Volcanic Eruptions

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Volcanic Eruptions

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Volcanic eruptions can inject into the stratosphere tens of teragrams of chemically and microphysically active gases and solid aerosol particles that can affect the Earth's radiative balance and climate and disturb the stratospheric chemical equilibrium. The volcanic aerosol cloud forms in several weeks by the conversion of sulfur dioxide (SO_2) to sulfate aerosol and its subsequent microphysical transformations. The resulting cloud of sulfate aerosol particles, with a residence time of a couple of years, has important impacts on both shortwave and longwave radiation. The resulting disturbance to the Earth's radiation balance affects surface temperatures through direct radiative effects as well as through indirect effects on the atmospheric circulation. These aerosol particles also serve as surfaces for chemical reactions that can deplete stratospheric ozone.

*Volcanism has long been implicated as a possible cause of weather and climate variations. Even 2000 years ago, Plutarch and others pointed out that the eruption of Mt. Etna in 44 BC dimmed the Sun and suggested that this caused crops to shrivel and produced famine in Rome and Egypt. Because of their large effects in the English-speaking world, the largest eruptions of the past 250 years have each drawn attention to the atmospheric and potential climatic effects. The 1783 eruption in Iceland produced large effects all that summer in Europe. Benjamin Franklin, the US ambassador to France published the first paper on the subject in more than 1800 years, suggesting that the Lakagigar eruption in Iceland in 1783 might have been responsible for the abnormally cold summer of 1783 in Europe and the cold winter of 1783–1784 (*see ***Franklin, Benjamin****, Volume 1). If an eruption identical to the 1783 Laki eruption took place today, air traffic in the Northern Hemisphere would be disrupted for six months or more. The 1815 Tambora eruption produced the year without a summer in 1816 (*see ***Volcanic Eruption, Tambora****, Volume 1) and inspired Mary Shelly to write Frankenstein that summer while vacationing on the shores of Lake Geneva, Switzerland. She and her husband, Percy Bysshe Shelley and their friend Lord Byron had a contest to see who could write the scariest ghost story, inspired by the cold, gray weather that kept them housebound. Mary Shelley won.*

On average, major volcanic eruptions have occured about every 20 years over the last few centuries (see Table 1). The most extensive study of the impacts of a single volcanic eruption was carried out by the British Royal Society examining the 1883 Krakatau eruption (*see* **Volcanic Eruption, Krakatau**, Volume 1). The Society produced a beautiful volume including watercolors of the volcanic sunsets near London. This eruption was probably the loudest explosion of historic times, and the book includes color figures of the resulting pressure wave's four circuits of the globe as measured by microbarographs.

The 1963 Agung eruption produced the largest stratospheric dust veil in the Northern Hemisphere (NH) in more than 50 years, and inspired many modern scientific studies. While the Mt. St. Helens eruption of 1980 was very explosive, it was a lateral blast and did not inject much sulfur into the stratosphere, where aerosol particles can remain several years and have a world-wide effect on global average temperature. Because no materials reached the stratosphere, this eruption had very small global effects and its tropospheric effects lasted only a few days. However, it occurred in the US, and so received much attention. In contrast, the subsequent 1982 El Chichón and 1991 Mt. Pinatubo eruptions produced very large stratospheric aerosol clouds and large climatic effects (*see* **Volcanic Eruption, El Chichón**, Volume 1; **Volcanic Eruption, Mt. Pinatubo**, Volume 1). Despite their different climatic influences, quantification of the size of these eruptions has proven difficult because different measures reveal different information. For example, one could examine the total mass ejected, the explosiveness, or the sulfur input to the stratosphere.

Volcanic eruptions inject several different types of particles and gases into the atmosphere (Figure 1) (*see* **Aerosols, Stratosphere**, Volume 1). In the past, it was only possible to estimate these volatile inputs based on measurements from active, but not explosive, eruptions and from remote sensing of the resulting aerosol clouds using lidar, radiometers, and satellites. The serendipitous discovery of the ability to monitor SO_2 using the Total Ozone Mapping Spectrometer satellite instrument, however, has given us a new tool to directly measure stratospheric injection of gases from eruptions.

