Geoengineering and the Middle Ages: Lessons from Medieval Volcanic Eruptions for the Anthropocene

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Abstract The existential challenge of mitigating anthropogenic climate change encouraged serious discussions on geoengineering approaches. One of them, Solar Radiation Management (SRM), would mean inserting aerosols into the atmosphere, thus imitating and perpetuating the cooling effects of large volcanic events, such as the 1815 Tambora eruption. However, artificially inserting sulphur aerosols into the atmosphere is connected with considerable uncertainties. One of them, pointed out by several climate scientists, is the different effects on temperature and precipitation in different parts of the globe. These are not the only ones, though. As the largest volcanic eruptions have taken place during the medieval times (ca 500–1500 CE), historical research can reveal further uncertainties in dating these eruptions and their connected socio-environmental effects, and hence on the actual climate and social impacts we might expect from SRM. A combination of humanist and scientific research on past volcanic eruptions therefore has the potential to produce a more precise understanding of past volcanic eruptions and their climatic consequences. As long as we do not acquire a consistent multi-disciplinary perspective on past volcanic eruptions, extreme caution should be taken before investing in geoengineering measures that include the artificial injection of sulphur aerosols in the atmosphere.

Keywords Volcanic eruptions · Geoengineering · Medieval history · Climate modelling · Sulphur injections

Geoengineering and the Anthropocene

The late chemist and Nobel Laureate Paul Crutzen (1933–2021) is well-known for having coined the term ‘Anthropocene’ in 2002, or at least for initiating the term’s unhampered global success (Crutzen 2002). Once confined to the spheres of academia, the term has, over the course of the last decade, become a familiar part of the

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global discourse on environmental change and humans' role in the ongoing climate crisis (Ellis 2018), both in the public sphere and academic disciplines, amongst them history. But Crutzen did not stop at formulating a concept to describe how humanity could now exert influence as a geological force, altering hemispherical material flows. Just four years later, Crutzen published another short essay on the potential of implementing a technological solution to ongoing global warming (Crutzen 2006): 'Albedo Enhancement by Stratospheric Sulphur Injections'. The subtitle went on to claim that this might be a solution to our society's dilemma in climate policy, but the article also meant to break a taboo by suggesting that humans could inject stratospheric aerosols—preferably sulphur-based—using balloons or equivalent technical means into the higher strata of the atmosphere to counteract anthropogenic climate change (Robock 2014).

Volcanic Cooling and Solar Radiation Management

The basic idea behind this is simple and yet fascinating (Rampino et al. 1988): Large volcanic eruptions eject all kinds of dust and chemicals into the atmosphere, which reach even into the lower levels of the stratosphere to an altitude of up to 10 kms. While the relatively heavy volcanic ash falls down within a few weeks, the lighter material remains in the highest parts of the troposphere or even the lower parts of the stratosphere. Sulphur dioxide in particular reacts here with water to form tiny droplets of sulphuric acid. These very small droplets or solid particles called aerosols get caught up in moving air masses and are thus transported around the globe (Mather and Pyle 2015): a thin, yet effective, aerosol layer then deflects a considerable fraction of solar radiation before it can reach the ground. Any larger sulphur injections have the potential to influence global climate for up to three years. After this time period, the remaining aerosol particles sink to the ground and no longer influence global or regional climate (Oppenheimer and Donovan 2015; Timmreck 2018: 11–12).

The best-known historical case study for such a volcanic event (Schmidt and Robock 2015) was the eruption of Mount Tambora in Indonesia in 1815, which caused global temperatures to plunge and precipitation to increase in 1816 (and to a somewhat lesser extent in following years). This phenomenon has suggestively been described as 'the year without a summer', and as it is a particularly popular topic in the geosciences (Zeilinga de and Sanders 2002; Francis and Oppenheimer 2004), it is reasonable to assume a Tambora-like situation also came to the mind of researchers when thinking about the mitigation of anthropogenic climate change.

