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Volcanic air pollution and mortality in France 1783–1784

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Abstract

The impact that volcanic eruptions may have upon environments far from the volcanic source is conventionally assumed to depend on climatic modification by emitted gases. However, recent research has suggested that the damage caused by the direct impact of volcanic gases, mainly H_2SO_4, may be profound. This paper highlights the severity of this mechanism by reference to human sickness and death in France and contiguous with the eruption of the Laki fissure in Iceland in 1783. This work demonstrates the gains which may be made by interdisciplinary teams of researchers and illustrates the valuable knowledge that remains to be revealed by further research in the French historical record. ***To cite this article: J. Grattan et al., C. R. Geoscience 337 (2005).***

Résumé

Pollution atmosphérique volcanique et mortalité en France de 1783–1784. Il est généralement admis que les gaz émis au cours d’éruptions volcaniques sont les principaux agents responsables de l’impact des éruptions sur de grandes distances, par leur action perturbatrice sur le climat. Cependant, des études récentes ont révélé la gravité des dommages provoqués par l’impact direct et local des gaz volcaniques, principalement sous forme de H_2SO_4. Cet article souligne l’importance de ce mécanisme, en se basant sur des données démographiques sur la mortalité et l’état de santé de la population française pendant l’éruption fissurale du Laki, qui eut lieu en 1783 en Islande. Ce travail démontre les avantages d’une approche interdisciplinaire en recherche et illustre la qualité et l’importance des informations préservées dans les archives historiques françaises, ressources encore largement inexploitées. ***Pour citer cet article : J. Grattan et al., C. R. Geoscience 337 (2005).***

Keywords: Volcanism; Laki; Atmospheric pollution; Sulphur; Mortality

Mots-clés : Volcanisme ; Laki ; Pollution atmosphérique ; Soufre ; Mortalité

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1. 1783 – Annus mirabilis

L’été 1783 fut caractérisé par des conditions climatiques extrêmes en Europe et l’hiver suivant fut l’un des plus sévères jamais observés en Europe et en Amérique du Nord. Le phénomène le plus étonnant de 1783 fut la persistance d’un brouillard étendu, sec et chargé en soufre. À l’époque, ce brouillard était communément attribué aux tremblements de terre en Calabre [7, 31], une autre explication populaire étant celle d’un fort taux d’évaporation du sol, supposément provoqué par l’été extrêmement chaud [21,25]. Le naturaliste français M. Mourgue de Montredon est considéré comme le premier, à l’extérieur de l’Islande, à avoir fait le lien entre le brouillard sec en Europe et l’activité volcanique du Laki, théorie qu’il exposa lors d’une conférence à l’Académie royale de Montpellier, le 7 août 1783 [22].

Des observations du brouillard sec sont conservées dans de nombreuses chroniques contemporaines, telles que des notes sur le temps, des journaux intimes, des publications scientifiques et des articles de journaux. Ces sources fournissent des informations directes et indépendantes sur les caractéristiques de la brume ainsi que sa répartition géographique, et ont été réunies pendant plus de 200 ans par de nombreux chercheurs (par exemple, [10,14,20,30,36] ; pour un compte rendu plus complet, voir [34]). Cet article se concentre sur les rapports effectués en France (Tableau 1). La Fig. 1 montre une carte de l’Europe avec les dates d’apparition du brouillard sec.

2. L’éruption de 1783–1784 du Laki et l’origine du brouillard sec

L’éruption fissurale du Laki de 1783 à 1784 en Islande rejeta environ 122 Tg de SO_2 dans l’atmosphère, maintenant un voile d’aérosol d’acide sulfurique (H_2SO_4) au-dessus de l’hémisphère nord pendant une durée minimale de cinq mois. Les panaches éruptifs engendrés au-dessus des fissures atteignirent 9 à 13 km d’altitude, et relâchèrent 95 Tg de SO_2 dans le courant polaire. Ceci engendra une dispersion vers l’est des émanations volcaniques qui, réagissant avec l’humidité atmosphérique, produisirent environ 180 Tg d’aérosols de H_2SO_4. Le reste du gaz (27 Tg) fut libéré au cours des écoulements de lave sur les terres du centre de l’Islande méridionale, ne participant pas de manière significative à la pollution atmosphérique engendrée par l’éruption.

Les trois premiers épisodes éruptifs relâchèrent plus de 40 Tg de SO_2 (capables de former jusqu’à 83 Tg d’aérosols de H_2SO_4) au cours des dix premiers jours de l’éruption. Trente-trois téragrammes de SO_2 (jusqu’à 67 Tg d’aérosols de H_2SO_4) furent injectés dans l’atmosphère lors des trois épisodes suivants. Ces émissions furent cependant réparties sur une période sensiblement plus longue, s’étalant du 26 juin au 30 juillet 1783.

