Volcanic Impacts on Short- and Long-Term Climate, Comparison with Anthropogenic Climate Change

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Jarðvísindadeild
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10 eininga ritgerð sem er hluti af
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Abstract

Volcanic eruptions cause the formation of sulphate aerosols in the atmosphere, which change radiative forcing and thereby have an impact on the climate system. In this paper, I summarise observed short-term effects, for example surface cooling. I then discuss how short-term volcanic forcing can be transformed into long-term climatic changes by long dynamical feedbacks and briefly look into how volcanic eruptions might increase the possibility of El Niño events. As historical examples for potentially volcanic caused climate change I will discuss The Little Ice Age and the Toba eruption ~74,000 years BP. I then compare recent anthropogenic climate warming with natural caused climate change, with special focus on volcanic forcing. Concerning possible future scenarios I will discuss the impact of modern climate changes, concentrating on human society.

Keywords: climate change, volcanic impacts, dynamical feedbacks

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1 Introduction

The Earth's climate is a complex and sensitive system. Natural climate changes have occured throughout its history, caused by various forcings including changes in solar output, increased volcanic activity and changes in thermohaline circulation (Bertler et al, 2011; Broecker, 2000; Robock, 2000). From the moment on when humans populated the planet, they had an impact on this system in different ways. This impact became most severe with the Industrial Era, when concentrations of greenhouse gases increased consistently and warmed the planet's lower atmosphere. Parallel to those anthropogenic caused changes, natural processes still continue the same way they did for thousands of years before humanity. Therefore, it is essential to understand and be able to seperate each of these processes.

This thesis focuses on the volcanic aspect of natural-caused climate changes. The first part of the paper summarises observed impacts of volcanism on short-term climate, such as radiative forcing. The second part deals with the quesion whether volcanic eruptions can impact long-term climate. This will be discussed by investigating how short-term volcanic forcings can be transformed into long-term climatic changes. This final section will look into the past by examining former climate changes like The Little Ice Age and glaciation after the Toba eruption ~74,000 years ago. A short discussion in the end deals with possible future scenarios.

2 Literature

Whether Volcanism on Earth can have an impact on short- and long-term climate is the subject of many scientific studies. In the following, a summary will be given on observed impacts on short-term climate. Later on you will find a debate in how far volcanic eruptions can influence long-term climate and how this is combined with ongoing anthropogenic climate change. This thesis is based on a literature research, especially Alan Robock's paper from 2000 provided guiding and valuable information.

2.1 Observed Impacts of Volcanism on Short-Term Climate

This part focuses on observed and analyzed volcanic impacts on short-term climate, which includes (1) Volcanic Inputs to the Atmosphere, (2) Radiative Forcing and (3) Weather and Climate Response (Reduction of Diurnal Cycle, Surface Cooling, Stratospheric Heating, Winter Warming of Northern Hemisphere (NH) continents, El Niño Southern Oscillation (ENSO)) (Robock, 2000).

2.1.1 Volcanic Inputs into the Atmosphere

Volcanic eruptions consist not only of magmatic material but emit lots of particles and gases into the atmosphere. As per Robock (2000), H2O, N2 and CO2 are predominating. He further argues that because of their natural existence in vast quantities in the atmosphere, erupted H2O and CO2 do not directly impact the greenhouse effect. Solid and lithic material - such as ash or tephra - fall out of the atmosphere very rapidly due to their big size, while erupted gases can be transported over large distances around the globe. Thereby, volcanic gases and aerosols present not only local but global hazards. Mainly, they have climatic impact by disturbing the Earth's radiation balance through direct radiative effects and through indirect effects on the atmospheric circulation, by which surface temperatures are affected (e.g. Surface Cooling [see chapter 2.1.3]) (Robock, 2000). These processes are shown in Figure 1.

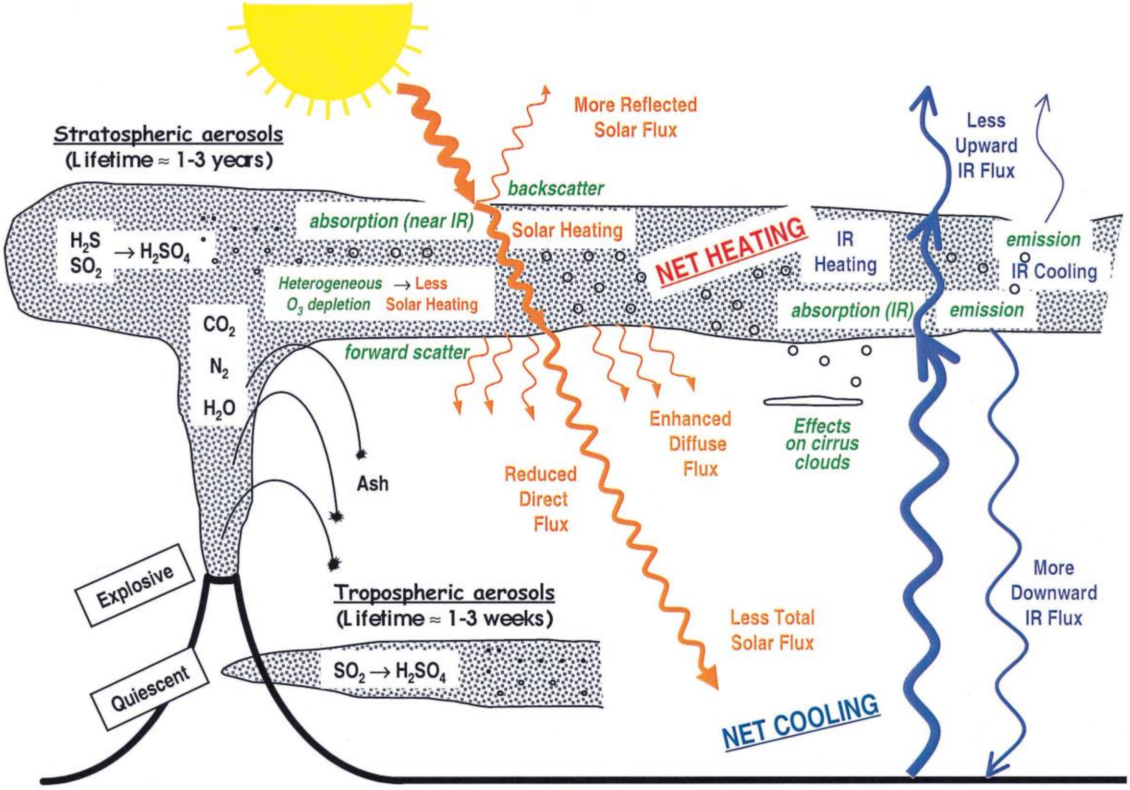

Figure 1: Volcanic Inputs into the atmosphere and their effects (edited by Robock, 2000; original version by Simarski, 1992)

The climatic impact of volcanic eruptions is not linked to the erupted amount of magma, as Rampino and Self (1984) showed. The controlling factor is rather the rate of sulphur-rich volatiles injected into the stratosphere (Rampino and Self, 1984; Newhall and Self, 1982). Mt Agung in 1963 and El Chichón in 1982 for example both caused considerable stratospheric aerosol clouds although the erupted magma was less than 0.5km³ (Rampino and Self, 1982). These sulphur species react with OH and H_2O to form H_2SO_4 on a timescale of weeks, and the resulting H_2SO_4 aerosols produce the dominant radiative effect from volcanic eruptions [*see chapter 2.1.2*] (Robock, 2000).

