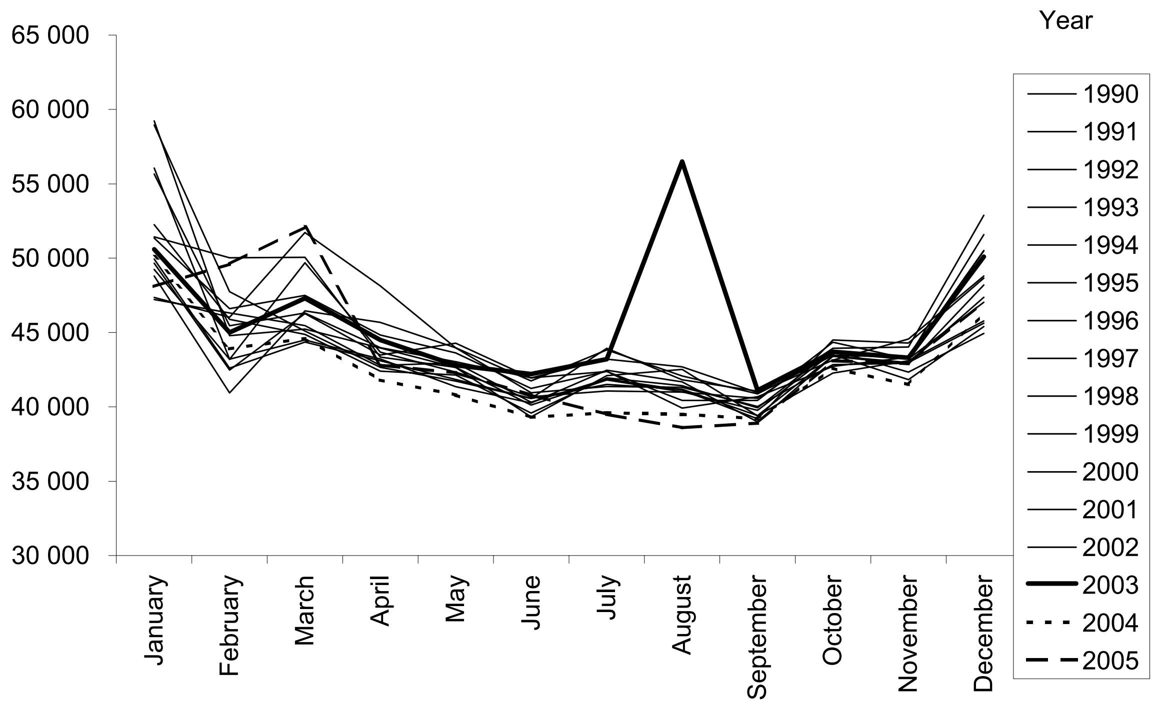


Source: Beaumel, Richet-Mastain and Vatan, 2005.

Characteristics of the French 2003 heat wave

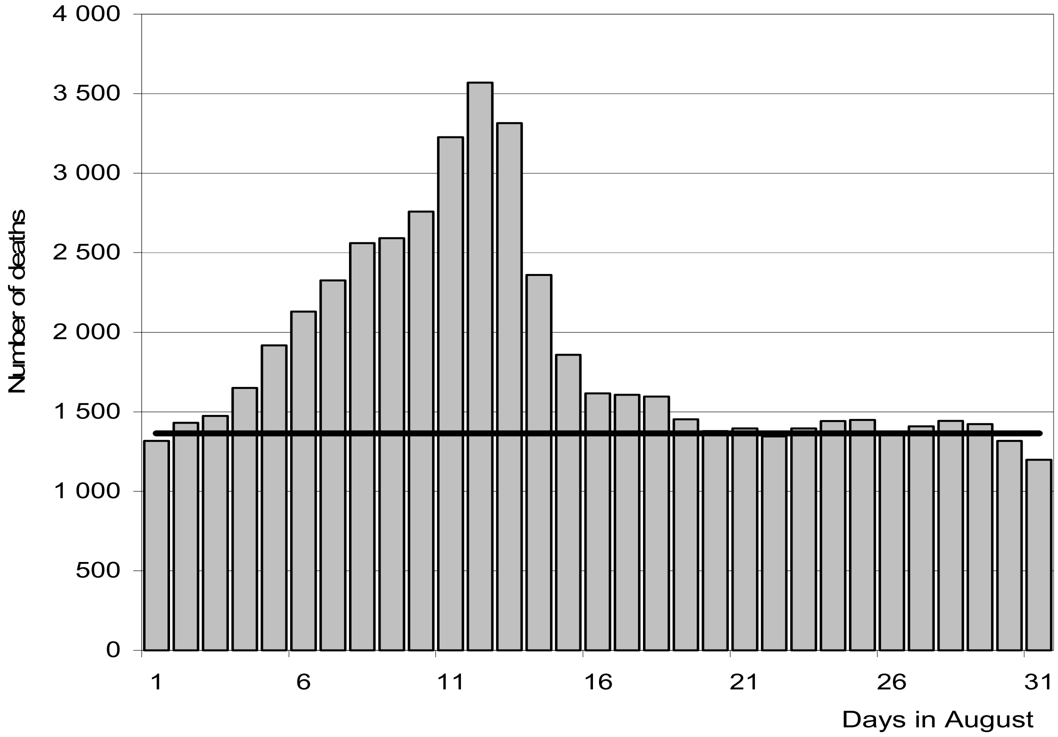
Such a large number of excess deaths as that recorded in France in August 2003 is clearly unusual during the Summer months in Western countries. Indeed, the month of August appears as the month typically characterised by the lowest level of mortality in recent demographic history (Figure 2). By contrast, it is not uncommon to observe episodes of large excess mortality during the Winter months in France as in other Northern countries. When looking at detailed mortality trends, episodes of excess of around 10,000 deaths due to flu epidemics are far from unusual. Part of the reason why these episodes do not elicit public outrage as did the August 2003 crisis is probably that they are expected and accompanied by much public health warning and encouragement for the elderly to get vaccinated so that public opinion feels that the government has done its job, but probably also because of their very diffuse impact, since the deaths attributable to flu epidemics are usually spread over several weeks or months. By contrast, the 2003 episode took everyone by surprise, in large part because of its suddenness, as the 15,000 excess deaths occurred over a fifteen day period, from August 4 to August 18 (Figures 3 and 4).

Figure 2. Total number of deaths per month, January 1990 to December 2005, France



Source: Beaumel, Richet-Mastain and Vatan, 2005.

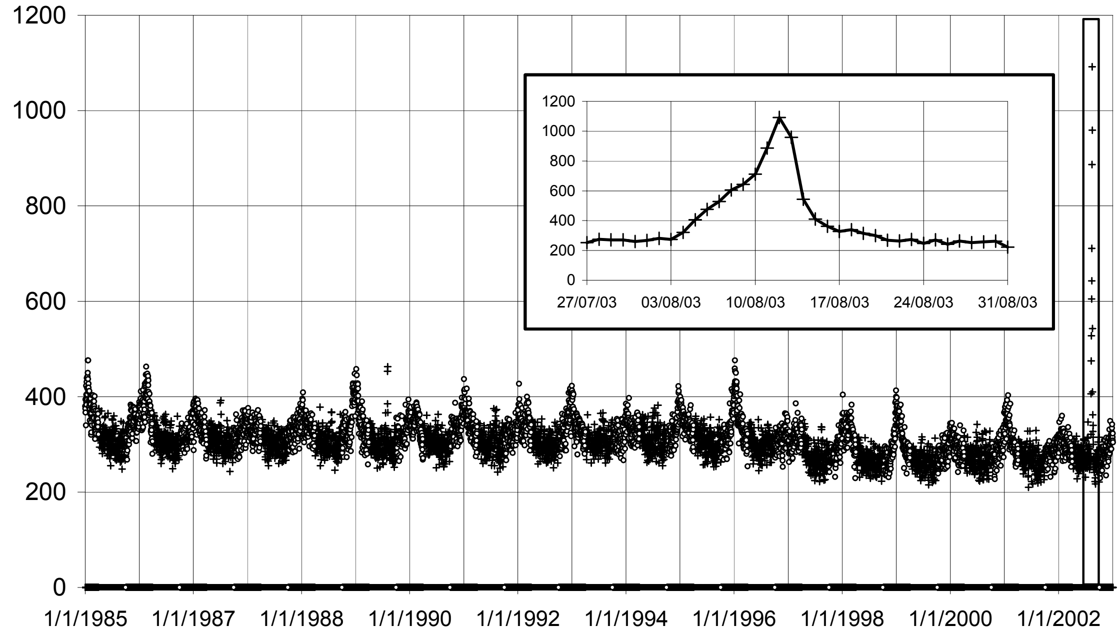
Figure 3. Number of deaths per day in August 2003 compared with the mean daily number of deaths during the months of August 2000 to 2002 (France)



Source: Hémon, Jougla 2003

Figure 4 presents the daily number of deaths in France main cities. It shows that deaths are indeed more numerous during Winter but also that many Summers are characterized with a few days when the number of deaths is significantly higher than average. However, the 2003 heat wave appears truly exceptional for two reasons: the maximum number of deaths reached more than four times the usual number of deaths, and the number of days with an excess number of deaths is remarkably large since the heat wave lasted for two entire weeks.

Figure 4. Number of deaths per day in 28 major cities of France, 1970 to 2003



Note: Winter days (from October to March) are marked with white dots; Summer days (from April to September) with black crosses.

Another characteristic of the 2003 mortality crisis is its high geographic concentration. As indicated by Map 2, only a relatively small number of *départements*[3] were hit, though those happened to be disproportionately populated. Indeed, the four *départements* with the highest excess mortality, that is more than 85% excess deaths during August 2003 compared to August 2000 to 2002, include 10.5 percent of France total population but more than 25 percent of all excess deaths. These four *départements* are located in the Paris metropolitan area (*départements* number 75, 92, 93 and 94). The geographic concentration of the health crisis is particularly striking considering the relative lack of correlation between objective measures of temperatures and excess mortality. Though all the *départements* in which a significant level of excess mortality was recorded also experienced record-high levels of night and day temperatures during that period, there is also a number of *départements* which experienced higher levels of temperature for a longer duration but hardly any excess mortality, in the South of France in particular. Excess mortality by *département* appears better correlated with excess, rather than absolute, temperature (Fouillet *et al.*, 2005; Invs, 2004). A progressive gradient in excess mortality is observed with an increase in the number of days, from one to more than eight, when day and night time temperatures respectively reached 9 and 5°C above the average for a month of August (Maps 1 and 2). Map 1, showing excess mortality by *départements*, overlaps quite well with Map 2, showing excess rather than absolute temperatures during the heat wave.

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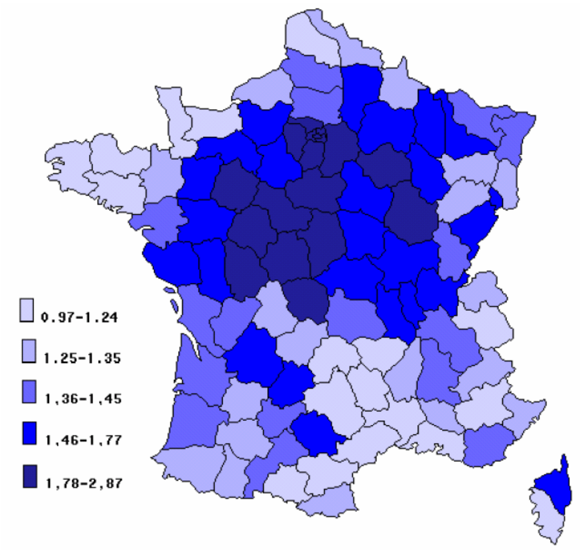
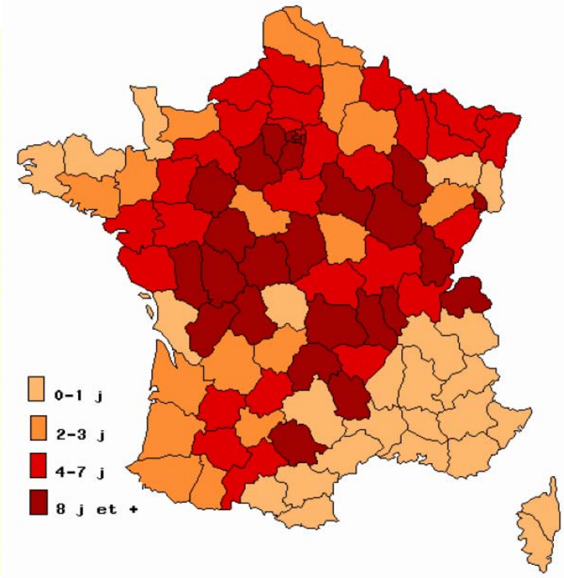
[3] Mainland France includes a total of 95 *départements*, the *département* being one of the most basic administrative units.

