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The Latest on Volcanic Eruptions and Climate

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What was the largest volcanic eruption on Earth since the historic Mount Pinatubo eruption on 15 June 1991? Was the Toba supereruption 74,000 years ago—the largest in the past 100,000 years—responsible for a human genetic bottleneck or a 1000-year-long glacial advance? What role did small volcanic eruptions play in the reduced global warming of the past decade? What caused the Little Ice Age? Was the April 2010 Eyjafjallajökull eruption in Iceland important for climate change? What do volcanic eruptions teach us about new ideas on geoengineering and nuclear winter? These are some of the questions that have been answered since the review article by *Robock* [2000]. Reviews by *Forster et al.* [2007] and *Timmreck* [2012] go into some of these topics in much greater detail.

It is well known that large volcanic eruptions inject sulfur gases into the stratosphere, which convert to sulfate aerosols with a lifetime of several months to about 2 years. The radiative effects of these aerosol clouds produce global cooling and are an important natural cause of climate change. Regional responses include winter warming of Northern Hemisphere continents and weakening of summer Asian and African monsoons. Even though there has not been a large eruption since the eruption of Mount Pinatubo in the Philippines on 15 June 1991, research continues to produce interesting results.

Small Volcanic Eruptions of the Past Decade

A number of eruptions injected sulfur into the lower stratosphere in the past decade, and they contributed to less global warming during that period than in the previous several decades, along with increased tropospheric pollution, a prevalence of La Niña, slightly lower solar irradiance, and reduced stratospheric water vapor [*Solomon et al.,* 2010]. The mean volcanic radiative forcing over the period 2000–2010 was about –0.1 watts per square meter, partially counteracting the observed +0.3 watts per square meter anthropogenic increase each decade [*Solomon et al.,* 2011].

The largest eruptions of the period were Soufrière Hills, Montserrat (16.72°N, 62.18°W; 20 May 2006); Kasatochi, in Alaska's Aleutian Islands (52.1°N, 175.3°W; 8 August 2008); and Sarychev, in Russia's Kuril Islands (48.1°N, 153.2°E; 12 June 2009). However, the Nabro, Eritrea (13°N, 41°E; 13 June 2011), eruption (Figure 1) resulted in a stratospheric sulfur injection of more than 1.5 megatons of sulfur dioxide, the largest since the 1991 Pinatubo eruption [*Bourassa et al.,* 2012]. The Nabro eruption was also very interesting because for the first time slow (taking 2 months) lofting of volcanic sulfate into the stratosphere from the upper troposphere by the Asian summer monsoon was observed [*Bourassa et al.*, 2012, 2013].

On 14 April 2010, the Eyjafjallajökull volcano in Iceland (63.6°N, 19.6°W; Figure 2) began to erupt. The eruption shut down air traffic in Europe for 6 days and continued to disrupt it for another month. There was no climatic impact from Eyjafjallajökull as the ash and SO_2, injected only into the troposphere, fell out of the atmosphere quickly, on the order of weeks. The sulfur dioxide emission was less than 50 kilotons, compared to about 20 megatons from the 1991 Pinatubo eruption, and its lifetime in the troposphere was 50 times less than if it had been injected into the stratosphere; thus its impact on climate was about 10,000 times less than that of Pinatubo. Its impact on society, however, by disruption of transportation, was huge and provided valuable lessons about how vulnerable society is to other such disruptions, such as from nuclear war [*Robock,* 2010].

The Toba Supereruption

While *Haslam and Petraglia* [2010] showed that a 1000-year glacial period started just before the eruption of the Toba volcano on the island of Sumatra, Indonesia, 74,000 years

