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Atmospheric and environmental effects of the 1783–1784 Laki eruption: A review and reassessment

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[1] The 1783–1784 Laki flood lava eruption in Iceland emitted ~122 megatons (Mt) SO_2 into the atmosphere and maintained a sulfuric aerosol veil that hung over the Northern Hemisphere for >5 months. The eruption columns extended to 9–13 km and released ~95 Mt SO_2 into the upper troposphere/lower stratosphere (i.e., the polar jet stream), enforcing a net eastward dispersion of the plumes which reacted with atmospheric moisture to produce ~200 Mt of H_2SO_4 aerosols. Away from source, the Laki aerosols were delivered to the surface by subsiding air masses within anticyclones. We show that ~175 Mt of H_2SO_4 aerosols were removed as acid precipitation and caused the extreme volcanic pollution (i.e., dry fog) that effected Europe and other regions in 1783. The remaining ~25 Mt stayed aloft at tropopause level for >1 year. The summer of 1783 was characterized by extreme and unusual weather, including an unusually hot July in western Europe, most likely caused by perseverance of southerly air currents. The following winter was one of the most severe winters on record in Europe and North America. In these regions, the annual mean surface cooling that followed the Laki eruption was about −1.3°C and lasted for 2–3 years. We propose that the upper troposphere/lower stratosphere aerosols from Laki disrupted the thermal balance of the Arctic regions for two summers and were the main mechanism for the associated climate perturbations. Eruptions of Laki magnitude have occurred in the recent past in Iceland and will occur again. If such an eruption were to occur today, one of the most likely immediate consequences would be disruption to air traffic over large portions of the Northern Hemisphere. *INDEX TERMS:* 0305 Atmospheric Composition and Structure: Aerosols and particles (0345, 4801); 8409 Volcanology: Atmospheric effects (0370); 0370 Atmospheric Composition and Structure: Volcanic effects (8409); 8414 Volcanology: Eruption mechanisms; 3344 Meteorology and Atmospheric Dynamics: Paleoclimatology

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1. Introduction

[2] Stratospheric aerosols produced by short-lived explosive volcanic eruptions have had small to moderate impacts on climate [e.g., *Self et al.*, 1981; *Rampino and Self*, 1984; *Hoffmann*, 1987; *Robock*, 1991, 2000]. Other types of eruptions have also caused marked atmospheric effects, most noticeably moderate volume (10–20 km^3) basaltic flood lava eruptions. Iceland is the only volcanic region in the world where eruptions of this type and scale are occurring on repeat intervals of 100s to 1000s of years. Such eruptions are characterized by high atmospheric sulfur fluxes, releasing between 5 and 9 megatons ($Mt = 10^{12}$ g) of SO_2 per cubic kilometer of magma erupted. In Iceland, the frequency of flood lava eruption is one event every 300–1000 years. Four such events have occurred in the last 1200, including the large volume eruptions of AD934–40 Eldgjá (19.6 $km^3 = 5.5 \times 10^{13}$ kg) and AD1783–1784 Laki (15.1 $km^3 = 4.2 \times 10^{13}$ kg) [e.g., *Thordarson et al.*, 2001]. Of these, Laki is by far the best documented, where the course of the eruption and other key parameters are better constrained than for any other of this type.

[3] Both observational data and model calculations show that flood lava eruptions typically produce relatively low (≤15 km) eruption columns [*Stothers et al.*, 1986; *Thordarson and Self*, 1993; *Woods*, 1993]. Consequently, atmospheric injection of volcanic gases and ash-size ejecta is mainly confined to the upper troposphere and lower stratosphere where aerosol residence time is poorly constrained but may be <1 year [e.g., *Jaenicke*, 1993]. However, with typical eruption durations of months to years, flood lava eruptions can maintain high atmospheric aerosol concentrations by replenishment of the sulfur gases by sequential eruption episodes [*Thordarson et al.*, 1996; *Thordarson and Self*, 1996, 1998]. Precisely this situation occurred during

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the 1783–1784 Laki basaltic flood lava eruption in Iceland when a pall of volcanic haze (or dry fog) hung over the North Atlantic, Europe, North Africa, and Asia for many months with serious consequences for many contemporary communities [e.g., *Traumüller*, 1885; *Kiessling*, 1885; *Thoroddsen*, 1914, 1925; *Thorarinsson*, 1979; *Stothers*, 1996; *Grattan*, 1998; *Durand and Grattan*, 1999]. A wealth of contemporary records describe the wide-ranging atmospheric effects and consequences of the Laki eruption. These records indicate that the volcanic haze it produced had a momentous impact on the environment that was felt almost immediately as well as generating longer lasting radiative climatic perturbations. Consequently, the Laki event provides a unique opportunity to assess environmental and climatic impacts of flood lava eruptions.

[4] We present a synoptic analysis of new and previously published information on the atmospheric, environmental, and climatic effects of the Laki eruption aimed at throwing further light on this important event. The treatment is centered on integrating historical data describing the Laki haze with available volcanological and climatic data. Therefore, it inescapably includes an appraisal of existing data in conjunction with the new information.

[5] The paper is divided into four sections. The first gives a brief summary of events in 1783, which is centered on the Laki event. It includes a synopsis of the eruption, emphasizing revised estimates of the temporal spacing of the SO_2 emissions, because the scope the atmospheric effects cannot be fully comprehended without an integrated knowledge of the course of events and critical volcanological parameters. In the second section, we evaluate historic information on the occurrence, appearance, and distribution of the Laki aerosol cloud along with a new assessment of atmospheric transport and removal mechanisms. We have previously suggested that the Laki stratospheric aerosol burden was 30–90 Mt [*Fiacco et al.*, 1994], which we here reassess to be 25–30 Mt. Even this smaller amount is equivalent to the Pinatubo global stratospheric loading [*McCormick et al.*, 1995] but in the Laki case the aerosol veil was confined to the northern part of the Northern Hemisphere. The third part is focused on volcanic pollution produced by the Laki aerosol cloud and its impact on the environment, whereas evidence for the climatic impact is reviewed in the fourth section. *Thordarson et al.* [1996] previously suggested that the Laki aerosol event lasted >1 year, while *Stothers* [1996, p. 86] asked "Could the aerosols that filled the northern troposphere and lower stratosphere in the summer of 1783 have triggered large climate anomalies that lasted for up to three years afterward?" Here we attempt to answer this question.

[6] The information presented will permit modelers to hindcast the Laki atmospheric effects in order to better understand the processes involved and to forecast climatic impacts for the next time such an eruption occurs. It will also assist development of more-sophisticated models of the transport, generation, and fate of sulfur gases and aerosols at various levels in the atmosphere from persistent eruptive sources.

2. The 1783–1784 Laki Eruption and Its Effects

2.1. Historic Perspective

[7] The year 1783 was frequently referred to in Europe as "Annus Mirabilis" (The Year of Awe) [*Steinthorsson*, 1992], because of the coincidence of several large-scale natural disasters and the extraordinary state of the atmosphere that caused great public concern. A very strong earthquake struck in Calabria, Italy, on 5 February, marking the onset of earthquake activity that lasted well into the summer [*Hamilton*, 1783]. In late February 1783, a submarine eruption off the southwest coast of Iceland formed a new island, "Nýey" (New Island) that disappeared shortly afterward [*Stephensen*, 1783; *Thorarinsson*, 1965]. In addition, Asama volcano in Japan erupted intermittently from May to August 1783 [*Aramaki*, 1956] and a small eruption occurred at Vesuvius in August. However, these eruptions were small (magma volume <0.2 km^3) and the total SO_2 mass they emitted into the atmosphere was inconsequential when compared to that of the Laki eruption [*Zielinski et al.*, 1994; *Camuffo and Enzi*, 1995; *Thordarson et al.*, 1996]. For example, the August 1783 eruption at Asama released about 0.3 Mt (3×10^8 kg) of SO_2 into the atmosphere, which is about 0.2% of the SO_2 mass from Laki [*Kohno et al.*, 1993].

[8] The most astonishing phenomenon of 1783 was the persistent and widespread sulfuric aerosol cloud, referred to in contemporary chronicles as the "dry fog", "*sol-röken*" (Swedish, Sun smoke), "*Höhenrauch*" (German, lofty smoke), or "*móða*" (Icelandic, haze). For simplicity, in this paper we use the Icelandic term *haze*. The earthquakes in Calabria were a common contemporary explanation for the haze [e.g., *Cotte*, 1783; *Melanderhjelm*, 1784; *van Swinden*, 1783]. Another popular explanation was evaporation of fumes from the soil, supposedly caused by the extreme summer heats [*de Lamanon*, 1799; *Soulavie*, 1783]. 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 [*de Montredon*, 1784]. Professor C. G. Kratzenstein at the University of Copenhagen [*Hólm*, 1784], the German naturalist *Johann L. Christ* [1783], and *Benjamin Franklin* [1784] put forward similar explanations a little later.

[9] Observations on the haze are 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, the state of the atmosphere, and the weather [e.g., *Kington*, 1988; *Grattan and Brayshay*, 1995; *Thordarson*, 1995]. In the last 200 years, scientists have used these accounts as sources of information on the distribution and effects of the Laki haze, the first being *Finnsson* [1796] who described the effects of the haze on livestock, vegetation and weather in his work on social and economic impact of famines in Iceland. Brief summaries on the appearance of the Laki haze over Europe were given by *Brandes* [1820] and *Kaemtz* [1836]. *Traumüller* [1885], *Kiessling* [1885] and *Thoroddsen* [1914, 1925] gave more comprehensive synopses of the first arrival and atmospheric effects of the haze in publications that were provoked by the aftermath of the 1883 Krakatau eruption. Information from contemporary accounts has also been used in more recent studies dealing with (1) social and/or environmental impact of the eruption in Iceland and parts of Europe [e.g., *Jackson*, 1982; *Grattan*,

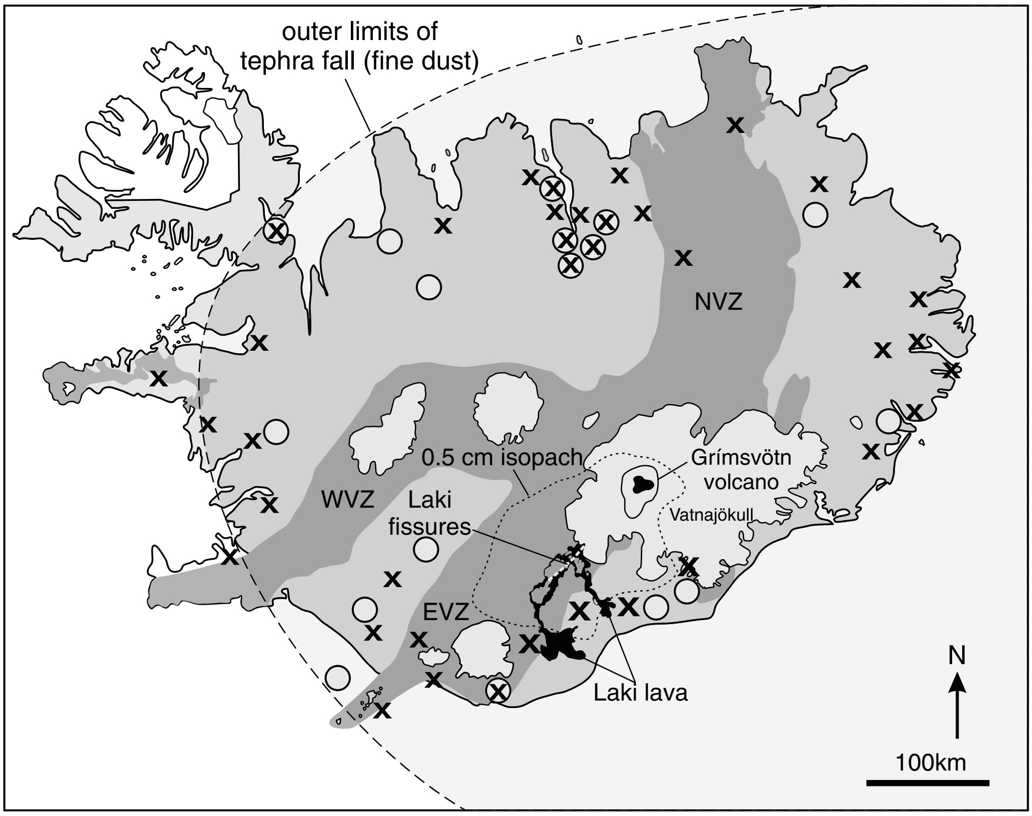

Figure 1. Geologic setting of the Laki fissures (white broken line) and lava flow (black) in relation to the active volcanic zones (dark grey) in Iceland. Abbreviations are: West (WVS), East (EVZ), and North (NVZ) Volcanic Zones. Also shown are 0.5 cm isopach (line of equal thickness; area = 7200 km^2) of the Laki tephra fall as well as the estimated outer limit of the area ($\sim$200,000 km^2) that was effected by fall out of very fine ash. Consequently, coating of fine ash covered bulk of the land surface ($\sim$100,000 km^2) in Iceland. Open circles show locations were fall of fine as was reported. The part of Iceland shaded grey show where >60% of the grazing livestock was decimated, mainly from chronic fluorosis. Crosses indicate locations or regions where reports on symptoms in livestock are consistent with fluor poisoning, large crosses indicate areas were livestock died in large numbers within 2–14 days of the onset of the Laki eruption. Data from contemporary accounts analyzed by *Thordarson* [1990, 1991, 1995].

1998; *Grattan and Brayshay*, 1995; *Jacoby et al.*, 1999; *Steinthorsson*, 1992; *Thorarinsson*, 1979, 1981; *Einarsson et al.*, 1984, and references therein], (2) possible climatic effects, in particular reduction of surface temperatures caused by the eruption [e.g., *Angell and Korshover*, 1985; *Sigurdsson*, 1982; *Wood*, 1984, 1992; *Thordarson*, 1995; *Thordarson and Self*, 2001], and (3) atmospheric H_2SO_4 mass loading, transport and turbidity [*Sigurdsson*, 1982; *Fiacco et al.*, 1994; *Stothers*, 1996; *Thordarson et al.*, 1996].

2.2. Eruption History

[10] The following brief account differs slightly from our previously published work, mainly in reassessment of eruption rates based on new evidence. The 8-month-long Laki eruption (8 June 1783 to 7 February 1784) in South Iceland formed the second largest basaltic lava flow in historic times (Figure 1), with volume of 14.7 ± 1 km^3 (= 4 × 10^{13} kg). Also, the pyroclastic fall deposit from Laki is the second biggest (after the 1755 Katla eruption) by an Icelandic eruption in the last 250 years. It has a volume of 0.4 km^3 (= 1.1 × 10^{12} kg), double the tephra fall volume of the 1980 Mt. St. Helens Plinian eruption [*Thordarson and Self*, 1993; *Sarna-Wojcicki et al.*, 1981]. Ten eruption episodes occurred during the first 5 months of activity, each featuring a short-lived (0.5–4 days) explosive phase followed by a longer-lasting phase of lava fountaining and lava emissions (Figure 2a). Typically, the explosive activity was of violent Strombolian to sub-Plinian type, where the erupting magma was largely disintegrated by explosive exsolution of volcanic gases. The eruption was most vigorous in the first 1.5 months, followed by a slight, but steady, decline in activity over the next 3 months. In the first 12 days, the eruptive fissures yielded $\sim$6 km^3 (= 1.65 × 10^{13} kg) of magma in the form of tephra and lava in three consecutive episodes, or $\sim$40% of the total erupted volume (Table 1). Peak magma discharge during this time was between 5000 and 6600 m^3/s. At the end of episode 5 in late July about 9 km^3 (= 2.5 × 10^{13} kg; $\sim$60%) of the magma had been erupted and $\sim$93% of the erupted volume had emerged at end of the tenth episode in October (Table 1). An important aspect of this declining trend is that the interval between successive eruption episodes increased with time. In the last 3.5 months, the

