VOLCANIC DRY FOGS, CLIMATE COOLING, AND PLAGUE PANDEMICS IN EUROPE AND THE MIDDLE EAST

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Abstract. Dry fogs spawned by large volcanic eruptions cool the climate by partially blocking incident sunlight and perturbing atmospheric circulation patterns. The climatic and epidemiological consequences of seven intense volcanic dry fogs of the past 21 centuries, detected in Europe and the Middle East, are investigated by using historical reports, supplemented by tree-ring data and polar-ice acidity measurements. The signal-to-noise ratio in the historical data is very high. In four cases, the first winter following the eruption was exceptionally cold. The eruptions preceding these frigid first winters are known, or strongly suspected, to have occurred at high northern latitudes. Two of the other dry fogs are linked unambiguously to tropical eruptions, after each of which the first winter was comparatively mild. The following few years tended to be cooler on the average in all six of the instances that can be checked. Famine and disease pandemics ensued, with the epidemics in all cases reaching the Mediterranean area within 1 to 5 years after the eruptions. In at least five cases, the contagion responsible for the mass mortality was probably plague.

1. Introduction

Benjamin Franklin's (1785) famous conjecture that volcanic eruptions might be able to temporarily cool the climate is to some extent supported by anecdotal evidence and by statistical compositing analyses for known volcanic eruptions of the past two centuries. Northern Hemisphere mean surface air temperatures apparently dropped several tenths °C for up to 5 years after the largest 19th and 20th century volcanic eruptions (Rampino et al., 1988; Angell, 1988; Bradley, 1988; Mass and Portman, 1989; Robock and Mao, 1995; Hansen et al., 1996; Kelly et al., 1996; Parker et al., 1996). On a closer examination, however, there appears to be strong regional and seasonal variability of the volcanic temperature signal. Continents may be warmer (compared to ordinary winters) during the first winter following most large eruptions, before the main cooling trend begins (Bradley, 1988; Robock and Mao, 1995; Kirchner and Graf, 1995; Kelly et al., 1996). This intriguing question remains open, though, for several reasons: El Niño-Southern Oscillation warming effects and other sources of natural variability still confuse the issue, the latitude of the volcanic eruption is an important factor, and regional temperatures are difficult to predict accurately with present general circulation models. Another unanswered question is whether a severe, volcanically-induced cooling of the climate always leads to widespread crop failure and epidemic disease. This

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little-studied problem has focused almost entirely on the great Tambora, Indonesia, eruption in 1815, but, as the discussion below shows, Tambora is in some ways special and therefore its circumstances cannot be immediately generalized.

By historic standards, the eruptions of the past two centuries (except for Tambora) were not enormous producers of stratospheric aerosols, which are believed to cool the climate by reflecting back some of the incident solar radiation and by changing atmospheric circulation patterns. Furthermore, the biggest of these relatively recent eruptions sampled only tropical latitudes. The present paper lays out a comparison of the climatic and epidemiological consequences of seven (including Tambora) huge aerosol events, detected by means of dry fogs in Europe and the Middle East during the past 21 centuries. At least three of these eruptions were extratropical, and all seven created aerosol optical depths over Eurasia that were equal to, or in some cases as much as twice, the size of Tambora's. Since the conclusions reached here depend on making various temporal correlations and then a synthesis, the present approach is a very broadbrush one, and the arguments are inevitably probabilistic, even though they are, we believe, physically well justified.