Les dates d’apparition du brouillard sec et dense rapportées par les observateurs terrestres (voir Fig. 1) sont conformes au scénario décrit ci-dessus. Le brouillard se forma plusieurs jours après le début de l’éruption lorsque les systèmes de hautes pressions, provenant de l’est, abaissèrent les masses d’air contenant les aérosols [12]. Ceci explique que le brouillard soit apparu en France (possiblement dès le 10 juin, après le 14–16 juin de façon certaine) avant d’être rapporté en Angleterre (le 21 juin).

3. Le brouillard sec, la maladie et la mortalité

Les fortes concentrations de gaz et d’aérosol produites par l’éruption du Laki ont été désignées par des travaux précédents [16,17] comme étant les facteurs responsables les plus plausibles de la hausse prononcée de la mortalité en Angleterre pendant l’été 1783. Les modèles de circulation atmosphérique proposés pour cette période [20] suggèrent que le reste de l’Europe aurait dû être pareillement affecté par la dispersion des gaz. Il est certain que, si les taux de mortalité s’avèrent d’amplitude similaire en Angleterre et en France, ce phénomène pourrait constituer un risque environnemental majeur d’échelle continentale. Les archives suggèrent que l’effet du brouillard sur l’environnement fut plus sévère en France et en Hollande qu’en Angleterre (Tableau 2).

3.1. Mortalité en France en 1783–1784

Les données anglaises sur la mortalité sont fournies par le document *Population History of England Database* [24]. Les données démographiques françaises ne sont malheureusement pas compilées aussi commodément. Rabartin comble cette lacune grâce à l’aide volontaire d'étudiants de l'université du Temps libre, qui visitent les archives locales et regroupent ces données, là où elles existent. Ceci a affecté de manière inévitable la gamme temporelle et géographique des données, mais a permis la visite des archives départementales à travers tout le pays. Ces données, en nombre limité, doivent être interprétées avec prudence. Néanmoins, les données d'obsèques recueillies ici confirment les comptes reproduits dans le Tableau 2 : un grand nombre de personnes décédèrent pendant l'été et l'hiver de 1783–1784. Nous présentons ici les données relatives à trois régions, quatre paroisses du Loiret, 44 paroisses de Seine-Maritime, et cinq d'Eure-et-Loir. Nous incluons le comté de Bedfordshire en Angleterre, afin de permettre une comparaison avec les données anglaises (Fig. 2). La mortalité amorça une hausse en août 1783 et atteignit des proportions de crise en septembre et octobre, le taux restant au-dessus de la moyenne jusqu'en mai 1784. La période couverte par les données disponibles est trop courte pour permettre une analyse statistique ; cependant, la similitude entre les données françaises et du Bedfordshire est claire : il est certain que, dans les deux pays, le taux de mortalité était anormal et qu'un vecteur externe en était responsable.

Compilant les données d'obsèques des 53 paroisses présentées ici, nous pouvons déduire que le taux mensuel moyen de mortalité était de 232. Entre août et octobre 1783, 1128 obsèques ont été enregistrées ; 432 obsèques (38 %) au-dessus de la moyenne. Entre août 1783 et mai 1784, 3104 obsèques ont été enregistrées, soit 784 obsèques (25 %) au-dessus de la moyenne.

De manière générale, les crises de mortalité touchent plus particulièrement les personnes âgés, physiquement faibles ou malades. Par conséquent, la maladie ou les catastrophes environnementales peuvent entraîner le décès prématuré des personnes vulnérables. Ce phénomène est clairement perceptible dans les données de Seine-Maritime. Entre août et octobre 1783, 844 personnes moururent, soit 394 de plus que pendant la même période en 1782. En revanche, 443 personnes de moins moururent en 1784, pendant la même période. Si cette tendance, détectée jusqu'ici dans neuf départements, s'avère se répéter dans l'ensemble de la France, l'impact de l'éruption du Laki sur la population française pourrait s'élever bien au-dessus des 16 000 personnes qui périrent pendant l'été 2003, en raison de la pollution atmosphérique et des températures élevées.

Les données démographiques recueillies indiquent qu'une hausse anormale de la mortalité s'est produite en France et en Angleterre. Il est raisonnable de proposer qu'un vecteur commun ait engendré des conditions environnementales critiques dans ces pays : les gaz émis par la fissure du Laki.

