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research

# The dating of volcanic events and their impact upon European society, 400-800 CE

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This paper discusses volcanic eruptions and their climate impact in Europe 400-800 CE. Combining historical evidence with that from proxy sources, it expands upon existing knowledge of these events as well as highlighting previously unrecognized or misdated eruptions. The four case studies indicate that the cumulative effect of two or more eruptions within a short space of time may have had the greatest impact on the historical record.
**Keywords**: volcano, eruption, climate, crises, sources

*L'articolo tratta delle eruzioni vulcaniche e del loro impatto in Europa tra il 400 e l'800 d.C. Combinando informazioni provenienti da diverse fonti, amplia l'attuale conoscenza di questi eventi, evidenziando inoltre eruzioni precedentemente sconosciute o mal datate. I quattro casi studio dimostrano l'impatto notevole che due o più eruzioni a breve distanza di tempo possono avere nel record storico-archeologico.*
***Parole chiave**: vulcani, eruzione, clima, crisi, fonti scritte*

That large volcanic eruptions can have a major climate impact has long been understood. Sulphate aerosols injected into the stratosphere by a powerful eruption can significantly diminish the amount of sunlight reaching the Earth's surface (Langmann 2014). Thus, in addition to the immediate devastation inflicted upon any human society in the vicinity of the eruption, a volcanic eruption of sufficient size has the potential to impact societies across the planet. In the case of really huge volcanic eruptions, on a par with or exceeding the extraordinarily violent 1815 eruption of Tambora, Indonesia, European temperatures can fall by up to 2.5°: enough to tip precarious medieval agricultural systems into crisis (Woods 2014; Parker 2014, pp. 17-21).

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To judge from the historical evidence, augmented by that of natural proxy sources, especially tree-rings and ice cores, several eruptions of sufficient force to impact significantly upon Europe's climate and society took place in the post-classical period. A detailed list of possible volcanic events of this nature (up to 630 CE) can be found in Table 1 of R.B. Stothers and M.R. Rampino's 1983 path-breaking paper, *Volcanic Eruptions in the Mediterranean before A.D. 630 from written and archaeological sources* (Stothers, Rampino 1983). Here we revisit and expand upon instances in which modern palaeoenvironmental data considered in tandem with the historical record both clarifies and asks further questions of the nature of these events. We further highlight several new dates in which the historical record may indicate the occurrence of previously unrecognized or misdated volcanic eruptions that affected Europe's climate. Our case studies emphasize the point that the cumulative effect of two or more eruptions that chanced to occur close together in time may often leave the most profound imprint in the historical record.

## 472

One of the most well-studied examples of a powerful volcano in this period is that of the eruption of Vesuvius, 6 November, 472 CE. Modern analysis of the eruptive and secondary deposits from this eruption show that the eruption phase was predominantly hydromagmatic (Mastrolorenzo *et al.* 2002, p. 33), a particularly violent form of eruption (Mastin, Witter 2000; Mastin *et al.* 2004). In other words, the magma interacted explosively with a great volume of water and blasted enormous quantities of ash high into the atmosphere. The volcanic cloud drifted northeastwards and ash landed at Constantinople, 1,242 km away.

Our historical sources for this event are mostly Byzantine and thus the ash fall on the God-Guarded City was the focus of their attention. Marcellinus, an imperial secretary, had moved to Constantinople from the Balkans around 500 CE and was probably an eyewitness to the fall of ash on his own lands: "Vesuvius, a parched mountain of Campania, with seething internal fires vomited out its entirely burned-up entrails and with nocturnal darkness falling upon the day, it covered up the whole face of Europe with dust. To remember their fear of this the Byzantines celebrate the memory of the ashes annually on 6 November"[1].

[1] Marcellinus Comes, *Chronicon* [hereafter MC], p. 90: *X. Marciani et Festi. Vesuvius mons Campaniae torridus intestinis ignibus aestuans exusta evomuit viscera nocturnisque in die tenebris incumbentibus omnem Europae faciem minuta contexit pulvere. huius metuendi memoriam cineris Byzantii annue celebrant VIII idus Novemb*. See also Croke 1995, p. 25 for a somewhat freer translation.

Given Marcellinus's status as a probable eyewitness, the details of his account should generally be preferred to those of later authors. Three such sources, written later in the 6th century, corroborate the ash fall, if not the year of the eruption or the precise calendar date of the ash fall. Procopius of Caesarea, a well-travelled advisor to the notable Byzantine general, Belisarius, observed briefly that an incident took place in which ash fell in Constantinople (Procopius of Caesarea, *De Bellis* [hereafter PC], 6.4.27). Theodorus Lector, based at the Hagia Sophia in Constantinople, wrote his *Historia Ecclesiastica* between 518 and 543 and in it he stated that, "in this year [473] ash fell, before which the clouds in the sky were seen to burn" (p. 177). In the chronicle of John Malalas, written around 570[2], is the following entry: "During his reign [Emperor Leo I, r. 457-474] there occurred in Constantinople a fall of ash instead of rain, and the ash settled on the tiles to a depth of four fingers. Everyone was terrified and went on processions of prayer saying, 'it was fire, but through God's mercy it was quenched and became ash'"[3].

A generation later, the anonymous compiler of the *Chronicon Paschale* drew upon Malalas for his similar account, although misdating the event to 469. "In this year it rained ash instead of rain in Constantinople; the ash lay on the tiles to a palm's depth. And all trembled, chanting litanies and saying, 'there was a fire and it was quenched, and ash was found since God was beneficent', in the month Dius, November 11th"[4]. Much later still, Theophanes "Confessor" (d. 818), Byzantine monk and abbot, wrote in his chronicle that, "in this year [473] dust came down from clouds that seemed to be burning, so that everyone thought it was raining fire. Everybody performed litanies in fear. The dust settled on roofs to the depth of one palm. Everybody said that it was fire and that it was put out and became dust through God's mercy"[5]. These accounts give evidence for a deep societal response to an unparalleled environmental event. For centuries after the eruption, processions were thus held in Constantinople to thank God that the city had been protected from a natural disaster that the citizens felt had been imminent. Did the volcano also impact in terms of the economic or agricultural life of the region? There certainly are historical reports of hardship around this time, but interestingly they come somewhat earlier than 472 and from regions to the west and north of Vesuvius.