2. Magnitudes of the Eruptions

The seven major eruptive events are listed in Table I, which briefly summarizes their main characteristics and the proposed associated phenomena. Documentation of the historical details and dates has been, or in one case soon will be, presented for all these events: AD 1815 (Post, 1977; Stothers, 1984a; Harington, 1992), AD 1783 (Wood, 1992; Fiacco et al., 1994; Stothers, 1996), AD 1258 (Stothers, 1999), AD 934 (Stothers, 1998), AD 626 (Stothers and Rampino, 1983a), AD 536 (Stothers, 1984b; Rampino et al., 1988), and 44 BC (Stothers and Rampino, 1983a; Rampino et al., 1988). Only the epidemiological information and some of the eruptive locations require additional documentation, as provided below. Contemporary dry fog and climatic information also is available for North America and the Far East in the case of the AD 1815 and AD 1783 eruptions (see the above references), and for northern China in the case of the eruptions of AD 536 (Pang and Chou, 1985) and 44 BC (Pang et al., 1986; Pang, 1991a). All the searches in the relevant European and Middle Eastern (but not Arabic) literature for the ancient and medieval periods were carried out by the present author, resulting in a relatively homogeneous database.

Dry fogs of volcanic origin are composed of aerosols consisting largely of sulfuric acid nuclei in a water solution. These aerosol veils become widely dispersed by vigorous tropospheric and stratospheric winds, with the result that some of the aerosols fall out over polar regions. All seven dry fogs in Table I have been correlated with unmistakable acidic layers in several deep Greenland ice cores (Hammer et al., 1980; Stothers and Rampino, 1983b; Zielinski, 1995). By using acidity measurements in both Greenland and Antarctic ice cores, as well as contemporary

TABLE I

Great dry fogs and associated phenomena in Europe and the Middle East due to volcanic eruptions

Phenomenon	AD 1815	AD 1783	AD 1258	AD 934	AD 626	AD 536	44 BC
Volcanic eruption	Tambora	Laki	El Chichón?	Eldgjá	?	?	Etna?
Eruption location	Tropics	North	Tropics	North	North?	North?	North
Dry fog initiation	June	June	January?	Summer	October	March	March
Dry fog duration (months)	>12	6	>8?		8–9	12–18	9–10
Peak visual optical depth	1	2				2.5	
First winter in Europe	Normal	Cold	Normal	Cold		Cold	Cold
First winter in Middle East	Normal	Cold	Normal	Cold		Cold	
Poor harvests and famine?	Yes?	Yes	Yes	Yes		Yes	Yes
Pandemic in Europe?	Yes?	No	No?	No?	No?	Yes	Yes
Pandemic in Middle East?	Yes?	Yes	Yes	Yes	Yes	Yes	Yes

observations of the anomalous extinction of sunlight and starlight and petrologic measurements of the near-source erupted sulfur (for known volcanoes), it has been possible to estimate the sulfate aerosol productions. Typical values turn out to be of the order of 10^2 megatons for these very large eruptions (e.g., Zielinski, 1995). Detailed estimates depend, of course, on knowing whether the unidentified volcanoes were tropical or extratropical, because the stratospheric aerosol clouds from high-latitude eruptions do not spread significantly into the tropics, whereas most tropical stratospheric eruption clouds eventually cover the whole globe. Whether or not an aerosol cloud becomes fully global can be determined from a comparison of the Greenland and Antarctic acidity records. Since each of the seven eruptions under discussion generated considerably more aerosols than did the very recent eruptions of El Chichón and Pinatubo, the associated climate impacts should be much greater than anything recently experienced.

3. First Winter

Meteorological conditions in Europe and the Middle East during the summer months of the year-long course of a dry fog of large magnitude have depended critically on the season of the dry fog's first appearance. Warm summers followed right after the June appearance of dry fog in AD 1815 and AD 1783, whereas chilly summers followed the first appearance of dry fog in the winter or very early spring of AD 1258, AD 536, and 44 BC. (The initiation dates for dry fogs in AD 934 and AD 626 were in the summer and autumn, respectively.)

The full climatic effects, however, are encountered later, during the first winter after the eruption. In four of the seven cases, the winters were so cold as to fit into the rare class of very severe ones that historically have occurred only once or twice a century (Easton, 1928; Lamb, 1977, p. 566; Alexandre, 1987). Despite the lack of quantitative temperature measurements before the 18th century, contemporary chroniclers did note the highlights of the most extreme weather events. A bellwether station was Baghdad, where extraordinary coldness and heavy snowfalls occurred in the winters of AD 536–537 and AD 934–935 (Stothers, 1984b, 1998) and the mean temperature between mid-December 1783 and mid-January 1784 was 3.4 °C lower than the year before (Cotte, 1788). (The Baghdad weather during the cold winter of 44–43 BC in Europe is not recorded.)