Map 1. mortality ratio by *département* in metropolitan France, from 1st to 20th August, 2003



Map2. Number of days when minimum and maximum temperatures are respectively 5°C and 9°C over the usual temperatures



Source: reprint from Fouillet et al., 2005, figures 1 and 3.

The long term mortality impact of the 2003 heat wave in France

The primary purpose of our research is to evaluate the long term mortality impact of the 2003 heat wave in France. The mortality consequences of the heat wave depend on how many people died altogether from the heat wave and on how long would have lived those who died during the heat wave, if they did not die during that period. The first part of the issue is relatively simple and has been readily assessed with an agreement on the number 15,000 using a range of different techniques, from the most rudimentary to the most sophisticated (Hémon and Jougla, 2003; Rey *et al*., 2005). The second part of the issue is more complex and requires the implementation of elaborate techniques of analysis and the examination of a minimum of two alternative hypotheses.

The first hypothesis is that the heat wave killed indiscriminately among the overall population. We already know that this is not sustainable considering the high concentration of heat wave victims in the highest age groups. Less than a month after the crisis, a preliminary analysis conducted on selected death records showed that over 80 percent of the heat wave victims were 75 years and older (Hémon et Jougla, 2003). Further research supported this finding (Canoui-Poitrine, Cadot and Spira, 2005 ; Invs, 2003 ; Rey et al., 2005). If anything, the heat wave killed disproportionately among the elderly. We also know that, by contrast with heat wave mortality in the United States, the majority of the August 2003 heat wave victims were women (Besancenot, 2002 ; Klinenberg, 2003). Our first hypothesis thus requires some specification, which is that age and sex alone are correlated with the probability of dying during the heat wave. In other words, we speculate that age and sex groups are homogeneous, i.e. that the heat wave victims would have lived as long as their peers in the same age and sex group in the absence of the heat wave. If the heat wave killed at random, those who died due to the heat wave were expected to live as long as those of the same age and sex based on the current life table for France. The number of years of life lost under this hypothesis is simply the sum of the expectations of life as it can be calculated for a cohort with the same sex and age characteristics as the victims, starting in August 2003 and under the mortality conditions assumed in the absence of the heat wave.

The second, alternative, hypothesis is that, due to unobserved heterogeneity, those who died during the heat wave would have died sooner than those who did not in their age and sex group even without the heat wave, due to poor inherent health status prior to August 2003. This is the harvesting hypothesis. The harvesting or frailty effect is defined as a selection effect of mortality among the frailest individuals such that the heat wave victims were fated to die within weeks or months of August 2003 in the absence of the heat wave. The operation of a harvesting effect is typically identified by a lower than expected number of deaths following a mortality crisis. Indeed, if there is a harvesting effect due to differential frailty, the deaths of the frailest temporarily inflate the number of total deaths during the crisis. By contrast, immediately after the crisis has passed, the total number of deaths is below the long run expected number due to the advancement of the victims' demises, so that there is a compensation in terms of mortality between the crisis period and the following period before the level of mortality returns to normal. The question of a possible harvesting effect is particularly relevant in the case of the French August 2003 episode given the remarkably low level of mortality recorded in 2004.

Most observers have assumed a correlation between the high mortality recorded in Summer 2003 and the low mortality of 2004 but statistical analysis of vital registration data has been scarce. Based on the analysis of data truncated to the month of June 2004, the point at which the number of deaths "missing" in 2004 equals that of the heat wave related victims, i.e. 15,000, the one study to have investigated the issue in France concluded to the full operation of a harvesting effect (Valleron and Boumendil, 2004). We find this conclusion unconvincing considering that its only basis is the coincidence between both numbers and since "missing" deaths continued to accumulate during the second part of 2004 to reach about 25,500 deaths over a total annual number of 535,000 deaths. The problem however is difficult to tackle given the lack of information about the health condition or any other indicator of frailty for the heat wave victims[4]. Indirect methods have to be implemented to explore this hypothesis.

We investigated the two alternative hypotheses using civil registration data and implementing three different approaches. The first approach derives from the idea that the frailest should have been the first to die during the two weeks long heat wave, so that victims during the first week of the heat wave had different characteristics than those of the second week. In the absence of information about prior health status of the victims, we decided to first assume a relationship between high age and frailty, in which case we would expect to find differences in the age structure of the victims of the first part of the heat wave, let's say those who died up to August

[4] A study conducted by Social Security found that the consumption of pharmaceutical drugs during the five months prior to the heat wave was significantly higher for people aged 70 and above who died in August 2003 than for people in the same age group who survived the crisis (CNAMTS, *Direction des statistiques et des études*, 2004), a result that tends to be used by proponents of the harvesting hypothesis to support the idea of a greater frailty of the heat wave victims compared to their peers. However, there is no reason to believe that such a finding is specific to the heat wave victims. Indeed, it is likely that all of those who die at any one point are greater consumers of pharmaceutical drugs during the few months prior to their death than others in their age group. Furthermore, since the study included all of those who died during the month of August 2003, both from the heat wave and independently from the heat wave, it is also possible that the over-medication applies to the later rather than to the former. We thus do not consider this study to be a scientifically rigorous argument in favour of the harvesting effect.

10, and the victims of the second part of the heat wave, those who died after August 10. Testing this assumption requires to estimate the detailed age and sex distribution of the heat wave victims by day of death. This estimation also feeds the second approach based on the examination of the age and sex distribution of the deaths “missing” during the following months. The idea is that, if one can indeed assume the operation of a harvesting effect, mortality during the period after August 2003 should be disproportionately low in the sex and age groups most affected by the heat wave. The third approach is based on the same line of reasoning but investigates the correspondence between the geographic rather than between the demographic characteristics of the August 2003 mortality crisis and the low mortality of the following months. The data and techniques implemented to follow all three approaches are described below in details.

Data

Individual records of death with information on day, month and year of occurrence as well as year of birth, sex and *département* of residence (the basic French administrative unit) of the deceased has been provided to us for the period 1996-2003 by the *Institut National de la Statistique et des Etudes économiques* (Insee), the institution in charge of collecting and analysing civil registration data in France. These data were made available to us in an electronic format[5]. We also used life tables published by Insee for France for the periods 1997-1999 and 2000-2002 as well as the distribution of the French population by sex and year of age on January 1st 2003 and January 1st 2004. As no reliable data is yet available at the individual level for 2004, we used the monthly total number of deaths by *département* for 2004. For obvious reasons, we excluded from our analyses the French overseas *départements*.

Methods

The basis of our analyses is a comparison of observed and expected mortality, both during the heat wave and during the following months. The comparison was carried out separately by age and sex, on the one hand, and by *département* of residence, on the other. The technique applied in studies and reports previously published on the mortality impact of the August 2003 heat wave was fairly rudimentary. It considers that the number of deaths expected for each month under study, whether just before, during or after the heat wave, is equal to the mean number of deaths during the same month for the three years before the crisis, i.e. 2000, 2001 and 2002. This method robustness has been demonstrated for estimating the total number of deaths by month and *département*, as the estimates of local population size available are not precise enough to allow for the implementation of more sophisticated techniques (Hémon and Jougla, 2003).

Estimating the age and sex structure of total number of deaths expected for 2003 and 2004

This method is attractive by its simplicity, but it is not appropriate for an estimation of expected deaths by age and sex, due to the irregular shape of the French age pyramid (Figure 5). These variations reflect France demographic history over the past century. Because the heat wave killed mostly among the elderly, the impact of the First World War on the age pyramid is particularly detrimental. Indeed, the main demographic impact of the war was to prevent and delay a large number of births so that those cohorts born in 1915-1919 are particularly small. Individuals aged

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[5] We thank our colleages Catherine Beaumel, Aline Desesquelles, Guy Desplanques and Lucile Richet-Mastain, from Insee, *Département de la démographie,* for having provided us with all the data used in this paper.

83 to 87 on January 1st, 2003 are consequently much fewer than those in the surrounding age groups. Consequently, we cannot limit the analysis to a comparison of the mean number of deaths in 2000-2002 with August 2003 for each sex and single year of age as previous studies have done for large age categories (Hémon and Jougla, 2003 for instance) but need to take into account the large independent variations in the size of the population at risk.

Figure 5. Population pyramid at 1-1-2003. France

Source: Beaumel, Richet-Mastain and Vatan, 2005.

A second, more elaborated, technique thus had to be used. We first projected the trends in the probability of death for each sex and year of age from the 1997-1999 to the 2000-2002 life table. We are fortunate that mortality trends in France are fairly smooth compared to other European countries, such as Italy. In the latter, the reference period used to estimate the expected number of deaths during Summer 2003 in the absence of the heat wave has a considerable impact on the estimated number of heat wave victims, hence the large variations in the number of victims successively announced, from less than 8,000 to about 20,000 (Istituto Nazionale di Statistica, 2005). In France, by contrast, the estimated number of heat wave victims is very robust: it falls very close to 14,800 whether a rudimentary technique or a more sophisticated one, such as that described here, is implemented. The number of deaths by sex and age for all of 2003 was estimated by applying the projected probabilities to the population by age and sex on January 1st 2003. For 2004, the same method was used, i.e. continuing the trend in the probabilities of death from 1997-1999 to 2000-2002 all the way to 2004, but the probabilities were applied to the population by age and sex on January 1st 2004 corrected for the heat wave deaths. More specifically, we added the heat wave victims to the number of people alive on January 1st 2004 for the age group they would have reached by then since the purpose of the calculation is to estimate the number of deaths that would have been recorded in 2004 in the absence of the 2003 heat wave crisis.

Estimating the monthly number of deaths by age and sex in 2003 and subsequently

To calculate the monthly number of deaths by sex and age rather than for the whole year, we further refined our estimates of the expected number of deaths per month by single year of age and sex by taking trends in seasonality into account. Indeed, analyses not showed here indicate that, though the *level* of mortality during Summer months is typically lower than that of Winter months and *variations* from one Summer to the next are relatively small, notwithstanding the 2003 episode, compared to variations from one Winter to another, deviations from the average tend to decline over time for Winter while this is not the case for Summer. Consequently, the proportion of deaths expected in August 2003 if the heat wave had not occurred would have been larger than that calculated for the previous years. Trends in seasonality were incorporated into our calculations using a log-linear regression on death probabilities at each sex and age, using three-year period life-tables by month (1997-1999 and 2000-2002) published by the Insee, to extrapolate the monthly probabilities of death by sex and age in 2003 by years of age. The implementation of the mortality projection to the population on January 1st, 2003 thus carried out produced a number of deaths by age and sex for every month from January 2003 to December 2004 for France as a whole. For 2005, provisional data is available for the monthly total number of deaths but not by age and sex, nor by *département*.

Estimating the expected number of deaths in each départements *in 2003 and 2004*

Ideally, we would have liked to also estimate the number of deaths by age and sex in each *département* but the aforementioned data constraints did not allow us to take age and sex into account at that geographic level so that spatial analysis was carried out on the comparison between the expected and the observed overall number of deaths by *département* using the rudimentary technique rather than the sophisticated one. More specifically, to estimate both the number of excess deaths in August 2003 and the deficit of 2004 at the level of the *départements* we resorted to the rather crude method of estimation based on the comparison between the total number of deaths recorded in August 2003 and the mean number of deaths recorded in August 2000, August 2001 and August 2002 (used as the expected number of deaths) in each *départements* [6]. Similarly, the degree of under-mortality in the months following the heat wave was estimated by comparing the total number of deaths from September 2003 to the end of 2004 with the adjusted mean number of deaths in 2000, 2001 and 2002 in each *départements*.

Size effects at the *département* level were further controlled by using a scaling factor where indicated in the rest of the paper. Scaling was carried out by dividing both the excess deaths of August 2003 and the missing deaths of the subsequent months by the mean monthly number of deaths in each *départements* during the 2000-2002 period. This technique allows for a direct comparison of the over-mortality of the heat wave and the under-mortality of the following

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[6] This method has been proved to be robust at the *département* level, compared to more sophisticated methods based on populations and probabilities of death by sex and age (Hémon, Jougla 2003).

months between *départements* independently from their demographic weight. This is particularly useful considering that the heat wave related mortality crisis disproportionately hit those *départements*, i.e. located in the Ile de France region, which happen to be the most populated. The technique was more specifically implemented as follow.