4. Discussion

L'éruption fissurale du Laki a engendré une pollution atmosphérique d'échelle continentale, a eu un impact grave sur l'environnement européen et a provoqué des maladies, de manière tout a fait similaire aux conséquences attendues en cas d'accident polluant moderne. La réaction physiologique aux problèmes environnementaux varie selon la personne concernée, sa force physique et la durée de l'exposition. Les études actuelles sur les incidents anthropogènes de pollution de l'air au centre et à la périphérie des grandes villes suggèrent qu'en plus de toucher les groupes à problèmes respiratoires, ces accidents peuvent provoquer une hausse globale de la mortalité, étant donné que d'autres groupes, comme ceux présentant une maladie cardio-vasculaire, peuvent se révéler extrêmement vulnérables à ce type de pollution.

Dans cette période courte, des taux élevés de mortalité ont pu être observés à travers la France et l'Angleterre et avoir été également rapportés dans le Nord de la Hollande [39]. Il est clair qu'à bien des égards, les événements de 1783 sont typiques des accidents modernes de pollution atmosphérique. De plus, tous les diagnostics de maladie rapportés pendant les mois d'été de 1783 suggèrent une pollution d'origine atmosphérique. Nos connaissances actuelles sur les processus environnementaux actifs de l'époque ainsi que les données quantitatives et qualitatives disponibles désignent les émissions de gaz volcaniques acides comme l'agent principal des événements de 1783. La détermination de la cause de l'augmentation des décès pendant l'hiver nécessite une étude plus approfondie, ceci n'étant pas forcement lié à la pollution atmosphérique. Cependant, en se basant sur les commentaires reportés dans le Tableau 2, il est fort possible que les personnes tombées malades au cours de l'été soient restées extrêmement fragilisées, et donc particulièrement vulnérables aux conditions de l'hiver volcanique de 1783–

1784. Nous avons montré dans cet article qu'une crise notable de la mortalité en France a coïncidé avec une éruption volcanique d'amplitude importante, et nous avons présenté nombre d'arguments qui permettent d'établir un lien certain entre les deux événements. Afin d'établir de manière indiscutable cette relation, il serait nécessaire de compiler les données françaises de la mortalité sur une échelle nationale.

1. 1783 – The *Annus mirabilis*

The summer of 1783 was characterized by extreme and unusual weather in Europe and the following winter was one of the most severe on record in Europe and North America. 1783 has been referred to in Europe as *Annus mirabilis* (Year of Awe, or Wonders [26]) because of the coincidence of several large-scale natural disasters, and the extraordinary state of the atmosphere. In addition in 1783, Asama volcano in Japan erupted violently in July and a small eruption occurred at Vesuvius in August. However, the effects of these eruptions were inconsequential when compared to those produced by Laki gas and aerosols [40].

The most astonishing phenomenon of 1783 was the persistent and widespread sulphuric dry fog. The earthquakes in Calabria were a common contemporary explanation for the fog (7, 31). Another popular explanation was evaporation of fumes from the soil, supposedly caused by the extreme summer heats [21, 25]. Outside Iceland, the French naturalist M. Mourgue de Montredon is credited for being the first to tie the dry fog in Europe to volcanic activity in Iceland; he did so in a lecture at the Royal Academy of Montpellier, France on 7 August 1783 [22].

Observations of the dry fog were recorded in numerous contemporary chronicles such as weather logs, personal diaries, scientific publications, and newspaper articles. These valuable sources provide direct and independent information on the attributes and dispersal of the haze, and have been collated by many researchers over a period of more than 200 years [10, 12,20,30,36] (for a more complete account, see [34]). This paper concentrates on reports from France (Table 1) and Fig. 1 shows a map of Europe with the dates of the first arrival of the dry fog.

2. The 1783–1784 Laki eruption and the origin of the dry fog

The 1783–1784 Laki fissure-fed flood lava eruption in Iceland emitted about 122 Tg of SO_2 into the atmosphere and maintained a sulphuric acid (H_2SO_4) aerosol veil that hung over the Northern Hemisphere for at least five months. Eruption columns above the vents extended to 9–13 km and released 95 Tg of SO_2 into the polar jet stream, enforcing a net eastward dispersion of the plumes which reacted with atmospheric moisture to produce about 180 Tg of H_2SO_4 aerosols. The remainder of the gas (27 Tg) was released from the lava flows as they spread up to 70 km across central southern Iceland and probably did not significantly contribute to the widespread atmospheric pollution event caused by the eruption.

Over Europe, the Laki H_2SO_4 aerosols were delivered from the upper troposphere and lower stratosphere to the surface by subsiding air masses associated with anticyclones, causing an extensive dry fog or haze [5, 11,13,30,33,35]. About 175 Tg of the aerosols were removed as acid precipitation and caused the extreme volcanic dry fog that effected Europe in 1783 [9].