[2] Ioannis Malalae, *Chronographiae* [hereafter JM]. For translation see Jeffreys *et al.* 1986.

[3] JM, pp. 205-206. By contrast with the fires of Hell, which do not become ash. Issiah 66.24. For Emperor Leo I (401-474) see Martindale 1980, pp. 663-664.

[4] *Chronicon Paschale* [hereafter CP]. For translation see Whitby, Whitby 1989, pp. 90-91.

[5] Theophanes, *Chronographia* [hereafter TC]. For translation, see Mango, Scott 1997, p. 169.

Hydatius, bishop of *Aquae Flaviae* (Chaves, Portugal), was born c.400 in a town just inside the borders of southern Galicia in Spain (Hydatius, *Continuatio Chronicorum Hieronymianorum* [hereafter CH], p. 4). He wrote a chronicle that finishes in 469 CE (CH, pp. 5-6). Thus Hydatius was contemporary with the relevant events he describes. Furthermore, great confidence can be given in regard to the dating of the reports that concern us, due to the fact that Hydatius recorded a solar eclipse in 464 CE: "Olympiad 311, year 3. On Monday, 20 July, from the third hour to the sixth, the sun was perceived to be diminished in its light to the appearance of the moon on the fifth day" (CH, p. 117). Precise confirmation of this eclipse, to within three hours, is available from modern calculations[6].

For 467 CE Hydatius (CH, p. 128) wrote:

> "Envoys returning from the king of the Goths brought back news of a number of portents seen in Gaul. [They said] that before their eyes … another sun, like the real one, seemed to have appeared immediately … at sunset; that, when the Goths had gathered together on a certain day for their assembly, the iron sections and the blades of the spears which they carried in their hands had for a time not kept their natural appearance of iron but changed colour: some were green, some red, others yellow or black".

And for the following year, 468 CE:

> "The year proved unusually harsh at this particular time and the weather and all the fruit of winter, spring, summer, and autumn were confused.
> … not far from the above-mentioned *municipium* [Aquae Laeae], some type of seeds fell from the sky. These seeds were very green like grass and looked like lentils but were bitter to the taste. And there were many other portents which would take too long to recount"[7].

6 Here from Espenak, Meeus 2006. Online in: http://eclipse.gsfc.nasa.gov/SEsearch/SEsearchmap.php?Ecl=04640720 [accessed 7 January 2015].

7 CH, p. 123. Stothers, Rampino 1983, p. 6362 note this account but assume it must relate to the eruption of 472. "Other portents" may refer to an event noted by CP, pp. 89-90 and Victor of Tunnuna,*Chronicum cum reliquiis ex Consularibus Caesaraugustanis et Iohannis Biclarensis Chronicon*, p. 17, which Newton 1972, p. 682 catalogues as a comet, although uncertainly. This event warrants further examination.

Sidonius Apollinaris, nobleman of Lyon and later bishop of Clermont wrote in a letter of prospective grain shortages in Rome in 468 CE: "I rather fear that there may be an uproar in the theatres if the supplies of grain run short, and that the hunger of all the Romans will be laid to my account" (Sidonius Apollinaris, *Epistulae*, I, 10). In his own famous history, commenting on the letters of Sidonius, Gregory, bishop of Tours (c.539–594), wrote that for c.471–474 CE there was a great and long-lasting period of famine in Burgundy (Gregory of Tours, *The History of the Franks*, II.24). Jordanes, a Byzantine *notarius* who had lived near the Danube in modern Bulgaria, wrote a history (c.551 CE) that included descriptions of the great river being frozen so solid that armies could pass over it. Jordanes stated that this took place sometime after the battle of Bolia (Jordanes, *Getica*, V.1.130), a battle whose date is contested by modern historians, but which was either 469 CE or 470 CE. Further references to the frozen Danube at around this time come from Eugippius, the founder of a monastery near Naples. Eugippius was an eyewitness to a number of winters in which the river froze, but unfortunately his *Life of St Severinus of Noricum* was vague about the specific dates in which this happened. From the other events described in the *Life*, what may be determined is that the freezing of the Danube occurred several times in the decade 460–470 CE.

Although very terse, a contemporary set of annals with a focus on Ravenna adds another piece of valuable information. The *Fasti Vindobenses* (sometimes known as *Anonymus Cuspiniani*, since they were published by Johnannes Cuspinianus in 1553), record that in 467 CE, "no small mortality of cattle took place" (*Fasti Vindobenses*, p. 305). The term *mortalitas* was used both for diseases and mortality periods such as occurred after harsh winters, where animals died (or were perhaps in some cases slaughtered) in large numbers due to lack of fodder. In this instance, the cause of the large decline in the cattle population may be linked to a disease that is reported to have broken out among cattle in China[8].

In examining this evidence, it appears plausible to suggest that we might be dealing with two volcanic events within five years of each other: an unknown volcano in c.467 and Vesuvius in 472. If there was indeed an eruption near 467, the climate cooling it caused may have triggered frozen rivers and been related – either directly, through lack of fodder, or indirectly by weakening the disease resistance of the animals – to a collapse in cattle numbers in Europe. More speculatively, the dust and aerosols from

[8] Zhang 2004, v. I at 467, 468, 469. For a case study of a medieval cattle panzootic spreading from East to West see Newfield 2009.

this hypothetical eruption may also have helped promote the atmospheric conditions necessary for the manifestation of a "second sun" at sunset.

