Supplementary material to “Volcanism and the Atmosphere”

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After the 2002 Santorini meeting, a list of important scientific questions was drawn up to provide targets for future research [Robock, Alan, 2002: Blowin’ in the wind: Research priorities for climate effects of volcanic eruptions. *Eos*, *83*, 472]. Ten years later we can review those recommendations in light of the highlights of research findings presented at this latest Chapman conference.

What exactly goes into the atmosphere during a volcanic eruption? It has long been known that volcanic SO_2 introduced into the stratosphere causes climate change, while ash and gas in the troposphere is an aviation hazard. New results showed that the growth of stratospheric sulfate particles limits their effects on climate for very large eruptions, that the Asian summer monsoon provides a new pathway for stratospheric injection from the upper troposphere, and that significant amounts of halogens (Cl, F, and Br) - also released in volcanic eruptions - have been detected in tropospheric and stratospheric plumes. Furthermore, new remote sensing observations and trajectory models allowed a detailed assessment of the transport and dispersal of the Eyjafjallajökull ash plume.

How do quiescent emissions change over time? It has been found that quiescently degassing volcanoes are strong sources of halogens in the troposphere. This includes HCl and photochemically active Cl_2 and HOCL. Robert Martin reported on the uptake of halogens into acidic sulfate particles and the deposition of trace metals such as mercury around Mt. Etna. Deanna Donohue presented results of 3-D modeling of the atmospheric chemistry of quiescently outgassing volcanoes such as Etna. This is expected to improve our understanding of plume chemistry and the health and environmental effects of trace gas emissions from long-term degassing.

How can we better quantify the record of past climatically significant volcanism? One of the highlights of the meeting was the sessions on historical eruptions and their effects. Evidence of past eruptions comes from historical records, ice cores, tree rings and volcanological investigations of the products of the eruptions. These data can provide case studies of the effects of volcanic eruptions on the atmosphere. Several talks concluded that the maximum volcanic eruption that we might expect in the near term is a Magnitude 7 event like the Tambora AD 1815 eruption, which may have a return period of about 200 years. The Tambora event was associated with significant climate perturbation and 1816 is widely known as the “Year Without a Summer” with serious famine and high food prices in Europe and eastern North America. A modern Tambora aerosol cloud would most likely cause severe problems for crop productivity in many parts of the world. Áslaug Geirsdóttir reported on the largest Holocene basaltic eruption (24 km^3), the ~8.6 ka BP Thjórsárhraun flood lava event (the lava flow is near the conference site), which may correlate with a cooling period seen in ice core and other climate proxy records.

Another question addressed at the meeting was: Did volcanism trigger the Little Ice Age? Gifford Miller presented data showing that the Little Ice Age began abruptly between 1275 and 1300 AD, (with an intensification of summer cold and ice growth between 1435 and 1455) after decades of unusually intense volcanic activity. Some apparently large eruptions (with large acidity peaks in polar ice cores) such as the AD 1258 and 1171 events are still not confidently connected with a source volcano. Furthermore, climate models show that closely spaced eruptions can produce decades long North Atlantic cooling with positive sea-ice feedbacks. During a session on proxy data, David Ferris presented a new 6,000-year record of volcanic fallout from the West Antarctic Ice Sheet Divide ice core, which shows a high frequency of volcanic events correlated with the inception of the Little Ice Age.

It was also noted that the season in which an eruption occurs can have a relatively large effect on the impact of volcanic aerosols, and on the amounts of sulfuric acid aerosols that fall out over the northern and southern hemisphere icecaps. Sulfate deposition on the Greenland and Antarctic ice sheets has been found to be non-linear with respect to eruption magnitude. The impact of post-eruption atmospheric circulation changes on ice-core records of volcanism was also discussed.

There was debate concerning how well tree-ring based reconstructions of temperature changes match the observational climatic record at times of large volcanic eruptions. Michael Mann presented his evaluation that tree ring reconstructions of temperature in some cases show muted signals of climate change and may be missing some events entirely, whereas Rosanne D’Arrigo argued that tree ring records are complete and that volcanically induced cold events show up clearly in tree-ring data. Phil Jones presented evidence that tree-ring reconstructions show that cool north European summers are linked in general to times of explosive volcanic eruptions.

Large effusive Icelandic eruptions like the Laki AD 1783 and the Eldgjá AD 939 and their climatic impacts were also discussed. Anja Schmidt pointed out the importance of tropospheric aerosols in these large flood lava eruptions. The 939 AD Eldgjá was erupted from the Katla volcanic system and Thor Thordarson reported that the AD 939 Eldgjá eruption not only produced a large lava flow (a minimum of 780 km^2 in area), but also numerous phreatomagmatic and magmatic tephra fall units, which collectively amount to more than 5 km^3 of tephra, comparable to sizable explosive eruptions like Pinatubo 1991. The tephra deposit produced by Eldgjá is one of the four largest tephra layers in Iceland since Settlement (874 AD).

Can we design an improved system for measuring and monitoring the volcanic gases and aerosols resulting from future eruptions? Several talks were focused on more accurate tracking of plumes of SO_2 and ash from ground-based and satellite observations, to provide rapid information for aviation authorities. For example, satellite derived products have been developed to provide information to forecasters at Volcanic Ash Advisory Centers (VAACs).

