NH33-1141

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

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1. Mt. Pinatubo in the Philippines erupted in 1991

- 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

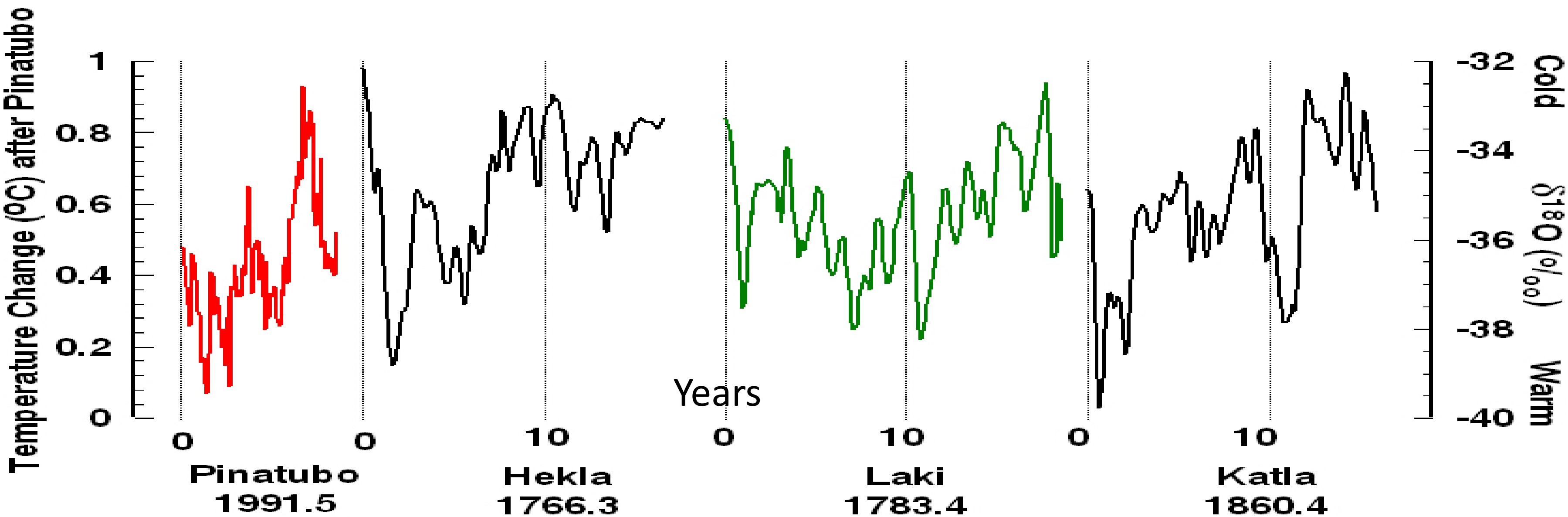
- Nature cycles 43 Mt sulfur through the atmosphere each year while man, since 1965, has emitted 57 to 75 Mt sulfur each year, a 150% increase. Man increases natural emissions of CO_2 by less than 4% each year

- Under normal circumstances SO_2 remains only a few days in the atmosphere, but by 1978, SO_2 concentrations in the free troposphere in the northern hemisphere averaged 122 pptv
- Large amounts of SO_2 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 SO_2 injected into the troposphere causes a regional dry fog that leads to significant warming
- Oxidizing large amounts of SO_2 to H_2SO_4 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