Table 1 Major volcanic eruptions of the past 250 years

Volcano	Year of eruption
Grimsvotn (Laki or Lakagigar), Iceland	1783
Tambora, Sumbawa, Indonesia	1815
Cosiguina, Nicaragua	1835
Askja, Iceland	1875
Krakatau, Indonesia	1883
Okataina (Tarawera), North Island, New Zealand	1886
Santa Maria, Guatemala	1902
Ksudach, Kamchatka, Russia	1907
Novarupta (Katmai), Alaska, US	1912
Agung, Bali, Indonesia	1963
Mt. St. Helens, Washington, US	1980
El Chichón, Chiapas, Mexico	1982
Mt. Pinatubo, Luzon, Philippines	1991

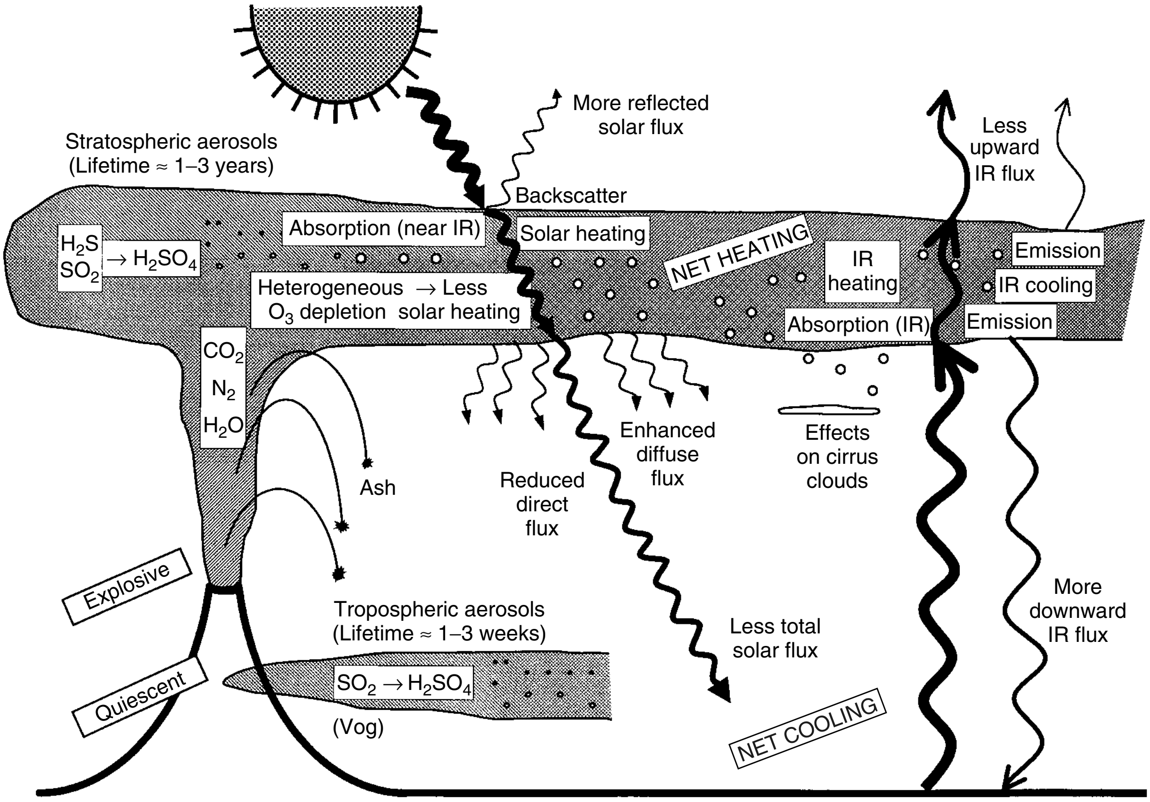

Figure 1 Schematic diagram of volcanic inputs to the atmosphere and their effects. (Adapted from Plate 1 of Robock, 2000, © Copyright, American Geophysical Union)

The major component of volcanic eruptions is magmatic material, which emerges as solid, lithic material or solidifies into large particles that are referred to as *ash* or *tephra*. These particles fall out of the atmosphere very rapidly, on time scales of minutes to a few days, and thus have no climatic impacts. However, this temporary large atmospheric loading can reduce the amplitude of the diurnal cycle of surface air temperature in the region of the tropospheric cloud, and this material is very dangerous for aircraft. But these effects disappear as soon as the particles settle to the ground. When an eruption column still laden with these hot particles descends down the slopes of a volcano, the resulting 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 79 AD Vesuvius eruption is the most famous example.

