Conor Kostick and Francis Ludlow

Medieval History, Explosive Volcanism, and the Geoengineering Debate

Abstract[1]**:** One of the most important issues facing humanity is the rise in temperature of the planet. One current line of investigation for the reversal of global warming is that of using one or more of a suite of geoengineering (or climate engineering) techniques known as solar radiation management (SRM) in order to reflect sunlight back into space. The Paris Agreement of 2015, COP21, invited further research into this kind of geoengineering solution. One idea is to artificially emulate the effect of large volcanic eruptions, which can certainly lead to global cooling. Here, medieval history offers a perspective from which to help understand the challenges that geoengineering may present and inform our choices. The closest natural parallel to stratospheric aerosol injection (SAI) geoengineering are volcanic eruptions and case studies of their climatic (and subsequent societal) impacts are much needed.

By studying historical explosive volcanism, medieval history provides a laboratory for understanding the climatic and societal impacts of geoengineering in the form of reports of extreme weather and societal stresses such as subsistence crises and even conflict arising from scarcity induced resource competition. We argue that this history must be taken seriously in the discussion about whether to proceed with solar geoengineering. The twentieth and twenty-first centuries have been volcanically quiescent relative to earlier centuries, but this can change at any time. In particular, advocates of a geoengineered solution have to appreciate the relevance of the question: what will happen if the planet experiences another period in which one or more sulphur-rich VEI 5 to 7 eruptions occur, if we have already laden the stratosphere with sulphates artificially? The medieval experience of such eruptions can point to an answer that serves as a warning.

1 This publication represents a contribution to the "Historical Dynamics of Violence, Conflict and Extreme Weather in Medieval Ireland" (CLIMCONFLICT) project. This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No. 709185. Francis acknowledges additional support and input from the Trinity Centre for Environmental Humanities, Trinity College Dublin, and the Volcanic Impacts of Climate and Society (VICS) Working Group of PAGES. Both Conor and Francis acknowledge the contribution of Chaochao Gao and Or Amir in an earlier collaborative work from which this paper draws, with permission of Elsevier, see Chaochao Gao / Francis Ludlow / Or Amir / Conor Kostick, Reconciling Multiple Ice-Core Volcanic Histories. The Potential of Tree-Ring and Documentary Evidence, 670–730 CE, in: Quaternary International 394 (2016), pp. 180–193, online (DOI): https://doi.org/10.1016/j.quaint.2015.11.098 (last accessed 15/05/2019).

Conor Kostick and Francis Ludlow, Department of History, School of History & Humanities, Trinity College Dublin, Dublin 2, Ireland, conorkostick@gmail.com / ludlowf@tcd.ie

https://doi.org/10.1515/9783110546316-003

Keywords: geoengineering, sulfate aerosol injection, global warming, explosive volcanism, early medieval, annals, chronicles, climate history, historical climatology

Explosive Volcanism and Geoengineering

Record-breaking weather extremes, from hurricanes to flooding and drought, continue to occur at a pace greater than expected under natural climate variability,[2] consistent with a warming climate system. It has thus become increasingly attractive among scientists and policymakers to consider counteracting global warming, and hence hopefully its more deleterious impacts, through technological means. In the near future it will likely become technologically feasible for society to lower global annual average temperatures by artificially blocking a fraction of sunlight from reaching the planet's troposphere or surface, using one or more of a suite of geoengineering (or climate engineering) techniques known as solar radiation management (SRM). These techniques are under increasingly intensive research by climate scientists and engineers, with a growing discussion among economists and policymakers regarding their potential implementation as a remedy to global warming.

Among existing SRM proposals, perhaps the most prominent and (in the near term) technologically and financially feasible is that of the stratospheric aerosol injection (SAI) of chemical compounds that would act to reduce average tropospheric temperatures by changing the Earth's albedo (i. e., reflectivity). Sulphur dioxide (SO_2) gas injected into the stratosphere would, for example, oxidize to form sulphate aerosol particles known to efficiently back-scatter incoming solar direct (shortwave) radiation to space. Geoengineering the climate in this manner is an idea that ultimately derives from long-standing yet still evolving understandings of the atmospheric and climatic consequences of explosive volcanism.[3] Historically, a suggestive link was posited by the ancient Roman author, Virgil, between the explosive release of materials from an eruption of Etna (Sicily) in 44 BCE and a widely noted episode of diminished and discoloured sunlight and other unusual

---

2 Christopher B. FIELD / Vincente BARROS / Thomas F. STOCKER / Quin DAHE / David Jon Dokken / Kristie L. EBI / MICHAEL D. MASTRANDREA / Katharine MACH / Gian-Kasper PLATTNER / Simon K. ALLEN / Melinda TIGNOR / Pauline M. MIDGLEY (eds.), Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. Special Report of the Intergovernmental Panel on Climate Change, Cambridge 2012.

3 Alan ROBOCK / Douglas G. MACMARTIN / Riley DUREN / Matthew W. CHRISTENSEN, Studying Geoengineering with Natural and Anthropogenic Analogs, in: Climatic Change 121(3) (2013), pp. 445–458; see also Alan ROBOCK, Stratospheric Aerosol Geoengineering, in: Roland HESTER / Roy M. HARRISON (eds.), Geoengineering of the Climate System (Issues in Environmental Science and Technology), Cambridge 2014, pp. 162–185.

atmospheric optical phenomena.[4] Other authors such as Pliny the Elder variously described the atmospheric phenomena seen in the Mediterranean region at the time or the severe cold weather in this and the next several years,[5] with Plutarch explicitly noting a link between the diminished sunlight and its impact on climate and agriculture.[6] Thus Plutarch describes how:

> all that year [i. e., 44 BCE] the [sun's] disk was pale and without radiance. The heat that came down from it was feeble and reduced. By reason of the weakness of the warmth penetrating it, the atmosphere became thick, murky and heavy. Grain and fruits withered and shrivelled on account of the ambient coldness.[7]

Later, in 1784, Benjamin Franklin conjectured that the prolonged eruption of the Icelandic fissure volcano *Lakagígar* (translatable as "craters of Laki" and more often just called "Laki") that began in the previous year (8 June) explained the unusual cold in Europe and North America in the year that followed.[8] A more significant advance in modern understanding occurred after the great 1883 eruption of Krakatau, Indonesia, especially in the work of geologist and mining engineer Rogier D. M. VERBEEK in a classic report commissioned by the Dutch government. This detailed the atmospheric ef-

4 See Virgil's 'Georgics' 1.466–73, as cited by Philis Y. FORSYTH, In the Wake of Etna, 44 B. C., in: Classical Antiquity 7(1) (1988), pp. 49–57, here p. 50. Note that new ice-core-based volcanic forcing histories suggest that the atmospheric phenomena (or 'dust veil') at this time is likely to have originated in a major tropical eruption, c. 44 BCE, being perhaps the third largest of the past 2,500 years on the evidence of sulfate levels deposited within polar ice sheets. This is supported by observations of diminished and discoloured sunlight in Chinese sources from the period. This does not, however, necessarily mean that the probable eruption of Etna in 44 BCE made no contribution, see Michael SIGL / Mai WINSTRUP / Joseph R. MCCONNELL / Kees C. WELTEN / Gill PLUNKETT / Francis LUDLOW / Ulf BÜNTGEN / Marc W. CAFFEE / Nathan CHELLMAN / Dorthe DAHL-JENSEN / Hubertus FISCHER / Sepp KIPFSTUHL / Conor KOSTICK / Olivia J. MASELLI / Florian MEKHALDI / Robert MULVANEY / Raimund MUSCHELER / Daniel R. PASTERIS / Jonathan R. PILCHER / Martin SALZER / Simon SCHÜPBACH / Jorgen Peder STEFFENSEN / Bo M. VINTHER / Thomas E. WOODRUFF, Timing and Climate Forcing of Volcanic Eruptions for the Past 2,500 Years, in: Nature 523 (2015), pp. 543–549.

5 FORSYTH (note 4).

6 See Plutarch ('Caesar' 69), as cited in Peter BICKNELL, Blue Suns, the Son of Heaven, and the Chronology of the Volcanic Veil of the 40s B. C., in: The Ancient History Bulletin 7(1) (1990), pp. 2–11.

7 Translation after ibid., p. 9, and we follow BICKNELL's determination that Plutarch refers here to 44 BC. Plutarch does not, however, appear to have connected the eruption of Etna to the atmospheric phenomena he describes.

8 Alexandra WITZE / Jeff KANIPE, Island on Fire. The Extraordinary Story of Laki, the Volcano that Turned Eighteenth-Century Europe Dark, London 2014, p. 125. Franklin mistakenly attributed the eruption to 'Hecla' rather than Laki; see Sigurdur THORARINSSON, Greetings from Iceland. Ash-Falls and Volcanic Aerosols in Scandinavia, in: Geografiska Annaler 63A(3/4) (1981), pp. 109–118; see also Benjamin FRANKLIN, The Meteorological Imaginations and Conceptions, in: Memoirs of the Literary and Philosophical Society of Manchester 3 (1785), pp. 173–177.

fects of the eruption, including changes in atmospheric clarity and opacity caused by high-altitude aerosol particles of volcanic origin that had encircled the globe within two weeks of the eruption.[9] Through the twentieth century, and particularly with the advent of meteorological satellite observations since the 1960s[10] and other ground-based remote sensing techniques (lidar, radar), the process by which volcanic aerosol clouds can trigger hemispheric and even global-scale average cooling has become increasingly understood.[11] The bulk of this cooling arises from the creation of sulphate aerosol particles (when volcanic SO_2 or H_2S explosively injected into the stratosphere oxidize to form H_2SO_4) that can efficiently backscatter incoming solar radiation to space, thereby reducing tropospheric temperatures.[12]

An oft-cited 2006 essay by Nobel Laureate Paul CRUTZEN provided considerable additional impetus to research into geoengineering via stratospheric aerosol injection (SAI),[13] by clearly articulating an imperative and rationale for research into such technology as a potential means of counteracting catastrophic global warming, hence breaking a perceived taboo around research into such technologies.[14] Present estimates of the cost of implementing SAI suggest it would be relatively inexpensive for a large country or group of countries to engage in this form of geoengineering, from "a few billion dollars" per year up to US $ 10 billion.[15] This is a modest amount when set against declared national military budgets (e. g., $ 595.5 billion in 2015 by the USA).[16] Already – backed by Bill Gates – millions of dollars have been spent in developing an

9 Jelle ZEILINGA DE BOER / Donald Theodore SANDERS, Volcanoes in Human History. The Far-Reaching Effects of Major Eruptions, Princeton 2002, p. 158.

10 The first weather satellite was released in 1959, but not considered as successful as planned. More successful launches occurred throughout the 1960s, see William J. BURROUGHS / Bob CROWDER / Ted ROBERTSON / Eleanor VALLIER-TALBOT / Richard WHITAKER, The Nature Companions Weather Watching, San Francisco 2003, pp. 80–81.

11 Also see important early twentieth-century work by William Jackson HUMPHREYS, Volcanic Dust and Other Factors in the Production of Climatic Changes, and their Possible Relation to Ice Ages, in: Bulletin of the Mount Weather Observatory 6 (1913), pp. 1–34.

12 Alan ROBOCK, Volcanic Eruptions and Climate, in: Reviews of Geophysics 38 (2000), pp. 191–219.

13 Paul J. CRUTZEN, Albedo Enhancement by Stratospheric Sulfur Injections: A Contribution to Resolve a Policy Dilemma?, in: Climatic Change 77(3–4) (2006), pp. 211–219.

14 So described by Mark G. LAWRENCE / Paul J. CRUTZEN, Was Breaking the Taboo on Research on Climate Engineering via Albedo Modification a Moral Hazard, or a Moral Imperative?, in: Earth's Future 5(2) (2007), pp. 136–143. Research into SAI existed before CRUTZEN's 2006 essay and the wider special section of "Climatic Change" that it prefaced, but the essay was certainly followed by a rapid expansion of publications on the topic. For examples of earlier relevant work, particularly pertaining to SAI, see Robert E. DICKINSON, Climate Engineering: A Review of Aerosol Approaches to Changing the Global Energy Balance, in: Climatic Change 33 (1996), pp. 279–290.

15 Ryo MORIYAMA / Masahiro SUGIYAMA / Atsushi KUROSAWA / Kooiti MASUDA /Kazuhiro TSUZUKI / Yuki ISHIMOTO, The Cost of Stratospheric Climate Engineering Revisited, in: Mitigation and Adaptation Strategies for Global Change 22 (2017), pp. 1207–1228.

16 Figure from https://www.nationalpriorities.org/campaigns/military-spending-united-states (last accessed 15/05/2019).

active research program into SAI geoengineering. China's Ministry of Science and Technology has announced that it will invest $ 3 million and employ fifteen researchers (and accept forty students) at Beijing Normal University, Zhejiang University and the Chinese Academy of Social Sciences to develop a geoengineering research programme. This will not be an experimental programme, rather it will explore the theoretical possibilities as well as the related legal and policy implications.[17]

By contrast, the Harvard-based research funded by Bill Gates and other philanthropists is designing experiments into the subject. David KEITH and Frank KEUTSCH are constructing a 'StratoCruiser', a collection of sensors and spraying devices attached to a high-altitude balloon. Their intention is to launch the balloon from a site in Tucson, Arizona. The StratoCruiser will test the impact of various particles (sulphur dioxide, alumina, and calcium carbonate) it has sprayed to examine the extent to which the stratosphere becomes more reflective, determine what chemical reactions have taken place and identify whether the aerosol mists disperse or coalesce. World View Enterprises have already begun to construct and test the balloon.[18] The locations of many other geoengineering projects (from research to experimentation, and not restricted to SAI) are shown at map.geoengineeringmonitor.org, with 800+ projects in 2017 versus 300 in 2012.[19]

In July 2017, about 100 scientists gathered at the Grand Summit Hotel near Boston to discuss climate engineering. Hosted under the auspices of the Gordon Research Conferences, this event was held under 'Chatham Rules', in other words, in privacy and without a record being taken to facilitate an open dialogue among participants on what is a generally controversial topic, though the agenda and keynote speakers were publicly available. Subsequent interviews with delegates at the conference suggested a broad acceptance that of all the possible approaches to geoengineering considered, SAI is likely to be the easiest to model and, in the event that it proves problematic, to reverse.[20]

Several key concerns have been repeatedly expressed over the prospect of SAI geoengineering. Most common is that it does not address the underlying increase in atmospheric greenhouse gas concentrations and hence does not address other

17 James TEMPLE, Harvard Scientists Moving Ahead on Plans for Atmospheric Geoengineering Experiments, in: MIT Technology Review, 27/03/2017, online: https://www.technologyreview.com/s/603974/harvard-scientists-moving-ahead-on-plans-for-atmospheric-geoengineering-experiments (last accessed 15/05/2019).

18 Ibid.

19 This map (https://map.geoengineeringmonitor.org/ [last accessed 15/05/2019]) is provided by the ETC Group and the Heinrich Böll Foundation, with the caveat that there is no fully complete record of geoengineering projects available.

20 Robinson MEYER, To Stop Global Warming, Should Humanity Dim the Sky? The world's top geoengineering researchers met off the record to discuss the possibility in Maine last month, in: The Atlantic, 07/08/2017, online: https://www.theatlantic.com/science/archive/2017/08/geoengineers-meet-off-the-record/536004/?utm_source=feed (last accessed 15/05/2019).

associated deleterious impacts such as ongoing ocean acidification as these waters continue to absorb CO_2. Indeed, it seems possible that research into SAI and other geoengineering technologies may even militate against emissions reductions. This is the much-discussed 'moral hazard' problem. Here it has been argued that progressing not only toward actual implementation, but even primary research into SAI, may hamper efforts to achieve a more definitive solution through greenhouse gas emissions reduction and cessation. It is certainly plausible to consider that any development potentially allowing the continuance of current economic practices (whilst avoiding global average temperature increase) may be highly attractive to politicians and policy makers who have struggled with conflicting imperatives (perceived trade-offs between short to medium term economic growth goals versus climate action)[21] and have often been successfully influenced by vested interests via lobbying or regulatory capture. These interests (e. g., fossil fuel and petrochemical companies) would thus not only profit from continuing to externalize the costs of greenhouse gas emissions, but also potentially profit from public-borne costs of implementing SAI or other geoengineering.[22]

If research and the development of practical SAI technologies do indeed serve to diminish the drive for emissions control, this may contribute to a 'lock in' effect in which the implementation of SAI or related SRM geoengineering becomes an increasingly credible proposition to counteract the deleterious impacts of global warming, and once implemented, becomes essential to continue as emissions reductions fail to be achieved at the necessary level. Such concerns can be countered by pointing, legitimately, to the ongoing failure to deliver truly meaningful (i. e., globally agreed, legally binding and effective at limiting warming to under 2°C) emissions reductions. Lawrence and Crutzen thus suggest that while geoengineering research may pose a moral hazard, there simultaneously exists a moral imperative to understand the possibilities, costs and benefits of such technologies and facilitate the potential for their deployment.[23] Such a view is further supported by genuine concern over the existence of both unanticipated and anticipated-but-uncertain thresholds, tipping points, feedbacks and surprises in climate and related ecological processes responding to continued global warming,[24] and which may shift public and political perceptions towards acceptance of the need for a rapid geoengineering intervention if the technology has developed to allow this. This argument is bolstered by modelling that suggests, in a scenario in which rising temperatures and associated impacts required emergency

21 Failure to act on climate change will in the longer term likely prove a greater impediment to economic growth as climate change impacts continue to magnify.

22 Here, for example, regarding the costs of producing immense volumes of SO_2 or other SRM geoengineering prerequisites.

