Blowin' in the Wind

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Volcanic eruptions inject gases and ash into the atmosphere, with climatic impacts on time scales up to decades. At the AGU Chapman Conference on Volcanism and the Earth's Atmosphere, held in Santorini, Greece, June 17-21, 2003, 108 scientists gathered to discuss the current level of understanding of volcanic emissions and the atmospheric response, and to outline topics for future interdisciplinary collaboration that will lead to better understanding and prediction of the effects of future large explosive eruptions. Perched on the rim of the caldera of the 17th Century BCE eruption that has been linked to the legend of Atlantis, the decline of the Minoan civilization in Crete, and the Biblical stories of the parting of the Red Sea and the Egyptian plagues, the Thera Foundation Conference Center served as a perfect venue for the conference. On the last day of the meeting, the entire group discussed future research priorities, organized by the important scientific questions. Continued research is needed and will be focused on these issues:

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. What are the magmatic controls on how much sulfur is emitted from eruptions? 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?

How do quiescent emissions change over time? What is their current source strength? Explosive eruptions are not the only volcanic source to the atmosphere. While quiescent emissions have regional rather than global impacts, they are important in the context of anthropogenic tropospheric aerosols [*Graf et al.*, 1997]. If the source strength changes significantly over time, this can produce large regional climate changes. More monitoring of the chemistry and magnitude of continuing quiescent emissions will be essential if we are to understand issues such as the impact of anthropogenic aerosols.

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 of past eruptions. Several new ice core analyses were presented by Ellen Mosley-Thompson, Drew Budner, and Andrei Kurbatov, but more are needed, especially from Alaska and other high Arctic sites. Unlike many other attempts to reconstruct past climate and its forcing, the evidence from past volcanic eruptions is preserved in ice cores, waiting for us to analyze it. 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. More study is also needed of possible volcanic components of distal sediments on land and in lakes and deep oceans. Volcanic geology and stratigraphy remain important areas of study, and continued refinement of petrologic methods will enhance interpretation of in situ deposits. Archeology and biostratigraphy of deposits associated with eruptions are relatively untapped approaches that can help to date and interpret the local environmental impact of past eruptions.

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 may be significant gaps in observations of the next major volcanic eruption. Near vent observations, 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 will significantly enhance our ability to monitor small and medium size eruptions. 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. It would be relatively cheap and quick to fill in this gap [*Robock and Antuña*, 2001]. 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.

How can we better model the climatic impact of eruptions, including microphysics, chemistry, transport, radiation, and dynamical responses? A few general circulation models 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. 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 discussed above, 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. An important ancillary activity is to better characterize the climatic response to past volcanism, with tree ring analysis being an important source of information.

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. But there have been larger high latitude eruptions in the historic past which have also had profound influences, the most notable recent one being the 1783 Laki fissure eruption in Iceland [*Franklin*, 1784]. Thor Thordarson, Ellie Highwood, and David Stevenson presented new analyses of emissions from the 8-month-long eruption and climate model simulations of its effects, and demonstrated the need for additional work on this topic. The eruption 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*, 2002]. 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 is an area of intensive research. Can volcanic examples be used to improve current models? Do the 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.

Some research aimed at answering the above questions is already under way, nurtured by the interactions of the volcanology and climate communities at this Chapman Conference. An AGU book with papers from the Chapman Conference will be published next year. Continued support by funding agencies to enable all of the research listed above would produce valuable scientific results. "The answer, my friend, is blowin' in the wind." [*Dylan*, 1962]

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