Let us consider one *département*:

$D(m,t)$ is the number of deaths during month m of year t.

"*base*" refers to the period 2000-2002, so that $D(m,base)$ is the mean number of deaths during the month(s) m of 2000-2002.

$D(base)$ is the mean monthly number of deaths in 2000-2002 .

X is the difference between the number of deaths during August 2003 and the usual number of deaths in August: $X=D(8,2003)-D(8,base)$.

Y is the difference between the number of deaths from September 2003 to December 2004 and the usual number of deaths in that period, so that:

$$Y=D([9,2003] \text{ to } [12,2004]) - D([9,base] \text{ to } [12,base]) - D([1,base] \text{ to } [12,base])$$

Y and X are scaled by the mean number of deaths:

$$x=X / D(base) \text{ and } y=Y / D(base).$$

x and y are then directly comparable, so that if we assume a complete harvesting effect (and no other change), then:

$$y = - x.$$

Results

Age and sex characteristics of the August 2003 heat wave related deaths

Our projection method yielded an estimated 14,748 deaths attributable to the heat wave, a number very close to the 14,802 deaths calculated with the more rudimentary technique based on the mean number of deaths for a month of August in the three years prior to the crisis. Our estimation represents an excess of 35% over the number of deaths expected for August 2003.

Table 1. Heat wave victims by sex and age group

Age group	Number of heat wave victims			Percent distribution		
	Male	Female	Total	Male	Female	Total
0-9	19	-15	4	0,36	-0,15	0,03
10-19	-3	-20	-22	-0,05	-0,21	-0,15
20-29	40	-16	24	0,76	-0,17	0,16
30-39	109	-35	74	2,07	-0,36	0,50
40-49	246	58	304	4,69	0,61	2,06
50-59	343	228	571	6,55	2,40	3,87
60-69	551	456	1 007	10,52	4,80	6,83
70-79	1 326	1 888	3 214	25,32	19,85	21,80
80-89	1 849	3 593	5 442	35,29	37,78	36,90
90 and over	759	3 371	4 130	14,49	35,45	28,01
Total	5 238	9 509	14 748	100,00	100,00	100,00

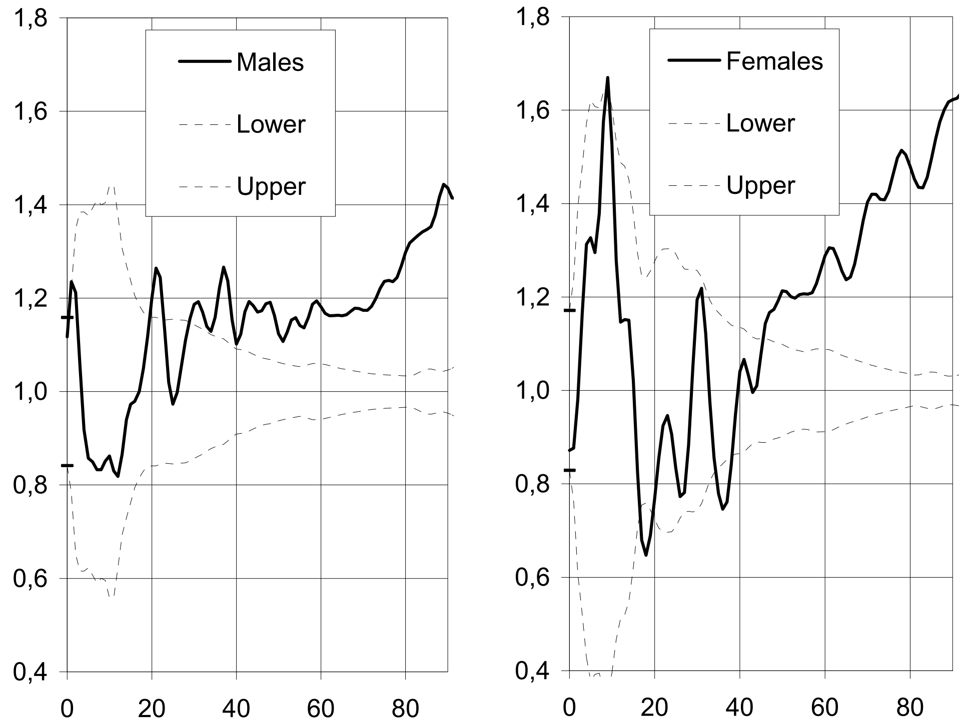
Note: the projection technique implemented is described in details in the methodological section of the paper.

The two most striking features of the crisis are that it killed disproportionately among elderly and among women: about 85 percent of the victims were aged 70 and over (93 percent for women, 75 percent for men) and above 65 percent were women (Table 1). The over-representation of women among the heat wave victims is to underline not only because of its scope but also because it is opposite to what was found in some others of the most documented heat wave mortality crises, such as in the United States (Benbow, 1997; Besancenot, 2002). Our detailed analysis shows that the large sex differential found in France is, for the most part, not due to the differential age structure of the male and female populations, i.e. it is not due to the fact that women are increasingly over-represented as age goes up due to their higher life expectancy than men. Indeed, when standardizing by exact year of age, the difference is only slightly reduced, so that women still account for 60 percent of all excess deaths. As indicated by Figure 6, showing the ratio of the actual to the expected probabilities of death by sex and year of age in August 2003 and its associated 5% confidence interval, the sex differential is mostly significant after age 60 and increases progressively afterwards[7]. Among women, mortality appears to be significantly higher than expected at ages above 45, and the ratio increases regularly thereafter, from 1.2 at 50 to 1.6 at 85. Above 50, excess mortality is smaller for men: it is 1.2 at 70 and 1.4 at 85. Between the ages of 30 and 45, male mortality is 20% higher than expected, while no significant

[7] Because of large random variations, we smoothed the ratios with a three years of age moving average with coefficients 0.3-0.4-0.3. Three iterations of this smoothing procedure leads to a seven years of age moving average with coefficients 0.027; 0.108; 0.225; 0.280; 0.225; 0.108 and 0.027. Variances have been estimated with the Normal approximation of the Poisson Law and take into account correlations due to the smoothing procedure. Ratios at age 0 are not smoothed.

difference is found for women. Before 30 years of age, the ratios are not significant with the possible exception of infant male mortality[8].

Figure 6. Ratio of observed to expected probabilities of death by sex and age in August 2003



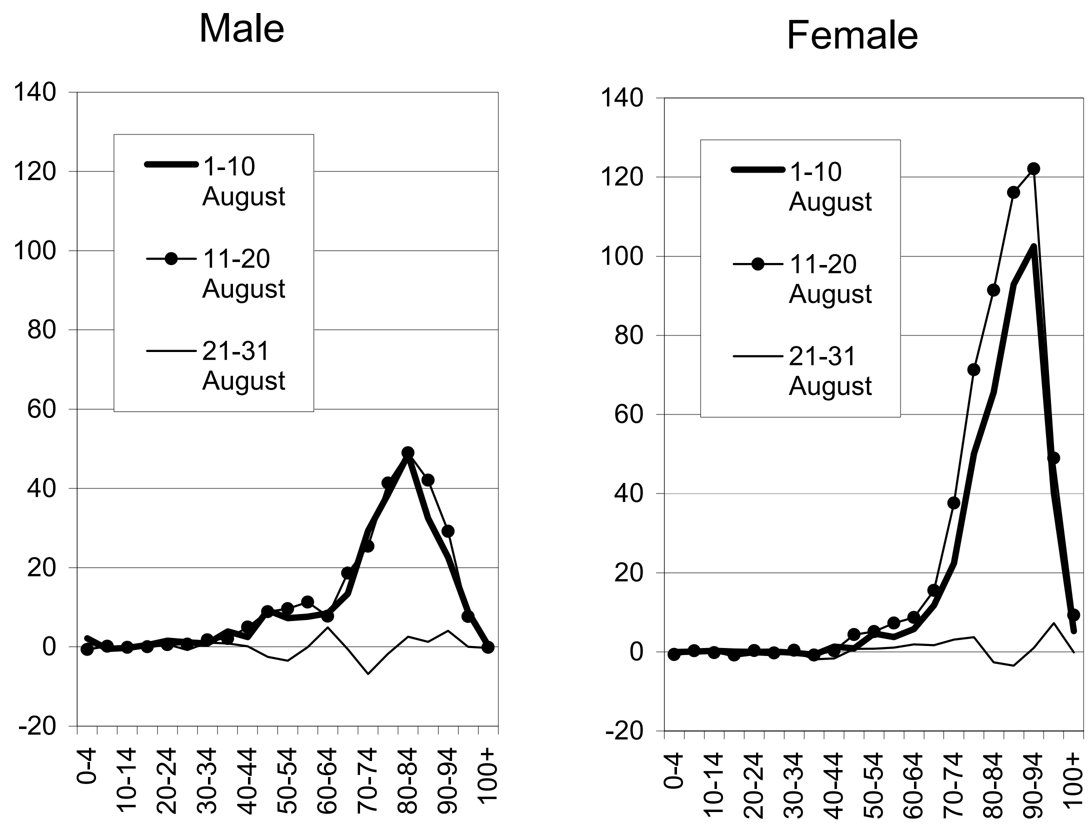
Note: for each age, the curves "Lower" and "Upper" mark the limits of the confidence interval for the relative risk, under the Poisson assumption, taking into account the seven years of age moving average.

[8] Though one study found a significant excess mortality for male below one, of about 25% for the period of 1-20 August 2003 (Rey et al., 2005), another analysis found no heat wave related mortality among infants during the same period and only 3 heat wave related deaths specifically identified among children below 15 (Invs, 2005; Hémon *et al.* 2003). Furthermore, findings from Rey et al.'s study are questionable to the extent that the estimated number of excess infant deaths is 25 with an AR1 model including a fixed monthly factor and the excess deaths are concentrated in the first days of the heat wave and in the Paris region (Rey et al. 2005). In this study, the number of excess deaths diminishes to only 18 when seasonality is allowed to vary and no excess death is found among young girls or boys aged 1-19. In any event, considering the extremely small number of deaths for infants and young children in an average month of August, no more than 25 deaths out of the total 15,000 or so heat wave related deaths can be attributed to young children.

Investigating harvesting in the short term

Exploring the harvesting hypothesis, we estimated the age and sex structure of the heat wave victims for three separate periods, i.e. August 1-10, August 11-20 and August 21-31. In the centre of the country, where the crisis was most severe, the heat wave covered the period from August 4 to August 18, so that the first two periods in our study correspond roughly to, respectively, the first and the second stage of the episode and the third to its immediate aftermath. If a frailty effect related to age had been operating, we would expect the frailest, assumed to be the oldest, to have died first, followed during the later days of the heat wave by less frail, thus younger, victims. Under the harvesting hypothesis, we thus expected to find that those deceased during the first ten days of August to have been older on average than those who died during the following ten days. Similarly, the structure of mortality for the last days of August, that is after the heat wave, should have been even younger than expected since some of the elderly at risk would have died during the first three weeks of the month. The comparison is based on the mean daily number of deaths by sex and age expected in August 2003 when projecting the trends in the probabilities of death observed from 1997-1999 to 2000-2002 following the technique based on death probabilities estimates described in the previous section. Figure 7 represents the overall distribution of estimated daily excess deaths by age and sex and for each of the three time periods. Excess deaths were grouped by 5-years of age to facilitate comparison between the three time periods.

Figure 7. Daily number of heat wave related deaths (O-E) by sex, August 2003



The results provide evidence against the frailty hypothesis to the extent that the distribution of deaths by sex and age for the first ten day period of August 2003 is not significantly different from that of the following ten day period. Compared to an expected daily number of deaths of 1,340 (see Figure 2), the excess reached a daily mean of 650 and 800 deaths during the first ten days of August and the ten following days, respectively. The mean age at death is 75 and 76 years for men during, respectively, the first and the second of these two periods and it is 85 years for women during both periods. Furthermore, the distribution of deaths by sex and age during the later ten days of August, after the end of the heat wave crisis, shows no difference with the expected distribution while we would have expected fewer deaths in the age groups most affected by the heat wave under the harvesting hypothesis.

