Climatic Impacts of Volcanic Eruptions

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Chapter Outline

GLOSSARY

aerosol Any suspended particle in the atmosphere. An aerosol can be a liquid droplet, such as sulfuric acid, or a solid, such as ash or tephra.

Arctic Oscillation A strengthening or weakening of the polar vortex in the Northern Hemisphere, the main pattern of oscillation of winter variation of extratropical atmospheric circulation. For a positive mode, with a strong vortex, winter temperatures are above normal over Northern Hemisphere continents.

El Niño A periodic warming of the tropical Pacific Ocean that increases global average temperature and produces patterns of positive and negative regional temperature and precipitation variations.

geoengineering Ideas for deliberate, large-scale manipulation of the environment to counteract global warming. The technology does not currently exist, but suggestions include producing a permanent stratospheric aerosol cloud in the stratosphere.

lidar Light detection and ranging. Sending a pulse of laser light into the atmosphere and measuring the reflection from aerosols. The timing of the reflected pulse tells the distance, and the strength of the reflection gives the amount. Using multiple wavelengths can give information about the size distribution of the aerosols.

nuclear winter The climate response to nuclear war. Smoke from targeted cities and industrial areas would rise into the stratosphere, block sunlight, and cool the surface. A nuclear war between the United States and Russia could produce temperatures below freezing in the summer over land, killing all crops and sentencing most people on the Earth to starvation.

ozone depletion Destruction of stratospheric ozone from reactions with anthropogenic chlorine. Aerosols in the stratosphere serve as surfaces for heterogeneous reactions, enhancing ozone depletion.

troposphere The lowest layer of the atmosphere from the surface up to 8 km at the poles and 18 km in the tropics. Weather takes place in the troposphere, including clouds and precipitation. The troposphere is well mixed, and the average lifetime of aerosols is about 1 week.

stratosphere The second layer in the atmosphere from the boundary with the troposphere (the tropopause) up to about 50 km. The stratosphere has little vertical motion and no precipitation, so the average lifetime of volcanic sulfate aerosols is 1−2 years.

1. INTRODUCTION

Explosive volcanic eruptions affect climate by injecting gases and **aerosol** particles into the **stratosphere**. In most cases, the eruption directly injects SO_2 into the stratosphere, but for the 2011 Nabro eruption, the largest since Mt Pinatubo in 1991, the eruption put most of the sulfur into the upper **troposphere**, and the summer Asian monsoon pumped the sulfur into the stratosphere over the next couple months. Only if the eruption cloud is rich in SO_2, will the eruption produce a long-lived aerosol cloud of sulfate aerosols that form over the next few weeks. Otherwise, explosive eruptions that only produce large ash particles, such as the 1980 Mount St Helens eruption, can produce a large local weather perturbation but do not have long-lasting climatic effects. Some volcanoes, such as Kilauea and Etna, produce large tropospheric emissions of sulfate aerosols, and only if there is a dramatic change in these emissions, will climate be changed. Stratospheric aerosol clouds last for several years, reflecting sunlight and cooling the surface. These clouds also absorb both solar (near infrared) and terrestrial radiation, heating the lower stratosphere. Volcanic aerosols also serve as surfaces for heterogeneous chemical reactions that destroy stratospheric ozone, which lowers ultraviolet (UV)

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TABLE 53.1 Major Volcanic Eruptions of the Past 250 Years. Volcanic Explosivity Index (VEI; Newhall and Self, 1982) Data are from the Smithsonian Global Volcanism Program, http://www.volcano.si.edu/world/largeeruptions.cfm. Stratospheric Loading is from Gao et al. (2008) and Sato et al. (1993), Updated at (http://data.giss.nasa.gov/modelforce/strataer/). The VEI is a Logarithmic Measure of the Explosivity and not of the Potential to Cause Climate Change

Volcano	Year of Eruption	VEI	Global Stratospheric Sulfate Loading (Tg)
Laki (or Lakagigar), Iceland	1783–1784	4+	93[1]
Unidentified	1809	6?	54
Tambora, Sumbawa, Indonesia	1815	7	110
Cosiguina, Nicaragua	1835	5	40
Krakatau, Indonesia	1883	6	22
Okataina (Tarawera), North Island, New Zealand	1886	5	2
Santa María, Guatemala	1902	6?	4
Novarupta (Katmai), Alaska, the United States	1912	6	11[1]
Gunung Agung, Bali, Indonesia	1963	5	17
Mount St Helens, Washington, the United States	1980	5	0
El Chichón, Chiapas, Mexico	1982	5	14
Mt Pinatubo, Luzon, Philippines	1991	6	30
Cerro Hudson, Chile	1991	5+	?

