VOLCANOES

Role in Climate

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Introduction

0448-P0005 Explosive volcanic eruptions affect climate by injecting gases and aerosol particles into the stratosphere. Only if the eruption cloud is rich in SO_2 will the eruption produce a long-lived aerosol cloud, in response to the sulfate aerosols that form over the next few weeks. Otherwise, explosive eruptions that only produce large ash particles, such as the 1980 Mount St Helen's eruption, can produce a large local weather perturbation, but do not have long-lasting climatic effects. Some volcanoes, such as Kiluaea and Etna, produce large quiescent tropospheric emissions of sulfate precursors, but 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 absorption and reduces the radiative heating in the lower stratosphere, but the net effect is still heating. 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. There is no evidence that volcanic eruptions can produce El Niños, but ENSO variations must be considered when searching the climatic record for volcanic signals, as they have similar amplitudes and time scales.

There have been several large volcanic eruptions in the past 250 years (**Table 1**), and each has drawn attention to the atmospheric and potential climatic effects. The 1783 Lakagigar eruption in Iceland produced large effects in Europe, causing Benjamin Franklin, the United States ambassador to France, to publish the first paper on the subject in more than 1800 years. The 1815 Tambora eruption produced the "Year Without a Summer" in 1816 and inspired Frankenstein, written by Mary Shelley on the shores of Lake Geneva, Switzerland. The 1883 Krakatau eruption was the largest explosion ever observed, and the sound wave was tracked on microbarographs for four complete circuits of the Earth, taking almost 2 days for one circuit. The Royal Society report on this eruption published 5 years later remains the most extensive report on the atmospheric effects of a volcanic eruption. The 1963 Agung eruption produced the largest stratospheric dust veil in more than 50 years in the NH, and inspired many modern scientific studies. The subsequent 1982 El Chichón and 1991 Mount Pinatubo eruptions produced very large stratospheric aerosol clouds and large climatic effects. Quantification of the size of these eruptions is difficult, as different measures reveal different information. For example, one could examine the total mass ejected, the explosiveness, or the sulfur input to the stratosphere. 0448-P0010

Volcanic Emissions

Volcanic eruptions inject several different types of particles and gases into the atmosphere (**Figure 1**). These volatile inputs can be assessed based on 0448-P0015

Table 1 Major volcanic eruptions of the past 250 years 0448-T0001

Volcano	*Year of eruption*
Lakagigar or Skaftaéldar, 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, United States	1912
Gunung Agung, Bali, Indonesia	1963
Mount St Helen's, Washington, United States	1980
El Chichón, Chiapas, Mexico	1982
Mount Pinatubo, Luzon, Philippines	1991

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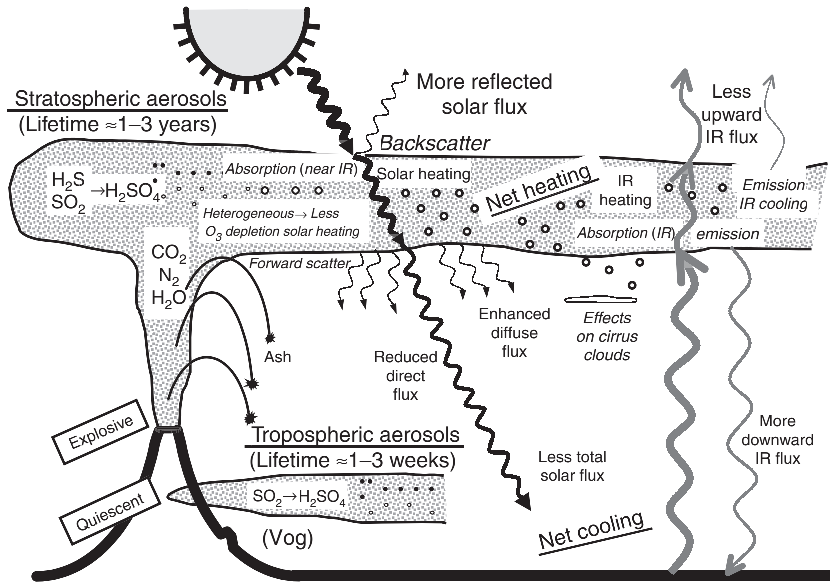

0448-F0001 **Figure 1** Schematic diagram of volcanic inputs to the atmosphere and their effects. (Adapted with permission from Plate 1 of Robock (2000), © owned by the American Geophysical Union.)

measurements from active, but not explosive, eruptions and remote sensing of the resulting aerosol clouds from lidar, radiometers, and satellites. The Total Ozone Mapping Spectrometer (TOMS) satellite instrument is an important tool, as it can also monitor SO_2, allowing us to directly measure stratospheric injection of gases from eruptions. The Stratospheric Aerosol and Gas Experiment (SAGE) series of limb-scanning instruments provides the longest series of profiles of volcanic aerosols in the stratosphere.