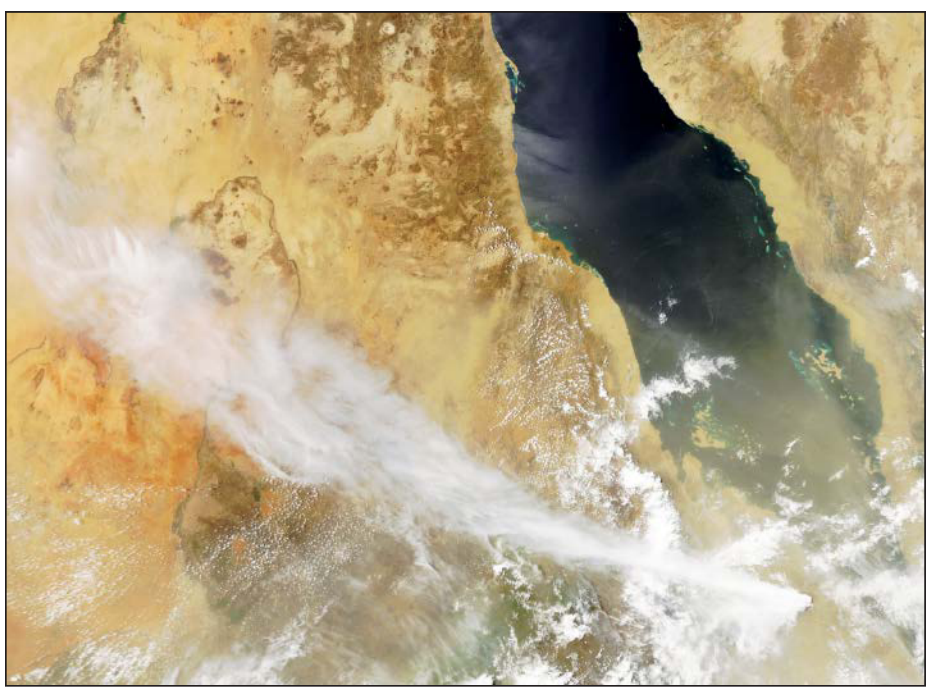

Fig. 1. Plume from the Nabro volcanic eruption in Eritrea, the largest eruption in 20 years in terms of its stratospheric sulfur input. NASA Moderate Resolution Imaging Spectroradiometer (MODIS) image from 13 June 2011 (http://earthobservatory.nasa.gov/NaturalHazards/view.php?id=50988).

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Fig. 2. The side of Eyjafjallajökull during a field trip for the AGU Chapman Conference on Volcanism and the Atmosphere, 13 June 2012.

ago, disproving the theory that the eruption produced a major glacial advance, the question of whether there could have been a human genetic bottleneck [e.g., *Ambrose,* 1998] produced by the death of most humans in a volcanic winter just after the eruption is still not resolved. *Robock et al.* [2009] used simulations of up to 900 times the 1991 Pinatubo stratospheric injection and found a decade-long volcanic winter that could indeed have made the food supply for humans problematic, but *Timmreck et al.* [2010] incorporated the idea of *Pinto et al.* [1989] that aerosols would grow in size, lessening their lifetime and radiative forcing per unit mass, and found a much smaller climatic response. *Lane et al.* [2013] found a small climate change averaged over several decades at a lake in Africa following the Toba eruption, but this result does not support their claim that there could not have been a short-lived, catastrophic volcanic winter.

The Cause of the Little Ice Age

Miller et al. [2012] showed that in a climate model a series of very large volcanic eruptions in the second half of the thirteenth century cooled Earth so much that an Arctic sea ice feedback caused the cooling to persist until the recent global warming that started in the nineteenth century and thus that these volcanic eruptions were the cause of the Little Ice Age. This finding agreed with evidence from vegetation that had been killed and then preserved by ice sheet advances on Baffin Island following the largest eruptions of the period, the 1258 Rinjani (Indonesia) and 1452 Kuwae (Vanuatu, in the South Pacific Ocean) eruptions. It also agrees with *Zanchettin et al.* [2012], who found changes in the North Atlantic Ocean circulation following volcanic eruptions that imply strengthened northward oceanic heat transport a decade after major eruptions, which contributes to persistent cooling over Arctic regions on decadal time scales. *Berdahl and Robock* [2013] supported this result, showing with a regional climate model that the Baffin ice sheet could persist even after volcanic forcing disappeared, given a cooler surrounding Arctic climate. *Miller et al.* [2012] showed that while solar variations may also reinforce Little Ice Age climate variations, they were not necessary to initiate the Little Ice Age.

Volcanic Eruptions as Analogs

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, includes upward injection of the aerosols to the stratosphere, rapid global dispersal of stratospheric aerosols, removal of the aerosols, heating of the stratosphere, ozone depletion [*Mills et al.,* 2008], and cooling at the surface under this cloud. This outcome is still possible with the current global nuclear arsenal [*Robock et al.,* 2007a; *Toon et al.,* 2008]. The use of only 100 nuclear weapons of the size that destroyed Hiroshima in 1945 could produce climate change unprecedented in recorded human history [*Robock et al.,* 2007b], which could produce significant decreases of agriculture in the main grain-growing regions of the world, the United States [*Özdoğan et al.,* 2013] and China [*Xia and Robock,* 2013]. This climate change would depend on the weapons being targeted on cities and industrial areas [*Toon et al.,* 2007], but new climate model simulations support these results [*Stenke et al.,* 2013; M. Mills, personal communication, 2013]. As this theory cannot be tested in the real world, volcanic eruptions provide analogs that support these aspects of the theory.

Recent suggestions that society consider using geoengineering to control global climate through the creation of a permanent stratospheric aerosol cloud have used volcanic eruptions as an analog [e.g., *Crutzen,* 2006; *Robock et al.,* 2008, 2013]. Volcanic eruptions show that a stratospheric aerosol cloud would indeed cool the surface, reducing ice melt and sea level rise, and increase the terrestrial carbon sink. But volcanic eruptions also indicate that a stratospheric aerosol cloud would produce ozone depletion, allowing more harmful ultraviolet radiation at the surface, reduce summer monsoon precipitation [e.g., *Trenberth and Dai,* 2007] and even produce drought, produce rapid warming if geoengineering were suddenly stopped, reduce solar power, damage airplanes flying in the stratosphere, and degrade surface astronomical observations and remote sensing [*Robock et al.,* 2013]. This raises many issues about the wisdom of geoengineering, and there are many other reasons why geoengineering may be a bad idea [*Robock,* 2008, 2012].

The Next Eruption

Is society ready for the next large volcanic eruption? It would be very useful to develop a rapid response system and a system for continuous observations for the next large volcanic eruption [*Robock et al.*, 2013]. This would help us to learn about volcanic impacts on the atmosphere and to learn about geoengineering,

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