[1] *Northern Hemisphere only.*

absorption and reduces the radiative heating in the lower stratosphere, but the net effect is still heating. This also allows more UV radiation to reach the surface. As this chemical effect depends on the presence of anthropogenic chlorine, it has only become important in recent decades. Tropical eruptions produce asymmetric stratospheric heating, producing a stronger polar vortex and associated positive mode of the **Arctic Oscillation** in tropospheric circulation. This pattern is one of enhanced warm advection over Northern Hemisphere (NH) continents in winter, producing winter warming after large tropical eruptions. Although observations and some climate models show this response, many modern climate models still do a poor job of simulating this dynamic response to tropical volcanic eruptions. There is no evidence that volcanic eruptions can produce **El Niños**, but El Niño/Southern Oscillation variations must be considered when searching the climatic record for volcanic signals, as they have similar amplitudes and timescales.

There have been several large volcanic eruptions in the past 250 years (Table 53.1), and each has drawn attention to the atmospheric and potential climatic effects. The 1783 Laki eruption in Iceland was followed by a very warm summer and then a very cold winter in Europe, causing Benjamin Franklin, the U.S. Ambassador to France, to publish the first paper on the subject in more than 1800 years. The 1815 Tambora eruption, combined with the effects of the unidentified 1809 eruption, produced the "Year Without a Summer" in 1816 and inspired *Frankenstein*, written by Mary Shelley on the shores of Lake Geneva, Switzerland, that summer. The 1883 Krakatau eruption was the largest explosion ever heard, and the sound wave was tracked on microbarographs for four complete circuits of the Earth, taking 33 h for one circuit. The Royal Society (UK) report on this eruption published 5 years later (which misspelled the volcano name as Krakatoa) remains the most extensive report on the atmospheric effects of a volcanic eruption (Symons, 1888). The observations of the westward propagation of the resultant volcanic cloud were a hint at strong easterlies in the stratosphere, an atmospheric layer yet to be discovered. The 1963 Agung eruption produced the largest stratospheric aerosol cloud in more than 50 years and inspired many modern scientific studies. The subsequent 1982 El Chichón and 1991 Mt Pinatubo eruptions produced very large stratospheric aerosol clouds and large climatic effects.

2. VOLCANIC EMISSIONS

Quantification of the size of volcanic eruptions is difficult, as different measures reveal different information. For example, one could examine the total mass ejected, the