23 Lawrence / Crutzen (note 14).

24 For a review, see National Research Council, Abrupt Impacts of Climate Change: Anticipating Surprises, Washington / DC 2013.

intervention, even rapid emissions cuts (i. e., more severe than cuts presently optimistically foreseen) would not bring climate back under 'control' as rapidly as SAI.[25]

Just as there are uncertainties and unknowns associated with the impacts of continued global warming, however, these also exist for SAI geoengineering. Here, the discussion is more speculative, in part because of incomplete understandings of the climate system and its linkages to related earth and ecological systems, and because the majority of research into the impacts of geoengineering necessarily depends upon climate or earth system modelling. These models are becoming increasingly sophisticated, capturing earth system processes in ever more detail, and certainly provide a valid means of exploring the consequences of geoengineering at a broad level (such as estimating the reduction of mean global temperatures). But they remain models, with inherent uncertainties,[26] and challenges remain in simulating climate responses to forcings such as sulphate aerosols,[27] including on finer spatial (local to regional) scales. This is critical because it is at local to regional scales that individuals and societies must experience climate and plan for extreme weather, and at this scale that societies will experience the variable impacts of possible SAI geoengineering.[28] Of particular concern in this respect are impacts from geoengineering on regional precipitation and hydroclimates.

While temperature impacts have historically been the dominant focus of volcanic climatic impact studies, recent work using improved climate modelling and

25 Detlef P. VAN VUUREN / Elke STEHFEST, If Climate Action Becomes Urgent: The Importance of Response Times for Various Climate Strategies, in: Climatic Change 121(3) (2013), pp. 473–486. More specifically, the authors find (ibid., p. 473) that "reduction rates [. . .] [of] up to 6% [per year] [. . .] could effectively reduce climate change, but only with a noticeable delay" and with "temperatures [. . .] above those in the year of policy introduction for more than 70 years [. . .]" while "a strategy based on SRM is shown to have much shorter response times [. . .]".

26 For relevant discussion, see Sajjad EGHDAMIRAD / Fiona JOHNSON / Ashish SHARMA, How Reliable are GCM Simulations for Different Atmospheric Variables?, in: Climatic Change 145(1–2) (2017), pp. 237–248. See also Section 6.2.2 of Tamsin L. EDWARDS, Hydrometeorological Hazards Under Future Climate Change, in: Jonathan ROUGIER / Steve SPARKS / Lisa HILL (eds.), Risk and Uncertainty Assessment for Natural Hazards, Cambridge 2013, pp. 151–189.

27 As example, KASHIMURA et al. note a "high uncertainty in modelled processes of sulfate aerosols and clouds" (p. 3339) in their assessment of results from the G4 experiment of the Geoengineering Model Intercomparison Project (GeoMIP), which represents a major effort to model the likely impacts of SRM geoengineering, see Hirokie KASHIMURA / Manabu ABE / Shingo WATANABE / Takashi SEKIYA / Duoying JI / John C. MOORE / Jason N. S. COLE /Ben KRAVITZ, Shortwave Radiative Forcing, Rapid Adjustment, and Feedback to the Surface by Sulfate Geoengineering: Analysis of the Geoengineering Model Intercomparison Project G4 Scenario, in: Atmospheric Chemistry and Physics 17(5) (2017), pp. 3339–3356; cf. http://climate.envsci.rutgers.edu/GeoMIP (last accessed 15/05/2019).

28 As stated in Francis LUDLOW / Alexander R. STINE / Paul LEAHY / Enda MURPHY / Paul A. MAYEWSKI / David TAYLOR / James KILLEN / Michael G. L. BAILLIE / Mark HENNESSY / Gerard KIELY, Medieval Irish Chronicles Reveal Persistent Volcanic Forcing of Severe Winter Cold Events, 431–1649 CE, in: Environmental Research Letters 8(2) (2013), L024035.

paleoclimatic proxies such as precipitation-sensitive tree rings have shown significant impacts on global to regional precipitation and hydrology following volcanic eruptions.[29] These impacts arise from both the direct radiative impact of volcanic sulphate aerosols (in which lower average surface temperatures can lead to a net decrease in evaporation and hence a net decrease in global average precipitation) and a dynamical impact that may be even more important (leading to notable changes in the regional distribution of precipitation). These responses are complex and much depends upon the location of stratospheric sulphate aerosol loading. High-latitude eruptions in the Northern Hemisphere (e. g., Icelandic, Alaskan, Kamchatkan) alter the Earth's radiative balance by primarily cooling the Northern Hemisphere where the aerosols are concentrated. This then diminishes the boreal (i. e., Northern Hemispheric) summertime heating that drives the northward migration of monsoon winds and associated rainfall each summer.[30] Some 70 % of global population now live in monsoon dependent regions,[31] including some of the Earth's poorest peoples whose livelihoods may be profoundly affected by monsoon weakening. An awareness of the hydroclimatic impacts of past volcanic eruptions already acts as a caution in

29 Prominent examples are Charles E. Iles / Gabriele C. Hegerl / Andrew P. Schurer / Xuebin Zhang, The Effect of Volcanic Eruptions on Global Precipitation, in: Journal of Geophysical Research 118 (2013), pp. 8770–8786; Brendan M. Buckley / Roland Fletcher / Shi-Yu Simon Wang / Brian Zottoli / Christophe Pottiere, Monsoon Extremes and Society over the Past Millennium on Mainland Southeast Asia, in: Quaternary Science Reviews 95 (2014), pp. 1–19; Charles E. Iles / Gabriele C. Hegerl, The Global Precipitation Response to Volcanic Eruptions in the CMIP5 Models, in: Environmental Research Letters 9 (2014), 104012; Martin Wegmann / Stefan Brönnimann, Volcanic Influence on European Summer Precipitation through Monsoons: Possible Cause for "Years without Summer", in: Journal of Climate 27 (2014), pp. 3683–3691; Charles E. Iles / Gabriele Hegerl, Systematic Change in Global Patterns of Streamflow Following Volcanic Eruptions, in: Nature Geoscience 8 (2015), pp. 838–842; Fei Liu / Jing Chai / Bin Wang / Jian Liu / Xiao Zhang / Zhiyuan Wang, Global Monsoon Precipitation Responses to Large Volcanic Eruptions, in: Scientific Reports 6 (2016), 24331; Mukund Palat Rao / Benjamin I. Cook / Edward R. Cook / Rosanne D'Arrigo / Paul Krusic / Kevin J. Anchukaitis / Allegra N. LeGrande / Brendan M. Buckley / Nicole K. Davi / Caroline Leland / Kevin Lee Griffin, European and Mediterranean Hydroclimate Responses to Tropical Volcanic Forcing over the Last Millennium, in: Geophysical Research Letters 44 (2017), 55894.

30 See note 29; see also Luke Oman / Alan Robock / Georgiy L. Stenchikov / Thorvaldur Thordarson, High-Latitude Eruptions Cast Shadow over the African Monsoon and the Flow of the Nile, in: Geophysical Research Letters 33 (2006), L18711; Brian Zambri / Alan Robock, Winter Warming and Summer Monsoon Reduction after Volcanic Eruptions in Coupled Model Intercomparison Project 5 (CMIP5) Simulations, in: Geophysical Research Letters 43 (2016), pp. 10,920–10,928, and Joseph G. Manning / Francis Ludlow / Alexander R. Stine / William R. Boos / Michael Sigl / Jennifer R. Marlon, Volcanic Suppression of Nile Summer Flooding Triggers Revolt and Constrains Interstate Conflict in Ancient Egypt, in: Nature Communications 8 (2017), A900.

31 Mahyar Mohtadi / Matthias Prange / Stephan Steinke, Palaeoclimatic Insights into Forcing and Response of Monsoon Rainfall, in: Nature 533 (2016), pp. 191–199.

this respect,[32] with the potential for similar impacts from SAI geoengineering being frequently cited as a key area requiring further research.

The likelihood of unequally distributed hydroclimatic impacts implies that there may be both winners and losers from potential SAI geoengineering implementation. Modelling suggests that a scenario in which SAI geoengineering preferentially loads the Southern Hemisphere stratosphere with sulphate may, for instance, enhance precipitation in the African Sahel and produce a potentially beneficial 'greening' of a region known for prolonged and often socially catastrophic drought.[33] This greening may, however, come at the expense of other regions such as parts of South America that may experience a drying from the same shifting precipitation patterns that would benefit the Sahel.[34] Modelling work has begun to test strategies in which SAI injection would be tailored (e. g., with multiple injection locations, varied seasonally) to serve multiple climatic goals, not just a reduction of average global surface temperatures.[35]

---

32 See for examples Kevin E. TRENBERTH / Aiguo DAI, Effects of Mount Pinatubo Volcanic Eruption on the Hydrological Cycle as an Analog of Geoengineering, in: Geophysical Research Letters 34 (2007), L15702; Zhihong ZHUO / Chaochao GAO / Yuqing PAN, Proxy Evidence for China's Monsoon Precipitation Response to Volcanic Aerosols over the Past Seven Centuries, in: Journal of Geophysical Research 119 (2014), pp. 6638–6652; Jim M. HAYWOOD / Andy JONES / Nicolas BELLOUIN / David STEPHENSON, Asymmetric Forcing from Stratospheric Aerosols Impacts Sahelian Rainfall, in: Nature Climate Change 3 (2017), pp. 660–665.

33 The proposed mechanism involves a more pronounced northward boreal summer migration of the Intertropical Convergence Zone (ITCZ) allowing a greater penetration of the related monsoon winds and rainfall in the Sahel region, see HAYWOOD et al. (note 32). Historical documentary and tree-ring evidence of monsoon variability in China over the past seven centuries also suggests that eruptions occurring in the Southern Hemisphere are associated with increased monsoon precipitation, as per ZHUO / GAO / PAN (note 32).

34 HAYWOOD et al. (note 32).

35 See as examples Zhenyu DAI / Debra K. WEISENSTEIN / David W. KEITH, Tailoring Meridional and Seasonal Radiative Forcing by Sulfate Aerosol Solar Geoengineering, in: Geophysical Research Letters 45(2) (2018), pp. 1030–1039, online (DOI): https://doi.org/10.1002/2017GL076472 (last accessed 15/05/2019); Simone TILMES / Jadwiga H. RICHTER / Ben KRAVITZ / Douglas MACMARTIN / Michael M. MILLS / Isla R. SIMPSON / Anne S. GLANVILLE / John T. FASULLO / Adam S. PHILLIPS / Jean-Francois LAMARQUE / Joseph TRIBBIA / Jim EDWARDS / Sheri MICKELSON / Siddharta GOSH, CESM1(WACCM) Stratospheric Aerosol Geoengineering Large Ensemble (GLENS) Project, in: Bulletin of the American Meteorological Society 99 (2018), pp. 2361–2371, online (DOI): https://doi.org/10.1175/BAMS-D-17-0267.1 (last accessed 15/05/2019); Ben KRAVITZ / Douglas G. MACMARTIN / Michael J. MILLS / Jadwiga H. RICHTER / Simone TILMES / Jean-Francois LAMARQUE / Joseph J. TRIBBIA / Francis VITT, First Simulations of Designing Stratospheric Sulfate Aerosol Geoengineering to Meet Multiple Simultaneous Climate Objectives, in: Journal of Geophysical Research: Atmospheres (2017), online (DOI): 10.1002/2017JD026874 (last accessed (15/05/2019); Anton LAAKSO / Hannele KORHONEN / Sami ROMAKKANIEMI / Harri KOKKOLA, Radiative and Climate Effects of Stratospheric Sulfur Geoengineering Using Seasonally Varying Injection Areas, in: Atmospheric Chemistry and Physics 17(11) (2017), pp. 6957–6974; Xiaoyong YU / John C. MOORE / Xuefeng CUI / Annette RINKE / Duoying JI /Ben KRAVITZ / Jin-Ho YOOND, Impacts, Effectiveness and Regional Inequalities of the GeoMIP G1 to G4 Solar Radiation Management Scenarios, in: Global and Planetary Change 129 (2015), pp. 10–22.

Such work can hopefully lead to understandings of how unequal impacts can be minimized for both precipitation and temperatures. It appears unlikely, however, that all adverse climatic impacts can be negated or equally distributed,[36] and political choices (dense with moral and ethical considerations) will hence need to be made regarding trade-offs between costs and benefits of different strategies.[37] Even, indeed, if an equal distribution of climatic impacts were somehow ultimately achievable, disparities in the wealth and adaptability of regions are still likely to promote unequal socioeconomic impacts that may be as difficult, if not more so, to model and plan for as the climatic impacts.

The above provides further reason why many scholars, including proponents of geoengineering research, stress that emissions reductions must accompany any SRM geoengineering, so that the causes and not only the symptoms of global warming are treated (though we may wonder how effective such emphasis from geoengineering researchers on the need to prioritize emissions reductions can be). It is also why there have been urgent calls for considerations of how the deployment (and even basic research into) SRM technologies will be governed. Achieving widely binding and effective governance is, however, likely to prove challenging. Jesse REYNOLDS' study of the evolution of nuclear power governance as a parallel for geoengineering concludes "that climate engineering research will most likely be promoted and will not be the subject of a binding multilateral agreement in the near future",[38] while Olaf CURRY suggests that "ideas about global governance of geoengineering rely on heroic assumptions about state rationality and a generally pacific international system".[39] Related concerns range from the possibility of larger nations 'going rogue' in implementing geoengineering unilaterally if to their own benefit,[40] or others in implementing counter-geoengineering schemes,[41] if reaching consensus under situations

36 Katharine L. RICKE / Morgan GRANGER / Myles R. ALLEN, Regional Climate Response to Solar-Radiation Management, in: Nature Geoscience 3(8) (2010), pp. 537–541.

37 Douglas G. MACMARTIN / David W. KEITH / Ben KRAVITZ / Ken CALDEIRA, Management of Trade-Offs in Geoengineering through Optimal Choice of Non-Uniform Radiative Forcing, in: Nature Climate Change 3(4) (2013), pp. 365–368.

38 Jesse REYNOLDS, The International Regulation of Climate Engineering: Lessons from Nuclear Power, in: Journal of Environmental Law 26(2) (2014), pp. 269–289, here p. 269.

39 Olaf CURRY, The International Politics of Geoengineering. The Feasibility of Plan B for Tackling Climate Change, in: Security Dialogue 48(4) (2017), pp. 297–315, here p. 297.

40 Florian RABITZ, Going Rogue? Scenarios for Unilateral Geoengineering, in: Futures 84 (2016), pp. 98–107; see also John C. MOORE / Ying CHEN / Xuefeng CUI / Wenping YUAN / Wenjie DONG / Yun GAO / Peijun SHI, Will China be the First to Initiate Climate Engineering?, in: Earth's Future 4(12) (2016), pp. 588–595.

41 Andy PARKER / Joshua B. HORTON / David W. KEITH, Stopping Solar Geoengineering Through Technical Means: A Preliminary Assessment of Counter-Geoengineering, in: Earth's Future 6(8) (2018), pp. 1058–1065, online (DOI): doi.org/10.1029/2018EF000864 (last accessed 15/05/2019).

in which regional equality of impacts proves impossible,[42] or if designing an effective mechanism for compensating regions most adversely affected by SRM geoengineering proves too difficult. Providing compensation for those nations now affected most severely by global warming (often those that are not historically responsible for the greatest greenhouse gas emissions) continues to prove contentious, with existing provisions and proposals largely deemed inadequate.[43] There is little reason to think that designing successful compensatory mechanisms for SAI impacts will prove easier, nor designing and implementing successful international emergency aid in the event of adverse (especially if novel and unexpected) consequences.

Scholars have indeed suggested the potential for novel harmful consequences, foremost of which is known as the 'termination effect'. This describes a return to pre-SAI temperatures occurring rapidly due to the short (one to two year) residence time of sulphate aerosol in the atmosphere, and making for potentially unpredictable impacts on ecological, agricultural, and economic systems unable to adapt to the sudden change.[44] Such a scenario has been posited under conditions of political or economic uncertainty, or as part of a 'double catastrophe' in which a first catastrophe (e. g., pandemic disease) triggers a second catastrophe from the sudden cessation of geoengineering.

As the potential of geoengineering responses to global warming are examined, can medieval history offer a perspective from which to help understand the challenges that geoengineering may present and inform our choices? We believe so. As the closest natural parallel to SAI geoengineering,[45] improvements to our knowledge of volcanic climatic impacts are still needed. The number and size of eruptions occurring during the twentieth and twenty-first centuries for which satellite and instrumental observations are available is limited, representing a key constraint. Even the modelling of temperature impacts from explosive eruptions, generally less complex

42 Ricke / Granger / Allen (note 36).

43 A set of essays that addresses the issue of climate justice and its intersection with geoengineering is Christopher J. Preston (ed.), Climate Justice and Geoengineering. Ethics and Policy in the Atmospheric Anthropocene, London, New York 2016.

44 H. Damon Matthews / Ken Caldeira, Transient Climate-Carbon Simulations of Planetary Geoengineering, Proceedings of the National Academy of Sciences 104(24) (2007), pp. 9949–9954; Seth D. Baum / Timothy M. Maher Jr. / Jacob Haqq-Misra, Double Catastrophe: Intermittent Stratospheric Geoengineering Induced by Societal Collapse, in: Environment Systems and Decisions 33 (2013), pp. 168–180; Andreas Oschiles, Temperature Debt of Solar Geoengineering, in: Nature 554 (2018), p. 423; Christopher H. Trisos / Giuseppe Amatulli / Jessica Gurevitch / Alan Robock / Lili Xia / Brian Zambri, Potentially Dangerous Consequences for Biodiversity of Solar Geoengineering Implementation and Termination, in: Nature Ecology & Evolution 2 (2018), pp. 475–482, online (DOI): https://doi.org/10.1038/s41559-017-0431-0 (last accessed 15/05/2019); Andy Parker / Peter J. Irvine, The Risk of Termination Shock from Solar Geoengineering, in: Earth's Future 6(3) (2018), pp. 456–467, online (DOI): https://doi.org/10.1002/2017EF000735 (last accessed 15/05/2019).