0448-P0020 The major component of volcanic eruptions is from 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 time scales of minutes to a few days, and thus have no climatic impacts. 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.

0448-P0025 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 planet'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 that sink to the ocean bottom, and some of the C has 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 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 372 ppm) 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 possibly sometimes as H_2S. These sulfur species react with H_2O to form H_2SO_4 on a time scale of weeks, and the resulting H_2SO_4 aerosols produce the dominant radiative effect from volcanic eruptions. The 1982 El Chichón eruption injected 7 Mt of SO_2 into the atmosphere, and the 1991 Pinatubo eruption injected 20 Mt. 0448-P0030

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 0448-P0035

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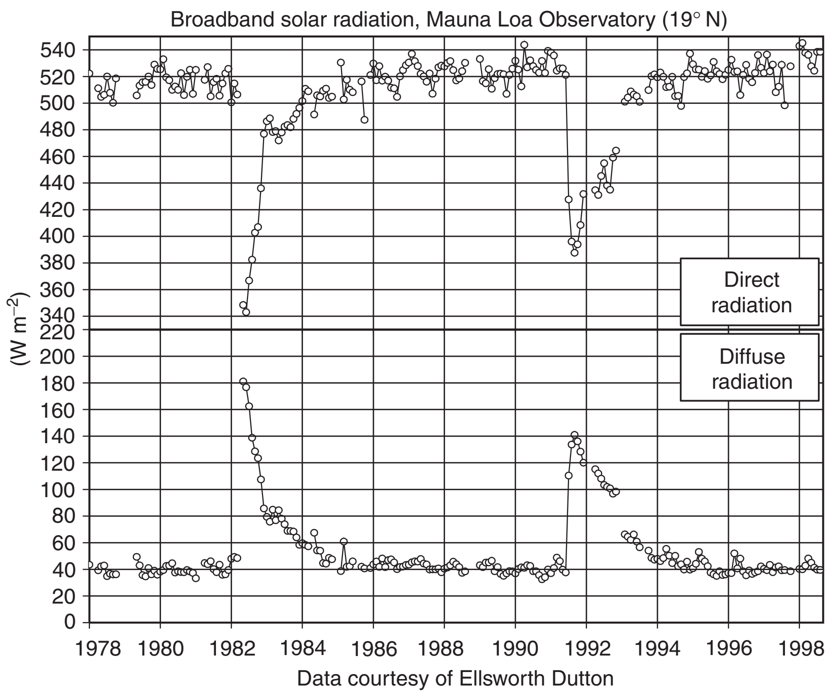
extending approximately from the Equator to 30° N. Subsequent dispersion of a stratospheric volcanic cloud depends heavily on the particular distribution of winds at the time of eruption. In trying to reconstruct the effects of older eruptions, dispersion adds a further complication, as the latitude of the volcano is not sufficient information.

0448-P0040 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 14% of the total natural and anthropogenic emission, cooling 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.

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 1**). Some of the radiation is scattered back to space, increasing the planetary albedo and cooling the Earth–atmosphere system. The sulfate aerosol particles (typical effective radius of 0.5 μm, about the same size as 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. **Figure 2** illustrates this effect using observations from the Mauna Loa observatory in Hawaii. 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. Although the El Chichón radiative effect at Hawaii was larger, this is because it was centered at the latitude of Hawaii, while only the edge of the larger Pinatubo cloud was monitored. 0448-P0045



0448-F0002 **Figure 2** Direct and diffuse broadband radiation measurements from the Mauna Loa observatory, measured with a tracking pyrheliometer and shade disk pyranometer on mornings with clear skies at a solar zenith angle of 60°, equivalent to two relative air masses. The reduction of direct radiation and enhancement of diffuse radiation after the 1982 El Chichón and 1991 Pinatubo eruptions are clearly seen. Years on abscissa indicate January of that year. (Data courtesy of E Dutton. **Figure 4** from Robock (2000), © owned by the American Geophysical Union.)