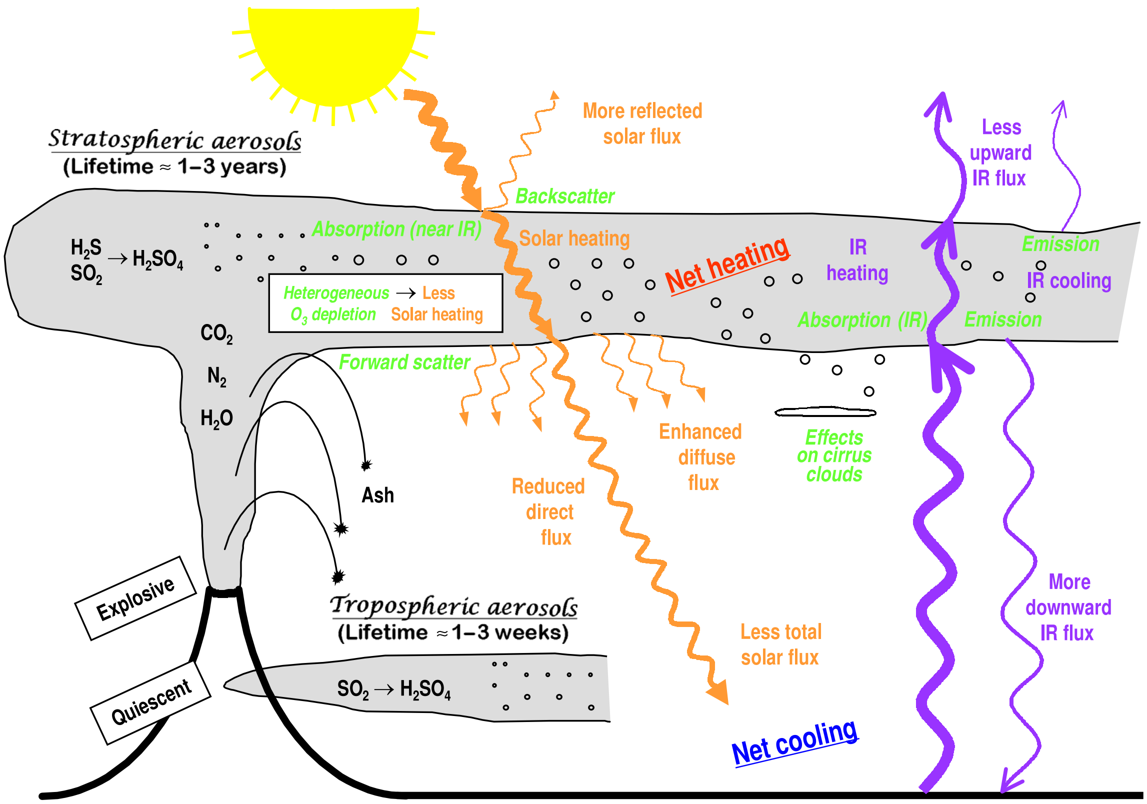

FIGURE 53.1 Schematic diagram of volcanic inputs to the atmosphere and their effects. *Plate 1 of Robock (2000), ©Copyright, American Geophysical Union.*

explosiveness, or the sulfur input to the stratosphere. While the first two of these are of great interest to volcanologists, as they relate to the geology and the local hazards, it is the third that determines the climatic impact. Thus, you will find climatologists and volcanologists disagreeing on the largest volcanic eruptions in the past. For example, although the 1980 Mount St Helens eruption was a tremendous blast and was assigned a Volcanic Explosivity Index of 5, the blast was lateral, full of solid material, and injected negligible amounts of sulfur to the stratosphere. It had a large impact on local weather for a few days (Robock and Mass, 1982), but no global climatic impact (Robock, 1981).

Volcanic eruptions inject several different types of particles and gases into the atmosphere (Figure 53.1). The gases can be assessed based on measurements from active, but not explosive, eruptions, but it is not clear that these would be the same from strong, explosive eruptions. In situ measurements from balloons and airplanes have been used to measure the bottoms of the resulting stratospheric aerosol clouds, but remote sensing from **lidar**, radiometers, and satellites is needed for global coverage. Still, there are gaps in our ability to monitor volcanic clouds in detail because the thickest parts of the clouds require lidar and satellite orbits prevent continuous monitoring. Several satellites routinely monitor SO_2, allowing us to directly measure stratospheric injection of gases from eruptions.

The major component of volcanic eruptions is the matter that emerges as solid, lithic material or solidifies into large particles, which are referred to as ash or tephra. These particles fall out of the atmosphere very rapidly, on timescales of minutes to a few days, and thus have no climatic impacts but are of great interest to volcanologists, as seen in the rest of this encyclopedia. When an eruption column still laden with these hot particles descends down the slopes of a volcano, this pyroclastic flow can be deadly to those unlucky enough to be at the base of the volcano. The destruction of Pompeii and Herculaneum after the AD 79 Vesuvius eruption is the most famous example.

Volcanic eruptions typically also emit gases, with H_2O, N_2, and CO_2 being the most abundant. Over the lifetime of the Earth, these gases have been the main source of the Earth's atmosphere and ocean after the primitive atmosphere of hydrogen and helium was lost to space. The water has condensed into the oceans, the CO_2 has been changed by plants into O_2 or formed carbonates, which sink to the ocean bottom, and some of the C has turned into fossil fuels. Of course, we eat plants and animals, which eat the plants, we drink the water, and we breathe the oxygen, so each of us is made of volcanic emissions. The atmosphere is now mainly composed of N_2 (78%) and O_2 (21%), both of which had sources in volcanic emissions.