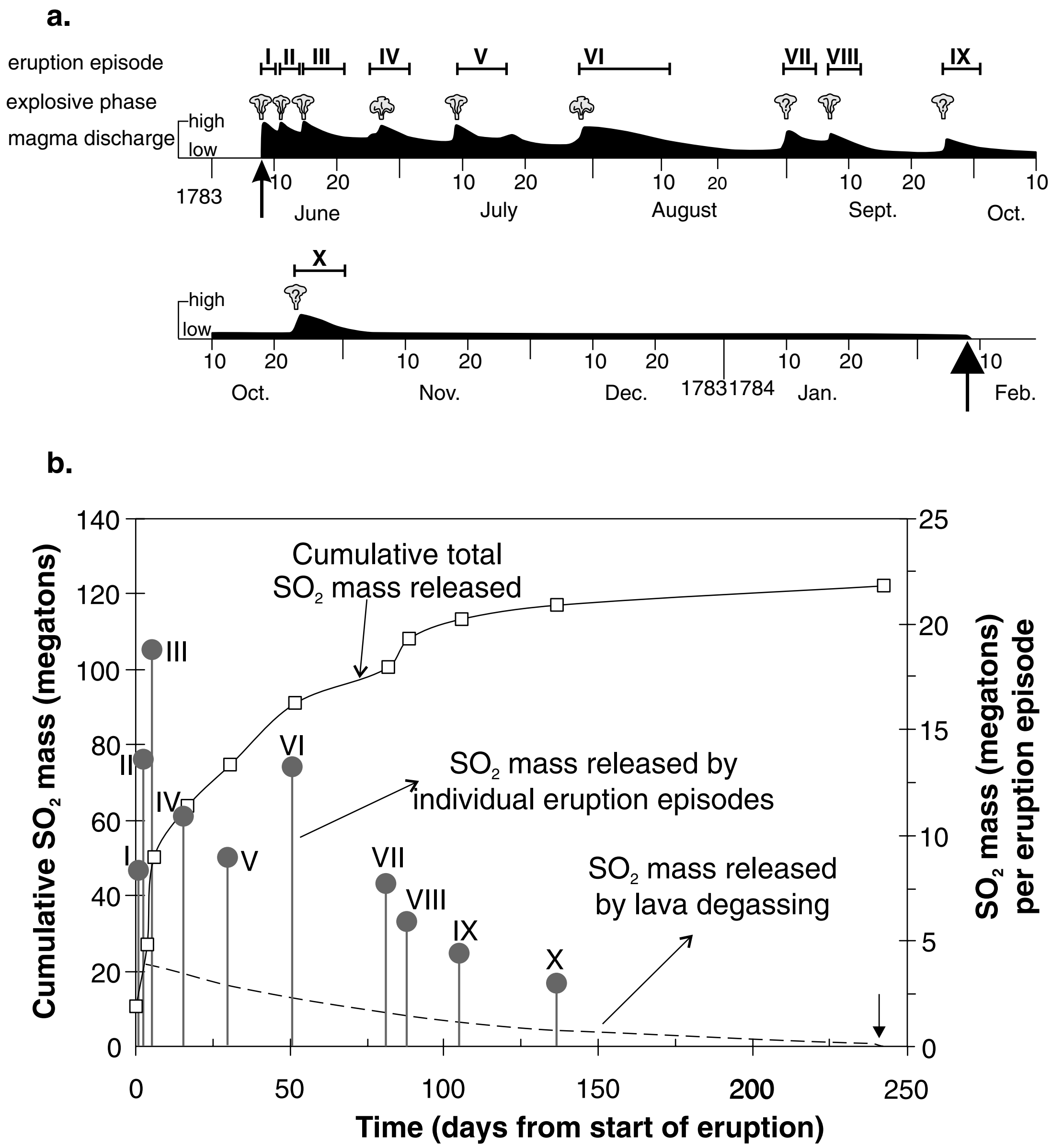

Figure 2. (a) Diagrammatic presentation of the sequence of events during the Laki eruption showing the timing and duration of the 10 eruption episodes (labeled I–X) as well as the occurrence of explosive phases and fluctuations in the magma eruption rates. *Arrows* indicate onset and termination of Laki eruption; *eruption clouds* denote an explosive phase at Laki fissures; the *black curve* shows qualitatively changes in the magma discharge with time. Horizontal bars indicate duration of each eruption episodes. Modified from *Thordarson and Self* [1993]. (b) Atmospheric SO_2 mass loading by the Laki eruption. Solid line and open squares show the cumulative SO_2 output (scale to the left). Vertical bars and filled circles show SO_2 mass released at the vents during each eruption episode and the broken line indicates sulfur mass released by the lava (scale to the right). Arrow indicates the end of the Laki eruption.

eruption was characterized by quiet emission of lava and gas.

[11] A specific estimate made from observations of the Laki explosive eruption columns between June and August 1783 show that their height was in excess of 9 km [*Stephensen*, 1783]. The fact that such high columns persisted into the third month of activity implies that the columns were higher in the early stages of the eruption when its intensity was greater. Model calculations indicate that eruption columns reached heights >13 km during the early phases and that columns >10 km high were maintained for the first 3 months [*Thordarson and Self*, 1993; *Woods*, 1993]. Consequently, the Laki eruption columns reached well into the westerly jet stream (Figure 3), which dominates the atmospheric circulation above Iceland at the tropopause level [*Jónsson*, 1990].

2.3. Atmospheric Venting of Sulfur

[12] The petrologic estimate of the amount of SO_2, H_2O, Cl, and F released by Laki eruption into the atmosphere is

Table 1.

(a) Revised Data on Eruption Episodes, Magma Volume per Episode, and Atmospheric SO_2 Mass Loading by Laki

Eruption Episode	Episode Duration	Timing of Peak SO_2 Emission	Magma Volume, km^3	SO_2 Released, Total, Mt	SO_2 Released, Vents, Mt	Percent of Total Mass Released, Vents	H_2SO_4 Aerosol Yield, Mt
I	8–10 June	8 June	1.25	10.3	8.3	6.8	17.0
II	11–13 June	11–12 June	2.01	16.7	13.5	11.1	27.6
III	14–21 June	14–15 June	2.80	23.2	18.7	15.3	38.2
IV	25 June to 1 July	26–28 June	1.61	13.4	10.8	8.9	22.1
V	9–21 July	9–10 July	1.33	11.0	8.9	7.3	18.2
VI	29 July to 9 Aug.	29–30 July	1.97	16.3	13.2	10.8	26.9
VII	31 Aug. to 4 Sept.	31 August?	1.15	9.6	7.7	6.3	15.8
VIII	7–14 Sept.	7 Sept.	0.87	7.3	5.9	4.8	12.0
IX	24–29 Sept.	24–25 Sept.	0.66	5.4	4.4	3.6	9.0
X	25–30 Oct.	25 October	0.44	3.6	2.9	2.4	6.0
Last 3 months	1 Nov. 1983 to 7 Feb. 1984	–	0.61	5.1	4.1	3.4	8.4
Total			14.70	122	98.5	80.7	201.1

(b) Estimated Upper Atmospheric Sulfur Mass Loadings[a]

Episodes Subtotal	Magma Volume, km^3	SO_2 at Vents, Mt	SO_2 at Vents Cumulative, Mt	H_2SO_4 Aerosol Yield, Mt	H_2SO_4 Aerosol Yield Cumulative, Mt
I+II+III	6.1	40.6	40.6	82.9	82.9
IV+V+VI	4.9	32.9	60.3	67.2	123.1
VII+VIII	2.0	13.6	87.1	27.7	177.8
IX+X	1.1	7.3	94.4	15.0	192.8
Last 3 months	0.6	4.1	98.5	8.4	201.1

[a]Loadings are given for periods 8–15 June (episodes I–III), 25 June to 9 August (episodes IV–VI), 31 August to 14 September (episodes VII–VIII), 24 September to 30 October (Episodes IX–X), and the last 3 months.

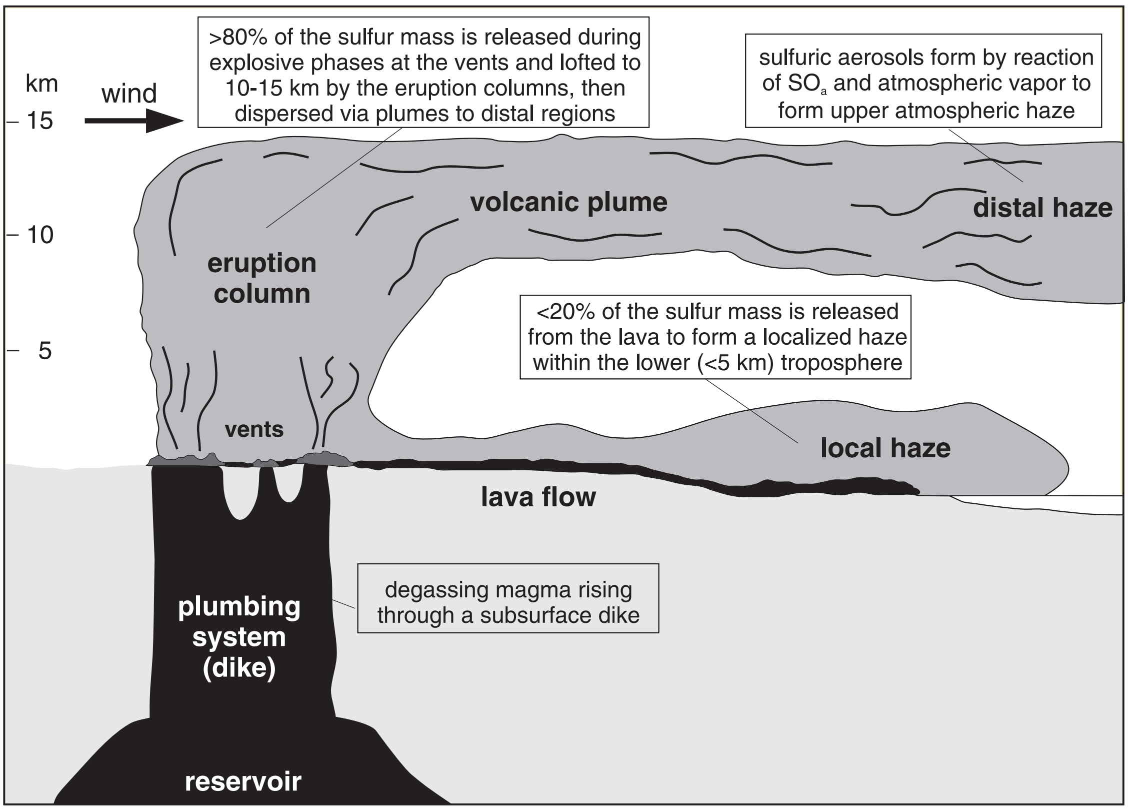

Figure 3. A schematic illustration showing the key features of the two-stage degassing in flood lava eruptions. Modified from *Thordarson et al.* [1996].

~122, 235, 15, and 7 Mt (Mt = 1 $\times$ 10^9 kg), respectively [*Thordarson et al.*, 1996]. About 96% of this mass was released into the atmosphere during the first 5 months of the eruption. Just over 80% of the SO_2 mass (= 98.5 Mt) was released at the vents and then carried by the eruption columns to lower stratospheric altitudes (>9 km; Figure 3). This SO_2 release value yields a theoretical sulfuric aerosol mass of ~200 Mt, assuming a composition of 75 wt % H_2SO_4 and 25 wt % H_2O for the aerosols [*Thomason and Osborne*, 1992] and a complete conversion of SO_2 to H_2SO_4 aerosols. The mass of magmatic water released into the atmosphere by the activity at the Laki fissures exceeded the amount of SO_2 by a factor of 1.9. This water mass alone is enough to convert almost all of the sulfur into H_2SO_4. Thus, taking this into account in conjunction with available atmospheric vapor, it is not unreasonable to assume that bulk of the SO_2 released by Laki was converted into sulfuric aerosols during dispersion of the plumes away from the source.

[13] The lower stratospheric mass loading of SO_2 (and other volatiles) from Laki was spread over at least 5 months and bulk of the gas was released during the recurring explosive phase at the onset of each of the 10 eruption episodes (Figure 2b and Table 1). The first three eruption episodes, where the main explosive phases were spaced at intervals of 3 days, released about 8, 13, and 19 Mt of SO_2 into the polar jet stream, respectively. This represents a total SO_2 mass loading of ~40 Mt (= potential aerosol yield of ~83 Mt H_2SO_4 aerosols) over the first 8–10 days of the eruption or about 40% of the total mass released at the vents. The next three episodes were spaced at ~2 weeks intervals and each of the explosive phases released between 9 and 13 Mt of SO_2 into the polar jet stream. The total mass injected into the atmosphere during this period was ~33 Mt SO_2 (= ~67 Mt H_2SO_4 aerosols) but this loading was spread out over a significantly longer time period (i.e., 26 June to 30 July). Between 31 August and 25 October, another 20 Mt SO_2 (= ~43 Mt H_2SO_4 aerosols) were released in four eruption episodes at 1-week to 1-month intervals (Table 1 and Figure 2b). Only about 4 Mt SO_2 were released into the atmosphere during the waning stages of the eruption after October 1783.

[14] We assess that most of the widespread aerosol cloud (haze) that spread over the Northern Hemisphere in June to October 1783 was derived from degassing at the Laki vents (see below) and that the 25 Mt of SO_2 released gradually from the lava flow over the 8-month-long eruption affected only the southern part of Iceland. While the most intense haze was impacting Europe, the lava flow had not reached its full extent [*Thordarson and Self*, 1993], and the lava source area that emitted about 0.2–0.3 Mt per day of SO_2 was not very large. In any case, because this gas was released into the boundary layer, residence times for the lava-derived SO_2 and aerosols would have been short (days) due to high dry deposition rates and rainout [*Stevenson et al.*, 2001].

[15] Estimates of atmospheric H_2SO_4-aerosol mass loading by Laki using ice core acidity data range from 100 to 280 Mt [*Clausen and Hammer*, 1988; *Hammer*, 1977]. These estimates are calculated using midstratospheric (>15 km) dispersal of radioactive nuclides and assume a global dispersion for the aerosol cloud. They do not take into account volcanological factors such as the eruption duration and style, pulses of high sulfur mass loading, or atmospheric fractionation of the volatile mass. They also did not consider that the Laki aerosol plumes were dispersed at atmospheric heights between 7 and 15 km and latitudes above 35°N [*Lamb*, 1970; *Thordarson*, 1995]. We previously showed that the 1784 H_2SO_4 acidity peak in Greenland ice cores represents only a fraction of the Laki aerosol cloud or the component that remained in the lower stratosphere for more than a year [*Fiacco et al.*, 1994]. By an independent method, *Stothers* [1996] obtained 200 Mt of H_2SO_4 for the total aerosol column mass loading between June and August 1783 using information on atmospheric turbidity over Europe.

3. The Laki Haze: Occurrence, Transport, and Physical Properties

3.1. Contemporary Sources

[16] We have examined more than 130 documents containing information on the attributes and the occurrence of the Laki haze and its consequences for the environment and the weather. These sources cover the Northern Hemisphere from 35°N to well above the Arctic Circle but the majority is from the North Atlantic region and Europe (Figure 4; see also Appendix A, Table A1). A complete compilation (in English) of the contemporary text used in this study is given by *Thordarson* [1995] (data available upon request from the senior author).

[17] The first appearance of the Laki haze is well documented and much of this information has been around since the time of the eruption [e.g., *van Swinden*, 1783]. Later, *Traumüller* [1885] and *Thoroddsen* [1914] presented more complete compilations on the timing of the first appearance of the Laki haze. More recently, similar information was given by *Fiacco et al.* [1994] and *Stothers* [1996]. Although the compilation presented here is similar to those mentioned above, there are significant differences. First, we have included a number of new observations from Iceland, Greenland, and other Nordic countries. Second, the compilation includes direct or indirect information on the occurrence of the haze in North America and in the regions over the Atlantic Ocean between Labrador and the Azores. These sources have been discovered recently and confirm the hemispheric dispersal of the haze above 35°N [*Demarée et al.*, 1998; *Jacoby et al.*, 1999].