45 Robock et al. (note 3).

than precipitation responses, can prove challenging to reconcile with historical observations.[46] While the best-known hemispheric to global-scale response to major explosive volcanism is a summer season cooling, scrutiny of instrumental data and natural archives are increasingly revealing a marked spatial variation in the aftermath of major explosive eruptions.[47] Variation in response can be influenced by the season and location of an eruption, its chemical composition, as well as by interactions between the climatic influences of eruptions and pre-existing modes of atmospheric and climatic variability, including the state of the North Atlantic Oscillation and El Niño-Southern Oscillation.[48] These complexities must be more fully understood and strategies developed to achieve a more uniform response under SAI. Human-environmental interactions (including interactions with disease environments perturbed by climatic shocks) are even more difficult to model. It is by turning to the past that we can begin to sketch an answer.

The Role and Sources of Medieval Historical Climatology

Historical Climatology straddles the divide between history and climatology,[49] and provides an evolving methodology for extracting evidence of past climatic conditions

46 Climatic responses observed after several major tropical eruptions in the modern period include, for example, a dynamically induced winter warming over Northern Hemispheric continental landmasses, which has proven challenging to reproduce in climate models. See recent progress by Brian ZAMBRI / Allegra N. LEGRANDE / Alan ROBOCK / Joanna SLAWINSKA, Northern Hemisphere Winter Warming and Summer Monsoon Reduction after Volcanic Eruptions over the Last Millennium, in: Journal of Geophysical Research: Atmospheres 122 (2016), pp. 7971–7989.

47 Sébastien GUILLET / Christophe CORONA / Markus STOFFEL / Myriam KHODRI / Franck LAVIGNE / Pablo ORTEGA / Nicolas ECKERT / Pascal Dkengne SIELENOU / Valérie DAUX / Olga V. CHURAKOVA (SIDOROVA) / Nicole DAVI / Jean-Louis EDOUARD / Yong ZHANG / Brian H. LUCKMAN / Vladimir S. MYGLAN / Joël GUIOT / Martin BENISTON / Valérie MASSON-DELMOTTE / Clive OPPENHEIMER, Climate Response to the Samalas Volcanic Eruption in 1257 Revealed by Proxy Records, in: Nature Geoscience 10 (2017), pp. 123–128, and Francis LUDLOW, Volcanology: Chronicling a Medieval Eruption, in: Nature Geoscience 10(2) (2017), pp. 77–78.

48 Alan ROBOCK, Volcanic Eruptions and Climate, in: Reviews of Geophysics 38 (2000), pp. 191–219; Jihong COLE-DAI, Volcanoes and Climate, in: Wiley Interdisciplinary Reviews: Climate Change 1(6) (2010), pp. 824–839; Ben KRAVITZ / Alan ROBOCK, Climate Effects of High-Latitude Volcanic Eruptions. Role of the Time of Year, in: Journal of Geophysical Research: Atmospheres 116 (D1) (2011), online (DOI): https://doi.org/10.1029/2010JD014448 (last accessed 15/05/2019); Allegra N. LEGRANDE / Kostas TSIGARIDIS / Susanne E. BAUER, Role of Atmospheric Chemistry in the Climate Impacts of Stratospheric Volcanic Injections, in: Nature Geoscience 9 (2016), pp. 652–655.

49 Christian PFISTER, Climatic Extremes, Recurrent Crises and Witch Hunts. Strategies of European Societies in Coping with Exogenous Shocks in the Late Sixteenth and Early Seventeenth Centuries, in: The Medieval History Journal 10 (2007), pp. 33–73.

from historical archives and, increasingly, for combining this with evidence from natural archives, often especially high-resolution proxy sources such as tree-rings and ice cores.[50] Although a comparatively young discipline,[51] its contribution to understanding the human impacts of past extreme weather events has already been important.[52] The integration of evidence from written and natural archives is particularly crucial for the medieval period in which human records are relatively scant compared to the wealth of information available from the abundance of texts available after 1500 CE, the period that has to date received the greatest attention from historical climatologists.[53] Using methodologies developed within the discipline, we can examine past cases of climatic perturbations forced by the injection of sulphates into the stratosphere by major explosive volcanic eruptions and any ensuing societal impacts, thereby contributing to understandings of the potential consequences of SAI geoengineering. In undertaking such research, the medievalist is catapulted into the heart of a research field and debate that has important consequences for the future of humanity.

Historical Climatological research into the high and particularly early medieval periods has until recently been hampered by (1) concerns over the reliability of ice-

50 For overviews, see Christian PFISTER / Rudolf BRÁZDIL / Mariano BARRIENDOS, Reconstructing Past Climate and Natural Disasters in Europe Using Documentary Evidence, in: PAGES News 10(3) (2002), pp. 6–7, and Rudolf BRÁZDIL / Christian PFISTER / Heinz WANNER / Hans VON STORCH / Jürg LUTERBACHER, Historical Climatology in Europe – The State of the Art, in: Climatic Change 70 (2005), pp. 363–430.

51 The discipline has grown in prominence since the 1990s (see works such as Hubert H. LAMB, Climate, History and the Modern world, 2nd ed. London 1995, and Astrid E. OGILVIE / Graham FARMER, Documenting the Medieval Climate, in: Mike HULME / Elaine BARROW [eds.], Climates of the British Isles: Past, Present and Future, London, New York 1997, pp. 112–134), but important framing works were published in the 1960s and 1970s (e. g. Emmanuel Le Roy LADURIE, Times of Feast, Times of Famine. A History of Climate since the Year 1000, London 1971, and Wendy T. BELL / Astrid E. OGILVIE, Weather Compilations as a Source of Data for the Reconstruction of European Climate During Medieval Period, in: Climatic Change 1 [1978], pp. 331–348), while further relevant work is recognizable in earlier decades still (e. g., Charles E. P. BROOKS, Historical Climatology of England and Wales, in: Quarterly Journal of the Royal Meteorological Society 54 [1928], pp. 309–317).

52 This is an increasing focus of historical climatologists (as advocated by Christian PFISTER, The Vulnerability of Past Societies to Climatic Variation. A New Focus for Historical Climatology in the Twenty-first Century, in: Climatic Change 100 [2010], pp. 25–31) and complements work by a growing number of climate historians, who generally place less emphasis on climate reconstruction and more on the role of climate in human history; see, e. g., Sam WHITE, The Climate of Rebellion in the Early Modern Ottoman Empire, Cambridge 2011, and ID., A Cold Welcome: The Little Ice Age and Europe's Encounter with North America, Cambridge 2017.

53 As per classic works of historical climatology such as Raymond BRADLEY / Philip D. JONES (eds.), Climate Since A.D. 1500, rev. ed., London 1995; Francis LUDLOW / Charles TRAVIS, STEAM Approaches to Climate Change, Extreme Weather and Social-Political Conflict, in: Armida DE LA GARZA / Charles TRAVIS (eds.), STEAM: Transdisciplinary Approaches to Science, Arts, Humanities & Technology Studies, New York 2018, pp. 33–65.

core chronologies from which to identify the timing of past eruptions, (2) a relative paucity of well replicated tree ring chronologies, with generally fewer tree-ring samples available compared to the later medieval and early modern periods, and hence a potentially less reliable ('noisier') climate signal preserved within these chronologies, and (3) the scarcity (actual and perceived) of historically reliable written evidence. These challenges have now been either resolved, or are in the process of being so, and we elaborate upon each in turn below.

Ice core data on past volcanic activity comes to us from glaciers and ice sheets that provide a record of acidity and other chemical and physical traces that have been preserved by the compression of annual snowfall into layers of ice. This annual layering (Figure 1), most easily visible in high snowfall accumulation sites, allows ice-core scientists to count layers backwards and create a history of past explosive volcanism that can pinpoint the timing and volume of fallout of volcanic sulphate and tephra (i. e., volcanic glass) to specific calendar years. There are, however, several reasons why a volcanic signal might not be accurately preserved in the ice. The complexities of broader scale atmospheric circulation patterns as well as local weather conditions will influence the specific timing and volume of sulphate deposited,[54] while post-depositional processes such as drifting and wind scouring of fallen snow may also bias a signal.[55] The use of multiple ice-cores from dispersed locations can thus improve estimates of the volume of sulphate released by any given eruption and help to prevent over- or under-estimation of likely climatic impacts.[56]

54 Gregory A. ZIELINSKI / Jack E. DIBB / Qinzhao YANG / Paul A. MAYEWSKI / Sallie WHITLOW / Mark S. TWICKLER / Mark S. GERMANI, Assessment of the Record of the 1982 El Chichón Eruption as Preserved in Greenland Snow, in: Journal of Geophysical Research 102(D25) (1997), pp. 30,031–30,045; Chaochao GAO / Luke OMAN / Alan ROBOCK / Georgiy L. STENCHIKOV, Atmospheric Volcanic Loading Derived from Bipolar Ice Cores. Accounting for the Spatial Distribution of Volcanic Deposition, in: Journal of Geophysical Research 112(D9) (2007), online (DOI): https://doi.org/10.1029/2006JD007461 (last accessed 15/05/2019); Christoph T. PLUMMER / Marc A. CURRAN / Tas D. VAN OMMEN / Sune Olander RASMUSSEN / Andrew D. MOY / Tessa R. VANCE / Henrik B. CLAUSEN / Bo VINTHER / Paul A. MAYEWSKI, An Independently Dated 2000-yr Volcanic Record from Law Dome, East Antarctica, Including a New Perspective on the Dating of the 1450s CE Eruption of Kuwae, Vanuatu, in: Climate of the Past 8 (2012), pp. 1929–1940.

55 David A. FISHER / Nils REEH / Henrik B. CLAUSEN, Stratigraphic Noise in Time Series Derived from Ice Cores, in: Annals of Glaciology 7 (1985), pp. 76–83; ZIELINSKI et al. (note 54).

56 See examples of this approach by Thomas CROWLEY / Gregory A. ZIELINSKI / Bo VINTHER / Roberto UDISTI / Karl KREUTZ / Jihong COLE-DAI / Emiliano CASTELLANO, Volcanism and the Little Ice Age, in: PAGES News 16 (2008), pp. 22–23; Chaochao GAO / Allan ROBOCK / Caspar AMMANN, Volcanic Forcing of Climate Over the Past 1500 Years. An Improved Ice Core-Based Index for Climate Models, in: Journal of Geophysical Research. Atmospheres 113(D23) (2008), online (DOI): https://doi.org/10.1029/2008JD010239 (last accessed 15/05/2019; see also the correction by ID., Correction to "Volcanic forcing of climate over the past 1500 years: An improved ice core-based index for climate models", in: Journal of Geophysical Research. Atmospheres 117[D16] [2012],

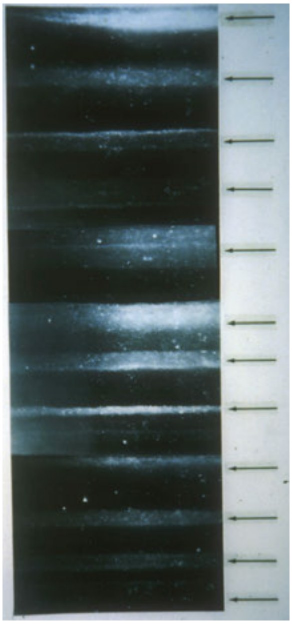

Figure 1: One metre section of the Greenland Ice Sheet Project 2 (GISP2) ice-core from 1885 metres depth. This section of the core is dated to c. 16,880 YBP (years before present) and the beginning of each annual layer is denoted by an arrow. The GISP2 site (Summit, Greenland, 3207m elevation, 72.6 N, 38.5 W) experiences sufficiently high snowfall accumulation to facilitate annual layer identification. Picture courtesy of Deb Meese.

A key consideration when employing ice-core evidence relates to the accuracy and precision of the chronologies (or timescales) available.[57] As well as visual inspection of the ice, measurements of seasonally varying levels of dust and chemical species provide additional parameters for identifying and counting annual layers.[58] Even with multiple parameters available, the identification of individual annual layers involves some subjectivity. A landmark study on the GISP2 Greenland ice-core that

online (DOI): https://doi.org/10.1029/2012JD018052 [last accessed 15/05/2019]); Michael SIGL / Joseph R. MCCONNELL / Lawrence LAYMAN / Olivia MASELLI / Ken MCGWIRE / Daniel PASTERIS / Dorthe DAHL-JENSEN / Jørgen Peder STEFFENSEN / Bo VINTHER / Ross EDWARDS / Robert MULVANEY / Sepp KIPFSTUHL, A New Bipolar Ice Core Record of Volcanism from WAIS Divide and NEEM and Implications for Climate Forcing of the Last 2000 Years, in: Journal of Geophysical Research. Atmospheres 118(3) (2013), pp. 1151–1169, online (DOI): https://doi.org/10.1029/2012JD018603 (last accessed 15/05/2019), and Matthew TOOHEY / Michael SIGL, Volcanic Stratospheric Sulfur Injections and Aerosol Optical Depth from 500BCE to 1900CE, in: Earth System Science Data 9 (2017), pp. 809–831.

57 Accuracy here relates to whether a volcanic signal registered in an ice core falls on or within (in the cases where estimates are provided as ranges) a chronology or timescale's cited age or date estimate. An accurate date may be more or less precise, e. g., an age estimate for a volcanic signal of say, 853 CE +/- 5 years is less precise than 853 CE +/- 2 years.

58 Such chemical species include nitrates, calcium, and chloride; further discussion is provided by Claus U. HAMMER, Ice-Core Chronology, in: Peter G. KNIGHT (ed.), Glacier Science and Environmental Change, Malden 2006, pp. 398–403.

compared results from independent layer counters was thus able to group counters into 'splitters' and 'lumpers', with splitters tending to identify a greater number of annual layers than actually existed by artificially dividing individual layers, and lumpers the opposite, though less divergence occurred between counters of greater experience.[59] Uncertainties in annual layer counting may be estimated and controlled for by the use of chronological reference horizons in the ice, with such horizons including volcanic sulphate signals tied to eruptions of historically (and hence independently) known date, ideally corroborated by tephra in the ice corresponding to known tephra chemistries from the presumed source volcano and eruption. In cases where reference horizons are erroneous but unknowingly used to adjust or constrain ice-core timescales, the accuracy of estimated dates will be compromized. This is particularly the case when the dates offered by ice-core timescales claim a high precision, in which the actual date of an event will more easily fall outside of its estimated date-range if the relevant time-scale has been influenced by erroneous reference horizons. The utility of volcanic dates for climatic or societal impact analyses grows with increasing precision, but there is a clear trade-off between accuracy and precision, and precise dates can be actively misleading in serving to obscure links between volcanism, climate and society if they are inaccurate.

An undiagnosed error of approximately seven years in the first millennium CE of the important Greenland Ice Core Chronology 2005 (GICC05) timescale was in fact identified by Mike BAILLIE in 2008.[60] This timescale was developed based upon layer counting and synchronization of three major Greenland ice cores, the GRIP, NGRIP and Dye-3.[61] An error of less than a decade in dating is in some senses small. It is negligible for studies examining climatic changes on multi-millennial time-scales, for example, but is of sufficient magnitude to have hampered efforts to assess the role of explosive volcanism as a driver of climatic variability on inter-annual timescales in the early medieval period, and to understand

59 Richard B. ALLEY / Christopher A. SHUMAN / Debra A. MEESE / Anthony J. GOW / Kendrick C. TAYLOR / Kurt M. CUFFEY / Joan J. FITZPATRICK / Pieter M. GROOTES / Gregory A. ZIELINSKI / Mar RAM / Glenn SPINELLI / Bruce C. ELDER, Visual-Stratigraphic Dating of the GISP2 Ice Core. Basis, Reproducibility, and Application, in: Journal of Geophysical Research 102(C12) (1997), pp. 26367–26381.

60 Michael G. L. BAILLIE, Proposed Re-Dating of the European Ice Core Chronology by Seven Years prior to the 7th Century AD, in: Geophysical Research Letters 35(15) (2008), online (DOI): https://doi.org/10.1029/2008GL034755 (last accessed 15/05/2019).