It seems most probable that this second sun reported by Hydatius for 467 may have been a "sun dog" or "mock sun" (*parhelion* in scientific terminology). In his classic work on atmospheric colour and optics, Marcel Minnaert describes the formation of lunar and solar haloes resulting from the interaction of sunlight with high-altitude ice crystals (Minnaert 1954, pp. 190-193). Richard Stothers has also drawn attention to observations of second suns in the classical era – their spectacle ensuring that contemporary observers paid note[9]. Mechanisms by which volcanic eruptions might promote (or indeed suppress) *parhelia* by altering high altitude temperatures, circulation, humidity, opacity, chemistry and providing condensation nuclei are little studied[10]. Yet volcanic dusts and aerosols are known to induce deeply red twilights as well as discoloured solar discs and coloured rings through a variety of mechanisms. These "Bishop's Rings" must be considered plausible candidates for at least some historical descriptions of "second suns" (Lynch, Livingston 2001; Vollmer 2005; Fantz 2004). The confluence of a double sun in association with the perceived discolouration of iron weapons and subsequent dramatic temperature falls in Europe for the following years may well be symptomatic of a volcanically perturbed atmosphere and climate.

Natural proxy data from ice-cores can also be interrogated to examine these years. Thus, atmospheric sulphate deposition in the GISP2 Greenland ice-core suggest just one volcanic event, dated to c.472[11], when sulphate deposition on the Greenland ice appears anomalously high, at 62.01 ppb (in terms of total non-sea-salt sulphate), with 55.15 ppb considered a threshold above which volcanic eruptions may be distinguished from background deposition rates (Ludlow *et al.* 2013). This may well represent the fallout of sulphate from Vesuvius in 472. Tephra analysis would prove especially valuable in confirming this identification, in particular because the resolution of data from the GISP2, though state-of-the-art in the 1990s, is now somewhat low, with each sulphate measurement representing approximately 2.5 years for our period (Mayewski *et al.* 1997). Alongside damage to the core (particularly in the

[9] Stothers 2009, *passim*. For observations in a later historical context, see Janković 2000.

[10] An association between lunar haloes and volcanic dust-veils is noted in passing by Grattan, Pyatt 1999. These authors cite Camuffo, Enzi 1994, who summarize historical observations of the "sun and moon surrounded by bloody halos" preceding or following (probable) volcanic dry fogs. Whether the haloes described by historical observers are the same as the haloes as presently scientifically defined, and associated with the formation of parhelia, rather than coronae, requires careful consideration.

[11] More precisely, 471.70 on the Meese-Sowers GISP2 time-scale; see Ludlow *et al.* 2013 and references therein.

6th century) and small expected errors in annual layer counting, this introduces some uncertainty in both the dating and number of volcanic events registered in the c.472 sulphate deposition signal.

Higher resolution sulphate data from Greenland is now also available. Here the NGRIP ice-core identifies moderate volcanic sulphate deposition at 461 and 463, while the NEEM ice-core also identifies moderate deposition at 461 and 463, but with deposition from the latter event extending to 464[12]. Neither core ostensibly support either an eruption in c.467 or 472. Michael Baillie has, however, provided compelling evidence that the GICC05 (Greenland Ice Core Chronology 2005) timescale upon which both the NGRIP and NEEM dates are based may exhibit an error of up to seven years in the 6th and 7th centuries, and potentially beyond (Baillie 2008 and 2010). If a correction of seven years also applies to our period of interest, this suggests two volcanic events at c.468 and c.470/471. In light of an expected additional small c.2 year uncertainty in annual layer counting[13], the ice-core evidence appears consistent with the implications of a careful examination of the historical evidence, namely that Vesuvius 472 followed another major eruption approximately five years earlier.

## 536

> "The whole city [Constantinople] was disturbed, and the earth with all that is upon it shook at the arrival of Agapetus [Pope Agapetus I arrived in Constantinople, March 536]. The sun began to become dark at daytime, and the moon by night, while the ocean was stormy with spray [alternatively: clouded by spray] from the 24th of the same month of this year [March, 536] until the 24th of June of the following [indiction] year fifteen [537] … The winter was [so] harsh that from the unusual amount of snow the winged creatures perished, and … [from here there are lacunae in the manuscript] there was affliction … that people in … from awful things and … not in each place that they were exposed to it".
>
> (*The Chronicle of Pseudo-Zachariah Rhetor*, p. 370).

12 For NGRIP data, see Plummer *et al.* 2012. For NEEM data, see Sigl *et al.* 2013.

13 The possibility of a small c.2 year potential uncertainty in GICC05 dates (cf. Vinther *et al.* 2006) is separate to the 7-year block correction proposed by Baillie 2008. The former relates to sporadic errors in annual layer counting, while the latter is likely to result at least partly from misidentified and mis-dated volcanic age markers that are central to the construction and verification of ice-core chronologies. These age-markers may derive from historically documented eruptions of presumed-known identification in ice-core sulfate and tephra measurements or of presumed-known historical date. An example is the assumption based on weak historical evidence that the volcanic eruption of Eldgjá (Iceland) occurred in c.934 rather than c.939 as proposed by several scholars (see main text).

This report in a text containing material from Zacharia, bishop of Mytilene (probably elected in the 530s) of a fifteen-month cloud that diminished the sun, obscured the moon, and was associated with a terrible winter has been much discussed. The historical evidence has been assessed in an impressive paper by Antti Arjava and we need not repeat it in detail here[14]. It is necessary to briefly summarise, however, the information from the historical sources identifying a year of anomalous atmospheric conditions in the Mediterranean. A valuable eyewitness description of the bleak foggy year comes from a letter by the Praetorian Prefect for Italy, Magnus Aurelius Cassiodorus Senator, who observed a blue-coloured sun and wrote that its loss of heat lasted nearly the whole year[15]. Unfortunately, the letter was not dated and historians have variously estimated its date of composition to 534, 536, or 537 (Barnish 1992, p. 180).

From Procopius, the advisor to Belisarius, comes a similar description of a weak sun for a whole year (PC, 4.14). Also, when, in the mid 6th century, the Byzantine official, John Lydos, came to the part of the treatise he was composing on portents, he recalled the strange appearance of the sun and described a fog lasting for nearly the whole year of October 535 to September 536. He also added that the agricultural produce of that time was destroyed. In analyzing the relevant passage in Lydos, Arjava noted the emphasis on the cloud being wet, which, if Lydos is accurate, may point away from a volcanic (or sole volcanic) explanation (John Lydos, *De Ostentis*, trans. in Arjava 2005, p. 80).