[18] The dates reported here for the first appearance of the Laki haze at the indicated locations are obtained directly from the contemporary sources, which were reexamined to ensure accurate reporting. The majority of these dates are obtained from contemporary weather logs or official reports. The weather logs contain records of observations made three times a day [e.g., *Kington*, 1988] and their reporting is accurate to the day. Moreover, our analysis reveals that reported dates from two stations, Copenhagen and Geneva, are incorrect and these erroneous dates most likely resulted from mistakes in printing of the original document [*Thordarson*, 1995]. Most of the weather logs also include time-continuous recordings on the occurrence of the haze, including a few that incorporate systematic descriptions of its appearance, and thus provide useful temporal and spatial information about its perseverance, distribution and inten-

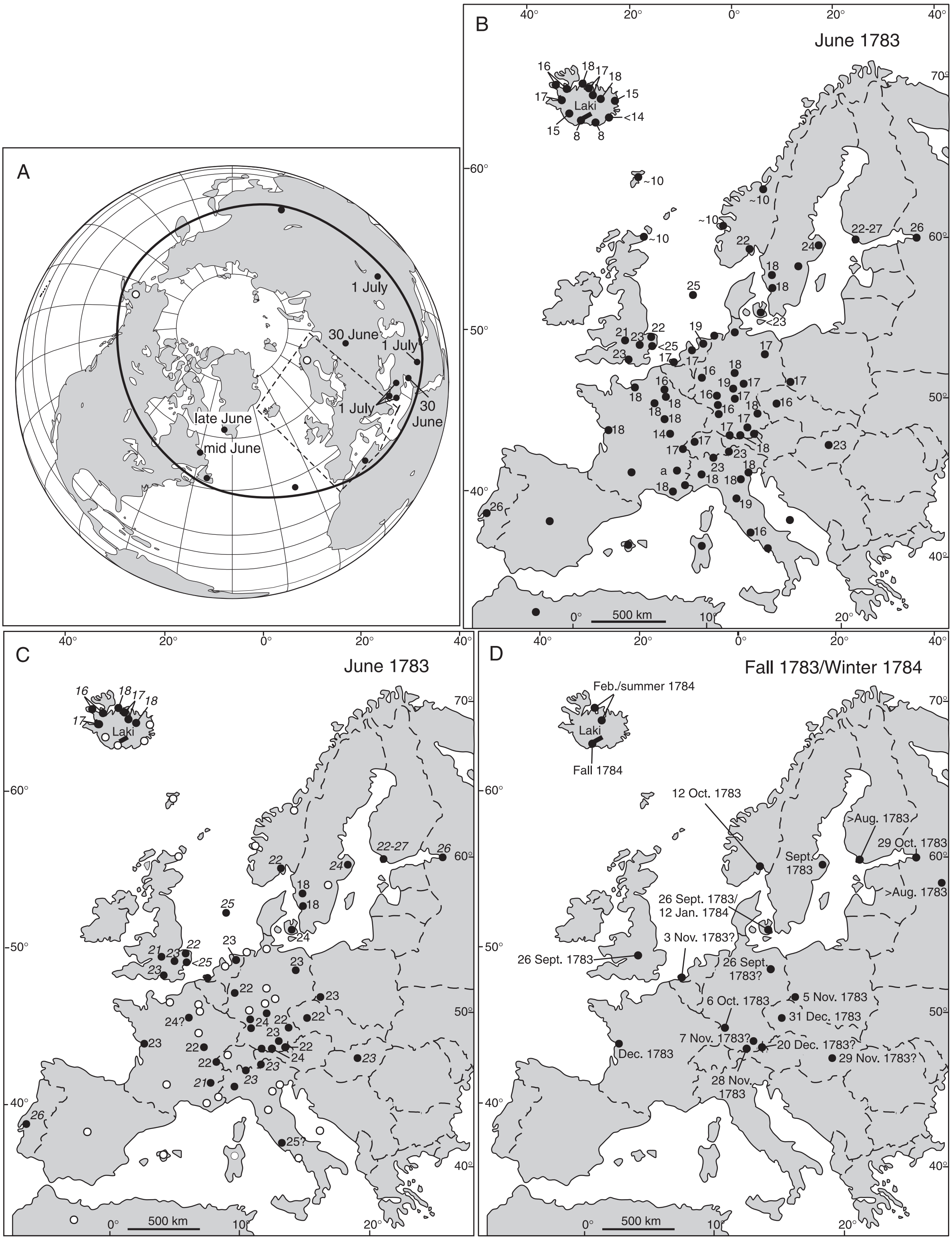

Figure 4. Occurrence of the Laki haze. The maps show: (a) Locations and timing of the first appearance of the Laki haze in June 1783 in the Northern Hemisphere. *Dots*, locations; *numbers*, dates of observation. The box (broken line) outlines region shown in (b) to (d). Open circles indicate sites where appearance of the haze is inferred from tree ring data. (b) Map of Europe showing locations and timing of the first appearance of the Laki haze in June 1783. Dots without numbers indicate sites where dates of observations are not specified. (c) Dates (in June) when thick lower tropospheric haze appeared over Iceland and Europe for the first time. Numbers in italic font indicate dates of first arrival and open circles show observation sites where the sudden increase in haze opacity is not specified. (d) Last observed occurrence of the Laki haze.

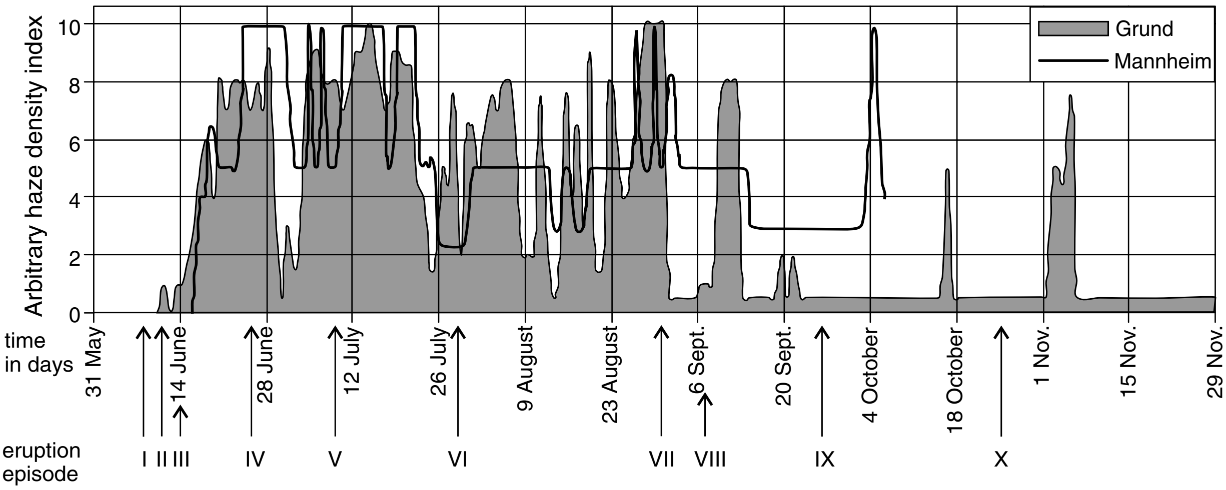

Figure 5. Plot showing the changes in relative haze opacity with time during the summer and fall 1783. The Icelandic series is based on weather logs and observations by *Jónsson* [1783, 1785] at Grund in Northern Iceland and the German series on the weather logs from Mannheim [*Hemmer and König*, 1783]. In order to enable graphic representation of the historic data on the changes in haze opacity the descriptive terminology was converted into numerical values (from 0 to 10) in accordance with the scaled index of *Thordarson* [1995].

sity. Several of the dates reported here are obtained from personal diaries and newspaper articles. Their validity has been confirmed by comparison with the information from the closest weather stations.

3.2. First Appearance of the Haze and Subsequent Developments

[19] In the first week, the Laki plumes brought sulfuric haze, ashfall, and acid rain over the rural districts of Iceland to the south and southeast of the fissures, causing the Sun to appear blood red and reducing its natural warmth. This local effect may have been produced by boundary layer aerosols or gas derived from the lava flow and also from low plumes blown southwards from the eruptive fissure. A dark blue sulfuric haze was observed to cover southeast Iceland by 14 June, but in eastern Iceland the haze may have appeared as early as 9, and no later than 13 June. However, it was not until 9–11 days after the onset of the eruption (i.e., between 16 and 18 June) that a strong haze appeared in northern and western Iceland (Figure 4; see also Appendix A, Table A1). It is precisely reported that in these regions the haze arrived as a thick ''fog'' carried in over the land from the sea by northerly winds, the opposite direction from that of the Laki fissure to these regions.

[20] The first appearances of the Laki haze outside Iceland are documented below. A smoky haze was first noticed in the region around Nuuk (Godthåb) in Greenland in late June 1783, and in the Atlantic between Labrador and the Azores in summer 1783 (Figure 4a; see also Appendix A, Table A1). From the writings of *Hólm* [1784] it can be deduced that the Faeroe Islands, the west coast of Norway, and possibly the northern tip of Scotland (Caithness), had the first experience with acid rain and ashfall from Laki around 10 June. In western and southern Europe the haze was first noticed between 16 and 19 June (Figure 4b) when it was described as being ''spread in a vast space, relatively thin, and transparent'' [*Le Golft*, 1783; *Presus*, 1783; *Soulavie*, 1783]. As indicated by the reported opacity of the haze, its intensity increased greatly over western and central Europe between 22 and 24 June [*Beguelin*, 1783; *Heinrich*, 1783; *Hemmer and König*, 1783; *Maret*, 1783; *Presus*, 1783; *Seignette*, 1783; *Strnadt*, 1783], which coincided with its first appearance in the lower troposphere and the onset of a semistationary, high pressure system over Europe (Figure 4c). At this time the haze was first noticed in England, the higher regions of the French and Swiss Alps, the Nordic countries, and in Eastern Europe.

[21] By 26 June almost all Europe was covered by thick dry fog (Figure 4b; see also Appendix A, Table A1) with haze first noticed in both Lisbon and St. Petersburg on 26 June and reaching Moscow on 30 June. The haze appeared in Tripoli, Lebanon (then part of Syria), toward the end of June and by 1 July it covered the sky above the Altai Mountains in central Asia, ~7000 km from source. Other evidence [*Demarée et al.*, 1998; *Jacoby et al.*, 1999] shows overwhelmingly that Laki haze occurred over Alaska and China, indicating that the sulfuric aerosol plumes covered the Northern Hemisphere from ~35°N all the way to the North Pole (Figure 4a).

[22] Data from the historic weather logs show that the opacity of the Laki haze varied greatly during the summer and fall 1783. In general, these records show that high opacity was associated with periods when the haze extended down into the lower troposphere. During periods of relatively low haze opacity, the haze resided at higher altitudes and was most pronounced at the horizon at sunrise and sundown. Several of the weather logs contain time-continuous observations of the haze.

[23] Two of these time series, one from Northern Iceland and one from Germany, have been investigated in order to examine the relative changes in the haze opacity with time (Figure 5). These records reveal several interesting aspects about the appearance of the haze in the lower troposphere over Iceland and Europe. On average, the opacity of the

Table 2. Height in Degrees Above the Horizon to Which the Sun and the Sky Were Masked by the Laki Haze[a]

Location	Month	Strong Dimming	Complete Extinction
Copenhagen, Denmark	late June	20°	10°
	August	20–30°	
Mannheim, Germany	late June		40–90°
	August	8–12°	3°
Amsterdam, Holland	July	20°	10°
La Rochelle, France	late June	10°	
	August	17°	17°
Windsor England	August	18–20°	

[a]Strong dimming, degrees at which the haze completely obscured the stars and the Moon or caused such a strong dimming of the Sun that it could be gazed at with naked eyes. Complete extinction: degrees above the horizon at which the haze enforced a complete visual extinction. Data from *Bugge* [1783], *Hemmer and König* [1783], *Seignette* [1783], and *Cavallo* [1784].

lower troposphere was greatest from late June to mid-July and then tapered off with distinct late pulses of high opacity recorded throughout the Fall of 1783. The records also demonstrate that atmospheric opacity varied greatly on the timescale of weeks to months, with a periodicity that closely mimics the episodic behavior of the Laki eruption. This is consistent with episodic peaks in the atmospheric injection of sulfur dioxide at the source vents [*Thordarson et al.*, 1996]. When examined in detail, however, there is not a simple correlation between the timing of eruption peak episodes and periods of high opacity and the records indicate a 1- to 2-week-long delay between the pulses of SO_2 release at the vents and appearance of the densest tropospheric haze. Furthermore, there is no systematic correlation between the appearance of intense tropospheric haze at the two stations. In some instances the haze intensity increased simultaneously, whereas in others there is a significant time difference between the appearance of dense haze (Figure 5).

3.3. Altitude of the Haze

[24] The contemporary records principally document the observable occurrence of the Laki haze in the lower troposphere rather than contain direct information on the absolute height of the aerosol cloud. However, descriptions of strong dimming or total extinction of celestial objects at elevations of 10° to 40° above the horizon along with exceptional duration and brightness of the dusk from the horizon to the zenith (Table 2 and Appendix A, Table A2) show that the Laki haze/aerosol cloud extended to substantial heights. Furthermore, observations from widely spaced locations indicate that the haze was little affected by low level winds or rainfall, suggesting that a significant proportion of the aerosols resided at the tropopause level or higher.

[25] This conclusion is further supported by descriptions of pale or red Sun around noon, dull reflections from white objects on clear days, and especially, haze at two levels in the atmosphere, a thin upper atmospheric haze and a thicker haze near the surface [*Calandrelli*, 1783; *Hólm*, 1784; *Matteuci*, 1783; *Onuphrio*, 1783; *Presus*, 1783; *Schwaiger*, 1783; *Toaldo*, 1783]. Although the upper atmospheric haze was described as thin and transparent it still caused a considerable dimming of the Sun. The lower atmospheric haze typically set in as a blue fog in the evening and grew in intensity over the night, but as the day progressed it lifted up from the surface. Taking the distance to the horizon to be ~25 km the visual extinction of celestial objects at elevations of 10° to 40° above the horizon indicates heights of 5 to 16 km height for the Laki aerosol clouds. Although not conclusive these calculations correspond well with the independent estimates of eruption column heights [*Thordarson and Self*, 1993]. This also agrees well with the results of *Fiacco et al.* [1994], which indicate that a portion of the Laki aerosol cloud remained aloft at lower stratosphere altitudes (9–13 km) for at least 1 year after the eruption.

3.4. Last Occurrence of the Haze

[26] Reports on the last occurrence of the Laki haze are ambiguous. Most sources indicate that the haze disappeared in the period between mid-September and late October, coinciding with the time when magma discharge dropped significantly at the Laki fissures [*Thordarson and Self*, 1993]. However, information in the contemporary weather logs indicates that the mid-September to late October dates refer to the last appearance of noticeable lower tropospheric haze. Several records [*Kettel*, 1783; *Presus*, 1783; *Schwaiger*, 1783; *Strnadt*, 1783; *Toaldo*, 1783] report presence of haze toward the horizon, occurrences of red Sun, or a thin upper atmospheric haze, through November and December 1783 (Figure 4d). A red Sun was seen in Copenhagen until late February 1784 [*Hólm*, 1784]. In summary, the available data indicates that the lower tropospheric component of the haze disappeared from the atmosphere over Europe in late fall 1783, whereas the upper troposphere-lower stratosphere component persisted well into the winter of 1783–1784.

3.5. Atmospheric Transport and Dispersal of the Laki Haze

[27] Descriptions of ashfall associated with the Laki eruption indicate a net eastward dispersal of the eruption plumes. Information on volcanic plumes from other Icelandic eruptions show that eastward dispersal from source within the westerly jet stream at altitudes <15 km is most common [*Jónsson*, 1990; *Thorarinsson*, 1954, 1976, 1981; *Lacasse*, 2001]. Reports on ashfall from historic eruptions in Iceland show that the eruption plumes travel to mainland Europe in 16 hours when following a straight path and up to 50 hours when following meandering waves within the jet stream [*Nordenskiöld*, 1876; *Mohn*, 1877; *Thorarinsson*, 1949, 1954]. These travel times indicate mean transport velocities of 15 to 18m/s for a volcanic eruption plume from a typical Icelandic eruption. Historic records also show that atmospheric perturbations such as volcanic haze (dry fog), blood red Sun and unusual twilights are normally noticed much later, typically 1 to 3 weeks after the onset of the eruption [e.g., *Lamb*, 1970; *Thorarinsson*, 1981]. This delayed occurrence of optical perturbations cannot be attributed to events at the eruption source, because in each case the eruptive vigor and magma discharge was greatest at the beginning. The delay is best explained by the time it takes to convert SO_2 to H_2SO_4, a reaction that has a typical e-folding rate of 2–4 weeks in the lower stratosphere [*Hoffmann*, 1987; *Schoeberl et al.*, 1993].

[28] We now evaluate atmospheric transport mechanisms of the Laki aerosol plumes by using the information on the appearance of the haze in junction with reconstructed daily synoptic weather maps for Europe in the years 1781 to 1785 (Figures 4 and 6). These maps are constructed from detailed analysis of daily weather observations from about 115 weather stations across Europe (including Iceland) and are thought to be a good representation of the large-scale features dictating the day to day weather. When assessing the dispersal mechanism of the Laki haze it is important to recognize that: (1) the bulk of erupted sulfur dioxide was lofted by the eruption columns to 9–13 km altitude, (2) the resulting plumes were dispersed from source at the tropopause level, traveling at velocities between 15 and 18 m/s, and thus were able to reach mainland Europe in 1–2 days, and (3) the haze first appeared in North and West Iceland 8–10 days after the onset of activity at the fissure whereas in Europe it appeared 8–15 days after the eruption began.

[29] The first map (10 June 1783) represents the general weather pattern during the period 8–12 June when the Faeroe Islands, western Norway, and Caithness in Scotland experienced their first encounter with ashfall and haze from Laki (Figure 4b). The map indicates a cyclonic circulation system that traveled from Iceland across the Norwegian Sea to Scandinavia between 8 and 12 June (Figure 6a).

[30] The weather pattern shown on Figure 6a is consistent with the reported occurrences of ashfall and acid precipitation; a southeast dispersal of the initial Laki plume over the Faeroe Islands and North Scotland and then a northeast curl of the plume along the west coast of Norway. These occurrences appear to have been confined to areas facing the source and did not affect regions east and south of the Caledonian mountain range [*Hemmer and König*, 1783; *Nicander*, 1783; *van Swinden*, 1783; *Wilse*, 1783]. This evidence suggests that the ash-rich portion of the initial plume subsided rapidly down into the lower troposphere [cf. *Holasek and Self*, 1995]. However, the eruption column of the first explosive phase penetrated the tropopause and consequently the bulk of the gaseous mass from this first phase was most likely dispersed in the lower stratosphere and the upper troposphere. Manual tracking of cyclone and anticyclone generation and movements over the North Atlantic for the period 8–12 June indicate a northeasterly flow for the westerly jet stream above Iceland (Figure 6a). Thus the aerosol cloud was carried northward over the Arctic, which explains absence of the haze at more southerly latitudes at this time. As mentioned above, thick haze appeared with northerly winds in northern Iceland between 16 and 18 June (see Appendix A, Table A1). This occurrence is inconsistent with direct lower tropospheric transport of aerosols from source (see below).

