Climatic Impact of Volcanic Emissions

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ABSTRACT

Studying the impacts of volcanic eruptions on climate is important because it helps us improve climate models, it allows us to make seasonal and interannual climate forecasts following large eruptions, it provides support for nuclear winter theory, and it allows us to separate the natural causes of interdecadal climate change from anthropogenic effects, giving us greater confidence in the attribution of recent global warming to anthropogenic causes. While much has been learned since the large 1991 eruption of Mt. Pinatubo in the Philippines, there are still quite a few outstanding research problems, which are discussed here. These questions include: What exactly goes into the atmosphere during an explosive eruption? How can we better quantify the record of past climatically-significant volcanism? Can we design an improved system for measuring and monitoring the atmospheric gases and aerosols resulting from future eruptions? How can we better model the climatic impact of eruptions, including microphysics, chemistry, transport, radiation, and dynamical responses? How do high-latitude eruptions affect climate? How important are indirect effects of volcanic emissions on clouds? Where are the important potential sites for future eruptions?

1. Introduction

Volcanism has long been implicated as a possible cause of weather and climate variations. *Franklin* [1784], *Humphreys* [1913, 1940] and *Mitchell* [1961] were pioneers in their association of volcanic eruptions with climate change. More recently, *Lamb* [1970, 1977, 1983], *Toon and Pollack* [1980], *Toon* [1982], and *Robock* [2000, 2002a, 2003a, 2003b] presented reviews of these effects. An AGU monograph [*Robock and Oppenheimer*, 2003] contains many articles on all aspects of this subject. There are however many outstanding research problems and this paper focuses on frontiers and challenges in this area. First, a brief summary of the known effects serves to set the stage for a focus these outstanding research questions.

a. How volcanic eruptions affect weather and climate

Volcanic eruptions can inject into the stratosphere tens of teragrams of chemically and microphysically active gases and solid aerosol particles, which affect the Earth's radiative balance and climate, and disturb the stratospheric chemical equilibrium (Figure 1). The volcanic cloud forms in several weeks by SO_2 conversion to sulfate aerosol, and its subsequent microphysical transformations. The resulting cloud of sulfate aerosol particles, with an e-folding decay time of approximately 1 year, 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. In cold regions of the stratosphere, these aerosol particles also serve as surfaces for heterogeneous chemical reactions that liberate chlorine to destroy ozone in the same way that water and nitric acid aerosols in polar stratospheric clouds produce the seasonal Antarctic ozone hole (Figure 1).

The major component of volcanic eruptions is magmatic material, which 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 weeks in the troposphere. Figure 2 illustrates the dramatic effects of the ash from the 1991 Mt. Pinatubo eruption in the Philippines. Small amounts can last for a few months in the stratosphere, but have very small climatic impacts. *Symons* [1888], after the 1883 Krakatau eruption, and *Robock and Mass* [1982], after the 1980 Mt. St. Helens eruption, showed that this temporary large atmospheric loading reduced the amplitude of the diurnal cycle of surface air temperature in the region of the tropospheric cloud. But these effects disappear as soon as the particles settle to the ground. Continuous volcanic emissions, including fumaroles and small episodic eruptions, add sulfates to the troposphere, but their lifetimes there are much shorter than those of stratospheric aerosols (Figure 1). Therefore they are not important for climate change, but could be if there is a sudden change or a long-term trend in them develops. Global sulfur emission of volcanoes to the troposphere is about 14% of the total natural and anthropogenic emission [*Graf et al.*, 1997], but has a much larger relative contribution to radiative effects. Many volcanic emissions are from the sides of mountains, above the atmospheric boundary layer, and thus they have longer lifetimes than anthropogenic aerosols.