Emissions of sulphate aerosols absorb both solar and terrestrial radiation. When emitted into the tropical stratosphere, they are spread by the stratospheric circulation and thereby cause globally averaged tropospheric cooling, which is accompanied by localized heating in the lower stratosphere. An example is the 1883 Krakatau eruption, whose aerosol cloud circled the globe in 2 weeks (Chenoweth, 2001; Symons, 1888). This can result in major dynamical feedbacks (Driscoll et al, 2012; Robock, 2000), which will be discussed in *chapter 2.2.2*.

Volcanic aerosols also contribute to ozone depletion. They provide a surface for heterogeneous chemical reactions that destroy ozone (Solomon et al., 1996; Solomon, 1999), which lowers ultraviolet absorption and thus reduces the radiative heating in the lower stratosphere. Nevertheless, the net effect in the stratosphere is still heating (Robock, 2000). However, as this chemical reaction depends on the presence of anthropogenic chlorine it has only become important in recent decades. This will be discussed later on [*see chapter 2.2.4*].

Meteorological changes caused by Radiative Forcing can be traced back over long time periods and are documented in several historical writings. Even 2000 years ago, the Greek historian Plutarch and others (Forsyth, 1988) pointed out that the eruption of Mount Etna in 44 BC dimmed the sun and suggested that the resulting cooling caused crop loss and famine in Rome and Egypt (Robock, 2000). Also records of ancient China and Rome refer to changes in the sky after the 186 AD Taupo eruption in New Zealand (Wilson et al, 1980).

Volcanic eruptions can emit big amounts of sulphur aerosols into the air, which have an average size of about 500nm. Due to this small size and light weight they have a longer life-time than bigger particles like ash and dust. On a time-scale of about one month, sulphur species react with water vapour to form sulphate aerosol (H_2SO_4). The resulting H_2SO_4 aerosols produce the dominant radiative effect from volcanic eruptions. In the stratosphere these particles remain suspended for a longer time than particles in the troposphere, where they get quickly removed by precipitation. As visible light is arranged from 400-700nm on the electromagnetic spectrum, the sulphur aerosols with 500nm are exactly in this boundary. This is the reason why they scatter a lot of light. The radiative effect is defined by scattering of UV radiation. Some of the light is backscattered, which results in a net cooling at the surface. Much of the solar radiation is forward scattered, resulting in increased diffuse radiation.

As per Robock (2000), volcanic impacts on solar radiation can be clearly observed in the eruptions of the 1963 Agung, 1982 Chichón and 1991 Pinatubo, shown in Figure 2.

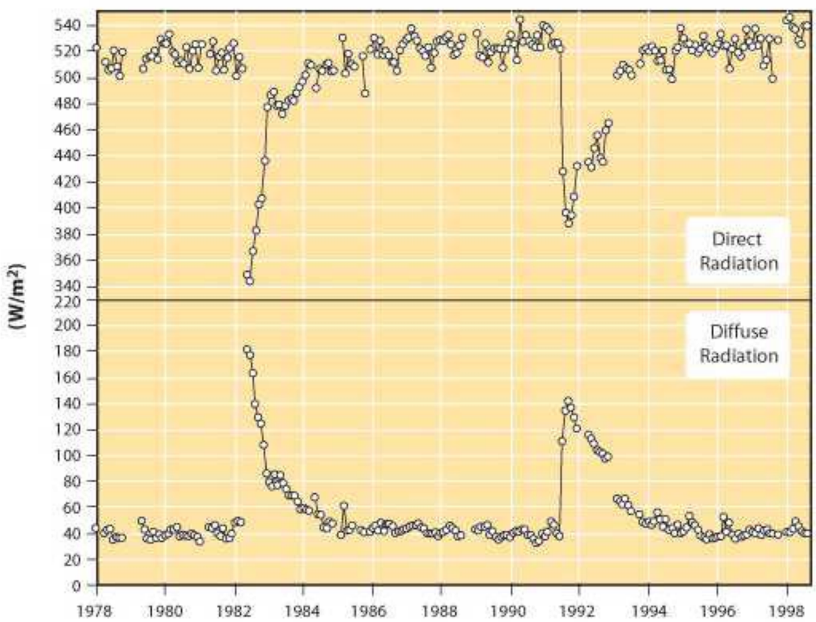

Figure 2: Direct and Diffuse Radiation from the 1982 El Chichón and 1991 Pinatubo eruption (Original data from NOAA, 1994-1995).

Furthermore, Kravitz and Robock (2011) suggest that the time of year of the eruption represents a controlling factor. In a recent paper, they show that high-latitude volcanic eruptions have larger effects on climate if they occur in late spring to early summer, provided the eruption is large enough. They even say it is "unlikely to have climate effects if it erupts in the winter, unless the eruption is particularly large". This is due to seasonal variation in insolation patterns and sulphate aerosol deposition rates.

2.1.2 Radiative Forcing

It is a matter of common knowledge that emitted volcanic particles have effects on solar radiation. Firstly by reduction of direct radiation (=backscattering), secondly by increase in diffuse radiation (=forward scattering). Another effect is stratospheric heating caused by partial absorption of solar radiation in the near infrared (near-IR), as shown in Figure 1.

Backscattering is the dominant radiative effect at the surface and results in a net cooling, often referred to as a "Volcanic Winter". This surface cooling is the main climatic change caused by particles in the atmosphere. Robock et al (2000) point out that in the tropics and in the midlatitude summer these radiative effects are larger than most other climatic forcings, as there is more sunlight to block. Robock and Mao (1995) superposed the signals of Krakatau, Santa Maria, Katmai, Agung, El Chichón and Pinatubo, and found that the maximum cooling is approximately one year following the eruptions. They furthermore propose that the cooling generally ranges from 0.1°-0.2°C. Surface cooling will be discussed more precisely in *chapter 2.1.3*.

A reduction of direct radiation is resulting by reflection of the setting sun from the bottom of stratospheric volcanic aerosol layers. This process produces the characteristic red sunsets. Thereby, paintings and historic descriptions can serve as a window to the past, helping to detect past eruptions. An example is the painting by Edward Munch in 1893 "The Scream", inspired by the 1883 Krakatau eruption in Indonesia (Olson et al, 2004).

Increase in diffuse radiation by foward scattering, on the other hand, causes milky white sky. This effect is so strong that it can be easily seen by the naked eye. Volcanic emissions have longer lifetimes than anthropogenic aerosols and the consequent radiative forcing from such emissions is only a little less than anthropogenic effects (Robock, 2000).

