Understanding Volcanoes May Be the Key to Controlling Global Warming

Society of Vacuum Coaters
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Large volcanic eruptions cause global cooling of ~0.5°C for ~3 years.

Frequent large volcanic eruptions appear to cause global warming of several °C within decades.

Mt. Pinatubo in the Philippines, June 15, 1991
Global Warming in the 20th Century

We have warmed the ocean ~0.8°C
Scientists say
Man caused global warming by emitting greenhouse gases, primarily **carbon dioxide** and **methane**.

Climate deniers say
It happened before and it will happen again! It is only natural, not manmade!
We Will Explore Two New Observations

1. Evidence that global warming in the past was initiated by large, nearly continuous emissions of sulfur dioxide (SO$_2$) from volcanoes over decades and that this happened 14 times in the last 46,000 years.

2. Evidence that global warming in the 20$^{th}$ century was initiated by large, continuous emissions of sulfur dioxide (SO$_2$) by humans burning fossil fuels, especially coal.
But Peter, That Is Preposterous!!

1. SO$_2$ erupted into the stratosphere by large volcanic eruptions typically cools the earth for ~3 years.

2. The atmospheric concentration of CO$_2$ is 387 ppmv while the concentration of SO$_2$ is much less than 90 ppbv, 3 to 4 orders of magnitude less.

3. CO$_2$ lasts ~100 years in the atmosphere while SO$_2$ lasts only days to weeks.

SO$_2$ simply cannot be an important greenhouse gas absorbing infrared energy.
“This paper is almost irresponsible in its disregard for known science.”

Anonymous Reviewer
November 2008
Photons from the sun make life on earth possible

“Solar ultraviolet radiation plays a decisive role in almost all aspects of the chemistry of the atmosphere.”

Grant W. Petty, 2006, in his book *A First Course in Atmospheric Radiation*

The origin of oxygen
The origin of ozone
The primary structure of the atmosphere
The oxidation of pollutants

The primary **initiator** of global warming
Energy Budget of the Atmosphere

Incoming solar radiation: 342 W m⁻²
Outgoing infrared radiation: 235 W m⁻²
Total incoming solar radiation: 1370 W m⁻²

Ultraviolet (SO₂)

Outgoing infrared radiation

Based on Kiehl and Trenberth (1997)
A cloudy night feels warmer than a clear night.

Greenhouse Gases

Solar Absorbing Gases

Visible & Ultra-violet

A bright sun feels hotter than a cloudy sun.

Infrared

390 Wm$^{-2}$

1370 Wm$^{-2}$
SO$_2$ absorbs strongly in UV-A.

- Sunburn damages DNA.
- UV-C, UV-B, UV-A, and visible wavelengths are shown.
- Two orders of magnitude.
- Bad ozone.
Energy of a photon:
\[ E = h\nu = \frac{hc}{\lambda} \text{ Joules} \]

Concentrations:
- \( \text{H}_2\text{O} = 0 \text{ to } 2\% \)
- \( \text{CO}_2 = 0.0385\% \)
- \( \text{CO}_2 = 385,000 \text{ ppbv} \)
- \( \text{CH}_4 = 1,700 \text{ ppbv} \)
- \( \text{NO}_2 = 35 \text{ ppbv} \)
- \( \text{O}_3 = 10 \text{ ppbv} \)
- \( \text{SO}_2 = 1 \text{ to } 93 \text{ ppbv} \)
Heat generated is proportional to 

\[ \text{Energy In} \times \text{Absorption Intensity} \times \text{Concentration} \]
Sulfur is one of the trace substances which is always found in the atmosphere, even in the most remote areas.

“Sulfur, as an important atmospheric constituent, has received very little attention.”

(Sulfur in the atmosphere, JGR:65 p. 227)
Junge predicted that amounts of $\text{SO}_4^{2-}$ (oxidized $\text{SO}_2$) measured in the snow in Greenland should show a linear increase since 1915 proportional to increasing $\text{SO}_2$ pollution.

Junge emphasized that his data were “noisy and limited” and that they did not show the expected relationship. He concluded that

1. “Either the estimates are inaccurate”
2. “Or industrial $\text{SO}_2$ is washed out so rapidly that no substantial fraction penetrates into the Arctic”
76% of the layers for the previous 2000 years contained no "volcanic" sulfate. 34 contiguous layers, largest number in the last 13,000 years.
High Rates of Volcanism Are Contemporaneous with Rapid Warming

Circles show the number of contiguous layers containing sulfate

Temperature with 11 century smoothing

Preboreal Warming

Younger Dryas

Bolling Warming

Oldest Dryas

Last Glacial Maximum

H1
Warming Vs Contiguous Layers with Sulfate

Circles include the number of contiguous layers containing sulfate

Numbers are Dansgaard-Oeschger Events

Paleolithic Revolution

Thousand Years Before Present

46 40 34 28 22 16 15 14 13 12 11 10 9

Warmer Colder

Thousand Years Before Present

16 15 14 13 12 11 10 9

Warmer Colder
A few decades every 2500 years
Only 5.8% of the time
Mt. Pinatubo, Philippines, 1991
Temperature Drop After Pinatubo