Another useful historical reference concerning the event, though reported much later, comes from an author, Michael, the late 12th century patriarch of the Syriac Orthodox Church, who can be shown to be faithful to his other source materials. In an entry for the year October 536 – September 537, Michael wrote that the sun was feeble for eighteen months and that as a consequence the fruits did not ripen and the wine tasted like sour grapes (Michael the Syrian, *Chronicle*, pp. 220-221).

There are several prominent debates concerning this event. Was it volcanic at all? It has been conjectured that the anomalous fog and coincident climatic extremes arose as result of a cometary impact or airburst that loaded the upper atmosphere with particulates[16]. Or be-

[14] Stothers 1984; Rampino *et al.* 1988, especially pp. 87-88; Arjava 2005; Gunn 2000; Keys 1999, pp. 17-24.

[15] Cassiodorus, *Variae*. See also the references to a blue sun associated with a volcanic dust-veil in the 40s BC in Bicknell 1993.

[16] Baillie 1999, pp. 193-194, a view later revised in Baillie 2008. See also Clube, Napier 1991, p. 46; Baillie 1994; Rigby *et al.* 2004.

cause the fog was described by Lydos as wet, in contrast to the atypical volcanic "dry" fog, that it may have resulted from a natural atmospheric phenomenon currently unknown to science (Arjava 2005, p. 93). As Arjava noted in 2005, it does not help to clarify matters that until recently the ice core data, which would normally be the firmest source for an indication of major volcanic activity, was "missing, flawed, or poorly dated" (Arjava 2005, p. 77). The attempt by a more recent (2008) ice core study to suggest the identification of a "new and well-dated" equatorial explosion as the source of the cloud is not as secure as it seems, particularly if – as seems probable – Michael Baillie's argument about the need to re-date the GICC05-dated ice cores by approximately seven years in the 6th century is correct (Larsen *et al.* 2008; Baillie 2008).

Although they did not make the case for a revised ice core chronology, Stothers and Rampino also favoured a volcanic explanation for the fog, and argued for an equatorial rather than mid to high-latitude (Northern Hemispheric) candidate eruption on the basis that, "it should be noted that the Byzantine annalists give the duration of the dimming of the sun as close to one year, whereas the chroniclers slightly farther south mention 18 months. This suggests a volcanic aerosol cloud that may have slowly spread northward" (Stothers, Rampino 1983, p. 6362). The nature of our historical sources, however, do not really lend themselves without risk to the kind of argument that depends upon a level of exactness that the sources' authors may not have been pursuing. Thus, when Cassiodorus, Procopius and Lydos wrote of a year-long event and Michael of an eighteen-month event they were likely speaking loosely. Our one source that gives more appearance of a precise dating for the cloud is Zacharia, who was in Constantinople at this time, and who stated that it was a 15 month event. With a difference now of only three months, it may be reading too much into the fact that Michael, based in Melitene (modern day Malatya), 850 km south-east of Constantinople, wrote of the cloud lasting 18 months, to securely infer that an equatorial volcano caused the fog. In a later paper, moreover, Stothers came to prefer a more northerly candidate for the 536 event on the basis of the similarity of the signal of 536 to long-lasting volcanic clouds from other known and more northerly eruptions (Stothers 1999, p. 718).

While a contribution from a cometary impact or airburst cannot be definitely ruled out, and indeed the cause(s) of the climatic perturbation in this period need not conform to a human desire for a neat "either/or" explanation, on the present balance of evidence from the historical sources,

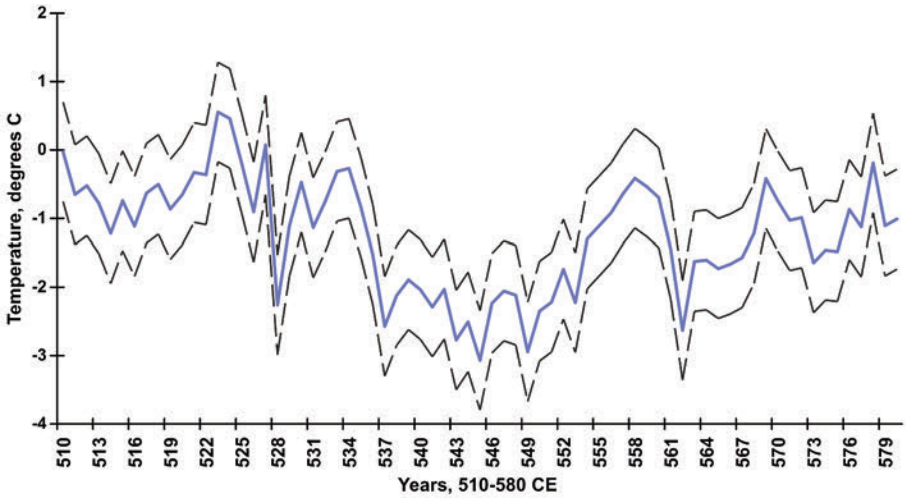


Fig. 1. Central European June to August temperature anomalies (solid blue line), 510-580 CE, in degrees Celsius relative to the 1901-2000 period. Dashed black lines represent +/-1 Root Mean Square Error values of the calibration period (1864-2003) (Büntgen *et al.* 2011).

the event appears likely to be volcanic in origin[17]. Baillie has also made a persuasive case, largely on the evidence of tree-rings and bristlecone frost-rings, that there was a two stage environmental downturn in this period, caused by "an initial large northern eruption in 536 with a second reinforcing eruption close to the equator in 540-541" (Baille 2008, p. 4). The prolonged character of the climatic disturbance across these years is clear in many tree-ring chronologies for the Northern Hemisphere. Exemplary of the European climatic response is an extended temperature downturn c.536-554 as shown in figure 1, representing Central European June to August temperatures reconstructed from 1089 Stone Pine (*Pinus cembra*) and 457 European Larch (*Larix decidua*) ring width series counted from living and sub-fossil samples in high-elevations in the Austrian Alps and surrounding areas (Büntgen *et al.* 2011).