[31] The second map (17 June 1783) represents the weather pattern between 13 and 20 June when the Laki haze first appeared in North and West Iceland and over the western and southern regions of Europe (Figure 4b). An isolated cyclonic cell remained stationary over the British Isles and southern Scandinavia for 10 days and is likely to have diverted the main stream of the westerlies into two bands (Figure 6b).

[32] The circulation pattern around 17 June (Figure 6b) clearly implies a jet stream transport of gases and aerosols, which is consistent with early descriptions of transparent and widespread haze. The haze was only reported from regions where sky was clear and not noticed over the British Isles and southern Scandinavia because of cloud cover. Moreover, a thick haze appeared with northerly winds in north and west Iceland between 16 and 18 June (see Appendix A, Table A1). This occurrence is inconsistent with a direct lower tropospheric transport of Laki aerosols from the source. For that reason it must represent a component of the aerosol plumes that was carried northward by jet stream during the first week of the eruption and consequently reintroduced into the lower troposphere by eddy dispersion along isentropic surfaces or by a tropopause folding event behind the polar front [*Holton et al.*, 1995] and then carried southward over Iceland by northerly surface winds.

[33] The third map represents the weather pattern between 21 June and 5 July when a thick lower troposphere haze appeared all over Europe (Figure 4c) and caused severe damage to vegetation in Scandinavia, Germany, Holland, England, and France [*Bryant*, 1783; *Maret*, 1783; *van Swinden*, 1783; *White*, 1789; *White*, 1970]. This map shows a cyclone over Iceland and a large quasi-stationary anticyclonic pressure system over Western Europe, indicating partial blocking and a two-level diversion of the upper westerlies (Figure 6c).

[34] The circulation pattern shown on Figure 6c rules out direct lower tropospheric transport of gases and aerosol from above the Laki fissures to Europe because surface winds in Iceland would have dispersed the plume to the north. If a part of the westerly jet stream curled north over Iceland and then back to the south a large portion of the Laki plumes may have been carried directly over Europe at the tropopause level. However, this alone does not explain the widespread lower tropospheric haze present over Europe at the time and a mechanism involving vertical transfer of the aerosol mass from the upper to the lower troposphere is required.

[35] As the Laki cloud converged on the quasi-stationary anticyclone over Europe a large portion of the aerosols were transported from the jet stream level toward the surface within subsiding air masses (Figures 6c and 7). The aerosols spread in a spiral-like fashion across the continent, accumulating at the subsidence inversion level at $\sim$1 km altitude. Transfer of aerosols across the inversion level and into the surface boundary layer is likely to have been enhanced by vertical mixing of air, driven by the diurnal cycle of heating and cooling of the Earth's surface. This mechanism explains the widespread occurrence of the thick lower troposphere haze in Europe between 21 June and 5 July.

[36] In Norway and Sweden the tropospheric haze first appeared on 23 to 24 June with southerly winds [*Melanderhjelm*, 1784; *Nicander*, 1783; *Wilse*, 1783] and in Hungary and Switzerland the tropospheric haze was brought in by northerly winds on 23 June [*Onuphrio*, 1783; *Weiss*, 1783]. This dispersal pattern is consistent with winds generated by an anticyclone over Western Europe (Figure 6c). Moreover, it offers an explanation for the relationship between occurrences of thick haze and thunderstorms commonly mentioned in the contemporary accounts [e.g., *de Lamanon*, 1799; *de la Lande*, 1783; *Soulavie*, 1783]. The thick haze normally appeared either just before or right after thunderstorms, which are usually generated by the

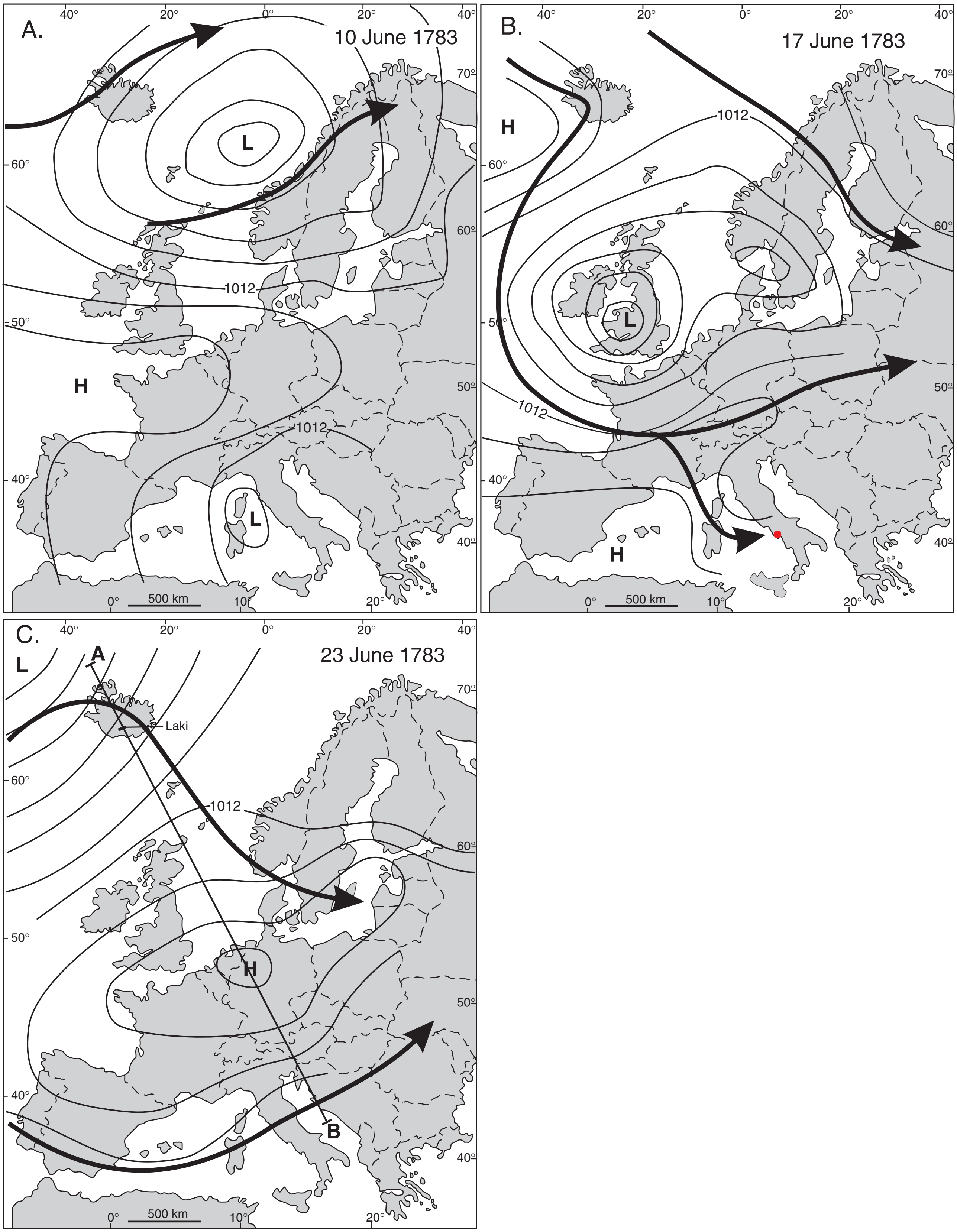

Figure 6. Synoptic weather maps for: (a) 10 June 1783, (b) 17 June 1783, (c) 23 June 1783, showing the main weather and circulation patterns over Europe for the periods 8–12 June, 15–19 June, and 22–25 June, respectively. The *solid lines* represent isobars at 4 millibar intervals. The 1012 millibar isobar marked because it usually separates anticyclonic from cyclonic systems. The inferred flow path of the westerly jet stream is shown by the *heavy solid lines*. Maps drawn using the data of *Kington* [1988].

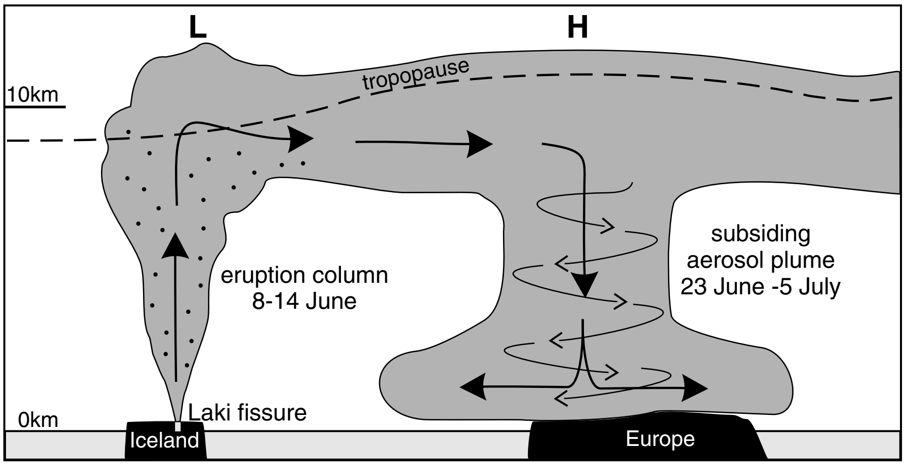

Figure 7. Simplified cross section (A–B on Figure 6c) from Iceland to mainland Europe showing the dispersal and development of the Laki plumes in the first 3–4 weeks of the eruption. Eruption columns produced by explosive activity at the Laki fissures carried ash, SO_2, and other gases to altitudes of 9–12 km. The sulfur-rich plumes (shaded) were dispersed eastward over Europe by the polar jet stream. Due to convergence of airflow at the tropopause level, the Laki aerosol cloud was sucked into a large quasi-stationary high-pressure cell (H) located over Europe at the time and reintroduced into the lower atmosphere by the subsiding air masses, spreading in a spiral-like fashion across the continent. The *arrows* indicate subsiding air within the core of the anticyclone from mid or upper tropospheric levels.

cold fronts that precede or follow warm anticyclones (Figure 7).

3.6. Upper Tropospheric and Lower Stratospheric Haze

[37] The strong twilights and the unusual coloration of the Sun, the Moon, and the sky caused by the Laki haze provide indirect information on the aerosol size [*Lamb*, 1970; *Stothers*, 1996]. The red and pink colored Sun and sky toward the horizon commonly observed at times of sunrise and sundown (see Appendix A, Tables A1 and A2), indicate that the upper troposphere/lower stratosphere haze consisted of submicrometer aerosol droplets. A white or bluish-green Sun is mentioned at times when thick lower troposphere haze covered Europe. This implies aerosol sizes in the range of 1–5 μm, reflecting growth by reaction with atmospheric vapor during subsidence from higher altitudes to the surface.

[38] Strong visual extinction by the Laki haze is indicated by descriptions stating that the Sun could be gazed at with the naked eye, even at noon, and by strong dimming or total blocking of the Sun, the Moon, and the stars at elevations between 8° and 40° above the horizon (Table 2 and see Appendix A, Table A2). The visual extinction at the zenith can be estimated by:

$$\left[(\Delta m)_0^D + 0.20\right] \sec Z = 3.4$$

where $(\Delta m)_0^D$ is the visual extinction at the zenith due to volcanic haze in mag units (astronomical magnitudes) and Z is the apparent zenith angle. The factor 0.2 is the visual extinction of clear air per unit air mass, and the factor 3.4 is the normal visual extinction at an apparent zenith angle of 87.5° [*Stothers*, 1984]. The chronicles indicate that the haze obscured the Sun at apparent zenith angles ranging from 0° to 82° (Table 2 and see Appendix A, Table A2). It follows that the observed visual extinction of the Laki haze falls in the range from 0.3 to 3.2 mag. *Beguelin* [1783], *Hemmer and König* [1783], and *Presus* [1783] describe a total blocking of the Sun over Europe in late June that lasted for several days, which implies visual extinction in excess of 1.5 mag (or Z ∼60°) for the lower tropospheric haze. Strong dimming of the Sun at elevations between 10° and 20° is mentioned in accounts from all of the geographic regions mentioned. This phenomena was noticed for many months after the onset of the Laki eruption and was clearly associated with the upper troposphere/lower stratosphere component of the haze (see Appendix A, Table A1). This information indicates a visual extinction on the order of ∼0.8 mag (range 0.4 and 1.0 mag) for the upper troposphere/lower stratosphere haze. This value corresponds to an excess optical depth (τ_D) of ∼0.7 (range 0.4 and 0.9).

[39] Alternatively, the visual extinction of the upper troposphere/lower stratosphere component of the Laki haze has been estimated by using the absolute calibration of the extinction by the Krakatau aerosol cloud, which is given as $(\Delta m)_0^D = 0.19X$ [*Stothers*, 1984]. X is the measured volcanic acidity signal in the ice cores measured in units of microequivalents (μeq). For Laki this relationship is $(\Delta m)_0^D = 0.05X$, because its aerosol cloud was confined to latitudes above 35°N whereas the Krakatau aerosol cloud was of global extent. The mean amplitude of the Laki acidity signal in the ice cores is 15.1 μeq ± 7 μeq [*Hammer*, 1977; *Clausen and Hammer*, 1988; *Fiacco et al.*, 1994]. This value indicates an excess visual extinction for the Laki haze of $(\Delta m)_0^D = \sim 0.8 \pm 0.4$ ($\tau_D = \sim 0.7$), a value that agrees well with the estimate given above. Therefore, we conclude that the upper troposphere/lower stratosphere component of the Laki haze, which resided in the atmosphere for more than a year, had mean optical depth of ∼0.7. This value is significantly higher (about 2 times) than the

measured optical depth (τ_D = 0.3 and 0.4) for the midstratospheric aerosol cloud produced by the 1991 Pinatubo eruption in the Philippines [e.g., *Valero and Pilewskie*, 1992]. Despite similar mass values, about 30 Mt for the Pinatubo H_2SO_4 aerosol cloud [e.g., *Self et al.*, 1996] and ~25 Mt for the lower stratospheric component of the Laki cloud (see below), this difference in optical depths is not surprising because the dispersion of the Pinatubo cloud was more than double that inferred here for the Laki cloud.

3.7. Optical Properties and Implications for Aerosol Particle Size and Optical Depths

[40] When evaluating the climatic effects of the Laki eruption it is important to differentiate between the potential effects of the lower tropospheric and upper troposphere/lower stratosphere components of the haze. The atmospheric residence time of the lower tropospheric aerosols is on the order of days to weeks, but the aerosols residing in the upper troposphere/lower stratosphere remained aloft for more than a year at altitudes between 9 and 13 km [*Jaenicke*, 1984]. It is also important to know the relative amount of H_2SO_4 mass loading for each component.

[41] The Laki acidity signal in the ice cores is equivalent to an estimated 184 ± 80 kg H_2SO_4 per km^2 and as mentioned previously represents the mass that had long-term residence in the upper troposphere/lower stratosphere. Assuming a complete coverage for the high altitude haze above latitude of 35°N, then this value gives a total H_2SO_4 aerosol mass of 24 ± 10 Mt for this component of the haze. If we accept 0.7 ± 0.4 as being a reasonable value for the optical depth of the upper troposphere/lower stratosphere component of the Laki haze then its aerosol mass can be estimated independently by:

$$M_D = \frac{4\pi R^2 r\rho\tau_D}{3Q}$$

where M_D is the aerosol mass, R is the radius of the Earth, Q is an efficiency factor for scattering and absorption by the aerosols. The factors r and ρ are the aerosol particle radius and density. Adopting typical modal values of $Q = 2$; $r = 3 \times 10^{-7}$ m; $\rho = 1500$ kg m^{-3} [*Stothers*, 1984], we obtain ~27 Mt ± 10 Mt of H_2SO_4 aerosol mass, a value very compatible with the one obtained above. However, we note that the above calculation is sensitive to the values assumed for the mean aerosol radius. Therefore, it would be desirable to evaluate these results with the help of numerical simulations aimed at determining more carefully the characteristic size of the Laki aerosol size at the tropopause level.

[42] In summary, we estimate that from June to October 1783 the Laki eruption released ~95 Mt SO_2 into the polar jet stream, an amount that would yield a potential H_2SO_4-aerosol-mass-loading in the order of 200 Mt (Table 1). Our estimate indicates that ~25 Mt of H_2SO_4 aerosols were retained in the lower stratosphere for more than a year, corresponding to an excess optical depth (τ_D) of 0.7. About 85% (~175 Mt) of the aerosol mass was removed from the atmosphere in summer and fall 1783 and represents the amount that contributed to the volcanic pollution outside of Iceland. Our estimates of SO_2 yield are probably underestimates [*Thordarson et al.*, 1996], thus even if the amount of H_2SO_4 aerosol generated is not as high a proportion as we calculate, the overall mass of aerosols could still have been 200 Mt.

4. Volcanic Pollution From Laki and Its Effects on the Environment

4.1. Environmental Impact in Iceland

[43] The damaging effects of the volcanic haze and fallout of very fine ash was noticed everywhere in Iceland and it seriously affected vegetation, animals, and people [*Finnsson*, 1796; *Steingrímsson*, 1783; *Steingrímsson*, 1788]. In the first day of the eruption, the plumes carried ash and acrid rainfall over the rural areas closest to Laki. The acidity of the rainfall was such that drops burned holes in dock leaves and caused wounds on skin of animals and humans. The inhabitants also complained of irritation in the eyes.