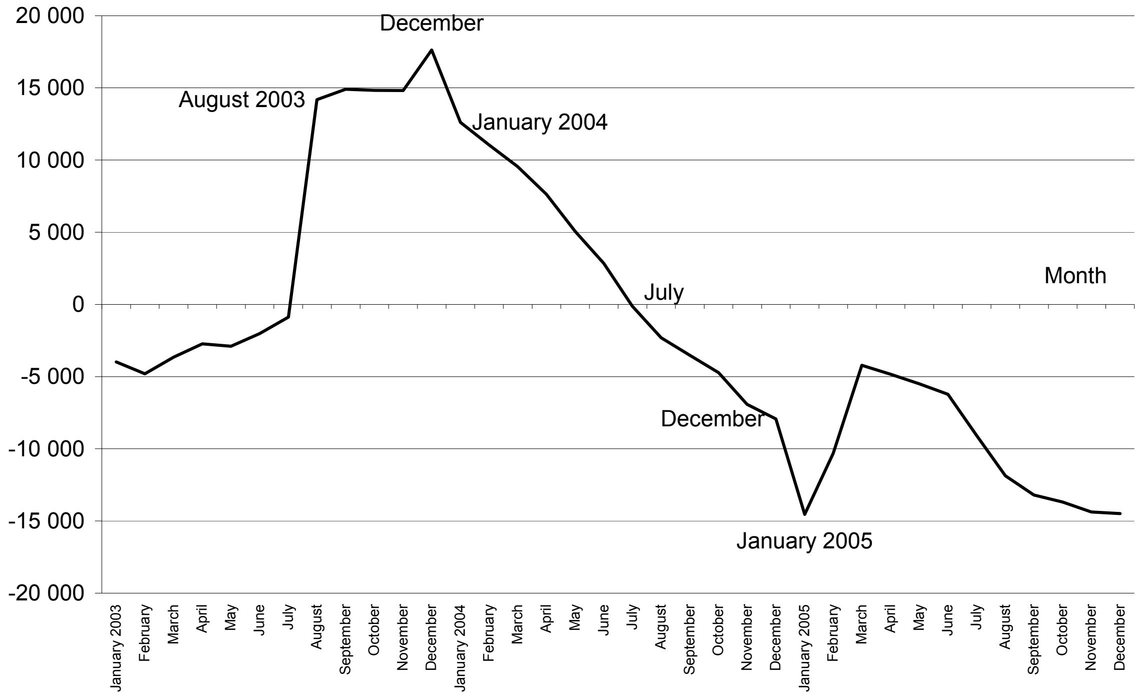
We recognize, however, that one can readily argue that frailty is, to some extent, independent from age so that those people who died during the first few days of the heat wave were indeed more vulnerable than those who died later but a comparison of the deceased in both periods based on age and sex only is unable to distinguish between the frail and the robust. An alternative hypothesis would be that some harvesting did occur, but that it was fully compensated by delayed deaths, some people having been weakened by the heat wave and dying in the aftermath of the crisis and earlier than they would have otherwise. If such delayed deaths did occur in the days or months after the heat wave, the harvesting effect could be difficult to isolate in the short term.

Investigating harvesting in the long run

To further investigate this issue, we compared the number of deaths for every single month of 2003, 2004 and 2005 with that recorded during the same month of the previous three years. Figure 8 presents the cumulated number of deaths from January 2003 to December 2005, compared to the mean for the corresponding months of 2000-2002. In January and February 2003, the number of deaths was smaller than in the same months of 2000-2002, and nearly 5,000 fewer than expected deaths were counted. From March to July, however, the monthly number of deaths was a little larger, so that by the end of July 2003 the cumulated number of deaths was very close to the corresponding figure for 2000-2002. After August 2003 and its 15,000 excess deaths, the numbers of deaths in September, October and November were very similar to the previous years. In December, we find an excess 3,000 deaths, so the cumulated number of excess deaths reached a maximum of 18,000 at the very end of the year 2003. In 2004, the smaller than expected level of mortality is clear and uniform. In every single month of that year the number of deaths was lower than the mean for the same months of 2000-2002 so that by the end of 2004 the deficit reached a total of approximately 25,500 deaths, thus representing an over-compensation of nearly 8,000 for the heat wave crisis and the additional, smaller, December 2003 mortality peak. Mortality was again lower than expected throughout 2005, except for the months of February and March, when it rebounded. The overall deficit from January 2004 to December 2005 was twice as large as the excess mortality of August 2003, suggesting that after the August 2003 crisis, the "normal" level of mortality had become significantly and possibly permanently lower than prior to the crisis.

Flu epidemics explain most of the month-to-month fluctuations in mortality during the period 2003-2005, except of course for the August 2003 episode. Flu epidemics in France typically spread over the entire Winter season, from December to February but with a calendar that is not uncommonly shifted early or late, depending on the year. Winter 2002-2003 was in particular one of the few recent Winters exempted from the epidemics, so that there were hardly any flu deaths in January and February 2003 compared to the previous years. This pattern explains the lower than expected level of mortality recorded in the early months of 2003. In the following Winter, that is Winter 2003-2004, flu occurred in the early season so that December 2003 exhibited a high level of mortality relative to the previous years while mortality was lower than usual in January and February 2004. It is possible that the relatively small number of flu victims in the early weeks of 2004 results from the unusually small size of the population at risk due to the heat wave crisis but that would not explain why mortality was continuously lower than expected from previous mortality trends throughout the rest of 2004 and up to the end of January 2005. A flu epidemics took place in February and March 2005, later than in typical Winters, which accounts for the increase in mortality during those two months. Data are not yet available to comment on the flu epidemics for the 2005-2006 Winter season.

Figure 8. Monthly cumulated number of deaths, relative to the same months of years 2000-2002

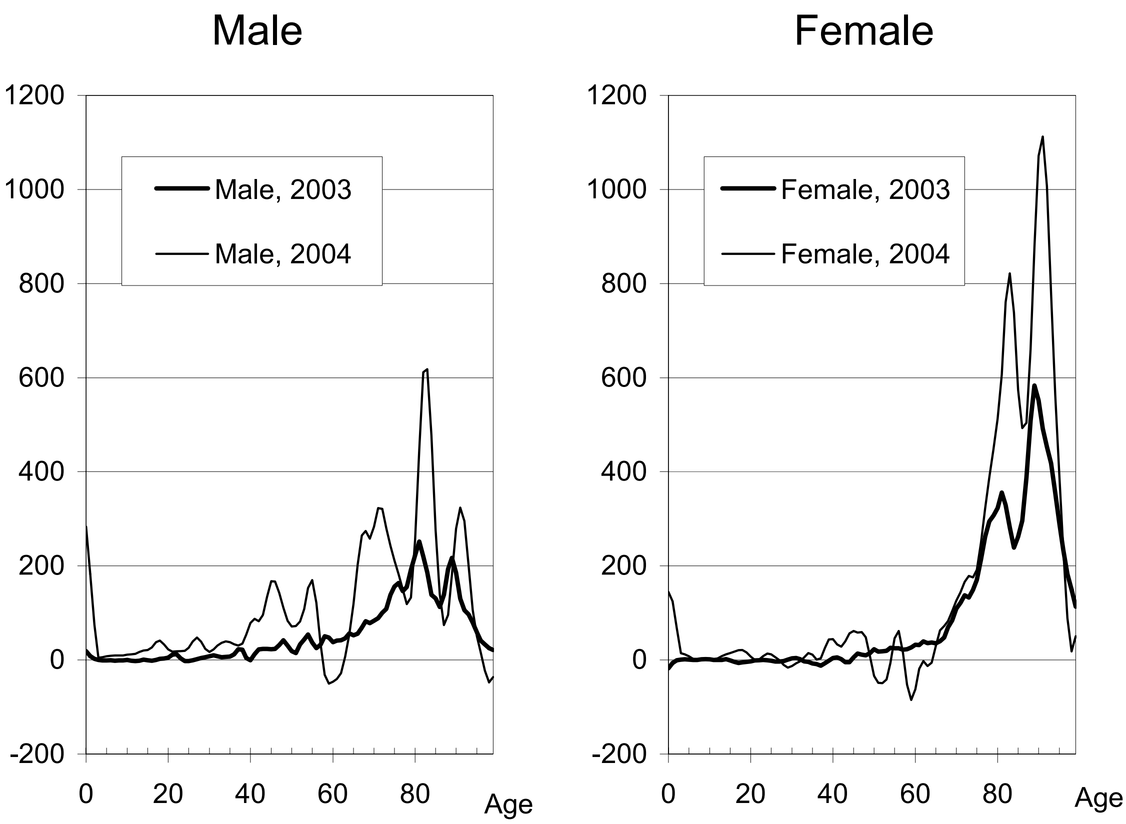


The main conclusion at this point is that we do not find any clear evidence of harvesting. If there has indeed been a harvesting effect following the August 2003 heat wave, this effect must have been spread over a period of several months, up to the end of 2004 at a minimum. The hypothesis of a "lagged" harvesting is not likely. It would imply that harvesting began at the end of 2003 but was compensated by some excess deaths of people who suffered from the heat wave and died in the subsequent months. If the 2004 decline in mortality is attributed to harvesting, then around 5,000 excess "delayed" deaths in September to December 2003 must be attributed to the heat wave. Nevertheless, harvesting would also have taken place in 2004 for these "delayed" deaths, as the total cumulated number of excess deaths becomes negative during that year. Consequently, we compared the demographic characteristics and the geographic location of the heat wave victims with those of the "missing" deaths for the entire year 2004 and chose not to concentrate only on the first half of 2004 up to the point when full compensation occurred.

Age and sex characteristics of the " missing" deaths of 2004

Figure 9 shows how deaths "missing" in 2004 are distributed by sex and age. It indicates that, for men, their number is way above that of the number of heat wave victims for every single year of age from about 17 to 88 and, for women, the gap is even larger, starting at 65. In other words, though the age and sex structure of the deaths "missing" in 2004 roughly mirror that of the heat wave related deaths, their absolute number is far higher than that of the August 2003 victims for each sex and for nearly all years of age. At this point, we cannot thus dismiss the possibility that the deaths "missing" in 2004 include all of the heat wave related deaths in addition to others, of unknown origin. To further investigate this issue, we thus analyzed the geographic correlation between excess mortality in August 2003 and deficits in mortality in the following months.

Figure 9. Distribution by sex and age of heat wave related deaths (August 2003) and of the missing 2004 deaths



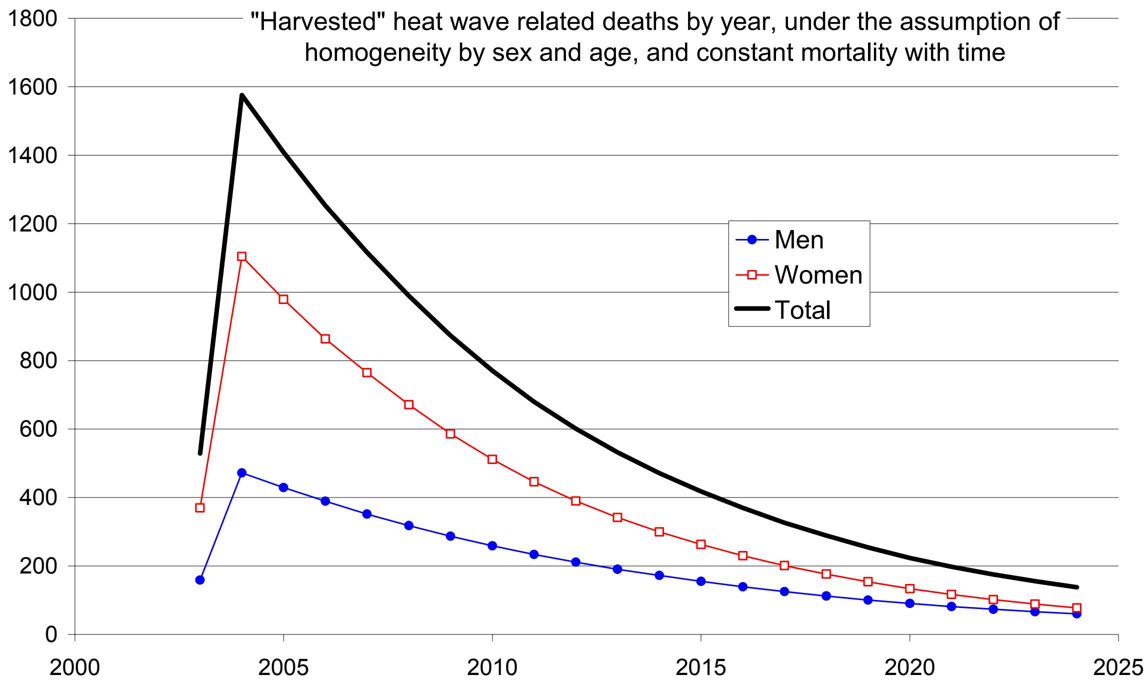
Note: Data by age have been smoothed with a moving average (coefficients 0.3-0.4-0.3)

The construction of a distribution by sex and year of age of the heat wave related victims let us estimate the number of years lost under our first hypothesis, that is assuming no frailty effect, i.e. those who died during the heat wave would have lived as long as those who did not in the same sex and age groups.