Volcanic eruptions typically also emit gases, with water (H_2O), nitrogen (N_2) and carbon dioxide (CO_2) being the most abundant. Over the lifetime of the Earth, these gases have been the main source of the planet's atmosphere and ocean, once 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 oxygen (O_2), with some of the C turned into fossil fuels. Of course, we eat the plants and animals that 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 the less abundant gases, both H_2O and CO_2 are important greenhouse gases; however their atmospheric concentrations are so large (e.g., CO_2 is at only 370 ppm and growing) that individual eruptions have a negligible effect on their concentrations and do not directly impact the greenhouse effect. 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 sometimes as hydrogen sulfide (H_2S). These sulfur species react with H_2O to form sulfuric acid (H_2SO_4) on a time scale of weeks, and the resulting H_2SO_4 aerosols produce the dominant radiative effect from volcanic eruptions. For example, the 1982 El Chichón eruption injected 7 megatonnes (Mt) of SO_2 into the atmosphere, and the 1991 Pinatubo eruption injected 20 Mt.

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 two weeks. Both the 1982 El Chichón cloud and the 1991 Pinatubo cloud circled

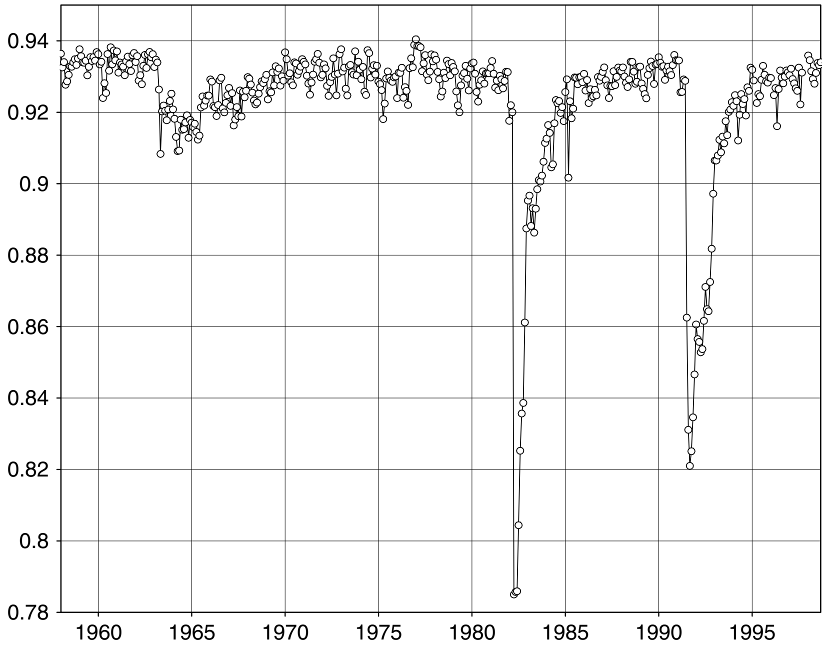

Figure 2 Broadband spectrally-integrated atmospheric transmission factor, measured at the Mauna Loa Observatory, Hawaii (19 °N). Effects of the 1963 Agung, 1982 El Chichón, and 1991 Mt. Pinatubo eruptions can clearly be seen. Years on abscissa indicate January of that year. (Data courtesy of E Dutton, NOAA CMDL, Boulder)

the globe in three weeks. Although El Chichón (17 °N) and Mt. 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 Mt. 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 those 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 in that part of the atmosphere are much shorter. Global sulfur emission by volcanoes to the troposphere is about 14% of the total natural and anthropogenic emission, thereby leading to a cooling influence at the surface. Only if there is a long-term trend in these emissions, however, will they be important contributors to climate change; nevertheless, they must be considered when evaluating the effects of anthropogenic sulfate emissions.

