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The Persistently Variable "Background" Stratospheric Aerosol Layer and Global Climate Change

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Recent measurements demonstrate that the "background" stratospheric aerosol layer is persistently variable rather than constant, even in the absence of major volcanic eruptions. Several independent data sets show that stratospheric aerosols increased in abundance since 2000. Near-global satellite aerosol data imply a negative radiative forcing due to stratospheric aerosol changes over this period of about –0.1 W/m^2, reducing the recent global warming that would otherwise have occurred. Observations from earlier periods are limited but suggest an additional negative radiative forcing of about –0.1 W/m^2 from 1960 to 1990. Climate model projections neglecting these changes would continue to overestimate the radiative forcing and global warming in coming decades if these aerosols remain present at current values or increase.

Understanding climate changes on time scales of years, decades, centuries, or more requires determining the effects of all external drivers of radiative forcing of the Earth's climate, including anthropogenic greenhouse gases and aerosols, natural aerosols, and solar forcing, as well as natural internal variability. Much debate has focused on whether the rate of global warming of the past decade or so is consistent with global climate model estimates (*1*), requiring careful examination of all radiative forcing terms. Most of the global warming of the past half-century has been driven by continuing increases in anthropogenic greenhouse gases (*2*), but natural aerosols from particular "colossal" volcanic eruptions [see the index of volcanic activity definitions in (*3*)] have significantly cooled the global climate at times, including for example the "year without a summer" experienced after the eruption of the Tambora volcano in 1815 and notable cooling after the Pinatubo eruption in 1991 (*4*, *5*). As used here, "colossal" or "major" refers to specific volcanic eruptions that have been generally recognized not only as extremely large but also as having injecting a great deal of gaseous sulfur directly into the tropical stratosphere. Tropical eruptions are thought to be especially important for climate change because the injected material can be transported into the stratospheres of both hemispheres and affect the entire globe for many months.

The cooling effect of volcanic eruptions mainly arises not from the injected ash, but from SO_2 injected by plumes that are able to reach beyond the tropical tropopause into the stratosphere, whereupon the SO_2 oxidizes and temporarily increases the burden of stratospheric particles. Stratospheric aerosols are composed largely of dilute sulfuric acid droplets that effectively reflect some incoming solar energy back to space. The radiative cooling due to increases in these particles is linked to the associated optical depth increases. Observations show that the volcanic particles from the colossal eruptions of El Chichón and Pinatubo in 1982 and 1991, respectively decayed from the stratosphere with e-folding times of about a year (*5*).

Early measurements of the stratospheric aerosol layer around 1960 by Junge (*6*) were carried out at a time when no colossal eruptions had occurred in many years. These data are subject to large instrumental uncertainty, but suggested an apparent "background" stratospheric aerosol layer, with aerosol burdens too small to measurably influence the global climate system. Crutzen (*7*) proposed that the dominant source of the background stratospheric aerosol layer was carbonyl sulfide (OCS), since other sulfur sources were thought to be too reactive or too soluble in rainwater to reach the stratosphere in significant amounts. But observations of the amount of background stratospheric aerosol since at least the 1970s using improved instrumentation reveal abundances that are far too large to be due mainly to OCS (*8*). Some studies have suggested that an important source of the background stratospheric aerosol layer may be anthropogenic sulfur (e.g., SO_2 from coal burning, biomass burning, etc.) that can be transported from the troposphere to the stratosphere in some locations (*9*, *10*). One study (*11*) estimated that the radiative forcing of the background stratospheric aerosol layer since 1750 would be about –0.05 W/m^2 if dominated by human-made SO_2 emissions during the industrial era, which is clearly far smaller than tropospheric aerosol and carbon dioxide forcing (about –1 W/m^2 and +1.9 W/m^2, respectively). While radiative forcing on longer time scales is determined by well-known factors, here we present one example of a much wider variety of forcings that can be important on decadal time scales.

High quality ongoing measurements of stratospheric aerosols using lidars or balloons have been carried out at a limited number of sites around the world, and records extend back to the 1970s in some locations. The input and decay of material from major volcanic eruptions is readily observed but changes in the underlying "background" have also been noted. Hofmann and coworkers (*12–14*) argued that the "background" stratospheric aerosol layer increased by 5-9%/year through the 1960s, 1970s, and 1980s, and again at about 5-7% in the 2000s. However, in the 1990s stratospheric aerosols decreased by similar magnitudes. Other authors (*15*) recently noted the likely importance of volcanoes, suggesting that changes in the "background" were variable, and that trends were sensitive to the time interval considered. Our focus here is on how any such changes would affect climate change.

