Volcanic Aerosol Climate Forcing , 1979-2015

Global values derived from Lunar Eclipse observations

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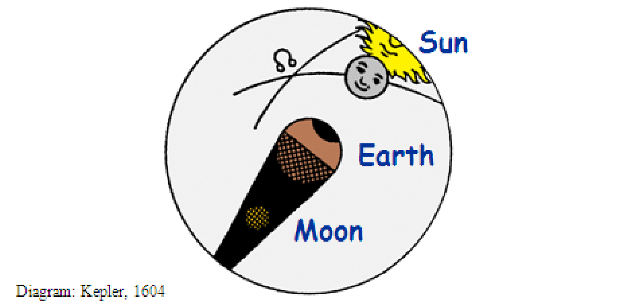
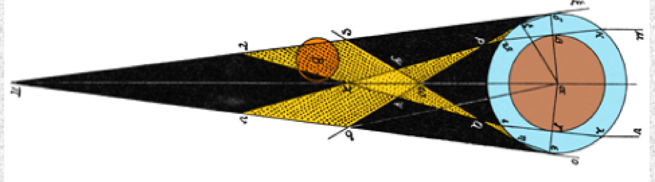
What is a Lunar eclipse

About once per year on average, a Lunar Eclipse occurs when the Moon passes through the Earth's shadow. At these times we can measure the effect of volcanoes on Earth's climate.



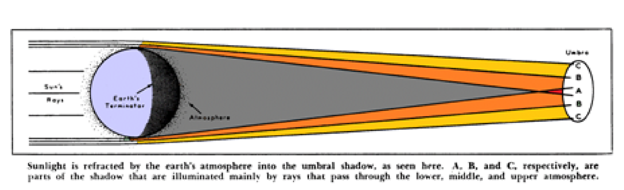
Sun light (coming from the right) is refracted (like a lens) into the Earth's umbra and onto the Moon during a lunar eclipse.
From J. Kepler, "Astronomiae pars Optica" (1604)



Kepler wrote that sunlight is reddened & dimmed as it passes through "mists and smoke" in the Earth's atmosphere (mostly stratosphere, we now know), causing the eclipsed moon to appear orange, red, or darker.

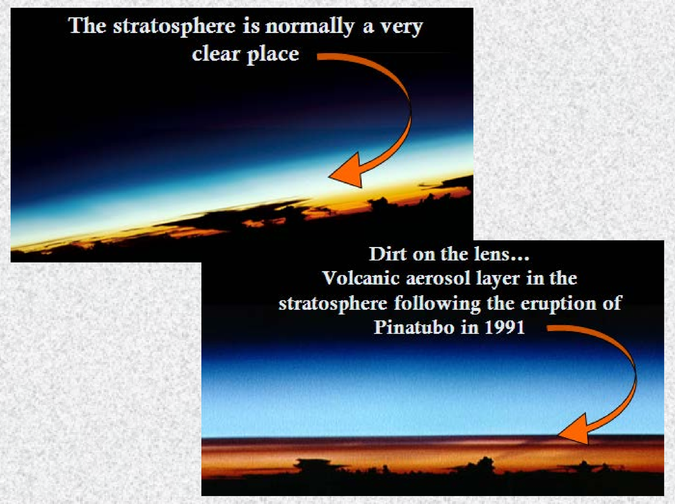
How volcanoes affect eclipses

Most of the sunlight that illuminates the moon during an eclipse passes through the stratosphere 15-40 km altitude