61 Bo M. VINTHER / Henrik B. CLAUSEN / Sigfus J. JOHNSEN / Sune O. RASMUSSEN / Katrine K. ANDERSEN / Susanne L. BUCHARDT / Dorthe DAHL-JENSEN / Inger K. SEIERSTAD / Marie-Louise SIGGAARD-ANDERSEN / Jorgen P. STEFFENSEN / Anders SVENSSON / Jesper W. OLSEN / Jan HEINEMEIER, A Synchronized Dating of Three Greenland Ice Cores Throughout the Holocene, in: Journal of Geophysical Research. Atmospheres 111(D13) (2006), online (DOI): https://doi.org/10.1029/2005JD006921 (last accessed 15/05/2019).

the impact of such variability on early medieval society. It is regrettable that with compelling evidence of an error presented in 2008, and reinforced in 2010,[62] that timescales were not more rapidly revised. This issue was compounded both by the rescaling of independent ice-core chronologies onto the GICC05,[63] and the counting of new ice-cores on the assumption that the GICC05 was correct, having an error of at most +/-1 year during the Common Era, and a claimed tree-ring-like precision.[64] Work led by Michael SIGL and published in 2015 supported the veracity of BAILLIE'S proposed chronological corrections and established a revised ice-core timescale and associated volcanic history for the past 2,500 years.[65] This work identified errors accumulating from approximately the mid-thirteenth century, before the great 1257 Samalas eruption (which provides a clear global marker event in polar ice-cores). This correction was achieved thanks in part to the recent identification of two cosmic events, one in 775 CE and another at 994 CE that registered through anomalous ^{10}Be levels in ice cores and $^{14}CO_2$ in tree rings.[66]

If the compact layering of ice provides one of the most valuable sources of natural proxy data, its worth is matched by that available from tree rings. Of all available natural archives, tree-rings provide one of the most important means of understanding how past climatic conditions varied on a year-to-year (interannual) timescale.[67] Since the growth of trees is strongly controlled by climate, variations

62 Michael G. L. BAILLIE, Volcanoes, Ice-Cores and Tree-Rings: One Story or Two?, in: Antiquity 84 (2010), pp. 202–215.

63 Bo M. VINTHER / Henrik B. CLAUSEN / David A. FISHER / Roy M. KOERNER / Sigfus J. JOHNSEN / Katrine K. ANDERSEN / Dorthe DAHL-JENSEN / Sune O. RASMUSSEN / Jorgen P. STEFFENSEN / Anders M. SVENSSON, Synchronizing Ice Cores from the Renland and Agassiz Ice Caps to the Greenland Ice Core Chronology, in: Journal of Geophysical Research 113(D8) (2008), online (DOI): https://doi.org/10.1029/2007JD009143 (last accessed 15/05/2019)

64 HAMMER (note 58), p. 398.

65 SIGL et al. (note 4).

66 Fusa MIYAKE / Kentaro NAGAYA / Kimiaki MASUDA / Toshio NAKAMURA, A Signature of Cosmic-Ray Increase in AD 774–775 from Tree Rings in Japan, in: Nature 486 (2012), pp. 240–242; Ilya G. USOSKIN / Bernd KROMER / Francis LUDLOW / Juerg BEER / Michael FRIEDRICH /Gennady KOVALTSOV / Sami K. SOLANKI / Lukas WACKER, The AD775 Cosmic Event Revisited. The Sun is to Blame, in: Astronomy & Astrophysics 553 (2013), L3, online (DOI): https://doi.org/10.1051/0004-6361/201321080 (last accessed 15/05/2019).

67 Peter D. JONES / Keith R. BRIFFA / Timothy J. OSBORN / Janice M. LOUGH / Trang D. VAN OMMEN / Bo M. VINTHER / Juerg LUTERBACHER / Elizabeth R. WAHL / Francis W. ZWIERS / Mark E. MANN / Gregory A. SCHMIDT / Caspar M. AMMANN / Brendan M. BUCKLEY / Kim M. COBB / Jhonatan ESPER / Hugues GOOSSE / Nicol GRAHAM / Emily JANSEN / Thorsten KIEFER / Christian KULL / Michael KÜTTEL / Ellen MOSLEY-THOMPSON / Jonathan T. OVERPECK / Nadja RIEDWYL / Mauro SCHULZ / Alexander W. TUDHOPE / Ricardo VILLALBA / Helen WANNER / Elisabeth WOLFF / Elena XOPLAKI, High-Resolution Palaeoclimatology of the Last Millennium. A Review of Current Status and Future Prospects, in: The Holocene 19 (2009), pp. 3–49.

in the widths of annual growth rings have allowed climatic conditions to be inferred for past centuries, and increasingly, millennia. It is thus possible to examine the climatic impacts of major explosive eruptions using tree-ring data, with pronounced growth minima (and sometimes visible physical damage in the form of 'frost rings') often following such eruptions.[68] Even, however, if volcanic climatic impacts were evenly distributed in space and time, tree-ring responses would likely vary by species and location, sometimes over quite short distances.[69] The complexities of tree-ring evidence and how it registers climatic influences must thus be understood for its credible interpretation by medieval historical climatologists. An eruption that has left a strong signal in ice-cores and/or in the historical record may not, for example, find a clear expression in 'complacent' trees growing in favourable environmental locations.[70] Human disturbances affecting tree growth (e. g., forest management practices such as coppicing) or natural disturbances from insect or fungal pathogen outbreaks may also complicate the identification of any climatic response.[71] Sensitive ('stressed') trees that grew at or near their environmental limits, such as in arid or cold high-altitude or high-latitude locations, are thus often favoured when making climatic inferences, as are those from locations less likely to be influenced by human activity. If volcanic climatic impacts are experienced by the tree mainly

68 Matthew SALZER / Malcolm HUGHES, Bristlecone Pine Tree Rings and Volcanic Eruptions over the Last 5000 Years, in: Quaternary Research 67 (2007), pp. 57–68; see also Keith R. BRIFFA / Philip D. JONES / Fritz H. SCHWEINGRUBER / Timothy J. OSBORN, Influence of Volcanic Eruptions on Northern Hemisphere Summer Temperature over the Past 600 Years, in: Nature 393 (1998), pp. 450–455; Rosanne D. D'ARRIGO / Gordon C. JACOBY, Northern North American tree-ring evidence for regional temperature changes after major volcanic events, in: Climatic Change 41 (1999), pp. 1–15.

69 Divergence in climate-growth responses can occur in particular circumstances over even comparatively small distances if trees are sampled across an area with a steep altitudinal gradient, or in nearby sites but with a different aspect, or between comparatively water-logged (e. g., lake margin) locations versus those further inshore; see discussion by Carolyn COPENHEAVER / Laura E. HENDRICK / John W. HOUCHINS / Christopher D. PEARCE, Changes in Growth and Dendroclimatic Response of Trees Growing Along an Artificial Lake, in: The American Midland Naturalist 163 (2010), pp. 134–145; Ernst VAN DER MAATEN, Climate Sensitivity of Radial Growth in European Beech (Fagus sylvatica L.) at Different Aspects in Southwestern Germany, in: Trees 26 (2012), pp. 777–788, and Elisabeth DÜTHORN / Lea SCHNEIDER / Oliver KONTER / Philipp SCHÖN / Mauri TIMONEN / Jan ESPER, On the Hidden Significance of Differing Micro-Sites on Tree-Ring Based Climate Reconstructions, in: Silva Fennica 49(1) (2015), Article 1220, online (DOI): https://doi.org/10.14214/sf.1220 (last accessed 15/05/2019).

70 A straightforward discussion of sensitive versus complacent trees is given in Marvin A. STOKES / Terah L. SMILEY, An Introduction to Tree-Ring Dating, Chicago 1968, pp. 10–11. More recent isotopic and densitometric analyses have, however, made improved use of 'complacent' tree-ring data; for a summary see Raymond S. BRADLEY, Palaeoclimatology. Reconstructing Climates of the Quaternary, 3rd ed. Oxford 2015, pp. 456–458.

71 Kristof HANECA / Ilse BOEREN / Joris VAN ACKER / Hans BEECKMAN, Dendrochronology in Suboptimal Conditions: Tree Rings from Medieval Oak from Flanders (Belgium) as Dating Tools and Archives of Past Forest Management, in: Vegetation History and Archaeobotany 15 (2006), pp. 137–144.

during the spring-summer growing season, the response is likely to be of greater magnitude than for other seasons when the tree is partially or fully dormant. A lagged or multi-year growth responses can also occur in response to extreme weather, potentially in cases when trees are able to temporarily sustain themselves through stored energy reserves (carbohydrates), and soil or bedrock moisture reserves.[72] It follows that responses to explosive volcanism may be potentially influenced by preceding conditions – reduced precipitation following a major eruption may be less impactful if this followed a period of abundant precipitation, and vice versa.

Using large numbers of trees (and multi-tree 'chronologies') from dispersed sites allows broader climate signals to be extracted by minimizing influences from local site-specific environmental and micro-climatic influences. Improvements in the temporal and spatial coverage of tree-ring data (from ongoing field campaigns and improved sharing of sometimes closely guarded earlier-collected data) is thus of great importance. So too is the development of new means of extracting climatic data from these tree-rings, most prominently measurement of the density of each year's latewood growth, which can often be more strongly correlated to climate. Thus, the increasing availability of tree-ring chronologies spanning several millennia has led to the creation of a number of robust chronologies such as the 3512-year Qilian juniper (*Juniperus przewalskii*) precipitation-sensitive ring-width chronology from the Tibetan plateau,[73] or the 4064-year Siberian larch (*Larix sibrica*) temperature-sensitive chronology, also from a high latitude in the Yamal Peninsula, western Siberia.[74] Other important series include a 2140-year Scots pine (*Pinus sylvestris*) maximum latewood density

72 Nathalie BRÉDA /Vincent BADEAU, Forest Tree Responses to Extreme Drought and Some Biotic Events: Towards a Selection According to Hazard Tolerance?, in: Comptes Rendus Geoscience 340 (2008), pp. 651–662; Flurin BABST / Marco CARRER / Benjamin POULTER / Carlo URBINATI / Burkhard NEUWIRTH / David FRANK, 500 Years of Regional Forest Growth Variability and Links to Climatic Extreme Events in Europe, in: Environmental Research Letters 7(4) (2012), 045705; Christian PFISTER / Oliver WETTER / Rudolf BRÁZDIL / Petr DOBROVOLNÝ / Rüdiger GLASER / Jürg LUTTERBACH / Sonia I. SENEVIRATNE / Eduardo ZORITA / Maria-Joao ALCOFORADO / Mariano BARRIENDOS / Ursula BIEBER / Karl H. BURMEISTER / Chantal CAMENISCH / Antonio CONTINO / Uwe GRÜNEWALD / Jürgen HERGET / Iso HIMMELSBACH / Thomas LABBÉ / Danuta LIMANÓWKA / Laurent LITZENBURGER / Andrea KISS / Oldřich KOTYZA / Øyvind NORDLI / Kathleen PRIBYL / Dag RETSÖ / Dirk RIEMANN / Christian ROHR / Werner SIEGFRIED / Jean-Laurent SPRING / Johan SÖDERBERG / Sebastian WAGNER / Johannes P. WERNER, Tree-Rings and People – Different Views on the 1540 Megadrought. Reply to Büntgen et al. 2015, in: Climatic Change 131 (2015), pp. 191–198; Daniella M. REMPE / William E. DIETRICH, Direct Observations of Rock Moisture: A Hidden Component of the Hydrologic Cycle, in: Proceedings of The National Academy of Sciences 115(11) (2018), pp. 2664–2669.

73 Bao YANG / Shuyuan KANG / Fredrik Charpentier LJUNGQVIST / Minhui HE / Yan ZHAO / Chun QIN, Drought Variability at the Northern Fringe of the Asian Summer Monsoon Region over the Past Millennia, in: Climate Dynamics 43(3–4) (2014), pp. 845–859.

74 Rashit M. HANTEMIROV / Stepan G. SHIYATOV, A Continuous Multimillennial Ring-Width Chronology in Yamal, Northwestern Siberia, in: The Holocene 12(6) (2002), pp. 717–726.

temperature-sensitive chronology from Northern Scandinavia,[75] and a 2407-year Pedunculate and Sessile oak (*Quercus robur* and *Quercus petraea*) precipitation-sensitive chronology from Central Europe.[76] This latter tree-ring sequence is particularly important because it comes from the same region as many of our European documentary sources. These chronologies and others are now being increasingly employed in creating spatialized temperature and precipitation (or related hydroclimatic) reconstructions,[77] and we return to these chronologies in the following section.

Where medieval historical climatologists fit into this picture is in applying their expertise in accessing and interpreting the evidence of written sources and, indeed, in understanding the contingencies of human history, the motivations for human behaviours and the interplay of forces that have driven historical change.[78] Medieval texts often provide accounts of weather and (frequently associated) societal stresses such as famine and plague, but the many reasons that might motivate medieval scribes to include such accounts highlights the need to treat all such material critically.[79] The prospective reliability of any given account is often related to the genre of the source text. Consider a text that celebrates the life of a saint and describes a drought that was ended by parading the saint's relics or otherwise invoking his or her intercession, as is the case with Adso's of Montier-en-Der 'Miracles of Saint Mansuy' or Adomnan's of Iona 'Life of Saint Columba'.[80] Or perhaps an author wished to praise the deeds of a king and emphasize a military

75 Jan ESPER / David C. FRANK / Mauri TIMONEN / Eduardo ZORITA / Rob J. S. WILSON / Jürg LUTERBACHER / Steffen HOLZKÄMPER / Nils FISCHER / Sebastian WAGNER / Daniel NIEVERGELT / Anne VERSTEGE / Ulf BÜNTGEN, Orbital Forcing of Tree-Ring Data, in: Nature Climate Change 2 (2012), pp. 862–866.

76 Ulf BÜNTGEN / Willy TEGEL / Kurt NICOLUSSI / Michael MCCORMICK / David FRANK / Valerie TROUET / Jed O. KAPLAN / Franz HERZIG / Karl-Uwe HEUSSNER / Heinz WANNER / Jürg LUTERBACHER / Jan ESPER, 2500 years of European Climate Variability and Human Susceptibility, in: Science 331 (2011), pp. 578–582.

77 See for example the use of European oak ring width chronologies by Edward R. COOK et al., Old World Megadroughts and Pluvials during the Common Era, in: Science Advances 1(10) (2015), e1500561. Spatialized reconstructions covering the entirety of the Early Medieval period are, as yet, rare.

78 Relevant work for the early medieval period includes Michael MCCORMICK / PAUL E. DUTTON / Paul A. MAYEWSKI, Volcanoes and the Climate Forcing of Carolingian Europe, A.D. 750–950, in: Speculum 82 (2007), pp. 865–895, and Timothy P. NEWFIELD, Domesticates, Disease and Climate in Early Post-Classical Europe: The Cattle Plague of c. 940 and its Environmental Context, in: Journal of Post-Classical Archaeologies 5 (2015), pp. 95–126.

79 See the summary discussion regarding the assessment of source reliability in BRÁZDIL et al. (note 50).

80 Francis LUDLOW / Conor KOSTICK, European Climate History, 400–1000 CE, in: Timothy P. NEWFIELD / Richard ORAM / Philip SLAVIN (eds.), Handbook of Medieval Environmental History, vol. 1: The Early Middle Ages, Leiden (in preparation).

success in the face of adversity from a river in flood. A whole range of motives, likely to distort actual events or even invent them entirely, must be considered and an assessment made as to the reliability of both the text as a whole, and particular accounts therein.

Even with annals and chronicles, often more straightforward than hagiography, the subjective interests of the authors mean that they are not suitable to derive the kinds of lengthy reconstructions that historical climatologists often seek. One author, writing for a period of twenty years might have a keen interest in whether the crops did well or poorly, another might have a fascination with celestial events.[81] And if a text comes to us in the hand of one, later, compiler, it is usually challenging to identify when a new chronicler has taken over the record keeping. While such a text might appear to indicate that a period of unpredictable harvests was followed by one of relative stability, it might, in fact, be indicating only that the author has changed. The silences in such records must therefore be treated with great caution, though it is important to recognize that collective silences may be more meaningful as the medieval era progresses and sources become more abundant. Just as evidence cannot be uncritically accepted, nor, however, should it be uncritically dismissed, even for saint's lives, and there are cases in which independent dendrochronological evidence supports the evidence of extreme weather reported in saints' lives.[82] Historical Climatology can only be successful by utilising the source-criticism and language skills of the medieval historian.

For much of the medieval period then, the historical sources are often best used not as a basis for long quantitative sequences of climate information but as qualitative evidence for specific events in narrow periods. And in this they can be spectacularly valuable. Our particular interest in this chapter is in the early medieval period, which has sometimes been dismissed as being impenetrable for a climate and social history due to the difficulty of working with the sources of the period. It has been argued that due to the relative paucity of European written sources in the period following the collapse of the Western Roman Empire, it is not possible to obtain accurate climate information from the 'imprecise', 'exaggerated', and 'unreliable' material that is available.[83] The U.S. National Research Council's assessment of the issue is that "there are [...] weather records preserved in Irish and Norse

81 Francis LUDLOW, Assessing Non-Climatic Influences on the Record of Extreme Weather Events in the Irish Annals, in: Patrick J. DUFFY / William NOLAN (eds.), At the Anvil: Essays in Honour of William J. Smyth, Dublin 2012, pp. 93–133.

82 LUDLOW / KOSTICK (note 80).

83 LAMB (note 51); Christian PFISTER / Jürg LUTERBACHER / Gabriela SCHWARZ-ZANETTI / Milène WEGMANN, Winter Air Temperature Variations in Western Europe during the Early and High Middle Ages (AD 750–1300), in: Holocene 8(5) (1998), pp. 535–552.

annals back to the middle of the first millennium [. . .] but their dating is imprecise and descriptions of weather and climate are often exaggerated."[84] An artificial horizon has therefore been raised, which discourages entry into the past by medieval historical climatologists beyond a certain point.

We believe that there is, in fact, sufficient historical material to reach useful conclusions about the impact of explosive volcanism on early medieval society (and therefore to raise questions about the extent to which our contemporary social structures and technologies are vulnerable). But in making such assessments, it is important to stress that extreme weather does not impact on communities in a crude or deterministic fashion. Rather, the particular social structures and even ideologies of different societies mediate their vulnerabilities, leading to potentially different outcomes for different polities in the face of the same stressors.[85] Pre-existing instabilities, such as periods of warfare, may make a region more vulnerable to the impact of volcanic cooling, while a robust system of state-organized relief, such as occurred in China in 704, can mitigate the societal consequence of a major climate stressor.[86] Again, the relationship between the atmospheric changes following a significant volcanic eruption and the outbreak of epidemics and epizootics is not a straightforward one.[87] There is considerable variation in the importance of extreme cold weather to the spread of certain pathogens and there may well be important steps in the emergence of a major epidemic event that are not always met. For instance, famine and mass migration may be essential prerequisites for a major outbreak of disease, yet whether a climatic shock arising from a major eruption leads to these events will depend on the societal context.