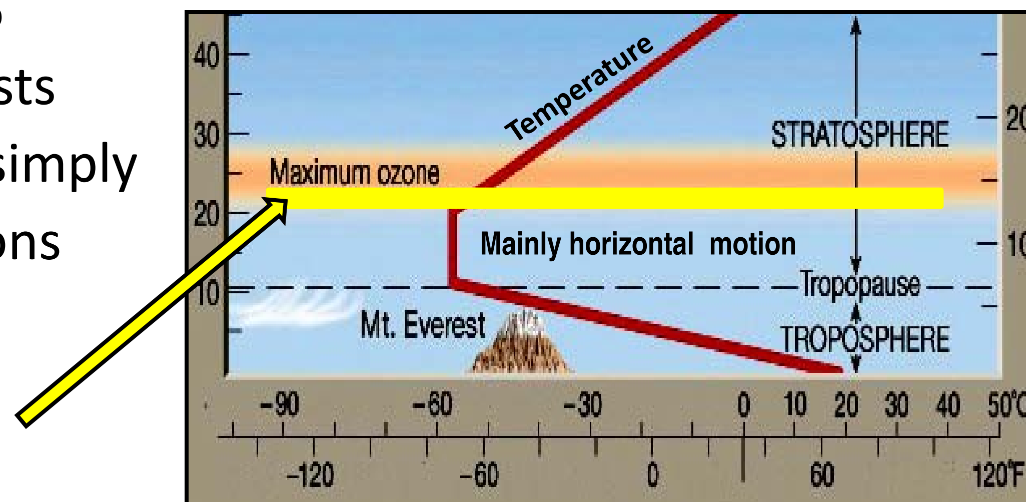


The following points focus on the effects of Pinatubo in June, 1991

4. Stratospheric aerosol lowered surface temperatures by 0.5^{o}C for 3 years

- 17 Mt SO_2 erupted into the stratosphere was oxidized by OH and 3 parts water to 99% pure sulfuric acid (75% H_2SO_4 and 25% H_20) 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