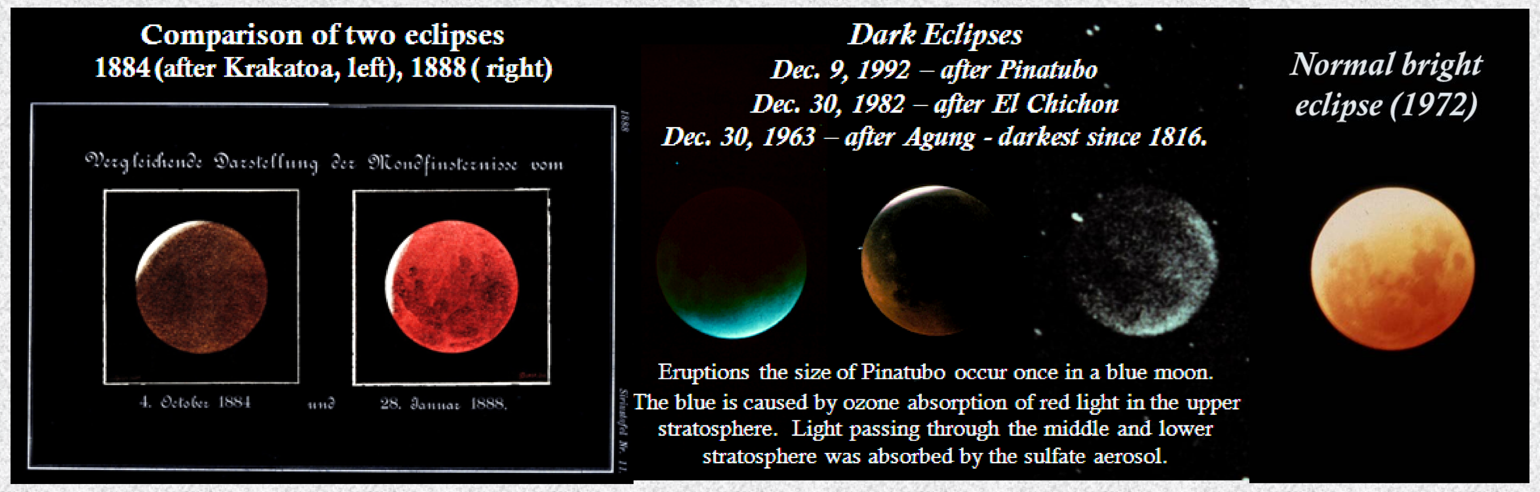


Sunlight is refracted by the earth's atmosphere into the umbral shadow, as seen here. A, B, and C, respectively, are parts of the shadow that are illuminated mainly by rays that pass through the lower, middle, and upper atmosphere.

... which is where volcanic aerosols concentrate and persist for years after an eruption.
Put "dirt" in the stratospheric light path, and the eclipse becomes darker.



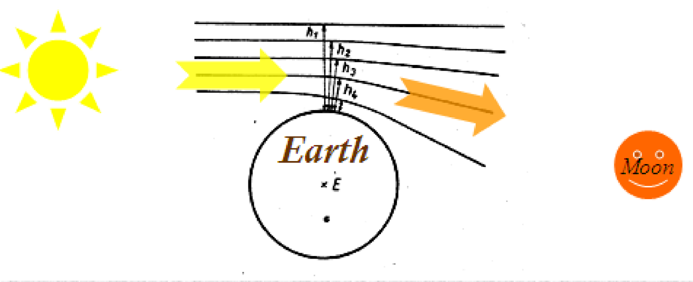
Volcanic effect on appearance of eclipses



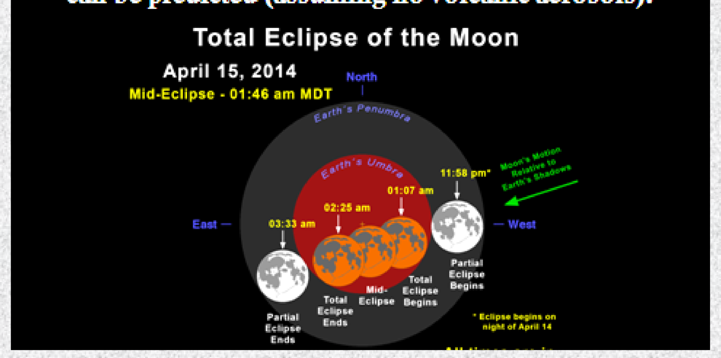
Calculating the amount of volcanic aerosol

First, calculate the bending and attenuation of sunlight passing at different altitudes, to predict the amount of light reaching various parts of the umbra.