Of these abundant gases, both H_2O and CO_2 are important greenhouse gases, but their atmospheric concentrations are so large (even for CO_2 at only 400 ppm in 2013) that individual eruptions have a negligible effect on their concentrations and do not directly impact the greenhouse effect. Global annually averaged emissions of CO_2 from volcanic eruptions since 1750 have been at least 100 times smaller than those from human activities. Rather the most important climatic effect of explosive volcanic eruptions is through their emission of sulfur species to the stratosphere, mainly in the form of SO_2, but possibly sometimes as H_2S. These sulfur species react with H_2O to form H_2SO_4 on a timescale of weeks, and the resulting sulfate aerosols produce the dominant radiative effect from volcanic eruptions.

The 1982 El Chichón eruption injected 7 MT of SO_2 into the atmosphere. There has not been a large stratospheric injection since 1991, when Mt Pinatubo in the Philippines put about 20 MT of SO_2 into the lower stratosphere. In 2008, Kasatochi (in the Aleutian Islands of Alaska); in 2009, Mt Sarychev (in the Russian Kamchatka Peninsula); and in 2011, Nabro (in Eritrea), each put about 1.5 MT of SO_2 into the lower stratosphere, and these eruptions contributed to the reduced global warming of the past decade. The Eyjafjallajökull eruption in Iceland in 2010, while very disruptive of air traffic for weeks, had so little SO_2 and with a short lifetime of a week or so in the troposphere that it had no impact on climate.

Once injected into the stratosphere, the large aerosol particles and small ones being formed by the sulfur gases are rapidly transported around the globe by stratospheric winds. Observations after the 1883 Krakatau eruption showed that the aerosol cloud circled the globe in 2 weeks. Both the 1982 El Chichón cloud and the 1991 Pinatubo cloud circled the globe in 3 weeks. Although El Chichón (17°N) and Pinatubo (15°N) are separated by only 2° of latitude, their clouds, after only one circuit of the globe, ended up separated by 15° of latitude, with the Pinatubo cloud straddling the equator and the El Chichón cloud extending approximately from the equator to 30°N. Subsequent dispersion of a stratospheric volcanic cloud depends heavily on the particular distribution of winds at the time of eruption. For trying to reconstruct the effects of older eruptions, this factor adds a further complication, as the latitude of the volcano is not sufficient information.

Quiescent continuous volcanic emissions also add sulfates to the troposphere, but their lifetimes there are much shorter, although longer than anthropogenic sulfates, as they are emitted from the sides of mountains rather than at the surface. The local pollution produced by the emission of the Kilauea crater on the Big Island of Hawaii is called "vog" (volcanic fog). Global sulfur emission of volcanoes to the troposphere is about 15% of the total natural and anthropogenic emission, producing cooling at the surface. Only if there is a long-term trend in these emissions, will they be important for climate change; nevertheless, they must be considered when evaluating the effects of anthropogenic sulfate emissions.

3. RADIATIVE INTERACTIONS AND CLIMATE FORCING

The major effect of a volcanic eruption on the climate system is the effect of the stratospheric cloud on solar radiation (Figure 53.1). Some of the radiation is scattered back to space, increasing the planetary albedo and cooling the Earth's atmosphere system. The sulfate aerosol particles (typical effective radius of 0.5 μm, about the same size as the wavelength of visible light) also forward scatter much of the solar radiation, reducing the direct solar beam but increasing the brightness of the sky. After the 1991 Pinatubo eruption, the sky around the sun appeared more white than blue because of this. After the El Chichón eruption of 1982 and the Pinatubo eruption of 1991, the direct radiation was significantly reduced, but the diffuse radiation was enhanced by almost as much. Nevertheless, the volcanic aerosol clouds reduced the total radiation received at the surface.