- 1985 to 2010
- HadCRUT3 Global Temperature Change, °C
- Pinatubo
- Very strong El Niño
Large Volcanic Eruptions Form Aerosols

A gaseous suspension of fine solid or liquid particles

17 megatons of SO$_2$ erupted from Pinatubo formed an aerosol 20 to 23 kilometers high that was 99% pure sulfuric acid + water.
Aerosols Reflect Sunlight

- Reflected solar radiation
- Reflected by clouds, aerosol and atmosphere
- Absorbed by the surface
- Absorbed by the atmosphere
- Incoming solar radiation
- Reduced by 0.7%
- Latent heat
Effects of Pinatubo

Surface temperature $\downarrow$ 0.5$^\circ$C for 3 years

Therefore global water vapor $\downarrow$ 3% and precipitation $\downarrow$ 3 SD

Ocean temperature $\downarrow$ and thus sea level $\downarrow$

Diffuse radiation $\uparrow$ and thus photosynthesis $\uparrow$ 23%

Therefore carbon dioxide $\downarrow$

Ozone $\downarrow$ 5% Ozone hole $\uparrow$ 17%

OH $\downarrow$ 10% for year and thus oxidizing capacity $\downarrow$

Therefore Methane $\uparrow$ Carbon monoxide $\uparrow$ Ethane $\uparrow$
Winter Temperatures Were Actually Higher Over Northern Continental Land Masses

Robock (2002)
Volcanic Aerosols Have the Greatest Effect in Summer

But Greenhouse Gases May Become Dominant in Winter

When the sun is more directly overhead

And greenhouse gases will accumulate and become even more dominant if new eruptions occur before the greenhouse gases are removed
Cooling For 3 Years Lasts Much Longer in the Ocean

Eruption of Krakatoa in 1883

Gleckler et al. 2006
Modeled Cumulative Sea Level Change
Due to Volcanic Activity

But the net rise in sea level since 1900 is 20 cm (33 Pinatubos)

Gregory et al., 2006
A Change in the Mean Temperature of the Earth Means a Change in the Mean Temperature of the Ocean

The upper 3 m (10 ft) of the ocean stores as much heat as the whole atmosphere.

The average depth is 3,790 meters (12,430 feet)
Effects of Pinatubo

All of these effects were caused by adding 17 Mt SO₂ plus sufficient water primarily to the lower stratosphere.

A mere 3.4 parts per billion

But concentrated between 17 and 25 km (17%) and thus 20 parts per billion.
Why Was the Aerosol So Effective?

Ozone layer formed by effects of UV light on $O_2$

17 Mt $SO_2$ erupted into the vicinity of the ozone layer

$SO_2$ oxidized by OH created from ozone by UV

Up to 921 Mt $H_2O$ erupted simultaneously

$H_2SO_4$ has a very low vapor pressure

Aerosol concentrated by temperature inversion

Horizontal winds in stratosphere spread $SO_2$ efficiently

Covered 42% of the earth within 2 months

These factors typically not effective in troposphere
Eruption of Lakigigar, Iceland 1783, VEI = 4

14.7 km³ basalt from a 27 km long fissure
122 Mt SO₂ (5 times Pinatubo) 80% in the troposphere
Trees, crops damaged by H₂SO₄ in Iceland, Scandinavia, Italy
>47,000 people killed from respiratory problems and famine

Lakigigar

Eyjafjallajökull (March 2010)
A Dry Fog or Haze Settled Over Europe

Grund, Iceland, NNW 80 mi (130 km)
Mannheim, Germany, ESE 1400 mi (2250 km)
Haze is Common in Polluted Cities

Laki haze:
- Noticeable smell of $\text{SO}_2$ (burnt match)
- Severe irritation to respiratory passages
- Severe sulfuric acid damage to vegetation
- Dimmed sunlight
- Raised daytime temperatures $3^\circ\text{C}$
“Solar ultraviolet radiation plays a decisive role in almost all aspects of the chemistry of the atmosphere.”