Include refraction, scattering, and absorption by clear air in the stratosphere & mesosphere, and an assumed cloud distribution ~50% in the troposphere.



The brightness of the moon depends on its path through the umbra and distance from the Earth.
Knowing the eclipse's geometry, the moon's brightness can be predicted (assuming no volcanic aerosols).



Observed minus Calculated

After calculating the brightness of an eclipse for a clear, volcanic aerosol free atmosphere, go out and observe the eclipse. The brightness of the eclipse, in stellar magnitudes, can be observed with eye or photometer. Or, find observations in the literature.

The difference, Observed minus Calculated, is caused mostly to volcanic aerosols, and can be converted into an aerosol optical thickness.

Due to the grazing path length along the limb of the Earth, the dimming of the moon is roughly 40x the aerosol optical depth.

Summary Abstract

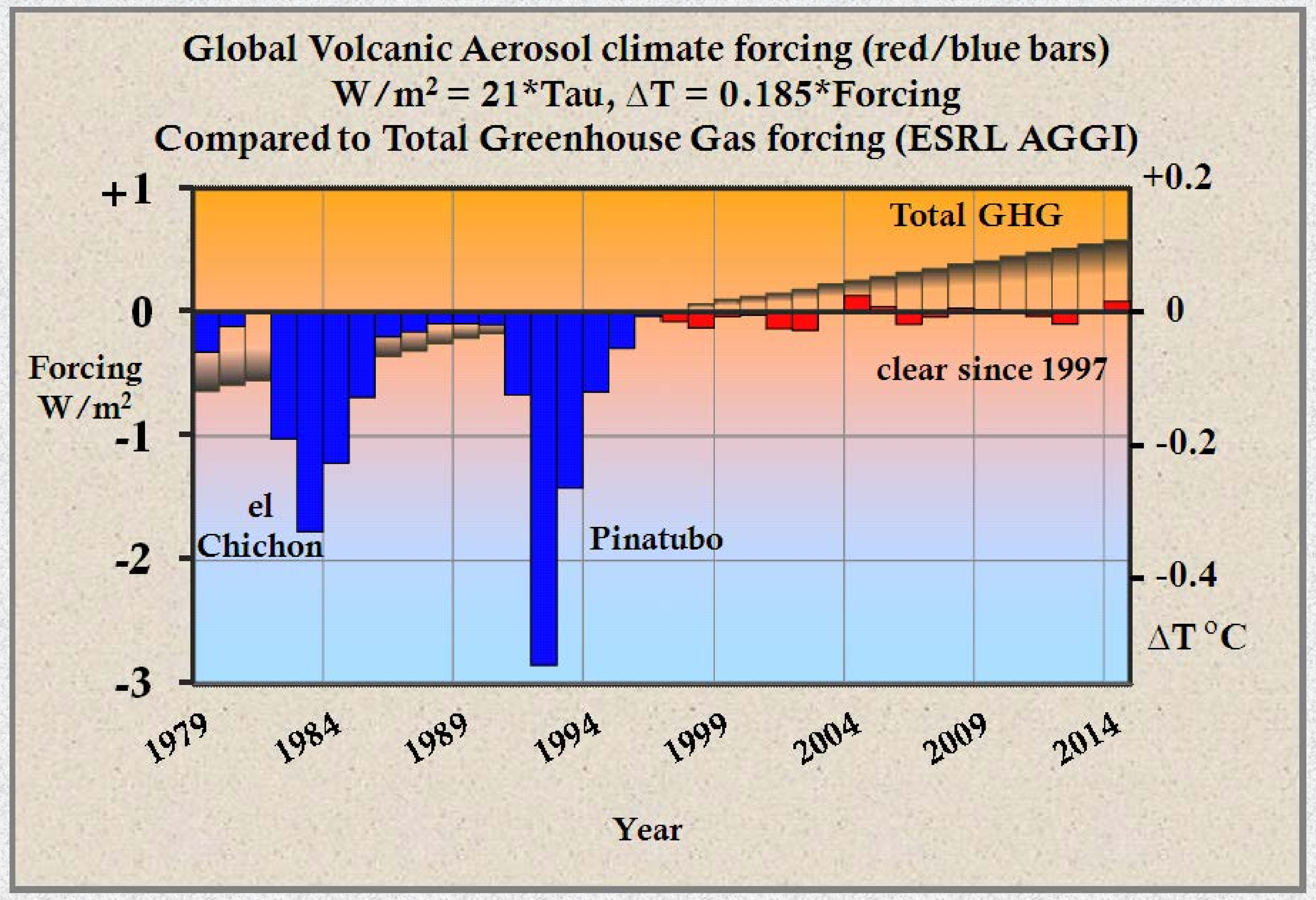
In 2004, Hofmann et al. summarized five decades of stratospheric aerosol observations, "Surface-Based Observations of Volcanic Emissions to the Stratosphere", in Volcanism and the Earth's Atmosphere, AGU Monograph 139. Among the records were lunar eclipse aerosol optical depth (AOD) determinations, updated here to April, 2015.