Number of years lost to the heat wave

The 15,000 persons who died because of the heat wave were older on average than others who died in 2003 independently from the heat wave: heat wave related deaths occurred at a mean age of 81.4 (75.6 for men and 84.6 for women), as against 76.2 (71.8 and 80.7 respectively) for all deaths in 2003. Would these 15,000 men and women have survived in the absence of a heat wave, we can estimate the occurrence of their deaths, under the assumption that they would have experienced the same probabilities of deaths as other people in the same sex- and age-group. Using the life table of 2000-2002 as an estimation of the probabilities of dying, the heat wave victims had a remaining life expectancy of 7.8 years (9.2 for men and 7.0 for women). Figure 10 shows how these deaths would have been distributed over the years following the heat wave, starting with the last four months of 2003 (September to December) and following with each successive 12 months period. Under the "no harvesting" hypothesis, 530 of the total 15,000 heat wave victims would have been expected to die in the period of September-December 2003 and 1,576 deaths during the year 2004, making up a total of 2,105 deaths. The jump in the curve corresponding to 2004 reflects the fact that many of the heat wave victims are found in the oldest age groups, in which the probability of dying within 12-15 months in the 2000-2002 life table is very high. However, if, as we defend, the low level of mortality in 2004 and 2005 is due to a permanent decline in the probabilities of deaths compared to the years before 2003, then applying the probabilities of death of the 2000-2002 life table over-estimates mortality during the following years. Taking into account the ongoing decline in mortality would have lead to a longer expectation of life for the heat wave victims and would have resulted in a lower jump for 2004 in Figure 10. Our estimated number of years of life lost to the heat wave should thus be regarded as standing at the low end and we can consider that a larger number of years of life were probably lost if we accept the no harvesting hypothesis.

Figure 10. Estimated number of deaths of Heat wave related victims had they not die during the heat wave, assuming homogeneity

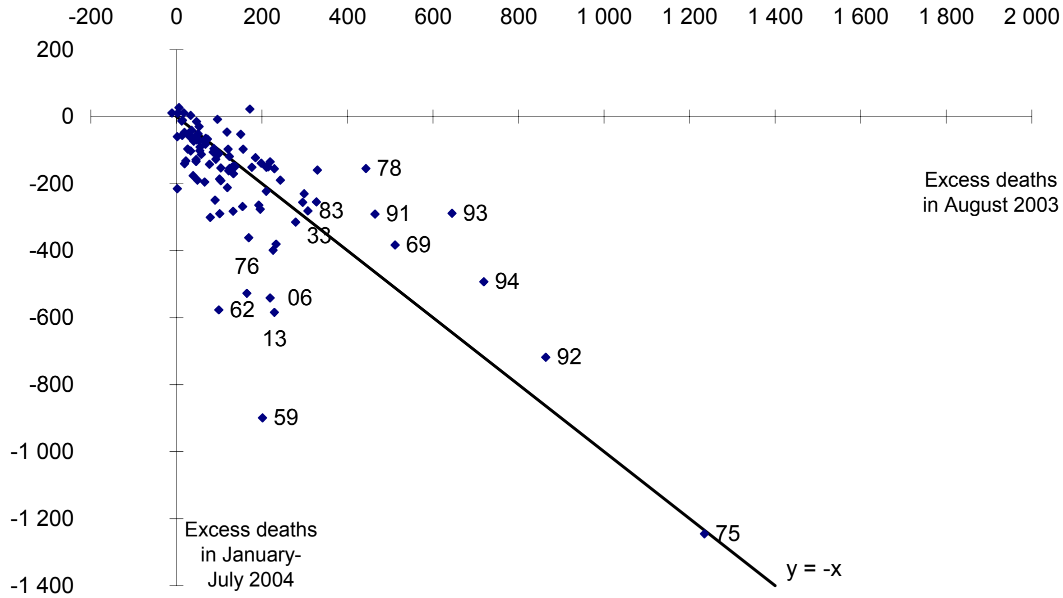


Investigating spatial correlations between excess and deficits in mortality

After estimating the number of excess deaths in August 2003 by *département*, we first compared it to the number of "missing" deaths from January through July 2004, the period at the end of which full compensation occurred at the national level.

In the *Île-de-France* region, corresponding to the larger Paris metropolitan area, *départements* with a large excess number of deaths also exhibited a large number of missing deaths during the first part of 2004 (Figure 11) so that the *départements* of the larger Paris area (75, 78, 91, 92, 93 and 94) fall near the line ($y = -x$). The city of Lyon (69) exhibits a similar pattern. However, no such systematic pattern is found for the other *départements* in which a dramatic decline in the number of deaths was also recorded during the first seven months of 2004. In Northern France (*départements* 59 and 62), in the South (13, 06) and in the West (76) (Map 2), the under-mortality of the first months of 2004 is much larger than the excess recorded in August 2003.

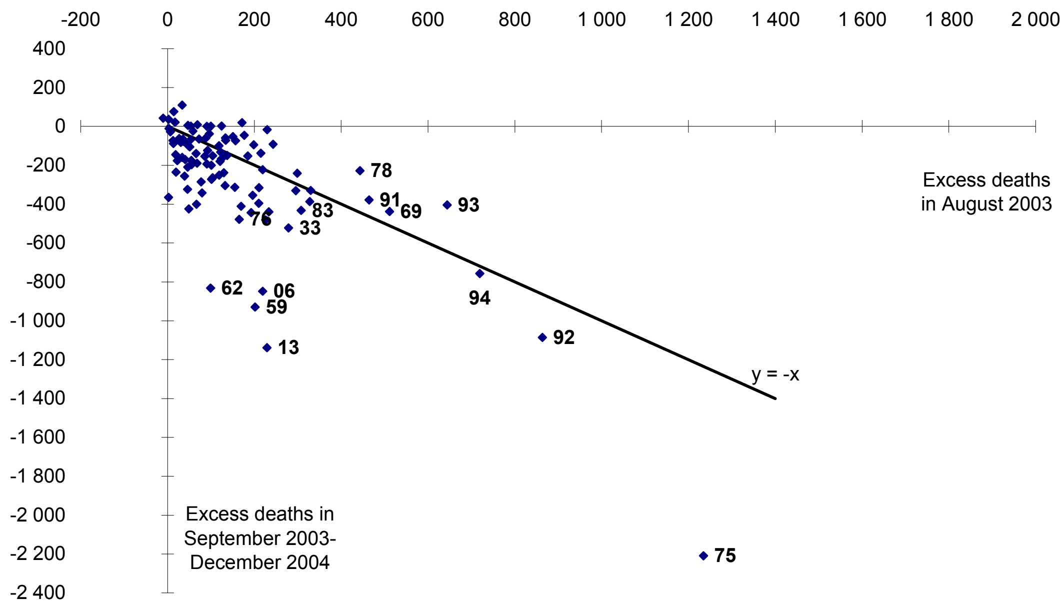
Figure 11. Joint graph of excess deaths in January to July 2004 (vertical axis) and excess deaths in August 2003 (horizontal axis), by *département*



Note: the line (y=-x) represents hypothetical full harvesting.

The negative correlation with August 2003 is weaker for the period September to December 2003, as well as for the period August 2004 to December 2004. Looking at the months from September 2003 to December 2004 as a whole, we obtain the following figure :

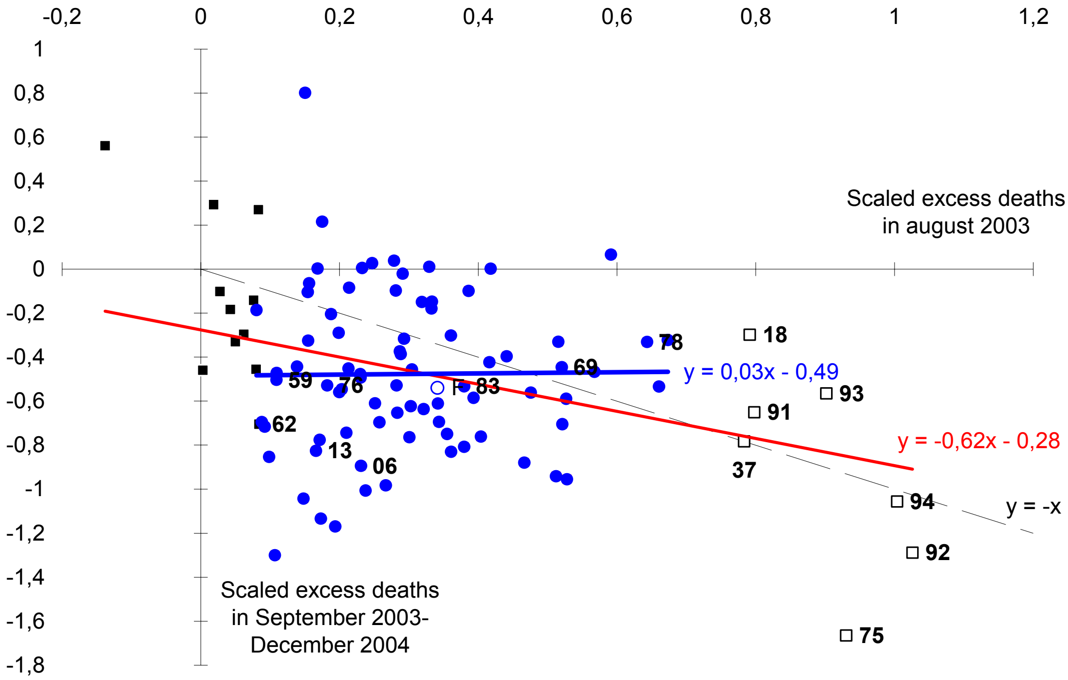
Figure 12. Joint graph of excess deaths in September 2003 to December 2004 (vertical axis) and excess deaths in August 2003 (horizontal axis), by *département*



The relation seems to be strong for the *départements* of Paris larger metropolitan area (78, 91, 92, 93, 94) and the city of Lyon (69). However, for the city of Paris (75), the decline in 2004 is much larger than the number of excess deaths in August 2003: 2,200 vs. 1,200. Again, the large deficit in the North (59, 62) and the South (13, 06) appears to be mostly unrelated to the small number of excess deaths during the heat wave.

In the previous two graphs, no account has been taken of possible size effects. Because those *départements* most affected by the mortality impact of the heat wave are also the most populated, the figures were adjusted by dividing them by the mean monthly number of deaths for each *département* during the period 2000-2002. This technique enables a direct comparison, for each *département*, of excess deaths during August 2003 and missing deaths during the subsequent months.

Figure 13. Joint graph of scaled* excess deaths in September 2003-December 2004 (vertical axis) and excess deaths in August 2003 (horizontal axis), by *département*.



* The difference between observed and expected deaths is standardised by the mean number of monthly deaths in 2000-2002. For each *département,* a deviation of +1 means that the number of excess deaths is equal to the average monthly number of deaths in 2000-2002.

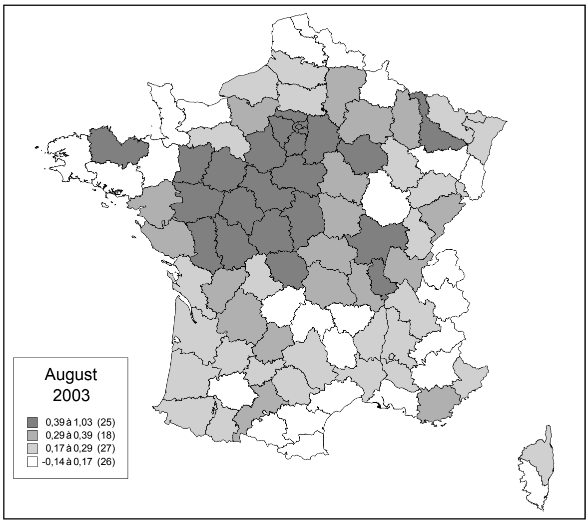
As showed on Figure 13, the relationship is slightly modified when *département* figures are thus adjusted. Two *départements* in the center of the country, i.e. *Indre-et-Loire* (37) and *Cher* (18), appear to have suffered a large excess number of deaths during the heat wave, which was not previously obvious because of their small population size. However, the overall picture is unchanged: the *départements* with the largest relative number of excess deaths remain those located in the larger Paris metropolitan area (75, 91, 92, 93, 94).