[44] Reports from locations elsewhere are testimony that the haze was accompanied by a sulfurous smell and fallout of burning (acid) rain, along with fine black-ash and white dust (sulfuric precipitates?) that stained metal objects. People complained that the haze caused weakness, shortness of breath, and throbbing of the heart. Most of the birch trees, shrubs, and mosses were killed; these plants disappeared from many regions in Iceland for 3 and 10 years after the eruption and in some areas they never returned. Everywhere the grass in cultivated fields withered down to the roots and grass growth was stunted [e.g., *Thorarinsson*, 1979; *Thordarson*, 1995].

[45] Lethal sickness in the grazing livestock is mentioned in official reports from almost all parts of Iceland (Figure 1), featuring symptoms characteristic of chronic fluorosis such as softening and deformation of bones and joints, dental lesions, and outgrowth on the molars (known as "gaddur" [spike] in Iceland). In most parts of the country this sickness was most noticeable in late summer through early winter 1783 [e.g., *Pétursson et al.*, 1984]. However, in southeast Iceland, where the Earth was covered with fine ash containing high abundance of Pele's hair, this sickness was noticed almost immediately and resulted in mass deaths within 8 and 14 days after the onset of the eruption [*Steingrímsson*, 1783; *Guðmundsson*, 1783; *Einarsson and Einarsson*, 1786]. In all more than 60% of the grazing livestock died in less than a year, mainly from chronic fluorosis (Figure 1) [*Pétursson et al.*, 1984].

[46] As the population at the time was entirely rural and based its livelihood on farming and fishing, the disastrous effects of the eruption led to a famine lasting from 1783 to 1786. It is referred to in Icelandic chronicles as the "Haze Famine." This famine led to severe malnutrition in humans (evident from widespread occurrence of scurvy), which together with other diseases that afflicted the people, caused the death of ~20% of the population [*Finnsson*, 1796; *Hálfdánarson*, 1984].

4.2. Environmental Impact in Europe

[47] In western and northern Europe the haze was often identified to have a sulfurous odor and wet and dry deposition of sulfuric acid caused considerable damage to vegetation [e.g., *Grattan*, 1998; *Grattan and Pyatt*, 1994; *Thordarson*, 1995; *Thordarson and Self*, 2001]. Ashfall and acid precipitation recurred in the Faeroe Islands throughout the summer of 1783 and the sulfur smelling haze caused

sickness in humans and withering of vegetation in Norway [*Brun*, 1786; *Hólm*, 1784]. Corn and other vegetation was scorched and withered away when the haze appeared in Denmark and Sweden, which in conjunction with long-lasting drought resulted in failure of the summer harvest [*Hólm*, 1784; *Thorarinsson*, 1981; *Thordarson*, 1995]. In England, damage to vegetation due to acid precipitation was first noticed between 23 and 25 June. Withering of corn was noticed in Norfolk [*Bryant*, 1783] and in Selbourne, southern England; the blades of wheat turned yellow and looked as if scorched by frost [*White*, 1970].

[48] In Holland, the haze brought a very distinct sulfuric odor, which was especially noticeable between 23 and 25 June [*van Swinden*, 1783]. At the same time, many people experienced troublesome headaches, respiratory difficulties, and asthma attacks. The trees and plants lost their green color and the ground was covered with falling leaves and the fields appeared as they commonly do in October or November [*van Swinden*, 1783; *Thordarson and Self*, 2001]. These observations on damage to trees and other plants from acid precipitation are identical to those induced by industrial pollution [*Park*, 1987]. It clearly demonstrates the magnitude of the Laki volcanic pollution in distant regions.

[49] A few sources [*van Swinden*, 1783; *Pétursson*, 1784; *Hólm*, 1784] report fallout of white or grayish-white dust from the atmosphere associated with appearance of thick low altitude haze. At the same time, no condensation of watery dew was detected. These occurrences, reported from northwestern Europe, were most likely caused heavy fallout of aerosols resulting in dry condensation of sulfuric compounds. Also, in Holland, the haze tinged brass pillars on doors with a whitish color and in Switzerland it was observed to cause strong discoloring of printed matter fresh off the press [*van Swinden*, 1783]. Similar descriptions on the effects of the haze are found in sources from Germany and France [*Thordarson*, 1995].

[50] Overnight frost is reported on several occasions during the summer in weather logs and other sources from southern Germany, France, England, and Sweden. The same weather stations report early morning and early evening temperatures well above freezing, or between 10° to 15°C [*Donaubauer*, 1783; *Egel*, 1783; *Heinrich*, 1783; *Hemmer and König*, 1783; *Liessen and Phennings*, 1783; *Maret*, 1783; *Nicander*, 1783; *Planer*, 1783; *Schwaiger*, 1783]. Such dramatic temperature changes over a period of several hours are very unlikely during the summer at these locations [*Thordarson*, 1995].

[51] In this context it is important to note that the contemporary observers often, but erroneously, ascribed the injury to the vegetation to night-frost, as was alluded to by a correspondent to The Norwich Mercury on 19 July 1783:

> A correspondent is of the opinion that the late blast which affected the progress of vegetation was not a FROST as has been erroneously supposed, for then in the morning the footsteps of the cattle on the grass would have turned black, but he rather imagines that the air received such a concussion by the late earthquakes at Messina and elsewhere, that it became impregnated with sulphurous particles and had all the qualities of lightning without being inflammable [from *Thordarson*, 1995].

[52] Thus it is possible that the reports of overnight frost originated from observations of scorched and blackened vegetation caused by acid precipitation from the Laki haze. This is consistent with findings in Fennosandinavia and Alaska where narrow tree rings and low late wood density in the year 1783 are attributed to volcanic pollution [*Schove*, 1954; *Briffa et al.*, 1988; *Jacoby et al.*, 1999], significantly enlarging the area directly affected by the "noxious dews" from Laki.

4.3. Magnitude of Environmental Effects

[53] Although the contemporary records provide vivid accounts of the environmental effects of Laki, it is difficult to grasp its true magnitude by descriptions alone. As shown above, the total upper troposphere-lower stratosphere sulfuric aerosol loading by Laki was on the order of 200 Mt (= 150 Mt of pure H_2SO_4). About 85% (i.e., ~130 Mt of pure H_2SO_4) of this mass was removed from the atmosphere via acid precipitation in the summer and fall of 1783. Assuming even dispersal for the Laki aerosol plume across the Northern Hemisphere between latitudes of 35° and 90°N, this amount is equal to deposition of ~1000 kg of sulfuric acid per km^2 over a period of 5 months. However, the contemporary records show that the spatial and temporal distribution of the Laki haze was not uniform and the regions closest to the source were affected more than those further away. The regions from Iceland to Eastern Europe in the sector between the Mediterranean and the Arctic were affected the most and clearly subjected to acid precipitation well in excess of 1000 kg H_2SO_4/km^2. Judging from the pattern of SO_2 emissions with time (Figure 2b), the magnitude of this precipitation would have been greatest toward end of June through the beginning of July and again around mid to late August 1783, which is consistent with the observed trend of haze intensity (Figure 5). The first three eruption episodes (8–14 June) put enough SO_2 into the jet stream to produce ~60 Mt of sulfuric acid, which when integrated over the lowest 10 km of the atmosphere amounts to a mean concentration of ~60 ppb across the Northern Hemisphere above 35°N. It is likely that the atmospheric concentrations of sulfuric compounds at this time were significantly higher in the sector from Iceland to Eastern Europe, because the descriptions of the immediate effects of the acid precipitation on vegetation suggests atmospheric concentrations in excess of 1 ppm [*Park*, 1987].

[54] As shown above, the severe fluorine poisoning (fluorosis) was found in the grazing livestock all over Iceland. There is a good correspondence between spatial distribution of reports describing symptoms in livestock consistent with chronic fluorosis and fall out of fine ash from Laki (Figure 1). A similar relationship between distal fallout of fine ash and occurrence of severe fluorosis is found for a number of other historical eruptions in Iceland [e.g., *Thorarinsson*, 1979; *Óskarsson*, 1980] and support the notion that there was a causal link between these two occurrences in 1783. Experiments have shown that if the fluorine content exceeds 250 ppm of the dry mass of grass, it leads to chronic fluorosis that kills the animals in several days [*Sigurdarson and Pálsson*, 1957]. Several months of feeding on grass containing more than 20–40 ppm fluorine causes a mild fluorosis in grazing livestock.

[55] Approximately 8 Mt of fluorine were released into the atmosphere by the Laki eruption [*Thordarson et al.*, 1996]. *Óskarsson* [1980] showed that effective chemical

adsorption of soluble fluorine onto surfaces of tephra grains occurs within an eruption column at temperatures below 600°C. Also, the fine-grained tephra has larger surface area per unit mass than the coarser fraction and thus it can carry more fluorine. Consequently, heavily fluorine-contaminated tephra has the potential to toxify environments at a great distance from the source. The total mass of the Laki tephra is 1.1×10^{12} kg, of which 1.8×10^{11} kg were deposited as fine ash (<1 mm) at distances >50 km from the source [*Thordarson and Self*, 1993].

[56] Data from *Óskarsson* [1980] can be used to evaluate the magnitude of fluorine deposition in Iceland by the Laki eruption. He shows that ~900 ppm of volatile fluorine were removed from the 1970 Hekla eruption plume by the fine tephra fraction ($\leq$0.5 mm). Thus, after accounting for difference in the fluorine content of the Laki and Hekla magmas (F_{Laki}/F_{Hekla} = 0.55) [*Thordarson et al.*, 1996; *Sigvaldason and Óskarsson*, 1986] and assuming similar plume conditions, about 500 ppm (=500 mg/kg) of fluorine are likely to have been removed from the Laki plume by condensation onto fine ash particles. This implies that the total removal of fluorine by adsorption onto fine ash was about 9×10^7 kg or equivalent to an regional deposition of ~500 mg fluorine per km^2 of land in Iceland. This should be regarded as a minimum estimate because it ignores the potential contribution of acid precipitation from the haze. However, it is well above the known toxic limits for grazing animals [*Sigurdarson and Pálsson*, 1957] and clearly demonstrates the magnitude of the environmental toxication from the Laki eruption. Evidence of fluorosis in grazing animals has not yet been found in the historic records in countries outside of Iceland. It is possible, however, that livestock in the Faeroe Islands, Scotland, and Norway were affected by mild fluorosis.

5. Effects of the Laki Haze on Northern Hemisphere Weather and Climate

5.1. Testimony of Climatic Impact

[57] Accounts describe the winter 1782–1783 as being difficult in most parts of Iceland followed by relatively fair conditions in the spring [*Gunnlaugsson and Rafnsson*, 1984; *Ogilvie*, 1986, 1992]. The cold and harsh summer in 1783 was attributed to the presence of the volcanic haze. Elsewhere in the Northern Hemisphere weather in the summer of 1783 was unusual and extreme [e.g., *Kington*, 1978, 1988; *Steinthorsson*, 1992; *Thordarson*, 1995; *Thordarson and Self*, 1993; *Wood*, 1992].

[58] July and August 1783 were dry and hot in southwest, west, and northwest Europe [*Hólm*, 1784; *de Lamanon*, 1799; *Melanderhjelm*, 1784; *White*, 1789, 1970]. The weather was fair in central and eastern Europe, but very unstable and relatively cold in Russia and Siberia [*Engel*, 1783; *Euler*, 1783; *Presus*, 1783; *Renovantz*, 1788; *Weiss*, 1783]. For example, considerable snow fell on 23 June around Rezeszow in Poland and heavy snow cover was reported in July near Moscow. At the same time, unusually frequent, intense thunder- and hailstorms were reported form all over Eurasia [e.g., *Cotte*, 1783; *de Lamanon*, 1799; *Renovantz*, 1788; *Soulavie*, 1783].

[59] Other regions of the Northern Hemisphere also experienced unusual weather conditions. In early July, the districts near the Altai Mountains experienced harsh overnight frost. Severe drought was reported from India and the Yangtze region in China and in general the summer was extremely cold all over China [*Mooley and Pant*, 1981; *Pant et al.*, 1992; *Wang and Zhao*, 1981; *Xu*, 1988]. The summer 1783 is singled out as particularly calamitous time in Japan. A widespread failure of the rice harvest caused by unusually low late-summer temperatures and high precipitation resulted in the most severe famine in the nation's history [*Arakawa*, 1955; *Mikami and Tsukamura*, 1992]. This weather pattern is attributed to persistent northeasterly winds induced by blocking of the jet stream by stationary anticyclones situated off the east coast of Japan [*Arakawa*, 1957].

[60] In July 1783 the northern, western and part of central Europe experienced an unusual heat wave (Figure 8) as demonstrated by the following description from Vienna dated 6 August 1783:

> We have experienced here the greatest heat ever remembered in this country. According to a report from the Imperial Observatory on the 28th ult. (July) the Reamur's thermometer was at 22° (= 27.5°C), on the next day it rose to 23° (= 28.8°C), the 30th to 24° (= 30.0°C), the 31st to 25° (= 31.3°C) and on the 1st fell again to 14° (= 17.5°C). (*The Morning Herald*, London, 2 September 1783)

July 1783 is also the second warmest on record in England after 1995 [*Kington*, 1978; *Manley*, 1974; *Parker et al.*, 1992] (see also East Anglia Climate Research Unit Central England Temperature data set at www.cru.uea.ac.uk). It was also very warm in Scandinavia [*Hólm*, 1784; *Melanderhjelm*, 1784]. This heat wave occurred when the intensity of the Laki haze was the greatest in Western Europe. Records from 20 European stations in the late 1700s [*Jones et al.*, 1985] show that in the western part of Europe the 1783 July surface temperatures are 1.0 to 3.0°C higher than the 30-year mean centered on 1783 (Figure 9). July temperatures were near or just below the norm in eastern and southern Europe.

[61] The winter 1783–1784 in Iceland was very severe and was characterized by unusual weather conditions. It began unusually early, between September and October [*Arnórsson*, 1784a, 1784b; *Eggertsson*, 1784; *Einarsson*, 1784; *G. Ketilsson*, 1784; *M. Ketilsson*, 1784; *Thodal*, 1784; *V. Thórarinsson*, 1784], with intense and long-lasting frosts that completely covered the lowlands and the fjords with thick ice [*Jónsson*, 1784; *Ketilsson*, 1783; *M. Ketilsson*, 1784; *Pétursson*, 1784; *Sveinsson*, 1784; *S. Thórarinsson*, 1784]. This is a rare but not unprecedented occurrence in Iceland's climate history. Fords in northern part of Iceland remained frozen until late May to early June 1784. Reports from west- and north-Iceland give surface air temperatures below −15°C for most of the winter, with repeated occurrences of values as low as −25°C [*Ketilsson*, 1783; *M. Ketilsson*, 1784; *S. Thórarinsson*, 1784]. These are unusually cold surface temperatures for Iceland, because the 1901–1990 winter mean for west and north Iceland are −0.9 and −1.7, respectively [*Einarsson*, 1991]. 1784 was also a very severe sea-ice year and the drift ice appeared in North Iceland on New Years day. The 1784 summer was cold with overnight lowland temperatures often below freezing. In west, north, and east Iceland the soil was frozen at grass-root levels in the cultivated fields well into the month of July [*Eggertsson*, 1784; *G. Ketilsson*, 1784]. The winters 1784–1785 and 1785–1786 were also very cold in

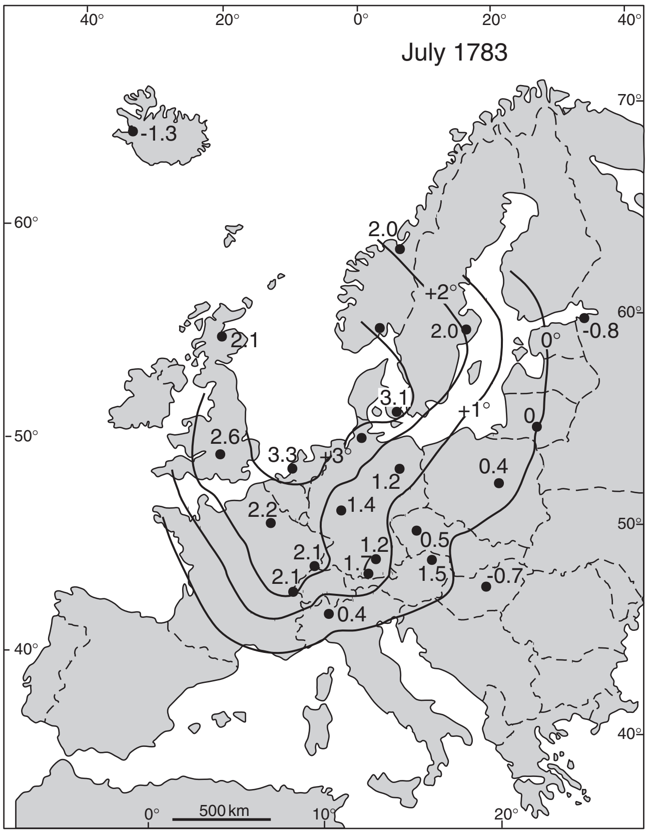

Figure 8. Deviation of the 1783 July surface temperatures from the 1768–1798 mean. Numbers are given in degrees centigrade and the distribution of the anomaly is indicated by isotherms, drawn at 1°C intervals.