About once per year, on average, the moon is totally eclipsed; the moon is then illuminated by sunlight refracted into the umbra, primarily by the stratosphere. Stratospheric aerosols can affect the brightness of the eclipsed moon, and AOD can be determined from the difference between observed and predicted brightness.

AOD data from 1979 to 2015 show that the eruptions of el Chichon (1982) and Pinatubo (1991) reduced the solar heating by 2 W/m2 and 3 W/m2, respectively. Since 1996, stratospheric AOD have been near zero; this is the longest period with a clear stratosphere since before 1960.

Between 1979-1995 and 1996-2014, mean AOD decreased from 0.035 to 0.002, corresponding to a net increase in climate forcing of +0.7 W/m2 (e.g. Hansen et al., 2002). This is slightly greater than the +0.6 W/m2 increase due to total long-lived greenhouse gases over the same period (ESRL, 2014). Computed radiative equilibrium temperature changes between the same intervals are +0.13C due to decreasing AOD and +0.11C due to increasing GHG, accounting for most of the observed +0.27C warming of MSU global temperatures. After subtracting AOD and GHG effects from annual MSU temperatures, over half of the residual variance can be attributed to el Niño/la Niña (Multivariate ENSO Index).

Global Volcanic Aerosol climate forcing 1979-2014, measured from Lunar Eclipse observations