Large volcanic eruptions inject sulfur gases into the stratosphere, which convert to sulfate aerosols with an e-folding residence time of about 1 yr (Figure 1). Large ash particles fall out much quicker. The radiative and chemical effects of this aerosol cloud produce responses in the climate system. By scattering some solar radiation back to space, the aerosols cool the surface, but by absorbing both solar and terrestrial radiation, the aerosol layer heats the stratosphere (Figure 1). Because the sulfate aerosol particles have an effective radius of about 0.5 μm, equivalent to the wavelength of visible light, they interact more strongly with the shortwave solar radiation than the longwave (~10 μm) radiation being emitted by the surface and atmosphere. The shortwave interaction includes some absorption in near infrared wavelengths, producing some heating of the top of the aerosol cloud, but mostly scattering. The light which is backscattered is essentially reflected from the Earth-atmosphere system, cooling the planet. Much of it is forward scattered, resulting in more downward diffuse radiation, and less direct downward radiation. In the longwave, the aerosol cloud absorbs upward radiation from the surface and atmosphere, heating the aerosol cloud. It emits downward, producing some compensation for the reduction in downward solar radiation, but this longwave effect is an order of magnitude smaller than the shortwave effect, so the net effect is surface cooling, except in the polar night where there is no sunlight. The aerosol cloud also emits upward, but much less radiation than the surface. Thus, to satellites trying to measure sea surface temperatures or vegetation indices, the volcanic aerosol cloud produces an interference, which must be addressed. These effects are illustrated in Figure 1.

For a tropical eruption, the stratospheric heating is larger in the tropics than in the high latitudes, producing an enhanced pole-to-equator temperature gradient, especially in winter. In the Northern Hemisphere winter, this enhanced gradient produces a stronger polar vortex, and this stronger jet stream produces a characteristic stationary wave pattern of tropospheric circulation resulting in winter warming of Northern Hemisphere continents [*Perlwitz and Graf*, 1995; *Kodera et al.*, 1996; *Thompson and Wallace*, 1998, 1999a, b]. This indirect advective effect on temperature is stronger than the radiative cooling effect that dominates at lower latitudes and in the summer. After the Pinatubo eruption, the observed ozone depletion was largest in the high latitudes of the Northern Hemisphere in the second year after the eruption, enhancing the strengthening of the polar vortex and enhancing winter warming in the second year after the eruption [*Stenchikov et al.*, 2002]. The quasi-biennial oscillation of stratospheric winds also modulates these effects [*Stenchikov et al.*, 2004].

b. Reasons to study the volcanic impacts on climate

Studying the effects of volcanic eruptions on climate is important for several reasons. First, it helps us to improve climate models. Volcanic eruptions are an important natural cause of climate change on many time scales. Studying the responses of climate to volcanic eruptions helps us to better understand important radiative and dynamical processes in the climate system. Large volcanic eruptions, like the 1991 Mt. Pinatubo eruption in the Philippines, produce short (2-3 yr) but large perturbations to the climate system. While we cannot use them to test long-term processes, such as changes in the thermohaline circulation, we can take advantage of them to examine some short time-scale feedback processes and impacts. If a climate model responds correctly to a volcanic eruption, it gives us more confidence that the timing and amplitude of future global warming will be well simulated by the model. For example, *Soden et al.* [2002] showed that without the most important positive feedback in the climate system, the water vapor feedback, a state of the art climate model is unable to reproduce the observed global cooling following the Pinatubo eruption. These results provide quantitative evidence of the reliability of water vapor feedback in current climate models, which is crucial to their use for global warming projections.

Second, our current understanding of the effects of large volcanic eruptions provides us a capability to make seasonal and interannual climate forecasts of Northern Hemisphere winter warming and summer cooling following large tropical eruptions [*Robock*, 2000]. Thus we can be confident in predictions of global cooling in the summer following large tropical eruptions, unless there is a large simultaneous El Niño, as in 1982 following the El Chichón eruption. We can also now predict that there will be a circulation response in the first one or two Northern Hemisphere winters following a large tropical eruption, resulting in winter warming of continents. We can account for the effects of the modulation of this response by the phase of the quasi-biennial oscillation.

Third, volcanic eruptions provide an analog for some parts of nuclear winter theory. 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 [*Turco et al.*, 1983, 1990; *Robock*, 1984, 1996], 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 we cannot perform this experiment in the real world to test the theory, the similar climate responses to volcanic eruptions provide an analog for these phenomena and give us more confidence in climate model simulations of this worst of all possible anthropogenic impacts on climate. In fact, *Rampino and Self* [1992] explicitly acknowledge this when they refer to a "volcanic winter" as the effect of a massive volcanic eruption.

