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Volcanism, the atmosphere and climate through time

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13.1 Introduction

Volcanism can affect the environment on timescales of weather (days to weeks) and climate (months to years). In the past 250 years, the atmospheric and climatic effects of several volcanic eruptions have been witnessed and documented by scientist and non-scientist alike. For example, the 1783–1784 Laki eruption in Iceland, which was followed by hot summer temperatures and cold winter temperatures in central Europe (Thordarson and Self, 2003; Oman *et al.*, 2006a; Schmidt *et al.*, 2012b), was described in great detail by an Icelandic priest (Steingrímsson, 1788). The 1815 Tambora eruption in Indonesia caused the 'Year Without a Summer' in 1816, which inspired Mary Shelley's *Frankenstein*.

The scientific understanding of the climatic effects caused by short-lived explosive volcanic eruptions has advanced greatly in the past five decades, mainly due to theoretical work and observations following the eruptions of Agung in 1963, Mount St Helens in 1980, El Chichón in 1982 and, in particular, Mount Pinatubo in 1991 (for reviews see Robock, 2000; Timmreck, 2012).

In the past two decades, the climate relevance of effusive volcanic activity injecting gases mainly into the troposphere has become more recognized (e.g. Graf *et al.*, 1997; Schmidt *et al.*, 2012a), and also the atmospheric and climatic effects of small- to moderate-sized explosive eruptions (e.g. Solomon *et al.*, 2011; Neely *et al.*, 2013). However, we are only beginning to understand how large-volume flood basalt eruptions such as the Deccan Traps in India at around 65 Ma may have affected the environment.

This chapter provides an overview of the impact of various eruption types and styles on Earth's atmosphere and climate through time.

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13.2 Volcanism on Earth

The size of a volcanic eruption can be expressed in terms of the volume (km^3) or mass (kg) of magma produced. The Volcanic Explosivity Index (VEI) uses volcanological data such as eruption column height and ejecta volume to measure the relative magnitude of an eruption's explosivity using an open-ended logarithmic scale (except for VEI between 0 and 2) (Newhall and Self, 1982). The fragmentation of volatile-rich magma during explosive volcanic eruptions produces large quantities of volcanic tephra, and generally the likelihood that ejecta reach stratospheric altitudes increases with increasing VEI. There are, however, examples of VEI 5 eruptions, such as the 1980 Mount St Helens eruption, which injected little sulfur into the stratosphere, and thus had no impact on climate (Robock, 1981).

One of the largest eruptions in the twentieth century, the 1991 Mount Pinatubo eruption, had a VEI of 6 and produced a bulk magma volume of about 10 km^3. For context, the 1815 Tambora eruption (VEI 7) had a bulk volume > 100 km^3. The 1783–1784 Laki eruption in Iceland greatly exceeded twentieth-century lava volumes, yielding about 15 km^3 of extrusives in eight months (Thordarson and Self, 2003).

Past episodes of continental flood basalt (CFB) volcanism produced huge lava volumes on the order of tens of millions of cubic kilometres. Examples include the emplacement of the Deccan Traps, 65 Ma (Late Cretaceous; $> 10^6$ km^3); or the Columbia River Basalt Group (Western United States), 17–10 Ma (Middle Miocene; $\sim$ 210,000 km^3), including the Roza flow, 14.7 Ma ($\sim$ 1,300 km^3). As also discussed in Chapters 5 and 11, CFB volcanism is typified by numerous, recurring large-volume eruptive phases, each lasting decades or longer. On geological timescales, the climactic pulses that build up an entire CFB province are short-lived – typically about 1 Ma or less. For the assessment of the environmental perturbations it is, however, important to recognize the pulsed nature of CFB volcanism, with the duration of non-eruptive phases (usually centuries to millennia) outlasting the duration of individual eruptive phases (years to decades). An individual decade-long eruptive phase would have yielded between 10^3 and 10^4 km^3 of extrusives building up pāhoehoe-dominated lava flow fields (see Chapter 11 for details; Self *et al.*, 2006; 2008). Despite emplacing huge magma volumes, individual eruptions would rarely have exceeded a VEI of 4 and, typically, volcanic gases would have been injected into the upper troposphere and lower stratosphere (see Chapter 11). There is, however, evidence that some CFB provinces were associated with more violent silicic eruptions (e.g. Bryan and Ferrari, 2013; see also Chapter 1].