Most of the 122 Tg of SO_2 released by Laki was emitted into the atmosphere during the first five months of the eruption along with ∼7 Tg of chlorine and ∼15 Tg of fluorine [35]. Just over 80% of this volatile mass (98 Tg SO_2) was released at the vents and injected by the eruption columns up to lower stratospheric altitudes. This amount of SO_2 yields a theoretical sulphuric aerosol mass of 200 Tg, assuming a composition of 75 wt.% H_2SO_4 and 25 wt.% H_2O for the aerosols [32] and complete conversion of SO_2 to H_2SO_4 aerosols. The actual amount of aerosol formed may have been somewhat less due to dry deposition of some of the SO_2 [29].

The first three eruptive pulses released a total SO_2 mass loading of 40 Tg (capable of forming up to 83 Tg H_2SO_4 aerosols) over the first 10 days of the eruption. The next three pulses injected 33 Tg SO_2 (up to 67 Tg H_2SO_4 aerosols) into the atmosphere, but this loading was spread out over a significantly longer time period, from 26 June to 30 July.

Contemporary observations and model calculations indicate that the eruption columns of gas and ash above the fire fountains reached heights over 13 km above the vents during the early phases and that

Table 1
Selected reports of the first occurrence and appearance of the haze (dry fog) in France from the Laki eruption, which began on 8 June 1783 (after [34], and references therein)

Tableau 1
Sélection de rapports sur la première apparition de brume (brouillard sec) en France à partir de l'éruption du Laki qui a commencé le 8 juin 1783 (selon [34] et les références qui y sont incluses)

Saint-Quentin, France (49°50′N, 3°15′E)	10–18 June	The people of our countryside, far from being scared by the fogs that have persisted for about six weeks (letter dated 21 July, 178), give thanks to the Divine Providence that these fogs while stopping some of the sun's rays have prevented the heat from increasing which would have been hard to bear.
Dijon, France (47°20′N, 5°E)	14 June	A singular haze or fog, by no means a common occurrence, was reported here in June. This unusual haze was seen here little before midday on 14 June.
Le Havre, France (49°40′N, 0°5′E)	18 June	On 18 June, after some fogs that were interrupted by rains, there followed a permanent fog until 1 August. It was not very thick: one could see up to a league and a half away. But it must have reached high into the upper atmosphere, because at noon the light reflected by white objects had a light tint such as the colour of a dry leaf. Also since we could look at this star (the sun) without getting blinded two hours before sunset, as it was then red as if we were seeing it through a smoked glass.
Paris, France (48°50′N, 2°15′E)	18 June	According to de Lamanon (1783), the haze first appeared in Paris on 18 June.
La Rochelle, France (46°10′N, ∼1°W)	18 June	The rising sun was red, without any shine and seen this way until 6 a.m. After that the haze appeared to fade away, such that the sky appeared clear at 2 p.m. but the sun bright red. Some time before sunset the haze enveloped us again. In addition, occurrence of 'dry fog' is noted on the evenings of 6 and 7 June. These occurrences may be related to the eruption at the Grímsvötn volcano in May 1783.
Provence, France (43°40′N, ∼5°E)	18 June	Since the 18th, a singular fog, such as the oldest men here have before not seen, has reigned in most parts of Provence. The atmosphere is filled with it; and the sun, although extremely hot, is not sufficiently so to dissipate it. It continues day and night, though not equally thick, because sometimes it clouds the neighbouring mountains. The haze appeared concurrently at locations separated by great distances; in Paris, Salon, Turin, and Padua the haze also first appeared on 18 June.
Grenoble, France (45°15′N, ∼5°50′E)	21 June	As reported in the newspaper *Affiches de Dauphiné*.

columns more than 10 km high were maintained for the first three months [27,28,33,38]. Consequently, the Laki eruption columns reached well into the westerly jet stream which dominates the atmospheric circulation above Iceland at the tropopause level, which is 8–9 km in summer [18].

The dates of arrival of the dense dry fog to observers on the ground (Fig. 1) are consistent with the scenario above. It started when high pressure systems moving initially from the east pulled down air masses containing the aerosols [12] several days after the start of the eruption. This explains the arrival in France (questionably as early as the 10th, but certainly by the 14–16 June) *before* it was first reported in England (21 June).