Fourth, the study of volcanic effects on climate allows us to separate the natural causes of interdecadal climate change from anthropogenic effects. The major potential causes of climate change on an interdecadal to centennial time scale are solar variations, volcanic eruptions, and anthropogenic greenhouse gases. Anthropogenic land surface changes and aerosols are less important globally, but may be more important regionally. To understand how important anthropogenic effects are on climate, and to attribute the 0.6°C ± 0.2°C warming of the past century [*Jones et al.*, 1999; *Folland et al.*, 2001] to its causes, we must understand the strength of the natural causes of climate change. *Free and Robock* [1999] showed that the major causes of climate change from 1600 to 1850 were natural, with volcanic eruptions being the most important. However, they found that natural causes could not explain the warming of the past century and a half, but that it could be well simulated when anthropogenic forcing was included. These and other results led *Houghton et al.* [2001] to conclude that most of the warming of the second half of the 20th century was caused by human pollution of the atmosphere. In addition, sulfur emissions into the troposphere above the boundary layer from volcanoes produce a substantial amount of tropospheric aerosols [*Graf et al.*, 1997]. Resolving uncertainty in the amount and timing of these slow volcanic emissions into the troposphere will produce a better understanding of the record of tropospheric sulfate aerosols, their contribution to radiative and cloud microphysical changes, and thus their relative role in climate change.

Fifth, the response to volcanic eruptions allows us to better understand the impacts of anthropogenic climate change on life [*Robock*, 2003b]. The response of the biosphere to the Pinatubo eruption illustrated its sensitivity to climate change and clarified portions of the carbon cycle. For example, the unusually large number of polar bear cubs born in the summer of 1992 was due to the characteristic winter and summer temperature responses of the climate system. The largest cooling in the summer of 1992 was in the center of North America, and as a result, the ice on Hudson Bay melted almost a month later than normal that year. Polar bears, who feed and have babies on the ice, were much heavier and had more healthy cubs that summer. Biologists call them the "Pinatubo Bears" [*Stirling*, 1997]. While the cool conditions in the summer after the Pinatubo eruption was very beneficial for the Hudson Bay polar bears, and there were many more bears born that year than the year before or after, the long-term concern for these bears, and many other plants and animals in the Arctic, however, is the opposite impact from global warming. This is an example of how the benefits of Pinatubo from global cooling teach us about the negative impacts of anthropogenic global warming. In addition, enhanced vegetation growth from more diffuse and less direct solar radiation took more carbon dioxide out of the atmosphere than normal, temporarily reducing the observed long-term increase in carbon dioxide [*Gu et al.*, 2002, 2003; *Farquhar and Roderick*, 2003], thus adding to our understanding of the carbon cycle.

2. Outstanding research problems

Robock [2002b] discussed outstanding problems in understanding the effects of volcanic eruptions on the atmosphere and on climate, but did not have room to go into detail and completely explain why these issues were important and what current ideas have been proposed. An enumeration of these scientific questions is important as guidance for funding agencies and to give ideas to graduate students and other researchers for dissertation topics and project ideas. Here I expand on that article and discuss several of these issues in greater depth.

What exactly goes into the atmosphere during an explosive eruption? The impacts of volcanic eruptions on weather, climate, and atmospheric chemistry depend on what materials eruptions put into the atmosphere. Climatically significant inputs include sulfur species (especially SO_2), halogens, H_2O, and fine silicate particles. *Textor et al.* [2004] discussed our current understanding of the input to the atmosphere from both tropospheric slow release of gases by fumaroles and steam plumes from dormant volcanoes and the eruption of lava with weak degassing and also episodic, explosive eruptions which put material into the stratosphere, but many questions remain. What are the magmatic controls on how much sulfur is emitted from eruptions? For example, the partitioning of sulfur between solid igneous mineral phases (sulfides and sulfates) that remain in the crust and gaseous phases (H_2S and SO_2) is critical to understanding volcanic sulfur budgets and emissions, but is far from being well understood [e.g., *Wallace*, 2001]. Volcanoes appear to erupt far more SO_2 than they should on the basis of solubility laws and this excess sulfur problem remains unresolved. When eruptions take place in wet environments, how much of the water in the plume is primary magmatic water, as compared to entrained water from the atmosphere or from lakes or the ocean?