13.3 Volcanic gas emissions

Water vapour (H_2O) and carbon dioxide (CO_2) are the most abundant volatile species released during a volcanic eruption, but in the short term their effect on atmospheric composition is negligible because of the insignificant relative contribution to the high atmospheric background concentrations of H_2O and CO_2. However, on the timescale of the age of Earth, volcanic 'outgassing' has been the source of our current atmosphere (see also Chapter 14).

Compared to 35,000 Teragrams (Tg) of anthropogenic CO_2 emissions per year, estimates of the CO_2 flux from present-day subaerial and submarine volcanism range between 130 and 440 Tg (Gerlach, 2011, and references therein). Self *et al*. (2008) estimated that the Deccan Traps released up to 14 Tg of CO_2 per km^3 of lava erupted (assuming a degassing efficiency of 80%). For a typical decade-long CFB eruptive phase producing a total lava volume of 1,000 km^3 this equates to 1400 Tg of CO_2 per year, which is one order of magnitude smaller than the current anthropogenic flux.

Volcanic eruptions also release halogen species (mainly bromine oxide, hydrogen chloride, hydrogen bromide and hydrogen fluoride), which play an important role in volcanic plume chemistry (von Glasow, 2010). Over the industrial era, anthropogenic chlorofluorocarbon (CFC) emissions have resulted in high stratospheric chlorine and bromine concentrations. These halogens destroy stratospheric O_3 efficiently, leading to phenomena such as the Antarctic 'ozone hole'. Stratospheric O_3 depletion was also observed after the eruptions of El Chichón in 1982 and Mount Pinatubo in 1991 because volcanic aerosol particles serve as surfaces for heterogeneous reactions promoting conversion of less reactive (anthropogenic) chlorine/bromine species into more reactive forms (Solomon *et al*., 1998; Solomon, 1999 for a review). Therefore, in general, the chemical impact of volcanic eruptions is to exacerbate anthropogenic-driven O_3 destruction. Anthropogenic chlorine concentrations are steadily declining; hence, future eruptions will not deplete stratospheric O_3 except if an eruption itself injects sufficient chlorine (in the form of hydrochloric acid) into the stratosphere; this is a matter of debate (e.g. Tabazadeh and Turco, 1993; Kutterolf *et al*., 2013; see also Chapter 16). Chapter 20 discusses how halogen-bearing species emitted by flood basalt eruptions could have resulted in global-scale O_3 depletion during the end-Permian (252 Ma) emplacement of the Siberian Trap province.

To date, sulfur dioxide (SO_2) is the sole volcanic volatile species that has been observed to alter the radiative balance of the atmosphere, because of its conversion to volcanic sulfuric acid aerosol. Sulfur species contribute between 2% and 35% by volume of the gas phase, and SO_2 and hydrogen sulfide (H_2S) are most abundant. In the troposphere, H_2S rapidly oxidizes to SO_2, which commonly has a chemical

lifetime of hours to days. If released into the stratosphere, the lifetime of SO_2 increases to about 3 weeks due to slower removal processes than in the troposphere. SO_2 is removed from the atmosphere via dry and wet deposition ('acid rain/snow') or oxidization to form sulfuric acid aerosol. Gas-phase oxidation of SO_2 by the hydroxyl radical ($OH\cdot$) forms sulfuric acid (H_2SO_4) vapour, which is a low volatility compound that forms new particles ('nucleation') and/or rapidly condenses to grow existing particles to larger sizes. Within clouds, SO_2 undergoes aqueous-phase oxidation via reactions with dissolved hydrogen peroxide (H_2O_2) or ozone (O_3). Volcanic sulfuric acid particles are typically composed of 75% by weight of H_2SO_4 and 25% by weight of H_2O (Bekki, 1995).