Case Study: 670–730 CE

One period that we have previously looked at in some detail is that of 670–730 CE,[88] being frequently overlooked by historical climatologists and yet also witness to a sequence of substantial explosive volcanic eruptions with sulphate deposition

84 National Research Council, Surface Temperature Reconstructions for the Last 2,000 Years, Washington / D.C. 2006.

85 Katiuscia FARA, How Natural Are "Natural Disasters"? Vulnerability to Drought of Communal Farmers in Southern Namibia, in: Risk Management 3 (2001), pp. 47–63; Monica JUNEJA / Franz MAUELSHAGEN, Disasters and Pre-Industrial Societies. Historiographic Trends and Comparative Perspectives, in: Medieval History Journal 10 (2007), pp. 1–31; Geoffrey PARKER, Global Crisis: War, Climate Change and Catastrophe in the Seventeenth Century, New Haven 2013.

86 For further examples, see Lillian M. LI, Fighting Famine in North China. State, Market, and Environmental Decline, 1690s–1990s, Stanford 2007.

87 See the important work of Timothy NEWFIELD on early medieval disease and climate, e. g. NEWFIELD (note 78).

88 GAO et al. (note 1).

evident in multiple Greenland ice-cores. The period thus provides a useful case study both for illustrating the application of medieval historical climatology and for examining the societal impact of past volcanic climate forcing. Our goals in originally examining this period were (1) to assess the veracity of the above-discussed ice-core chronological corrections proposed by BAILLIE and MCANENEY, using both tree-ring and documentary evidence, and (2) to highlight the value of and challenges inherent in reconciling multiple signals of explosive volcanism in the available Greenland ice-cores for this period (Figure 2). Our analysis supported the veracity of BAILLIE and MCANENEY's proposed corrections in work that again highlights the value of the sources and skillset of medieval historians in addressing major scientific challenges.[89] In our present essay, we emphasize the extent to which our analysis also revealed the climatic impact of these eruptions and the related vulnerability of society across multiple regions despite their different social systems and variable resilience to climatic shocks.

Adjusted according to BAILLIE and MCANENEY's proposed chronological corrections,[90] greater agreement can be observed between volcanic signals from Greenland ice-cores, resulting in a more coherent volcanic history for this period, in which at least six climatically significant volcanic events can be deemed to have occurred, datable approximately to 681, 684–6, 692–3, 697, 706–7 and 730–3 (see Figure 2).[91] While multiple volcanic eruptions occur each year,[92] even very explosive events may not have a significant climatic impact if they are not particularly sulphurous or if most material is ejected laterally rather than into the high atmosphere, as per the major May 1980 eruption of Mt. Saint Helen's, Washington, USA.[93] These six eruptions are of significance, therefore, in having deposited notable volumes of sulphate in Greenland. We can further assess their climate-altering potential by comparing the size of their ice-core sulphate signals against those of known high-VEI and climatically impactful eruptions such as Tambora in 1815 and Krakatau in 1883. After adjusting its chronology by adding seven years, the NEEM S1 dataset registers the largest individual sulphate signal in our period for the year 681 CE, with a measured sulphate deposition of 117 % of the Tambora and 246 % of the Krakatau eruptions. This suggests an immense sulphur-rich eruption capable of

89 The substance of these corrections was also independently confirmed and has been incorporated in state-of-the-art ice-core-based volcanic forcing reconstructions; see SIGL et al. (note 4).

90 The dating of the volcanic signals in Figure 2 reflects the proposed chronological corrections of BAILLIE and MCANENEY, namely an adjustment of +7 years to signals on the GICC05 chronology (i. e., Dye3, GRIP, NGRIP, NEEM) and, for parity, a correction of +5 years to Crête.

91 GAO et al. (note 1). In generating this list, only events identified in at least two independent cores are selected, to increase confidence in the credibility of the volcanic eruptions identified, after the approach of GAO et al. (note 56).

92 Lee SIEBERT / Tom SIMKIN / Paul KIMBERLY, Volcanoes of the World, 3rd ed. Berkeley 2010.

93 Alan ROBOCK, The Mount St. Helens Volcanic Eruption of 18 May 1980: Minimal Climatic Effect, in: Science 212 (1981), pp. 1383–1384.

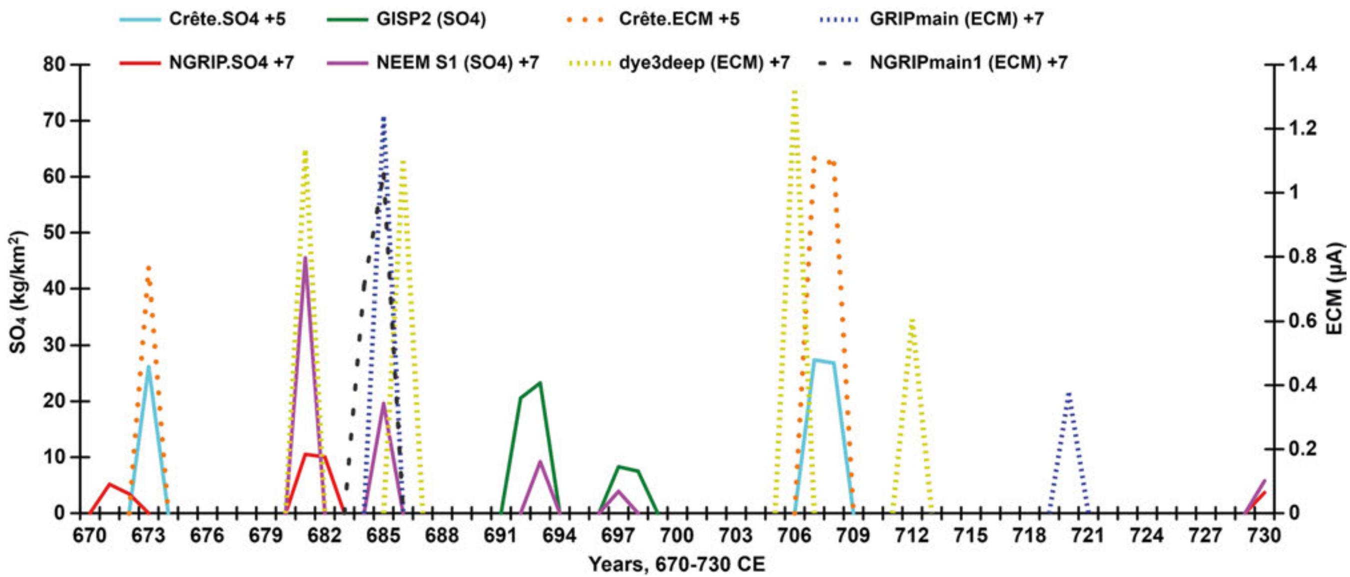

Figure 2: Prospective volcanic signals identified in eight time-series from six Greenland ice-cores. Solid lines show sulphate data in units of SO_4 (kg / km^2) on the left-hand vertical axis, while dashed lines represent electrical conductivity measurements (ECM) in units of μA on the right-hand vertical axis, reflecting a broader spectrum of acids in the ice, including sulphate other volcanic products. Chronological adjustments applied to each time series are noted in the figure legends. Further details on each ice-core are provided in the Appendix (Table A1).

bringing about extensive and severe global cooling, with Antarctic ice-cores also registering a major sulphate signal at this time and hence identifying the eruption as likely having occurred in the tropics.[94] Such high-magnitude sulphur-rich eruptions are infrequent and when they do occur can provide important examples of the challenges societies experience in the face of sudden severe alterations to climate and underlying ecosystems.[95]

The largest ice-core sulphate signal of the past 2,500 years was the product of a VEI 7 'Super-colossal' scale eruption of Samalas volcano on Lombok island, Indonesia, in 1257,[96] an event that induced severe and spatially complex patterns of cooling in the Northern Hemisphere.[97] Comparing the six events signalled in the Greenland ice for 670–730 CE to Samalas, we can calculate the following comparative magnitudes for their sulphate deposition: 681 (44 %), 684–6 (24 %), 692–3 (14 %), 697 (5 %), 706–7 (17 %) and 730–3 (7 %). Starting in approximately 681, therefore, the planet experienced a major injection of sulphate into the atmosphere, with a notable clustering of subsequent eruptions that would have likely sustained the cooling effect of the initial eruption. Few scholars have appreciated this period as one likely to have seen dramatic temperature drops, following closely after the cessation of the recently proposed Late Antique Little Ice Age (c. 536–660 CE).[98] Our research suggests that the period 670–730 CE, and particularly c. 680–710, is one that holds potentially valuable insights into the climatic and societal responses to sustained explosive volcanism, with relevance to concerns over the climatic and societal consequences of geoengineering.

An examination of relevant tree ring sequences confirms that these sixty years were unusual in experiencing a downturn in temperature. Figure 3 depicts two long tree-ring-based temperature reconstructions for continental Europe and the Southern Colorado Plateau, each registering a sustained temperature decrease beginning in

94 SIGL et al. (note 4). In this forcing reconstruction, the date of the 681 event is given as 682, a date that can be considered highly accurately to within +/-1 year.

95 For historians and other scholars, such eruptions can be considered historiographical tools or diagnostic tests of societal vulnerability and resilience to sudden climatic change, as outlined by LUDLOW (note 47).

96 Franck LAVIGNE / Jean-Philippe DEGEAI / Jean-Christophe KOMOROWSKI / Sébastien GUILLET / Vincent ROBERT / Pierre LAHITTE / Clive OPPENHEIMER / Markus STOFFEL / Céline M. VIDAL /Surono Indyo PRATOMO / Patrick WASSMER / Irka HAJDAS / Danang Sri HADMOKO / Edouard DE BELIZAL, Source of the Great A.D. 1257 Mystery Eruption Unveiled, Samalas Volcano, Rinjani Volcanic Complex, Indonesia, in: Proceedings of the National Academy of Sciences 110(42) (2013), pp. 16742–16747.

97 GUILLET et al. (note 47); LUDLOW (note 47).

98 Ulf BÜNTGEN / Vladimir S. MYGLAN / Fredrik Charpentier LJUNGQVIST / Michael MCCORMICK / Nicola DI COSMO / Michael SIGL / Johann JUNGCLAUS / Sebastian WAGNER / Paul J. KRUSIC / Jan ESPER / Jed O. KAPLAN / Michiel A. C. DE VAAN / Jürg LUTERBACHER / Lukas WACKER / Willy TEGEL / Alexander V. KIRDYANOV, Cooling and Societal Change During the Late Antique Little Ice Age from 536 to around 660 AD, in: Nature Geoscience 9 (2016), pp. 231–236.

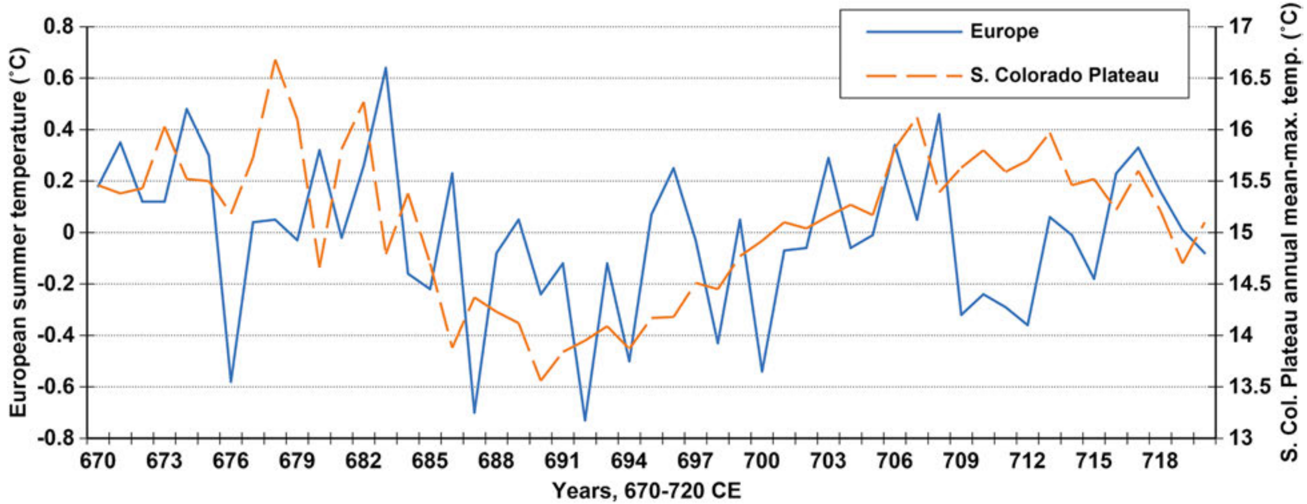

Figure 3: Solid line shows the PAGES 2k Consortium European summer temperature reconstruction relative to 1961–1990 mean (left vertical axis), while the dashed line shows the SALZER and KIPFMUELLER mean-maximum temperature reconstruction from the southern Colorado Plateau (right vertical axis), 670–720 CE. Both reveal a marked temperature decline from the early 680s.

the early 680s and continuing variably into the first decade of the 700s.[99] SALZER and KIPFMUELLER have, moreover, specifically highlighted the years 683–700 as the coldest period in their 2262-year temperature reconstruction for the southern Colorado Plateau.[100] In addition to long multi-millennium temperature reconstructions, which are still comparatively rare, we may draw upon the previously discussed precipitation-sensitive tree-ring-chronologies available for the Tibetan Plateau and Central Europe, in addition to the chronologies from Northern Scandinavia and Yamal that exhibit a dominant sensitivity to growing season temperature. Using these four chronologies, we can identify ten years of notably reduced tree-ring growth that distinguish themselves by co-occurring in at least two of the four regions. The dates of these years of pan-regional growth minima, shown in Table 1, frequently match the timing of volcanic signals in the ice. It is possible to quantify this. Between 670 and 730 CE (inclusive), the average number of tree-ring minima in years associated with volcanic signals is 0.31,[101] while the average number of minima in years not associated with volcanic activity is 0.09. In other words, there exists a much greater (more than three times) average incidence of tree-ring minima occurring within a small number of years of volcanic signals than otherwise. We have confidence, therefore, in drawing the conclusion that the explosive volcanism identified in the chronologically adjusted ice-core evidence notably perturbed hydroclimatic patterns in far flung regions of the Northern Hemisphere.

What do the available written records tell us of these events and their consequences? Between 670 and 730 CE, our survey identified relevant reports of extreme weather and major societal stresses (subsistence crises, epidemic or epizootic disease, and mass human or animal mortality) which occur 29, 16, and 31 times in sources for Europe, the Near East and China, respectively. Events were included or excluded from our analysis according to a scale of historical reliability shown in Table 2. This is a filtering system devised in order to avoid the errors of earlier compilers of extreme weather events and indications of social stress, who simply listed all the reports they came across, without any attempt to weigh them for reliability.[102] Our scale prioritizes eyewitnesses, but even the evidence of such observers cannot be used uncritically. For the purposes of our analysis, we included data only from categories 1 and 2, ranked as most reliable, and excluded those from 3

99 PAGES 2k Consortium, Continental-Scale Temperature Variability during the Past Two Millennia, in: Nature Geoscience 6 (2013), pp. 339–346.

100 Matthew W. SALZER / Kurt KIPFMUELLER, Reconstructed Temperature and Precipitation on a Millennial Timescale from Tree-rings in the Southern Colorado Plateau, U.S.A., in: Climatic Change 70 (2005), pp. 465–487.

101 By 'associated', we mean here any minima occurring within -1 to +3 years (inclusive) of the dates of our volcanic signals, a margin that allows for small remaining uncertainties in the dating of our volcanic signals, and the possibility of a lagged or multi-year climatic and tree-ring-growth response to the eruptions.

102 See discussion in BELL / OGILVIE (note 51), and OGILVIE / FARMER (note 51).

Table 1: Sets of co-occurring tree-ring minima (widths and/or maximum latewood densities) in which growth is at least 1.25 standard deviations below the 670–730 CE mean of each series, in the same or directly consecutive years in two or more regions.*

Years	Series or chronology region and minima years
675–676	Qinghai-Tibet (675), Yamal (675), N. Scandinavia (676)
681	Qinghai-Tibet (681), N. Scandinavia (681)
683–684	Central Europe (683), Yamal (684)
687	N. Scandinavia (687), Central Europe (687)
692	N. Scandinavia (692), Central Europe (692)
696	Qinghai-Tibet (696), Central Europe (696)
700	Qinghai-Tibet (700), Yamal (700), N. Scandinavia (700), Central Europe (700)
705–707	N. Scandinavia (705), Central Europe (706), N. Scandinavia (707)
711	Qinghai-Tibet (711), Central Europe (711)
724–725	Central Europe (724), Qinghai-Tibet (725)

* Table adapted from Gao et al. (note 1).

Table 2: Scale for ranking the prospective reliability of source material.*

Data Rating Confidence Level	Rationale
1	Eyewitness or contemporary with a reliable chronology.
2	Eyewitness or contemporary but with some chronological uncertainty. *Or* Neither eyewitness nor contemporary but has a reliable chronology and accurately conveys the information from earlier sources.
3	Eyewitness or contemporary but with evidence of errors or fabrications. *Or* Neither eyewitness nor contemporary and with an unreliable chronology.
4	Neither eyewitness nor contemporary and with evidence of errors or fabrication.