The following maps confirm that the correlation is weak. The map on the left hand side shows the number of deaths in August 2003 standardized by the mean monthly number of deaths in the three years 2000-2002. The right hand side map shows the difference between the number of deaths from January to July 2004, relative to the same reference monthly number of deaths during the years 2000-2002, plotted with an inverse scale to increase comparability: the two maps would overlap perfectly if the mortality deficit of early 2004 mirrored the excess of August 2003. This is obviously not happening: while excess mortality in August 2003 is highly concentrated in the centre of the country, under-mortality in 2004 is scattered all over the map, both phenomena appearing spatially unrelated.

Maps 3 and 4. Excess mortality during the heat wave of August 2003 and subsequent decrease in January to July 2004, by *département*

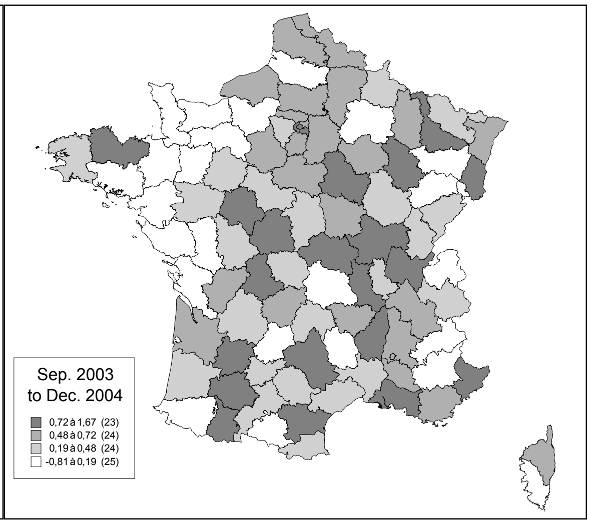
Map 3. Scaled excess mortality during August 2003

[D(8,2003) - D(8,base)] / D(base)



Map 4. Scaled missing deaths during September 2003 to December 2004 :

-[D(9,2003to12,2004)
-D(9to12,base)-D(1to12,base)] / D(base)



The regression line plotted on Figure 13 for the scaled numbers of deaths in all *départements* corresponds to the following equation:

$$y = -0.62\,x - 0.28$$

Applying the results of the equation to the excess deaths of August 2003 for all *départements*, we would attribute 9,300 of the about 25,500 "missing" deaths in 2004 to a harvesting effect. However, the regression fit is very poor and the relation seems to be limited to two very distinct groups of *départements*, namely those where relative excess mortality in August 2003 was greater than 70% and those which experienced no excess mortality in August 2003 (a less than 10% increase) nor a deficit in 2004. To improve the fit and narrow down the effect, we progressively restricted the number of *départements* included in the regression model. Starting with a model including all *départements* (model 1), we first excluded the one outlier *département* which recorded a smaller than expected number of deaths in August 2003 (model 2), then the seven *départements* with the largest relative excess mortality in August 2003 (model 3), then both the *département* excluded in model 2 and the *départements* excluded in model 3 (model 4) and, finally (model 5), all the *départements* in which relative excess mortality in August 2003 was either smaller (lower than 10 percent) or larger than average (70 percent and higher). The results are showed in Table 2 with one line per model. The first column refers to the *départements* included in the analysis, the second provides the regression equation, the remaining three columns indicate the number of deaths "missing" in 2004 due to a harvesting in August 2003 estimated from the equation. The numbers in column 3 simply result from a direct application of the equation to the number of heat wave victims and the number of deaths missing in 2004 in the *départements* defined in column 1. The second to last column shows the number of the deaths missing in 2004 due to a harvesting effect estimated from the equation for all *départements* described in the first column, to which are added the 4,500 heat wave victims of the seven most affected *départements* for which we are willing to accept full harvesting. For instance the 8,800 deaths of model 3 in column 4 result from adding the 4,300 harvested deaths estimated from the equation in column 2 to the 4,500 heat wave victims of the excluded seven *départements*. The numbers corresponding to the first two models are identical in column three and four because the 4,500 deaths are already included in the numbers in column 3. In column 5, instead of adding 4,500 deaths, we added 2,200 corresponding to what we estimated to be the "true" harvesting effect in those seven most affected *départements* as further discussed below (see Figure 18 and Table 3).

Table 2. Regression equations of scaled excess deaths in September 2003-December 2004 against excess deaths in August 2003, by *département*, with several sets of *départements*.

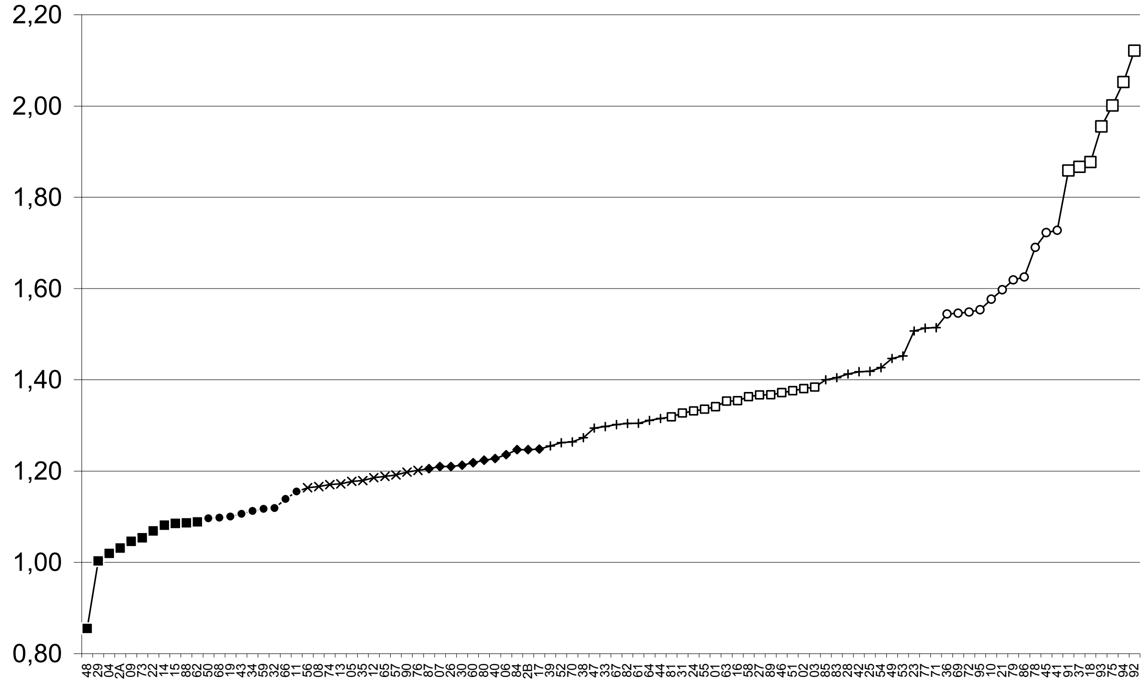
(1)	(2)	(3)	(4)	(5)
Set of *départements* used for the regression	Regression equation	Estimated harvesting		
		In the set	All (a)	All (b)
1. All *départements*	$y = -0.62\ x – 0.28$	9,300	9,300	9,300
2. All *départements* except one, which had less deaths than usual in August 2003	$Y = -0.54\ x – 0.31$	8,100	8,100	8,100
3. All *départements* except the the seven *départements* with the largest relative increase in deaths during August 2003	$Y = -0.41\ x – 0.33$	4,300	8,800	6,600
4. All *départements* except the one with less deaths than usual in August 2003 and the seven *départements* with the largest relative increase in deaths during August 2003	$y = -0.25\ x – 0.38$	2,625	7,125	4,925
5. All *départements* where the relative increase in deaths during August 2003 was largest than 10% and lower than 70%	$y = +0.03\ x – 0.49$	0	4,500	2,300

(a) Under the assumption that all 4,500 excess deaths during August 2003 in the first group of *départements* were leading to harvesting

(b) If only 2,200 of them may be attributed to harvesting, the other missing deaths being attributable to other factors (see Figure 18 and Table 3 below).

Excess relative mortality is largest for a group of seven *départements*, showed with white squares on Figure 13. These seven *départements* represent 60,000 annual deaths (2000-2002). For comparative purposes, we have first ranked all other *départements* according to the relative mortality impact of the August 2003 heat wave (Figure 14) and grouped them so that each group combines to the same overall number of annual deaths, i.e. about 60,000, as the first one. The number of groups of *départements* thus defined is nine.

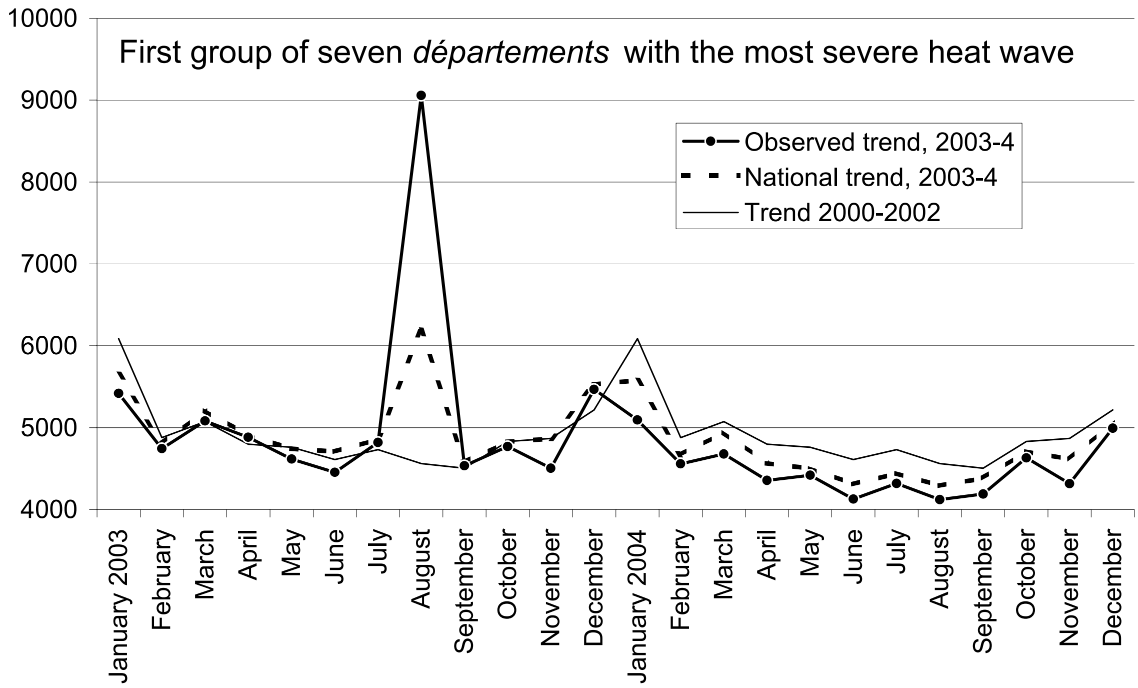
Figure 14. Excess mortality in August 2003, by *département*, relative to August 2000-2002 (O/E), sorted according to the severity of the mortality crisis



Figures 15 to 17 show the monthly trend in the number of deaths, for the first, second and eighth groups of *départements*. The thick dotted curve presents the actual number of deaths per month from January 2003 up to December 2004. The full thin curve shows the expected monthly number of deaths estimated from the average for the same months of 2000, 2001 and 2002 in the *départements* of the group under consideration. The dashed curve represents the estimated monthly number of deaths assuming that mortality trends were the same in the group under consideration as for mainland France as a whole, for each month in 2003-2004.It is computed as follows: for each month in 2003-2004, the observed monthly number of deaths in 2000-2002 in each *département* is multiplied by the ratio of deaths in that month for the country as a whole, to the mean number of deaths during the same months of 2000-2002. The dashed curve can also be interpreted as the number of deaths in each group of *départements* that would have been observed if the trend between 2000-2002 and 2003-2004 had been the same in all of the *départements*. The dashed curve is below the full thin curve for all months when, at the national level, mortality has been lower in 2003-2004 than in 2000-2002. The dotted curve is below the dashed curve in the *départements* where deficits in mortality are larger than at the national level.

For the first group of *départements* (Figure 15), the number of deaths nearly doubled in August 2003 with an excess 4,500 deaths, compared to 2000-2002. In addition, in this group of *départements*, a strong harvesting effect is possible: the deficit in 2004 is more pronounced that for the country as a whole as showed by the fact that the dotted curve is lower than the dashed one for nearly every month.

Figure 15. Monthly number of deaths, from January 2003 to December 2004.