There has not been a large stratospheric injection of volcanic SO_2 since the 1991 Mount Pinatubo eruption, which released about 20 Tg of SO_2 into the stratosphere. For comparison, the current anthropogenic SO_2 flux is about 116 Tg per year. The 1982 El Chichón eruption injected ~ 7 Tg of SO_2 into the stratosphere. Between the years 2000 and 2012 there has been a series of small- to moderate-sized eruptions (VEI 3–4) injecting at the most ~ 1.3 Tg of SO_2 during an individual eruption (Nabro, 2011, in Eritrea). In comparison, individual decade-long CFB eruptive phases would have released up to 5,000 Tg of SO_2 (Self *et al.*, 2008). The Roza flow, the best-studied CFB eruptive phase, released about 1,200 Tg of SO_2 per year for a decade or longer into altitudes between 7 and 13 km (Thordarson and Self, 1996). For context, Laki was one of the largest historic flood basalt events and injected about 120 Tg of SO_2 in 8 months (Thordarson and Self, 2003, and references therein).

The annual sulfur flux from continuously degassing and sporadically erupting volcanoes is about 13 Tg, based on measurements at 49 volcanoes 'only' (Andres and Kasgnoc, 1998). The uncertainties on this estimate are large (about $\pm$ 50%); hence, there is also a large uncertainty on the magnitude of the radiative effects induced by these emissions (Graf *et al.*, 1997; Schmidt *et al.*, 2012a). With the advent of the satellite era, more numerous measurements of the volcanic sulfur flux have become available (e.g. Carn *et al.*, 2013) but the picture is still far from complete.

13.4 Atmospheric and climatic impacts of volcanic aerosol

Figure 13.1 illustrates how volcanic gases and particles affect atmospheric composition, chemistry and Earth's climate. Tephra is a major constituent of a volcanic cloud associated with explosive eruptions. Airborne tephra particles rapidly fall out of the atmosphere within minutes to days, hence their climatic effects are mostly negligible (Robock, 1981; Niemeier *et al.*, 2009). Continent-sized ash deposits produced by super-eruptions (VEI $\geq$ 8), however, may induce short-term climate

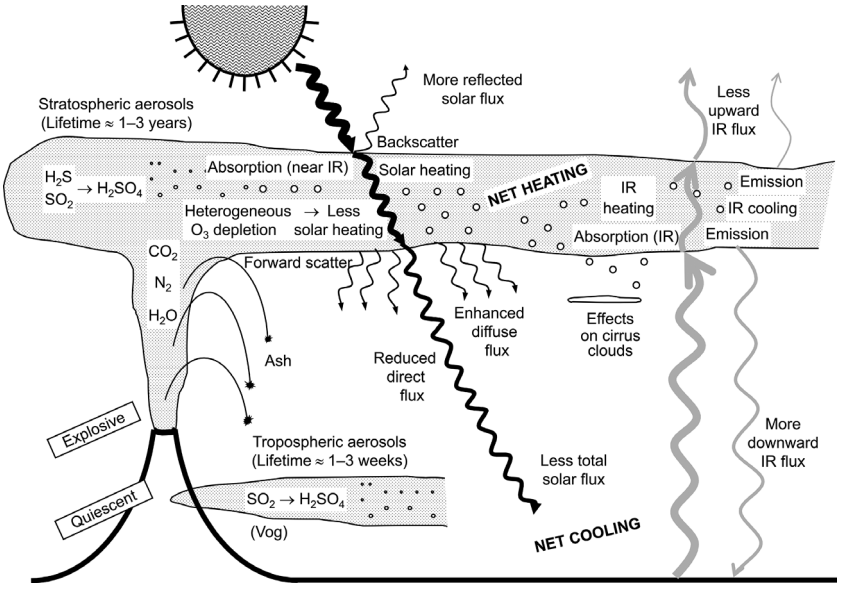

Figure 13.1. Schematic diagram showing the effect of volcanic gases and particles on the atmospheric composition and Earth's climate. Adapted from Plate 1 of Robock (2000).