Figure 1 indicates the major radiative processes resulting from the stratospheric aerosol cloud from a major volcanic eruption. The most obvious and well-known effect is on solar radiation. Because the sulfate aerosol particles are about the same size as the wavelength of visible light, with a typical effective radius of 0.5 µm, and they have a single-scatter albedo of about 1, they strongly interact with solar radiation by scattering visible light. Some of the light is backscattered, reflecting sunlight back to space, increasing the net planetary albedo and reducing the amount of solar energy that reaches the Earth's surface. This is the dominant radiative effect at the surface and results in a net cooling there. Much of the solar radiation is forward-scattered, however, resulting in enhanced downward diffuse radiation that somewhat compensates for the large reduction in the direct solar beam.

The longest record of the effects of volcanic eruptions on atmospheric transmission of radiation is the apparent transmission record from the Mauna Loa Observatory in Hawaii (see Figure 2). The effects of the 1963 Agung, 1982 El Chichón, and 1991 Mt. Pinatubo eruptions can be clearly seen. Although the Mt. Pinatubo eruption produced the largest stratospheric input of the three, the center of the El Chichón cloud went directly over Hawaii, while only the edge of the Mt. Pinatubo cloud was observed. The Agung cloud was mostly in the Southern Hemisphere, so only the edge was seen in Hawaii.

The reflection of the setting Sun from the bottom of stratospheric volcanic aerosol layers produces the characteristic red sunsets that are used as one means of detecting past eruptions. The famous 1893 Edvard Munch painting, *The Scream*, shows a red volcanic sunset over the Oslo harbor produced by the 1892 Awu (Indonesia) eruption.

Volcanic eruptions can affect the climate system over many time scales (Table 2). The largest known eruption of the past 100 000 years was the great Toba (on

Table 2 Effects of large explosive volcanoes on weather and climate

Effect/mechanism	Begins	Duration
Reduction of diurnal cycle Blockage of shortwave and emission of longwave radiation	Immediately	1–4 days
Reduced tropical precipitation Blockage of shortwave radiation, reduced evaporation	1–3 months	3–6 months
Summer cooling of NH tropics and subtropics Blockage of shortwave radiation	1–3 months	1–2 years
Reduced Sahel precipitation Blockage of shortwave radiation, reduced land temperature, reduced evaporation	1–3 months	1–2 years
Stratospheric warming Stratospheric absorption of shortwave and longwave radiation	1–3 months	1–2 years
Winter warming of NH continents Stratospheric absorption of shortwave and longwave radiation, dynamics	6–18 months	1 or 2 winters
Global cooling Blockage of shortwave radiation	Immediately	1–3 years
Global cooling from multiple eruptions Blockage of shortwave radiation	Immediately	Up to decades
Ozone depletion, enhanced ultraviolet (UV) radiation Dilution, heterogeneous chemistry on aerosols	1 day	1–2 years

Sumatra, Indonesia) eruption about 71 000 years ago, which occurred intriguingly close to the beginning of a major glaciation (although a cause and effect relationship has yet to be established). Volcanic aerosols can be important causes of temperature changes for several years following large eruptions, and, even on a 100-year time scale, they can be important when their cumulative effects are taken into account. This is a very significant consideration when analyzing the extent of global warming, because 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. New analyses of the volcanic loading of the atmosphere, based on ice core records, have helped identify the effects of volcanic eruptions in the climate record.

Individual large eruptions certainly produce global or hemispheric cooling for two or three years, and this signal can now be more clearly in climate records. It has also been found that the winter following a large tropical eruption is warmer over the NH continents. This counter-intuitive effect is due to a nonlinear response through atmospheric dynamics. It has also recently been realized that volcanic aerosols provide a surface for heterogeneous chemical reactions that destroy ozone. Indeed observations following the Mt. Pinatubo eruption have documented midlatitude ozone depletion caused by volcanic effects.

