Explosive Volcanic Eruptions and the Atmosphere

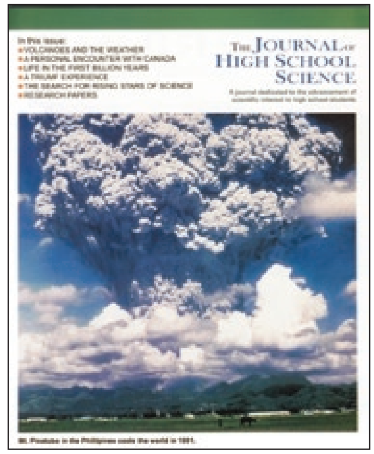
A Personal Reflection by Kevin Hamilton

The energy generated by radioactive decay inside the earth is eventually released to the atmosphere through various geothermal processes. On rare occasions, some of this energy is released in extremely brief and powerful explosive volcanic eruptions, sometimes called **Plinian eruptions** after the Roman naturalist **Pliny the Elder**, who perished studying the great eruption of Mt. Vesuvius in 79 AD. Plinian eruptions are devastating, the hot gases, debris falls, and tsunamis often killing many people.

The abruptness and enormous dynamical and chemical effects of such eruptions, however, also make them natural experiments that can be studied to elucidate important aspects of atmospheric behavior. Recently I was asked to write a cover article on "Volcanoes and the Weather" for the *Journal of High School Science*, a Canadian journal aimed at a worldwide audience of high school students (Hamilton, 2004). This invitation led me to reflect on how much meteorologists have learned through studying the aftermath of major eruptions, and on my own engagement with several very different aspects of volcanic effects over my career.

Summer Cooling

My introduction to the area of volcanic effects came unexpectedly in the mid-1980s when, as a new faculty member at McGill University in Montreal, Canada, I visited the university archives to study the long, continuous record of daily weather observations taken on the McGill campus. In the archives I happened to discover two of the earliest manuscript diaries of amateur instrumental weather observers unearthed anywhere in Canada. Most notably, I found the daily diary and weather record of **Rev. Alexander Sparks**, a clergyman living in Quebec City (47°N, 71°W) who took temperature observations at 8 a.m., noon, and 3 p.m. local time every day from December 1798 until the day of his death in March 1819. I recognized that this record included 1816, which is remembered in New England as the "year without a summer" and was famous for very cold summer weather and resulting crop failures. Coincidentally, the first thorough history of the weather in 1816 had just been published by the famous oceanographer **Henry Stommel**, with a focus on U.S. data (Stommel and Stommel, 1983). I was able to use the detailed records of Rev. Sparks, diaries from other amateur observers, and contemporary newspaper accounts to demonstrate that the anomalies seen in the United States in the summer of 1816 had clear counterparts in eastern Canada (Hamilton, 1986). The June–August 1816 mean temperatures at Quebec City were about 2°C lower than those during the previous decade. Even a heavy snowstorm was recorded on June 7, 1816—a month later than any snow accumulation at Quebec City in modern records. The following year, 1817, was also unusually cold in Rev. Sparks' observations.



Stommel and Stommel (1983) made a strong case that the climate anomalies in the summer of 1816 were geographically widespread (at least in the Northern Hemisphere) and resulted from the Plinian eruption of Mt. Tambora that had occurred a year earlier (April 1815) on the Indonesian island of Suwa. Today we know that a major explosive eruption ejects hot gases and solid aerosol material that can rise high into the stratosphere. Even the finest solid aerosol material mostly falls out over the first few weeks after the eruption, but a long-lasting effect is provided by increased sulfur content due to the stratospheric injection of sulfur dioxide. The sulfur dioxide reacts with the water vapor in the stratosphere to produce a thin layer of very small (typically <0.5 micron diameter) sulfuric acid droplets. These droplets do not settle gravitationally but remain in the stratosphere until the large-scale circulation flushes them back to the lower atmosphere, a process taking about two years. Since the aerosol layer reflects incident sunlight, we expect global-mean cooling of the lower atmosphere for the first two years following major Plinian eruptions, and that this cool anomaly may be most intense in the summer hemisphere (where the incident sunlight is strongest). This effect can be seen in the instrumental surface-air temperature record, and the spectacular Tambora eruption almost certainly caused the exceptional weather anomalies of 1816.

The Free Oscillations of the Global Atmosphere

The Tambora eruption is thought to be the largest in the last millennium in terms of total explosive power and volume of material ejected; but another very large and spectacular Indonesian eruption occurred in 1883, when the island of Krakatoa exploded. In 1815 it took several months for the world to get a clear picture of what had happened at Mt. Tambora, and little scientific investigation of the eruption's effect was conducted until the 20th century. By contrast, the existence of a world-wide telegraph network and an active international scientific community in 1883 meant that the eruption of Krakatoa was followed in near real-time by much of the world, and scientific investigation of the effects began immediately. The initial scientific studies were reviewed in *The Eruption of Krakatoa and Subsequent Phenomena*, published in 1888 by the Royal Society of London.