Crutzen's initiative from 2006 has ignited an ongoing public and scientific debate on the feasibility of using geoengineeering to mitigate climate change (Hamilton 2013; www.geoengineeringmonitor.org). A global overview of research projects on this so-called Solar Radiation Management (Boettcher et al. 2017) reveals an obvious concentration of these in anglophone countries such as the US, the UK and Australia (https://map.geoengineeringmonitor.org). Of these 23 projects, only seven propose the controlled injection of sulphur dioxide into the stratosphere to cool ground temperatures in an attempt to mimic the natural cooling effects of a big volcanic eruption. Notably, only three have actually conducted experiments on how to release sulphates, while the other four projects have relied on climate modelling to simulate the effects of artificial aerosol injections. Other projects have followed different paths of Solar Radiation Management: Some have preferred the injection of water droplets rather than sulphate aerosols, aiming to create brighter clouds that would deflect sunlight before it even reaches the ground. Other approaches aim to thin cirrus clouds to allow more heat to escape into space. And there are more ideas out there, such as enhancing ocean surface albedo by adding stable, nondispersive foam or microbubbles to the sea. Even more audacious studies have explored ideas such as clearing large areas of boreal forests in Russia to provoke a cooling effect, as snow-covered plains deflect sunlight more efficiently than snow-covered trees. So, stratospheric aerosol injection is just a small fraction of current research on solar radiation management, and, of course, a key concern is that it is not addressing the underlying increase in atmospheric greenhouse gases at all. In the political realm, it is criticized as being influenced by lobbyists supported by big corporations such as Shell and ExxonMobil with an urgent and vital interest in technology-based fixes to anthropogenic global warming. There are further concerns about and criticisms of the long-term governance of such aerosol injection projects and their possible weaponization (Costick and Ludlow 2020: 47–50).

All Kinds of Uncertainties

There are a number of climate- or climate-model-related uncertainties associated with stratospheric aerosol injection and its potential impact on human societies.

First, climate models are a crucial tool for understanding both future and past climatic changes and the role of climate drivers such as large volcanic eruptions, as these eruptions affect all components of the Earth System (Timmreck 2012; 2018: 10). Yet it is important to remember that modelling depends largely on instrumental and satellite measurements after the 1991 Pinatubo eruption, the best-researched and only large volcanic eruption with a considerable climatic impact in the twentieth century (Timmreck 2012: 548–549). Yet climate models still have difficulty reliably reproducing the well-known impact of the Pinatubo eruption, probably because many influencing factors on the actual volcanic impact such as the El Niño-Southern Oscillation are still poorly understood (Ibid.: 550–551; Cole-Dai 2010: 831).

Climate models are also key to estimating how artificial manipulation such as the injection of sulphate aerosols might influence global, regional and local climates. In particular, the finer scales down to regional and local weather impacts are hardly understood. Furthermore, climate reconstruction studies have focused on the changes in temperature after major volcanic eruptions while paying far less attention to the impacts on global and regional precipitation. A lot depends on the region where the volcanic eruption takes place: high-latitude eruptions in the Northern hemisphere (Kravitz and Robock 2011; Oman et al. 2005) change precipitation—for example, by weakening tropical monsoons—in a different way to tropical eruptions. Sulphate aerosol injections might produce winners and losers, or at least a rather unevenly distributed modification of climatic conditions over several years (Wegmann et al. 2014; Swingedouw et al. 2017).

This danger of uneven climate change—probably connected to a post-eruption effect of winter warming across the Northern parts of Eurasia (Zanchettin et al. 2013; Zambri et al. 2017)—has been clearly documented for 1816, the 'year without a summer', for while most of the continent faced severe cooling and continuous precipitation, Eastern Europe was hardly affected. Grain harvests failed in most parts of Europe (Post 1977), as an impressive memorial site, the so called Thanksgiving Box in the church of St. Michael in Schwäbisch Hall in southwest Germany demonstrates: four very small loaves of bread remember the famine year 1816, while the first wheat ears of the 1817 harvest were also preserved (Fig. 1). But summer temperatures were normal or even above average in Eastern Europe: Russian and Ukrainian grain producers profited from bountiful harvests that they sold to their starving neighbours at a considerable profit in 1816 and the following years. In fact, the rise of the port city of Odessa on the Black Sea (Herlihy 1986) has been associated with this economic success story after the Tambora eruption.