Iceland and the cold spell following the Laki eruption lasted until 1786 [*Kristinsdóttir*, 1984].

[62] Winter 1783–1784 was one of the most severe in Europe and North America in the last 250 years, with periods of unusual and long-lasting frosts reported from both continents [*Ludlum*, 1966; *Rudloff*, 1967]. Articles describing the severity of the winter occurred in various European newspapers in late winter and early spring, a typical example being:

> A winter so tedious and severe has never been experienced in this country [*The Morning Herald*, *London*, 23 March 1784].

[63] The winter was unusually cold in western Norway. Sources from Bergen indicate that the summer was also cold, with frequent overnight frosts [*Thordarson*, 1995]. In January boats could not cross the straits between the Danish islands because of ice cover. It was extremely cold on the Jutland peninsula, which in mid-April was still covered by ~1-m-thick snow. There the winter conditions lasted well into May. Harsh wintry conditions still prevailed in Hamburg on 16 March and the severity of the winter is compared to that of the years 1709 and 1740. In Amsterdam, the severity was such that people could drive wagons on ice across the Markersee. The ice along the North Sea coast of Holland was so extensive that two persons skated from the village Nordwyk to Schweningen, a distance of ~25 km.

[64] Reports from Paris in late February describe a long-lasting freeze in January and February with persistence temperatures of −4°C. Also the ice and snow hindered commuter travel, causing a severe shortage of firewood in the city. From Vienna came similar news on shortage of firewood and other merchandise, because the Danube River was completely frozen over and prevented all transport. The winter was very severe in Italy [*Camuffo and Enzi*, 1992] such that the lemon crops in northern Italy were totally destroyed by intense frost around New Year's Day. Similar reports concerning the severity of the winter are also known from Munich, Prague, and Moldavia.

[65] The arrival of spring thaw raised the water of all major rivers in central and south Europe to such a degree that floods caused enormous property damage. For example; Prague and Meissen suffered much damage by floods, described as the greatest floods ever experienced in these cities. In Dresden, floods in the same river destroyed more than 100 ships that were under construction at the time. Mannheim was completely flooded by the waters of Rhine and floods occurred in the rivers Daunbe and Dneister in late February. The Spanish cities of Seville and Cádiz were described as being "under water," presumably from flooding of the Guadalquivir River.

[66] The long winter of 1783–1784 is described as one of the three landmark winters of the century in eastern United States, the others being 1740–1741 and 1779–1780 [*Baron*, 1992; *Ludlum*, 1966; *Sigurdsson*, 1982]. Commencing in mid-November and lasting well into spring (i.e., April to May), it caused the longest known closure by ice in the harbors and channels of Chesapeake Bay. The Mississippi River was filled up with ice fragments at New Orleans between 13 and 19 February 1784.

5.2. Testimony of Climatic Impact in Late Eighteenth Century Instrumental Temperature Records

[67] Late eighteenth century temperature records are available from 26 stations in Europe [*Jones et al.*, 1985] and three in North America [*Groveman and Landsberg*, 1979; *Landsberg et al.*, 1968; *Reiss et al.*, 1980]. We have plotted the mean summer, winter, and annual surface temperature deviations for these regions over a 31-year period (1768–1798) centered on 1783 (Figures 9a–9c). As an example, the long New Brunswick temperature series shows that the winter of 1783–1784 is the coldest at that station over the last 250 years [*Reiss et al.*, 1980].

[68] These records show that the summer temperatures in 1783 were above average (Figure 9a), but are far from indicating exceptionally warm weather conditions. They also show that considerable temperature variations existed between regions and with time [*Thordarson*, 1995]. In north, west, and central Europe the mean summer temperature was about 1.0°C above 1768–1798 mean, mainly because of the unusually hot July. In North America, east and south Europe the summer temperatures were close to the average and no July anomaly is apparent. It is noteworthy that at the same time unusually cold weather conditions prevailed in Japan because of blocking of the jet stream by anticyclones [*Arakawa*, 1957]. The 1784 summer mean temperatures are only a little lower than the 1768–1798 mean ($\Delta T = -0.3$°C) despite that the summer was cool in west and north Europe ($\Delta T = -1.1$°C). This

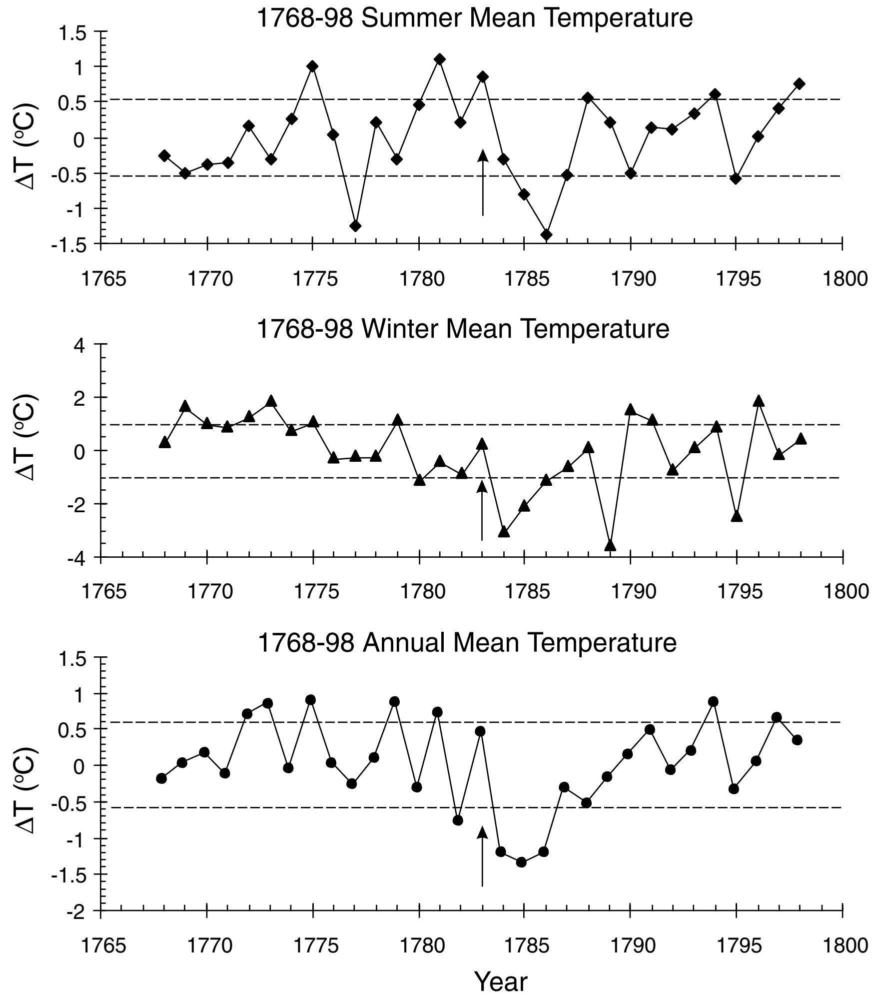

Figure 9. Late eighteenth century mean surface temperature deviations (°C) for a 31-year period centered on 1783, the eruption year of Laki. (a) Summer, (b) winter, and (c) annual. Data from 29 stations in Europe and northeastern United States were used in this reconstruction. The standard deviation (2σ) of the 31-year mean is shown by *broken lines*.

was followed by two relatively cool summers, especially in Europe, where $\Delta T = -0.9°C$ (Figure 9a).

[69] The winter mean temperature deviations (Figure 9b), indicate a very sharp and strong cooling in 1783–1784 over Europe and eastern United States, on the order of −3°C. This cooling was followed by a gradual recovery over the next 4 years. Outside of these regions the only climatological data available to us is from Japan, therefore it is difficult to assess the winter conditions in other parts of the Northern Hemisphere. The long-time series of freezing dates of Lake Suwa and reconstructed winter temperatures for Tokyo provide information on the winter conditions in Japan in the years following the Laki eruption [*Arakawa*, 1954; *Gray*, 1974]. These data sets indicate normal winter temperatures in Japan for the winter of 1783–1784, but cold condition over the winter of 1784–1785 with temperatures 1.2°C below the 1768–1798 mean.

[70] Deviations from the 1768–1798 annual mean temperature show that the 3 years following the Laki eruption were by far the coldest years of the 31-year period, with 1.3–1.4°C cooler temperatures than the mean (Figure 9c). The data also indicate that the recovery to normal temperatures took an additional 2 to 3 years. This is in agreement with the results of *Angell and Korshover* [1985] on the effects of Laki on surface temperatures in the Northern Hemisphere using data from six stations. They also estimated a probable mean reduction in surface temperatures of 0.3–0.5°C for the whole Northern Hemisphere over the same years.

[71] The significance of the surface cooling that followed the Laki eruption can be evaluated further by analyzing the temporal distribution of the coldest years and seasons within the 31-year period centered on 1783. This is accomplished by registering the 4 coldest years, summers, and winters at each station and then summing up the number of occurrences for each year from all the stations [*Thordarson*, 1995]. Although this type of an analysis is not sensitive to the amplitude of the signal, it is useful in assessing its statistical significance because the procedure is sensitive to the occurrence of cold years and seasons on a regional scale. As long as the temperature records from each station are internally consistent, this method also eliminates ambiguities in the data introduced by discrepancies between stations. Such discrepancies can arise from differences in type of instruments used, method of observation, and time in the

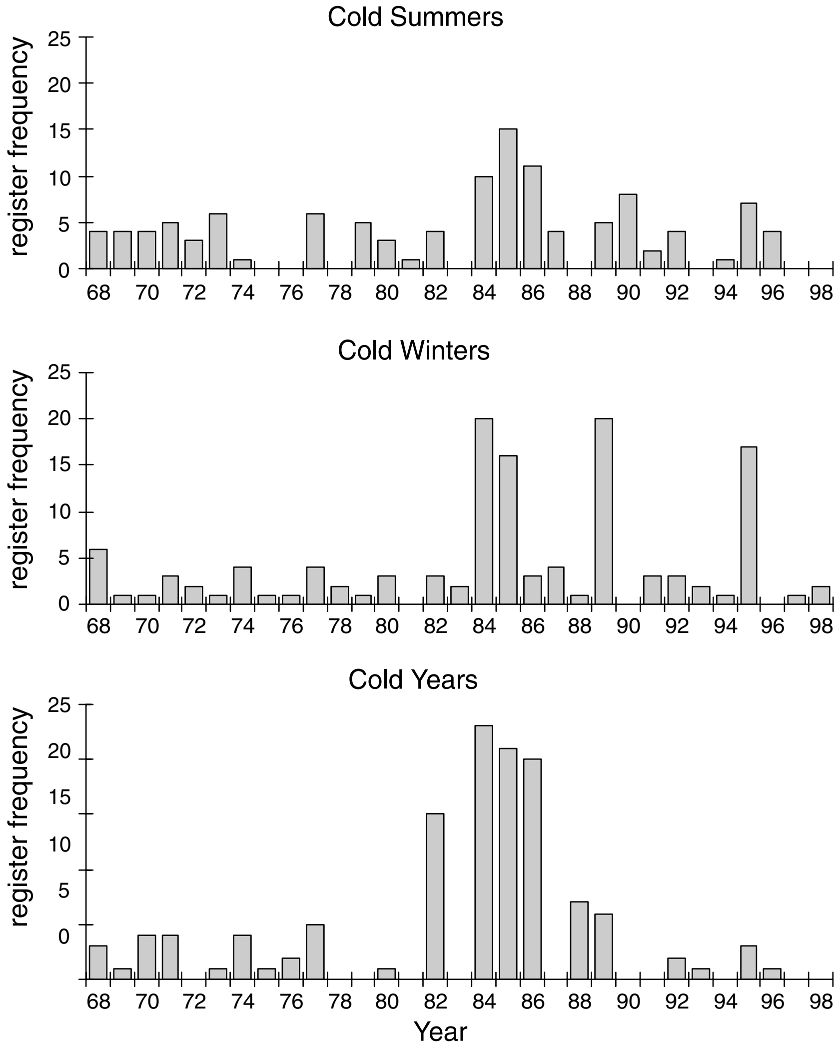

Figure 10. Frequency distribution of cold summers, cold winters, and cold years in Europe and eastern United States during the period 1768 to 1798. The analyses are based on registering the 4 coldest years at each station and then adding the number of occurrences for each year from all of the stations involved. See text for further details.

day that measurements were taken. The effect of such discrepancies can be significant in this type of data sets, because the number of stations included in the analyses is small. For the same reason, and because we include the 4 coldest years and seasons from each station, this method also minimizes the effects of extreme, but local, meteorological events.

[72] This analysis clearly shows that the cooling over Europe and North America for the years 1784 to 1786 is statistically significant (Figures 10a–10c). It also demonstrates that 1784, 1785, and 1786 have by far the highest frequency of coldest years and summers in this time period (Figures 10a and 10c). The winters 1783–1784 and 1784–1785 also register with high frequency, but are closely matched by the winters of 1788–1789 and 1794–1795 (Figure 10b). The signal for the winter 1785–1786 does not reveal anything unusual.

5.3. The Laki Haze and Its Climatic Effects

5.3.1. The July Heat Wave

[73] It has been suggested that the unusual July heat wave in western and northern Europe resulted from a short-term greenhouse warming induced by the emissions from Laki and caused by high SO_2 concentrations in the lower troposphere [*Wood*, 1992; *Rampino et al.*, 1995; *Grattan and Saddler*, 1999]. The July anomaly is strongest in western Europe and declines gradually with increasing distance from Laki, which can be taken as support for the above hypothesis. However, it is challenged by the fact that at the same time cool conditions prevailed in Iceland and Faeroe Islands [*Hólm*, 1784; *Jónsson and Pálsdóttir*, 1992; *Lievog*, 1783], regions which were consistently exposed to the gaseous emissions from Laki. Also, unusually warm temperatures are not seen in the August temperature records from the same European stations although the sulfuric haze was still present in abundance [*Thordarson*, 1995]. An alternative explanation is that the warm spell may have been caused by somewhat unusual developments in the atmospheric circulation pattern over Europe in July 1783.

[74] Analysis of weather types over the British Isles in July 1783 shows high frequency for southerly weather conditions (Figure 11), which is an unusual occurrence

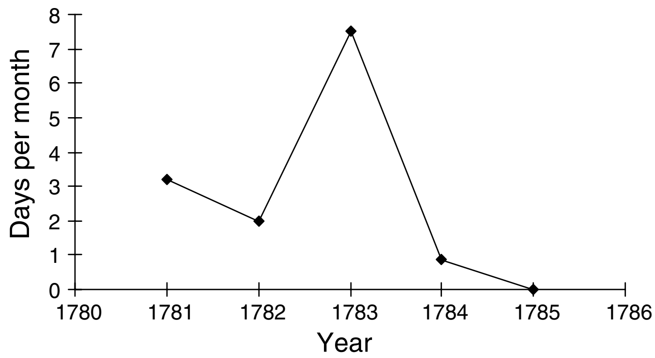

Figure 11. Frequency of southerly weather type over the British Isles in the month of July for the years 1781 to 1785. Data from *Kington* [1988].

[*Kington*, 1988]. A high frequency of southerly weather over Britain is consistent with persistent presence of anticyclones over central or northern Europe in July 1783, which produces a circulation pattern that would maintain the flow of warm air masses from the south in over western and northern Europe and could be the primary cause for the extraordinary heat. In this context, it is interesting to note that at the same time unusual circulation endured over Japan. However, whether this atypical circulation pattern on the opposite sides of the Northern Hemisphere evolved because of the atmospheric aerosol loading by the Laki eruption is a question that remains to be resolved.

5.3.2. Longer-Term Climatic Effects of the Laki Haze

[75] The evaluations presented here demonstrate that the surface temperatures in Europe and North America in 3 years following the Laki eruption were well below average. In fact, the years 1784–1786 appear to be the coldest years in the latter half of the eighteenth century (Figures 9 and 10).

[76] The upper troposphere/lower stratosphere component of the Laki haze corresponds to a hemispheric wide burden of ~25 Mt H_2SO_4 (τ_D = 0.7), an opacity that would have significantly increased the planetary albedo over the Northern Hemisphere. Thus, a drop of 1.5°C in the annual mean surface temperature over Europe and North America (Figure 9c) in the 3 years following the Laki eruption appears to be consistent with a direct offset of the radiative thermal balance of the atmosphere at the higher Northern Hemisphere latitudes. However, the results of *Fiacco et al.* [1994] indicate that bulk of the Laki haze was removed from the atmosphere by late summer of 1784. Consequently, the low annual temperatures in the years 1785 and 1786 cannot be a directly attributed to radiative perturbations caused by the Laki haze. Nonetheless, back-to-back occurrence of cold years in Europe and North America implies a common source for this short-term climatic excursion and its close temporal association with Laki indicates that these two events are related. Is it possible that a 1-year-long perturbation suppressed the climatic system to such a degree that it took two additional years for it to recover to a "normal state"?

