Large volcanic eruptions affect climate in many more ways than just cooling

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- Emitting up to $921$ Mt $H_2O$ $234$ Mt $CO_2$ $19$ Mt $SO_2$
- Sending tephra & gases to $35$ km, $18$ km above the tropopause
- Largest volcanic eruption since 1912

2. $SO_2$ has the greatest effect on climate and plays a much larger role in warming than currently assumed

- Nature cycles $43$ Mt sulfur through the atmosphere each year while man, since 1965, has emitted $57$ to $75$ Mt sulfur each year, a $150\%$ increase. Man increases natural emissions of $CO_2$ by less than $4\%$ each year
• Under normal circumstances SO₂ remains only a few days in the atmosphere, but by 1978, SO₂ concentrations in the free troposphere in the northern hemisphere averaged 122 pptv.
• Large amounts of SO₂ injected by volcanic eruptions into the lower stratosphere spread horizontally very efficiently to form a sulfuric acid aerosol that diffuses sunlight globally, cooling the earth.
• Similar amounts of SO₂ injected into the troposphere causes a regional dry fog that leads to significant warming.
• Oxidizing large amounts of SO₂ to H₂SO₄ uses up the oxidizing capacity of the atmosphere, causing concentrations of greenhouse gases such as methane and carbon monoxide to accumulate.
• Sulfuric acid has a very low vapor pressure and is the key ingredient forming cloud condensation nucleii, clouds, and precipitation, determining how much water, the most important greenhouse gas, the atmosphere can hold.
3. Typical global temperatures following major volcanic eruptions

Sudden decrease of approximately 0.5°C for 3 years
Followed by a gradual net warming after 7-8 years

The following points focus on the effects of Pinatubo in June, 1991
4. Stratospheric aerosol lowered surface temperatures by 0.5°C for 3 years

- 17 Mt SO₂ erupted into the stratosphere was oxidized by OH and 3 parts water to 99% pure sulfuric acid (75% H₂SO₄ and 25% H₂O) aerosol
- Aerosol formed near the base of the ozone layer at 20 to 23 km and spread around the world in 21 days
- Maximum cooling in tropics 3 months later but mass mixing ratios did not return to background until 1998
- E-folding time for formation 33 days in tropics, 13.5 months in the Arctic
- Decreased irradiance by 2.7%
- This stratospheric aerosol exists almost all of the time and is simply enhanced by volcanic eruptions

Sulfuric acid aerosol
5. Cooling the atmosphere for 3 years cools the ocean for decades

A suite of climate models shows that cooled ocean surface water sank hundreds of meters after the eruption of Krakatoa in 1883 and persisted for more than 120 years.

The thermal effects lower sea level and accumulate.

Eruption of Krakatoa


Gregory et al., J. Clim., 19:4576, 2006
6. Less sunlight reduced evaporation, precipitation, and runoff

- Global precipitation and river runoff decreased 3 and 3.7 standard deviations below normal
- The eruption increased water vapor in the upper troposphere and lower stratosphere. Its effects are unclear but imply warming

7. Stratospheric temperatures rose 3.5°C within 90 days

- Caused primarily by the aerosol absorbing infrared radiation
- Heated aerosol rose as much as 2 km causing some evaporation and reforming
- Increased radiative cooling of the stratosphere but decreased cooling of the troposphere
8. Decreased ozone

- Largest drops in ozone ever observed by satellite
- Ozone plus ultraviolet light forms OH that oxidize SO$_2$
- Erupted debris slows formation of ozone
- Heterogeneous processes on aerosol surfaces destroy ozone
- Largest ozone reductions 4-5 months after the eruption
- Diameter of ozone hole increased 17%