It seems likely that the second loading of sulphates into the atmosphere in the early 540s compounded the crisis in many parts of Europe, a crisis enormously deepened by, and plausibly connected to, the outbreak of plague in 541 (Keys 1999, pp. 17-24; Stothers 1999; Stathakopoulos 2000).

[17] New tracers of extraterrestrial interactions with the Earth continue to be developed and may in due course provide a much needed clarification. See, for example, Kurbatov *et al.* 2010.

## 626/627

A darkened sun was observed in far-flung regions of Europe and the Near East in the year c.627, yet in part because several of the relevant sources described this event as a nominal solar eclipse, the significance of these observations for identifying what was likely a major volcanic dust-veil has been under-recognized. The salient point is that there was no solar eclipse of any kind observable from Europe or the Near East in 627, nor indeed in 626 or 628 (Espenak, Meeus 2006), while other details in several of the key reports are inconsistent with a solar eclipse, in particular the extended duration of the event.

For Europe, most reports come from Ireland, with one potentially British observation. "A dark year" (*annus tenebrosus*) say both the *Annals of Tigernach*[18] and *Annals of Ulster* with characteristic terseness for this early period (*The Annals of Ulster*, p. 113). These are high- and late-medieval Irish sources, respectively, and though they exhibit some chronological errors, they generally incorporate earlier eyewitness sources faithfully in terms of their textual details. We thus follow Daniel McCarthy's systematic corrections to the chronology of the Irish annalistic texts, which are verifiable by reference to events of independently known date, such as solar and lunar eclipses. On McCarthy's corrected chronology, the Irish "dark year" falls in 627 CE[19]. From Britain, a 10th-century Welsh source that preserves quite early material, the *Annales Cambriae*, also states that, "the sun was obscured"[20].

In a further Irish text, the *Annals of Inisfallen*, an "eclipse of the sun" (*ecclipsis solis*) also falls in 627 on McCarthy's corrected chronology (*Annals of Inisfallen*, p. 87), and provides a valuable illustration of the understanding required of any given text's history and character that is needed to credibly interpret reports of natural phenomena. This is particularly the case when the phenomena in question were exotic to early

[18] *Annals of Tigernach*; Niocaill (trans) 2010. Online in http://www.ucc.ie/celt/published/T100002A/index.html [accessed 9 January 2015].

[19] McCarthy 2005 aligns the Irish dark year with the independently-known Near Eastern dust-veil of 627 (see main text) as part of his efforts to correct the early Irish annalistic chronology. His corrected chronology does not, however, depend upon this single alignment. Thus, several further events of independently-known date are also used to determine the corrections required to the Irish annalistic chronology in this period. When these are applied to the dark year, the event is independently placed in 627. McCarthy notes, however, the inevitable remaining potential for small dating errors in this early period of Irish annalistic recording.

[20] *Annales Cambriae*, p. 46. This entry is listed at 624, but Remfry 2007 judges the date to be inaccurately transmitted, correcting the manuscript's 624 to 627. There is a possibility that the *Annales Cambriae* draws upon early Irish material for this observation, though it may also represent an independent British (Welsh) observation.

medieval authors, and in their spectacle, loaded with symbolic and religious potency that might tempt authors to misrepresent and exaggerate descriptions to suit their own purposes, or, in their unfamiliarity, attempt to make existing reports conform to their understandings of natural phenomena. The *Annals of Inisfallen* is a high- to late-medieval source with a very unreliable chronology in its earlier centuries of coverage. It can be shown that the first scribe of this text, working c.1092 in Munster, often severely abbreviates and emends early material copied from its sources (McCarthy 2008). In the present case, it seems highly likely that he has emended what must have been an unsatisfactorily ambiguous description in his source and (in contrast to the faithful rendering in *Tigernach* and *Ulster*) "corrected" the description to a more familiar solar eclipse. An eclipse cannot, of course, extend for an entire year.

From the Near East come several somewhat fuller accounts of what is in high probability the same event, all ultimately derived from a lost 8th-century work, Theophilus of Edessa's *Chronicle*. R.G. Hoyland has reconstructed the following entry from the excerpts of this source made by the two later authors Agapius of Manbij in his *Kitab al-'Unvan* (2.2, pp. 399-547) and Michael the Syrian: "there was an eclipse of the sun and it lasted from October [626] until June [627], that is, for nine months" (Hoyland 2011, p. 73). This is, again, clearly too extended a period to represent a genuine solar eclipse and is instead consistent with potentially prolonged solar dimming arising from high-altitude volcanic dust and aerosols.

A late 13th century source, heavily dependent on Michael the Syrian and therefore ultimately Theophilus, is the *Chronography* of Bar Hebraeus. A reliable transmitter of his earlier source material, Bar Hebraeus has slightly more detail for the event:

> "And in the sixth year of the Arabs a portion of the hemisphere of the sun departed, and there was darkness from the month of the First Teshrin [October 627] till the month of Haziran [June 628]. [It lasted so long] that men used to say that the sphere of the sun would never become whole and perfect again. And the zanta, that is to say the sickness of the shar'ata tumour, broke out in Palestine, and tens of thousands of men died of the disease".
>
> (Bar Hebraeus, *Chronicon Syriacum*, Budge (trans) 1932, 1.90).