* This ranking system is also employed in Sigl et al. (note 4).

and 4. This is a simple enough statement to make, but what lies behind it is important for making clear the contribution medievalists make to issues such as the potential societal and climatic consequences of geoengineering. In order to access the historical documentation, the training in source criticism that a medievalist receives is necessary in order to carry out such an evaluation of a text. Even within the same text there can be variation in how it scores on our scale, from passage to passage. For example, we exclude some material found in Hermann of Reichenau (d. 1054), which we ranked 3, as we can see that in several instances he erroneously re-dated the information from his sources. As Hermann came closer to writing about his own times, however, his entries score a 1. Sometimes it becomes possible to assess the dating system of a text against independently dated natural events, such as a report of a solar or lunar eclipse, or well attested human events, such as the death of a leading noble. But always it proves necessary to examine the level of certainty for each source dynamically, through time.

In further analysing the available evidence, the medieval historical climatologist must invest considerable effort in the meteorological interpretation of events, and in our case in particular to identify events of only localized significance (such as small-scale or isolated flash flooding) with the potential to occur in any year given the large spatial domain examined, regardless of any volcanic climatic perturbation. Such events are excluded from Tables 3 to 5 below, which we provide as a research resource detailing prospective large-scale extreme weather events and societal stresses for Europe, the Near East and China for the volcanically active years 670–730 CE. A further key consideration in constructing these tables has been to identify events duplicated between the extant sources, and which may (owing to chronological errors introduced in the copying and transmission of texts, for example) be found under distinct years and hence appear as potentially separate events.[103] The level of duplication of events in the extant Irish annalistic sources is highlighted in Figure 4 as an example, which, if not accounted for would artificially inflate the apparent number of extreme events and societal stresses identified through time.[104] It is also of clear importance to understand that some silences in Tables 3–5 arise from discontinuities in the available records, relating to their differing periods of coverage, as well as lacunae in the manuscripts. There may be a meaningful difference between a year or period for which scant evidence exists of extreme weather or societal stresses if that period is densely covered by many versus few sources, or indeed if the sources available are comparatively numerous but provide only a thin coverage in terms of events reported per year.[105] Figure 4 shows the degree to which the extant Irish annalistic sources exhibit discontinuities in their coverage of the 670–730 CE period. Variable levels of coverage is a consideration that should be made more explicit in work drawing the written heritage remaining from the medieval era.

---

103 See discussion in Ludlow / Travis (note 53).

104 Ludlow et al. (note 28); Id. / Travis (note 53).

105 A more complete consideration of this issue in the case of the Irish Annals may be found in Ludlow (note 81).

Table 3: Extreme weather, famine and mortality in Europe (Western, Central & Northern Mediterranean), 670–730 CE.

Date (CE)	Event categories	Representative excerpts [1]	Probable event locations [2]	Source texts or authors
670	Snow; Scarcity & famine	"A great snowfall occurred. A great famine."*	Ireland	16*, 17
671	Animal mortality, unspecific	"A great mortality of birds, so that on sea and land a very foul stench was noticeable [. . .]."*	England	1, 23*
671	Human mortality, disease	"A plague sent from heaven came upon them [i. e. people of Mercia, Central England] which, through the death of the body, translated the living stones of the church [i. e. people, metaphorically, referencing Ecclesiastes] from their earthly sites to the heavenly building [. . .]."	England	2
674–676	Drought; Scarcity & famine	"For three years before his coming into the kingdom [Wilfrid was in South Saxony from c. 677] no rain had fallen in those parts, so that a most terrible famine assailed the populace and pitilessly destroyed them."	England	2
677	Human mortality, disease	"A great death from the east followed this apparition [a comet]." [3]	Italy	3
680	Human mortality, disease	"[. . .] many of the kingdoms of Britain were attacked by a virulent plague [. . .]."* ——— "The eighteenth day of June bore a lunar eclipse [this, for reference, is correctly dated]. And in the same month and the following months of July, August and September there was a great mortality in the town of Rome, more serious than anyone of these times or those of another pope could remember. Such that parents with their children and brothers or sisters were carried away two at a time on biers to their tombs. And in a like manner that mortality spread out around the suburbs and military camps all about."† [3] ——— "A most severe leprosy in Ireland called bolgach." ‡	England, Wales, possibly incl. Scotland*, Italy†, Ireland‡	2*, 3†, 4, 16‡, 17, 18, 19, 21, 22

682	Human mortality, unspecific	"[. . .] a great mortality throughout all the island of Britain."*	England, Wales, possibly incl. Scotland	4*, 6, 8
683	Human mortality, disease	"Beginning of the mortality of children in the month of October."*	Ireland	5, 16*, 17, 18, 19, 20
684	Human mortality, disease	"The mortality of the children."*	Ireland	4, 5, 8, 16*, 17, 18, 20
688	Human mortality, disease	"[. . .] bubonic plague spread mercilessly at this time."	Spain	7
699	Animal mortality, disease	"A murrain of cattle in the land of the Saxons."*	England	16*, 18, 19
700	Animal mortality, disease; Scarcity & famine; Human mortality, famine; Human mortality, disease; Frost; Ice	"The cattle mortality broke out in Ireland on the Kalends of February [1st February, Julian Calendar] [. . .]."* ——— "Famine and pestilence in Ireland for three years [i. e. 698–700], so that man ate man."* ——— "A great frost in this year so that the lakes and rivers of Ireland froze [. . .]."†	Ireland	5, 16*, 17, 18†, 19, 24, 25, 26
701	Animal mortality, disease	"The mortality of cows."* [4]	Ireland	16*, 17
704	Animal mortality, disease	"The strages [a cattle disease] [. . .] in the valley of the Levin Water."	Scotland	17
708	Animal mortality, disease	"The murrain of cows raged again."*	Ireland	16, 18
708	Severe weather, unspecific	"A hard winter."* ——— "A harsh winter."†	Germany	9*, 10†

(continued)

Table 3 (continued)

Date (CE)	Event categories	Representative excerpts [1]	Probable event locations [2]	Source texts or authors
709	Severe weather, unspecific; Poor harvests/ Crop damage	"A harsh year and a failing of the crops."* [3] __________ "A harsh spring and a failing of the crops." † [3]	France and/or Germany	10*, 11†, 12, 13, 14, 15
709	Human mortality, disease	"A pestilence called bacach [. . .] in Ireland."*	Ireland	16*, 17, 18
714	Drought	"A great drought."*	Ireland	16, 17*
719 [5]	Drought; Heat	"A hot summer befell."* __________ "A parched summer."† __________ "A dry summer." ‡	Wales, Ireland [5]	4*, 8†, 16‡

Notes:

[1] In any given year, multiple sources may often provide relevant information, frequently corroborating or duplicating other sources. Given the large number of sources, we provide select representative excerpts only, quoting where possible the sources considered most reliable. The specific sources from which excerpts derive are indicated by symbols (*, †, ‡, etc.).

[2] Event locations/extents are provided by present-day country names. Because of complex textual histories, and/or ambiguity in the descriptions, the locations/extents of events are indicative only (e. g. source provenance does not always equate to the location of events described therein, and events are not necessarily restricted to locations described or inferred).

[3] Translation by Conor Kostick.

[4] Although this report does not explicitly identify disease as the cause of this cattle mortality, it can be inferred with reasonably certainty that this represents a continuation of the cattle disease reported in preceding and following years in Ireland and Britain.

[5] In light of uncertainties in the chronologies of both Welsh sources at this time, and evidence of their use of early Irish observations, we align the report of hot / dry summers in 720 in the 'Red Book of Hergest' ('Brut Y Tywysogyon') and 'Annales Cambriae' in 721 with the Irish observation of a dry summer in 719. Whether, therefore, the drought was also experienced in Wales is uncertain.

[6] This table represents an update (version 1.1, 01/03/2019) to the version published by Chaochao Gao / Francis Ludlow / Or Amir / Conor Kostick, Reconciling Multiple Ice-Core Volcanic Histories. The Potential of Tree-Ring and Documentary Evidence, 670–730 CE, in: Quaternary International 394 (2016), pp. 180–193, online (DOI): https://doi.org/10.1016/j.quaint.2015.11.098 (last accessed 15/05/2019).

Sources: 1: 'Anglo-Saxon Chronicle', 2: 'Bede's Ecclesiastical History', 3: 'Liber Pontificalis', 4: 'Red Book of Hergest' ('Brut Y Tywysogyon'), 5: Fragmentary 'Annals of Ireland', 6: 'Brenhinedd Y Saesson', 7: 'The Chronicle of 754', 8: 'Annales Cambriae', 9: 'Brief Annals of St Gallen', 10: 'Annales Almannici', 11: 'Annals of Lorsch Abbey', 12: 'Annals of St Nazaire', 13: 'Annals of St Gallen major', 14: 'Annals of Quedlinburg', 15: 'Annals of Wissembourg', 16: 'Annals of Ulster', 17: 'Annals of Tigernach', 18: 'Chronicon Scotorum', 19: 'Mageohagan's Book', a.k.a. 'Annals of Clonmacnoise', 20: 'Annals of Insifallen', 21: 'Hermann of Reichenau's Chronicle', 22: 'Bernold's Chronicle', 23: 'Chronicle of Æthelweard', 24: 'Annals of the Four Masters', 25: Annals from the 'Book of Leinster', 26: 'Egerton Annals', 27: Paul the Deacon, 28: Marianus Scotus, 'Chronicon', 29: 'Annales Mettenses Priores'.

Table 4: Extreme weather, famine and mortality in Near East, 670–730 CE.

Date (CE)	Event categories	Representative excerpts [1]	Probable event locations [2]	Source texts or authors
670	Cold; Ice; Snow; Poor harvests/Crop damage; Human mortality, weather; Animal mortality, weather	"A harsh winter."* ——— "There was a severe cold and many men as well as beasts suffered hardship."† ——— "There was a harsh winter: much cold, ice and snow. Olive trees and vines shrivelled up in Syria and Mesopotamia. Many men and beasts died."‡ ——— "Much snow fell and there was a severe cold; many men and beasts died."§	Syria & Iraq	1*, 2†, 10‡, 14§
670	Human mortality, disease	"In this year there was a pestilence in al-Kufa [Iraq]."*	Iraq	11*, 12, 13
672	Human mortality, disease	"A plague befell the people in Egypt and Palestine."*	Egypt & Palestine	2, 14*
673	Human mortality, disease	"Again pestilence in al-Kufa."	Iraq	11

Between 1 October 675 & 30 September 676	Locusts; Human mortality, disease; Scarcity & famine, Misc.; Rats or mice; Poor harvests/Crop damage, misc.	"A plague occurred in Egypt."* Also: "There was a great plague of locusts in Syria and Mesopotamia."* ——— "The rats became numerous in Syria and Phoenicia [in present-day Lebanon & Syria] and destroyed the crops, causing a great food shortage. The following year there were locusts."† [3] ——— "Plague occurred among the people in Egypt and Palestine. Mice were numerous in Syria with the result that a great famine occurred there."‡	Egypt, Syria & Iraq*; Syria & Lebanon†; Egypt & Palestine, Syria‡	1, 2*, 3, 4, 10†, 14‡
679	Animal mortality, disease	'[God] brought plague upon the oxen, so that we might come to our senses.'		3
683	Ice; Poor harvests/Crop damage; Animal mortality, weather	"[. . .] there was a severe winter, and the Euphrates was frozen over, and olive groves and vineyards withered, and beasts, and cattle, and birds came to an end."	Syria & Iraq	4
Between 29 August 683 & 30 September 684 [4]	Scarcity & famine; Human mortality, disease; Drought	"In this year there was a famine and a great plague in Syria."* ——— "In this year pestilence swept through al-Basra [in Iraq] [. . .] Drought in Damascus [in Syria]. The people go out to pray for rain."†	Syria*†; Iraq†	2*, 5, 11†, 14
Between 18 August 684 & 6 August 685	Human mortality, disease	"In this year broke out in Basra [in Iraq] 'the sweeping pestilence' and many of the inhabitants of the town died."	Iraq	13

(continued)

Table 4 (continued)

Date (CE)	Event categories	Representative excerpts [1]	Probable event locations [2]	Source texts or authors
Between 28 July 686 & 30 September 687 [5]	Scarcity & famine; Human mortality, disease; Human mortality, famine	"In this year there was a famine in Syria and many men migrated to the Roman country."* ——— "In this year 67 [i. e. 686/687] the accursed plague began there had been nothing like it, and I hope that there will be nothing like it again." Also: "Many fell down and died on the roadways, such was the grip of the famine."† ——— "In this year was the plague in Egypt and many people died of it."‡	Syria*; Egypt‡	2*, 3†, 12‡
Between 17 July 687 & 4 July 688	Drought	"There was a drought in Syria and from the hardship of it the people could not participate in the raids [to Byzantium]."	Syria	13
Between 5 July 688 & 23 June 689 [6]	Human mortality, disease	"In this year was the sweeping plague in al-Basra [Iraq]."	Iraq	12
Between 24 June 689 & 13 June 690	Human mortality, disease	"In this year there was pestilence [wabā'] in Egypt."* ——— "The plague in Fustat (Miṣr) [in Egypt]."†	Egypt*†	12*, 15†
Between 1 May 694 & 21 April 695	Human mortality, disease	"In this year there was a plague in al-Basra [in Iraq]."	Iraq	12

Between 19 March 698 & 30 September 699 [7]	Human mortality, disease	"[. . .] a plague fell upon the City [Constantinople, present-day Istanbul] and destroyed a multitude of men within four months."* ——— "In this year the people of Syria suffered from pestilence and many died, and so nobody went out on raids in this year."†	Turkey*, Syria†,	6*, 11, 12, 13†
Between 9 March 699 & 30 September 700 [8]	Human mortality, disease	"There was a great plague."* ——— "In this year occurred in Basra [in Iraq] the sweeping pestilence."†	Iraq†	1*,11†
Between 14 February 701 & 2 February 702	Scarcity & famine	"While in Baghdad there is no shortage of grains, in al-Basra [in Iraq] and Syria the prices raise and there is dearth."	Iraq & Syria	13
703	Cold; Ice	"Due to the biting cold and the icy storm, the violently intense weather detained the forces of the Arabs [. . .]" Also: "Those who escaped the sword [at the battle of Vardanakert, January 703] fell into the River Eraskh [Araxes or Araks] which was frozen over on account of the severe weather."* ——— " [. . .] It seems that extreme coldness preceded this [i. e. preceded the pestilence reported for 704 / 705 below]."†	Armenia*; Iran†	16*, 13†

(continued)

Table 4 (continued)

Date (CE)	Event categories	Representative excerpts [1]	Probable event locations [2]	Source texts or authors
Between 1 October 704 & 24 December 705 [9]	Human mortality, disease	"There was a large and violent plague on earth, so that there were not enough people to bury the dead. It occurred mainly in the region of Saroug [Serugh, in Syria]."* ——— "Pestilence occurred in this year, which was called 'the pestilence of the maidens', [because] the maidens died in it. It happened in al-Sham [Syria], al-Basra and al-Wasit [both in Iraq]."† ——— "In this year the people of the area of Merv [in Khurasan, eastern Iran] suffered from pestilence. It seems that extreme coldness preceded this [see 703 above]."‡	Syria*; Syria & Iraq†; Iran‡	7*, 11†, 12, 13‡
706	Drought; Poor harvests/ Crop damage; Scarcity & famine	"In this year the Nile didn't reach the needed level, and prices of commodities in Egypt inflated a great deal [. . .] and the people of Egypt experienced great difficulties because of this."	Egypt	12
Between 18 October 711 & 6 October 712	Drought	"The people of Ifriqiyya [Roman province of Africa] suffer from a difficult drought and pray for rain."*	Tunisia, with parts of western Libya & eastern Algeria	11, 13*

Between December 712 & February 713	Human mortality, disease; Drought; Locusts; Poor harvests/Crop damage, misc.; Poor harvests/Crop damage, weather	"[. . .] from December [712] to February [713], there occurred [as] a judgment a great plague in the land, and many people perished in it, mercilessly." Also: "While these two terrible afflictions [10] were still running their course together without any relaxation or end, God sent to the land a third affliction, known as the bubonic plague; countless people were buried without pity in all sorts of places." Also: "[. . .] God sent to the land a third affliction, known as the bubonic plague; countless people were buried without pity in all sorts of places." Also: "[. . .] God also sent upon the land a dearth of rain, and locusts that destroyed vineyards, sown fields and plants." Also: "After this there was heavy hail in various regions, damaging vineyards and plants."	Syria & Turkey	8
Between 26 September 713 & 14 September 714	Human mortality, disease	"In this year there was a plague called 'plague of the notables', during which numerous people died. It was especially in al-Wasit [in Iraq]."	Iraq	12
717 [11]	Snow	"That winter proved very severe in Thrace, so much so that for a hundred days the earth could not be seen beneath the congealed snow."* ———— "The remainder of the [Arab] fleet, after sailing up the Thracian Bosporus, put in at the harbor of Sosthenion [in Cyprus] and wintered there. That winter happened to be very severe and so much snow fell that the ground was made invisible for a hundred days."†	Thrace: comprising modern southeast Bulgaria, northeast Greece, and part of north Turkey*†	2*, 6†
718 [12]	Misc.: boiling seas; Earthquake	"On 15 August, the Hagarenes moved off [from Constantinople] [. . .] The remainder [after surviving sinking by storm] were going through the Aegean Sea when a [. . .] fiery hail fell upon them and brought the sea-water to a boil, and as the pitch of their keels dissolved, their ships sank in the deep, crews and all." Also: "Earthquake in Syria."	Aegean & Syria	2

(continued)

Table 4 (continued)

Date (CE)	Event categories	Representative excerpts [1]	Probable event locations [2]	Source texts or authors
Between 3 August 718 & 22 July 719	Human mortality, disease	"In this year there was pestilence (*ṭāʿūn*) [. . .]."*	Iraq [13]	11*, 12
721	Drought; Poor harvests/ Crop damage; Scarcity & famine	"[. . .] the water in the wells failed so completely that the villagers had to walk as far as seven miles to draw water. And there was a scarcity of crops."	Turkey	4
723	Earthquake; Human mortality, disease; Locusts	"On Monday evening, 28 February [723], there was a violent tremor in all the land of Syria, which crushed and buried innumerable people. Moreover, there was a fatal epidemic and locusts without end."	Syria	9
724	Human mortality, disease	"[. . .] there was a pestilence caused by the disease of tumours, especially in Beth Nahrin [i. e. Mesopotamia]."* ——— "In this year there was a pestilence [wabāʾ] in Egypt."†	Iraq*; Egypt†	4*, 15†

Between 18 May 725 & 30 September 726 [15]	Human mortality, disease; Misc., volcanic island formation	"There was a plague in Syria [. . .]". Also: "In the summer season of the same year, indiction 9 [726], a vapour as from a fiery furnace boiled up for a few days from the depth of the sea between the islands of Thera and Therasia. As it gradually became thicker and filled with stones because of the heat of the burning fire, all the smoke took on a fiery appearance. Then, on account of the density of the earthy substance, pumice stones as big as hills were thrown up against all of Asia Minor, Lesbos, Abydos, and coastal Macedonia, so that the entire surface of that sea was filled with floating pumice. In the midst of so great a fire an island that had not previously existed was formed and joined to the Sacred Island [. . .]."* ——— "[. . .] near the islands called Thera and Therasia, which lie in the Cretan sea. During the summer season the watery deep happened to belch forth a quantity of smoky steam, out of which, as the air became thicker, a fire burst and, after the fire, an enormous mass of pumice-like stones was cast out, so that they formed a kind of island [. . .] The sea in those parts was everywhere covered by the immense quantity of stones that were thrown up, and they spread from there as far as Abydos and the coast of Asia. The adjacent water was so hot that one could not even touch it."† ——— "In this year was a heavy pestilence [*ṭāʿūn shadīd*] in Syria (al-Sham)."‡ ——— "There was a severe plague in Syria; various pustules and ulcers afflicted people."§	Syria & Aegean Sea*†; Syria‡§	1, 2*, 6†, 11‡, 12, 13, 14§,

Notes:

[1] In any given year, multiple sources often provide relevant information, frequently corroborating or duplicating other sources. Given the large number of sources, we provide select representative excerpts only, quoting where possible the sources considered most reliable. The specific sources from which excerpts derive are indicated by symbols (*, †, ‡, etc.).