Fig. 1 'Erntedankkasten' (=Thanksgiving Box) in St. Michael, Schwäbisch Hall, Germany, presenting small bread loaves and wheat ears from 1816 and 1817. Picture: Klaus Graf, CC-BY SA 3.0, Wikimedia Commons

Beyond these uncertainties, previous research has focused on another crucial point: What we can learn from history is the irresolvable danger that, even after artificial sulphur injections in the atmosphere, assuming these could be controlled and targeted precisely, additional natural eruptions might change the overall-picture and drive global climatic conditions in highly problematic states as it happened, because of all-natural repeating eruptions, as was the case, for instance, in the sixth and seventh centuries (Costick and Ludlow 2020: 92–94).

The Role of Medieval History: More Precision

Medieval history has a special task in this context, as the greatest explosive volcanic eruptions of the past two millennia happened in the medieval period (Sigl et al. 2015; Toohey and Sigl 2017; Costick and Ludlow 2020; see also Fig. 2). First, a double eruption in the sixth century that triggered the so-called Late Antique Little Ice Age; then, eruption of the Samalas volcano in Indonesia in the mid-1250s; and, finally another, yet unidentified eruption event in the mid-fifteenth century, which was known as the Kuwae eruption until new research rightfully challenged the validity of this identification (Németh et al. 2007).

How do we know about these past volcanic eruptions? Without a single exception, and in stark contrast to the famous eruptions of the nineteenth century such as Tambora and Krakatoa (Simking and Fiske 1983; Winchester 2003), we do not have any written eyewitness accounts of medieval volcanic eruptions on a scale that could influence global climate. Narrative texts from the medieval period originating from the area of modern Indonesia do not provide concise chronologies, and other areas, such as premodern Melanesia, did not produce written records but relied on an oral tradition of genealogies that likewise do not provide reliable dating of reported

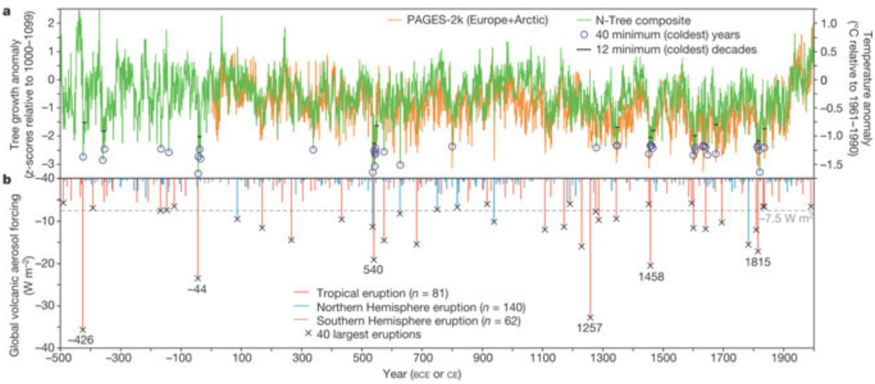

Fig. 2 Global volcanic aerosol forcing and Northern Hemisphere temperature variations for the past 2500 years. *Source* Sigl et al. 2015, Fig. 3

events. Even if we had more detailed information about the dates of volcanic eruptions in the premodern period, we could hardly estimate their influence on climate from such accounts, for such deduction requires information regarding the amount of sulphur injected into the atmosphere, something a medieval observer could hardly quantify with naked eye.

The key to determining the magnitude of the sulphuric injection caused by a specific eruption can be found in the polar ice shields (Cole-Dai 2010). The aerosols of sulphuric acid fall in precipitation within a maximum of three years, most already in the year after the eruption. The annual snowfall layers in polar regions, mainly Greenland and Antarctica, are compressed into layers of ice, each containing distinctive chemical and physical traces, from Sahara dust to sulphuric acid. Scientists count these layers backwards and measure these traces—for example, sulphuric acidity—in each layer to create a chronology that provides us with a good record of past volcanic eruptions that ejected large quantities of sulphur into the atmosphere and hence, most probably, influenced global climate (Cole-Dai 2010).

