White paper on

Measuring the Impacts of Volcanic Eruptions on Climate and Atmospheric Chemistry

Owen B. Toon
UCB 600
LASP
University of Colorado
Boulder, CO 80303
303-492-1534
toon@lasp.colorado.edu

Paul Newman
Code 610.0
NASA/GSFC
Greenbelt, MD 20771
(301) 614-5985
Paul.A.Newman@nasa.gov

Alan Robock
Department of Environmental Sciences
Rutgers University
14 College Farm Road
New Brunswick, NJ 08901-8551 USA
+1-848-932-5751
robock@envsci.rutgers.edu

Anja Schmidt
School of Earth and Environment
University of Leeds
Leeds, United Kingdom
A.Schmidt@leeds.ac.uk

Susan Solomon
Department of Earth, Atmospheric and Planetary Sciences
Massachusetts Institute of technology
Boston, Massachusetts
solos@MIT.EDU

1. Key challenge: Understanding the impact of volcanic eruptions on climate and atmospheric chemistry

Stratospheric hazes created by explosive volcanic eruptions have been observed to scatter sunlight back toward space, reducing the Earth's radiative heating and cooling the surface. The cooler surface and troposphere are also associated with reduced atmospheric water vapor and precipitation. Volcanic sulfate aerosols also absorb sunlight and terrestrial radiation, heating the stratosphere, which for optically thick volcanic clouds can lead to stratospheric dynamical changes, spreading the volcanic aerosols in latitude more quickly and more extensively than would occur without this heating. Heterogeneous chemical reactions that occur on volcanic cloud particles alter stratospheric chemistry and lead to changes in ozone concentrations. Scattering of sunlight by volcanic clouds creates a variety of optical phenomena including: hazy skies during the day; large bright regions of the sky near sunset and sunrise, which can make it difficult to see and cause traffic accidents; a change in the ratio of diffuse to direct sunlight, which has an impact on photosynthesis and carbon uptake; changes in ultraviolet light which alter photochemical reaction rates; and beautiful twilight displays. Each of these changes, and others noted in Table 1, are important not only because of their potential impacts on humans and the environment, but also because they teach us about how the atmosphere works, serve as tests of Earth system models, provide analogs of how stratospheric aerosol geoengineering might function (including the growth and transport of sulfate aerosols as well as the climate response), and provide examples of the sensitivity of climate to perturbations in the Earth's radiation budget. In addition, information on volcanic impacts provides foreknowledge for government officials and policy makers. For all of these reasons it is important that the science community measure the structure and properties of rapidly evolving volcanic clouds and the response of the climate and atmospheric chemistry to these clouds.

2. Why is this challenge timely?

During the past decade advances in measurements of the atmospheric state and advances in analysis techniques have allowed the science community to measure the perturbations to surface temperature, tropospheric temperature, stratospheric temperature, clear-sky shortwave radiation, atmospheric water vapor, and precipitation following relatively modest injections of volcanic material into the stratosphere. These injections, for example, have contributed to the slowing of global warming in the past decade, the so-called "global warming hiatus." Given the intense focus on climate change it is increasingly important that we be able to disentangle volcanic effects from human-produced forcings of climate.

Models of volcanic aerosols effects on climate have advanced in the past decade and several are capable of tying together the complex evolution of atmospheric chemistry, particle microphysics, radiative forcing and climate change that occur after eruptions. We have reached an unprecedented ability to understand and organize the complex atmospheric system.

New observations from aircraft, balloon and satellite measurements have expanded our capability to measure this problem's various components.

Taken together, these advances in measuring the atmospheric state, gases, and aerosols, and modeling the impacts of particles on climate and chemistry, would allow us to evaluate the impact of the next major volcanic eruption, if we are well prepared to do so immediately after it occurs. This would also improve the understanding of the effects of more numerous smaller eruptions.

3. Why are space-based observations fundamental?

The atmospheric state is currently measured with a large network of ground-based, balloon and satellite instruments. However, the complexity of volcanic impacts on climate and chemistry requires that a large number of particulate and gaseous species be measured (see Tables 2 and 3). Satellites can measure many of these parameters, and are essential to obtain a global data set as the clouds evolve.

The odds of a volcanic eruption whose stratospheric cloud is able to force the climate at more than 1 W m^{-2}, such as that of Pinatubo in 1991, are about 3% in a given year. However, the Microwave Limb Sounder instrument detected 22 injections of SO_2 into the stratosphere, or near the tropopause, in a period of 10 years so there are approximately two small events for study each year. Some of these SO_2 injections were too small to modify measurably the stratospheric optical depth, except locally. From 2000 to 2015, global or tropical optical depth measurements from satellites revealed 7 detectable perturbations from volcanic injections. The larger optical depth changes were associated with measured changes in clear-sky shortwave radiation of order 0.05 to considerably greater than 0.1 W m^{-2}. Analyses of climate perturbations showed a detectable signal from at least 5 of these eruptions. Therefore, the odds of a volcanic eruption with both a detectable injection and an impact on the climate are about 30% in a given year, with even larger odds of smaller-magnitude eruptions that can nonetheless provide information about chemical, microphysical, and transport processes.