3. The dry fog, human illness and mortality

Previous work [16,17], has suggested that the concentrations of gases and aerosols derived from the Laki fissure eruption, were the most probable cause of a

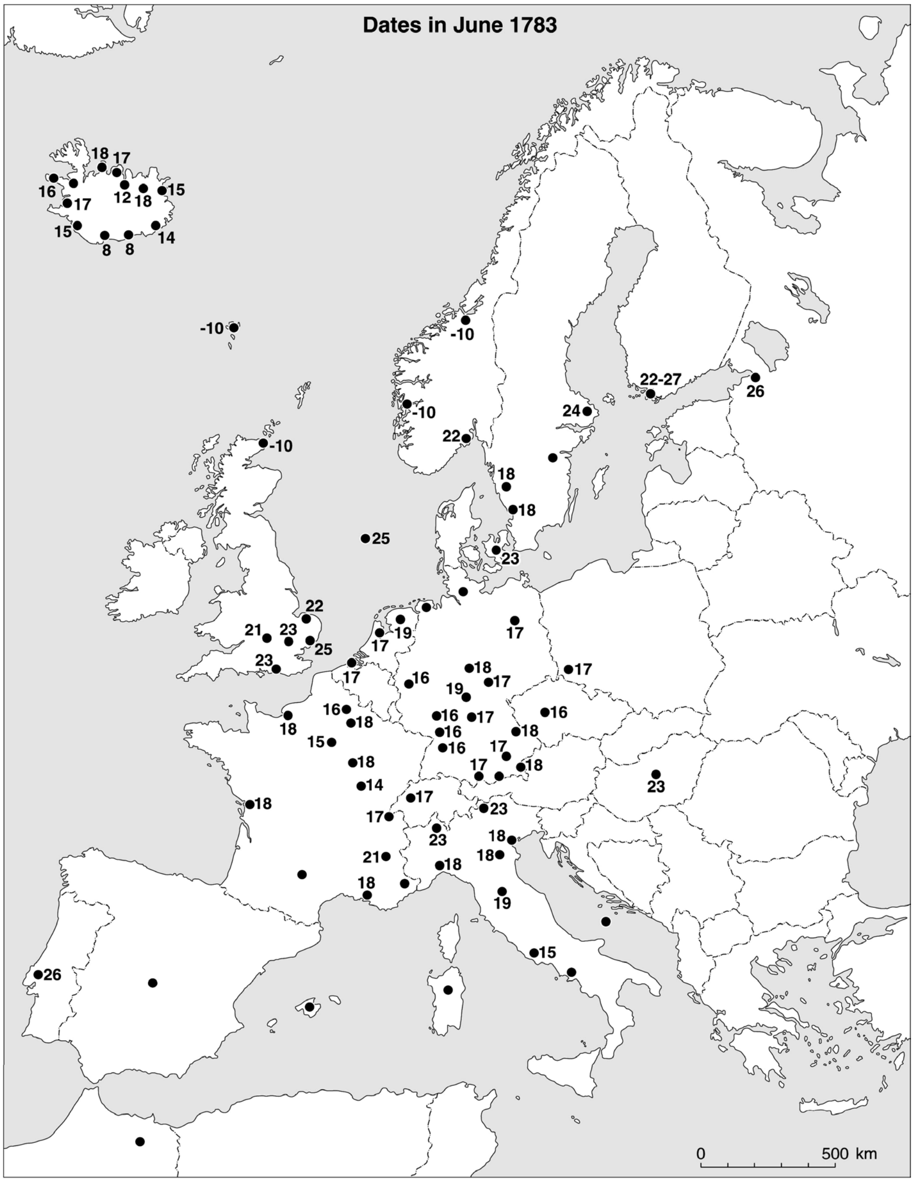

Fig. 1. Dates in June 1783 and sites of reports of first appearance in Europe of Laki dry fog. Dots show location of observation; numbers are date of observation; dots without numbers indicate observation sites where date of observation was not specified. Adapted from [34].

Fig. 1. Dates de juin 1783 et sites des rapports relatant la première apparition en Europe du brouillard sec de Laki. Les points montrent la localisation des observations ; les nombres représentent la date d'observation ; les points sans aucun chiffre indiquent des sites d'observation où la date d'observation n'est pas spécifiée. Adapté de [34].

pronounced mortality crisis in England in the summer of 1783, where mortality was greater than 10% in excess of the moving 51-year mean and over 10 000 more people died than would have been expected in a normal year. The atmospheric circulation patterns of the period [20] would have ensured that the rest of Europe ought to have been similarly affected. Certainly, if mortality patterns in England and France are similar, it could point to the operation of an overarching environmental vector, perhaps on a continental scale.