[2] Event locations/extents are provided by present-day country names. Because of complex textual histories, and/or ambiguity in the descriptions, the locations/extents of events are indicative only (e. g. source provenance does not always equate to the location of events described therein, and events are not necessarily restricted to locations described or inferred).

Table 4 (continued)

[3] We assign the year October 675 to September 676 to these events. Though we note some small dating divergence between the sources that is difficult to fully reconcile, we favour the more consistent source 14 (Agapius of Manbij).
[4] Between the start of the Hijri year 64 and the end of the Byzantine indiction.
[5] Between the start of the Hijri year 67 and the end of the Byzantine indiction.
[6] The Arabic historians examining earlier records found the dating here uncertain. We follow the reconciliation of the dates made by Ibn Taghribirdi.
[7] Between the start of the Hijri year 79 and the end of the Byzantine indiction.
[8] Between the start of the Hijri year 80 and the end of the Byzantine indiction.
[9] Between the start of the Hijri year 85 and the end of the Byzantine indiction.
[10] Regarding "the two terrible afflictions" cited by Source 8 for 713/714, the first is the unspecific plague (the first cited event for this year in our excerpts) and the second is an earthquake in Antioch, in present-day Turkey, not cited in our excerpts.
[11] This winter falls under the year 716 in the 'Chronicle of Theophanes Confessor' (Source 2), but we prefer the later date of Nikephoros (Source 6) as more certain at this point as he links the severe winter to the siege of Constantinople, which began 717 and ran into 718.
[12] The volcanic activity described for 718 may reflect pre-cursor activity for the volcanic island formation listed under 725/726, although some uncertainty exists over exact locations and dates.
[13] The location of this pestilence is not fully certain, but possibly al-Basra, Iraq.
[14] This is almost certainly an error for the flood of 740 but we include it here (but not in our calculations – main article text) for completeness sake.
[15] Between the start of the Hijri year 107 and the end of the Byzantine indiction.
[16] This table represents a direct reproduction of the v1.0 iteration published by Chaochao GAO / Francis LUDLOW / Or AMIR / Conor KOSTICK, Reconciling Multiple Ice-Core Volcanic Histories. The Potential of Tree-Ring and Documentary Evidence, 670–730 CE, in: Quaternary International 394 (2016), pp. 180–193, online (DOI): https://doi.org/10.1016/j.quaint.2015.11.098 (last accessed 15/05/2019).

Sources: 1: 'Theophilus of Edessa's Chronicle', 2: 'Chronicle of Theophanes Confessor', 3: John Bar Penkaye, 4: 'The Chronography of Bar Hebraeus', 5: 'Two Inscriptions on a Church at Ehnesh', 6: Nikephoros, 7: 'Chronicle of Zuqnin', a.k.a. Pseudo-Dionysius of Tel-Mahre, 'Chronicle', 8: 'A Chronicle of Disasters', 9: 'Two Chronicles up to AD 819/46', 10: Michael the Syrian, 'Chronicle', 11: Ibn al-Jawzi, 12: Ibn Taghribirdi, 13: Al-Ṭabarī, 14: Agapius of Manbij, 15: Al-Mawā'iẓ, 16: Ghewond, 'History'.

Table 5: Extreme weather, famine and mortality in China, 670–730 CE.

Date (CE)	Event categories	Paraphrased summaries, with months / seasons, locations / extents [1]	Source texts or authors
677	Drought; "No snow in winter" (NSW)	Month 4 [i. e., Chinese Lunar month, spanning May 4th to Jun 2nd, Julian Calendar], drought in Henan, Hebei, Shandong, Jiangsu, Anhui, Hubei.* ——— No snow in winter.† [3]	1*†, 2* [2]
679	Frost; Animal mortality, disease; Scarcity & famine; Snow	Month 8 [Sep 8th to Oct 6th], frost in Shaanxi, Ganshu, Ningxia. Also: Cattle plague reported in spring. Famine in Henan Luoyang in spring, propagating to Shannxi in the autumn.* ——— Month 10 [Nov 7th to Dec 5th], heavy snow, and the Turks invaded the [Tang] camp, countless soldiers thereby died.†	2*, 3†
681	Drought; Frost; Scarcity & famine; Cold; Animal mortality, unspecific	Drought, frost and great famine in Shannxi. Also: Extreme cold, and the nation's horse stock was destroyed; more than 180,000 horses died. [4]	2
682 into 683	Scarcity & famine; Human mortality, famine; Drought; Locusts; Poor harvests/ Crop damage; Human mortality, disease; Human mortality, famine	Great famine widely across Shannxi and Hubei, cannibalism in the capital.*[5] ——— Starting in Month 6 (682) [Jul 7th to Aug 5th], in Shannxi, drought and a locust plague following flooding, damages all the crops; plus epidemic diseases. Month 12 (682) [Dec 31st (682) to Jan 29th (683)], bodies cover the road between Luoyang and Xi'an.†	1*,2*†,3*
686	NSW	No snow during winter, location unspecified.	2
687 695	Scarcity & famine Frost	Great famine nationwide, especially in Shandong [and] Guangnei. "Frost killed the grass" in Zhejiang [between Jul 17th and Aug 15th]. Also: "frost during mid-summer when the land was warm, this phenomena was never seen before."	2,3 2

(continued)

Table 5 (continued)

Date (CE)	Event categories	Paraphrased summaries, with months / seasons, locations / extents [1]	Source texts or authors
696	Drought	Month 4 [Mar 6th to Apr3rd], nationwide drought, and the government issued a tax relief order.	1
700	Snow; Drought	Heavy snow in Xi'an and Luoyang [between Apr 9th and May 8th]. ——— Drought in Shanxi, Shangxi, Gansu, Inner Mongolia in summer [specific months unidentified].	2
701	Snow; Scarcity & famine	Famine through the spring across Henan, Shangdong, Jiangsu, Anhui, Hubei.† ——— Month 3 [Apr 9th to May 8th], heavy snow in Jiangsu, Zhejiang.*	3*, 2†
703; 703–704	NSW	No snow in the winter.† [6]	2
704	Atmospheric phenomenon; Snow; Rain; Human mortality, famine; Human mortality, weather	Opaque sky during daytime, and heavy rain/snow lasting from Sep 30th to Dec 26th, or longer. [7] Also: people in the capital died from hunger and cold and the government distributed relief supplies.	1
705	Drought; Poor harvests/Crop damage	Summer 705, drought and grain price increase.	2
706–707	Drought; Scarcity &famine; Human mortality, famine	Lack of rain from winter 706 to summer 707 and widespread famine, even the king must reduce his meal services (706); drought spreads to more than 20 states in the summer of 707. More than 2,000 people died from hunger (707).	1, 2

715	Locusts	Month 7 [Jul 29thto Aug 31st] of 715, locusts in Henan, Shandong, Hebei, Jiangsu, Anhui, Hubei.	1, 2, 3
716	Locusts; Poor harvests/Crop damage, misc.	Summer of 716, locusts in Henan, Shandong, Hebei "eat all the crops, [and] sound like wind and rain". [8]	1,3
721	NSW	No snow in winter.	1
723	Snow	Month 11 [Nov 29thto Dec 27th], heavy snow accumulated for more than three *chi* [3 chi = 1 meter] in Shaanxi, Henan, Shandong, Hebei, southern Anhui and Jiangsu.	1
724	Drought; Frost; Poor harvests/Crop damage	Drought in parts of Shanxi, Hebei, Henan, Shandong in month 7 [Jul 21st to Aug 19th]; drought in two cities of Shaanxi in month 9 [Sep18th to Oct 17th]. —————— Month 8 [Aug 20th to Sep 17th], frost killed the crops in parts of Shanxi, Shaanxi.	2
727	Frost; Drought; Animal mortality, unspecific	Autumn, 17 states reported frost and drought. —————— Spring, cattle mortality in Hebei, Henan, and northern Shandong.	1
728	Drought	Drought in many parts of Henan, Shandong, Jiangsu, Anhui, Hubei; month unknown.	2

Notes:

[1] Event locations/extents are provided by present-day state names. Because of complex textual histories, and/or ambiguity in the descriptions, the locations/extents of events are sometimes indicative (e. g. events are not necessarily restricted to locations described or inferred). Specific event dates (if given) are provided in the Chinese Lunar (lunisolar) Calendar, and where pertinent are converted to the Julian calendar; [see square brackets] and reflected in the "Date (CE)" column.

[2] Where more than one source provides relevant information per year (often corroborating or duplicating information in other sources), we identify the sources from which excerpted quotes and summaries are drawn, with the symbols *, †, ‡, etc.

Table 5 (continued)

[3] Though their meteorological implications are somewhat ambiguous and merit further study, reports of "no snow in winter" (or elsewhere "pray for snow") are taken as implying either anomalously low winter precipitation or anomalously mild winters; see discussion of these reports in Guoqiang Chu / Qing Sun / Xiaohua Wang / Junying Sun, Snow Anomaly Events from Historical Documents in Eastern China During the Past Two Millennia and Implication for Low-Frequency Variability of AO/NAO and PDO, in: Geophysical Research Letters 35(14) (2008), online (DOI): https://doi.org/10.1029/2008GL034475 (last accessed 15/05/2019). We abbreviate these reports as "NSW" in the Event Categories column.

[4] The source is not specific as to the cause of the great loss of horses: disease, weather, conflict, or some combination thereof. We thus categorize this report as "Animal mortality, unspecific" (event categories column).

[5] The Capital moved to "Dongdu" (now Luoyang) between 690–705 CE. Pre-690 and post-705, the capital was located in Chang'an (now Xi'an).

[6] The phrasing of this report suggests, though with some ambiguity, that the conditions began in the winter of 703 and continued until the second lunar month of 704 (which started March 3rd in the Julian Calendar). Elsewhere, in absence of such indications, or more refined within-year dating, we assign NSW reports by default to the year in which they are reported.

[7] Different chapters of the 'Annals of the Tang Dynasty (old)' provide somewhat varying descriptions for these events. In particular, the chapter 'Wu Xing Zhi' relates that from September, snow and rain lasted for more than 150 days, whereas in the chapter of 'Zhe Tian Huang Hou (Queen Zhetian) Ji' it is related that heavy rain and snow lasted from September to November.

[8] It seems that a good harvest from the previous year prevented famine on this occasion.

[9] This table represents a direct reproduction of the v1.0 iteration published by Chaochao Gao / Francis Ludlow / Or Amir / Conor Kostick, Reconciling Multiple Ice-Core Volcanic Histories. The Potential of Tree-Ring and Documentary Evidence, 670–730 CE, in: Quaternary International 394 (2016), pp. 180–193, online (DOI): https://doi.org/10.1016/j.quaint.2015.11.098 (last accessed 15/05/2019).

Sources: 1: 'Old Tang History', 2: 'New Tang History', 3: 'Zizhi Tongjian'.

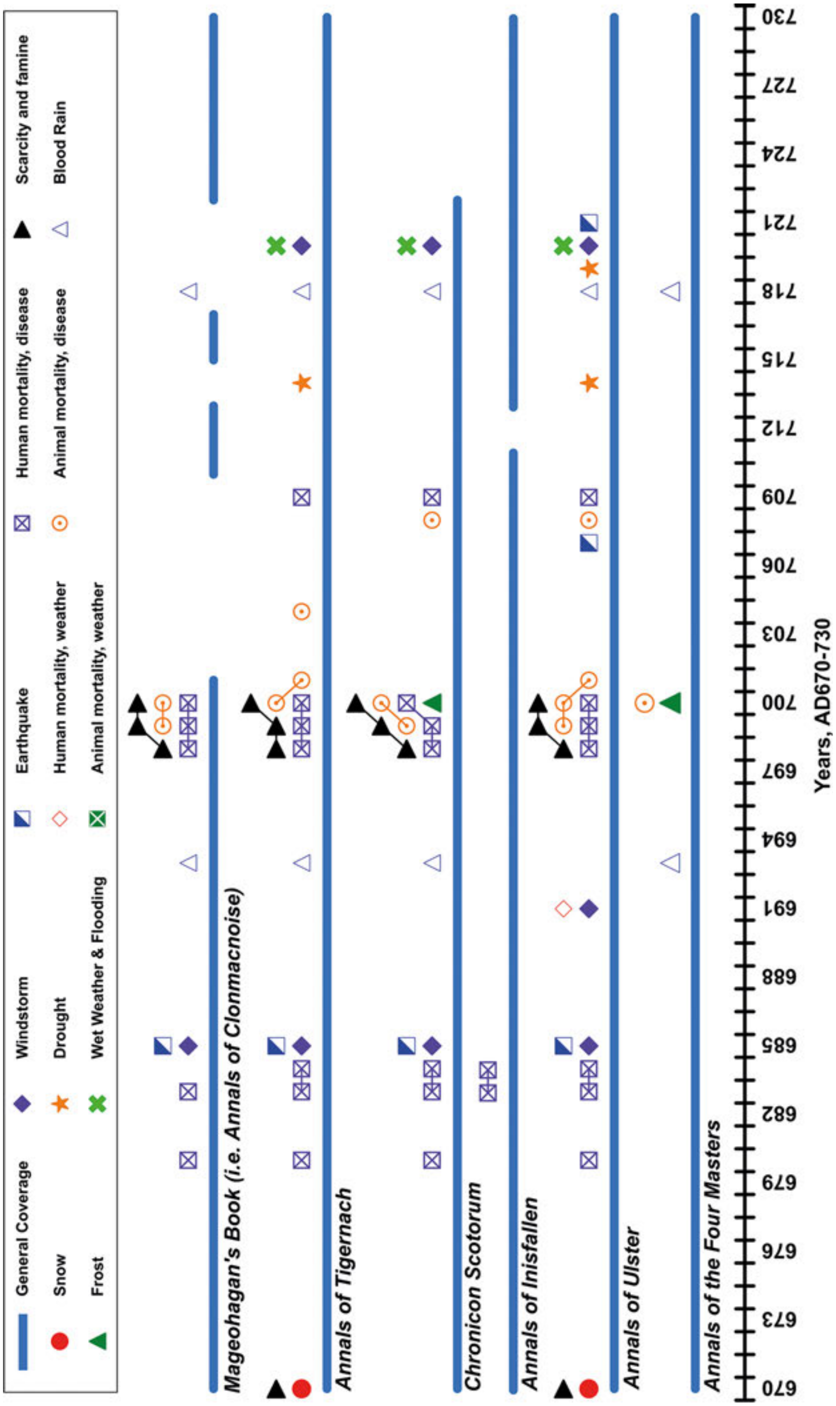

Figure 4: Time series of extreme weather and major societal stresses reported in the extant Irish annalistic texts between 670–730 CE.