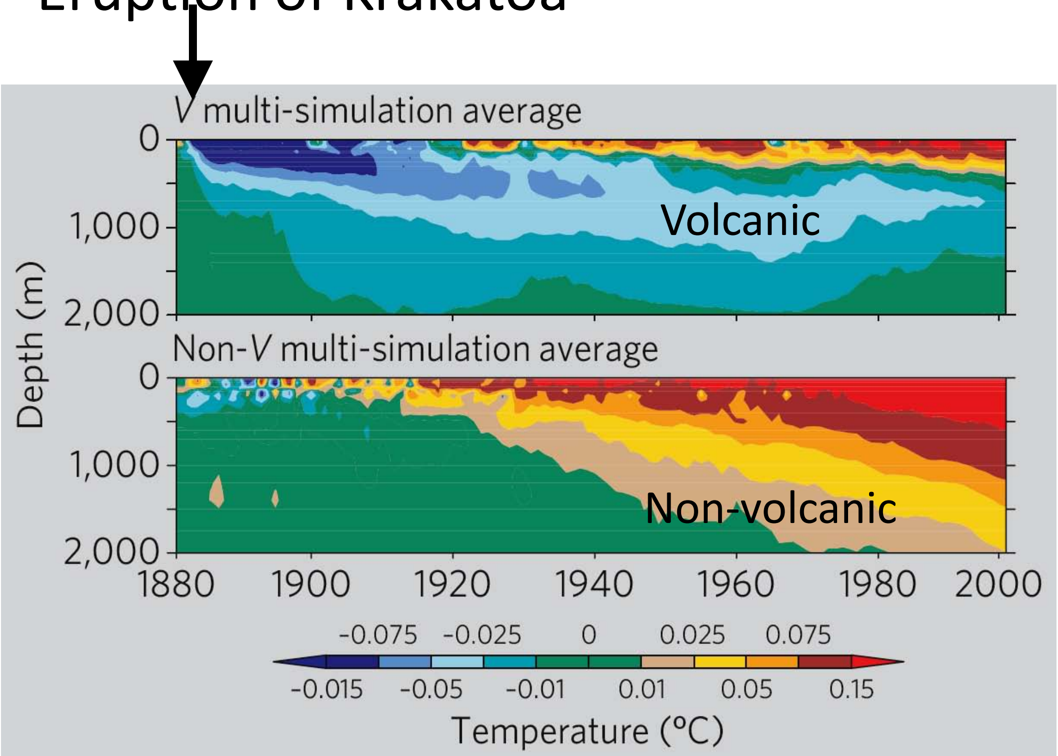
Sulfuric acid aerosol



5. Cooling the atmosphere for 3 years cools the ocean for decades

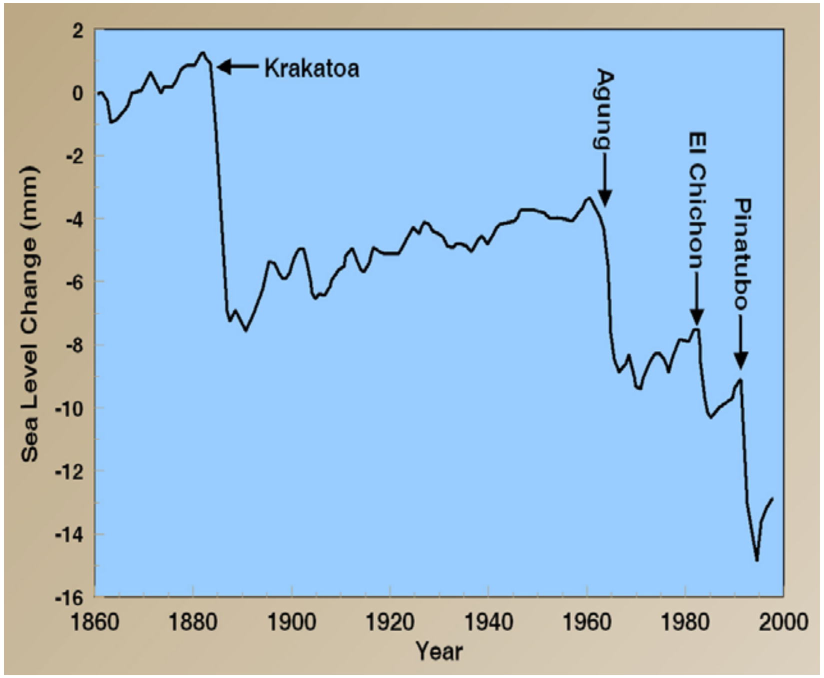
A suite of climate models shows that cooled ocean surface water sank hundreds of meters after the eruption of Krakatoa in 1883 and persisted for more than 120 years

Eruption of Krakatoa



Gleckler et al., Nature, 439:675, 2006

The thermal effects lower sea level and accumulate



Gregory et al., J. Clim., 19:4576, 2006

6. Less sunlight reduced evaporation, precipitation, and runoff

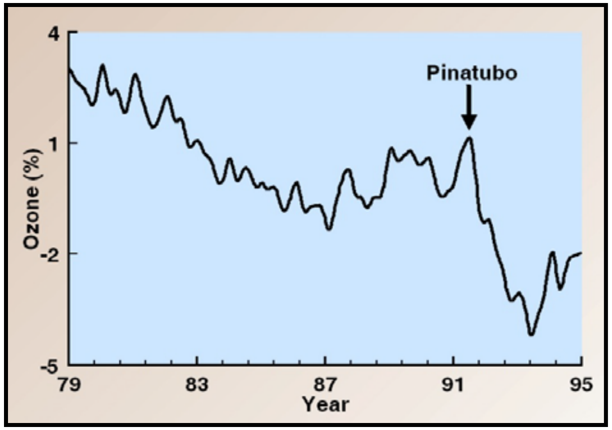
- Global precipitation and river runoff decreased 3 and 3.7 standard deviations below normal
- The eruption increased water vapor in the upper troposphere and lower stratosphere. Its effects are unclear but imply warming