In contrast, the first winters after the eruptions of AD 1815 and AD 1258 were quite normal. Nothing definite is known about the winter of AD 626–627.

After modern volcanic eruptions, the slight warming over continents that occurs during the first winter following the eruption is most prominently seen at high and middle north latitudes, at least in the case of tropical eruptions. Robock and Mao (1995), however, have suggested that a cooling develops at northern latitudes during the first winter after a northern high-latitude eruption, if El Niño warming effects are initially removed from the temperature data. For much bigger eruptions of the past, nature has done the experiment with an enhanced signal-to-noise ratio. A straight analogy of these older eruptions with modern eruptions would predict that the eruptions of AD 1783, AD 934, AD 536, and 44 BC must have occurred at high or middle north latitudes, whereas those of AD 1815 and AD 1258 must have occurred at tropical latitudes. The evidence available from documentary records and from ice cores confirms, or at least supports, these predictions, as will now be shown.

Identified eruptions are the following three: Tambora, Indonesia, in AD 1815; Laki, Iceland, in AD 1783; and Eldgjá, Iceland, in AD 934.

The eruption of AD 1258 produced roughly equal amounts of fallout per unit area over Greenland and Antarctica, and so must have been tropical (Langway et al., 1988; Palais et al., 1992). El Chichón, Mexico, has been suggested as a possible source, although there remain some minor geochemical problems with this identification (Tilling et al., 1984; Palais et al., 1992).

Because no noticeable Antarctic acidity peak occurs anywhere close to 44 BC (Hammer et al., 1997), the eruption of 44 BC must have been a northern one. Etna, Italy, erupted violently that year and may have spawned the contemporary Mediterranean dry fog (Stothers and Rampino, 1983a). However, the Greenland acidity signal is confusing, the date from one ice core being 50 $\pm$ 4 BC (Hammer, 1984) and from another ice core the two separate years 53 $\pm$ 2 BC and 43 $\pm$ 2 BC, due to the presence of two acidity peaks (Zielinski, 1995). Zielinski has suggested that the older eruption of 53 (or 50) BC was a very high-latitude one.

Similar confusion exists with regard to the AD 536 event. The same two Greenland ice cores indicate dates of AD 516 $\pm$ 4 (Hammer, 1984) and AD 530 $\pm$ 2 (Zielinski, 1995), while an Antarctic ice core yields, approximately, AD 505 (Hammer et al., 1997). If these three signals happen to have been more poorly dated than presently believed and are actually synchronous, a tropical eruption would be implied. Rabaul, Papua New Guinea, is a possibility (Stothers, 1984b). Glaciochemically, however, the Greenland signal dated at AD 516$\pm$4 resembles the signal left by the later Eldgjá eruption (Herron, 1982). It is more probable, therefore, that the event responsible was a northern, possibly Icelandic, eruption, and perhaps not associated with the AD 536 event. But in view of the close similarity between the dry fog of AD 536 and the dry fogs due to Eldgjá and Laki, the AD 536 event (presumably detected in Greenland as at least the AD 530 $\pm$ 2 acidity signal) was probably a northern eruption. Clube and Napier's (1991) and Baillie's (1994) conjectures of a meteoritic impact as a source of this dry fog seem unnecessary.

Less information is available concerning the AD 626 eruption. Greenland ice cores show acidity levels strongly peaking in AD 623 $\pm$ 3 (Hammer et al., 1980) and AD 640 $\pm$ 2 (Zielinski, 1995), the latter date agreeing with a date of approximately AD 639 from an acidity signal in the Antarctic ice sheet (Hammer et al., 1997). Again, perhaps two eruptions took place, the later one occurring in the tropics and the earlier one occurring at some high northern latitude, but probably outside Iceland (Hammer, 1984) and presumably associated with the AD 626 Mediterranean dry fog (Stothers and Rampino, 1983a).