[77] The northerly location of the Laki fissures (~64°N) and the timing of the eruption may be the key to the puzzle because sulfur-rich eruptions at high latitudes are likely to cause high concentrations of volcanic aerosols in the Arctic atmosphere [*Graf*, 1992]. Information from available Arctic sites (e.g., Figure 4b) is consistent with a heavy H_2SO_4 aerosol burden in the Arctic and the GISP ice core data implies it remained in the Arctic atmosphere through the summer of 1784. Accordingly, this aerosol burden may have caused strong disruption of the Arctic thermal balance over two summer seasons when the incoming radiative flux is at its peak [*Moritz et al.*, 1990; *Parkinson et al.*, 1987]. The net effect of this type of perturbation is substantial heating of the Arctic atmosphere and subsequent reduction of the equator-pole thermal gradient. The consequence of this excess heating would be a weaker westerly jet stream and development of mixed or meridional circulation.

[78] Weakening of the westerly jet stream in the wake of the Laki eruption is consistent with the available historic climatic data. *Kington* [1988] showed that the frequency of progressive (westerly) weather over the British Isles during 1781–1785 was well below the 1860–1978 5-year running mean, with a sharp reduction in 1784 and 1785 (Figure 12). Similar reductions were observed for central Europe in 1783 and 1784, although the anomaly is less pronounced. Other evidence that indicate a weaker jet stream are flood and drought patterns in China from 1783 to 1785 [*Wang and Zhao*, 1981], severe drought in India caused by weaker summer monsoons [*Mooley and Pant*, 1981; *Pant et al.*, 1992], and the late summer stagnation of the polar front along the Pacific coast of Japan [*Arakawa*, 1955; *Mikami and Tsukamura*, 1992; *Murata*, 1992].

[79] *Graf* [1992] used climate simulations to examine the effects of aerosol loading from a powerful volcanic eruption at high northern latitudes. The results indicate that the high-latitude radiation deficit, similar to that may have been caused by Laki, would have significant effects on the global climate. The model predicts a weakening of the westerly jet stream, prolonged winter monsoon conditions over India, and a development of a negative Walker anomaly in the Pacific. He also demonstrated that if the radiation anomaly were removed after 7 months, the forced weather and circulation pattern would still prevail for a few years. Graf's model results also indicate that the climate response to this type of forcing is not a uniform one, because it produces both negative and positive temperature anomalies and their distribution changes with the seasons. This may explain why the Laki signal is present in some dendrochronological records, but does not show up in others [e.g., *Briffa et al.*,

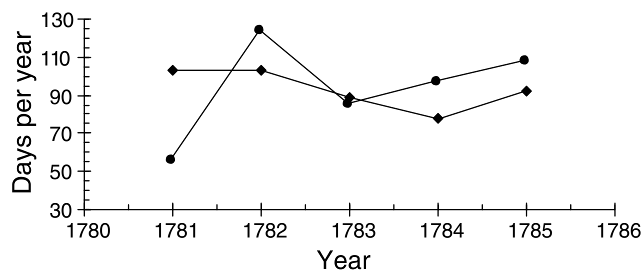

Figure 12. Frequency of westerly weather over the British Isles (diamonds) and central Europe (circles) during 1781 to 1785. Data from *Kington* [1988].

Appendix A

Table A1. The First Occurrence and Appearance of the Laki Haze

Location	Date	Comments
Prestbakki, Iceland (63°50′N, 18°02′W)	8 June	The haze was so thick and dim that light at noon was insufficient to write or read [*Steingrímsson*, 1783, 1788].
Skaftafell, Iceland (64°01′N, 17°00′W)	8 June	The great plague began on 8 June, when grass and trees withered, such that livestock became emaciated [*Einarsson and Einarsson*, 1786].
Lón, Iceland (64°22′N, 14°45′W)	<14 June	On 14 June a dark blue sulfuric smoke lingered over Hornafjörður in SE-Iceland on 14 June [*Björnsson*, 1783].
Djúpivogur, Iceland (63°59′N, 14°15′W)	9–12 June	After Whitsunday it became so dark because of the haze that it was difficult to find one's way up the mountains. The sky was red as blood at sunrise and sunset. This lasted until 12 or 14 September [*Sveinsson*, 1783, 1784].
Ketilstaðir, Iceland (65°13′N, 14°30′W)	15 June	Sunday of Trinity the eruption plume carried so much ash, sulfuric haze and darkness that one could not see from one farm to the next. This lasted the whole summer and the sun appeared blood red [*S. Thórarinsson*, 1784].
Grund, Iceland (65°31′N, 18°08′W)	17 June	12, 14, 15, and 16 June a thin bluish veil was seen in the surrounding mountains. 17 June thick haze was brought over the settlement with a NNW wind and the Sun became unusually red with a halo [*Jónsson*, 1785].
Svarfaðadalur, Iceland (65°35′N, 18°07′W)	17 June	Haze and smoke spread over the sky then sank to the surface carrying uncomfortable stench and odor [*Einarsson et al.*, 1984].
Hrafngil, Iceland (65°56′N, 18°33′W)	17 June	First signs of this unusual haze and mist were noticed in mid-June and became so great on 17 June that one could hardly see from one farm to the next [*Einarsson et al.*, 1984].
Hólar, Iceland (65°44′N, 19°07′W)	~15 June	A great misfortune was brought over this parish, as well as other parts of the country; a thick sulfuric haze not only coming from the fire emitting places in South Iceland, but also from the North; implying that fire may be up in Greenland or in the ocean North of Iceland. The haze covered the sky from 15 June to 21 September to the degree that often the sun was not visible at noon and when seen it was dark red [Author unknown; published in Kiobenhavnske Tidende 96, 1 December 1783].
Skagafjörður Iceland (65°40′N, 19°30′W)	17–18 June	On 17 June the wind turned to the NW and people noticed an unusual haze in the lower atmosphere that was blue in color. This haze was stationary and the sun was red [*Pálsson*, 1784].
Höskuldsstaðir, Iceland (65°45′N, 20°15′W)	~16 June	Haze first appeared after 15 June. A great haze and darkness covered the whole sky, such that the sun was hardly visible on cloudless days. The sun was blood red, especially in mornings and evenings. Gray dust, a mixture of ash and sulfuric salts, fell out of the haze off and on in the summer and fall [*Pétursson*, 1940].
Dalasýsla, Iceland (65°05′N, 21°45′W)	16 June	Haze was very dense/intense [*Ketilsson*, 1783, *M. Ketilsson*, 1784].
Stykkishólmur, Iceland (65°05′N, 22°45′W)	16 June	The sulfur and saltpeter moisture, smoke, ash, and sand that have been expelled from the earth fill the air to such a degree that the whole land is covered with darkness. These conditions have prevailed since eight days after Whitsunday and have completely deprived us of the normal shine of the sun. At sunrise and sunset the sun is like a fiery ball [*Arnórsson, 1783*; *Sunkenberg*, 1783].
Lambhús, Iceland (64°06′N, 22°00′W)	17 June	Haze first visible in the afternoon. The sun appeared very red and its warmth was reduced. It was believed that this haze was from the "Earth fire," which was burning in the eastern part of the country [*Lievog*, 1783].
Hafnarfjörður, Iceland (64°04′N, 21°58′W)	Summer 1783	The air constantly thick as it is loaded with "ash fog," especially when northerly and northwesterly winds prevail, such that the sun rarely appeared with its natural shine and its warmth was reduced [*Svendborg*, 1783].
Rangárvellir, Iceland (63°46′N, 20°22′W)	15 June	Fire and ash columns visible until 14 June. After that an incredibly dim haze, with dust bearing condensation, covered the Southern lowlands and by 19 June the whole island. The haze deprived us of sunshine, changed the normal appearance and warmth of the atmosphere. Precipitation of sulfuric material was noted in many regions and the dim haze caused navigation problems for fishermen [*A. Thorarinsson*, 1783].
Nuuk, Greenland (~64°N, ~52°W)	late June	A smoke-like cloud covered the sky [Unknown; Ephemerides Socieatis Meteorologiace Palatine, 1787: p. 48].
Faeroe Is. (62°N, 7°W)	~10 June	Acid precipitation and ashfall. Grass and tree leaves scorched [*Hólm*, 1784].
Norwegian Sea (~53°N, 10°W)	~10 June	Reports from ships sailing from Iceland to Denmark. Fallout of ash colored the deck and the sail black [*Hólm*, 1784].
Caithness, Scotland (58°30′ N, 3°30′ E)	10–16 June?	Ashfall; "year of the ashie"; spoiled crops [*Geikie*, 1903]
North Great Britain? (location not specified)	16 June	According to *Thoroddsen* [1914] some sources indicate that the haze first appeared in Great Britain on 16 June; "it remained for 2–3 months, and did not disappear until Michaelmass" (i.e., 29 September).
Heydon, England (52°50′N, 1°5′E)	22 June	On this day and the six that followed there was an uncommon gloom in the air, with dead calm and very profuse dew. The sun was scarcely visible even at midday and entirely shorn of its beams, so as to be viewed with the naked eye without pain. It caused the corn to wither [*Bryant*, 1783].
Selbourne, England (51°15′N, 1°5′W)	23 June	A hot, hazy, and a misty day in Selbourne. The blades of wheat in several fields are turned yellow and look as if scorched with frost. Sun was seen red through the haze [*White*, 1789, 1970].
Trondheim, Norway (63°20′ N, 10°30′ W)	~10 June	Acid precipitation and ashfall (?). Grass and tree leaves scorched [unpublished notes by S. Thorarinsson].
Bergen, Norway (60°30′ N, 5°20′W)	~10 June	Acid precipitation and ashfall (?). Grass and tree leaves withered [*Brun*, 1786].
Spydberg, Norway (59°30′N, 26°0′50″E)	22 June	Haze noted in the morning of 14 June; this may have been the first true occurrence of the Laki haze at Spydberg [*Wilse*, 1783].
North Sea (~55°N, 5°W)	25 June	Ships traveling between Norway and Holland were completely surrounded by haze from 25 to 30 June [*van Swinden*, 1783].

Table A1. (continued)

Location	Date	Comments
Denmark	June	Haze with a sulfuric odor; fall out of grayish white dust. Sun and moon appeared with red color [*Hólm*, 1784].
Copenhagen, Denmark (55°40′N, 12°30′E)	<24 June	Haze occupied lower portion of the atmosphere; below 20° of the horizon the sun could be gazed at continually with the naked eye [*Bugge*, 1783].
SW-Sweden (∼58°N, ∼13°E)	∼18 June	Appearance of the thick sun-smoke caused injuries to vegetation, leaves of trees and other foliate plants withered, the corn was scorched or turned yellow [Author unknown; Göteborgs Allehanda, 22 July 1783].
Stockholm, Sweden (59°15′N, 18°5′E)	24 June	The occurrence of sun-smoke is first specified on 24 June, but the thick fog that occurred between 12 and 14 June might be the first true occurrence of the Laki haze [*Nicander*, 1783].
Åbo, Finland (60°30′N, 22°E)	23–27 June	The "sun-smoke" was first noticed on clear days near end of June, between 23 and 27 June [Author unknown: Waderleks-Journaler 1783, 10 218–219].
St. Petersburg, Russia (59°55′N, 30°10′E)	26 June	Presence of "dry fog" is first noted on 26 June. It is possible that report of haze/fog on 14 June is the true first appearance of haze [*Euler*, 1783].
Moscow, Russia (55°20′N, 37°30′E)	30 June	The "dry fog" had definitely arrived at Moscow by 30 June, but it is possible that the haze or fog on 25 June represents the first appearance of the haze [*Engel*, 1783].
Zagan, Poland (51°35′N, 15°10′E)	17 June	In the morning a thin haze appeared and made the atmosphere very dry. It was as if the haze that absorbed all of the atmospheric moisture [*Presus*, 1783].
Prague, Czech (50°5′N, 14°30′E)	16 June	The western sky was hazy and the "dry fog" came over from the SSW across the Moldau River [*Strnadt*, 1783].
Buda, Hungary (47°30′N, 19°E)	23 June	On this day and to the end of the month this smoke of the earth constantly filled the atmosphere; it resembled a thick fog that was being continually replenished [*Weiss*, 1783].
St. Andex, Germany (∼48°N, ∼12°E)	18 June	18 June is the first day reporting the appearance of the haze or fog that lasted for several months [*Kettel*, 1783].
Tegernsee, Germany (47°45′N, 11°50′E)	18 June	As the result of the "dry fog" the sun was blood red as it was rising and setting [*Donaubauer*, 1783].
Peissenberg, Germany (47°50′N, 11°E)	17 June	The first appearance of the hemispheric haze that completely covered the sky [*Schwaiger*, 1783].
Munich, Germany (48°10′N, 11°30′E)	17 June	17 June is the first day reporting the appearance of the haze or fog that lasted for several months [*Huebpauer*, 1783].
Regensburg, Germany (49°N, 12°5′E)	18 June	On this day the "haze" (dry fog) was first observed [*Heinrich*, 1783].
Berlin, Germany (52°25′N, 13°20′E)	17 June	The sun was dull in its shine and colored like it had been soaked in blood [*Beguelin*, 1783].
Gottingen, Germany (51°30′N, 9°55′E)	18 June	18 June is the first day reporting the occurrence of the haze or fog that lasted for several months [*Gatterer*, 1783].
Erfurt, Germany (51°N, 11°E)	17 June	17 June is the first day reporting the appearance of the haze or fog that lasted for several months. It was first noticed in the evening [*Planer*, 1783].
Würtzburg, Germany (49°50′N, 9°55′E)	16 June	16 June is the first day reporting the appearance of the haze or fog that lasted for several months. It was first noticed in the evening [*Egel*, 1783].
Mannheim, Germany (49°30′N, 8°25′E)	16 June	The well known and long lasting "dry fog" that became more pronounced in the days that followed and spread all over Europe, was first noted on 16 June [*Hemmer and König*, 1783].
Rodheim, Germany (?)	16 June	Since this day and for the following six weeks the weather was very unusual because of the "Höhenrauch" [*Christ*, 1783].
Düsseldorf, Germany (51°15′N, 6°55′E)	16 June	16 June is the first day reporting the appearance of the Laki haze, which lasted for several months. It was first noticed in the morning [*Liessen and Phennings*, 1783].
Franeker, Holland (53°15′N, 5°30′E)	19 June	Nothing memorable occurred in June until the 19th day when the haze about which we are now concerned, began to appear here, at Franeker. This haze was present from 19 to 30 June. It was distinguished from the usual clouds by its constancy, density, and its great dryness [*van Swinden*, 1783].
Middelburg, Holland (51°30′N, 3°35′E)	17 June	The appearance of the Laki haze is first indicated on the evening of 17 June, then again on 19–30 June [*Perre*, 1783].
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 color of a dry leaf. Also since we could look at this star without getting blinded two hours before sunset, as it was then red as if we were seeing it through a smoked glass [*Le Golft*, 1783].
St. 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 1783). 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 [*Rigaot*, 1783].
Laon, France (49°40′N, 3°40′E)	18 June	On 18 to 24 June the fog was cold and humid with the wind coming from the south; from 24 June to 21 July the fog was warm and dry with northerly wind. One could with ease look at the sun with a telescope without a blackened lens and the sun was pale orange at noon [*de Lamanon*, 1783].
Paris, France (48°50′N, 2°15′E)	18 June	According to *de Lamanon* [1783] the haze first appeared in Paris on 18 June.
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. It was first seen shortly before midday, 14 June [*Maret*, 1783].

Table A1. (continued)

Location	Date	Comments
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 [*Seignette*, 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 Province. 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 neighboring mountains. The haze appeared concurrently at locations separated by great distances; in Paris, Salon, Turin, and Padua the haze first appeared on 18 June [*de Lamanon*, 1783].
Grenoble, France (45°15′N, ~5°50′E)	21 June	As reported in the newspaper Affiches of Dauphiny [*de Lamanon*, 1783].
Geneva, Switzerland (46°20′N, 6°10′E)	17 June	Fog of "a singular kind" appeared here, such that had not been observed by any previous students of Nature. On the 17th and 18th the haze was so thick that the sky was opaque [*Senebier*, 1783].
Neufchatel, Switzerl. (47°N, 6°55′E)	17 June	It appeared in the form of a vapor, now denser, now thinner, but through the horizon everywhere equally dispersed. The atmosphere was to such an extent obscured by this haze, that at nearly any hour of the day one could gaze at the sun without injury [*van Swinden*, 1783].
St. Gotthard, Switzerl. (46°35′N, 8°35′E)	23 June	The haze came from north and moved to southeast. It filled the atmosphere in abundance and deprived the sun of its shine, such that its light was faint and at noon one could gaze at it without injury [*Onuphrio*, 1783].
Ofen, Switzerland (46°40′N, 10°20′E)	23 June	The haze was first observed on 23 June and its presence was reported until the end of the month [*Traumüller*, 1783].
Turin (Torino), Italy (45°N, 7°40′E)	18 June	The haze was first observed in Turin on this day [*de Lamanon*, 1783].
Padua, Italy (45°30′N, 11°50′E)	17–18 June	According to *Toaldo* [1783] the haze first appeared on the 17th, but in the attached remarks he indicates the 18th as the date when the haze first appeared in the Veneto Region. Around this time Northern Italy was covered by the haze and sometimes accompanied by a uncomfortable sulfuric smell. In Padua the sun was seen red or reddish and deprived of its shine, such that it could be gazed at without injury. Often the sun appeared bluish white, the sky was white and the moon was red. The haze resembled a smoke or a dust cloud, so thick that objects at a half a mile distance could hardly be distinguished [see also *Thoroddsen*, 1914].
Bologna, Italy (44°30′N, 11°30′E)	19 June	19 June is the first day of reporting on the occurrence of a haze or fog that lasted for several months [*Matteuci*, 1783].
Rome, Italy (41°50′N, 12°30′E)	16 June	In the morning of 16 June the haze was seen toward the horizon and it was present in the atmosphere for the rest of the day. On 18 June the sky was covered with a thin veil or mist, the moonlight was red, and the sun's shine was dull [*Thoroddsen*, 1914].
Tripoli, Syria (34°30′N, 35°55′E)	30 June	From the end of June a very thick haze covered both the land and the sea; the winds blew as in wintertime; the sun could be seen rarely, and always with a bloody color, which was rare in Syria [*van Swinden*, 1783].
Altai Mountains, Asia (~49°N, 85°E)	1 July	On 1 July the haze (heerrauch) appeared and lasted until the 17th. On 12 July it was so cold that the thermometer, at noon and in the sun, did not rise higher than 11°C. This was followed by a series of days with quite severe frost overnight [*Renovantz*, 1788].