2.1.3 Weather and Climate Response

In addition to the above discussed impacts of volcanic eruptions on the atmosphere and solar radiation, Robock (2000) lists several weather and climate responses:

- Surface Cooling
- Reduction of Diurnal Cycle
- Stratospheric Heating
- Winter Warming
- North Atlantic Oscillation (NAO) and El Niños/Southern Oscillation (ENSO)

Surface Cooling: Reduced direct radiation due to volcanic aerosols in the stratosphere, where they have a lifetime of 1-3 years, causes surface cooling. Robock (2000) mentions that cooling is more pronounced in the tropics and midlatitudes, as there is more incoming radiation to block. He also refers to differences between Southern- and Northern Hemisphere, related to distribution of continents: Land surfaces respond quicker to change in radiation, which makes the NH more sensitive to radiation reduction from volcanic aerosols. Benjamin Franklin (1784) suggested that the Lakagigar eruption in Iceland in

1783 might have been responsible for the abnormally cold summer of 1783 in Europe. This, however, does not seem to completely correspond with the results of Robock and Mao (1995), who found that the maximum cooling occurs approximately 1 year following the eruptions and averages between 0.18–0.28C.

Robock and Mao suggest that in the first winter after major tropical eruptions and in the second winter after major high-latitude eruptions, North America and Eurasia warm by several degrees, while northern Africa and southwestern Asia cool by more than 0.5°C. They link this to El Niños/Southern Oscillation (ENSO) events that occurred at the same time as several large eruptions. Robock and Mao therefore assume that the warming produced by the ENSO masked the volcanic cooling during the first year after the eruption. While the volcanic response timescale is two years, the timescale of the ENSO response is only one year. Therefore, they suggest that the cooling in the second year is evident, whether the ENSO signal is removed or not.

This idea would rather suggest that the summer of 1784 would have been colder than the one of 1783.

<u>Reduction of Diurnal Cycle</u>: As mentioned before, volcanic eruptions put large amounts of ash into the troposphere. This often results in darkness during the day. The Mount St. Helens eruption in 1980, for example, caused darkness in an extent that in a city 135km from the eruption automatic streetlights went on in the middle of the day. To be correct, it should be mentioned that while the Mount St. Helens eruption had a large local effect on temperature, no other impact was identified on precipitation or atmospheric circulation. Its stratospheric input of sulphur was very small, and hence this very explosive eruption had a minimal impact on global climate. (Robock, 1981a; Robock, 2000)

<u>Stratospheric Heating</u>: After injection of volcanic aerosols, the lower stratospheric layer absorbs both near-IR from the sun and terrestrial upward IR flux, as shown in **Figure 1**. Thereby the stratosphere is heated. Robock (2000) names Pinatubo 1991 and El Chichón 1982 as eruptions that verifiable caused globally stratospheric warming - after the El Chichón eruption, it rose by about 1°C for about 2 years, after Pinatubo even ~2°C.

<u>Winter Warming</u>: Usually, as explained before, volcanic eruptions cause tropospheric cooling. But there's an exception in the Northern Hemisphere (NH), where indirect effects on atmospheric circulation produce winter warming which is stronger than the usual radiative cooling effects. This is due to the northern polar vortex, as volcanic eruptions strengthen the Jet Stream and thereby warm NH-continents rather than cooling. Such winter warmings were documented on the basis of tree-ring data by Lough and Fritts (1987) in North America. Subject of their investigation were volcanic eruptions within the period 1602 to 1900. They found winter warming lasting for 0-2 years after the eruptions.

Again, historical art can be the key to the past. Cold summers and gloomy days caused by the 1815 Tambora eruption inspired books like "Frankenstein" by Mary Shelley (Shelley, 1818) and "The Darkness" by Lord Byron (Robock, 2000).

2.1.4 North Atlantic Oscillation (NAO) and El Niños/Southern Oscillation (ENSO)

One controversial matter is whether volcanic eruptions produce El Niños. El Niño/Southern Oscillation (ENSO) is a result of complex air-sea interactions and causes periodic temperature-variations and interannual climate-fluctuations in the tropical Pacific. This event involves cooling and warming events and includes (1) La Niña, an enhancement of the east-to-west flow of water and air in the equatorial Pacific and (2) El Niño when the system reverses for a limited period. The term El Niño/ENSO event is in this paper applied to both warm and cold variations of tropical sea surface temperatures. Furthermore, ENSOs occur at irregular intervals of two to nine years and typically last one year (Robock and Mao, 1995).

As per Robock (2000), Radiative Forcing caused by volcanic eruptions in the tropics and in the midlatitude summer is generally larger than most other climatic forcings, as there is more sunlight to block. He points out, however, that in some locations in the tropics these effects can be overwhelmed by larger El Niños and gives as an example the eruption of El Chichón 1982 and a simultaneously occuring El Niño in 1982-83. Robock and Mao (1995) further mention Agung in 1963 and the El Niño in 1963, as well as Pinatubo in 1991 and an El Niño event in 1991-92.

Several studies have suggested a connection between El Niño events and explosive volcanic eruptions. By looking back over a 350-year period, Adams et al (2003) assume a doubling of the probability of an El Niño event occurring in the winter following a volcanic eruption. This hypothesises that this increased probability of El Niño events due to volcanic eruptions continues to hold up over several centuries. They therefore suggest that the eruption of a tropical volcano nudges the climate towards a “more El Niño-like state”. In their paper, they also discuss how the tropical Pacific ocean-atmosphere system may respond to external - both natural and anthropogenic – radiative forcing. By understanding how these events link with volcanic activity, we could potentially better understand how El Niño might respond to more recent anthropogenic changes on climate.

The ENSO is the dominant mode of interannual climate variability on Earth. Therefore it is required to understand whether this system itself undergoes changes, e.g. in response to radiative forcing or variations in the background climate itself.

2.2 Possible Impact of Volcanism on Long-Term Climate

Referring to Robock (2000), volcanic aerosols have a lifetime of maximum 3 years in the stratosphere and therefore radiative forcing does not cause decadal climatic changes but is rather short-termed. He assumes, though, that a series of volcanic eruptions is able to cause a decadal-scale cooling.

Several natural-caused climate changes have occurred throughout the Earth’s history. The most recent and therefore best studied are The Little Ice Age (LIA) and the preceding Medieval Warm Period (Bertley et al, 2010; Bradley et al, 2003; Robock, 2000). In the following chapter, I will review an example of past climate change: The Little Ice Age. Through records of volcanic aerosol loading of the atmosphere it is possible to retrace the causes of such recent climate changes (Bradley et al, 2003). Records are for instance provided by historical, tree ring and ice core data (Gao et al, 2008; Lough and Fritts, 1987; Bradley and Jones, 1993).

Later-on, long-term dynamical feedbacks will be examined that are assumed to change short-term volcanic impacts into long-term changes of climate. By going further back in history, it will be briefly discussed whether the supervolcano Toba in Indonesia was responsible for worldwide glaciation. Then, volcanic climate forcing serves as a representative for natural-caused climate change and will be compared with anthropogenic-driven climate change.