The volcanic record back to 1880, updated to 2015

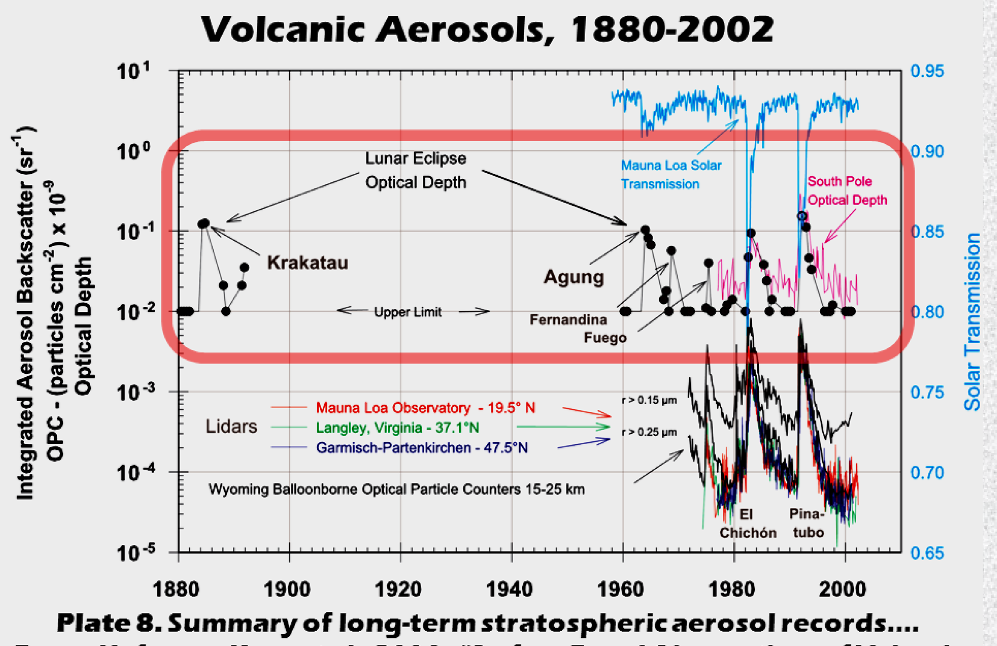
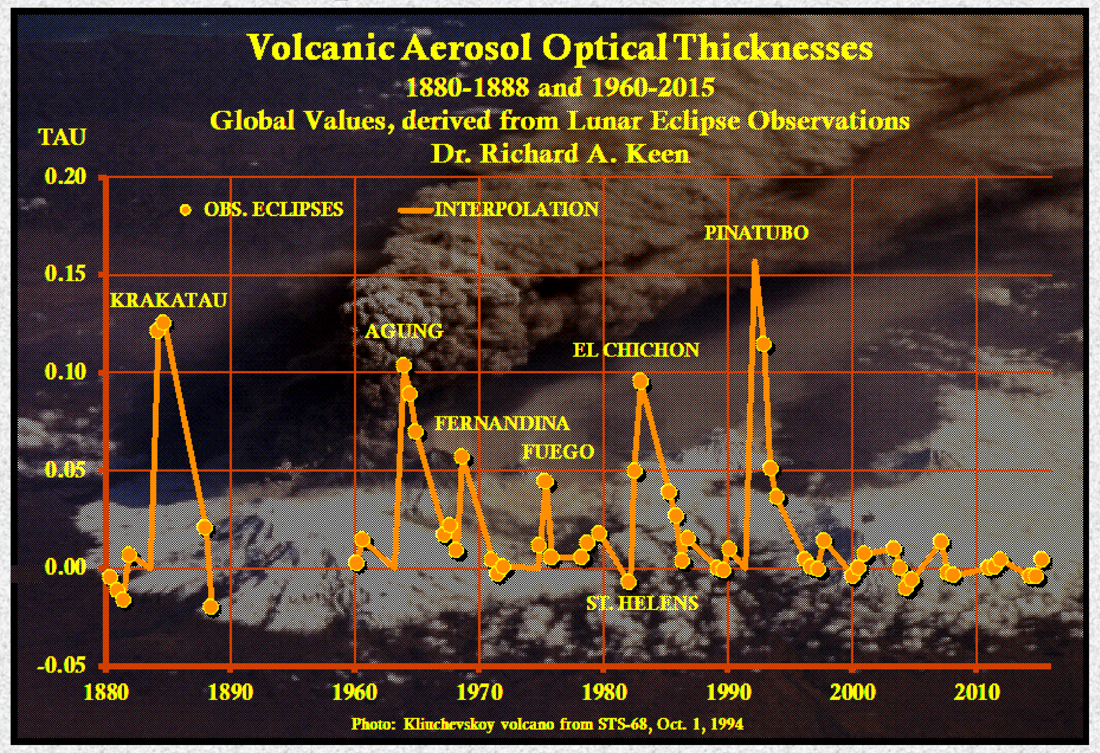
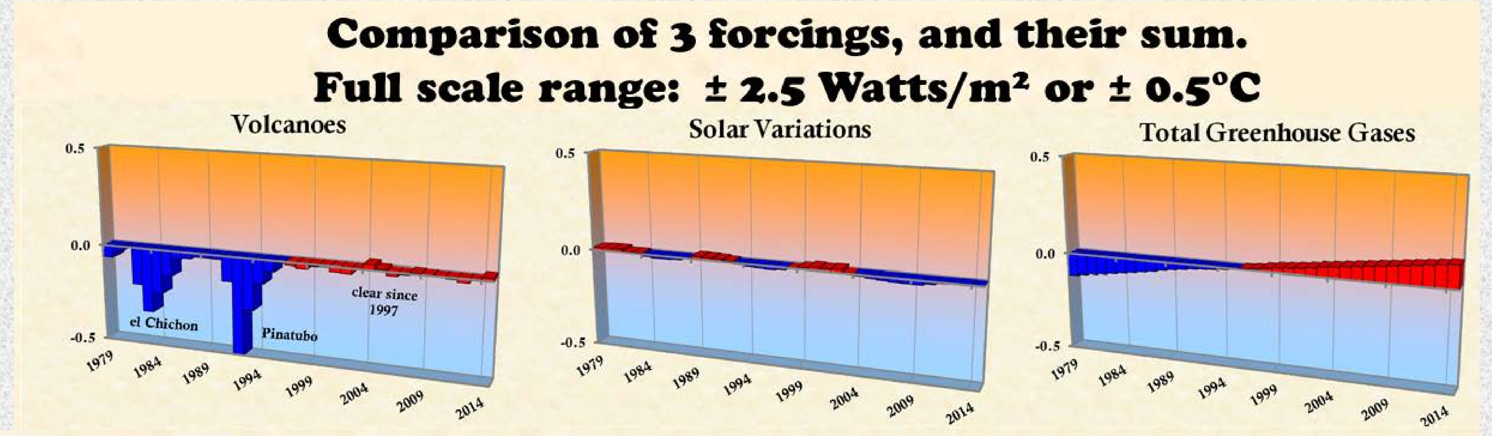