As the sun sets, the yellow and red light (because Rayleigh scattering removes the shorter wavelengths in the process that produces the blue sky) is reflected from the bottom of stratospheric volcanic clouds, producing a characteristic yellow and red sky 1/2—1 h after the time of sunset (Figure 53.2). This effect has been used in the past to detect distant eruptions and to estimate the height of the aerosol cloud and its extent. But such sunsets also inspire artists. After seeing the brilliant volcanic sunsets from the 1883 Krakatau eruption over Oslo, the Norwegian artist

FIGURE 53.2 Volcanic sunset over Lake Mendota in Madison, Wisconsin, in July 1982, 3 months after the El Chichón eruption. Photograph by Alan Robock. *Plate 4 from Robock (2000), ©Copyright, American Geophysical Union.*

Edvard Munch painted *The Scream* 10 years later. As he wrote in his diary, "I was walking along a path with two friends—the sun was setting—suddenly the sky turned blood red—I paused, feeling exhausted, and leaned on the fence—there were blood and tongues of fire above the blue-black fjord and the city—my friends walked on, and I stood there trembling with anxiety—and I sensed an infinite scream passing through nature."

4. CLIMATIC IMPACT OF VOLCANIC AEROSOLS

Stratospheric aerosol clouds from volcanic eruptions cool the Earth's surface for several years but produce winter warming over the continents in the NH. These and other effects are summarized in Table 53.2. Volcanic aerosols can be important causes of temperature changes for several years following large eruptions, and even on a millennial timescale they can be important when their cumulative effects are taken into account. This is 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.

Individual large eruptions produce global or hemispheric cooling for 2 or 3 years, but the winter following a large tropical eruption is warmer over the NH continents, and this counterintuitive effect is due to a nonlinear response through atmospheric dynamics. The winter warming pattern is illustrated in Figure 53.3, which shows the global lower-tropospheric temperature anomaly pattern for the NH winter of 1991–1992 following the 1991 Mt Pinatubo eruption. This pattern is closely correlated with the surface air temperature pattern where the data overlap, but the satellite data allow global coverage. The temperature over North America, Europe, and Siberia was much higher than normal and that over Alaska, Greenland, the Middle East, and China was lower than normal. In fact, it was so cold that winter that it snowed in Jerusalem, a very unusual occurrence. Coral at the bottom of the Red Sea died that winter because the water at the surface cooled and convectively mixed the entire depth of the water. The enhanced supply of nutrients produced anomalously large algal and phytoplankton blooms, which smothered the coral. This coral death had only happened before in winters following large volcanic eruptions. At the tropopause, the boundary between the troposphere and stratosphere, the strongest winds are found in the midlatitudes in the winter and are called the jet stream or polar vortex. The strength of the jet stream depends on the temperature difference (gradient) between the tropics and the polar region, which is largest in the winter when the polar regions cool. For a tropical eruption, the stratospheric heating from volcanic aerosols is larger in the tropics than in the high latitudes, producing an enhanced pole-to-equator temperature

TABLE 53.2 Effects of Large Explosive Volcanic Eruptions on Climate

Effect/Mechanism	Begins	Duration
Stratospheric warming	1–3 months	1–2 years
Stratospheric absorption of shortwave and longwave radiation		
Global cooling	Immediately	1–3 years
Blockage of shortwave radiation		
Global cooling from multiple eruptions	Immediately	Up to centuries
Blockage of shortwave radiation		
Winter warming of Northern Hemisphere continents	½–1½ years	1 or 2 winters
Differential stratospheric heating, dynamical interaction with troposphere		
Reduced tropical precipitation	Immediately	~1 year
Blockage of shortwave radiation, reduced evaporation		
Reduction of Asian and African summer monsoon	½–1 year	1 or 2 summers
Continental cooling, reduction of land–sea temperature contrast		
Ozone depletion, enhanced UV	1 day	1–2 years
Dilution, heterogeneous chemistry on aerosols		