What are the detailed chemical and microphysical transformations that occur in the eruption column and downwind plume, and how do they affect the composition of the stratospheric injection? In particular, if the eruption is rich in Cl, would all of it be washed out in the plume or would some be injected into the stratosphere, with consequences for ozone chemistry [*Tabazadeh and Turco*, 1993]? Does the injection of water vapor from the volcanic input plus that entrained from the atmosphere, especially in a moist, tropical environment, provide an important source of stratospheric water vapor, or is the amount negligible? Would subsequent heating of the lower stratosphere by radiative absorption by the aerosol cloud produce a warmer tropopause in the tropics, reducing the cold trap and producing an increased flux of water vapor into the stratosphere for a year or two? This seems to have happened after the 1982 El Chichón eruption, but not after the 1991 Mt. Pinatubo eruption [*Shepherd*, 2002]. Why? Does this mechanism explain part of the interdecadal upward trend in stratospheric water vapor, as suggested by *Joshi and Shine* [2003]?

How can we better quantify the record of past climatically-significant volcanism? To measure the natural climatic forcing from volcanic eruptions for the past, so that we may place anthropogenic climate change in context, we need a better record of the frequency and magnitude and sulfur-producing potential of past eruptions [e.g., *Halmer et al.*, 2002]. Previous volcanic indices, the dust veil index [DVI; *Lamb*, 1970, 1977, 1983], the volcanic explosivity index [VEI; *Newhall and Self*, 1982; *Simkin et al.*, 1981, *Simkin and Siebert*, 1994], and *Mitchell*'s [1970], all have limitations [*Rampino and Self*, 1982], as discussed in detail by *Robock and Free* [1995]. *Robock and Free* [1995] concluded that an ice-core-based index would potentially be superior, as it would include actual physical observations of the remnants of the climatically significant component (sulfate) of each eruption, if sufficient cores were available to overcome the natural noise in each individual core.

Although *Rind* [1996] estimates that the volcanic forcing is potentially easier to capture than the solar forcing (in particular the low frequency part), the initial volcanic sulfate loading in the atmosphere is uncertain if estimated using ice core sulfate flux data from only one or a few cores. *Robock and Free* [1995] showed that any pair of ice core records of volcanic sulfate is poorly correlated, but when a larger number were combined, the volcanic signal becomes clearer. *Zielinski et al.* [1997] pointed out that there still is no complete understanding of variability from core to core resulting in only a 75% chance that an El Chichón sized event is even recorded in any particular core. This is even the case for large eruptions as discussed by *Cole-Dai et al.* [2000] for the 1259 eruption [see also *Mosley-Thompson, et al.*, 2003]. Events can be missing and biases are potentially large using single or a small number of cores.

Now the scientific community has the opportunity to take advantage of a significantly larger number of ice core observations, and combine them with a new understanding of stratospheric transport, to produce an improved index of past volcanism to force climate models. *Robock and Free* [1995, 1996] and *Robertson et al.* [2001] collected data from a number of cores and generated hemispherically averaged volcanic sulfate fluxes. However, since the mid-1990s, a number of new high-resolution cores with very accurate age control have been drilled and new data have been published. New techniques have been developed to analyze cores for the volcanic signal [*Naveau et al.*, 2003] and to prescribe the latitudinal and seasonal distribution of stratospheric aerosols in the stratosphere [*Ammann et al.*, 2003]. Among the new cores becoming available are those of *Budner et al.* [2003] and *Mosley-Thompson et al.* [2003].

A major advance to allow better interpretation of the location of eruptions that produce ice core signatures would be better atmospheric models of transport and deposition that could trace sulfate aerosols from the vent to the ice. Such transport and deposition models are now being developed.