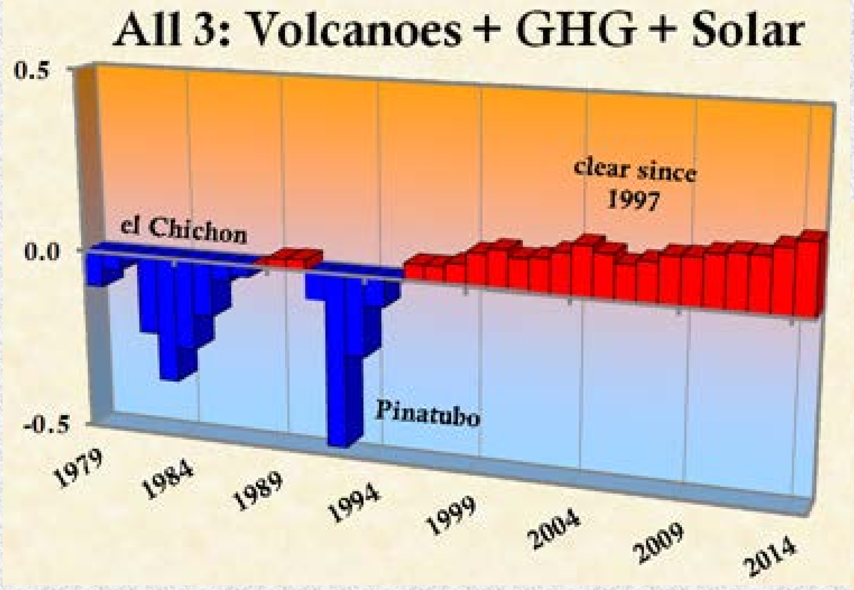
Plate 8. Summary of long-term stratospheric aerosol records....
From: Hofmann, Keen et al., 2004: "Surface-Based Observations of Volcanic Emissions to the Stratosphere", in Volcanism and the Earth's Atmosphere, Geophysical Monograph 139, American Geophysical Union



