Physical and Optical Properties of the Stratospheric Aerosol Layer

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Justification for this Talk

“Much debate has focused on whether the rate of global warming of the past decade or so is consistent with global climate model estimates, requiring careful examination of all radiative forcing terms.”

-Susan Solomon, 2011
OUTLINE

• The Stratosphere
• The Stratospheric Aerosol Layer
• The Effect of Volcanoes
• Climate Effects
• Climatology of the Aerosol Layer
• Geo-engineering and the Aerosol Layer
Temperature Structure of the Atmosphere
Stratospheric Dynamics
Removal of Stratospheric Air through Tropopause Folds
The Stratospheric Aerosol Layer

• A fine mist of concentrated sulfuric acid droplets enveloping the Earth from the tropopause to about 30 km.

• The droplets have a radius of about 0.07 microns and a concentration of about 10 per cubic centimeter.

• The particles are formed by homogeneous nucleation of gaseous sulfuric acid and water vapor.

• The sulfuric acid is formed from SO₂ injected into the stratosphere by volcanic eruptions and from OCS and SO₂ transported from the troposphere.
Black diamond = partial pressure of water in stratosphere

Red circle = partial pressure of $\text{H}_2\text{SO}_4$ in stratosphere
Gaseous Precursors
Microphysical Processes Affecting the Aerosol

• Homogeneous binary nucleation
  • Neither H₂O nor H₂SO₄ can nucleate under stratospheric conditions but the binary system can form.

• Coagulation
  • Particles collide and coalesce

• Condensation
  • Particles grow because water and sulfuric acid condense onto them.

• Sedimentation
  • Not very important because settling speed is so small.

• Transport
  • Particles are removed when they get trapped in the polar vortex and when they are swept into tropopause folds.
Life Cycle of Stratospheric Aerosol

- Tropical Stratospheric Reservoir
- Tropical Pipe
- Micrometeorites
- Evaporation
- Polar Vortex
- Nucleation
- Condensation and Coagulation
- Tropopause Fold
- ~17 km
- ~8 km

Equator Pole
The Effect of Volcanoes
Historical Volcanoes

Yellowstone, WY  700,000 years ago  Ejecta ~ 500 km^3
Also 2.1 million and 1.4 million years ago

Long Valley CA  700,000 years ago  ~ 500 km^3

Toba, Indonesia  70,000 years ago  ~ 500 km^3

Mt. Mazama OR  6650 years ago  ~ 500 km^3

Kikai (Japan)  6300 years ago  ~ 100+ km^3

Santorini (Thira)  3650 years ago  ~ 100+ km^3

Tambora  1815 current era  ~ 150+ km^3
(followed by the year without a summer)

Krakatoa  1883  ~ 20+ km^3

Pinatubo  1991  10 km^3
A 10-year volcanic winter triggered by the Toba eruption could have largely destroyed the food supplies of humans and therefore caused a significant reduction in population (a “bottleneck”).
Crater Lake, Oregon. Formed by Eruption of Mt. Mazama (7000 years ago)
Santorini (Thira) 3700 years ago
Tambora 1815 (Followed by the “Year without a Summer”)
Pinatubo 1991
Pinatubo, 1991
Effects

Volcanoes insert a large amount of SO\textsubscript{2} into the Stratosphere, producing a layer of sulfuric acid droplets that scatter solar radiation and absorb terrestrial (long wave) radiation

- Warms the stratosphere and cools the troposphere and surface
- Changes gaseous makeup of the stratosphere through O\textsubscript{3} destruction.
- Change mean stratospheric winds and consequently change tropospheric storm tracks.
Effects - continued

• May change Atlantic Ocean meridional overturning circulation, ocean heat content and sea level. This can result in long-term (hundreds of years?) climate effects if the cooling is transmitted to depths of thousands of meters.

• May affect precipitation and crop productivity.

• Cause warm anomalies in Northern Eurasia and cold anomalies in the Middle East and NorthEast Canada.
Forcing

The radiative forcing due to a doubling of carbon dioxide in the atmosphere is about

\[ +3.5 \text{ Watts/m}^2 \]

The radiative forcing due to Pinatubo was approximately

\[ -4 \text{ Watts/m}^2 \]
Climatology of the Aerosol Layer

Instruments used to measure the state of the aerosol layer include:

• Lidar systems (ground based and on satellites - CALIPSO)
• Lidar systems on aircraft (LaRC Aerosol Lidar, DLR OLEX lidar, Univ. of Rome ABLE lidar, etc.)
• Occultation measurements from Satellites (SAM, SAGE, POAM),
• Satellite borne spectrometers (OMI, MODIS, …)
• Balloon borne particle counters (Univ Wyoming)
• Impactors on aircraft (ER-2)
Figure 3.1: An illustration of solar occultation geometry
SAGE II Zonal Depiction of $\log_{10}$ Aerosol Extinction for January 1994
History of the Aerosol Layer: Lidar Observations

Lidar integrated backscatter from two tropical sites and two midlatitude sites. Triangles represent small volcanic eruptions. Lines between boxes are estimates of background conditions.
History of the Aerosol Layer: Optical Particle Counter (University of Wyoming). Number of particles greater than 0.15 μm (black) and greater than 0.25 μm (red) per cm$^3$. 
History of the Aerosol Layer: SAGE II: Solar Occultation 40-45 N
History of the Aerosol Layer: SAGE II: Vertical Crosssection Solar Occultation 0-5 N
History of the Aerosol Layer.
SAGE II Optical Depth
Aerosol Surface Area Density ($\mu$m$^2$/cm$^3$)
Problem: Not enough SO$_2$ or OCS

There is a problem with the picture we have presented in which high energy explosive volcanic events inject sulfur dioxide into the stratosphere to form an aerosol layer that gradually decays. The problem is that there is not enough SO$_2$ nor enough OCS to maintain the layer during volcanically quiescent periods.
Figure 2.21 History of anthropogenic Sulfur emissions in geographical regions from 1850 – 2000. From Stern [2003].
An Interesting Recent Study

Susan Solomon et al in Science, August 12, 2011, show that the stratospheric aerosol layer is maintained by small volcanic eruptions that maintain the stratospheric aerosol in a sort of “background” state.
Effect of Soufriere Hills, Tavurvur, Kasatochi and Sarychev, as measured by CALIPSO

Fig. 1. Evolution of the zonal mean scattering ratio at 532 nm between 17 and 21 km from the CALIPSO lidar measurements since June 2006. Plumes with scattering ratios greater than 1.15 that are observed in the tropics and at mid-latitudes are linked to the indicated volcanic eruptions; after (16).
Decay to 1960
Constant 2010-2020
Increases @ 5%/yr
For purposes of comparison
Over the decade since 2000

$\text{CO}_2$ increased by $\sim 0.5\%$ per year

for a radiative forcing of about $0.28 \text{ W/m}^2$

Stratospheric aerosols increased by $\sim 7\%$ per year

for a radiative forcing of about $-0.1 \text{ W/m}^2$
Geoengineering

Lowell Wood (and others) have suggested pumping SO$_2$ into the Arctic stratosphere to increase the number and size of the aerosol particles and cool the troposphere.
Can Dr. Evil Save the World?

QuickTime™ and a TIFF (LZW) decompressor are needed to see this picture.

From Rolling Stone, Oct, 2006
Thank You