7. Stratospheric temperatures rose 3.5^{o}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%



Randell et al., JGR 100:16753, 1995

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

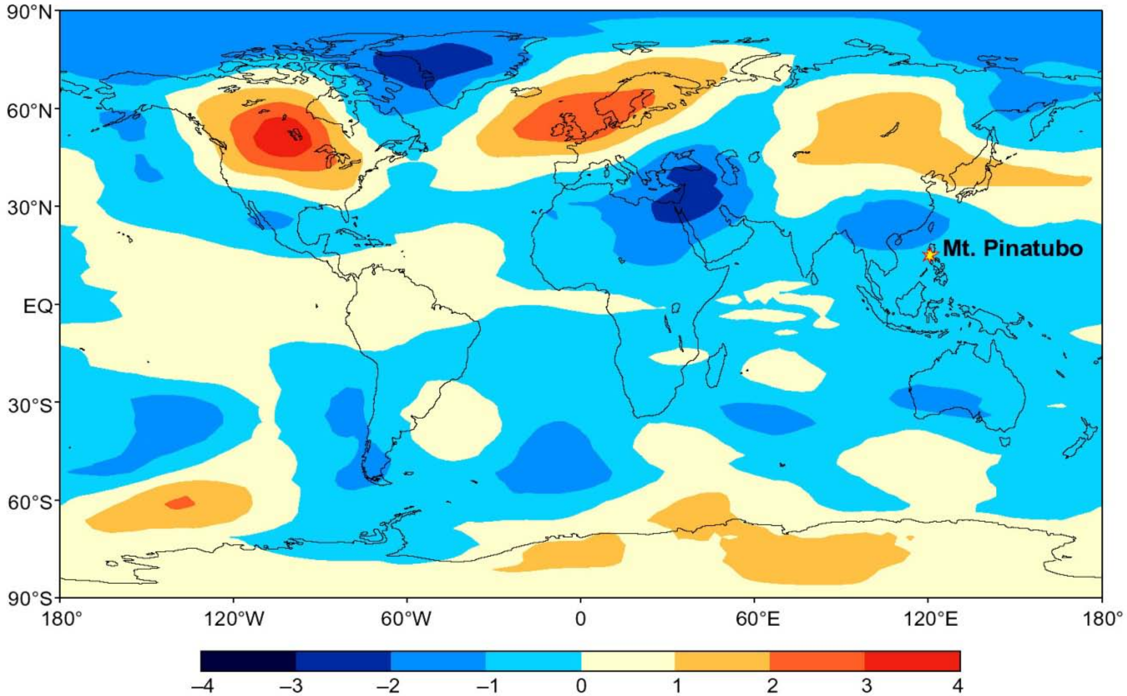
$$SO_2 + OH + M \rightarrow HSO_3 + M$$
$$HSO_3 + O_2 \rightarrow HO_2 + SO_3$$
$$SO_3 + H_2O + M \rightarrow H_2SO_4$$