Satellite instruments provide evidence that smaller volcanic eruptions can play a more significant role in affecting the background stratospheric aerosol burden than has often been thought (*16*, *17*). Figure 1 shows the first 4 years of aerosol load in the lower stratosphere (17-21 km) from the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) lidar measurements since the beginning of its mission in June 2006 [after (*15*), see also fig. S1]. These data indicate that emissions from two relatively minor tropical eruptions reached the stratosphere in significant amounts, in particular those from Soufrière Hills and Tavurvur (Fig. 1 and fig. S1). There is also some contribution to the global aerosol optical depth increase from summer season mid- to high-latitude eruptions that spread across much of the globe (*16*, *18*, *19*), but these may have a smaller effect on global climate change than lower latitude eruptions (*19*). Figure 1 suggests that it may be difficult if not impossible to define a "background" that is not affected to some degree by volcanic inputs over the past decade. The lack of major eruptions since 1991 has made the identification of this input much clearer than earlier measurements, but the data do not rule out some contribution to the increases in the stratospheric aerosol burden from anthropogenic sources [such as coal burning, see (*14*) as well].

Additional evidence for changes in the abundance of "background" stratospheric aerosol is provided by recent lidar and ground-based measurements from Mauna Loa, a particularly important site located in a remote location at high elevation where tropospheric aerosol burdens are often relatively small. Multiple instruments have been used at Mauna Loa for estimating or measuring total aerosol optical depth and atmospheric transmission. Here we present observations taken there on the cleanest days, when much of the aerosol burden likely resides in the stratosphere. Figure 2 shows three independent data records that all indicate increases in aerosol optical depth (or, equivalently, decreases in transmission) at Mauna Loa from the late 1990s to the late 2000s: from ground-based transmission data using the pyrheliometer ratioing methodology (*20*, *21*), a Precision Filter Radiometer [1999 to date (*22*)], and a stratospheric lidar (*14*). Figure 2 compares these data to the mean tropical and global stratospheric aerosol optical depths from combined satellite observations by the Stratospheric Aerosol and Gas Experiment (SAGE) II (1990–2005), Global Ozone Monitoring by Occultation of Stars (GOMOS, 2002-2009) and the CALIPSO lidar (2006–2010), see (*16*, *17*, *23–25*); the overlapping periods of the different satellite instruments allow accurate quantification of the trends over time (*17*). The four independent data sets from satellite, lidar, total transmission, and aerosol optical depth as shown in Fig. 2 jointly support the view that the "background" stratospheric aerosol layer has changed significantly over about the past decade [see (*25*)].

The satellite observations displayed in the bottom panel of Fig. 2 show increases in stratospheric aerosols from 2000–2010 of about 7% per year, which implies a change in global radiative forcing (Fig. 3) of about –0.1 W/m^2 [see (*25*) for information on optical parameters used]. As a point of comparison, over the decade since 2000, carbon dioxide increased by about 0.5% per year (*2*), leading to a change in radiative forcing of about +0.28 W/m^2. Thus, the rapid rates of observed change of stratospheric aerosol imply decadal changes in radiative forcing that are significant compared to those of the much larger but more slowly varying abundance of carbon dioxide since 2000.

Figure 3 presents a time series of radiative forcing estimated from near-global satellite (50N-50S) stratospheric aerosol optical depth data and the apparent transmission of the cleanest days each year at Mauna Loa. It should be emphasized that the pioneering volcanic aerosol forcing data set provided by NASA GISS (*26*) that is used in many global climate modeling simulations does include significant optical depths in several "background" periods prior to the late 1990s, in good agreement with the data shown in Fig. 3. However, Fig. 3 also demonstrates that the radiative forcing derived from the recent stratospheric aerosol data shows important differences from two stratospheric aerosol forcing data sets often used in climate modeling studies (*26*, *27*) around 2000, when both adopt near-zero values, i.e., much lower than the observations presented in Fig. 2. Thus, there would be an important missing cooling term for the past decade in climate models if they assume near-zero stratospheric aerosols at and after 2000.

We next use the Bern 2.5cc intermediate complexity climate model [(*28*) and references therein] to probe how recent and possible similar future changes in the optical depth of stratospheric aerosol could affect global climate change. The tropical and global satellite data together with the suite of different Mauna Loa observations suggest a decrease in global radiative forcing (Fig. 2) over the last decade. The model has been extensively compared to other earth system models of intermediate complexity as well as to Atmosphere-Ocean General Circulation Models [AOGCMs, see (*28*)]. The transient climate response (TCR) of the model employed here is slightly less than the mean of models assessed in IPCC (*2*); the "very likely" range of TCR across climate models suggests that the absolute effects of the stratospheric aerosol changes on climate considered below could be greater by about 80% or smaller by about 40%. However, the relative climate change impact of stratospheric aerosols over a decade as compared to other forcings such as carbon dioxide is not affected by the model TCR. While simplified compared to AOGCMs, the Bern model can be used to examine very small forced global temperature changes that could be difficult to quantify in AOGCMs against the computed noise of internal variability.