Grant W. Petty, 2006
**SO$_2$ in the Stratosphere**

SO$_2$ absorbs sunlight, warming the stratosphere

OH (formed by UV acting on O$_3$) oxidizes SO$_2$ to form an aerosol within months

The aerosol reflects, absorbs and scatters sunlight, cooling the earth

**SO$_2$ in the Troposphere**

Oxidized very slowly by OH and H$_2$O$_2$ because less UV and O$_3$ are available

Absorbs sunlight, warming the troposphere
### Sulfur Cycle

#### Natural Emissions

<table>
<thead>
<tr>
<th>Natural Emissions</th>
<th>Sulfur Mt/year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oceanic, DMS</td>
<td>15-35</td>
</tr>
<tr>
<td>Oceanic, H₂S</td>
<td>2.9</td>
</tr>
<tr>
<td>Oceanic, OCS</td>
<td>0.3</td>
</tr>
<tr>
<td>Oceanic, CS₂</td>
<td>0.2</td>
</tr>
<tr>
<td>Continental Biogenic</td>
<td>0.2</td>
</tr>
<tr>
<td>Biomass Burning</td>
<td>0.1</td>
</tr>
<tr>
<td>Volcanic Background</td>
<td>8-20</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>27-59</strong></td>
</tr>
</tbody>
</table>

#### Anthropogenic Emissions

<table>
<thead>
<tr>
<th>Anthropogenic Emissions</th>
<th>Sulfur Mt/year</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
<td>62</td>
</tr>
<tr>
<td>1979</td>
<td>75</td>
</tr>
<tr>
<td>1965</td>
<td>57</td>
</tr>
<tr>
<td>1950</td>
<td>32</td>
</tr>
<tr>
<td>1900</td>
<td>10</td>
</tr>
<tr>
<td>1850</td>
<td>1.5</td>
</tr>
<tr>
<td>Biomass burning</td>
<td>2.1</td>
</tr>
</tbody>
</table>

### In 1979:

- Anthropogenic emissions of SO₂ were 130% to 280% larger than the total natural emissions.
- Anthropogenic emissions of CO₂ and CH₄ were only 36% and 16% larger than the total natural emissions.
Sulfate in Greenland Changed Up and Down in Phase With Known Sulfur Emissions
Decrease in Sulfur Followed by Less Growth in Methane and Temperature
Meanwhile CO$_2$ Shows No Change!
But What About CO₂?

Man is adding ~8.4 Gt C/year or ~23 Mt C/day

The 1991 Pinatubo eruption added up to 234 Mt CO₂ or 63 Mt C

CO₂ is a greenhouse gas with an atmospheric concentration of 387 ppmv, increasing by 1.4 ppmv per year

CO₂ is removed from the atmosphere by
1. Photosynthesis in plants
2. Weathering of silicate rocks
3. Solubility in water (greater at lower temperatures)
4. Conversion by ocean organisms to tissues and hard body parts

CO₂ is added to the atmosphere by
1. Respiration by plants & animals
2. Decay of plants and animals
3. Combustion of organic material
4. Production of cement
5. Volcanic eruptions

Berner, 2006, GEOCARBSULF
SO$_2$ in the United States

71% Decrease in the national average from 1980 to 2008

Highest in the East

But strong in the Grand Canyon
But SO$_2$ Emissions Are Rising Again

Coal Consumption

- China
- FSU
- USA
- Other

Million tons
Conclusions

Sulfate levels in ice cores from central Greenland are observed to be unusually high during:

A: 14 short periods of rapid global warming between 46,000 and 11,000 BP (Dansgaard-Oeschger) implying short high rates of major volcanism

B: The period of most rapid global warming during the 20th century when anthropogenic emissions of sulfur were greatest

Much of the older sulfate can be traced via trace elements to volcanoes in Iceland and elsewhere

20th century sulfate can be traced in similar ways to smokestacks in northern Europe and northwestern Asia with sporadic contributions from central North America

The sources of SO2 are different, but the mechanism is the same

Humans caused 20th century warming
Conclusions (Continued)

SO$_2$ absorbs photons from the sun very strongly at wavelengths in the UV-A range just above 0.35 $\mu$m.

Photons below 0.35 $\mu$m form O$_3$ and OH and rarely reach the troposphere.

Photons in the 0.35-0.39 $\mu$m range are the most energetic from the sun to reach the lower troposphere.

This energy is turned into heat when SO$_2$ is present.

SO$_2$ from Laki volcano in 1783 heated Europe 3$^\circ$C.

Anthropogenic emissions of SO$_2$ were 130% to 280% larger than the total natural emissions.

Anthropogenic emissions of CO$_2$ and CH$_4$ were only 36% and 16% larger than the total natural emissions.
The Primary Conclusion

The primary initiator of global warming appears to be

solar absorbing gases (dominantly SO$_2$)

not greenhouse gases (dominantly H$_2$O and CO$_2$)
The Importance of SO$_2$ is Good News!!

We know how to reduce SO$_2$ emissions
We have done it very successfully in North America, Europe and Japan since 1979
The Clean Air Act in the United States
We can scrub it from smoke stacks and burn fuels in ways that reduce emissions
China has an aggressive program to reduce SO$_2$, but not aggressive enough
Reducing SO$_2$ emissions will also reduce both acid rain and premature life loss

Let’s get on with the job!
Sulfur dioxide initiates global climate change in four ways

2009
Thin Solid Films, Volume 517, Pages 3188-3203

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Our friends depend on us!