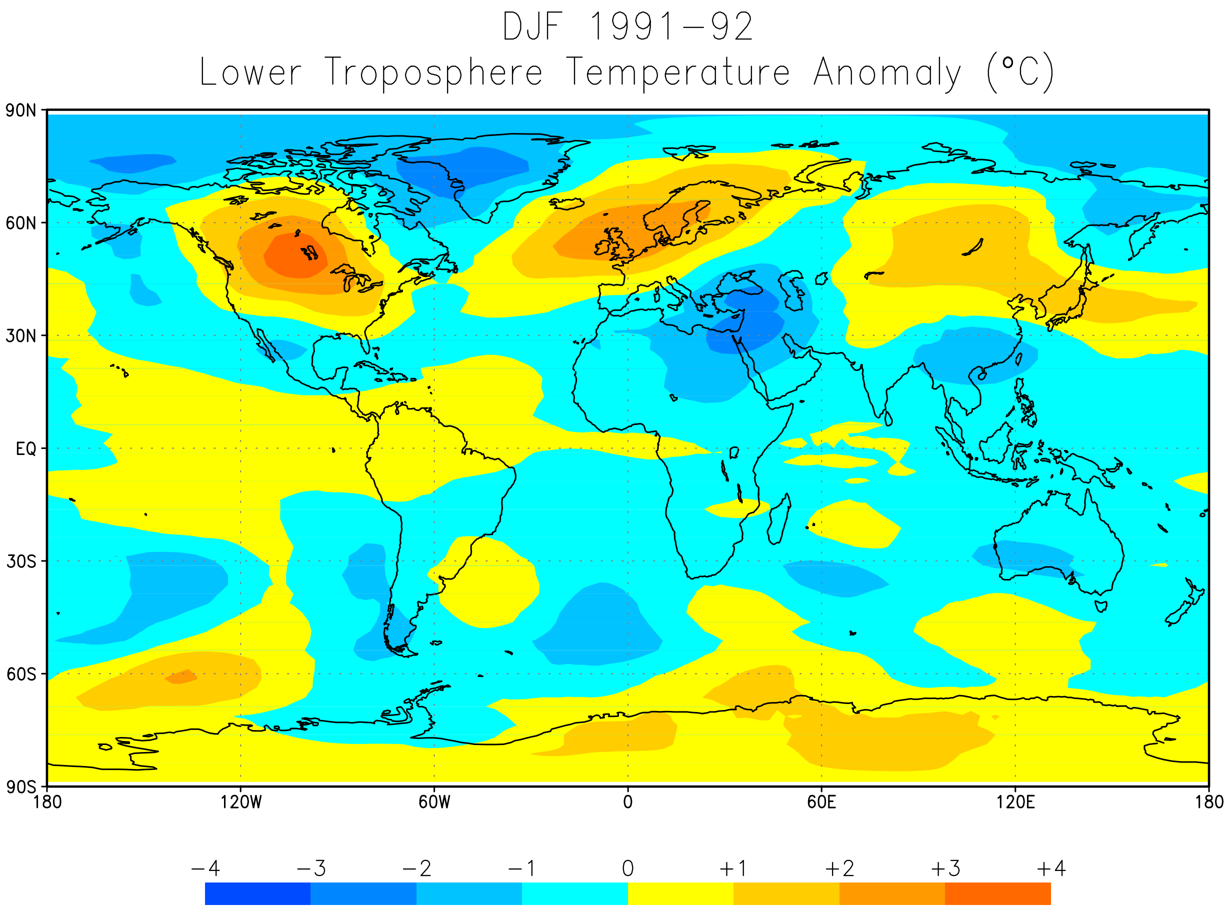

FIGURE 53.3 Winter (DJF) lower-tropospheric temperature anomalies (with the nonvolcanic period of 1984–1990 used to calculate the mean) for the 1991–1992 Northern Hemisphere winter (DJF) following the 1991 Mt Pinatubo eruption. This pattern is typical of that following all large tropical eruptions, with warming over North America, Europe, and Siberia, and cooling over Alaska, Greenland, the Middle East, and China. Data from Microwave Sounding Unit Channel 2R, updated courtesy of J. Christy and now called Channel 2LT. *Plate 8 from Robock (2000), ©Copyright, American Geophysical Union.*

gradient, and in the NH winter, a stronger polar vortex and winter warming of NH continents. The stronger jet stream produces a characteristic wind pattern in the troposphere, which warms some regions and cools other ones. This pattern is called the "Arctic Oscillation" and is the dominant mode of tropospheric variability. Tropical eruption clouds push the atmosphere into the positive phase of this natural variation. This indirect advective effect on temperature is stronger than the radiative cooling effect that dominates at lower latitudes and in the summer.