Ice cores will not give detailed information about tropospheric emissions of volcanoes, which could be very important for regional weather and climate. However, real-time observations and modeling are now being conducted by the nine Volcanic Ash Advisory Centers around the world, which issue warnings for aircraft, and their output could be archived over time. In addition, the new "A-Train" of satellites (Aqua, Cloudsat, Calipso, Parasol, and Aura) [*Stephens et al.*, 2002] will provide enhanced measurement capability for tropospheric aerosols.

Can we design an improved system for measuring and monitoring the atmospheric gases and aerosols resulting from future eruptions? In spite of current technology, without better planning and an investment in equipment, there will be significant gaps in observations of the next major volcanic eruption. To be ready for the next major eruption, given the lack of a global satellite monitoring system, we should have a fleet of stratospheric balloons, lidar-equipped airplanes, and stratospheric airplanes with the capability for in situ observations ready to be deployed within weeks of the eruption. While there are many lidar observatories in the Northern Hemisphere midlatitudes, and several in the Southern Hemisphere midlatitudes, there are no lidars in the Tropics designed for measuring stratospheric aerosols, with the exception of the one in Bandung, Indonesia (6.9°S, 107.6°E), which is plagued by bad weather. It would be relatively cheap and quick to fill in this gap [*Robock and Antuña*, 2001]. While the A-Train [*Stephens et al.*, 2002] will include the first space-based lidars, they will not be as sensitive as ground-based ones, and will need ancillary observations for calibration and validation. However, a new technique to measure SO_2 using observations from the TIROS Operational Vertical Sounder (TOVS) instrument, which has been in orbit on different satellites for the past 25 yr, will prove useful [*Prata et al.*, 2003].

Near-vent observations of volcanic gases and aerosol emissions, unless the eruption is forecast in advance as were Mount St. Helens in 1980 and Mount Pinatubo in 1991, will depend on work with local observers. As many volcanoes are in developing countries, a program to train, work with, and support local observers would significantly enhance our ability to monitor small and medium size eruptions.

Because of the diversity of observations available for eruptions, a data assimilation system using atmospheric models must be developed, which will be the only way to produce a stratospheric aerosol data set that can be used for atmospheric chemistry and climate calculations. The need for a stratospheric aerosol data set for general circulation model (GCM) studies covering an extended time interval has long been recognized [*Robock*, 2000, 2001]. *Sato et al*. [1993] developed a data set of zonally-averaged stratospheric aerosol optical depth at $\lambda = 0.55$ μm for the period 1850-1990. However, for GCM experiments, information about the spectral dependence of aerosol radiative properties and their vertical distribution is necessary. *Andronova et al*. [2000] calculated volcanic radiative forcing at the tropopause level using optical depths from *Sato et al*. [1993] and employed a regression relation estimated for the post-Pinatubo period using aerosol characteristics from *Stenchikov et al*. [1998], but did not produce the vertical distribution of aerosols.

The Stratospheric Aerosol and Gas Experiment (SAGE) and Stratospheric Aerosol Measurement projects [*McCormick et al*., 1979; *Mauldin et al*., 1985; *McCormick*, 1987; *Thomason*, 1991; *Veiga*, 1993] have provided more than 20 years of three-dimensional data of stratospheric aerosol spectral extinction, the longest such record. *Hitchman et al*. [1994] and *Stevermer et al*. [2000] used these data to study the zonal mean aerosol climatology. However, SAGE II only samples each latitude band every 40 days, does not cover polar regions, and has significant gaps in regions of heavy aerosol loading, where the aerosol cloud causes so much extinction of the solar signal that no retrievals were possible. SAGE III [*Thomason and Taha*, 2003] is now providing high-latitude coverage but sketchy low latitude observations. The eruption of El Chichón in 1982 (the second most important in terms of atmospheric impact in the second half of the 20th century after Mt. Pinatubo) was not covered by SAGE observations because the SAGE I instrument failed in 1981, and SAGE II was only launched in 1984. The

Stratosphere Mesosphere Explorer satellite did take some observations during the El Chichón period, but its observations will have to be combined with lidar [*Antuña et al*., 2002, 2003] and other data in the context of a data assimilation system to produce a consistent three-dimensional global stratospheric aerosol data set that can be used to study the climatic response during the last 20 years of the 20th century, which included the El Chichón and Pinatubo eruptions.