This report documented the propagation of a pressure (or infrasound) wave front around the world: Barographs recording pressure traces were operating at a number of observatories throughout the world. The pressure wave from the final explosion at Krakatoa was observable in all the recorded pressure traces several times at about 33-hour intervals. This was thought to indicate the passage of the wave several times around the world with a propagation speed of about 330 m/s (the circumference of the earth divided by 33 hours). The great English physicist **G.I. Taylor** showed that this was consistent with the propagation of a non-dispersive wave with properties similar to those for barotropic waves in a constant-depth fluid, and that the observations of the speed of the Krakatoa wave front pinned down the "equivalent depth" of the atmosphere (Taylor, 1929).

Half a century later, **Taroh Matsuno** combined Taylor's insight with his own classic treatment of the linear theory of planetary scale motions in the tropics (Matsuno, 1966) and showed there should be a discrete set of global normal modes or "free oscillations" of the atmosphere (Matsuno, 1980). The mode with the largest horizontal scale corresponds to an equatorial Kelvin wave and has a predicted period equal to the 33 hours observed for the passage of the Krakatoa pressure wave. Matsuno was able to show that long timeseries of atmospheric surface pressure data actually display a spectral peak around 33 hours. With my colleague **Rolando Garcia** of NCAR, I was able to follow up Matsuno's work with a more detailed investigation of the normal mode signals detectable in long surface pressure records (Hamilton and Garcia, 1986). I even speculated that similar phenomena should be observable in the Martian atmosphere. This hypothesis helped to motivate me to begin a project on modeling the Martian general atmospheric circulation when I joined the Geophysical Fluid Dynamics Laboratory (GFDL) in Princeton in 1987. This work eventually showed that the normal mode Kelvin wave on Mars is indeed observed and is important for the Martian circulation (Wilson and Hamilton, 1996).

"History" of the Quasi-biennial Oscillation

Another chapter of the 1888 Royal Society report on Krakatoa was devoted to describing the spread of the volcanic aerosols. Colorful twilights are produced by the sun's illumination of stratospheric aerosol, and the years after major eruptions are often remembered for spectacular sunrises and sunsets. The Royal Society investigators gathered reports from such sources as ship logs, diaries, and newspaper stories of the first observations of the twilight phenomena following the eruption. This enabled them to trace the spread of the aerosol cloud over several months. Figure 9 reveals the spread during the first two weeks after the eruption. Specifically, the western boundary of the area in which the twilight phenomena were reported is plotted for each day. The prevailing wind at the altitudes where the volcanic aerosol was located must have been strong (~30 m/s) easterlies.

This was the first indication of the nature of the wind field in the stratosphere (even though the existence of the stratosphere itself was not to be discovered until 1902). Much later, modern balloon observations showed that the winds in the tropical stratosphere actually undergo a Quasi-biennial Oscillation (QBO) involving transitions between prevailing easterlies and westerlies over a roughly 27-month cycle. The existence and properties of the QBO have been well observed with regular daily balloon sonde measurements since about 1950. As a hobby over many years, I collected whatever scattered observations of winds in the tropical stratosphere in the pre-1950 period I could find. In 1998, I published a review of these early observations, including the optical observations of the strong "Krakatoa easterlies" in 1883 (Hamilton, 1998). I concluded that the QBO has been a persistent feature of the circulation since at least 1883.

Winter Warming in Northern Europe and Asia

Like most atmospheric scientists, I was fascinated by reports of the eruption of Mt. Pinatubo in the Philippines in June 1991. This was the largest eruption in terms of ejected material since Mt. Tambora. My research at the time focused on meteorology and chemistry of the stratosphere, and I recall that many of