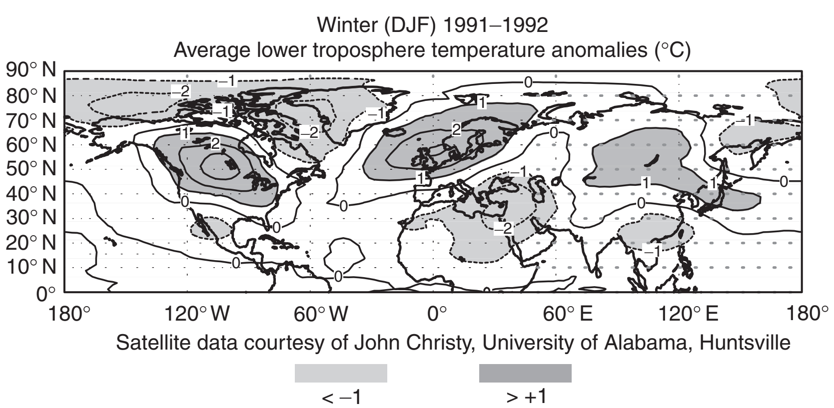
0448-P0050 As the sun sets, the red beam (because Rayleigh scattering removes the shorter wavelengths in the process that produces the blue sky) is reflected from the bottom of stratospheric volcanic clouds, producing a characteristic red sky one half to one hour after the time of sunset. This effect has been used in the past to detect distant eruptions and to estimate the height of the aerosol cloud and its extent.

Climatic Impact of Volcanic Aerosols

0448-P0055 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 2**. 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 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 3**, which shows the global lower tropospheric temperature anomaly pattern for the NH winter of 1991–92, following the 1991 Mount 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.

0448-T0002 **Table 2** Effects of large explosive tropical volcanic eruptions on climate

Effect/Mechanism	*Begins*	*Duration*
Stratospheric warming/Stratospheric absorption of short-wave and long-wave radiation	1–3 months	1–2 years
Global cooling/Blockage of short-wave radiation	Immediately	1–3 years
Global cooling from multiple eruptions/Blockage of short-wave radiation	Immediately	Up to decades
Winter warming of NH continents/Differential stratospheric heating, dynamical interaction with troposphere	$\frac{1}{2}$–$1\frac{1}{2}$ years	1 or 2 winters
Ozone depletion, enhanced UV/Dilution, heterogeneous chemistry on aerosols	1 day	1–2 years



0448-F0003 **Figure 3** Winter (DJF) lower tropospheric temperature anomalies (with the nonvolcanic period of 1984–90 used to calculate the mean) for the 1991–92 NH winter (DJF) following the 1991 Mount 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. Adapted with permission from **Figure 12** of Robock (2000), © owned by the American Geophysical Union.)

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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.

0448-P0060 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 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.

0448-P0065 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 50-year period from 1912 to 1963 when global climate warmed, the adjustment of the climate system to no volcanic forcing could produce warming. Furthermore, it is possible that feedbacks involving ice and ocean, which act on longer time scales, could 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. However, 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 interannual and interdecadal variations during this period were strongly affected by both volcanic eruptions and solar variations. The large warming of the past century, however, can only partially be explained by these natural causes, and can only be well simulated by including the effects of warming from anthropogenic greenhouse gases.

Ozone Impacts

Volcanic aerosols have the potential to change not 0448-P0070
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 ultraviolet and long-wave 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. 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 was much larger and reached 20%. 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 0448-P0075
volcanic eruptions causes less 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, as the aerosols backscatter less UV than the subsequent O_3 depletion allows through. The reduced O_3 absorption of short-wave and long-wave 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 0448-P0080
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.

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Discussion

0448-P0085 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 1982–83 El Niño and the 1982 El Chichón eruption and the smaller El Niño and Pinatubo eruption in 1991 suggested a cause and effect relationship. However, no plausible mechanism has been suggested, and further research into the oceanography of 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.

0448-P0090 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 climate models cannot test all the mechanisms involved in global warming over the next century, as long-term oceanic feedback are involved, which have a longer time scale than the response to individual volcanic eruptions. On the other hand, 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, heating of the stratosphere, and cooling at the surface under this cloud. As this theory cannot be tested in the real world, volcanic eruptions provide analogs that support these aspects of the theory.

0448-P0095 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.

See also

Aerosols: Climatology of Tropospheric Aerosols (0051); Observations and Measurements (0048); Role in Radiative Transfer (0053). **Climate:** Overview (0024). **Climate Prediction (Empirical and Numerical)** (0322). **Climate Variability:** Decadal to Centennial Variability (0107); North Atlantic and Arctic Oscillation (0109); Seasonal to Interannual Variability (0029). **Global Change:** Surface Temperature Trends (0005). **Lidar:** Backscatter (0205). **Radiative Transfer:** Absorption and Thermal Emission (0337). **Satellite Remote Sensing:** TOMS Ozone (0351). **Stratosphere - Troposphere Exchange:** Global Aspects (0394). **Stratospheric Chemistry and Composition:** Halogen Sources, Anthropogenic (0389). **Stratospheric Water Vapor** (0393). **Volcanoes:** Composition of Emissions (0447). **Weather Prediction:** Seasonal and Interannual Weather Prediction (0463).

Further Reading

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