2.2.1 Climate Changes during the last centuries: The Little Ice Age

The Little Ice Age (LIA) was a cooling period of the Northern Hemisphere (NH) during the 15^{th}-19^{th} century, with temperatures dropping about 0.6°C (Bradley and Jones, 1993; Mann, 2002) and superposed century-scale cold summer anomalies (Miller et al, 2012). It was a time of expanded glaciations and altered climate conditions in Europe, Polar Regions and northern latitudes of Asia and North America (Hunt, 2006; Mann, 2002).

Gao et al (2008) recently provided an improved ice core-based index for climate models. This opens new doors for investigating volcanic climate forcing over the past 1500 years. They document warm mean temperatures between the ninth and twelfth centuries as well as exceptionally high temperatures after 1850. Furthermore, the ice cores show coldest episodes occurring during the thirteenth, fifteenth and nineteenth century, which supports previous dating of the LIA.

What primary triggered the LIA is a still hotly debated issue. All in all, three major factors are assumed to have played a role: changes in solar output, increased volcanic activity and changes in thermohaline circulation (Bertler et al, 2011; Broecker, 2000; Robock, 2000), whereas Bertler et al (2011) contest the validity of the thermohaline circulation, an ocean current caused by changes in density. This ocean circulation is very sensitive to changes in precipitation - which change the salinity and thereby density of the water – and therefore climatic changes.

Whether the thermohaline circulation triggered the LIA is a strongly disputed matter. Broecker (2000) suggested that north-south directed overturning in the North Atlantic decreased during the LIA, resulting in a cooling in Europe. Bertler et al (2011) dispute this theory, bringing forward the argument that if this was the case, Antarctica should have warmed during the LIA when the Northern Hemisphere was cold. They argue that this interlinking was observed for other Dansgaard-Oeschger events (abrupt, large scale climate fluctuations that occurred several times during the last glacial period). But in contrast to the idea of the LIA just being the most recent of these Dansgaard-Oeschger events, Bertler et al (2011) showed that overall Antarctica was cooler during the LIA. Another interesting aspect of this study was that also New Zealand displays a cooling that began around 1250-1350 AD and peaked ~1500-1650 AD before recovering at the end of the 19^{th} century. They also found similar climate shifts in southernmost South America. The authors therefore conclude that the LIA was not caused by a change in the termohaline circulation, but rather by alternative forcing as mentioned above.

As per Miller et al (2012), intervals of sudden ice growth, dated in Arctic Canada and Iceland, are happening simultaneously with two of the most volcanically active half centuries of the past millennium. At the beginning of the LIA, there was an unusual 50-year-long episode with four large sulphur-rich explosive eruptions in the 13th century, each with global sulphate loading of more than 60 Tg. These sulphate aerosol peaks during the 13th century can be seen in **Figure 3**. Oppenheimer (2003) dates one massive eruption to 1258 AD from an unknown volcano, probably in a low-latitude. He assumes that this was the largest eruption of the historic period. Furthermore, he suspects tropical, sulphur-rich explosive eruptions with one occuring in 1257 AD.

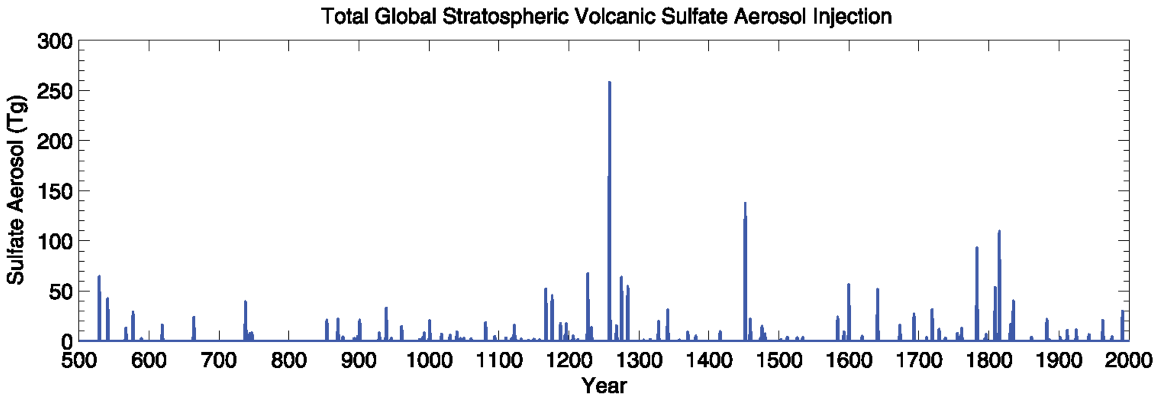

Figure 3: Increased sulfate aerosol injection into the stratosphere during the 13th century. Did these volcanic eruptions trigger the LIA? (Gao et al, 2008)

Besides accompanying summer cooling, Miller et al (2012) furthermore suggest that cold summers can be maintained long after volcanic aerosols are removed. They link this to long-term sea-ice/ocean feedbacks, which will be discussed further in *chapter 2.2.2.*

The causes of superposed century-scale cold summer anomalies, of which the Little Ice Age is the most extreme, remain debated. This is largely because the natural forcings are either weak or, in the case of volcanism, short lived (Miller et al., 2012). The following paragraph focuses on Miller et al's theory that the LIA was triggered by volcanism and then sustained by long-term sea-ice/ocean feedback:

Miller et al (2012) agree that several decadal eruptions may produce greater cooling than a single large eruption and explain multidecadal cold episodes. But they also say that many Canadian sites that became ice-covered ~1275-1450 AD, following episodes of strong explosive volcanism, remained ice-covered until the most recent decade. They assume that this long-lasting response can only be explained by a substantial and largely self-sustaining positive feedback. Miller et al (2012) supported this idea by completing an experiment based on a climate model. Their results show that late 13th century eruptions might have caused a net summertime energy decrease over the three centuries following the eruptions. This led to (1) increase in Albedo, (2) expanded sea ice and (3) lowered ocean temperatures, producing a persistent reduction in summer air temperature across Arctic North Atlantic continents. Zhong et al (2011) furthermore showed that increased southward sea ice export following the eruptions led to freshening and vertical stratification of the North Atlantic subpolar vortex, reducing open convection and thereby weakening the Atlantic meridional (north-south) overturning circulation. These changes might have reduced basal sea-ice melt, thus producing an expanded sea-ice state that sustained for centuries after the final eruption, without additional forcing.

To conclude, it is likely that the LIA was triggered by explosive volcanism and variations in solar output (Crowley and Kim, 1999; Miller et al, 2012; Robock, 2000). The cold conditions were then sustained by long-term sea-ice/ocean feedback (Miller et al, 2012) and continued until the 19th century.

An example of volcanism in this late period of the LIA is the 1815 Tambora eruption in Indonesia. It caused a global sulphate aerosol veil in the stratosphere which caused unusual cold weather in the following year in the northeastern USA, Maritime Provinces of Canada, and Europe. This period is commonly known as the “Year without a summer” 1816, which caused disastrous crop failures, starvation and epidemics on a global scale (Oppenheimer, 2003). Other dramatic NH-eruptions in that millenium were 1783-1784 Laki in Iceland and 1912 Katmai in Alaska, followed by extreme and unusual weather in Europe and North America (Robock, 2004).