Because of the problems attending the ice core dates before the 10th century AD, we are inclined to distrust these sections of the ice cores for precise dates. Indeed, our more securely obtained dates from historical and tree-ring data can stand alone.

4. After the First Winter

Documentary records that can yield the average climatic conditions in the Northern Hemisphere during the years following the first winter after a large volcanic eruption suggest cooling for 2 to 5 years. The eruptions for which this is known to be true on the basis of European reports are those of AD 1815, AD 1783, AD 1258, and AD 934. For the three eruptions older than this, no useful historical data are available, except for China, which experienced unusually cold summers in 43 and 42 BC (Pang et al., 1986; Pang, 1991a) and in AD 537 (Pang and Chou, 1985).

Tree-ring data can be used to supplement the dearth of documentary evidence in the case of these older eruptions. Dendrochronology confirms the existence of a succession of 5 or 6 relatively cold summers, detected from narrow rings in north temperate pines (*Pinus* spp.) and oaks (*Quercus* spp.), in AD 536-541 (Scuderi, 1990, 1993; Briffa et al., 1990; Baillie, 1991, 1994, 1995) and 43–39 BC (Scuderi, 1990; Baillie, 1991, 1995). Support for at least one summer freezing snap appears in the severe frost damage to the growth rings in California bristlecone pines (*P. aristata*) in AD 628 and 42 BC (LaMarche and Hirschboeck, 1984).

The long-term cold weather that followed the first winter was probably, in all but one or two cases, due to the lingering aerosol veil in the stratosphere. Greenland ice cores corroborate the continuation of heavy acid deposition during a 2 to 4 year period following each eruption, with the exception of the eruptions of AD 1783 and 44 BC, which show acidity signals only 1 year long. The case of 44 BC is puzzling, as the associated Mediterranean dry fog had a long duration from 44 to 42 BC, possibly caused by two closely spaced eruptions (Pang, 1991a; Baillie, 1991, 1995). However, if the acidity peak of around 53 (or 50) BC, which is much stronger and more prolonged than the one of around 43 BC, has been misdated and really refers to the eruption of 44 BC, the acid deposition would have been of the expected length. Nevertheless, there still remains one definite climatic anomaly: the 2–3 years of cold weather after AD 1783, which seems to have been due to the persistence of volcanically perturbed atmospheric circulation patterns.

5. Famine and Plague

Throughout the world, economies before the 20th century were largely based on agriculture and so fell naturally subject to the vicissitudes of weather. After the bitterly cold winters (or, in the case of the tropical eruptions, the normal winters) that followed the great Mediterranean dry fogs, famine became locally widespread, aggravated or caused by poor harvests during the chilly, rainy summers that accompanied or immediately followed the dry fogs. Severe famine can lead to disease in both animals and humans due to lowered body resistance. Feedback then occurs because the irreplaceable loss of farmers impacts negatively on agriculture. Therefore, widespread famine is often associated with great epidemics. In regions of endemic plague (e.g., central and western Asia and northeastern Africa), plague pandemics have resulted.

Historically, ‘plague’ and famine have often occurred together, even in merely local situations, such as besieged cities. It must be emphasized, however, that true (i.e. bubonic or pneumonic) plague is medically not a famine-induced disease but strikes the starving and well-fed alike. Famine’s role is thus indirect, as, for example, when hungry, plague-bearing rats are driven from the fields to seek out grain stockpiles, bringing them into intimate contact with humans. Famine can also cause nutrition-dependent diseases that leave the body with little resistance to other diseases, like plague. Some epidemics loosely called ‘plague’ by early historians were doubtless not cases of bubonic or pneumonic plague. Although we cannot be sure, therefore, that all the great pandemics enumerated below were true plague, most probably were, at least in part, and so it is convenient to refer to the lot as simply ‘plague’.