How can we better model the climatic impact of eruptions, including microphysics, chemistry, transport, radiation, and dynamical responses? A few GCMs have simulated the general climatic response to the 1991 Pinatubo eruption using a specified distribution of aerosols [*Stenchikov et al*., 1998]. Remaining problems include adequately accounting for the effects of the Quasi-Biennial Oscillation, microphysical evolution and transport of the aerosols, effects on ozone, the amount and impacts of water vapor injection into the stratosphere, and the regional response, although some progress is being made along those lines [*Stenchikov et al*., 2003, 2003]. Data assimilation experiments and model intercomparison programs, like the Pinatubo Model Intercomparison Project (PINMIP) now being carried out under the GCM-Reality Intercomparison Project for SPARC (GRIPS) [*Pawson et al*., 2000], will help to improve the models. The ultimate goal would be to couple conduit models of magma, plume models, and microphysical and transport models in the stratosphere to climate models to predict the impact of the next large eruption as soon as it occurs.

How do high-latitude eruptions affect climate? Most research on the impacts of volcanic eruptions on climate has focused on tropical explosive eruptions, such as the recent 1963 Agung, 1982 El Chichón, and 1991 Pinatubo eruptions. However, two of the largest eruptions of the past five centuries occurred at high latitudes of the Northern Hemisphere, the 1783-1784 Laki eruption in Iceland [*Franklin*, 1784; *Thordarson and Self*, 2003], and the 1912 Katmai eruption in Alaska. Mt. Hudson in Chile erupted in 1991, but its S emissions were much smaller than those of Pinatubo, so it was not possible to isolate its effects. The 8-month-long Laki eruption from a 27-km long fissure (Figure 3) affected air quality and climate for most of the Northern Hemisphere and if it occurred today could halt air traffic there for six months [*Thordarson and Self*, 2003]. The summer of 1783 had extreme and unusual weather. In the summer, the Arctic was unusually cold, but Western Europe was unusually hot. The people of Japan suffered through the most severe famine in their history. The winter of 1783-84, on the other hand, was one of the most severe in Europe and North America in the last 250 years.

The mechanisms by which this eruption produced these climate changes are not well understood. How could volcanic aerosols, which we normally think of as cooling the surface in the summer [*Robock*, 2000], have produced the record warm temperatures in Europe? Was the severe cold in the winter of 1783-84 a negative mode of the Arctic Oscillation, and if so how was it produced? The 1783 Asama eruption in Japan may have contributed to these effects, and needs to be considered when unraveling the climatic response. Questions that still need answers include whether high latitude eruptions can affect the climate in the other hemisphere, and what the effects would be of eruptions from high latitude Southern Hemisphere volcanoes.

How important are indirect effects of volcanic emissions on clouds? The indirect effect of tropospheric sulfate emissions on clouds [*Penner et al.*, 2001] is an area of intensive research. Sulfate aerosols serve as cloud condensation nuclei, and adding sulfate aerosols to clouds produces more, but smaller could droplets. This increases the albedo of the cloud, producing additional net cooling of the climate system, and is referred to as the “first indirect effect” of sulfate aerosols. In addition, the cloud lifetime and structure can change, the “second indirect effect.” Thus, sulfate aerosols can affect the atmospheric thermal structure, surface temperatures, and precipitation.

Can volcanic examples be used to improve current models? While climate scientists are concerned with anthropogenic sulfate emissions, they tend to be diffuse and misxed with other pollutants. Could the cloud response to intense volcanic emissions, such as in Hawaii or Sicily, be used to isolate and study these processes? Another, more difficult question to address, is whether volcanic aerosols from the stratosphere seed cirrus clouds and affect their optical properties and lifetimes?

Where are the important potential sites for future eruptions? For monitoring, emergency response, warning aircraft, and real-time prediction of climatic response, it would be helpful to know which volcanoes would be most likely to erupt. This will involve production of improved risk maps and catalogs of hazards. It will again require working with and supporting local observers.