This effect is not perceptible in any other group of *départements*. This is the case even for the second group which experienced quite a significant increase in mortality during the August 2003 crisis. In this second group of *départements, e*xcess mortality reached 60 percent, which represents a total of 3,400 excess deaths compared to 2000-2002, an effect nearly twice as large as that at the national level. However, even this group of *départements* does not exhibit a larger than average decline in the number of deaths in 2004 (Figure 16). The same lack of correlation holds for the other groups: in the sixth, seventh and eighth groups of *départements* (data for the eighth group are shown on Figure 17), where the number of excess deaths was much lower than for France as a whole in August 2003, the deficit in mortality observed in 2004 is as pronounced as elsewhere. It is only in the ninth group that the 2004 mortality deficit is significantly lower than average (not shown).

Figure 16. Monthly number of deaths, from January 2003 to December 2004.

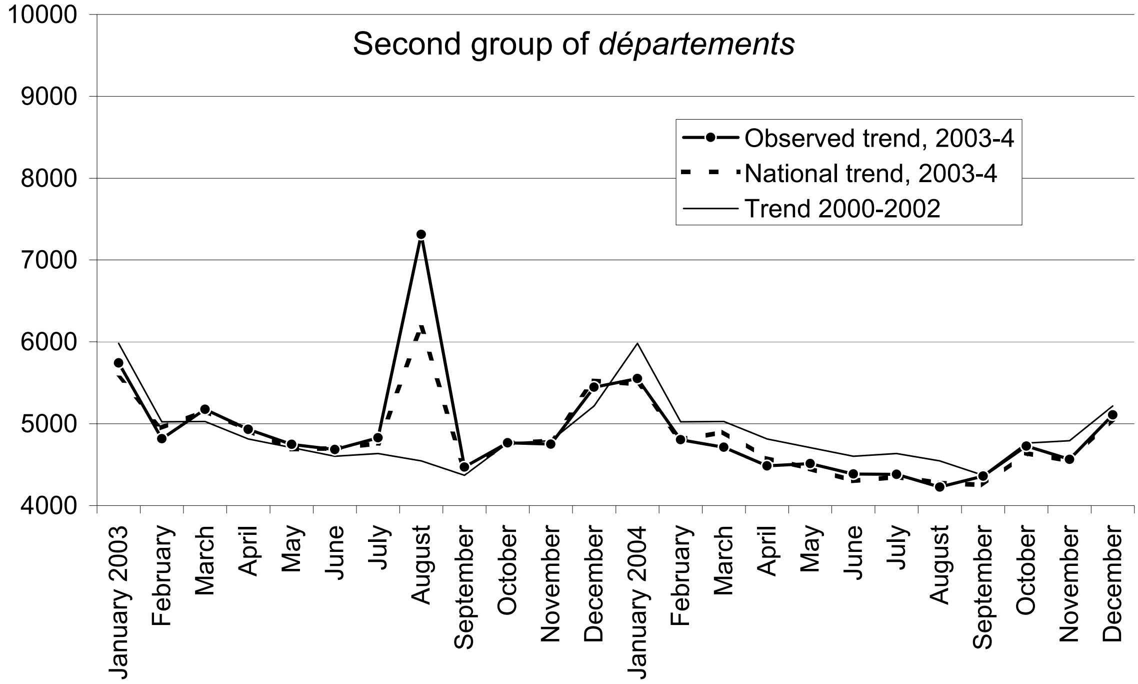
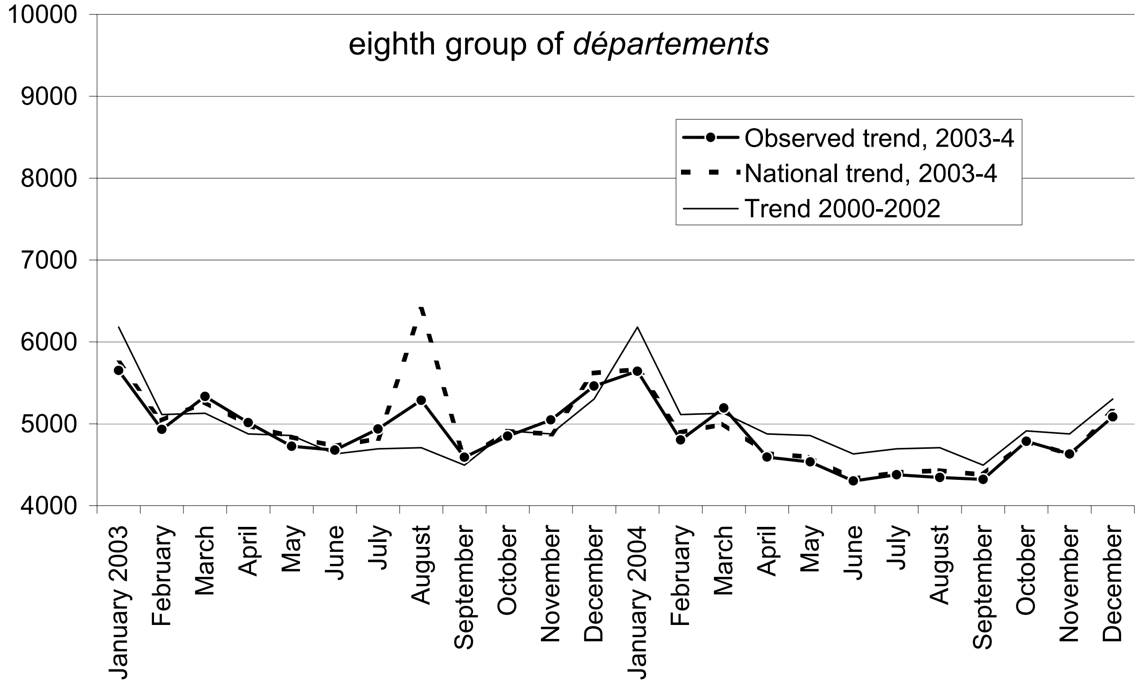


Figure 17. Monthly number of deaths, from January 2003 to December 2004.



If we exclude the two extreme groups of *départements*, i.e. the first one, where the heat wave had its largest impact and where we are willing to take a harvesting effect for granted, and the last one, in which there was no mortality increase in August 2003 and, hence, where we should not expect any harvesting effect, then the regression line no longer exhibits a negative relationship (Figure 13).

The relationship between the relative excess mortality in August 2003 and the deficit of the following months is thus restricted to a small number of *départements*. Going back to the absolute numbers of deaths, two regressions on all but the first group of *départements* and on all but the first and ninth groups of *départements* indicate that the decline of mortality at the national level may be responsible for 2,600 to 3,000 deaths averted in 2004 in each group of *départements*, irrespective of any excess deaths in August 2003 (Figure 18). The two corresponding equation lines lead to an estimated 2,600 to 3,200 missing deaths in the first group of *départements* due to the decline of mortality at the national level in 2004; the "harvesting effect" in the first group of *départements* is then estimated, by difference, to account for 1,900 to 2,500 "missing" deaths in 2004.

Figure 18. Relationship between the number of excess deaths in August 2003 (O-E) and the number of missing deaths in September 2003-December 2004, by group of *département* sorted by severity of heat wave mortality

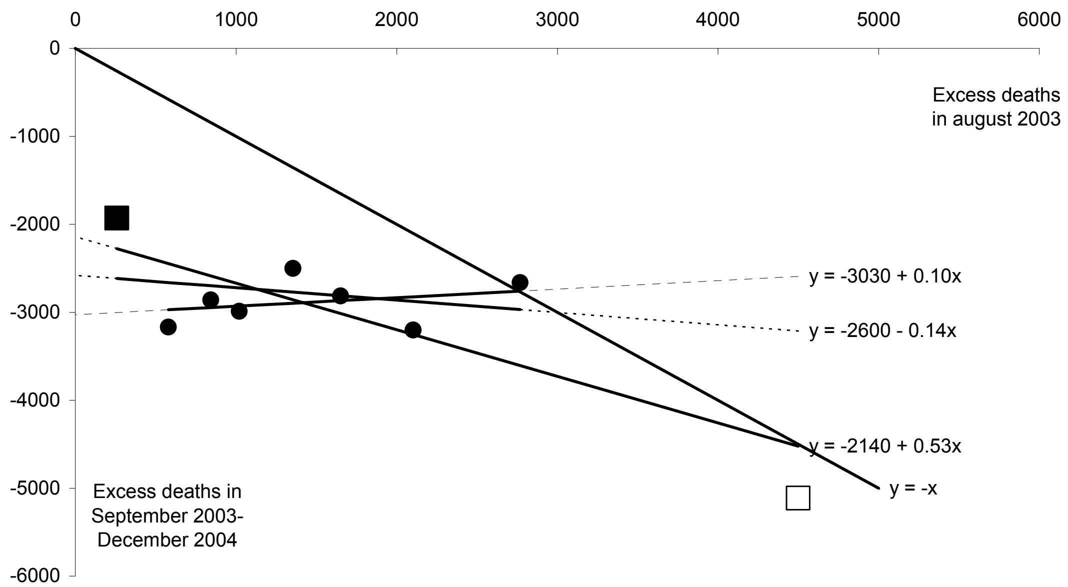


Table 3. Regression equations of excess deaths in September 2003-December 2004 against excess deaths in August 2003, by group of *département*, with several sets of *départements*.

(1)	(2)	(3)	(4)
Set of *départements* used for the regression	Regression equation	Estimated harvesting	
		In the set	All
1. All groups of *départements*	*y* = -0.53 *x* – 2,140	7,950	7,950
2. All *départements* except the first group	*Y* = -0.14 *x* – 2,580	1,470	3,770
3. All *départements* except the first and last groups	*Y* = +0.10 *x* – 3030	0	2,300

Using the second equation in Table 3, we may assume that, in each of the nine groups of *départements*, the following events occurred. First, a general decline in the level of mortality took place in 2004, leading to a deficit of 2,600 death in each group (23,400 deaths for the whole country); second, the jump (thereafter named "rebound") observed on Figure 10, corresponding to the 2,100 or so deaths that would have occurred among the heat wave victims in 2004 considering their age if they had not died during the heat wave, make up for about 14 percent of the total number of the heat wave victims. Third, in the first group of *départements*, in which the number of excess deaths during August 2003 has been the highest, a harvesting effect has likely occurred: the overall fall in mortality reaches 5,100 “missing deaths”, while the overall decline of 2,600 plus the “rebound” effect of 630 add up to 3,200, producing a difference of 1,900 additional “missing deaths” that could be attributable to harvesting.

In sum, we are willing to assume the possibility of a harvesting effect in the seven *départements* where the August 2003 mortality crisis was the most severe, considering the strong correlation found between the 2003 mortality excess and the 2004 mortality deficit in this first group. In these *départements*, excess mortality reached a total of 5,100 deaths, some 1,900 being attributable to a harvesting effect. In addition, we have estimated the number of heat wave victims who would have died in the period from September 2003 to December 2004 if they had not died during the heat wave, simply based on their sex and age among all 15,000 deaths of August 2003, in the absence of a harvesting effect (Figure 10). Because there is no statistical correlation between excess mortality in August 2003 and the deficit in 2004 in all other groups of *départements*, the remaining 2004 deficit in mortality cannot be accounted for by a harvesting effect in the rest of the country.

Investigating the impact on life expectancy

We successively estimated the impact of the heat wave on life expectancy in 2003, in 2004 and in 2005. For 2003, we first estimated the difference between the expectation of life for the year 2003 calculated from the observed deaths and that estimated from a projection of sex- and age-specific death probabilities based on 1997-1999 and 2000-2002 life tables, with a log-linear time trend. The result shows that while the expectation of life calculated for the year 2003 using the actual number of deaths reaches 75.80 for men and 82.88 for women, it would have been 76,05 and 83.18, a difference of 0.25 and 0.30 years, respectively, for men and women if the probabilities of death by sex and age in August 2003 had followed the log-linear trend from 1997-2002 for that month. The impact of the August 2003 mortality crisis on the expectation of life in 2004 is very simple under the no-harvesting hypothesis. Due to the heat wave, fewer people are alive at the beginning of 2004 and, consequently, fewer people are expected to die during the following 12 months. However, because those who died are supposed to have been randomly selected in each sex and age group, they would have had by definition the same probabilities of death at every age as those who survived, so that life expectancy would have been the same as that actually recorded for 2004.

We estimated the expected life expectancy in 2004 and 2005, in the absence of a harvesting effect, through a linear regression for years 1997-2002 (see figure FA2). This second method results in estimates very similar to our computations (life expectancy at birth of 75,98 and 83,17 for men and women respectively, as against 76,05 and 83,18), with a much simpler and more robust method*,* allowing us to use the most recent estimates, including provisional estimate of life expectancy at birth in 2005, to describe the trends following the 2003 heat wave crisis.