The most serious plague pandemic that occurred during the early medieval period happened in AD 541–544, during the Emperor Justinian’s time, when it swept through all the Middle East and southern Europe (Russell, 1968, 1985; Biraben and Le Goff, 1969). Later plague pandemics took place in Syria, Palestine, Iraq, and Egypt during the years AD 627–639 (James of Edessa, 708; Bar-Hebraeus, 1286; Dols, 1977) and AD 1784–1787 (Biraben, 1975). Plague also raged in AD 1258–1259 across Syria, southern Turkey, and Iraq (Bar-Hebraeus, 1286; Dols, 1977). All four episodes of epidemic plague belong to the class of major pandemics that occur very rarely – about once a century according to the statistics of plague and possible plague for the past 15 centuries compiled by Biraben (1975) and Dols (1977).

A severe pestilence (possibly plague) also broke out in 43 BC, at least in Egypt and most of Italy; this was one of only two serious pestilences reported for the second half of the first century BC, the other one occurring in 22 BC (Appian of Alexandria, 160; Cassius Dio, 229). The great pestilence of AD 941–942 in Iraq and Egypt is likely also to have been plague (Bar-Hebraeus, 1286; Stothers, 1998). In the case of Tambora, a severe plague epidemic had already started in 1812, three years before the eruption, and so Tambora is not a useful test case, although the eruption's effect on the climate system seems to have strongly intensified and prolonged the epidemic (Post, 1977).

The implied causal connection between large volcanic eruptions and plague, which is unfortunately untestable in the case of Tambora, has previously been suggested in the case of the great Justinian plague of AD 541–544 (Austin, 1985; Baillie, 1991, 1995). However, a delay of 5 years between the eruption of AD 536 and the arrival of plague in the Middle East has always cast some doubt about the validity of this connection, in the absence of other confirming evidence. Pang (1991b) also proposed that the Black Death of AD 1347–1350 in Europe might have been linked to large volcanic eruptions in 1345 and 1340, inferred from the occurrence of moderate-sized acidity peaks in Greenland and Antarctic ice cores. But the Black Death actually started in Asia at least 15 years before 1347 (Sarton, 1948). Finally, not all plague pandemics need (or even can) be attributed to volcanic eruptions, as the moderately chilly and wet weather associated with plague can presumably arise from other causes as well.

Rather, what should be expected is that, if a very large northern or tropical volcanic eruption does occur, plague would possibly ensue in the Mediterranean area as a consequence, with some inevitable delay incurred by the time required for the plague to spread from a focus in Asia or northeast Africa. Because the primary vectors of the plague bacillus are believed to be rat and human fleas and the human louse (Pollitzer, 1954), the spread of plague will usually follow military or commercial trade routes, and so may be either slow or fast depending on the prevailing political and social conditions. The routes between Africa, Asia, and Europe have existed since well before 44 BC, and so no special increase of traffic along them needs to be hypothesized.

Lastly, we note that the Justinian plague and the Black Death are famous chiefly because they spread so far in Europe, not because they were the main (or only) plague pandemics in history.

6. Conclusion

Although other causes of natural variability can sometimes produce unusual climatic and epidemiological events, the chance occurrence of such extreme events only 1 to 5 years after the appearance of a great Mediterranean dry fog (itself an extreme event) is a very unlikely coincidence. To have this happen purely by chance after six (omitting Tambora) of the seven biggest and best-studied Mediterranean dry fogs of the last 21 centuries would be most remarkable. In fact, since events like this occur only about once a century, the odds can be roughly estimated as $(5\ \text{yr}/100\ \text{yr})^6 \approx 10^{-8}$. The alternative conclusion, of course, is that each of these dry fogs perturbed the climate system in an important way for up to 5 years after the source volcano erupted. Agricultural crop failure and epidemic plague and other diseases then had adequate opportunity to develop on a massive scale.

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