Table 2
A selection of correspondence linking the dry fogs to ill health and death

Tableau 2
Sélection de correspondances entre les brouillards secs et mauvaise santé et mort

Curé of Broué [23]	Pendant cette obscurité du soleil, on n'entendait que maladie et morts très innombrables. While the sun was obscured there was a sickness which caused innumerable deaths.
Curé of Landelles [23]	Les brouillards ont été suivis de grands orages et de maladies qui ont mis au tombeau le tiers des hommes dans plusieurs paroisses. The fogs have been followed by great storms and sicknesses which have driven a third of the men in many parishes to their tombs.
Curé of Umpeau [23]	Au commencement de ce dégel, la paroisse de Champseru a été affligée d'une maladie pestilentielle ; les malades se sentaient pris a la gorge, quelques ignorants de chirurgiens ont commencé par la saignée et l'émétique ; depuis dix-sept jours, en voilà quatorze mors sur dix-huit. On prétend que les brouillards de mai, juin, juillet et août, qui offusquèrent le soleil qui paraissait rouge comme du sang, nous pronostiquaient ce fléau. Dieu en préserve ma paroisse ! Until the beginning of the thaw the parish of Champseru has been afflicted by a pestilential sickness. Patients were afflicted by a sickness of the throat. Many ignorant doctors treated it it by bleeding and applying emetics and after 18 days there were 40 dead. One pretends that the fogs of May, June, July and August that offended the sun and turned it red as blood forecast this curse. May God preserve my parish.
Swinden [31]	Ces gens avec les coffres faibles ont éprouvé une sensation semblable à cela éprouvée une fois exposés brûlant au soufre. Those people with weak chests experienced a similar sensation to that experienced when exposed to burning sulphur.
Brugmans [31]	Plusieurs personnes ont éprouvé le 24 après midi à l'air libre une pression incommode, mal de tête, une difficulté dans la respiration exactement semblable à celle qu'on éprouve quand on hume l'air imprégné d'une vapeur de soufre brûlant, les asthmatiques ont éprouvé des récidives. After the 24th, many people in the open air experienced an uncomfortable pressure, headaches and experienced a difficulty breathing exactly like that encountered when the air is full of burning sulphur, asthmatics suffered to an even greater degree.

The documentary record of the environmental impacts of the dry fog in France and the Low Countries suggest that they were worse than in England; powerful descriptions of air pollution induced illness and death come from France and the Netherlands (Table 2). The symptoms described all conform to those of modern air pollution incidents and suggest concentrations of sulphur in the air in excess of thresholds for human illness [1,37].

3.1. *Mortality in France in 1783–1784*

English mortality data is available from the *Population History of England Database* [24], but French demographic data is not so conveniently compiled. Rabartin is filling this gap with the voluntary assistance of students of the 'Université du Temps libre', who are visiting local archives and compiling these data where they exist. This has inevitably affected the temporal and geographical range of the data, but has ensured that departmental archives have been visited across the country. This limited data set does need to be interpreted with caution. Nevertheless, the burial data gathered to date confirm the accounts reproduced in Table 2, people were dying in great numbers in the summer and winter of 1783–1784. Here we present an outline of these data from three regions, four parishes from the Loiret, 44 parishes from Seine-Maritime and five parishes from Eure-et-Loir, and to enable a comparison with English data we include the county of Bedfordshire in England (Fig. 2). The mortality crisis began in August and reached crisis proportions in September and October and remained above average until May 1784. The timing of the mortality alone indicates the anomalous nature of the mortality crisis. Summer mortality in rural France in the Late Eighteenth century was normally at its lowest [2, (fig. 79)]. Statistical analysis of the French burial data presented here is precluded by the brief period of data currently available. However, the similarity between the French