3. Discussion

Some research aimed at answering the above questions is already under way, nurtured by the interactions of the volcanology and climate communities at the 2002 “Volcanism and the Earth’s Atmosphere” Chapman Conference [*Robock and Oppenheimer*, 2003], and subsequent conference sessions, such as those at the 2003 IUGG meeting in Sapporo. Future progress in understanding this important aspect of planetary interactions of the lithosphere with the climate system will result from well-funded projects that address the above questions. I look forward to seeing graduate students and other researchers tackle these interesting issues in the next few years.

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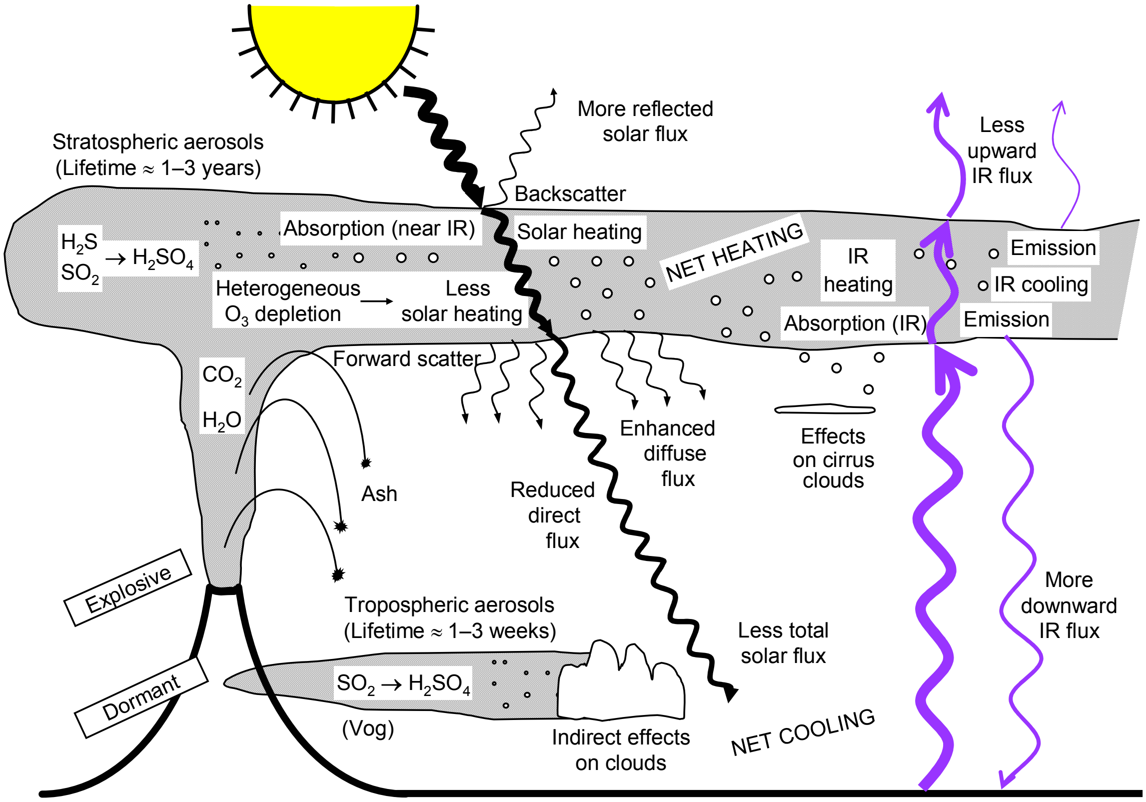
Figure 1. Schematic diagram of volcanic inputs to the atmosphere and their effects. [Adapted from Plate 1 of Robock (2000), © Copyright, American Geophysical Union.]

Figure 2. A World Airways DC-10 at Cubi Point Naval Air Station, 40 km from Mt. Pinatubo, tipped backwards from the volcanic ash on the stabilizer. What appears to be snow is actually volcanic ash on the ground. These large particles, while producing devastating local effects and short-term weather effects, fall out of the atmosphere too quickly to affect climate. [U.S. Navy photograph by R. L. Rieger]

Figure 3. The Laki cone row, looking southwest from the Laki mountain. Note bus and cars parked at bottom for scale. Cones in distance are obscured by rain shower. Photograph by Alan Robock, August 30, 2002.