That two independent and geographically distinct traditions of medieval record-keeping preserve the memory of an extended solar dimming

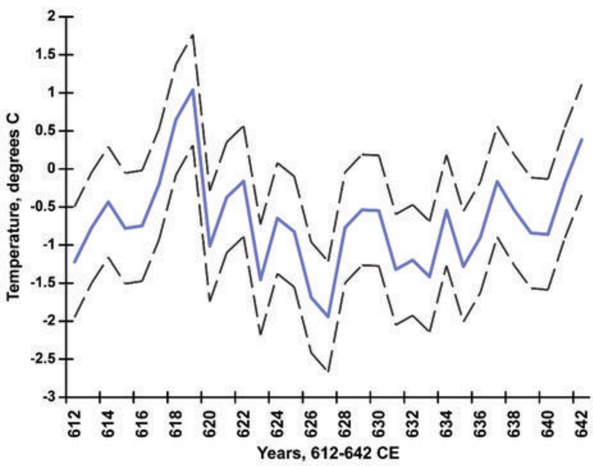


Fig. 2. Central European June to August temperature anomalies (solid blue line), 612-642 CE, in degrees Celsius relative to the 1901-2000 period. Dashed black lines represent +/-1 Root Mean Square Error values of the calibration period (1864-2003) (Büntgen *et al.* 2011).

in 627 lends considerable confidence to the identification of a candidate volcanic dust-veil in this year by Stothers and Rampino (Stothers, Rampino 1983, p. 6363). In a later article, Stothers expressed uncertainty over the ice core dates for this event, and argued that "our more securely obtained dates from historical and tree-ring data can stand alone" (Stothers 1999, p. 718). Indeed this is the case. Stothers and Rampino did not have sulphate data available from the recent NGRIP and NEEM Greenland ice-cores, which place deposition from a moderate volcanic event spanning 625.3 to 627.0 and 624.8 to 626.2, respectively (Plummer *et al.* 2012; Sigl *et al.* 2013).

While this appears to confirm what is suggested by the historical evidence, the comparatively small volume of volcanic sulphate deposited by this eruption (e.g. 14.3 ± 2.0 ppb, volcanic sulphate, in NEEM) is somewhat surprising given the geographical extent of the dust-veil and the marked reduction in the Central European temperature reconstruction in 625 and 626 (Büntgen *et al.* 2011; fig. 2). Both cores, however, also place a very considerable volcanic signal in the earlier 620s (i.e. 619.5 to 622.1 in NRGIP, and 619.1 to 622.3 in NEEM with 89.9 ± 3.2 ppb volcanic sulphate in this core)[21]. While a moderate single-year Central European temperature drop in 623 might relate to a volcanic event at these dates, this is an underwhelming response to such an immense volcanic event. If, however, Baillie's hypothesis of a c.7 year correction to the chronologies of these cores is correct, this major volcanic signal now

[21] The GISP2 does not clearly register an eruption in the 620s (see Zielinski *et al.* 1994 and Ludlow *et al.* 2013).

shifts forward to c.626-629 and is more consistent with the historical dust-veil observations and marked temperature drop 626-627. The smaller volcanic signals previously registering at c.624-627 now also occur across c.631 to 634, and are consistent with a secondary temperature minimum across 631-633 (fig. 2).

Of prospective societal and climatic impacts of volcanic events beginning c.627 and documented in the historical record, evidence of hardship in the Near East is found in the report of the famous Persian scholar, al-Tabarī. Writing in Baghdad in the early 10th century and being known to faithfully report the material from his sources, al-Tabarī noted a drought in 627-628[22]. For the following year he wrote that: "pestilence spread in Iran and most of the people died" (al-Tabarī, *Ta'rīkh al-rusul wa'l-mulūk*, 2, p. 229). Also for 628 comes a report based upon the dispatches of Emperor Heraclius, then leading an army into Perisa, as found in the 7th century Byzantine compilation, the *Chronicon Paschale*. This relates a "severe winter at the mountain of Zara [Persia]. From the 24 of the month of February until the 30th of the month of March it did not cease snowing"[23]. Of impacts associated with the secondary volcanic events registered in the Greenland ice in the 630s (assuming that Baillie's chronological corrections are correct), we suggest that further historical research may prove profitable here. For Asia, Jie Fei and colleagues have discussed the potential association between a volcanic event c.626, which they link to the above-discussed historical dust-veils, and climatic cooling from c.627-629, and the collapse of the Eastern Turkic Empire in 630. They cite major societal stresses including mass mortality of sheep and horses, a great famine, and subsequently a great human mortality (Fei *et al.* 2007). They also highlight that the powerful Chinese Tang dynasty experienced three successive years of frost disasters at this time.

## 763/764

In a pathbreaking 2007 paper in early medieval historical climatology – M. McCormick, P.E. Dutton and P.A. Mayewski's (2007) *Volcanoes and the climate forcing of Carolingian Europe A.D. 750-950* – the year 763

[22] It is increasingly clear that major volcanic eruptions do not only influence temperatures, but can have considerable impacts on precipitation variability, and that this impact can be discerned in historical records (see in the case of China, Zhuo *et al.* 2014). Examining reports of drought and flooding in early medieval Europe and the Near East may prove similarly revealing.

[23] Whitby, Whitby 1989, p. 186. Whether these conditions can be taken as severe relative to the expected winter climate of this mountain region requires further consideration.

was identified as one in which an extraordinarily difficult winter overtook effectively all of Europe. The low temperatures experienced and their long duration were associated with volcanic climate forcing on the basis of the GISP2 Greenland ice-core, in which sulphate deposition at c.767 (766.6 +/-2.5 years) indicated a substantial eruption (McCormick *et al*. 2007).

There is no need to repeat the thorough account of the European historical sources given in this paper, other than (1) to draw attention to the capability of volcanic forcing to induce extreme short-term temperature anomalies on significant spatial scales, and (2) the potential of early medieval records to help chart the spatial extent and seasonality of these climate anomalies.

This is of considerable importance given the degree to which the climatic impacts of eruptions can vary in intensity and even switch sign (i.e. from cooling to warming) between regions and across subsequent post-eruption seasons depending on a suite of factors that include the latitude of the eruption, the month of its occurrence, and pre-existing climate system states and atmospheric circulation patterns[24]. Thus, this cold winter registers in sources ranging from Ireland (where the snow lay on the ground for three months in 764[25]) to the Black Sea (which froze, creating ice so that thick that later, when iceburgs floated along the Bosphorus, they damaged the walls of Constantinople and provided a platform for adventurous children: Theophanes, *Chronographia*, p. 434).