Volcanic eruptions occur with little or no warning. Most volcanoes are located in the tropics or high latitudes, where few ground-based, balloon-borne or aircraft-borne instruments are readily available. Much of the interesting evolution occurs within a few months, but clouds persist for few years. These factors make satellites essential for many of the needed measurements. However, there are measurements that satellites currently cannot make, and satellites need to be calibrated. Therefore, aircraft and balloon measurements will also be needed.

4. What is the ability of existing satellites to make the needed measurements?

Table 4 lists the satellites that are currently in orbit and making relevant measurements. Numerous satellite instruments are able to measure SO_2. Several instruments are able to measure the column aerosol optical depth. However, most of these are not able to vertically profile the optical depth. Nadir-viewing instruments have difficulty detecting small volcanic clouds against the background of the tropospheric aerosols. The CALIOP lidar is very valuable for high-resolution vertical information. Limb sounders such as the Canadian OSIRIS or the SUOMI OMPS limb sounder also provide useful vertical profiles of aerosols. However, these measurements are not as straightforward as those from previous solar occultation measurements from instruments such as SAGE. Distinguishing clouds from aerosols near the tropopause challenges many space-based measurements.

Unfortunately, most of the satellites listed in Table 4 are aging. It is especially important that new lidars, and new solar occultation instruments are flown. There are new types of lidars, high spectral resolution lidars, which can directly measure aerosol optical depth. New lidars should also measure depolarization at visible and near infrared wavelengths so that dust and sulfates can be distinguished better than with CALIOP which only measures visible depolarization. There are also new types of solar occultation instruments that can be flown as constellations (to increase the frequency of measurements), and whose size, weight and cost are so small that they can be deployed as CubeSats. These instruments can measure the vertical profiles of optical depth of aerosols as well as the abundances of many stratospheric gases, such as water vapor, ozone, hydrochloric acid, and nitrogen oxides. They can also distinguish the composition of aerosols, for example distinguishing sulfuric acid from dust with spectroscopy. Instruments such as these will be essential in the future to accurately measure volcanic particles and their impacts. Table 5 summarizes the highest priority satellites.

5. How can we link space-based observations with other observations to increase the value of data for addressing key scientific questions and societal needs?

Robust ground-based, aircraft and balloon programs are essential for augmenting satellite observations of volcanic clouds. Table 5 summarizes the needed programs. These platforms should be used to complete our understanding of the stratospheric sulfur cycle, which has not been fully explored. They should also be used to investigate the properties of the ambient aerosol layer and its perturbations by small volcanic eruptions of the sort that occur every few years. Understanding the background aerosols structure and composition is necessary in order to understand how volcanoes perturb that layer.

The first step in this program should be development, testing, and evaluation of the instruments that are currently available to address the relevant issues in Tables 1-3. The second step should be to set up a rapid response program (~ 2 weeks) for small balloons so that measurements can be quickly deployed and made in clouds from small volcanic eruptions. Aircraft measurements should be directed to the later stages (1-2 months up to a few years) of volcanic cloud evolution. A plan should be set up to enable a relatively quick response using NASA aircraft. This plan will require that new instruments be developed and tested in advance.

6. What are the anticipated scientific and societal benefits?

Large volcanic eruptions have had dramatic global impacts on humans and the environment, as demonstrated by Mt. Pinatubo. Some eruptions could be devastating to modern society worldwide, but these are fortunately rare. Volcanic injections into the stratosphere teach us how the atmosphere works, serve as tests of Earth system models, provide examples of how stratospheric aerosol geoengineering might function, and provide examples of the sensitivity of climate to perturbations in the Earth's radiation budget. For all these reasons it is important that the science community measure the properties of rapidly evolving volcanic clouds and the response of the climate and atmospheric chemistry to them.

7. What science communities would be involved?

A wide range of science communities would be involved in this program. Both the stratospheric and global climate communities have worked on this problem. There are substantial theoretical activities underway both at NASA labs and at universities related to the issues discussed here. Satellite groups are making observations, and are also developing new instruments such as those discussed here.