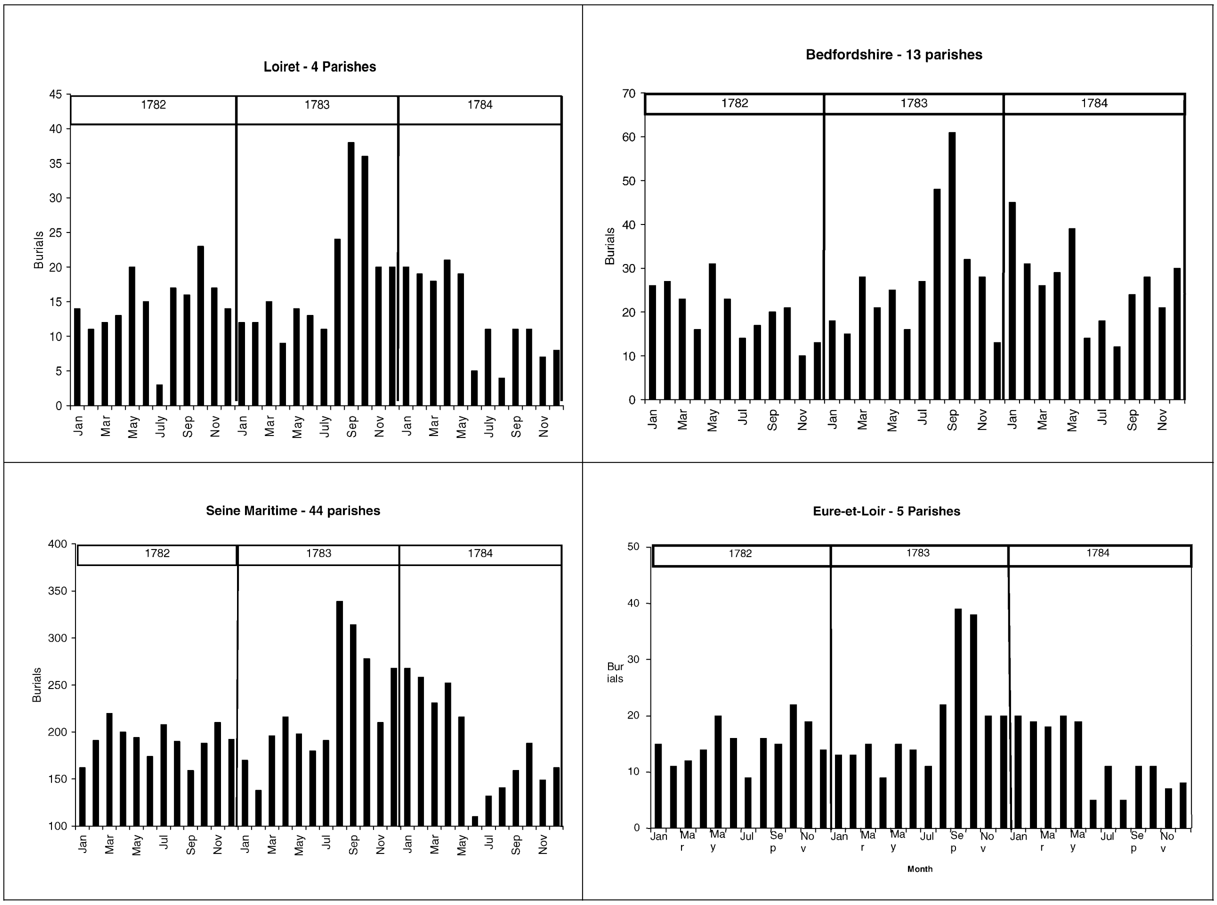

Fig. 2. Mortality patterns in French and British regions, 1782–1784.

Fig. 2. Diagramme de mortalité dans les régions françaises et anglaise pendant la période 1782–1784.

data and the data from Bedfordshire is clear and there are no grounds for rejecting the hypothesis that mortality in both countries was anomalously high and that an external vector was responsible.

Compiling the burial data from the 53 parishes presented here, we can see that monthly average mortality was 232. Between August–October 1783, 1128 burials were recorded, 432 burials, 38%, above the average. Between August 1783 and May 1784, 3104 burials were recorded, 784 burials, 25%, above the average.

Mortality crises typically cull the old, the weak and the sick from a population. Hence disease or environmental stress may result in the earlier deaths of vulnerable people. This phenomenon can be seen very clearly in the data from Seine-Maritime. Between August and October 1783, 844 people died, which is 394 more than occurred over the same period in 1782, conversely 443 less people died over the same period of 1784, they had died a year earlier! Fig. 3 presents the compiled data from the 53 parishes sampled. This data set confirms the trends established above, a substantial increase in mortality began in August 1783 and continued to October 1783; during this period 2366 people died, 1482 more than during the same period in 1782. If this pattern of mortality, detected so far in nine departments, is found to be repeated throughout France then Laki’s death toll in France may be far in excess of the 16 000 people who perished as a result of air pollution and high temperatures in 2003. There was certainly an increase in the ratio of deaths to births in the period 1780–1784 [4], which may reflect these stresses. These observations were broadly