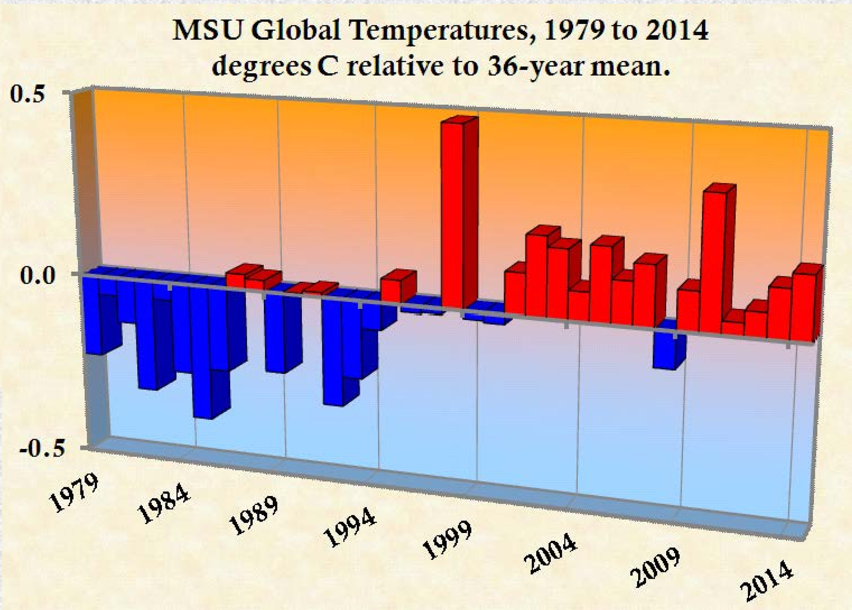
Implications for Climate

Comparison of Volcano, Solar TSI, and Greenhouse gas forcing, converted to ΔT(Radiative Equilibrium) ...