The winter warming pattern is illustrated in Figure 3, which shows the global lower tropospheric temperature anomaly pattern for the NH winter of 1991–1992, following the 1991 Mt. Pinatubo eruption (*see* **Tropospheric Temperature**, Volume 1). This pattern is closely correlated with the surface air temperature pattern where the data overlap, but the satellite data allow global coverage. The temperatures over North America, Europe, and Siberia were much higher than normal, and those over Alaska, Greenland, the Middle East, and China were lower than normal. In fact, it was so cold that winter that it snowed in Jerusalem, a very unusual occurrence. As another example of the extreme conditions, 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 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 indirect advective effect on temperature is stronger than the radiative cooling effect that dominates at lower latitudes and in the summer.

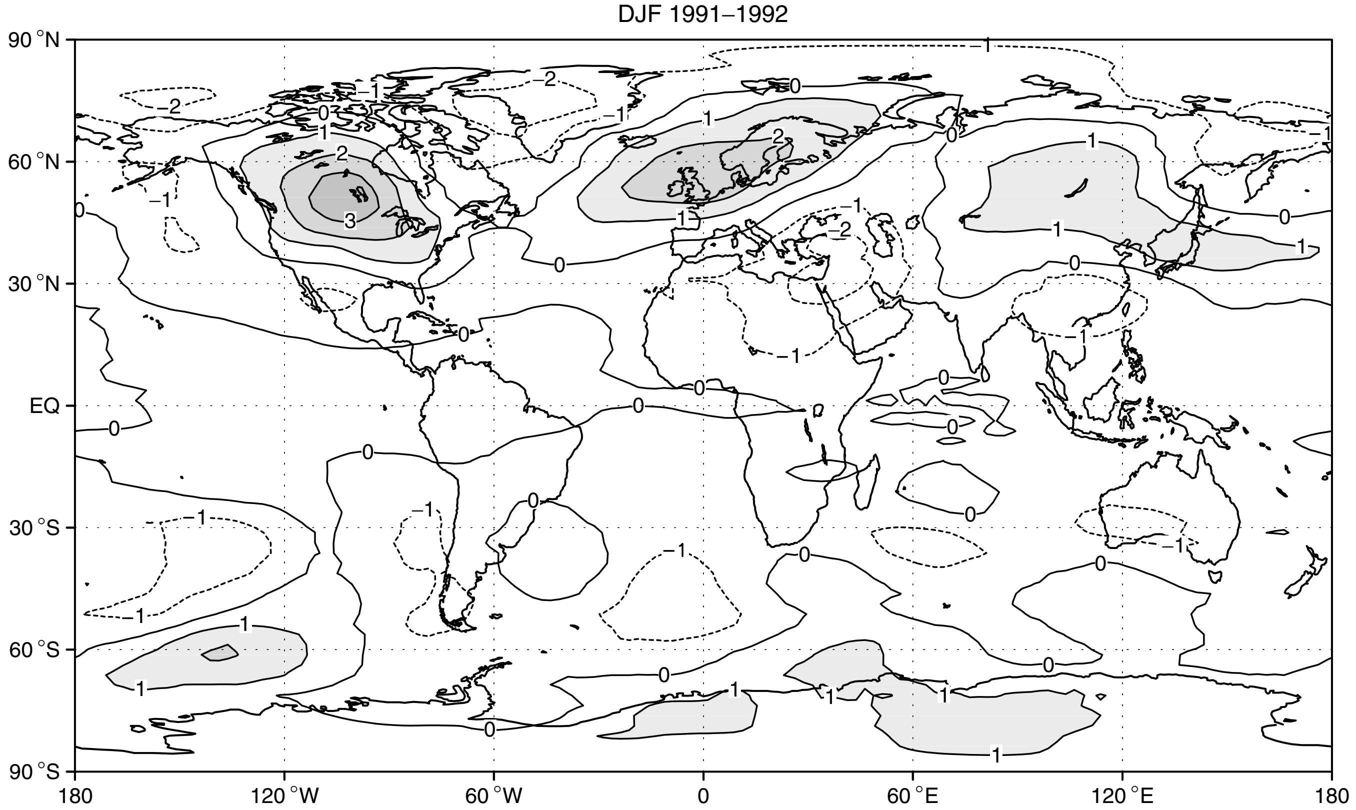

Figure 3 Winter (December January February, DJF) lower tropospheric temperature anomalies (K) (with the non-volcanic period of 1984–1990 used to calculate the mean) for the 1991–1992 NH winter (DJF) following the 1991 Mt. Pinatubo eruption. This pattern is typical of that following all large tropical 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 2LT, courtesy of J Christy, University of Alabama, Huntsville. Adapted from Plate 8, Robock, 2000, © Copyright American Geophysical Union.)

Because volcanic aerosols normally remain in the stratosphere no more than two or three years, with the possible exception of extremely large eruptions such as that of Toba approximately 71 000 years ago, the radiative effect of volcanoes is interannual rather than interdecadal in scale. A series of volcanic eruptions can, however, significantly raise the mean optical depth of the atmosphere 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 50-year period from 1912 to 1963, the adjustment of the climate system to an absence of volcanic forcing can (and apparently did) contribute to warming over this period. Furthermore, it is possible that feedbacks involving ice and ocean, which act on longer time scales, can transform the short-term volcanic forcing into a longer-term effect. As a result, the possible role of volcanoes in decadal-scale climate change remains unclear (*see* **Natural Climate Variability**, Volume 1). In particular, the current century is the warmest of the past five, with the early part of this period earning the moniker of the Little Ice Age due to its coldness (*see* **Little Ice Age**, Volume 1). Volcanic eruptions and solar variations are both likely to have been important contributors to the cooling of the Little Ice Age.

