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The Science Behind Sulfur Aerosols and Global Temperature Drops

*Mr. E. Deepanrajasiva
M.Sc. (Ag) Student (Environmental Science), TNAU, Coimbatore, Tamil Nadu, India
*Corresponding Author's email: deepanrajasiva@gmail.com

Frost struck New England farms in June and July of 1816, and harvests failed across Europe as grain prices climbed and hunger followed. The period became known as the "Year Without a Summer". Its origin lay on the other side of the world, in the April 1815 eruption of Mount Tambora in Indonesia, the most powerful eruption of the past several centuries (Rampino & Self, 1982; Stothers, 1984). Tambora showed that a volcano can chill the planet. Ash cannot be the reason, because it settles out within days or weeks, whereas the cooling lasted for years. The real driver is sulfur that is thrown high enough to remain aloft (Robock, 2000). The topic matters today for two reasons. Natural aerosol cooling is a factor that scientists must separate from human-caused warming when they read the temperature record. It is also the basis of solar geoengineering proposals, which suggest copying volcanoes to gain time against climate change (Crutzen, 2006; National Academies of Sciences, Engineering, and Medicine [NASEM], 2021).

From Gas to Veil: The Science

Stratosphere matters

The atmosphere is arranged in layers. Weather occurs in the lowest layer, the troposphere, where rain washes pollutants out within days to weeks. Above it lies the stratosphere, which begins roughly 10 to 15 km above most of the globe. It is dry and stable and has no rain to clean it, so material that reaches it can remain for one to three years (Robock, 2000; Timmreck, 2012). An eruption strong enough to break through the tropopause therefore delivers its sulfur straight into a long-lived layer.

The chemical conversion

Volcanoes emit sulfur mainly as sulfur dioxide (SO_2). In the stratosphere, hydroxyl radicals (OH) oxidise the gas to sulfur trioxide, which combines with water vapour to form sulfuric acid (H_2SO_4). The acid condenses into liquid droplets, usually less than one micrometre across, known as sulfate aerosols. The conversion takes weeks; after Pinatubo the SO_2 cloud declined with an e-folding time of about 35 days (McCormick et al., 1995; Self et al., 1996).

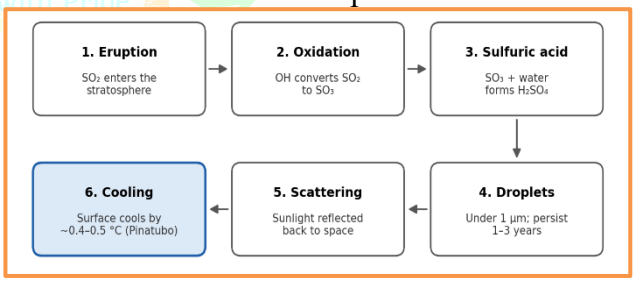

Figure 1. The sulfur aerosol pathway, from eruption to surface cooling (author's illustration, based on Robock, 2000, and McCormick et al., 1995).

Droplets cool the surface

The droplets are close in size to the wavelengths of visible light, which makes them very effective at scattering sunlight. A share of the scattered light returns to space, so less energy reaches the ground. Scientists call this a negative radiative forcing. At its peak, Pinatubo's forcing averaged roughly −3 to −4 watts per square metre over the globe (Hansen et al., 1992; Stenchikov et al., 1998).

The aerosols also absorb some of the heat that rises from the Earth. The stratosphere therefore warms while the surface cools (Dutton & Christy, 1992). This pairing of a warmer upper atmosphere above a cooler surface is a recognisable fingerprint of volcanic aerosols.

Features and Limits of the Cooling Effect

Volcanic cooling is strong but comes with clear limits, which Table 2 summarises.

Table 1. Characteristics of volcanic sulfur-aerosol cooling

Feature	What happens	Why it matters
Duration	Cooling lasts about 1–3 years	It is temporary and cannot offset long-term warming on its own
Strength	Grows with the amount of SO_2 reaching the stratosphere	Only large, explosive eruptions have a global effect
Latitude	Tropical eruptions spread to both hemispheres; high-latitude ones stay more regional	The volcano's location decides who is cooled
Side effects	Changes in rainfall, weaker monsoons, stratospheric warming	Cooling is not the only consequence
Ozone	Aerosol surfaces speed up ozone-destroying chemistry	Ozone loss followed Pinatubo

The cooling is also uneven. After large eruptions, global rainfall declined and monsoon circulation weakened, because a cooler surface evaporates less water and alters the temperature contrast between land and sea (Robock, 2000; Robock et al., 2008). In addition, the droplets provide surfaces on which ozone-destroying reactions proceed faster, and measurable ozone loss followed Pinatubo (Tilmes et al., 2008).

Imitating Nature: The Geoengineering Debate

In 1977 the Soviet climatologist Mikhail Budyko proposed that burning sulfur in the stratosphere could cool the planet (Budyko, 1977). The idea reached a wide audience in 2006, when the Nobel laureate Paul Crutzen, known for his work on ozone chemistry, argued that stratospheric sulfur injection deserved serious study as an emergency option if emission cuts failed (Crutzen, 2006). The attraction is that the approach would act quickly and might cost little compared with other climate measures. The risks, however, are considerable. Termination shock is a particular worry. Aerosols vanish within a few years, so stopping the injections while CO_2 remains high would let temperatures rebound quickly. Researchers have therefore suggested only modest, gradual and closely monitored schemes, if any at all (Keith & MacMartin, 2015). In 2021 the U.S. National Academies recommended a cautious research programme with strong governance and public engagement, not deployment (NASEM, 2021).

Conclusion

Sulfur aerosols are among the most effective natural climate regulators. One large eruption can lift millions of tonnes of sulfur dioxide into the stratosphere, where it becomes a reflective acid haze that cools the planet by several tenths of a degree for one to three years (Robock, 2000; Hansen et al., 1992). Tambora and Pinatubo demonstrate both the strength of this process and its costs, namely failed harvests, altered rainfall and temporary ozone loss.

Understanding this science has lasting value. It lets researchers test and improve climate models, as Pinatubo did (Soden et al., 2002), and it explains why imitating volcanoes is neither simple nor free of risk. Aerosol cooling treats a symptom, the temperature, and not the cause, which is the accumulation of greenhouse gases. For now the evidence suggests that sulfur aerosols are best seen as a natural experiment to learn from, and that cutting emissions remains the only lasting solution.

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