change (Jones *et al*., 2007), and Chapter 17 discusses the environmental impacts associated with ash deposition.

In contrast to airborne volcanic tephra, volcanic sulfuric acid aerosol particles can alter the radiative balance of Earth on timescales relevant for climate change due to their ability to scatter and absorb solar radiation (aerosol direct effect). Sulfuric acid aerosol scatters radiation across the entire solar spectrum due to its optical properties and typical particle radius of 0.5 μm (although there is a small degree of absorption in the near-infrared spectrum). Once in the stratosphere, volcanic sulfuric acid aerosol has a typical e-folding time of 9–12 months for tropical eruptions and 2–4 months for high-latitude eruptions (Kravitz and Robock, 2011). The top of a stratospheric aerosol cloud absorbs solar radiation in the near-infrared, whereas the lower stratosphere is heated by absorption of upward thermal infrared radiation (Stenchikov *et al*., 1998). An aerosol cloud also forward scatters some of the incoming solar radiation, resulting in enhanced downward diffuse radiation, thereby increasing the sky's brightness. The net radiative effect of explosive volcanic eruptions is, however, a reduction in surface temperatures because the scattering exceeds the absorption efficiency.

In the case of the 1991 eruption of Mount Pinatubo, stratospheric aerosol concentrations remained elevated for about 2 years, and globally averaged stratospheric temperatures increased by around 2–3 K 3 months after the eruption

(Labitzke and McCormick, 1992). About 18 months following the June 1991 Mount Pinatubo eruption, the peak reduction in globally averaged lower-tropospheric temperatures reached 0.5 K, with climate models predicting a cooling of the same magnitude when including water-vapour feedbacks and removing the El Niño–Southern Oscillation signal (Soden *et al.*, 2002, and references therein).

Kirchner *et al.* (1999) showed that the aerosol formed after tropical eruptions results in an enhanced pole-to-equator heating gradient in the lower stratosphere that creates a stronger polar vortex and associated positive mode of the Arctic Oscillation in tropospheric circulation. This results in a warming over northern America, northern Europe and Russia, and a cooling over the Middle East, during the first winter, and sometimes the second winter, following a tropical eruption (Robock and Mao, 1992; Graf *et al.*, 1993). This indirect advective effect on temperature is stronger than the direct radiative effect that dominates at lower latitudes and during summer. Figure 13.2 highlights that while observations confirm this 'winter warming' response the majority of current climate models fail to reproduce the magnitude of this effect (Driscoll *et al.*, 2012).

Research on tropical and high-latitude eruptions revealed that feedbacks between the additional aerosol loading and atmospheric dynamics can weaken the Asian and African summer monsoon systems (Oman *et al.*, 2006b). For high-latitude eruptions in particular, the season of eruption is important for assessing the magnitude of the climatic response (Schmidt *et al.*, 2010; Kravitz and Robock, 2011). Trenberth and Dai (2007) showed that after the 1991 Mount Pinatubo eruption precipitation over land and continental freshwater discharge decreased significantly between October 1991 and September 1992. Following Robock and Liu (1994), Haywood *et al.* (2013) showed that the asymmetric aerosol loading between the northern and southern hemispheres after eruptions can influence the sea surface temperature gradient in the Atlantic, which in turn affects Sahelian precipitation rates (three of the four driest Sahelian summers between 1900 to 2010 were preceded by an eruption in the northern hemisphere).