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 ozone (O_3) which has significant effects on ultraviolet (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 each 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 (*see* **Ozone Hole**, Volume 1; **Depletion of Stratospheric Ozone**, Volume 1). These reactions make anthropogenic chlorine available for chemical destruction of O_3. 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

Mt. Pinatubo eruption, a column O_3 reduction of about 5% was observed in midlatitudes, ranging from 2% in the tropics to 7% in the midlatitudes. 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 rapid decrease in ozone mixing ratio in the low latitudes. Decrease of the ozone concentration reduces UV absorption in the stratosphere, which modifies the aerosol heating effect. The net effect of volcanic aerosols on the surface UV flux is to increase it because the aerosols backscatter less UV than the subsequent O_3 depletion allows through (*see* **Ultraviolet Radiation**, Volume 1).

The significant 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 (*see* **Stratosphere, Ozone Trends**, Volume 1). Therefore, for the next few decades, large volcanic eruptions will have effects similar to Mt. Pinatubo, but after that, these O_3 effects will be significantly decreased and volcanic eruptions will have a stronger effect on atmospheric circulation without the negative feedback produced by O_3 depletion.

While the large 1982–1983 El Niño occurred just after the 1982 El Chichón eruption in Mexico, there is no evidence of a cause and effect relationship for this or any other eruptions. There is also no evidence that volcanic eruptions produce El Niño events. Because they can occur simultaneously, the climatic effects of El Niño and volcanic eruptions must be carefully separated to understand the climatic response to each.

Because 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. The theory of nuclear winter, which focuses on 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, heating of the stratosphere, and cooling at the surface under this cloud (*see* **Nuclear Winter**, Volume 3). Because testing this theory in the real world would involve global destruction, volcanic eruptions serve as analogues supporting various aspects of the theory.

While we have no idea when the next large tropical eruption will occur, our current understanding of the climatic impacts of volcanic eruptions suggest a likelihood of global cooling lasting about two years, and winter warming of the NH continents for one or two years.

See also: **Stratosphere, Temperature and Circulation**, Volume 1; **DVI (Dust Veil Index)**, Volume 3; **Lahars**, Volume 3; **VEI (Volcanic Explosivity Index)**, Volume 3; **Volcanic Eruptions: Mt Merapi, Indonesia**, Volume 3; **Volcanoes and Cities**, Volume 3; **Volcanoes and the Environment**, Volume 3.

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