Real-time observations of ash and aerosol clouds are now provided by several types of stationary and airborne instruments, and by instruments mounted on earth satellites. Presentations at the meeting included a host of satellite borne studies of ash and aerosol clouds. Passive remote sensing using microwaves, thermal infrared (TIR) and ultra-violet (UV) regions of the electromagnetic spectrum are used to detect the presence of gases and particles in the atmosphere. At present, there are UV instruments on six satellites making measurements going back to 1979. In the IR, there are also instruments on six different satellites capable of detecting SO_2 in the atmosphere. A promising new method presented at the meeting is detection of the thermal structure of the atmosphere from limb scanning of the earth by satellites using radio occultation methods.

Ash was sampled in several European sites; one clever study coordinated by the British Geological Survey and reported on by John A Stevenson analyzed ash deposition in the UK from more than 100 sticky tape samples, in part collected by the public. Deborah Lee reported on the WEZARD (weather hazards of aeronautics) program, which brings together the aviation industry and a group of 24 European National Meteorological Services to identify activities needed to develop a safer air transport system and limit the effects of disrupting volcanic events. The events of April 2010 led to the formation of a partnership of nine UK institutes, working with 24 international partners in the VANAHEIM consortium using observations and modeling of volcanic plumes.

Other presentations involved instrumentation to monitor SO_2 and ash in the atmosphere in real time. Several multi-sensor instruments mounted on satellites can measure atmospheric SO_2 using UV or IR sensor, at timescales back to 1979. The Canadian built OSIRIS instrument currently in operation on the Swedish Odin satellite has yielded ten years of atmospheric limb radiance spectra in the UV, visible and near infrared wavelengths, used to retrieve vertical profiles of stratospheric aerosols. Lidar and radiometers at several observatories are now measuring aerosol optical depth in the stratosphere. For aviation directly, the AVOID system, (Airborne Volcanic Object Infrared Detector) is a new development of forward-looking ash detection system mounted on airplanes that could give a warning when planes are >50 km from an ash cloud.

How can we better model the climatic impact of eruptions, including microphysics, chemistry, transport, radiation, and dynamical processes? Volcanic eruption simulations of a range of magnitudes have been carried out using coupled aerosol general circulation models that simulate the full micro-physical lifecycles of the volcanic aerosols and feedbacks between the aerosol and atmospheric dynamics. Numerical models were discussed that simulate transport and deposition of volcanic ash and aerosols, and model the effects of volcanic eruptions on regional and global scales. New models include dynamical compartments of the atmosphere and ocean and an interactive carbon cycle with modules of terrestrial vegetation and soils as well as ocean chemistry. Brian Toon presented results of a three dimensional microphysical/climate model to investigate microparticle behavior in the stratosphere after large eruptions such as the 1991 Pinatubo eruption. Models of the effects of volcanic eruptions on the hydrological cycle were also discussed.

Claudia Timmreck presented an earth system model of the climatic effects of a super-eruption – the 74 ka BP Toba event. She found negative feedbacks, especially in the microphysics and particle growth in dense volcanic aerosols, which may limit the climatic effects of very large eruptions (even as “small” as Tambora 1815). Simulations of tropical volcanic eruptions using a general circulation model with coupled aerosol microphysics were used to assess the influence of the season of eruptions on the aerosol perturbations demonstrating that it may be important to the climatic consequences.

How do high latitude eruptions affect climate? Two keynote talks addressed the 1912 eruption of the high-latitude Katmai volcano in Alaska, the largest eruption of the 20th Century, on the centenary of that event. It has been found that high latitude eruptions in general affect mostly one hemisphere. The cooling of the winter of 1783-84 following the Laki eruption may have been enhanced by a negative phase of the North Atlantic Oscillation and an El Niño event in the same year.

Where are the important potential sites for future eruptions? Iceland features on average one eruption every 4-5 years and in the first 12 years of the 21st Century it has already featured five eruptions; Hekla in 2000, Grímsvötn in 2004, flank and summit events at Eyjafjallajökull in 2010 and Grímsvötn again in 2011. In recent years several other volcanic systems have shown signs of unrest, including Krýsuvík, Katla, and Askja. The possibility of a Katla fissure eruption like the great 934-40 AD Eldgjá AD event is a considerable worry because it would cause significant climate change and disruption of air traffic, possibly for several months. Many past Icelandic eruptions must have severely affected mainland Europe and the entire Northern Hemisphere.

The pros and cons of geoengineering with stratospheric aerosols were discussed by Alan Robock using volcanic eruptions as a proxy for the injection of aerosols into the upper atmosphere. He showed that volcanic eruptions warn us that while stratospheric geoengineering could cool the surface, reducing ice melt and sea level rise, producing pretty sunsets, and increasing the CO_2 sink, it could also reduce summer monsoon precipitation, destroy ozone, allowing more harmful UV at the surface, produce rapid warming when stopped, make the sky white, reduce solar power, perturb the ecology with more diffuse radiation, damage airplanes flying in the stratosphere, degrade astronomical observations, affect remote sensing, and affect stargazing.

It is now apparent that even a very small eruption such as the summit eruption at Eyjafjallajökull in 2010 can result in severe problems for aviation. Imagine the problems for global air travel that would be associated with a Magnitude 7 Tambora-type eruption!