Figure 13.1 also shows that aside from the aerosol direct effect, aerosol particles can also alter cloud amount and albedo by acting as cloud condensation nuclei or ice nuclei, thus modifying the optical properties and lifetime of clouds ('aerosol indirect effects'). Whether volcanic particles alter cirrus cloud properties has been the subject of several studies with contradicting results (e.g. Sassen, 1992; Luo *et al.*, 2002; see Robock *et al.*, 2013 for a review). In contrast, the ability of volcanic sulfates to act as cloud condensation nuclei and their indirect effect on low-level warm clouds has been confirmed by means of measurements

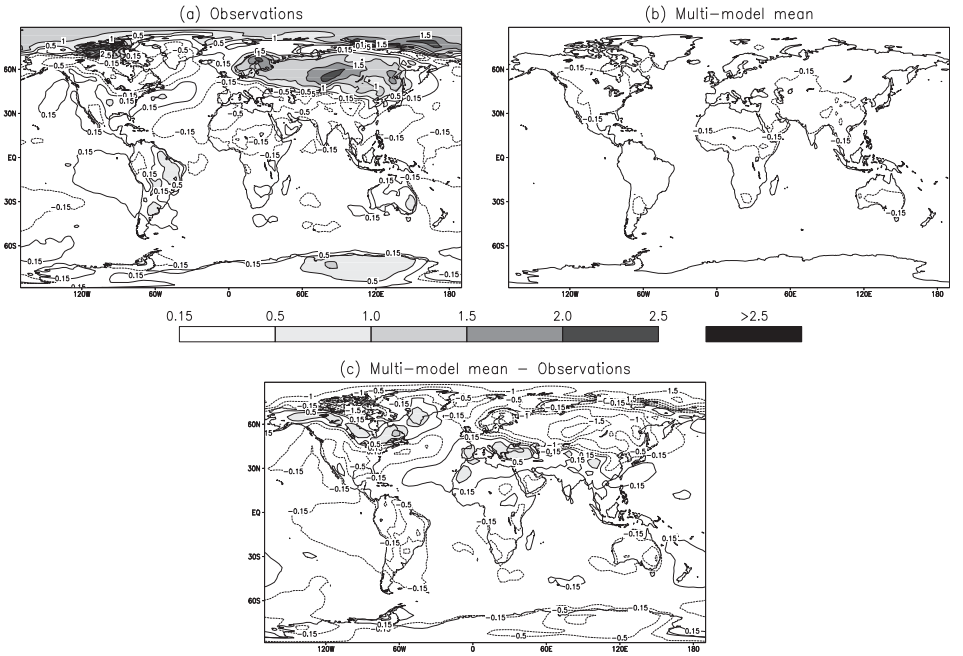

Figure 13.2 Comparison of the surface temperature changes (in K) as observed (a) and simulated by current climate models (b) averaged for two winter seasons after a major eruption in the tropics. The difference between modelled and observed surface temperature changes is shown in (c) with dashed contours (blue colours in colour version) indicating that modelled temperatures are too cold and grey-shaded contours (yellow colours in colour version) indicating that modelled temperatures are too warm compared to the observations. Figures reproduced based on data analysed and presented in Driscoll *et al*. (2012). A black and white version of this figure will appear in some formats. For the colour version, please refer to the plate section.

(e.g. Mather *et al*., 2003), satellite retrievals (e.g. Gassó, 2008), and modelling (e.g. Graf *et al*., 1997; Schmidt *et al*., 2010, 2012a).