There are, however, some inherent dating problems with this method: Snowfall deposits and thus the amount of sulphuric acid in one specific ice core might vary from place to place, so the only reliable information comes from cross-referencing multiple ice cores to identify widespread sulphur peaks. Furthermore, researchers cannot see the annual layers in ice cores that go back several hundred years, so they have to measure seasonal variations of dust or chemicals in these ice cores to identify annual layers. Eruption dates acquired using these methods may be off by two to five years (Cole-Dai 2010: 828–829). So, it comes as no surprise that researchers look for so-called stratigraphical markers: well-known volcanic events that should have left a considerable peak of sulphur in all ice cores. These events are used to synchronize peaks in different ice cores and validate their specific chronologies. For the nineteenth century, the Krakatoa and Tambora events are precisely dated and well documented in historical sources, but when it comes to the largest eruptions of the last two millennia—we have mentioned them before: The so-called Kuwae event in the fifteenth century, Samalas in the mid-thirteenth century, and a volcanic double-event in the sixth century—historical evidence is much scarcer and yet even more important.

Dating Uncertainty and Historical Sources

This is not to suggest that written sources can always be taken at face value, as there are obviously pitfalls. Let me demonstrate this with regard to what is widely accepted as the largest volcanic event of the last two millennia, the Samalas eruption that is now dated to 1257, although it was once dated to 1258 or even 1259. A key argument for dating the event to 1257 was advanced by Guillet et al. (2017) with reference to historical sources: First, he evaluated chronicles from the whole of the thirteenth century and counted the references to bad weather. In his results, 1258 stood out in an astonishing way, as we would expect after the most sulphur-rich

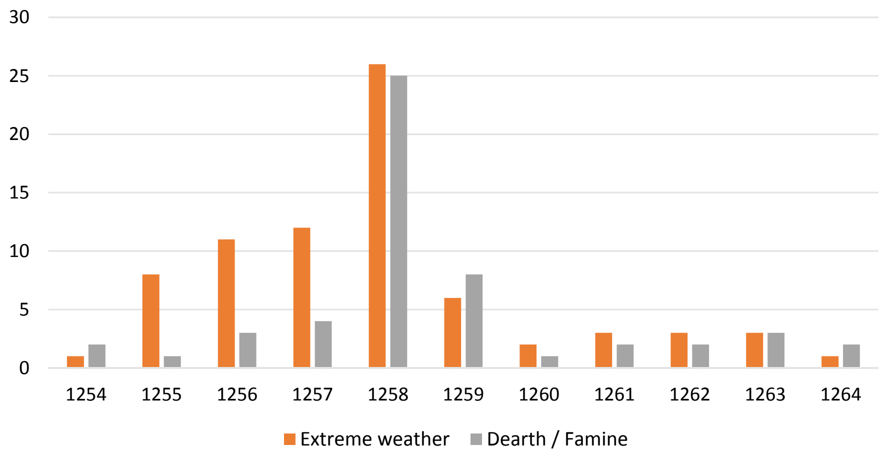

Fig. 3 Number of weather reports and accounts of dearth/famine per year. *Source* Bauch (2020)

eruption of the last two millennia. But there is a problem: While Guillet carefully collected all the relevant material from European chronicles for 1258, for the other years of the thirteenth century he relied on the important yet incomplete collection of Pierre Alexandre (1987), which focused exclusively on the territories of Continental Europe. Alexandre's collection does not include the British Isles, but the bulk of information on bad weather comes from English chroniclers. Excluding this body of sources for all years except 1258 is thus distorting the evidence from narrative sources to some extent. My alternative count (Bauch 2020) still shows a peak in 1258, but a period of extraordinarily bad weather set in as early as 1256 (Bauch 2020).