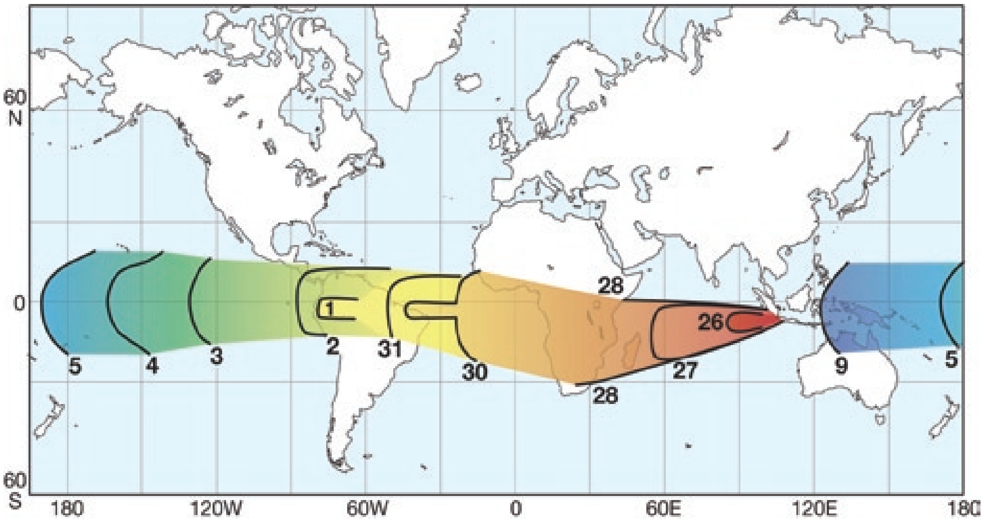


Figure 9. The black lines show the estimated western boundary of the aerosol cloud from Mt. Krakatoa on August 26, 27…September 9, 1883.

my colleagues in stratospheric science were irritated at first by the news of the Mt. Pinatubo eruption! NASA had just launched the one-billion-dollar Upper Atmosphere Research Satellite (UARS) to study stratospheric chemistry. My colleagues were unhappy that the eruption had "contaminated" the stratosphere and UARS would not measure in a clean-background stratosphere! In fact, many UARS instruments functioned for over a decade, and the Pinatubo eruption turned out to be beautifully timed for us—we could study the detailed evolution and effects of the aerosol layer in the early 1990s and then the clean stratosphere in the late 1990s when the Pinatubo aerosol had been flushed out. The satellite allowed the evolution of the aerosol layer and resulting chemical effects (the volcanic aerosol acts to catalyze ozone destruction) to be observed continuously and in three dimensions. This then set the stage for very detailed modeling of the atmospheric effects of the volcanic aerosol.

At the IPRC I have been working (with my colleagues **Georgiy Stenchikov** and **Alan Robock** of Rutgers University, and **V. Ramaswamy** of GFDL) on very sophisticated GCM simulations of the atmospheric circulation perturbation caused by the Pinatubo aerosol during 1991–94. The overall global cooling is easily reproduced in my model. More interesting to me, however, is a more subtle effect—namely the anomalously warm surface air temperatures that occurred in Northern Europe and Asia during the first two boreal winters after Pinatubo (and after most previous large eruptions). My model reproduces this winter warming (Stenchikov et al., 2002, 2004). Analysis of the simulation suggests that a downward dynamical coupling between the stratosphere (which is radiatively perturbed by the volcanic aerosol) and the lower atmosphere determines partly the geographical structure of the surface perturbation.

My work on modeling the effects of volcanic aerosol was discussed in *IPRC Climate,* Vol. 1, Fall 2001, and I wrote a review of the general issue of stratospheric dynamical influence on the troposphere for *IPRC Climate*, Vol. 2, Spring 2002. This is ongoing work, and I hope to report more results on the atmospheric effects of major volcanoes in a future issue of *IPRC Climate*.

Hamilton, K., 1986: Early Canadian weather observers and "the year without a summer." *Bull. Amer. Meteor. Soc.*, **67**, 524–532.

Hamilton, K., 1998: Observations of tropical stratospheric winds before World War II. *Bull. Amer. Meteor. Soc.*, **79**, 1367–1371.

Hamilton, K., 2004: Volcanoes and the weather. *J. High School Sci.*, **3**, 8–12.

Hamilton, K., and R. Garcia, 1986: Theory and observations of the short period normal mode oscillations of the atmosphere. *J. Geophys. Res.*, 91, 11867–11875.

Matsuno, T., 1966: Quasi-geostrophic motions in the equatorial area. *J. Meteor. Soc. Japan*, **44**, 25–43.

Matsuno, T., 1980: A trial search for minor components of lunar tides and the short period free oscillations of the atmosphere in surface pressure data. *J. Meteor. Soc. Japan*, **58**, 281–285.

Stenchikov, G., A. Robock, V. Ramaswamy, M. Schwarzkopf, K. Hamilton and S. Ramachandran, 2002: Arctic oscillation response to the 1991 Pinatubo eruption: Effects of volcanic aerosols and ozone depletion. *J. Geophys. Res.*, **107**, 4803–4818.

Stenchikov, G., K. Hamilton, A. Robock, V. Ramaswamy and M.D. Schwarzkopf, 2004: Arctic oscillation response to the 1991 Pinatubo eruption in the SKYHI GCM with a realistic quasi-biennial oscillation *J. Geophys. Res.*, **109**, doi:10.1029/2003JD003699.

Stommel, H. and E. Stommel, 1983: *Volcano Weather*. Seven Seas Press, 177 pp.

Taylor, G.I., 1929: Waves and tides in the atmosphere. *Proc. Roy. Soc.*, **A126**, 169–183.

Wilson, R.J., and K. Hamilton, 1996: Comprehensive model simulation of tides in the Martian atmosphere. *J. Atmos. Sci.*, **53**, 1290–1326 .

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