Table 1. Observed changes in climate and chemistry after eruptions

Observed	**Probable cause**
Cooling troposphere and surface	Reduction in shortwave forcing by aerosol
Tropopause and strat. warming	Sunlight and IR absorption by aerosol
Mid-lat. N.H. winter warming	Strat./troposphere dynamical interaction
Rapid spread of volcanic clouds	Alteration of atmospheric dynamics
Ozone loss / enhanced surface UV	Heterogeneous reactions on sulfate aerosols
Hazy skies/bright twilights/ reduction in shortwave at surface	Scattering by aerosols
Enhanced diffuse radiation at surface/ enhanced CO_2 sink	Scattering by aerosols
Change in stratospheric CH_4, H_2O	Change in dynamics, tropopause temperature
Change in tropospheric CO_2, CO, CH_4	Increase/Reduction in UV in troposphere, drop in sea surface T, coincidence
Reduction in water vapor column	Sea and land surface cooling
Reduction in global average precipitation	Reduction of solar heating of sea surface
Expected	
Cirrus cloud increase/decrease	Seeding by large sulfate particles
Cooler days	Loss of sunlight
Cooler nights	Loss of sunlight, little IR change
Polar amplification	Decreased poleward energy flux
Increase in sea ice	Polar cooling

Table 2 Particle properties that need to be determined as functions of time and space

Particle properties to measure	**Possible ranges**
Composition	Dust, sulfates
Size distribution	nm to tens of microns
Number	nm to tens of micron
Mass	
Area	
Shape	Spheres/fractals
Optical constants	Dust
Extinction optical depth	0.001 to 1
Scattering optical depth	0.001 to 1
Absorption optical depth	0.001 to 1
Scattering phase function	

Table 3 Gases that need to be measured

Gas to measure	**Purpose**
SO_2	Need to constrain cloud mass
H_2S, other sulfur gases that might be injected CS_2, COS	May be in plume and carry mass
H_2SO_4, other sulfur cycle components	Need to close sulfur cycle
Water vapor	May be significant esp. high altitude
HCl, other injected gases with halogens, N, etc	Quantify injections of ozone destroying species
Components of O_3 cycle	Understand perturbed chemistry
Tracers	Useful to examine altered dynamics

Table 4 Current satellites that measure volcanic material

Satellite/ Instrument	Agency	Region	Research operational	Type		Data Product(s)
Geostationary						
GOES – R/ ABI	NOAA/ NASA	Full Disc. America	Operational	IR	Day/ Night	mass column density, height
GomSat/ TEMPO	NASA	N. America	Research,	UV-VIS	Day	SO_2, UV Ash Index, advanced ash
Sentinel 4	ESA/ EUMETSAT	Europe	Operational	UV, IR	Day	SO_2 and index
GEMS	KSA	Korea, China	Research	UV-VIS	Day	SO_2 and AI (Ash)
MSG/ SEVIRI	ESA	Europe	Research,	IR		ash and SO_2
MTSAT	JMA	East Asia				
Polar Orbiting						
Aura/OMI/ MLS	NASA/KNMI/FMI		Research, pm	UV/microwave	Day	SO_2 and Aerosol index
Aqua/AIRS	NASA		Research,	IR/VIS	Day/ Night	SO_2, IR Ash Index (BTD), advanced ash, aerosol scattering
Aqua/Terra /MODIS/ MISR			am/pm			
Suomi/OMPS NP	NASA/ NOAA		Operational, pm	UV	Day	SO_2 and Aerosol index
MetOp/GOME2	ESA/ EUMETSAT		Operational, am	UV	Day	SO_2 and AI (Ash)
MetOp/IASI	ESA/ EUMETSAT		Operational, am/pm	IR	Day/ Night	SO_2, Ash Index (BTD), advanced ash
Suomi/VIIRS	NASA/ NOAA		Operational am/pn	IR	Day/ Night	SO_2, IR Ash Index (BTD) Particle scattering
Suomi/OMPS LP	NASA/ NOAA		Operational am	UV	Day	Aerosol profile
CALIPSO/ CALIOP	NASA		Research	VIS	Day/ Night	Particle scattering, aerosol profile
ISS/CATS	NASA		Research	VIS	Day/ Night	Particle scattering, aerosol profile
Odin/ OSIRIS	Canada		Research	UV/VIS	Day	Particle scattering, aerosol profile

Table 5 Summary of suggested program to measure volcanoes and their impact on atmospheric chemistry and climate

Continuous CALIPSO-type lidar instruments in space
Continuous solar occultation-type instruments in space
Inventory aircraft / balloon measurements and add or refurbish instruments.
Develop rapid deployment plan to catch initial evolution (~2 weeks).
Use small eruptions ~ 1 per year/ambient layer to develop payloads.
Agencies need to be prepared to act quickly. Requires a plan in advance.