Because volcanic aerosols normally remain in the stratosphere no more than 2 or 3 years, the radiative effect of volcanoes is interannual rather than interdecadal in scale. A series of volcanic eruptions could, however, raise the mean optical depth significantly over a longer period and thereby give rise to a decadal-scale cooling. If a period of active volcanism ends for a significant period, such as for the 51-year period from 1912 to 1963 when global climate warmed, the adjustment of the climate system to no volcanic forcing helped produce the warming. Furthermore, it is possible that feedbacks involving ice and ocean, which act on longer timescales, could transform the short-term volcanic forcing into a longer-term effect. The current century is the warmest of the past 10, with the previous several centuries called the Little Ice Age due to their coldness. Studies show that the planet cooled at the end of the thirteenth century, following the most volcanic period in the past 1500 years, including the largest eruption of the entire period, the 1257 Samalas eruption, which produced 258 Tg of sulfate aerosols in the stratosphere (Gao et al., 2008). Miller et al. (2012) showed that in a climate model, these eruptions cooled the Earth so much that an Arctic sea ice feedback caused the cooling to persist until the recent global warming, which started in the nineteenth century, and thus that these volcanic eruptions were the cause of the Little Ice Age. This agreed with evidence from vegetation that had been killed and then preserved by ice sheet advances on Baffin Island following the largest eruptions of the period, the 1257 Samalas eruption and Kuwae in 1452. The large warming of the past century, however, can only partially be explained by these natural causes, and in fact the second half of the twentieth century would have cooled due to volcanic eruptions if there had been no human emissions. The large warming of this period can only be explained by including the effects of warming from anthropogenic greenhouse gases.

While Haslam and Petraglia (2010) showed that a 1000-year glacial period started just before the 74 ka BP Toba eruption, disproving the theory that the eruption produced the ice advance, the potential for a human genetic bottleneck produced by the death of most humans in a volcanic winter just after the eruption is still not resolved. This eruption on the island of Sumatra left a caldera about 86-km long and 30-km wide, with a large island inside, the resurgent block of the caldera. It erupted 1000 times more rock than the 1980 Mount St Helens eruption and injected approximately 100−300 times the amount of SO_2 into the stratosphere than the 1991 Pinatubo eruption. Depending on the assumptions about the properties of the resulting sulfate particles in the stratosphere, climate model simulations produce global average coolings of 3−15 °C, lasting for a decade or more. The larger range would have certainly been devastating for many species. However, there are no observations or paleo-reconstructions with a high enough time resolution to tell whether there was a several-year volcanic winter.

5. OZONE IMPACTS

Volcanic aerosols have the potential to change not only the radiative flux in the stratosphere but also its chemistry. The most important chemical changes in the stratosphere are related to O_3, which has significant effects on UV and longwave radiative fluxes. The reactions that produce and destroy O_3 depend on the UV flux, the temperature, and the presence of surfaces for heterogeneous reactions, all of which are changed by volcanic aerosols. The heterogeneous chemistry responsible for the ozone hole over Antarctica in October every year occurs on polar stratospheric clouds of water or nitric acid, which only occur in the extremely cold isolated spring vortex in the Southern Hemisphere. Conditions in the NH are now changing and small O_3 depletions are being observed in spring there now, too. Reactions on polar stratospheric clouds make anthropogenic chlorine available for chemical destruction of O_3. However, sulfate aerosols produced by volcanic eruptions can also provide these surfaces at lower latitudes and at all times of the year. In fact, after the 1991 Pinatubo eruption, column O_3 reduction of about 5% was observed in midlatitudes, ranging from 2% in the tropics to 7% in the midlatitudes. Therefore, **ozone depletion** in the aerosol cloud is much larger and reaches 20%. The chemical ozone destruction is less effective in the tropics, but lifting of low-ozone-concentration layers with the aerosol cloud causes a fast decrease in ozone mixing ratio in the low latitudes.