A radiative forcing time series of well-mixed greenhouse gases and tropospheric aerosols (*25*) is used to provide a baseline model scenario against which test cases including different stratospheric aerosol radiative forcing changes for the past and future are compared. Figure 4 shows that the observed increase in stratospheric aerosol since the late 1990s caused a global cooling of about –0.07°C compared with a case in which near-zero radiative forcing is assumed after year 2000, as in the forcing data sets often used in global climate models. Figure 4 shows that stratospheric aerosol changes have caused recent warming rates to be slower than they otherwise would have been. While subject to much more instrumental uncertainty, Fig. 4 also suggests that the underlying increase in the "background" aerosols from the very low values indicated by observations around 1960 to the higher levels observed around 2000 probably reduced the global warming that would otherwise have occurred between 1960 and 2000 by about –0.05°C. Such changes in integrated radiative forcing also affect calculated thermal sea level rise rates (*29*). For the decade from 2000–2010, the observed stratospheric aerosol radiative forcing from satellites yields about 10% less sea level rise from thermal expansion than obtained assuming a background near zero as in (*26*), about 0.16 cm versus 0.186 cm; the data presented in Fig. 3 provides a basis for further study of these effects since 1960. In summary, while the values of radiative forcing due to the changing stratospheric aerosol amounts are small compared to e.g., colossal eruptions or tropospheric pollution aerosol, they are nevertheless can provide a significant contribution to the forcing changes that drive climate changes, particularly on decadal scales.

Future changes in stratospheric aerosols are unknown since the frequency and intensity of minor volcanic eruptions may be greater or less than in the past decade (Fig. 1), and future trends in anthropogenic SO_2 emissions as well as their ability to contribute to the stratospheric aerosol layer remain uncertain. Figure 4 shows several test cases probing a range of plausible changes that could occur in the coming decade to 2020. The Figure demonstrates that climate model scenarios that neglect the changes in background stratospheric aerosols relative to the year 2000 should be expected to continue to overestimate radiative forcing changes and the related global warming in the coming decade if the stratospheric aerosol burden were to remain constant at current values or continue to increase. On the other hand, if stratospheric aerosols were to decay back to their 1960 levels within the next decade, then the rate of warming would be faster, and the global average temperature is estimated to be 0.06°C greater by 2020. It should be emphasized that additional contributions to global climate variations of the past and future decades such as from solar variations, natural variability, or other processes are not ruled out by this study.

With the availability of improved satellite, lidar and ground-based data, the past decade has provided a unique opportunity to document the importance of "background" stratospheric aerosols changes in the absence of major volcanic eruptions. The changes in the stratospheric aerosol layer have probably affected the observed rates of decadal warming over the past decade, highlighting the importance of the variable stratospheric aerosol layer for past and future decadal climate predictability.

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Supporting Online Material
www.sciencemag.org/cgi/content/full/1206027/DC1
SOM Text
Fig. S1
Table S1
References

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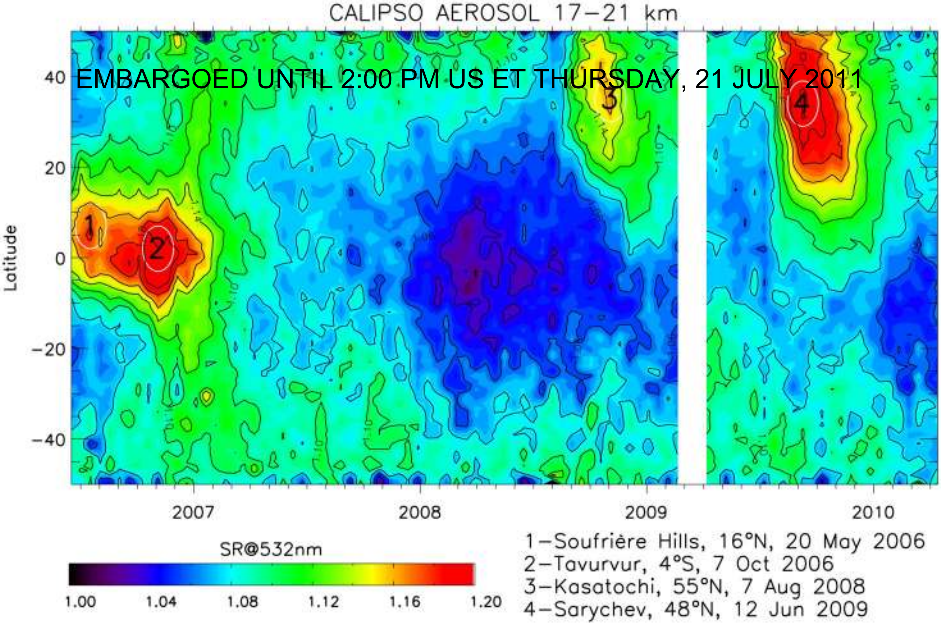
Fig. 1. Evolution of the zonal mean scattering ratio at 532 nm between 17-21 km from the CALIPSO lidar measurements since June 2006. Plumes with scattering ratios greater than 1.15 that are observed in the tropics and at mid-latitudes are linked to the indicated volcanic eruptions; after (*16*).