9. Used up available OH, slowing oxidation, causing CH$_4$ and CO to accumulate

- OH concentrations decreased by up to 20%
- E-folding time to form aerosol varied from 33 days to months
- CH$_4$ and CO concentrations increased

\[ \text{SO}_2 + \text{OH} + \text{M} \rightarrow \text{HSO}_3 + \text{M} \]
\[ \text{HSO}_3 + \text{O}_2 \rightarrow \text{HO}_2 + \text{SO}_3 \]
\[ \text{SO}_3 + \text{H}_2\text{O} + \text{M} \rightarrow \text{H}_2\text{SO}_4 \]
Where M is either N$_2$ or O$_2$
10. CO$_2$ concentrations decreased despite Pinatubo erupting up to 234 Tg CO$_2$

- Cooler ocean absorbed more CO$_2$
- Aerosol diffused sunlight causing a 23% increase in photosynthesis

11. Winter temperatures over continents were warmer than normal

- Role of the polar vortex?
- Role of greenhouse gases?

Robock, Science, 295:1242, 2002
12. Changes in greenhouse gases outlast cooling from the aerosols, leading to warming

In winter cooling by aerosol is less effective so increased greenhouse gases may explain warming. After 3 years changes in greenhouse gases clearly prevail.
13. Changes in ocean currents

The largest volcanic eruptions are typically followed within 6-8 years by exceptionally large El Niños. It is not clear whether eruptions and El Niños are related nor how they interact, but cool ocean surface water sinking must cause changes in ocean currents.

<table>
<thead>
<tr>
<th>Volcano Name</th>
<th>Country</th>
<th>VEI</th>
<th>Year Eruption</th>
<th>Year El Niño</th>
<th>Strength</th>
<th>Confidence Rating</th>
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<td>Peru</td>
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<td>1600.14</td>
<td>1600</td>
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<tr>
<td>Laki</td>
<td>Iceland</td>
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<tr>
<td>Krakatoa</td>
<td>Indonesia</td>
<td>6</td>
<td>1883.65</td>
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<tr>
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<td>1902.81</td>
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<td>1912.43</td>
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<td>Very strong</td>
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</table>

*Laki, a basaltic fissure eruption, emitted 5 times the sulfur emitted by Pinatubo.
Volcano history from www.si.edu/world/largeeruptions.cfm*
14. Increased SO$_2$ concentrations in the troposphere increased regional temperatures significantly

- In June, 1783, Laki, a basaltic fissure volcano in Iceland, erupted 122 Mt SO$_2$ primarily into the troposphere
- A “dry fog” settled over the North Atlantic, Europe, northern Africa and Asia
- This fog was oxidized to sulfuric acid by breathing, killing 10,521 in Iceland, 20,000 England, 16,000 France, & many in Japan and Alaska
- Acid damage to leaves and grass was prominent from Iceland to Finland to Italy
- Unusually dry and hot in Europe during summer
- Major cooling in Iceland and northernmost Asia
- Severe drought India and Yangtze region of China

Laki Fissure
15. What happened to global warming

• A major increase in sulfur emissions (black line) is mirrored by a major increase in sulfate measured in an ice core in central Greenland (red)
• When sulfur emissions were deceased in an effort to reduce acid rain, the rapid increase in methane (green) approached zero by 2000 showing an increasing oxidizing capacity, the rapid increase in temperature approached zero after 1998, suggesting a role for SO$_2$ in tropospheric heating, and the rate of increase in CO$_2$ continued to climb
• Average global temperatures have remained fairly constant since 1998
• Sulfur emissions are rising again due to major increases in the number of new coal-fired power plants in China, India, etc.
• When will temperatures begin to rise again?
16. Increased global dimming and brightening

- The increase in sulfur emissions is contemporaneous with the increase in global dimming, thought in most studies to be caused by anthropogenic pollution
- The decrease in sulfur emissions is contemporaneous with the onset of global brightening

17. The increase in sulfur emissions coincides with an increase in species extinction
I am working on a much more detailed paper focused on all the evidence for the role of SO$_2$ in the atmosphere.