Furthermore, Guillet's argument relied on a quote from a German chronicle that referred to the year 1258 as '*munkeliar*', a strange vernacular term, the meaning of which is very unclear (Guillet et al. 2017, Supplementary Material, S2). Guillet followed faithfully the interpretation of the nineteenth-century editors of this chronicle, who interpreted *munkeliar* to mean a year of fog and darkness, which could refer to the visual effects of an unusually dense aerosol layer that year. With the Tambora eruption in mind and thinking of the year without a summer in 1816 this sounds very reasonable. However, a closer look at the quote in question (Bauch 2020: 220) reveals that the chronicler is not talking about weather or the sun's intensity but rather about the low quality of food, especially wine. Etymological dictionaries of wine-growing in Germany confirm that the verb *munkeln* means that wine tastes mouldy, which, of course, could be the result of the undisputed bad weather in 1258. The key question here is whether or not the bad weather started before 1258 and whether we can find more convincing descriptions of a volcanic aerosol layer. I argue elsewhere that we can indeed find such descriptions and probably should redate the eruption to 1256 or even 1255 (Bauch 2020).

What is the importance of all this for current discussions on geoengineering with solar radiation management? As we have seen before, modelling is a key feature when simulating the impact of past volcanic eruptions, and these climate models are based upon presumably precise data on eruption dates, sulphur injections, and subsequent temperature reductions. In the Samalas case, though, the maximum drop in global temperatures of the Northern hemisphere is detected in 1259 (Guillet et al. 2017: 126), while the geographical distribution of cooling in the northern hemisphere was rather uneven. If, in fact, there was a delay of two or even three years between an eruption and the related hemispherical cooling, this strengthens previous doubts about the strength and uniformity of the cooling effect of sulphur injections in the atmosphere (Timmreck et al. 2009). We should remain cautious about the predictive reliability of model simulations when the basic facts on the largest volcanic eruptions in the past, such as dates, sulphur loads and associated cooling, remain so unclear.

Let me provide another example from the Middle Ages: the second-largest volcanic eruption of the past two millennia has been identified in ice cores for the mid-fifteenth century (Fig. 2). It was long associated with the submarine caldera of Kuwae in Vanuatu (Gao et al. 2006) and had been dated to 1452. Rather baseless speculation (Pang 1993) even connected it with major historical events such as the fall of Constantinople in 1453. Recent volcanological research has precluded the association of Kuwae with the mid-fifteenth century event (Németh et al. 2007). Tree-ring and ice-core research has suggested there might have been two eruptions in close temporal proximity (Sigl et al. 2013; Cole-Dai et al. 2013): Probably one around 1453, and another one, according to ice-core analysis in 1458, while tree-ring research indicates a drop in temperature in 1453 and 1466 and hence an eruption in 1465 (Esper et al. 2017; Stoffel et al. 2015; Wilson et al. 2017). This paradox (Fig. 4)