Table A2. Descriptions of the Altitude and Optical Effects of the Laki Haze

Location	Description and source
Copenhagen, Denmark	Here in Sjælland and Copenhagen, we noticed the unusual reddish appearance of the sun, especially during the period early June to 8 August. Throughout July the atmosphere, which was clear in itself, was loaded with such immense fumes and dust that the sun was only visible until 8 or 9 o'clock in the evening. The same is to say about the sun in the morning, and even at noon it did not shine brightly, appearing as red as it did in the evening. The same applies to the moon and the stars [*Hólm*, 1784]. In June: By day 24 dry fog occupied the lower portion of the atmosphere, to such an extent that the sun, when below 20° of the horizon, could be looked at ceaselessly with naked eyes. Meanwhile, the sun that normally is yellow appeared red. In July: As the sun approached the horizon below an altitude of 10°, its track could not be followed, not even when the cloud (dry fog) was thin. In August: The red colored sun could frequently be gazed upon with naked eyes without aggravation, even at altitudes of 20–30° above the horizon [*Bugge*, 1783].
South Halland, Sweden	The so-called "sun-smoke" has now for many weeks been permanently resting over the horizon, so thick that in mornings and evenings the sun appears completely red. If the origin of this smoke was exhalations from the ground, it should have disappeared with wind or after rain, but the opposite is the case: but after a rainy day it reappears as strongly as before [Göteborgs Allehanda, 22 July 1783; Stockholms Posten, No 171, 29 July 1783].
Berlin, Germany	From 17 to 29 June the shine of the sun was practically dull because the atmospheric haze, but on the other hand, the sun often appeared red in color at sunrise or sundown, as if it had been soaked in blood. The atmosphere, evidently, was stuffed with very thick exhalations that prevented transmission of the rays (sunshine), and particularly on 22, 23, 24, 26, and 28 June, whereby it could not be observed at all. July to October: Rising and setting sun was blood red and the atmospheric haze was said to be located up toward the sky [*Beguelin*, 1783].

Table A2. (continued)

Location	Description and source
Mannheim, Germany	At Mannheim the Laki haze was documented in a continuous succession from 16 June to 6 October. In late June the sky was almost completely concealed by the haze and accordingly the heavenly bodies were not seen below 40° of the horizon. In early August the sun was described as reddish at 8° above the horizon and at 5° the whole disc of the sun was red for 20 min. On 30 August the sun was seen descending into the haze at 12° above the horizon. Consequently, its horizontal diameter was enlarged but its vertical diameter was reduced, the sun became oval in shape and shining red. At 6° above the horizon its color was red like blood and its shape elliptical. At 3° above the horizon the sun disappeared altogether [*Hemmer and König*, 1783].
Peissenberg, Germany	On 17 June the *hemispheric haze* was present almost the whole day. On the 18th the atmosphere was completely filled with the hemispheric haze the entire day. At 8 p.m. the mountains were visible again as a storm from west lifted the haze. A complete cover of very thick haze (dry fog) was common over nights and in the mornings, but at midday the haze became thinner as the breeze lifted it. Past midday the haze became thicker again as it was replenished gradually. July through October: The hemispheric haze was present for most of this time and the appearance of the sky was commonly dull or pale. Typically in daylight hours the entire horizon was concealed by thick haze, which became thinner for a brief period over midday because the haze was lifted by a breeze, then it returned in the evening as thick as before. On several occasions haze was present in the higher levels of the atmosphere [*Schwaiger*, 1783].
Zagan, Poland	In the morning of 17 June a thin haze appeared, which caused the hygrometer to disclose continuous readings of almost no atmospheric humidity, as if the fumes had absorbed it. From this day and all through to September, October, and beginning of November it never disappeared completely. This dry fog is in essence a similar phenomenon as ‘‘Höhenrauch,’’ ‘‘Herrauch,’’ or ‘‘hegerrauch,’’ but surrounded us day and night. Heavy storms with lightning and violent rain had no effect on its presence. Some days in July the sun was hardly visible; mornings and evenings its color was exceptionally red, less so at midday when it was more yellowish green. Clouds did unquestionably not cause this coloration because the thick haze occupied the sky at the horizon. During the month of August the moon, when rising through the dry fog, could not be securely identified at altitudes below 6°. In September the dry fog moderately strong and almost all the western sky toward the horizon was red. On 25 September at 5 a.m. there were hardly any clouds in the sky toward the horizon, but indeed dry fog of moderate intensity coloring the sky bright yellow-green. At 5:30 a.m. the eastern sky was all red, but the dry fog of transparent color. In October: The haze occupied the middle atmosphere and clouds were unusually red in color. In November: During the first 5 days of this month a thick haze was seen toward the horizon at 6:30 a.m., but somehow not at the Zenith. Similar occurrences were also observed in the evening around 6 p.m. [*Presus*, 1783].
Prague, Czech	On 16 and 17 June the haze fell over from the SSW beyond the Moldau River, just as the mountain fog, and completely covered this region. Wind, rainfall or the thunderclouds that appeared in the southern sky did not affect this haze. The haze was thick all over and the sun appeared unusually pale through the cloud, such that it could be viewed by naked eyes without injury. At sunset the sun was blood red and the clouds in the North and the West displayed intense red color. With the rising sun the whole horizon became hazy, especially in the South [*Strnadt*, 1783].
Buda, Hungary	On 23 June and all the way to the end of this month the atmosphere was constantly loaded by the smoke of the earth, that resembled a thick fog that was continually replenished [*Weiss*, 1783].
Franeker, Holland	Across the haze the sun was perceived deep red, with brilliance at the edge; even at midday itself we were able to gaze at the sun with our naked eyes without injury. Objects scattered further were scarcely, and only unintelligibly perceived [*van Swinden*, 1783].
Amsterdam, Holland, 11 July 1783	For 8 days we have had extraordinary heats, concurrently the atmosphere is steadily so thick that the sun becomes extinct at 5 p.m. and resembles a glowing charcoal, then right after 7 p.m. it disappears. At the onset of night an unbelievable fog falls over, such that most of the vegetation in the fields looks burned and the leaves fall off the trees. This is very peculiar; because we have this weather regardless of the direction the wind is blowing [Odense Adresse-Contoirs Efterretninger, No 36, 18 July 1783].
Selbourne, England	The summer of the year 1783 was an amazing and portentous one, and full of horrible phenomena; for, besides the alarming meteors and tremendous thunderstorms that affrighted and distressed the different counties of this kingdom, the peculiar haze, or smoky fog, that prevailed for many weeks in this island, and in every part of Europe, and even beyond its limits, was a most extraordinary appearance, unlike anything known within the memory of man. By my journal I find that I had noticed this strange occurrence from 23 June to 20 July inclusive, during which period the wind varied to every quarter without any alteration in the air. The sun, at noon, looked as blank as clouded moon, and shed a rust-colored ferruginous light on the ground and floors of rooms, but was particularly lurid and blood-colored at rising and setting [*White*, 1789].
Le Havre, France	By 18 June, after a period of fogs that was 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, since at noon the light reflected by white objects had a light tint such as the color of a dry leaf. We could look at this star without getting blinded two hours before sunset, as it was then red as if we were seeing it through a smoked glass [*Le Golft*, 1783].
La Rochelle, France	On 18 June the rising sun was red, without any shine and was seen this way until 6 a.m. and after that the haze seemed 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. June 23: The shine of the sun was almost completely obscured by the haze and on the following days it was with a dull yellow color at midday. In early July the thick haze depleted the shine of the sun to such a degree that it did not produce shadows. In mid August the sun did not appear in the sky until 9 a.m. and by 5 in the afternoon it was bright red, deprived of its shine and at one moment it disappeared completely [*Seignette*, 1783].
Paris, France	4 July 1783. For a considerable time past the weather has been very remarkable here, a kind of hot fog obscures the atmosphere and gives the sun much of that dull appearance that the wintry fogs sometimes produce. The fog is not peculiar to Paris; those who come lately from Rome say that it is as thick and hot in Italy, and that even the tops of the Alps are covered with it, and travelers and letters from Spain affirm the same of that kingdom [*de la Lande*, 1783].

Table A2. (continued)

Location	Description and source
Burgundy, France	June 1783. The characteristics of the haze are to be not much thick, more or less transparent and widely spread in the vast space that it occupies. The character of ordinary clouds is to move when they are pushed by any wind. This cloud remains stationary. It varies only by a little more or a little less condense [*de Lamanon*, 1783].
Salon de Crau, Provence, France	June 1783. What brings me to believe that the haze occupies a large spread in length and in width is that, having observed it in Auxerre, I found it again in St. Seine below the springs of the river Seine. From the height of the mountains I can see that the entire horizon is bluish. Also what proves to me that it occupies equally a vast space in-depth or perpendicular height is that the springs of the Seine where I just wandered is one of the highest points and here still the cloud dominates these heights. The haze rises much above our highest mountains. On the upper plateau from which the Seine flows I have seen the sun darkening and become very red in the evenings and mornings. At the abbey of St. Seine, while observing those facts with the monks of the house, we have been able to fix our gaze lengthily on the sun without tiring our eyes. I cannot give a better expression of the modification of the sun's rays by the fog than to report our own words: "The sun would be well visible today with a telescope without darkening the lens." Then several people who saw the sun for the first time in this state thought at first that they were looking at the moon. Nevertheless, the sun at noon is more apparent. Seen in an almost perpendicular direction, the sun sends its rays through less thickness of the haze than when they come to us at a slant in the evening and the morning. At night the stars are obscured because a circle of thick haze wraps the horizon, but the sky shows above our heads and few stars are erased because the haze is not as thick [*Soulavie*, 1783].
Salon de Crau, Provence, France	June 1783. Lamanon learned that the haze was present all over Europe, he traveled to the highest peaks of the Provence, Dauphine, and Piedmont Alps to collect information regarding the haze. He concluded that it appeared concurrently at locations separated by great distances and when the haze first appeared in various locations the observed wind direction at the time varied from one location to another. The sun was blood red at rising and setting and very pale or with a dull shine over the day. Because many considered the haze to be confined to the lower atmosphere, Lamanon climbed to Lamanon climbed to the top of Mt. Vetoux (6200 feet) and noted that the haze was still above him. Senebier in Geneva wrote Lamanon stating that the haze was present above Mt. Saleve (3600 feet) and the highest peaks in the Alps. The shepherds in the Dauphine Alps stated that the haze was well above the locations where they kept their flock [*de Lamanon*, 1783].
Saint-Veran, Maconnais, France	In the later days of June and the early days of July, that is, at the end of the moon cycle of the first month and the beginning of the second, when the moon does not spread any light, we could see a luminosity at night almost equal to that which the moon provides when it is full, yet hidden by a cloudy and overcast sky. Its degree of intensity was such that we could very distinctly see objects distant by about one hundred fathoms. This phenomenon was apparent on the entire circle of the horizon; it occupied the whole celestial hemisphere and it was not momentary [*Robertjot*, 1784].
Geneva, Switzerland	The dry fog was of "a singular kind" and had not been observed by any previous students of Nature. The dry fog was so dense that it impeded the view of distant objects by an octant of light, took away the rays of the rising and setting sun and tinged it with a red color. It was of permanent nature, not affected by violent winds or very copious rains. The color of the haze was blue or bluish, but never gray. The haze was odorless and when it was present the atmosphere was very dry. It also extended above the highest peaks of the Alps [*Senebier*, 1783].
Neufchatel, Switzerland	According to Rev. Meuran and Dom. du Vasquier of the city of Neufchatel in Switzerland, the haze began to appear on 17 June in the form of a vapor, now denser, now thinner, but through the horizon everywhere equally dispersed. The atmosphere was to such an extent obscured by this haze, that at nearly any hour of the day one could gaze at the sun without injury. Often the summit of the Alps was clearly distinguished on the other side of the haze, not, to be sure, the base. Normal rain did not disperse the haze and it only gave ground to rain, which was accompanied by thunder, and even then with difficulty, and only for a short time. The east wind increased this haze, and only the stronger west wind was able to disperse it. Indeed, as soon as this stopped, the haze returned [*van Swinden*, 1783].
St. Gotthard, Switzerland	An unusual "upper atmospheric" haze or fog that first appeared in late June coming from the North moving toward the Southeast. This haze filled the atmosphere in abundance, even when the "normal fog" perished. This haze deprived the sun of its shine, such that its light was faint and caused the moon to appear with a golden yellow shine at night [*Onuphiro*, 1783].

1988; *Schove*, 1954; *Bradley and Jones*, 1992, and references therein].

6. Concluding Remarks

[80] The great Laki eruption had marked effects on the atmosphere and the environment in the Northern Hemisphere in 1783 and 1784. The Laki eruption emitted ~95 Mt of SO_2 into the atmosphere over a period of 5 months. In doing so, it produced a 200 Mt sulfuric aerosol loading that covered half of the Northern Hemisphere and the eruption sustained a 25 Mt H_2SO_4-aerosol loading in the upper troposphere/lower stratosphere for more than a year. Consequently, about 175 Mt of H_2SO_4 aerosol mass was removed from the atmosphere in summer and fall 1783 and caused the widespread volcanic pollution experienced outside of Iceland.

[81] Because the main mass loading of gaseous compounds from Laki were mostly confined to the upper troposphere and the lower stratosphere (9–13 km altitude), the dynamics of atmospheric transport, dispersal, and removal of sulfuric aerosols were very different from that of other eruptions where the SO_2-mass-loading was predominantly stratospheric (>15 km). The main differences were: (1) prolonged eruption with semisteady SO_2 mass-loading over a period of several months (Figure 2 and Table 1); (2) the dispersal of aerosol plumes was confined to the westerly jet stream above latitudes of 35°N (Figure 4a); (3) dispersal and atmospheric removal of the aerosols cloud was greatly effected by diurnal

changes in circulation pattern, where interaction between the jet stream and the broad scale vertical motions of the troposphere generated by cyclones and anticyclones were important (Figure 7). These differences need to be taken into account when assessing the climatic effects of the Laki eruption.

[82] Eruptions similar in style and magnitude to Laki will recur in Iceland and perhaps in other areas of basaltic volcanism. If such an eruption were to occur today, it would increase air-pollution drastically over large areas of the Northern Hemisphere for several months. The volcanic cloud is likely to be of near hemispheric dispersal and concentrated at altitudes between 7 and 15 km, which is the cruising-altitudes of most jet aircraft. The cloud would consist of submicrometer aerosols and ash particles and if entered by jet-driven aircraft it could result in immediate thrust loss and possibly engine failure [*Bernard and Rose*, 1990; *Casadevall*, 1992]. Hence a Laki-like haze would be a safety threat and might keep many planes grounded over large parts of Europe and N-America, which would have serious economic ramifications.

[83] A more serious long-term effect and of much greater concern, is how the natural ecosystems of these areas would respond to an event of this magnitude, especially in Europe, where they are already overstressed and weakened by human pollution [*Park*, 1987]. It is possible that a Laki-like eruption could seriously damage the natural habitat in these areas. Furthermore, the Laki event is the closest analog to a flood basalt eruption to have been observed and documented by man [*Thordarson and Self*, 1993]. A thorough understanding of the eruption dynamics and atmospheric effects of Laki will therefore provide a useful model for evaluating the climatic impacts of past flood basalt volcanism on Earth.

[84] Finally, despite the quality and value of the contemporary accounts for quantifying the impact of Laki, a full understanding of its effects cannot be acquired by analyzing the historic data alone. Further examination of the impact of the Laki eruption using this data as inputs for numerical climate circulation models would be very useful for furthering our understanding of climatic perturbation by flood lava events of Laki-like magnitudes and bigger.

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