13.5 Volcano-climate interactions through time

Rampino and Self (1982) noted that eruption size does not correlate with the magnitude of the climatic effect. Pinto *et al*. (1989) used a one-dimensional microphysics model to demonstrate that the volcanic impact on climate becomes self-limited with increasing SO_2 release because microphysical processes such as coagulation cause particles to grow to large sizes, which have a lower optical depth per unit mass and fall out of the stratosphere faster. Timmreck *et al*. (2010) and English *et al*. (2013) simulated an eruption thought to be representative of the Youngest Toba Tuff eruption (74 ka) using three-dimensional microphysics

models. These model simulations suggested a global mean temperature response about three times weaker (change of about –3.5 K) than previously estimated using climate models that did not consider microphysical processes. Pinto *et al*. (1989) and Bekki (1995) noted that oxidant depletion of OH· could prolong the climate response producing sulfuric acid aerosol more slowly and increasing the lifetime of SO_2, but Robock *et al*. (2009) suggested that this would be a small effect.

A reasonable rule of thumb might be that a minimum amount of 5 Tg of SO_2 injected into the stratosphere is likely to significantly alter Earth's radiative balance on timescales of months to years; however, there are complicating factors such as the season and latitude of an eruption as well as what temperature change we consider significant. In any case, simply extrapolating the magnitude of the climatic effects of present-day explosive volcanism to, for example, CFB volcanism is bound to be flawed due to the non-linear relationship between eruption magnitude and climatic effect, as well as the differences in eruption style.

13.5.1 Ancient large-scale CFB eruptions

Five Phanerozoic periods of CFB volcanism in particular have been the subject of a long-standing debate about their association with major environmental changes as evident from the proxy record of, for example, the abundances and diversity of planktonic foraminifera. However, the mechanisms by which CFB volcanism may have triggered these environmental changes remain enigmatic (for reviews see Officer *et al*., 1987 and Wignall, 2001; see also Chapter 11).

Most studies on CFB volcanism suggested, by analogy to present-day volcanism, a short-term cooling effect (lasting years to decades) from SO_2 and the formation of sulfuric acid aerosol; together with a long-term warming effect (lasting tens to thousands of years) from the seemingly 'high' volcanic CO_2 emissions. However, the annual volcanic CO_2 flux during an eruptive phase equates to about 4% of the current annual anthropogenic flux (Section 13.3). To date, there has been only one carbon-cycle modelling study, and it found a negligible effect of volcanic CO_2 emissions from the Deccan Traps on Late Cretaceous temperatures (Caldeira and Rampino, 1990). Whether volcanic CO_2 affected long-term weathering rates and/or ocean acidity could be addressed in future using carbon-cycle models. Alternative explanations for the long-term warming trend observed at the time of, for example, the Siberian Traps revolve around the dissociation of gas hydrates (see also Chapters 10, 12 and 20). Release of isotopically light carbon from gas hydrates may explain the negative

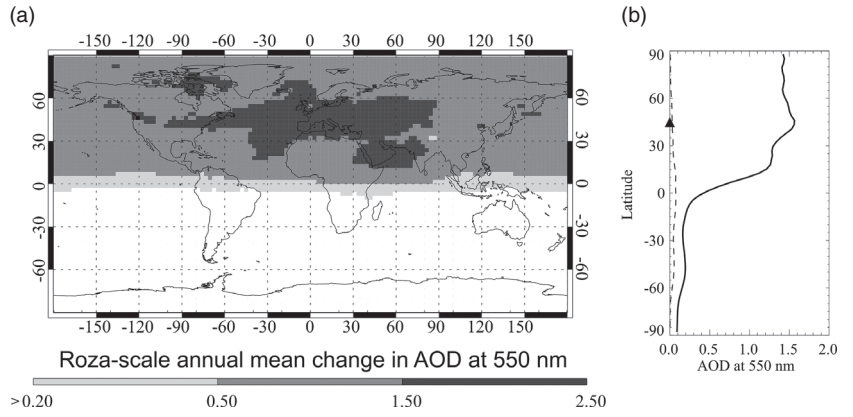

Figure 13.3 Aerosol–climate model simulation of a decade-long Roza-scale eruption (releasing 1200 Tg of SO_2 per year) with (a) showing the annual mean change in aerosol optical depth (AOD) at 550 nm for the tenth year of the eruption with respect to a pre-industrial control simulation, and (b) showing the latitudinal mean AOD for a pre-industrial control simulation (dashed) and the volcanically perturbed simulation (solid). The latitude of the eruption is indicated by the black triangle.

carbon isotope excursions at the end-Permian, rather than these excursions being due to the release of volcanic carbon (Wignall, 2001, and references therein).