Fig. 2. Apparent transmission observed at Mauna Loa (upper panel). Monthly values are determined from the highest transmission observed in each month that contained at least 10 observations. The annual values represent the mean of the 10 most transparent days of each year. Aerosol optical depths for Mauna Loa stratospheric lidar (middle panel) and ground-based optical depth data (for the 10 cleanest days from PFR, see text) are also shown along with tropical satellite data. The annual apparent transmission values are also plotted in the middle panel for comparison (+). The bottom panel compares the global optical depths used in many climate modeling studies [(*26*) and see http://data.giss.nasa.gov/modelforce/strataer/; (*27*)] to the measured values for 50°N-50°S from satellite data discussed in the text. The satellite data are integrated from 15-40 km and are screened to remove clouds; see (*25*).

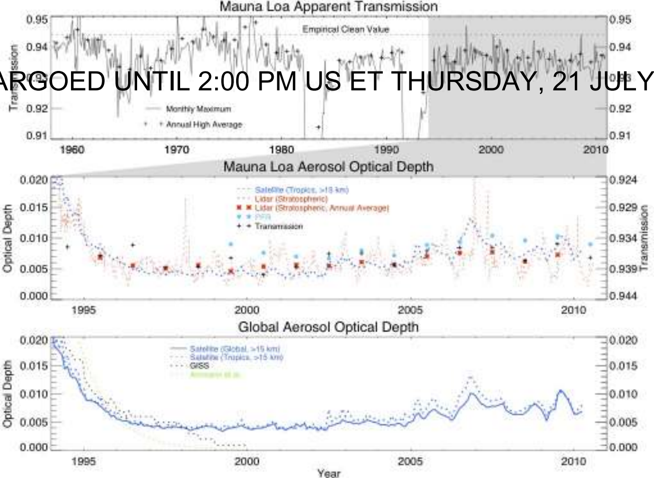
Fig. 3. Radiative forcing from stratospheric aerosols (scale at left). The forcings that have been used in many climate modeling studies are represented by the dotted black (*26*) and dotted green curves (*27*), while that derived here from satellite observations is shown in the solid blue curve [see (*17*, *25*)]; '+' symbols represent the Mauna Loa apparent transmission observations as in Fig. 2 (scale at right). The dashed-dotted green line represents our estimate of the radiative forcing changes of the evolving background stratospheric aerosol implied by the Mauna Loa transmission

data to the late 1990s. Three future test cases are also shown (dashed purple lines) in which aerosol forcing is held constant from 2010–2020, continues to increase in magnitude at 5%/yr, or decays back to the assumed 1960 level with a 3-year time constant.