This illustrates how volcanic eruptions have the power to destabilize economic- and ecological systems as well as human health on a global scale. It has to be reminded that such big volcanic eruptions can occur at any given time, thus we should learn from these historic catastrophes and be cautious.

As there is always an other side of the coin, Adams et al (2003) point out the possibility of opposite forced changes caused by El Niño to these mean-temperature decreases in the NH during the last centuries. That means that volcanic eruptions that partially triggered the LIA by changing radiation might have been responsible for El Niño events which warmed the tropical Pacific. This is the best example to see how complex processes on our planet are.

2.2.2 Long-Term Dynamical Feedbacks

One of the Earth’s most complex processes is dynamical feedback involving ice and ocean. Acting on longer time-scales, ice-ocean feedbacks could transform the short-term volcanic forcing into a longer-term effect (Robock, 2000) [see *chapter 2.2.1*].

To evaluate the significance of anthropogenic climate change, it is essential to place recent observed changes in a longer-term context. This can be done by studying dynamical feedbacks of climate variability such as the North Atlantic Oscillation (NAO) and El Niño/Southern Oscillation (ENSO), which influence long-term climate (Mann, 2007).

One of these dynamical feedbacks involves El Niño events [see *chapter 2.1.4*]. Hansen et al (2006) calculated that global surface temperature has increased about 0.2°C per decade in the past 30 years. They assume that the increased temperature in the Pacific may have increased the likelihood of strong El Niño events (Adams et al, 2003), such as the one of 1983, accompanying the El Chichón 1982 eruption. Hansen et al (2006) furthermore suggest that this critical ocean region, and probably the planet as a whole, is approximately as warm now as at the Holocene maximum and within ~1°C of the maximum temperature of the past million years. They conclude that global warming of more than ~1°C, relative to 2000 AD, will constitute “dangerous” climate change as judged from likely effects on sea level and extermination of species.

On the other hand, it is possible that variations in climate can conversely cause volcanic eruptions. Retreating glaciers and ice sheets for example can cause back-bouncing of the land as it gets released from the weight of the ice. Loading and unloading of ice and water masses leads to stress changes on the earth's crust, which might increase volcanic and seismic potential (Rampino et al, 1979). Zielinski et al (1996a) studied this issue and published a paper about how deglaciation might cause volcanism. Based on ice-core records in Greenland, they developed a record of explosive volcanism over the past 110,000 years with the largest and most abundant volcanic signals found during and following the last deglaciation (17,000-6000 yrs ago). A second period of enhanced volcanism was identified by Zielinski et al 35,000-22,000 years ago, leading up to and during the last glacial maximum. These results support a possible climate-forcing component in volcanism and suggest that increased volcanism often occurs during stadial/interstadial transitions within the last glaciations.

2.2.3 Glacial – Interglacial Periods

Geologically speaking, the Earth's climate is fluctuating between (1) a Greenhouse Earth, with no ice being present and (2) an Icehouse Earth with continental ice sheets being present. During an Icehouse Earth - which the Earth is currently in - geologists separate between Glacial (ice age) and Interglacial periods, which tend to last less than 1 million years. During Glacial periods the ice is advancing, while it is retreating during Interglacial periods. A period of lower temperatures during an interglacial period is known as a stadial whereas an interstadial is a warm period during a glacial period and not intensive or long enough to be considered an interglacial.

When talking about glaciations and volcanoes, the Toba eruption of ~74,000 years BP (Robock et al, 2009) comes to mind. Zielinski et al (1996b) describe the eruption of the Toba supervolcano on the island of Sumatra in Indonesia as the largest explosive event of at least the past 100,000 years. This eruption is suspected to have created a dense stratospheric dust and aerosol cloud, which might have had climatic effects (Rampino and Self, 1992). Apart from a brief, regional volcanic winter, it perhaps caused several years of hemispheric cooling, defined by Rampino and Self (1992) as a temperature decrease of 3°-5°C. Zielinski et al (1996b) also showed ice core evidence for a 1000-year cool period immediately following the eruption. Robock et al (2009) assume that for this to have happened, the forcing from the volcanic aerosols would have had to last for a long time, feedbacks must have amplified or lengthened the stratospheric forcing. They also mention that a short-term but large reduction in shortwave forcing might have been enough to push the climate system as a 'tipping point' into the stadial. Rampino and Self (1992) on the other hand suggest a feedback mechanism, in which the onset of a climate change was already going on before the eruption and might have even triggered the eruption itself.

Robock et al (2009) investigated additional mechanisms that may have enhanced and extended the forcing and response from such a large supervolcanic eruption. For instance, they calculated the effects of an eruption on stratospheric water vapour and model stratospheric chemistry feedbacks that might delay the conversion of SO_2 into sulphate aerosols and prolong the lifetime and radiative forcing of the stratospheric aerosol cloud. For their calculation, they used several hundred times the injection of Pinatubo in 1991, and none of the runs initiates glaciations. Robock et al's models showed that a Toba-like eruption could not produce a glacial advance, but could certainly produce a decade-long volcanic winter, having serious impacts on ecological systems. This also supports the theory that the Toba eruption may have contributed to a genetic bottleneck of the human species. Another interesting aspect they mention in their paper is an idea of Joshi and Shine (2003) that describes how additional water vapour can slightly counteract the cooling from an eruption. This theory includes warming of the tropical tropopause due to volcanic activity, which results in additional water vapour injected into the lower stratosphere. For eruptions the size of the 1991 Pinatubo eruption, they suggest that the additional water vapour produces a positive radiative forcing of about 0.1 Wm^{-2} which, however, has negligible opposed effects to the cooling.

All in all, volcanic aerosols generally remain in the stratosphere no more than 3 years and the radiative forcing from volcanoes is interannual rather than interdecadal in scale (Robock, 2000). In contrast, large supervolcano-eruptions like Toba ~74,000 years ago (Robock, 2009) can possibly present an exception, as they can change radiation over several decades (Robock, 2000).

2.2.4 Present Climate Change / Recent Global Warming

It needs no further discussion that the Earth has experienced countless climate changes throughout its past. But this fact is often abused in order to defend Global Warming as something natural and unavoidable. However, historic climate fluctuations like The Little Ice Age allow us to separate natural causes of climate change from anthropogenic effects. As Robock (2000) said, "The effects of volcanic eruptions on climate are very significant in analyzing the global warming problem, as the impacts of anthropogenic greenhouse gases and aerosols on climate must be evaluated against a background of continued natural forcing of the climate system from volcanic eruptions, solar variations, and internal random variations from land-atmosphere and ocean-atmosphere interactions." Furthermore, we can also gain a better understanding of how anthropogenic climate change will have impacts on various life-forms by observing past responses to volcanic eruptions. It has to be reminded that the question is no longer whether the climate is changing, but why?