One source that warrants further mention is the edited text known as the *Chronicon Moissiacense* (but which is, in fact, an amalgamation of two near-identical manuscripts, the *Chronicon Moissiacense* and the *Chronicon Anianense*), where, under 762, we read that "a great frost weighed down Gallia, Ilyria, and Thrace and many ripe olive and fig trees were withered by the frost. And even the bud of the crops was withered. And arriving at the following year a famine greatly depressed the aforementioned regions, such that many people perished from want of bread"[26]. If the date of 762 is accurate, the severe 763/764 winter may represent the culmination of a more prolonged cold spell. It seems likely, however, that the 762 date is erroneous. The manuscript at this point

[24] See Fischer *et al.* 2007 for discussion of the evolving spatial patterns of climatic impact in Europe after tropical eruptions. And see Kravitz, Robock 2011 for discussion of how the impact of an eruption can vary according to its latitude and the month of its occurrence (i.e. the climate exhibits a different sensitivity depending upon the location, month and season of the eruption).

[25] *Annals of Ulster*, dated using McCarthy's 2005 chronological corrections.

[26] *Chronicon Moissiacense*, p. 294: *Gelu magnum Gallias, Illyricum et Thraciam deprimit, et multae arbores olivarum et ficulnearum decoctae gelu aruerunt; sed et germen messium aruit; et supervenienti anno praedictas regions gravius depressit fames, ita ut multi homines penuria panis perirent.*

suffers a lacuna and the entry comes to us from the sister manuscript, the *Chronicon Anianense*. Moreover, the next piece of information in the text (which appears without a date), concerns the death of the first Carolingian king of the Franks, Pippin the Short, which occurred in 768. This further adds to the sense of chronological uncertainty in the text, but a definitive pronouncement on the accuracy of the 762 date requires further work.

Of the GISP2 evidence for a volcanic contribution to the severe 763/764 winter, it is notable that the c.767 (+/-2.5 years) sulphate deposition signal of 66.32 ppb[27], while quite substantial and certainly indicative of a major eruption, is moderate compared to many events in the centuries before and after. Eruptions that registered with greater sulphate deposition in the Greenland ice have sometimes left less impression in the historical record, even in following centuries when the sources are generally more abundant. As much as this may reflect the vagaries and intermittency of the historical record, it is also likely symptomatic of the great spatial variability and complexity of volcanic climatic impacts. The climate response to a volcanic eruption is not determined simply by the magnitude of sulphur dioxide injected into the high atmosphere, but by many further factors (some mentioned above) that are often unknown for medieval eruptions.

In the present case, a further eruption of slightly smaller magnitude registers in the GISP2 at c.757 (756.7 +/- 2.5 years), and may have plausibly amplified the climatic and social impact of the subsequent eruption. It is also important to note that the volume of sulphate deposited at each ice-core location can vary for the same event (Fisher *et al.* 1985; Zielinski *et al.* 1997), and thus a single ice-core does not always accurately reflect volcanic atmospheric sulphate loading. That the NGRIP ice-core does not clearly register any volcanic event in the 750s or 760s (Plummer *et al.* 2012), even when its chronology is adjusted by Baillie's +7 year correction, is illustrative of this. By contrast, applying Baillie's chronological adjustment to the NEEM ice-core identifies an eruption with volcanic sulphate deposition (of 31.1 +/- 6.1 ppb) spanning the years 755 to 758, and a further smaller event with deposition (of 17.6+/-2.9 ppb) between 763 and 766[28]. These adjusted dates are clearly consistent with the independent GISP2 chronology within the un-

[27] This is the total non-sea-salt sulphate deposition value, i.e. the background non-sea-salt sulphate deposition flux has not been removed.

[28] More precisely, each volcanic event in NEEM originally registers between 748.1 to 750.8 and 755.9 to 756.9 (see Sigl *et al.* 2013). We have rounded each date before applying Baillie's +7 year correction. The quoted sulphate values are again volcanic-only sulphate values, with background flux removed (being one reason why these values appear smaller than the quoted GISP2 sulphate values).

certainties associated with its lower resolution, thereby further suggesting a volcanic contribution to the remarkable 763/764 winter.

It is interesting to note, however, that this second eruption does not clearly register in the Central European June to August temperature reconstruction (Büntgen *et al.* 2011). Because, however, the historical record is not confined to reporting climatic anomalies in any given season, it can be used to complement tree-ring-based reconstructions that primarily reflect spring and summer climate. Thus, the fact our sources place most focus on the winter cold for 763/764 suggests a strongly seasonal impact associated with this eruption, at least for Europe. Further work on the historical record is warranted to examine the climatic impact of the first eruption, which may correspond to a Central European summer temperature minimum in 757[29].

## Discussion and conclusion

As ice core records of volcanic sulphate deposition grow in abundance and are analyzed at ever-greater resolution, an increasing number of past explosive volcanic eruptions are being identified. It is thus becoming increasingly clear that climate forcing from these events may have played a greater role in climate and human history than has been generally appreciated[30]. Our survey of major events 400-800 is by no means comprehensive, and we anticipate that as ice-core chronologies are improved, many further links will be identified between volcanic events, climatic extremes and societal stresses in the historical record. In the present paper, we have focused on four instances of volcanic climate forcing that illustrate the complexity of climate and human responses to eruptions, but also of the potential of combining diverse natural and human archives for this early and comparatively understudied period. In each of our studied cases, the occurrence of multiple eruptions within a few years of each other may have created a powerful cumulative effect[31]. Other periods wherein multiple closely-spaced eruptions are identifiable in the ice-cores, even where these eruptions are of comparatively moderate size, have the potential to act as valuable test-cases of human

[29] Büntgen *et al.* 2011. To date, Ludlow *et al.* 2013 have associated reports of heavy snowfall in 760 and 762 from the Irish Annals with the signal of this eruption in the GISP2.