Assuming now that all of the heat wave victims would have died in 2004 in the absence of a hot weather episode (a complete harvesting effect), then two compensating phenomena would have occurred. The first is that the excess deaths at each age x (in 2003) lead to missing deaths at age $x+1$ (in 2004): a mirror effect takes place with a lag of one year of age, and the overall effect would be to increase life expectancy by a lower amount than it was depressed in 2003 since the older the deceased, the lower the impact on life expectancy at birth. The second phenomenon is that life expectancy is more sensitive to a decline in the number of births than to an excess of deaths. Some simulations (not shown) indicate that all in all the mirror effect should be nearly perfect: if N excess deaths at time t induce a decline in life expectancy of d years at t, equivalent missing N deaths at time $t+1$ (at ages lagged one) lead to an increase in life expectancy of d at $t+1$. In other words, life expectancy in 2004 would have been equal to the expected life expectancy estimated following our projection method accrued by the number of years lost in 2003 due to the heat wave, that is 0.18 year for men and 0.29 years for women (Table 4).

Actually, expectation of life at birth jumped to 76.40 years for men and to 83.60 years for women in 2004 according to the latest Insee estimates (Richet-Mastain, 2006), an excess of 0.5 year above an expected level that would continue the trend observed in the 1997-2002 period. This result indicates that the gain in 2004 is much larger than would have been expected even with the most extreme hypothesis of a complete harvesting effect from August 2003 to the end of 2004. In 2005 life expectancy did not increase compared to 2004, but still appears to be higher than expected with an additional 0.25 years for men and 0.31 years for women, compared to the projection based on the trends for the period 1997-2002. Even assuming full harvesting over the two years following the crisis, with two thirds of the excess deaths leading to missing deaths in 2004 and one third to missing deaths in 2005, the discrepancy remains for 2005.

These findings clearly show that the increase in life expectancy in 2004 and 2005, as compared to the trend in the previous years, may only very partly be attributed to a harvesting effect and could initiate a new mortality pattern, at a permanently lower level, though with only two years of observation, it is premature to conclude to a long term decline in mortality at this point.

Table 4. Estimated and observed life expectancy at birth by sex, in 2003 and 2004

	Women			Men		
	2003	2004	2005	2003	2004	2005
1. Observed life expectancy	82,88	83,77	83,77	75,80	76,65	76,70
2. Expected without heat wave	83,17	83,31	83,46	75,98	76,22	76,47
3. Impact of the heat wave	-0,29			-0,18		
4. Impact of harvesting on one year		0,29	0,00		0,18	0,00
5. Estimated with complete harvesting		83,60	83,46		76,40	76,47
6. Difference remaining (1.-5.)		0,17	0,31		0,25	0,24
7. Impact of harvesting on two years		0,19	0,10		0,12	0,06
8. Estimated with harvesting on 2 years		83,50	83,55		76,34	76,53
9. Difference remaining (1.-8.)		0,26	0,21		0,31	0,18
10. Hypothesis of no harvesting		0,00	0,00		0,00	0,00
11. Estimated without harvesting		83,31	83,46		76,22	76,47
12. Difference remaining (1.-11.)		0,46	0,31		0,43	0,24

Conclusion

The 15,000 victims of the August 2003 heat wave are disproportionately found among the elderly and, more specifically, among elderly women. Nevertheless, the expected number of years lost for those people is not negligible. Assuming no harvesting effect, only about 2,000 of them would have died due to their age by the end of 2004 without the heat wave. An hypothesis of full harvesting would imply that all 15,000 victims would have died by the end of 2004 in the absence of a heat wave. Among them, some would have been expected to die by the end of 2003. Since the number of deaths recorded in the period September 2003 to November 2003 does not exhibit any deviation from the pattern expected from the previous years, one would have to assume either no harvesting effect or a full compensation of the harvesting effect and a phenomenon of heat wave related delayed mortality. An analysis of the distribution by sex and single year of age of the heat wave victims in relation with the deaths missing for the following year shows a high correlation which could be used in favour of the harvesting effect, though further analysis at the level of the *departments* suggests otherwise.

Spatial analysis of mortality comparing the excess number of deaths in August 2003 and the deficit in the subsequent period at the level of the *départements* shows that complete harvesting is not likely: if we exclude the seven *départements* where the heat wave was the most deadly and were a strong harvesting effect might have occurred (thus representing a total of 1,900 deaths), almost no correlation is found between the high mortality of August 2003 and the low mortality of 2004 at the level of the *départements*. Consequently, only about 4,000 deaths missing in 2004 can be attributed to the effect of the heat wave, 2,100 of which would have occurred on the sole basis of the age and sex distribution of the victims and another 1,900 from the harvesting effect. The two effects thus account for about one sixth of the decline observed between the period prior to 2003 and the year 2004. This estimate is an approximation, but the order of magnitude must be accurate: the mortality deficit of 2004 directly attributable to the heat wave crisis represents less than even a third of the 15,000 excess deaths of August 2003 and according to our calculations, the remaining two thirds of the heat wave victims could have been expected to live for another 8 years.

The fact that the heat wave did not necessarily killed the frailest is partly documented by a study among elderly intensive care unit patients which shows that the more disabled actually fared better, in terms of survival, than others in the same hospital during the heat wave due to increased attention from medical staff (Holstein et al. 2006). Other studies support this finding (Le Tertre et al., 2006). More generally, people who died during the heat wave were often living alone (Hémon and Jougla 2003; Rey et al., 2005), a common finding about heat wave victims (Besancenot, 2002 ; Klinenberg, 2003). This implies that the victims were at least independent enough to live by themselves and suggests that they would have likely lived many years without the heat wave, thus considerably more than a few extra days, weeks or even months.

Regarding the remaining 21,000 or so deaths "missing" in 2004, several hypotheses can be formulated, largely unrelated to the 2003 heat wave. The most likely is the unusual absence of a flu epidemics which typically kills about 7,000 to 10,000 individuals over a single Winter. This absence of flu has been described by some as the direct consequence of the heat wave (Valleron 2004). Indeed, the age structure of the victims of flu epidemics resembles that of the heat wave victims. A harvesting effect is thus not to be completely excluded. However, we should then have found a significant negative spatial correlation at the level of the *départements* between the degree of excess mortality of August 2003 and that of December 2003 when the flu typically starts, which was not the case.

The increasing cost of alcohol and tobacco, as well as severe policy measures against driving under the influence of alcohol, may have avoided an additional 2,000 to 5,000 deaths (Nizard, personal communication). But considering the demographic profile of deaths due to related causes, it would mainly explain the mortality deficit among young adult males rather than among the elderly.

All in all, 6,000 to 10,000 "missing" deaths thus remain to be explained. One hypothesis is that a special effort has been directed towards isolated elderly people as an indirect consequence of the heat wave. Indeed, in many urban areas, a special census of isolated elderly was conducted as part of a plan to prevent any future such crisis in case of extreme weather episodes but also as part of the general effort to improve the conditions of life of the elderly. Since women in France are more often isolated at old ages than men (Désesquelles and Brouard, 2003), this effort could have led to a larger decline for older women in most *départements*, independently from the direct mortality impact of the 2003 heat wave, in perfect agreement with the observed trend. However, the absence of data by both *département* of residence and single year of age at this point precludes any further analysis in this direction. Whatever the results yield by such a study, our general conclusion of a weak harvesting effect would however remain unchanged. Indeed, if the prevention measures had been stronger in those *départements* most affected by the heat wave crisis, it would increase the spatial correlation found in Figure 13, thus resulting in an overestimation of harvesting in the most-severely hit *départements*. Whether the mortality deficit recorded in 2004 can be directly or undirectly related to the 2003 heat wave episode, it remains that, as suggested by the continuous trend in 2005, mortality seem to have reached a new low level compared to the trend observed prior to 2003 though we need more time to definitely accept this conclusion.

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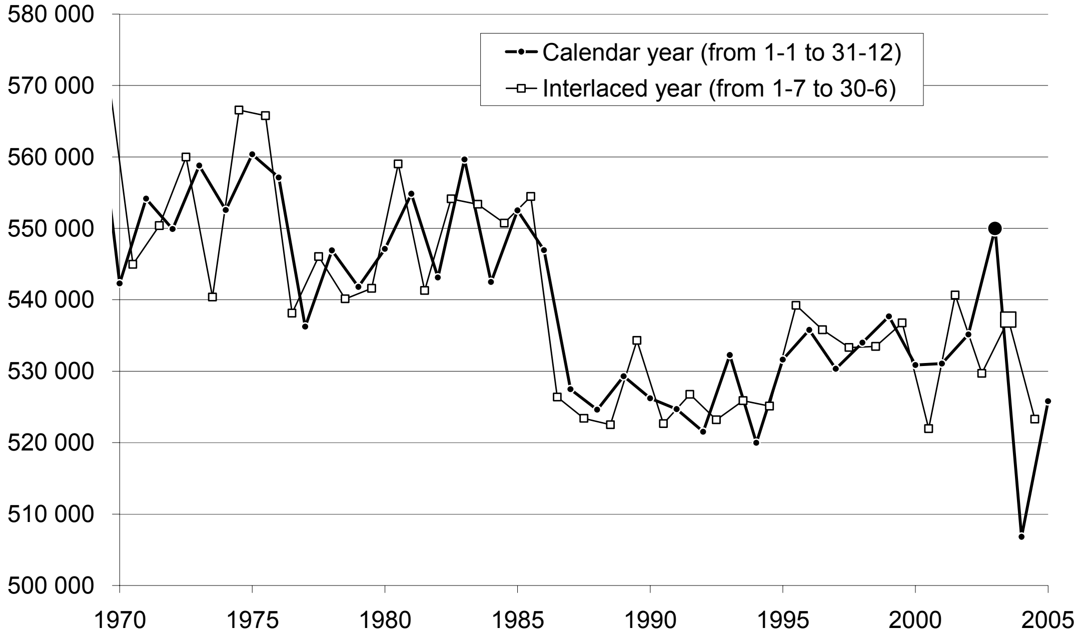
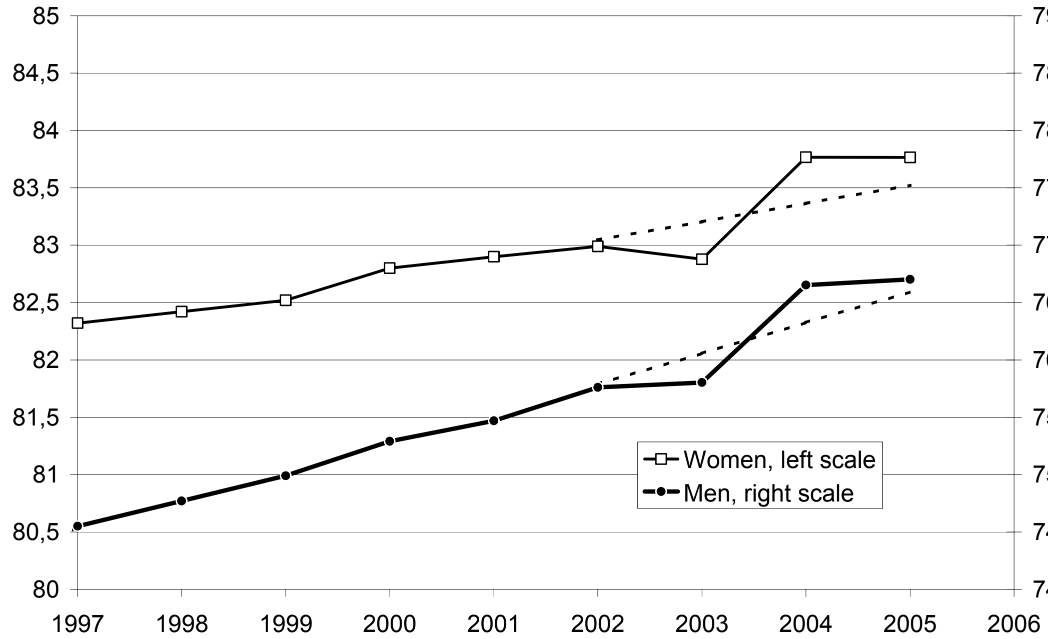
Appendix

F1A. Annual number of deaths. France 1970-2005. Calendar years, from 1st January to 31 December; Interlaced years, from 1st July to 30 June (next calendar year)



FA2 : data from Table 2. Life expectancy at birth, in years of age. Observed and expected from linear regressions based on years 1997-2002. Women on left scale, men on right scale



Source : Insee, monthly demographic database (Richet-Mastain 2006).