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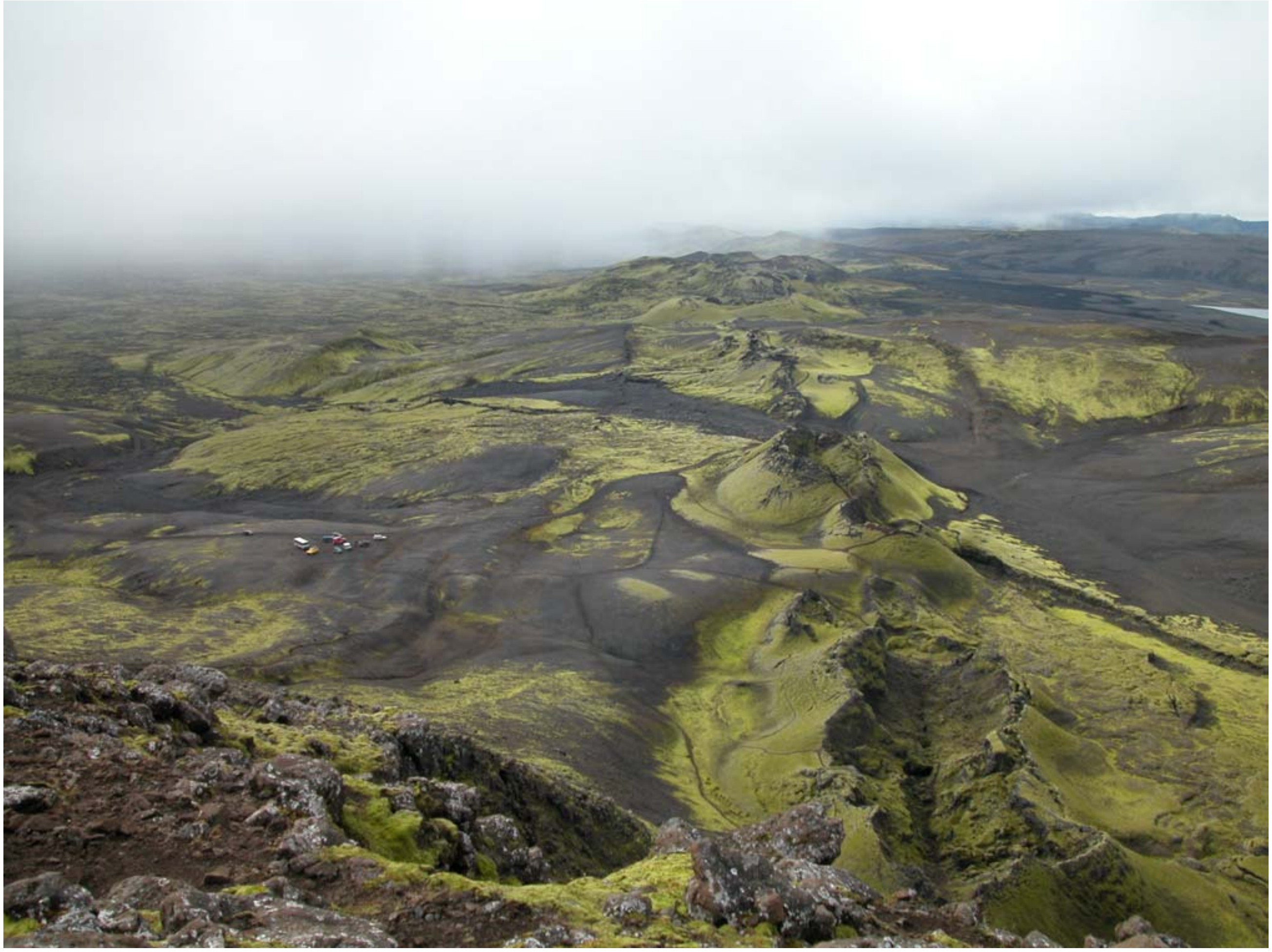

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