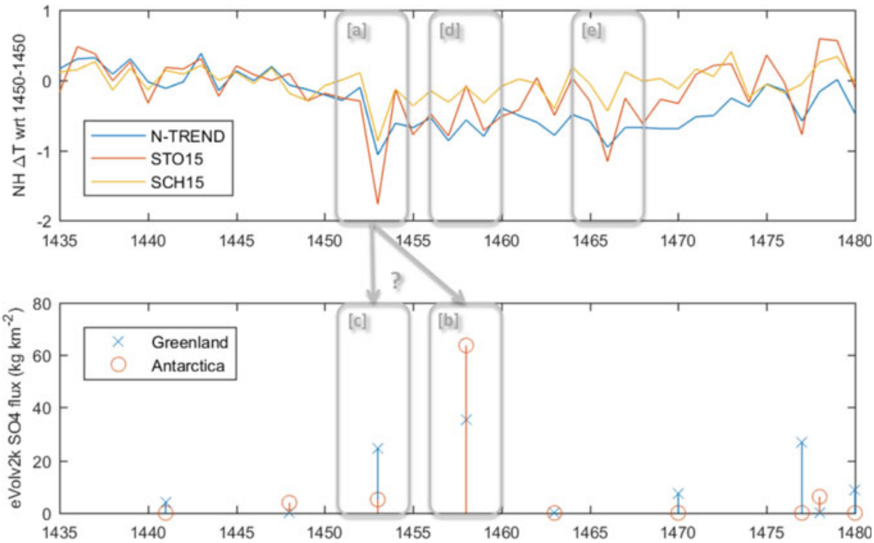

Fig. 4 Tree-ring-based reconstructed NH temperature anomalies (top) and average volcanic sulphate flux to Greenland and Antarctica (bottom), 1435–1480 Data from Toohey and Sigl 2017; Wilson et al. 2016; Stoffel et al. 2015; Schneider et al. (2015). Figure courtesy of Matthew Toohey

remains unsolved, especially as my analysis of historical sources (Bauch 2017) also points to 1465, with dramatic descriptions of a volcanic dust veil all across Europe in September 1464, while the climatic impact in 1453 is less well documented.

In a nutshell: The contradictory findings of ice-core research, dendroclimatology and history have not yet been reconciled. In other words, for none of the two of the largest volcanic eruptions of the past two millennia do we have consolidated evidence on eruption dates and hence on the connection between temperature decrease, precipitation and volcanic aerosols. What we should expect is, most of the time, a smooth fit of historical descriptions and dendroclimatological data, as both are annually resolved, yet often of different geographic origins and hence may not reflect the same local situations. Ice-core analysis is improving in the field of dating certainty, and yet still has its inherent uncertainties. But for any sulphur aerosol injection projects, we need a reliable attribution of specific eruptions and their reconstructed sulphur injections into the atmosphere. The work of traditional medievalists with narrative sources is crucial to the determination of best possible chronologies of past volcanic eruptions. Unless we can reasonably synchronize historical facts, ice-core data and tree-ring reconstructions, we should not assume that we have understood the complex climatic processes that followed large volcanic eruptions in the past two millennia.

Clarifying the Conditions of a Possible Future: Let Frankenstein Sleep

Let us return to the best-researched of all sulphur-rich volcanic eruptions of the past: Tambora. Many cultural phenomena have been associated with the experience of the year without a summer in 1816 (Wood 2015; Behringer 2015). Not all of these hypotheses are very well founded; however, one deserves our attention: When a group of young English writers, both men and women, decided to stay in their houses on Lake Geneva because of the ‘End of the World’ weather they were facing daily in this gloomy summer of 1816 that included 130 days of rain between April and September (Wood 2015: 1-11). One of them, 18-year-old Mary Godwin, better known by her later husband’s family name as Mary Shelley, began drafting a story that eventually entered the literary canon: *Frankenstein*. It is not a mere horror novel but a parable for the modern age about how humans underestimate the risk of their technological ambitions, only to be chased and finally overwhelmed by a monster of their own creation. I hope I have demonstrated how medieval history might help us re-evaluate epistemological uncertainties within the whole approach of solar radiation management via artificial aerosol injections.

Historians also respond to the concerns of their own times. If some medievalists turn their attention now to questions of past climate change, natural disasters or pandemics of the past, they are not merely following another ephemeral fashion. But they do what their predecessors have done before—they try to find answers for questions their contemporary societies have: What can we still ‘learn’ from history for pressing matters such as climate change and adaptation or preventive measures, especially from such a remote time such as the Middle Ages? A possibility that was the indirect line of argumentation in this contribution is the classical ‘orientation knowledge’ (Koselleck 1989a, b) that no longer naively assumes a direct learning from past events and yet stresses that historiography can unveil the ‘conditions of a possible future’ (Koselleck 1989a, b: 157). In our context of volcanic eruptions and adaptive measures to a changing future climate, this means that we can hardly (Bethke et al. 2017) interpret societal reactions to past volcanic eruptions as guidelines for future political decision-making. But we can take full advantage of the epistemological possibilities that a combined approach of different disciplines, with medieval studies one of them, provides us a better understanding of climatic impacts of historical eruptions and their potential to design projects of geoengineering. History can help us to make sure that Frankenstein was the only monster created by a human mind in the dimmed sunlight of a global sulphate aerosol layer.

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