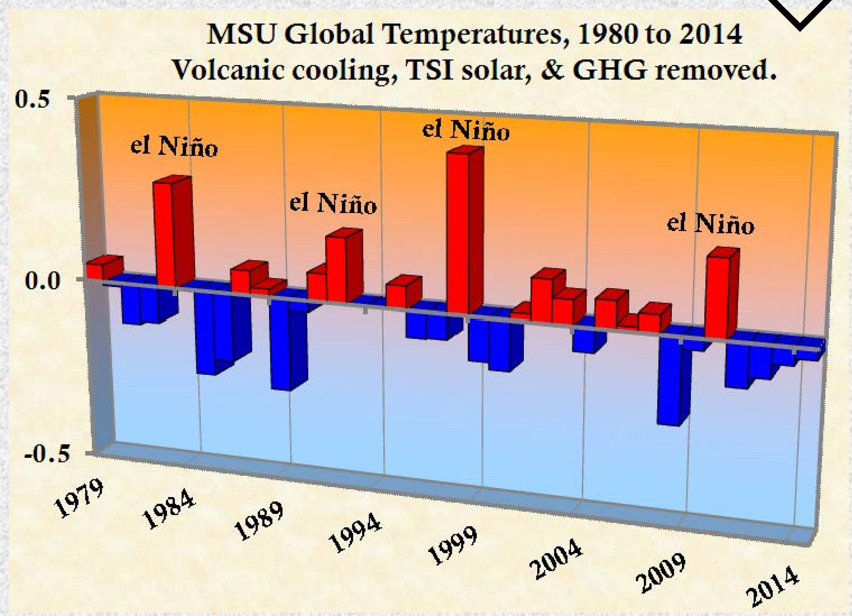




... with global satellite MSU temperatures

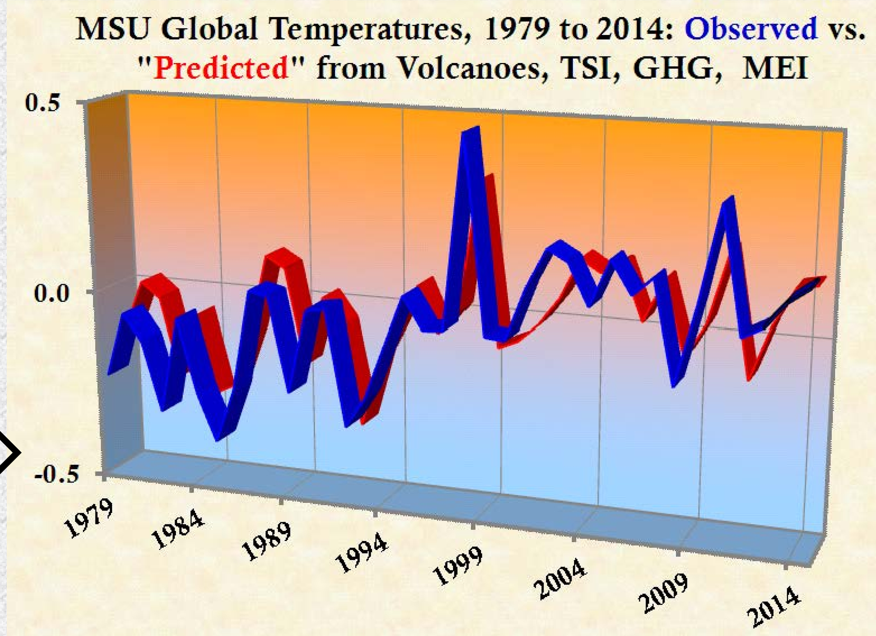


Subtract the radiatively forced ΔT (above) from the observed temperatures ...



... Leaving essentially el Niño. 57 percent of the residual variance (left) can be attributed to the Multivariate ENSO Index (MEI)

A reconstruction of annual temperatures, using only Volcanic and GHG forcing plus el Niño effect = 0.135*MEI, correlates with MSU global temperatures, r = 0.93



Implications for future global climate change

- **The Globe warmed +0.25 C during 1979-2014.**
- **Based on simple radiative calculations (no H_2O/cloud feedbacks, etc.), the clear stratosphere after 1995 is responsible for half of this warming (+0.12 C).**
- **Increasing Total GHG can explain most of the remainder, and the two combined (Volcanic aerosols and GHG) are sufficient to explain most of the observed warming with no additional feedback effects.**
- **Warming due to CO_2 alone is +0.08 C over 36 years.**
- **This implies a climate sensitivity to a doubling of CO_2 of +0.68 C, with no additional feedback warming.**
- **At current rates, CO_2 will rise from the current 400 ppm to 560 ppm by 2100 AD. The calculated warming is +0.33 C (assuming, of course, no volcanoes).**

Comparing the first and second halves of the 36-year period, the clearing of volcanic aerosols after 1995 appears responsible for half of the observed warming.

18- year averages: 1997-2014 minus 1979-1996

Climate forcing = –21*AOD (Hansen et al., 2002; IPCC 2001)
GHG from http://www.esrl.noaa.gov/gmd/aggi/index.html
$\Delta T (C) = 0.185 \cdot \Delta(\text{forcing } W/m^2)$, from $\Delta(\text{forcing}) = \Delta(\sigma T^4)$

Aerosol Optical Depth AOD	τ	ΔT from σT^4
AOD 1979-1996	0.031	
AOD 1997-2014	0.001	
AOD change	– 0.030	
AOD forcing change	+0.62 W/m²	+0.12 C
Total GHG forcing change (ESRL, 2012)	+0.61 W/m²	+0.11 C
MMTS Global Temp.		+0.25 C