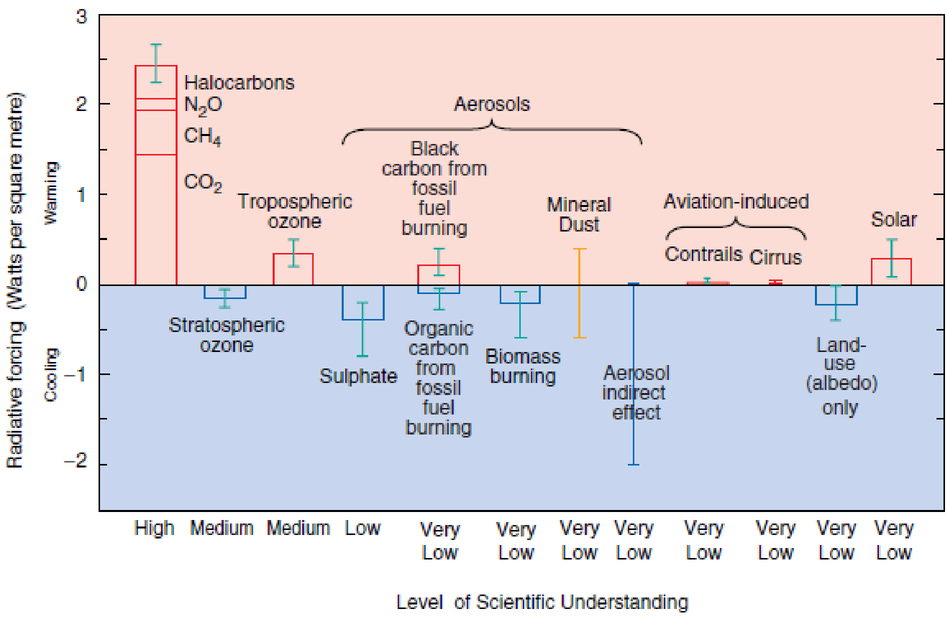

Figure 4: The global mean radiative forcing of the climate system for the year 2000, relative to 1750 (IPCC, 2001)

Figure 4 shows factors that produced warming (red) and cooling (blue) from 1750 to 2000 AD and to what extent this radiative forcing was occurring. Overall, it can be seen that warming-processes predominate. The warming effects of greenhouse gases furthermore overbalance the cooling effects caused by volcanic activity (sulphate; indirect effect of sulphate aerosols).

In order to distinguish between natural and anthropogenic caused climate changes, it is essential to understand the key factors of each. For the latter, CO_2 emissions are the dominant effect, increasing rapidly since the Industrial Era and raising the concentration in the atmosphere over the last 1000 years from 280 to > 367ppm (IPCC, 2001). For volcanic emissions, sulphur is predominating.

Recording to the IPCC report (2001), today's CO_2 concentration has not been exceeded during the past 420,000 years and likely not during the past 20 million years. When talking about long-term climate-driving gases, their residence time in the atmosphere, once emitted, is essential. The report points out that emissions of a greenhouse gas with a long atmospheric life-time is a quasi-irreversible commitment to sustained radiative forcing over decades to millennia, before natural processes can remove them. The authors indicate that this atmospheric residence time is an alarming factor about CO_2, as no single lifetime can be defined. The different rates of uptake by different removal processes let it vary from 5 to 200 years.

For volcanic activity on the other hand, sulphur is decisive in effecting climate. Natural S is basically only brought into the atmosphere by volcanic eruptions. As explained above, these sulphur species – mainly in the form of SO_2, sometimes as H_2S – react with OH and H_2O to form H_2SO_4 on a timescale of weeks (Robock, 2000). The resulting H_2SO_4 aerosols produce the dominant radiative effect from volcanic eruptions that is mainly resulting in surface cooling. At the same time, it causes ozone depletion, which we will get back to later on. Graf et al (1997) show that nowadays' global sulphur emissions of volcanoes to the troposphere are about 14% of the total natural anthropogenic emissions. However, he goes on to say that natural S sources are varying from anthropogenic ones in their source strength, which is smaller. The reasons therefore are different lifetimes due to different production and emission processes. Robock (2000) furthermore points out that volcanic sulphur has a much larger relative contribution to radiative effects, as they are mostly injected in higher altitudes, above the atmospheric layer, and thus have a longer lifetime than anthropogenic aerosols.

Robock (2000) reminds us of the fact that volcanic aerosols do not only change the radiative flux in the stratosphere, but also its chemistry. He goes on to say that the most important chemical changes in the stratosphere are related to O_3, which has significant effects on ultraviolet and longwave radiative fluxes. This ozone depletion, which results in the ozone hole over Antarctica in October each year, only occurs in the extremely cold isolated spring vortex in the Southern Hemisphere. These reactions make anthropogenic chlorine available for chemical O_3 depletion. Robock alerts that sulphate aerosols produced by volcanic eruptions can also provide these surfaces at lower latitudes and at all times of the year. That means the volcanic effect on ozone-chemistry is a new phenomenon, dependent on anthropogenic chlorine in the stratosphere. However, by legal counteraction, chlorine concentration has peaked in the stratosphere and is now decreasing. Robock says that therefore for the next few decades, large volcanic eruptions will have similar effects to Pinatubo, but after that these O_3 effects will go away and volcanic eruptions will have a stronger effect on atmospheric circulation without the negative feedback produced by ozone depletion.

Several studies have shown that unusually warm conditions have predominated since the 1920s. Bradley and Jones (1993) relate this to both a relative absence of major explosive volcanic eruptions and higher levels of greenhouse gases. Free and Robock (1999) showed that the major causes of climate change from 1600 to 1850 were natural, with volcanic eruptions being the most important. The warming trend from then on could not be explained by natural forces and are suspected to be primarily caused by human pollution of the atmosphere (see **Figure 5**).