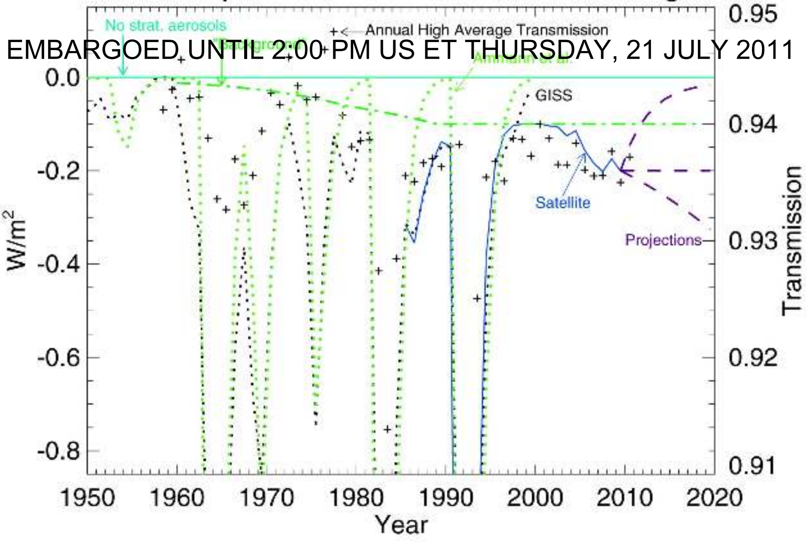
Fig. 4 Radiative forcing for six stratospheric aerosol forcing scenarios (upper panel, also see Fig. 3) and the resulting change in global average temperature since preindustrial times as calculated by the Bern earth system model of intermediate complexity (lower panel). Scenarios include: no stratospheric aerosol forcing (solid blue/green); only background aerosol forcing with no volcanoes (dashed-dotted green); stratospheric aerosol forcing from GISS optical depths transitioning to no stratospheric aerosol forcing after 2000 (black); forcing from GISS until 1998 then assuming forcing inferred from the global satellite optical depths (black followed by blue); this curve then splits into three future projections (dashed purple) as described for Fig. 3.

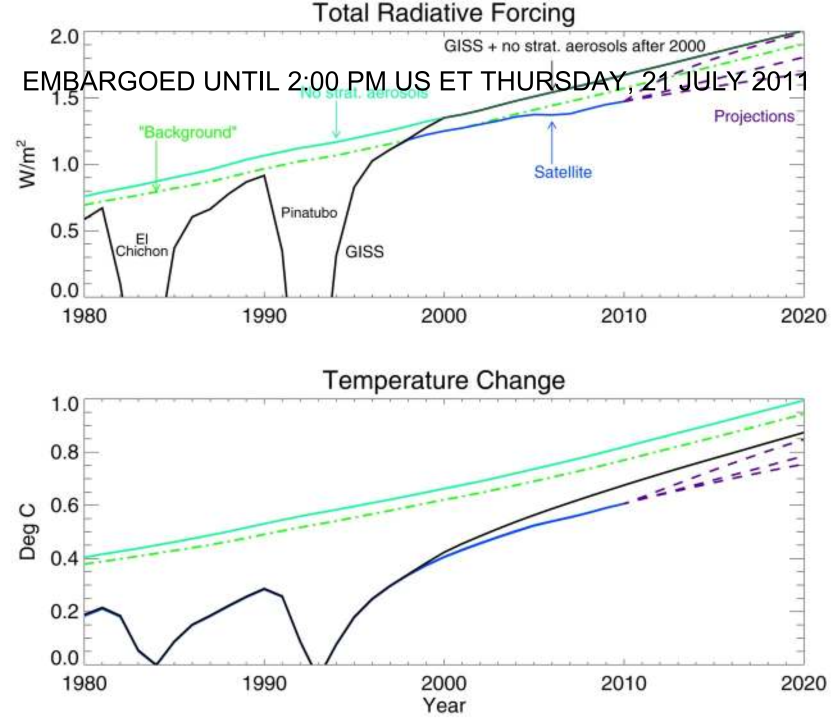


CALIPSO AEROSOL 17–21 km
Latitude
40
20
0
−20
−40
2007
2008
2009
2010
SR@532nm
1.00
1.04
1.08
1.12
1.16
1.20
1–Soufrière Hills, 16°N, 20 May 2006
2–Tavurvur, 4°S, 7 Oct 2006
3–Kasatochi, 55°N, 7 Aug 2008
4–Sarychev, 48°N, 12 Jun 2009


Mauna Loa Apparent Transmission
Empirical Clean Value
Monthly Maximum
Annual High Average
Transmission
0.95
0.94
0.92
0.91
1960
1970
1980
1990
2000
2010
Mauna Loa Aerosol Optical Depth
Satellite (Tropics, >15 km)
Lidar (Stratospheric)
Lidar (Stratospheric, Annual Average)
PFR
Transmission
Optical Depth
0.020
0.015
0.010
0.005
0.000
0.924
0.929
0.934
0.939
0.944
1995
2000
2005
2010
Global Aerosol Optical Depth
Satellite (Global, >15 km)
Satellite (Tropics, >15 km)
GISS
Optical Depth
Year

Stratospheric Aerosol Radiative Forcing




Total Radiative Forcing
GISS + no strat. aerosols after 2000
No strat. aerosols
"Background"
Projections
Satellite
Pinatubo
El Chichon
GISS
W/m^2
2.0
1.5
1.0
0.5
0.0
1980
1990
2000
2010
2020
Temperature Change
Deg C
1.0
0.8
0.6
0.4
0.2
0.0
1980
1990
2000
2010
2020
Year