For the 14.7 Ma decade-long Roza flow, Thordarson and Self (1996) estimated a change in aerosol optical depth (AOD) at 550 nm of between 7 and 13, which is at least 2.5 times larger than that for Toba (peak AOD of 2.6; *English et al.*, 2013). However, Thordarson and Self (1996) assumed that all SO_2 released is converted to sulfuric acid aerosol of a certain size. Accounting for oxidant availability and microphysical processes in a global model simulation of a Roza-scale eruption, A. Schmidt (unpublished data) found an annual mean AOD change of 1.2 when averaged over the northern hemisphere (Figure 13.3), which is significantly lower than previously estimated but nonetheless would have resulted in a substantial perturbation of climate if maintained for a decade. Since the climatic perturbations are relatively short-lived on geological timescales, A. Schmidt (unpublished data) suggested that better constraints on the frequency and duration of individual eruptions as well as non-eruptive phases are needed to fully quantify the magnitude and duration of the climatic and environmental effects (see also Chapter 11).

13.5.2 Post-2000 small- to moderate-sized eruptions (VEI 3–4)

The rate of global warming slowed between the years 2005 and 2012. Among other contributing factors, VEI 3–4 volcanic eruptions during that period contributed a

small negative radiative forcing by increasing stratospheric aerosol concentrations (Solomon *et al*., 2011; Vernier *et al*., 2011; Neely *et al*., 2013). Fyfe *et al*. (2013) estimated a global surface temperature response of at least –0.07°C.

The June 2011 eruption of Nabro (VEI 3–4) injected about 1.3 Tg of SO_2 into the upper troposphere (9–14 km), where seemingly the climate impacts would have been more muted than for an injection into the stratosphere. Bourassa *et al*. (2012), however, suggested that deep convection and interaction with the Asian summer monsoon lofted Nabro's SO_2 into the stratosphere, hence prolonging the aerosol radiative forcing.

These recent findings highlight the necessity for detailed observations of small-magnitude eruptions (VEI of 3 to 4) to allow for a better understanding of present-day climate change. Such findings might also change our view of what eruption magnitude and mass of SO_2 released into the atmosphere we need to consider relevant for climate change on decadal timescales, and also provide information of relevance for stratospheric geoengineering proposals with sulfuric acid aerosol.

13.6 Summary

Observations have confirmed that volcanic eruptions can have numerous impacts on our environment, mainly via the sulfuric acid aerosol direct effects, resulting in a reduction of surface temperatures, and changes in water-vapour concentrations and stratospheric heating rates. The latter results in pole-to-equator gradients that induce an indirect advective effect on surface temperatures referred to as winter warming. Transient and asymmetric volcanic aerosol forcings have been shown to weaken the Asian and African summer monsoons and to cause precipitation deficits in the Sahel. There is no observational evidence that eruptions force certain circulation modes such as El Niño but the issue remains a matter of debate. There is increasing evidence for an aerosol indirect effect on liquid water clouds induced by volcanic sulfuric acid particles but whether, and to what extent, explosive volcanic eruptions affect ice clouds remains debated.

Future eruptions will present an opportunity to test our current understanding and fill gaps in our ability to monitor volcanic clouds and to obtain detailed measurements. Climate models and observations have greatly enhanced our understanding of the climatic impacts of eruptions. However, we have not yet obtained sufficient observations of, for example, the temporal evolution of the aerosol size distribution in both the stratosphere and troposphere for different eruption sizes, which will be an acid test for climate and aerosol models.

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