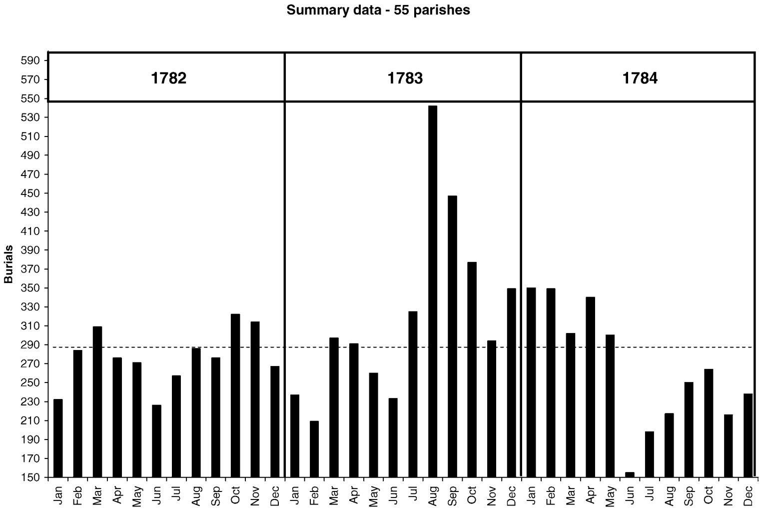

Fig. 3. Compiled data from 53 parishes in France. Dotted line = three-year monthly average: 287.

Fig. 3. Compilation des données de 53 paroisses en France. La ligne pointillée correspond à une moyenne mensuelle sur trois ans : 287.

confirmed by Biraben et al. [3, (fig. 36)], who noted an increase in deaths per 1000 inhabitants from 34 in 1778 to 37 in 1783. Indices of the annual French burial rate 1550–1790 suggest that the year 1783 was the seventh highest in that period [3, (fig. 35)]. Careful analysis of national mortality trends and a wider analysis of regional trends will be necessary before the scale and geographical extent of the mortality event can be fully assessed.

The data indicate that the anomalous mortality occurred across France and England; for such an event to occur it is reasonable to propose that a common vector was causing environmental stress in all these places, the gases from the Laki fissure.

4. Discussion

The events in France during the summer of 1783 appear typical of modern studies of air pollution that establish a link between air pollution, the ambient environment and mortality. The Laki fissure eruption generated air pollution on a continental scale, which had a severe impact upon the European environment, and induced a range of illnesses that we might expect to see during any modern air pollution incident. Physiological reaction to environmental stress varies according to both an individual's sensitivity and the strength and duration of exposure. Modern studies of anthropogenic air pollution incidents in and around major cities suggest that in addition to groups with respiratory disorders, death rates may rise as other vulnerable groups, such as those afflicted with cardio-vascular disease, are also physiologically stressed. Concentrations of SO_2 within the dry fog clearly passed critical thresholds for human health on many occasions and were responsible for severe respiratory dysfunction in many people and concentrations of SO_2 may have reached 1000 $\mu g\,m^{-3}$ for long periods of time [8]. The summer of 1783 is also associated with very high surface air temperatures, it has been suggested that the concentration of volcanic aerosols in the boundary layer of the atmosphere may have been responsible for this, but the precise mechanism responsible is not yet known [6,14,15]. These high temperatures can only have added to the physiological stress experienced in the summer of 1783. It is clear that in many respects the events of 1783 are typical of modern severe air pollution events, in addition all the contemporary accounts of illness reported in the summer months of 1783 point to air pollution. In the context of the environmental variables which may have been present in 1783, high concentrations of sulphur dioxide and high surface air temperatures, it is interesting to note in particular the work of Katsouyanni et al. [19]. This study, based on deaths reported in Athens over seven years, reported an extra 40 deaths per day when high air temperatures and air pollution acted in combination. Therefore, in many respects, the events of the summer of 1783 conform to the patterns established by the study of modern events of shorter duration.

In this short period, high rates of mortality may be observed across France and England and have also been reported in northern Holland [39]. It is clear that, in many respects, the events of 1783 are typical of modern severe air pollution events; in addition, all the contemporary accounts of illness reported in the summer months of 1783 point to air pollution. Uncertainty does surround the time lag in the data. Modern events impact upon mortality very quickly, whereas in 1783 the excess deaths occur over a much longer period. It may be that in modern events precursor conditions are worse and human sensitivity greater than in 1783, but this will necessarily be the focus of further research. However, our current knowledge of the environmental processes active at this time and the abundant qualitative and quantitative data available suggests acid volcanic gases were the key agent in the events of 1783. The excess deaths which occur in the winter may not have been directly caused by air pollution and require further study; however, a plausible hypothesis based on the comments recorded in Table 2, may be that people who were made ill in the summer remained ill and vulnerable through the notably cold volcanically induced winter of 1783–1784. This paper has demonstrated that a notable mortality crisis in France coincided with a major volcanic eruption, and established that reasonable grounds exist to associate the two events with some confidence. To resolve this question further data at both the national and regional scale must be compiled.

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