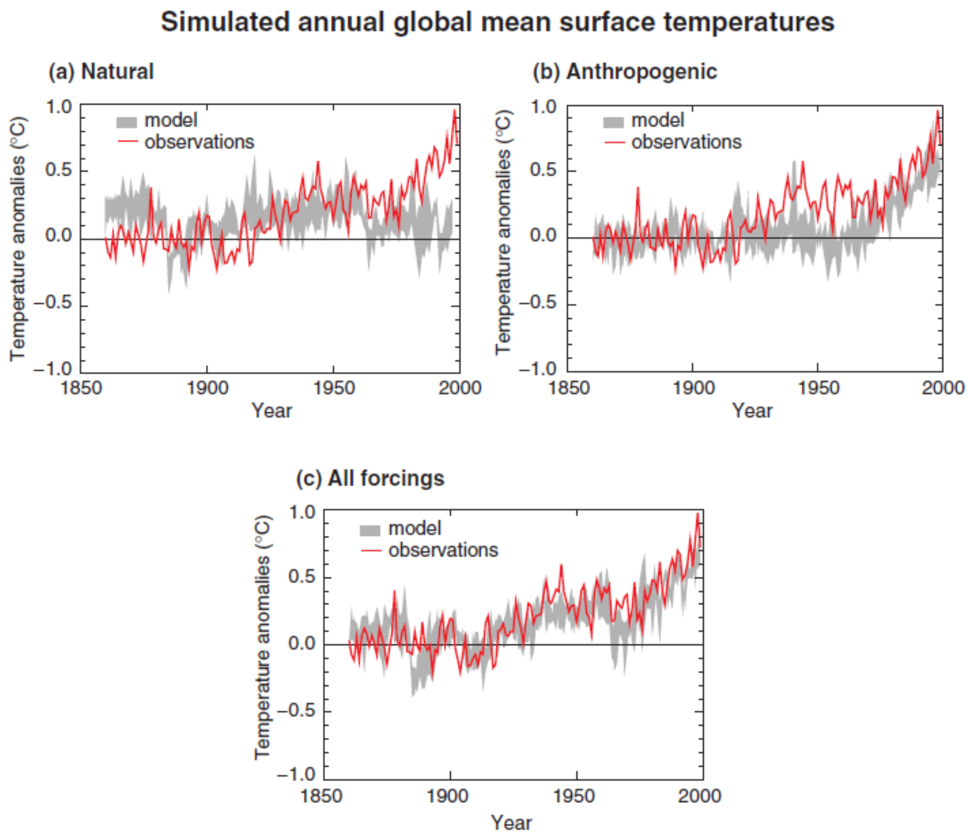

Figure 5: Climate Model to simulate the temperature changes that occur from both natural (solar variation and volcanic activity) and anthropogenic causes (IPCC, 2001)

Figure 5 shows that temperature increase in the last century cannot simply be explained by natural forces like solar variation and volcanic activity (a). Anthropogenic causes (b) show a better analogy, but the best match with observations is obtained when all factors are included (c) (IPCC, 2001). This suggests that most of the warming of the second half of the 20th century was caused by human pollution of the atmosphere (IPCC, 2001; Mann, 2007), but natural forces cannot be excluded either.

All in all, anthropogenic CO_2 is much larger in quantity than volcanic sulphur emissions. Carbon dioxide furthermore increases rapidly in the atmosphere, whereas volcanic eruptions did not get more frequent over the last decades. Sulphate aerosols temporarily counteract the heating caused by carbon dioxide, although in a negligible effect. Also a weakening in the thermohaline circulation is theoretically counteracting the heating. The

IPCC (2001) modelled a weakening of the ocean thermohaline circulation. Although this lead to a reduction of the heat transport into high latitudes of the NH, the IPCC shows that there is still a warming over Europe due to increased greenhouse gases.

Otherwise, quiescent continuous volcanic emissions like fumaroles and small episodic eruptions are not important for climate change. They only add sulphates into the troposphere, where their lifetime is short. Nevertheless, recording to Robock (2000) they could become important if there is a sudden change or they develop to a long-term trend.

3 Discussion

After analyzing past impacts of volcanic activity, we will now briefly discuss possible future events. Most of volcanic caused catastrophes have happened before humans populated the Earth, so it is essential to try to understand impacts of modern and future climate changes on human society.

The same dynamical feedbacks that responded to past volcanic forcing might follow anthropogenic forcing. It is likely that human-caused emissions have already nudged several dynamical processes and a domino effect has started. As discussed above, studies show that volcanic eruptions increase the probability of El Niño events. This raises the question whether rising temperatures due to anthropogenic impacts can do the same and thereby causing even more climate-fluctuations in the Pacific.

Another issue is melting of former ice-covered areas caused by global warming. On the one hand this means ecological changes (e.g. which species/organisms were hidden under the ice and are now released?) and on the other hand might cause higher volcanic activity (will this lead to another cooling like The Little Ice Age or rather cause warming dynamical feedbacks?) The future is always uncertain. But by understanding former processes and observing how past volcanic eruptions influenced life forms we can gain a better understanding of how the Earth's systems will respond to anthropogenic climate change.

When looking at former climate changes, The Little Ice Age already had huge impacts on food supply and health. In addition to these problems, economy in the modern globalized world represents another challenge. Not only global trade and currencies will be affected by climatic changes, but also the struggle for resources will be decisive. Fossil energy sources like oil and gas may get depleted in certain areas but released and detected in other places. Nations which had previously possessed the demanded resources are transformed from being the provider to being the consumer, giving several reasons for fights. Furthermore, rising sea levels and changing temperatures result in loss of fertile soil and habitable land, giving nations even more objects to compete for. This could result in global wars for resources.

Another danger which should not be neglected is the permanent possibility of super-eruptions, which would have higher impacts and set even more limits to resources.

4 Conclusion

Referring to climate-related issues, not the amount of magma put into the atmosphere is essential. Instead, the quantity of sulphur is decisive, which forms sulphate aerosols in the atmosphere. These aerosols have an impact on solar radiation, which causes meteorological changes with surface cooling being the most dominant. However, since volcanic aerosols have a lifetime of maximum three years in the stratosphere these climatic changes are short-termed.

Speaking of long-term climate, the author concludes that volcanic activity is able to trigger dynamical feedback mechanisms which could transform the short-term volcanic forcing into a longer-term effect. Conversely, evidence suggests that variations in climate can cause volcanic eruptions. An example therefore is the back-bouncing of land after ice melting due to stress changes on the Earth's crust. This suggests that increased volcanism often occurs during stadial/interstadial transitions within the last glaciations.

Furthermore, Adams et al (2003) assume an increased probability of El Niño events after volcanic eruptions. This leaves the question how the tropical Pacific ocean-atmosphere system may respond to external radiative forcing and therefore how it will respond to recent anthropogenic changes on climate. When talking about long-term climate, it is important to know whether this system of interannual climate fluctuations itself undergoes changes.

Especially I want to point out that climate changes nowadays don't only change the Earth's system and processes, but have a huge impact on human society. The following decades and centuries might witness a new category of war: The struggle for resources.

For climate-related investigations, the past is the key to the future. Understanding former climate fluctuations allows us to separate natural causes of climate changes from anthropogenic effects. Additionally, we can gain a better understanding of how anthropogenic climate change may impact life in the future.