In Figure 4, many reported events are duplicates (rather than independent accounts) arising from the shared textual ancestry, and must be placed on a unified time-scale to assist in distinguishing separate events from duplicates assigned to incorrect years. The years covered by each available text (defined as at least one event reported per year) are also shown in the horizontal blue lines, with several texts exhibiting clear lacunae. Applying the chronological corrections of MCCARTHY also relocates some events into apparent lacunae in the coverage provided by some texts.[106]

In our 61-year period of investigation then, extreme cold – as evidenced by reports of heavy or prolonged snowfall and long-lasting frosts – occurred in one or more of the three regions thirteen times (21.3 %). There were even more years with instances of drought, namely 27 (44.3 %). In terms of the challenges facing human societies in this period, mass human mortality occurred with extraordinary frequency. It is reported in at least one region for 36 (59 %) years and arose from various documented causes: indirectly as a result of scarcity and famine, or directly from extreme weather, or the outbreak of disease. In 10 years (16.4 %) there were poor or damaged harvests and in 20 (32.8 %) scarcity and famine. Epizootics struck with surprising frequency too. Eleven (18 %) years have reports of mass animal mortality resulting from unusual weather and disease (the mass animal mortality in 671 in Europe and 681 and 727 in China are not explicitly linked to any particular cause in the texts).

In any comparison of events from three different regions, some clustering might arise by chance, especially if the data run over several centuries. But here it is striking that we see multiple distinct moments when crises grouped between distinct regions in this comparatively short study period. More significantly, they do so around years that the ice-cores and tree-rings indicate experienced major explosive eruptions with severe climatic perturbation. As depicted in Figure 5, particularly notable years for multiple societal crisis are 681–4, 686–8, 698–701 and 704–7. These correspond well with the two largest volcanic signals identified in the Greenland ice-cores for this period, namely 681 and 684–6 at 44 % and 24 % the sulphate deposition volume of the great 1257 Samalas eruption, but perhaps more surprisingly also correspond to smaller volcanic signals in 697 (5 %) and 706–7 (17 %). This is an important observation regarding the vulnerability of early medieval society to even comparatively smaller eruptions, particularly if those eruptions compound the impacts of preceding larger events, and suggests that a further concern requiring detailed consideration is

106 The evolution of the Irish annalistic tradition is detailed most fully in Daniel MCCARTHY, The Irish Annals: Their Genesis, Evolution and History, Dublin 2008. A ground-breaking unified 'synchronized' chronology for Irish annalistic texts has been developed by ID., Irish Chronicles and their Chronology, 4th ed. online: www.cs.tcd.ie/Dan.McCarthy/chronology/synchronisms/annals-chron.htm (last updated 14/12/2011, last accessed 15/05/2019).

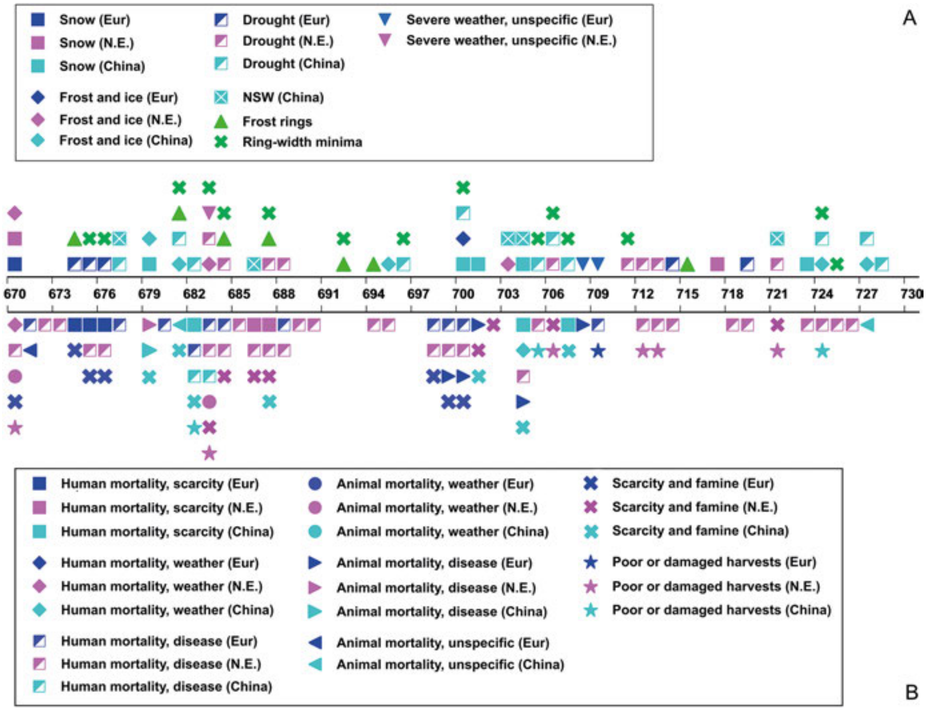

Figure 5: Historically documented meteorological extremes (panel A) and societal stresses (panel B) from 670–730 CE (horizontal axes) colour-coded by region (Europe [blue], Near East [pink] and China [aquamarine]). Frost-ring dates are taken from the compilation of Salzer and Hughes (note 68), as well as dates of inter-regional tree-ring minima, for comparison in the top panel (Table 1 specifies the regions from which the minima originate). Figure reproduced from Gao et al. (note 1).

the potential for a compounding of adverse consequences from even comparatively small explosive eruptions if occurring whilst SAI geoengineering is ongoing.

Conclusion

By studying historical explosive volcanism, medieval history provides a laboratory for understanding the possible climatic and societal impacts of geoengineering in the form of reports of extreme weather and societal stresses such as subsistence crises and even conflict arising from scarcity induced resource competition.[107] We argue that this history must be taken seriously in the discussion about whether to proceed with solar geoengineering. The twentieth and twenty-first centuries have been

107 Ludlow / Travis (note 53).

volcanically quiescent relative to earlier centuries, in terms of large climatically impactful eruptions, but this can change at any time. In particular, advocates of a geoengineered solution must appreciate the relevance of the question: what will happen if the planet experiences another period in which one or more sulphur-rich VEI 5 to 7 eruptions occur, if we have already laden the stratosphere with sulphates artificially?

The story our research tells is, in sum, that beginning with a massive eruption in 681, the climate of the planet was perturbed across a wide region, bringing about major social stress. Before the climate and human activity could recover, another large eruption took place, which combined with several other smaller but still notable eruptions to compound the climate effects and the human impact. For early medieval societies, whose resilience in the face of several years of extreme cold was precarious, this was a disaster that lead to mass human mortality, as attested by the sources. The period can, moreover, be seen as a parallel of the better-known climatic anomaly of c. 536–550, an event now also generally considered the product of multiple closely spaced volcanic eruptions, and coincident with the outbreak of the great Justinian plague.[108]

Contemporary society can be deemed immensely more resilient than the early medieval world. We recognize that, for example, with grain yields at 30 per seed rather than the 3 per seed that was typical for the period we discuss here, there is a far larger cushion between humanity and famine caused by crop failure (famines caused by war, sanctions, or an over-dependence on cash crops are another matter entirely). Yet there are features of modern society that render it more vulnerable in some ways than our medieval predecessors. Just-in-time production and a dependency of so many economies on rapid international trade creates a situation where, for example, if air traffic is heavily impeded across a wide region for several months, the consequences may be severe. Moreover, modelling of global tradeflows under climate shocks suggests that even apparently insulated western societies may face strain in cases of monsoon failure or other episodes of extreme weather in apparently far distant regions.[109]

108 Conor Kostick / Francis Ludlow, The Dating of Volcanic Events and their Impacts upon European Climate and Society, 400–800 CE, in: European Journal of Post-Classical Archaeologies 5 (2015), pp. 7–30; Matthew Toohey / Kristin Krüger /Michael Sigl / Frode Stordal / Henrik Svensen, Climatic and Societal Impacts of a Volcanic Double Event at the Sawn of the Middle Ages, in: Climatic Change 136(3–4) (2016), pp. 401–412.

109 David Seekell / Joel Carr / Jampel Dell'Angelo / Paolo D'Odorico / Marianela Fader / Jessica Gephart / Matti Kummu / Nicholas Magliocca / Miina Porkka / Michael Puma / Zak Ratajczak / Maria Cristina Rulli / Samir Suweis / Alessandro Tavoni, Resilience in the Global Food system, in: Environmental Research Letters 12(2) (2017), 025010, online (DOI): https://doi.org/10.1088/1748-9326/aa5730 (last accessed 15/05/2019); Michael J. Puma / Satyajit Bose / So Young Chon / Benjamin I. Cook, Assessing the Evolving Fragility of the Global Food System, in: Environmental Research Letters 10(2) (2015), 024007, online (DOI): https://doi.org/10.1088/1748-9326/10/2/024007 (last accessed 15/05/2019); Philippe Marchand / Joel A. Carr / Jampel Dell'Angelo / Marianela

Our conclusion then is that as the geoengineering option becomes more appealing in the face of increasingly damaging consequences arising from global warming and the fear that we might cross a tipping point that imperils humanity, we must nevertheless appreciate the historical perspective. And what this perspective demonstrates is that along with a strategy for pumping sulphates into the stratosphere, the unpredictability of explosive volcanism means that we must also develop one for mitigating their societal (and, if possible, even their climatic) impacts with extreme rapidity.

Appendixes

Table A1: Reference and attribute table of major ice-core datasets in Greenland.[A]

Data-set name	Location	Period covered	Approx. resolution	Measurement type [B]	Units
NEEM S1	77.5º N, 51º W	78–1997	1 / a	NSS SO_4	ng / g
NGRIPmain1	75.1º N, 42.3º W	190–1969	2 / a	ECM	
NGRIP.SO_4	75.1º N, 42.3º W	190–1969	1 / a	Total SO_4	μequiv / kg
GISP2	72.6º N, 38.5º W	1–1984	0.5 / a	NSS SO_4	ppb
Dye3deep	72.6º N, 37.6º W	1–1768	4 / a	ECM	
GRIPmain	71.3º N, 26.7º W	1–1642	4 / a	ECM	
Crête	71.1º N, 37.3º W	553–1778	4 / a	ECM	
Crête.SO_4	71.1º N, 37.3º W	553–1778	4 / a	NSS SO_4	kg / km^2

[A] Table adapted from Gao et al. (note 1).
[B] ECM, electrical conductivity measurement; NSS SO_4, non-sea-salt sulphate; NSS-conductivity, non-sea-salt conductivity.

Primary Sources

Abbreviations:

MGH SS Monumenta Germania Historica, Scriptores
MGH SRG Monumenta Germania Historica, Scriptores Rerum Germanicarum

Fader / Jessica A. Gephart / Matti Kummu / Nicholas R. Magliocca / Miina Porkka / Michael J. Puma / Zak Ratajczak / Maria Cristina Rulli / David A. Seekell / Samir Suweis /Alessandro Tavoni / Paolo D'Odorico, Reserves and Trade Jointly Determine Exposure to Food Supply Shocks, in: Environmental Research Letters 11(9) (2016), 095009, online (DOI): https://doi.org/10.1088/1748-9326/11/9/095009 (last accessed 15/05/2019).

A Chronicle of Disasters, trans. Sebastian P. Brock, in: Andrew Palmer / Sebastian P. Brock / Robert Hoyland (eds.), The Seventh Century in the Western Syrian Chronicles, Liverpool 1993, pp. 45–47.
Agapius of Manbij, Kitab al-'Unvan, ed. Alexander A. Vasiliev (Patrologia Orientalis 38 [8.3]), Paris 1912.
Al-Mawā'iẓ, al-Mawā'iz wa'l-i'tibār bi-dhikr al-khiṭaṭwa'l-athār, 3 vols., eds. Muhammad Zaynhum / Madiha al Sharqāwī, Beirut 1997–1998.
Al-Ṭabarī, Ta'rīkh al-rusul wa'l-mulūk, 11 vols., ed. Muhammad Abū Al-Fadl Ibrahim, Beirut 1967–1968.
Anglo-Saxon Chronicle, trans. George N. Garmonsway, London 1975.
Annales Alamannici, ed. Georg H. Pertz (MGH SS 1) Hanover 1826, pp. 22–30, 40–44, 47–60.
Annales Cambriae. A Translation of Harleian; PRO E.164/1; Cottonian Domitian, A 1; Exeter Cathedral Library MS. 3514 and MS Exchequer DB Neath, PRO E, ed. and trans. Paul M. Remfry, Shrewsbury 2007.
Annales Mettenses Priores, ed. Bernhard Eduard von Simson (MGH SRG 10), Hanover 1905, pp. 1–98.
The Book of Leinster sometime called the Book of Glendalough with introduction, analysis of contents, and index, ed. Robert Atkinson, Dublin 1880.
Annals of Insifallen, ed. and trans. Seán Mac Airt, Dublin 1944.
Annals of Lorsch Abbey, ed. Georg H. Pertz (MGH SS 1), Hanover 1826, pp. 7, 9, 10, 12, 15, 52–55.
Annals of Quedlinburg, ed. Georg H. Pertz (MGH SS 3), Hanover 1839, pp. 22–90.
Annals of St Gallen major, ed. Ildefons von Arx (MGH SS 1), Hanover 1826, pp. 73–85.
Annals of St Nazaire, ed. Georg H. Pertz (MGH SS 1), Hanover 1826, pp. 40–4.
Annals of the Four Masters, ed. John O'Donovan, Dublin 1851.
Annals of Tigernach, 2 vols., ed. Whitley Stokes, Felinfach 1993.
Annals of Ulster (to A.D. 1131). Part I: Text and Translation, ed. and trans. Séan Mac Airt / Gearóid Mac Niocaill, Dublin 1983.
Annals of Wissembourg, ed. Georg H. Pertz (MGH SS 3), Hanover 1839, pp. 33–72.
Bar Hebraeus, Chronicon Syriacum, ed. Paul Bedjan, Paris 1890.
Bede, Ecclesiastical History, ed. Bertram Colgrave / Roger A. B. Mynors, Oxford 1969.
Bernold of St Blasien (Constance), Chronicon, in: Die Chroniken Bertholds von Reichenau und Bernolds von Konstanz 1054–1100 (MGH SRG N.S. 14), ed. Ian S. Robinson, Hanover 2003, pp. 383–540.
Brenhinedd Y Saesson, or, The King of the Saxons: BM Cotton MS Cleopatra B v, and The black book of Basingwerk, NLW MS. 7006, ed. and trans. Thomas Jones, Cardiff 1971.
Brief Annals of St Gallen, ed. Georg H. Pertz (MGH SS 1), Hanover 1826, pp. 64–5.
Chronicle of Æthelweard, ed. Alistair Campbell, Edinburgh 1962.
Chronicle of Zuqnin, a.k.a. Pseudo-Dionysius of Tel-Mahre Chronicle, ed. Witold Witakowski, Liverpool 1996.
Chronicon Scotorum, ed. and trans. William M. Hennessy, London 1866.
Fragmentary Annals of Ireland, ed. Joan N. Radner, Dublin 1978.
Ghewond, History, ed. Zaven Arzoumanian, Philadelphia 1982.
Hermann of Reichenau, Chronicon, ed. Georg H. Pertz (MGH SS 5), Hanover 1844.
Ibn al-Jawzi, al-Muntaẓam fī ta'rīkh al-umam wa'l-mulūk, 19 vols., ed. M.A.Q. 'Āṭā et al., Beirut 1992.
Ibn Taghri Birdi, al-Nujum al-Zahira fī mulūk Miṣr wa'l-Qāhira, 5 vols., ed. William Popper, Berkeley 1936.
John Bar Penkaye, Riš Melle, in: Sebastian P. Brock (ed.), North Mesopotamia in the Late Seventh Century: Book XV of John Bar Penkaye's *Riš Melle*, in: Jerusalem Studies in Arabic and Islam 9 (1987), pp. 57–74.

Liber Pontificalis, ed. Theodor MOMMSEN (MGH Gesta Pontificum Romanorum 1), Berlin 1898.
Mageohagan's Book, a.k.a. Annals of Clonmacnoise, ed. Denis MURPHY, Dublin 1896.
Marianus Scotus, Chronicon, ed. Georg WAITZ (MGH SS 5), Hanover 1884, pp. 481–562.
Michael the Syrian, Chronique de Michel le Syrien, Patriarche Jacobite d'Antioche (1166–1199), 4 vols., ed. and trans. Jean Baptiste CHABOT, Paris 1916–1920.
New Tang History, 20 vols., ed. Ouyang XIU / Song QI, Beijing 1975.
Nicephorus Callistus Xanthopoulos, Historia Ecclesiastica, ed. Jacques Paul MIGNE, in: ID. (ed.), Patrologia Graeca, vols. 145–147, Paris 1865, vol. 145, cols. 559–1332, vol. 146, vol. 147, cols. 449–634.
Old Tang History, 16 vols., ed. Liu XU, Beijing 1975.
Paul the Deacon, Historia langobardorum, ed. Ludwig BETHMANN / Georg WAITZ (MGH SRG 48) Hanover 1878.
Red Book of Hergest (Brut Y Tywysogyon), ed. and trans. Thomas JONES, Cardiff 1955.
The Chronicle of 754, ed. Eduardo LÓPEZ PEREIRA, Zaragoza 1980.
Theophanes, Chronographia, 2 vols., ed. Carl De Boor, Leipzig 1883–1885.
Theophilus of Edessa's Chronicle, trans. Robert G. HOYLAND, Liverpool 2011.
Two Chronicles up to AD 819/46, trans. Andrew PALMER, in: Andrew PALMER / Sebastian P. BROCK / Robert HOYLAND (eds.), The Seventh Century in the Western Syrian Chronicles, Liverpool 1993, pp. 75–82.
Two Inscriptions on a Church at Ehnesh, trans. Andrew PALMER, in: Andrew PALMER / Sebastian P. BROCK / Robert HOYLAND (eds.), The Seventh Century in the Western Syrian Chronicles Liverpool 1993, pp. 71–73.
Widukind of Corvey, Rerum Gestarum Saxonicum, ed. Paul HIRSCH / Hans-Eberhard LOHMANN (MGH SRG 60), Hanover 1935.
Zizhi tongjian, ed. Sima GUANG, Beijing 1956.