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



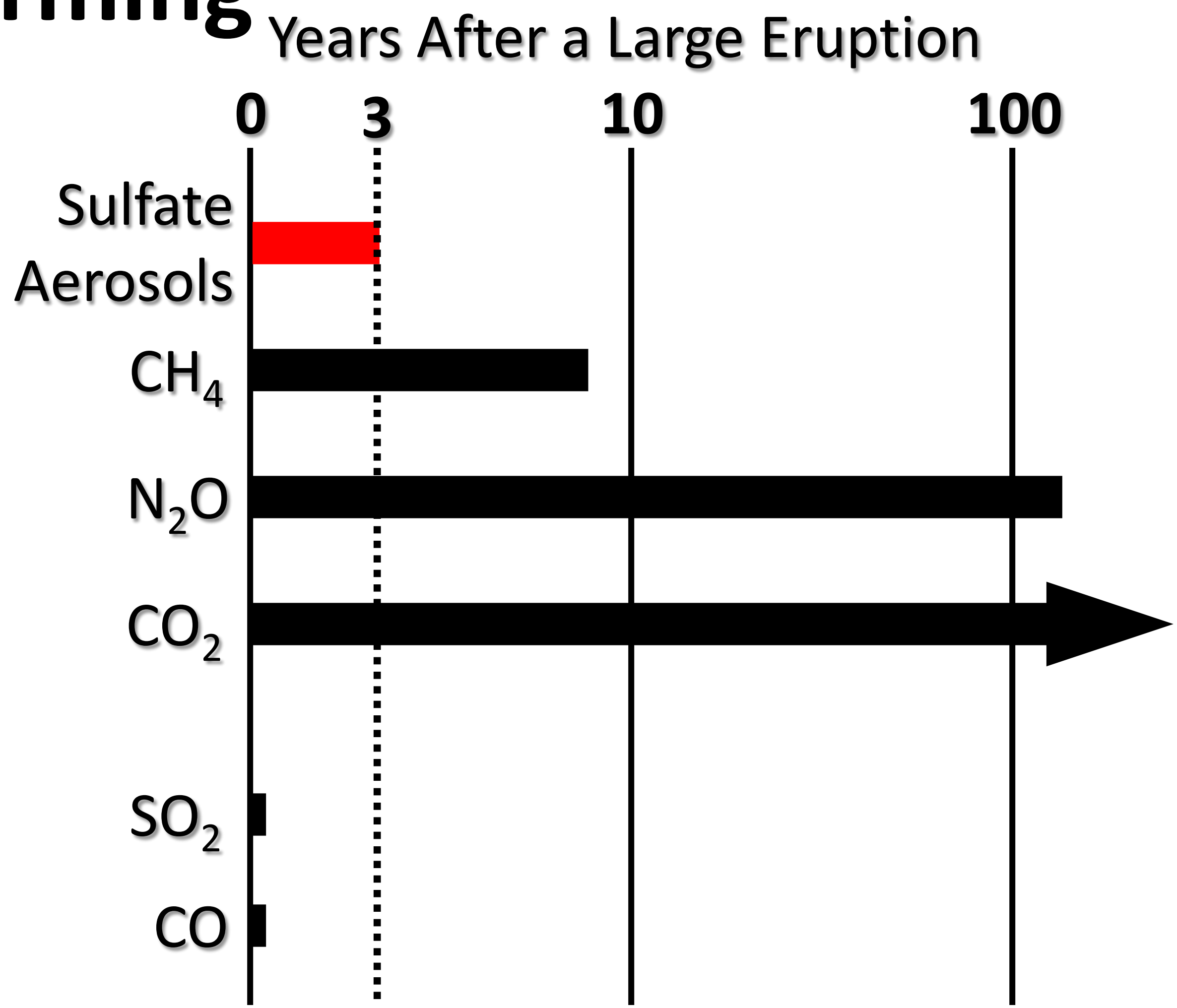
Robock, Science, 295:1242, 2002

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

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

All well-dated volcanic eruptions since 1600 with VEI >= 6

Volcano Name	Country	VEI	Year Eruption	Year El Niño	Strength	Confidence Rating
Huaynaputina	Peru	6	1600.14	1600	Strong	3
				1604	Moderate+	3
				1607-08	Strong	5
Laki	Iceland	4+*	1783.44	1783	Strong	3
				1786	Moderate+	3
				1791	Very strong	5
Tambora	Indonesia	7	1815.27	1817	Moderate+	5
				1819	Moderate+	5
				1821	Moderate	5
				1824	Moderate+	5
Krakatoa	Indonesia	6	1883.65	1884	Strong+	5
				1887	Moderate-	4
				1889	Moderate+	4
				1891	Very strong	5
Santa Maria	Guatemala	6?	1902.81	1902	Moderate+	4
				1904-05	Moderate-	4
				1907	Moderate	3
				1910	Moderate+	3
				1911-12	Very strong	5
Novarupta	Alaska	6	1912.43	1914-15	Moderate+	5
				1917	Strong	5
				1918-19	Moderate	5
Pinatubo	Philippines	6	1991.45	1991	Moderate	5
				1993	Moderate-	5
				1994	Moderate-	5
				1997-98	Very strong	5

* Laki, a basaltic fissure eruption, emitted 5 times the sulfur emitted by Pinatubo
El Niño history from Bradley and Jones, 1992
Volcano history from www.si.edu/world/largeeruptions.cfm