Decrease of the ozone concentration following volcanic eruptions causes less UV absorption in stratosphere, which modifies the aerosol heating effect. The net effect of volcanic aerosols on the surface UV flux is to increase it, as the aerosols back scatter less UV than the subsequent O_3 depletion allows through. The reduced O_3 absorption of shortwave and longwave radiation reduces the stratospheric heating effect and can affect the winter warming phenomenon described above.

The volcanic effect on O_3 chemistry is a new phenomenon, depending on anthropogenic chlorine in the stratosphere. While we have no observations, the 1963 Agung eruption probably did not deplete O_3, as there was little anthropogenic chlorine in the stratosphere. Due to the Montreal Protocol and subsequent international agreements, chlorine concentration has peaked in the stratosphere and is now decreasing. Therefore, for the next few decades, large volcanic eruptions will have effects similar 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 O_3 depletion.

6. DISCUSSION

There is no evidence that volcanic eruptions produce El Niño events, but the climatic effects of El Niño and volcanic eruptions must be separated to understand the climatic response to each. It had been suggested that the simultaneous appearance of the large 1982−1983 El Niño and the 1982 El Chichón eruption and the 1991 smaller El Niño and the Pinatubo eruption suggested a cause-and-effect relationship. However, no plausible mechanism has been suggested and further research into the oceanography of those El Niños shows that they started before the volcanic eruptions. Examination of the entire record of past El Niños and volcanic eruptions for the past two centuries also shows no significant correlation.

As volcanic eruptions and their subsequent climatic response represent a large perturbation to the climate system over a relatively short period, observations and the simulated model responses can serve as important analogs for understanding the climatic response to other perturbations. While the climatic response to explosive volcanic eruptions is a useful analog for some other climatic forcings, there are also limitations. For example, successful climate model simulations of the impact of one eruption can help validate models used for seasonal and interannual predictions. But they cannot test all the mechanisms involved in global warming over the next century, as long-term oceanic feedbacks are involved, which have a longer timescale than the response to individual volcanic eruptions. Theory tells us that volcanic eruptions also will produce multidecadal impacts on oceanic heat content and sea level, but these impacts are small and cannot be separated from other factors in observations.

The theory of "**nuclear winter**," the climatic effects of a massive injection of soot aerosols into the atmosphere from fires following a global nuclear holocaust, includes upward injection of the aerosols to the stratosphere, rapid global dispersal of stratospheric aerosols, removal of the aerosols, heating of the stratosphere, ozone depletion, and cooling at the surface under this cloud, still possible with the current global nuclear arsenal (Robock et al., 2007a; Toon et al., 2008). The use of only 100 nuclear weapons could produce climate change unprecedented in recorded human history (Robock et al., 2007b), which could produce significant decreases of agriculture in the main grain-growing regions of the world, the United States and China. As this theory cannot be tested in the real world, volcanic eruptions provide analogs that support these aspects of the theory.

Recent suggestions that we consider using **geoengineering** to control global climate through the creation of a permanent stratospheric aerosol cloud have used volcanic eruptions as an analog (e.g., Robock et al., 2013). Volcanic eruptions teach us that a stratospheric aerosol cloud would indeed cool the surface, reducing ice melt and sea level rise, and increase the terrestrial carbon sink. But volcanic eruptions also teach us that a stratospheric aerosol cloud would produce ozone depletion, allowing more harmful UV radiation at the surface, reduce summer monsoon precipitation and even produce drought, produce rapid warming if geoengineering were suddenly stopped, reduce solar power, damage airplanes flying in the stratosphere, and degrade surface astronomical observations and remote sensing (Robock et al., 2013). This raises many issues about the wisdom of geoengineering, and there are many other reasons why geoengineering may be a bad idea (Robock, 2008).

Given our current understanding of the climatic impact of volcanic eruptions, we can safely predict that following the next large tropical eruption, there will be global cooling for about 2 years and winter warming of the NH continents for 1 or 2 years. There will also be reduced summer monsoon precipitation over Asia and Africa. A large NH high-latitude eruption, if it occurs in spring or summer, will also produce a weak summer monsoon.

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