[30] The number of volcanic eruptions identified by Sigl *et al.* 2013 from high-resolution analyses of the NEEM ice-core is considerably greater, for example, than that identified from the lower resolution (though likely more accurately dated for much of our period) GISP2 by Zielinski *et al.* 1994.

[31] Recent work by Santer *et al.* 2014 (and see references therein) also suggests that even comparatively small explosive eruptions, where occurring in sufficient numbers within a short period of time, can have a larger climatic impact that has been broadly acknowledged to date.

response to severe short-term climatic anomalies, evidence of which can be furnished by the historical (and indeed archaeological and palaeoecological) record.

We have, however, attempted to stress uncertainties in the historical record, which must be treated with great care, particularly when used by for critical purposes such as the provision of chronological tie-points or age markers in the construction and verification of time-scales and chronologies. Given a desire to identify volcanic signals[32] in ice-cores (and indeed other natural archives such as speleothems and a variety of sedimentary archives) with apparently securely dated historical events (either of major volcanic eruptions themselves or their direct atmospheric consequences such as dust-veils) there is a danger that the historical record is employed uncritically. The potential for the historical record to provide salient information is undeniable, but so too is the need for collaboration between natural scientists, historians, textual scholars and other researchers if this valuable material is to be credibly employed to the benefit of multiple disciplines.

For the medieval historian, too, an appreciation of the climatic context in which historical events have unfolded is crucial to achieving a full understanding of human history. The authors, moreover, of our historical sources cannot be considered unaffected (materially or psychologically) by the events they experienced and record, or read and copy into their own works. This applies as much to environmental events and trends as any other. It is evident, for example, that annalists and other authors often tend to report exotic and spectacular natural phenomena in clusters[33]. Just as such clustered occurrences might be expected to make a greater impression upon contemporary observers, they might be expected by an author to make a greater impression upon readers regarding the importance of the human affairs being described. Given the potential utility of natural phenomena as signifiers of divine meaning (e.g., portents and endorsements) and the delivery mechanisms of divine judgement (e.g., retribution for humanity's sinfulness enacted by flood and plague)[34], it is little surprise that some authors may have been tempted to massage (and in rare cases fabricate) the occurrence and dating of such natural events to suit the purposes underlying their narratives. Thus, from Widukind of Corvey's *Deeds of the Saxons* (II.32) we read that:

[32] Such signals are not just limited to sulphate deposition, but include other chemical species as well as volcanic tephra particles.

[33] See the discussion of triple-portents in the Irish Annals by McCarthy, Breen 1997.

[34] For an introduction to the perception of natural phenomena as marvels and portents, see McCarthy, Breen 1997; Janković 2000; Whittock 2011.

> "Certain portents were revealed before the passing of King Henry [Henry I, the Fowler, 2 July 936], such as that while outside even though no cloudy tail covered it, the brilliance of the sun failed to appear but inside, that a red colour like blood poured through the windows of houses. The mount also, where the remains of the lord of things are buried, according to rumour, vomited many flames in that region. Furthermore, the left hand of a certain man having been cut off by the sword, almost a year later it was completely restored as he was sleeping, which was initially noted as a sign of a union instead of bloody lines. But there were comets and a great flood, and a cattle pestilence followed the flood".

This compilation of extraordinary events is clearly designed to impress upon Widukind's readers that King Henry was a person of great importance, sufficiently so that marvels would be sent from Heaven to indicate his imminent death. Is this clustering, therefore, an example of a kind of selection bias, where it is only in the mind of Widukind that such a concentration of unusual events occurs, because he has sought them out? Are these events examples of medieval credulity and irrationality? Not if we accept the argument of Richard Stothers that the diminution of the sun's brilliance, the red colour on walls, and the mount vomiting flames are evidence for an Icelandic eruption (of Mount Eldgjá), in which case the reference to the "lord of things" is to be credibly associated with the death of Úlfljótr, leader of the *Althingi*, the Icelandic lawmaking assembly[35]. In this case, then, we should certainly not automatically discard remarkable clusters of portents as being fabricated, and indeed there may be a deeper climatic connection between the "portents" connected to Eldgjá's eruption and the fact that a cattle pestilence took place in the subsequent years. A serious question mark, however, hangs over Widukind's exact choice of dating of the solar dimming and discoloration if a later c.939 date for the eruption of Eldgjá is correct. This later date is supported by the probable observation of a volcanic plume in the (at this point chronologically-reliable) Irish *Chronicon Scotorum* for 939[36].

[35] An explanation for this ambiguous portion of the text as suggested by Stothers 1998, p. 718.

[36] Without any overt political purpose that casts doubt upon its reporting of this event, the *Chronicon Scotorum* (Hennessy 1866) notes for 939 that "the sun was the colour of blood from the beginning of day to midday on the following day", thereby extending for too long to be a solar eclipse, and indeed no suitable solar eclipse (i.e. visible from Ireland) occurred in this year. See McCarthy, Breen 1997, McCormick *et al.* 2007, Oman *et al.* 2006 and Ludlow *et al.* 2013 for discussion of this observation. It can also be noted that a c.939 date for the eruption of Eldgjá is more consistent with the peak sulphate deposition date of c.938 in the GISP2 ice-core chronology (being independent of the GICC05 ice-core chronology criticized by Baillie 2008, 2010 and that places the eruption of Eldgjá at c.934).

While motives existed for some medieval authors to gather together instances of extraordinary weather and unusual celestial events to highlight significant historical moments in their accounts, it is also the case that the sudden and widespread appearance of societal stresses such as famine and disease provided a motivation for these authors to search for meaning and explanation by seeking and recording "portentous" events of the period. Given that a major volcanic eruption is readily capable of providing multiple "portents" (atmospheric and climatic) over vast geographical areas within the space of a small number of years, as well as inducing societal stresses, this is one type of climate forcing event that may help explain the often uneven and clustered distribution of the historical reporting of the marvelous and miraculous.

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