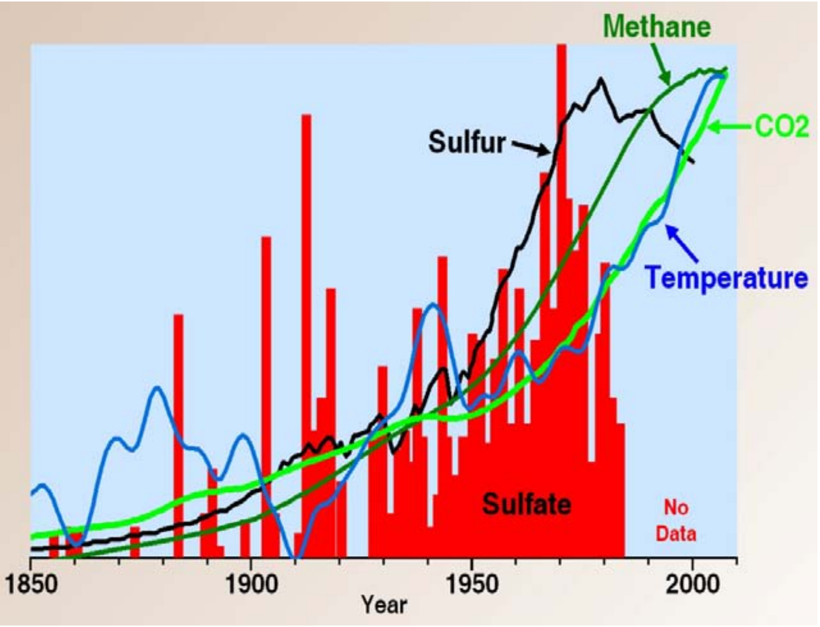
14. Increased SO_2 concentrations in the troposphere increased regional temperatures significantly

- 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

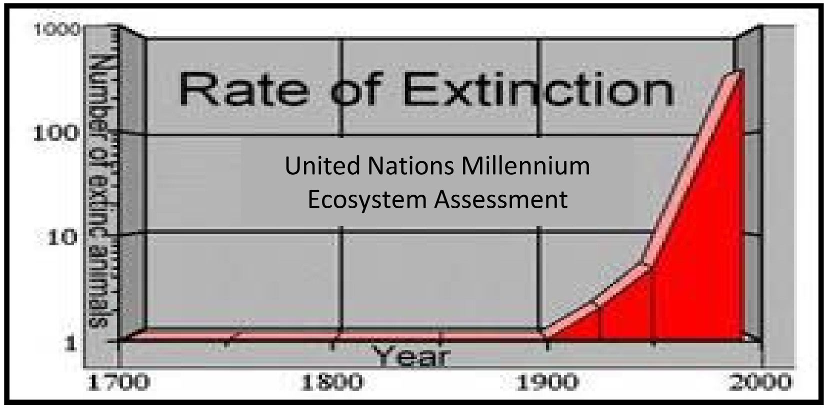


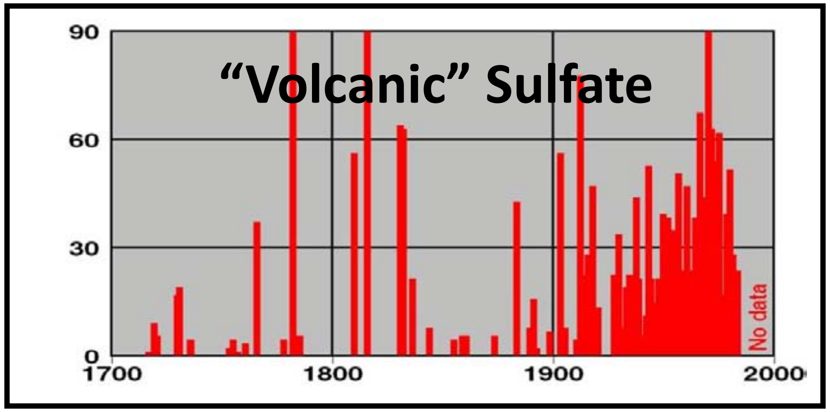
- Average global temperatures have remained fairly constant since 1998
- Sulfur emissions are rising again due to major increases in the number of new coal-fired power plants in China, India, etc.
- When will temperatures begin to rise again?