5 References

Adams, J.B., Mann, M.E., Ammann, C.M. (2003) Proxy evidence for an El Niño-like response to volcanic forcing. *Nature*, Vol 426, 274-278

Bertler, N.A.N., Mayewski, P.A., Carter, L. (2011) Cold conditions in Antarctica during the Little Ice Age — Implications for abrupt climate change mechanisms. *Earth and Planetary Science Letters*, Vol 308, 41-51

Bradley, R.S., Jones, P.D. (1993) 'Little Ice Age' summer temperature variations: their nature and relevance to recent global warming trends. ***The Holocene*, Vol 3*, 367-376***

Bradley, R.S., Hughes, M.K., Diaz, H.F. (2003) Climate Change: Climate in Medieval Time. S*cience*, Vol 302, 404-405

Broecker, W.S. (2000) Was a change in thermohaline circulation responsible for the Little Ice Age? *PNAS*, Vol 97, 1339-1342

Chenoweth, M. (2001) Two major volcanic cooling episodes derived from global marine air temperature. *Geophys. Res. Lett.*, Vol 28, 2963–2966

Crowley, T.J., Kim, K.Y. (1999) Modelling the temperature response to forced climate change over the last six centuries. *Geophysical Research Letters,* Vol 26, 1901-1904

Driscoll, S., Bozzo, A., Gray, L.J., Robock, A., Stenchikov, G. (2012) Coupled Model Intercomparison Project 5 (CMIP5) simulations of climate following volcanic eruptions. Submitted to *J. Geophys. Res*

EPICA Community Members (2006) One-to-one coupling of glacial climate variability in Greenland and Antarctica. *Nature*, Vol 444, 195–198

Forsyth, P.Y. (1988) In the wake of Etna, 44 B.C. *Classical Antiq.*, Vol 7, 49-57

Franklin, B. (1784) Meteorological imaginations and conjectures. *Manchr. Lit. Philos. Soc. Mem. Proc*., Vol 2, 122, (Reprinted in *Weatherwise*, Vol 35, 1982.)

Free, M., Robock, A. (1999) Global warming in the context of the Little Ice Age. *J. Geophys. Res*., Vol 104, 19,057-19,070

Gao, C., Robock, A., Ammann, C. (2008) Volcanic forcing of climate over the past 1500 years: An improved ice core-based index for climate models. *Journal of Geophysical Research*, Vol 113, 1-15

Graf, H.-F., Feichter, J., Langmann, B. (1997) Volcanic sulfur emission: Estimates of source strength and its contribution to the global sulfate distribution. *J. Geophys. Res*., Vol 102, 727-738

Hansen, J., Sato, M., Ruedy, R., Lo, K., Lea, D.W., Medina-Elizade, M. (2006) Global Temperature change. *Pnas*, Vol 103, 14288-14293

Hunt, B. G. (2006) The Medieval Warm Period, the Little Ice Age and simulated climatic variability. *Climate Dynamics,* Vol 27, 677-694

IPCC (2001): Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change [Houghton, J.T.,Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, K. Maskell, and C.A. Johnson (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 881pp.

Kravitz, B., Robock, A. (2011) The climate effects of high latitude volcanic eruptions: The role of the time of year. *J. Geophys. Res.*, Vol 116, 1-16

Lough, J. M., Fritts, H. C. (1987) An assessment of the possible effects of volcanic eruptions on North American climate using tree-ring data, 1602 to 1900 A.D.. *Clim. Change*, Vol 10, 219–239

Mann, M.E. (2002) Little Ice Age. *The Earth system: physical and chemical dimensions of global environmental change*, Vol 1, 504-509; edited by MacCracken and Perry in *Encyclopedia of Global Environmental Change*

Mann, M.E. (2007) Climate over the past two millennia. *Annual Review of Earth and Planetary Sciences*, Vol 35, 111-136

Miller, G.H., Geirsdóttir, A., Zhong, Y., (...), Thordarson, T. (2012) Abrupt onset of the Little Ice Age triggered by volcanism and sustained by sea-ice/ocean feedbacks. *Geophysical Research Letters*, Vol 39, 1-5

Newhall, C. G., Self, S. (1982) The volcanic explosivity index (VEI): An estimate of explosive magnitude for historical volcanism. *J. Geophys. Res.,* Vol 87, 1231-1238

NOAA (1994-1995) Climate Monitoring and Diagnostics Laboratory, Annual Report 23, Chapter 3.2

Olson, D.W., Doescher, R.L., Olson, M.S. (2004) When the sky ran red: The story behind The Scream, *Sky Telescope*, Vol 107, 29-35

Oppenheimer, C. (2003) Climatic, environmental and human consequences of the largest known historic eruption: Tambora volcano (Indonesia) 1815. *Progress in Physical Geography*, Vol 27, 230-259

Rampino, M.R., Self, S., Fairbridge, R.W. (1979) Can Rapid Climatic Change Cause Volcanic Eruptions? *Science*, Vol 206, 826-829

Rampino, M.R., Self, S. (1982) Historic eruptions of Tambora (1815), Krakatau (1883), and Agung (1963), their stratospheric aerosols, and climatic impact. *Quaternary research*, Vol 18, 127-143

Rampino, M.R., Self, S. (1984) Sulphur-rich volcanic eruptions and stratospheric aerosols. *Nature*, Vol 310, 677-679

Rampino, M.R., Self, S. (1992) Volcanic winter and accelerated glaciations following the Toba super-eruption. *Nature*, Vol 359, 50-52

Robock, A. (1981) The Mount St. Helens volcanic eruption of 18 May 1980: Minimal climatic effect. *Science*, Vol 212, 1383-1384

Robock, A., Mao, J. (1995) The volcanic signal in surface temperature observations. *J. Clim.*, Vol 8, 1086-1103

Robock, A., Free, M.P (1996) The volcanic record in ice cores for the past 2000 years. *Climatic Variations and Forcing Mechanisms of the Last 2000 Years*, edited by P. D. Jones, R. S. Bradley, and J. Jouzel, 533-546

Robock, A. (2000) Volcanic Eruptions and Climate. *Reviews of Geophysics*, Vol 38, 191–219

Robock, A. (2004) Climatic impact of volcanic emissions. The *State of the Planet: Frontiers and Challenges in Geophysics,* Vol 150, 125-134

Robock, A., Ammann, C.M., Oman, L., Shindell, D., Levis, S., Stenchikov, G. (2009) Did the Toba volcanic eruption of ~74 ka B.P. produce widespread glaciation? *J. Geophys. Res.*, Vol 114

Shelley, M. (1818) Frankenstein. *Bantam Books, New York*. (Classic edition, 209 pp., Bantam Books, New York, 1981)

Simarski, L.T. (1992) Volcanism and climate change. Special report, 27 pages

Solomon, S., Portmann, R.W., Garcia, R.R., (...), McCormick, M.P. (1996) The role of aerosol variations in anthropogenic ozone depletion at northern midlatitudes. *J. Geophys. Res*., Vol 101, 6713–6727

Solomon, S., (1999) Stratospheric ozone depletion: A review of concepts and history. *Rev. Geophys*., Vol 37, 275–316

Symons, G.J. (Ed.) (1888) The Eruption of Krakatoa, and Subsequent Phenomena, 494 pages, Trübner, London

Wilson, C.J.N., Ambraseys, N.N., Bradley, J., Walker, G.P.L. (1980) A new date for the Taupo eruption, New Zealand. *Nature*, Vol 288, 252-253

Zielinski, G.A., Mayewski, P.A., Meeker, L.D., Whitlow, S., Twickler, M.S. (1996a) A 110,000-Yr Record of Explosive Volcanism from the GISP2 (Greenland) Ice Core. *Quaternary Research*, Vol 45, 109–118

Zielinski, G. A., P. A. Mayewski, L. D. Meeker, S. Whitlow, M. S. Twickler, and K. Taylor (1996b) Potential atmospheric impact of the Toba Mega-Eruption ∼71,000 years ago. *Geophys. Res. Lett.*, Vol 23, 837–840