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





18. More information

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Thin Solid Films 517 (2009) 3188–3203

Contents lists available at ScienceDirect

Thin Solid Films

journal homepage: www.elsevier.com/locate/tsf

Special Feature

Sulfur dioxide initiates global climate change in four ways

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ARTICLE INFO

Available online 11 February 2009

Keywords:
Sulfur dioxide
SO_2
Carbon dioxide
CO_2
Global warming
Oxidation
Oxidizing capacity
Volcano
Volcanic eruption
Mass extinction
Tipping point
Methane

ABSTRACT

Global climate change, prior to the 20th century, appears to have been initiated primarily by major changes in volcanic activity. Sulfur dioxide (SO^2) is the most voluminous chemically active gas emitted by volcanoes and is readily oxidized to sulfuric acid normally within weeks. But trace amounts of SO_2 exert significant influence on climate. All major historic volcanic eruptions have formed sulfuric acid aerosols in the lower stratosphere that cooled the earth's surface ~0.5 °C for typically three years. While such events are currently happening once every 80 years, there are times in geologic history when they occurred every few to a dozen years. These were times when the earth was cooled incrementally into major ice ages. There have also been two dozen times during the past 46,000 years when major volcanic eruptions occurred every year or two or even several times per year for decades. Each of these times was contemporaneous with very rapid global warming. Large volumes of SO_2 erupted frequently appear to overdrive the oxidizing capacity of the atmosphere resulting in very rapid warming. Such warming and associated acid rain becomes extreme when millions of cubic kilometers of basalt are erupted in much less than one million years. These are the times of the greatest mass extinctions. When major volcanic eruptions do not occur for decades to hundreds of years, the atmosphere can oxidize all pollutants, leading to a very thin atmosphere, global cooling and decadal drought. Prior to the 20th century, increases in atmospheric carbon dioxide (CO_2) followed increases in temperature initiated by changes in SO_2.

By 1962, man burning fossil fuels was adding SO_2 to the atmosphere at a rate equivalent to one "large" volcanic eruption each 1.7 years. Global temperatures increased slowly from 1890 to 1950 as anthropogenic sulfur increased slowly. Global temperatures increased more rapidly after 1950 as the rate of anthropogenic sulfur emissions increased. By 1980 anthropogenic sulfur emissions peaked and began to decrease because of major efforts especially in Japan, Europe, and the United States to reduce acid rain. Atmospheric concentrations of methane began decreasing in 1990 and have remained nearly constant since 2000, demonstrating an increase in oxidizing capacity. Global temperatures became roughly constant around 2000 and even decreased beginning in late 2007. Meanwhile atmospheric concentrations of carbon dioxide have continued to increase at the same rate that they have increased since 1970. Thus SO_2 is playing a far more active role in initiating and controlling global warming than recognized by the Intergovernmental Panel on Climate Change. Massive reduction of SO_2 should be a top priority in order to reduce both global warming and acid rain. But man is also adding two to three orders of magnitude more CO_2 per year to the climate than one "large" volcanic eruption added in the past. Thus CO_2, a greenhouse gas, is contributing to global warming and should be reduced. We have already significantly reduced SO_2 emissions in order to reduce acid rain. We know how to do it both technically and politically.

In the past, sudden climate change was typically triggered by sudden increases in volcanic activity. Slow increases in greenhouse gases, therefore, do not appear as likely as currently thought to trigger tipping points where the climate suddenly changes. However we do need to start planning an appropriate human response to future major increases in volcanic activity.

I am working on a much more detailed paper focused on all the evidence for the role of SO_2 in the atmosphere