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

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*Science* **333**, 866 (2011);
DOI: 10.1126/science.1206027

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**Acknowledgments:** This research was supported as part of the Center for Molecular Electrocatalysis, an Energy Frontier Research Center funded by the U.S. Department of Energy, Office of Science, Office of Basic Energy Sciences. Pacific Northwest National Laboratory is operated by Battelle for the U.S. Department of Energy. Structural parameters for **4** are available free of charge from the Cambridge Crystallographic Data Centre under CCDC 828010. We thank J. A. S. Roberts for help with the simulations of the cyclic voltammograms.


**Supporting Online Material**

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21 March 2011; accepted 28 June 2011
10.1126/science.1205864


# 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 have 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 watt per square meter, 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 watt per square meter 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 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 injected 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 (the time interval in which an exponentially decaying quantity decreases by a factor of $e$) of about a year (*5*).

Early measurements of the stratospheric aerosol layer around 1960 by Junge *et al.* (*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), because 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 ($SO_2$ from coal burning, biomass burning, etc.) that can be transported


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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). Although 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 lidar instruments 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 are readily observed, but changes in the underlying background have also been noted. Hofmann and co-workers (*12*–*14*) argued that the background stratospheric aerosol layer increased by 5 to 9%/year through the 1960s, 1970s, and 1980s, and again at about 5 to 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 important 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 to 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 in 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 other 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 probably 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 instrument (*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 to 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, $CO_2$ 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 as compared to those of the much larger but more slowly varying abundance of $CO_2$ since 2000.

Figure 3 presents a time series of radiative forcing estimated from near-global satellite (50°N to 50°S) 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 Goddard Institute for Space Studies (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, which is 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 used the Bern 2.5cc intermediate complexity climate model [(*28*) and references therein] to probe how recent and possible sim-

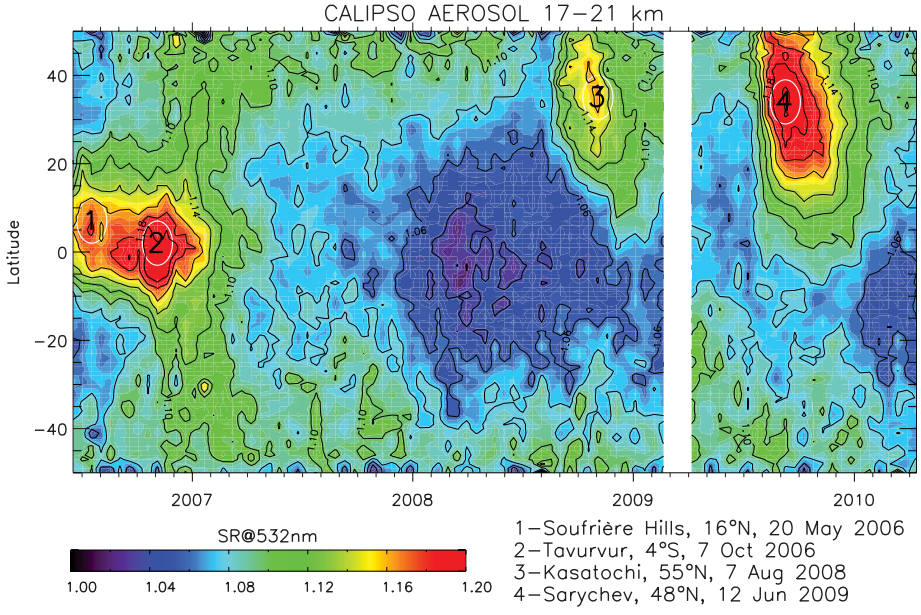



**Fig. 1.** Evolution of the zonal mean scattering ratio at 532 nm between 17 and 21 km from the CALIPSO lidar measurements since June 2006. Plumes with scattering ratios greater than 1.15 that are observed in the tropics and at mid-latitudes are linked to the indicated volcanic eruptions; after (*16*).

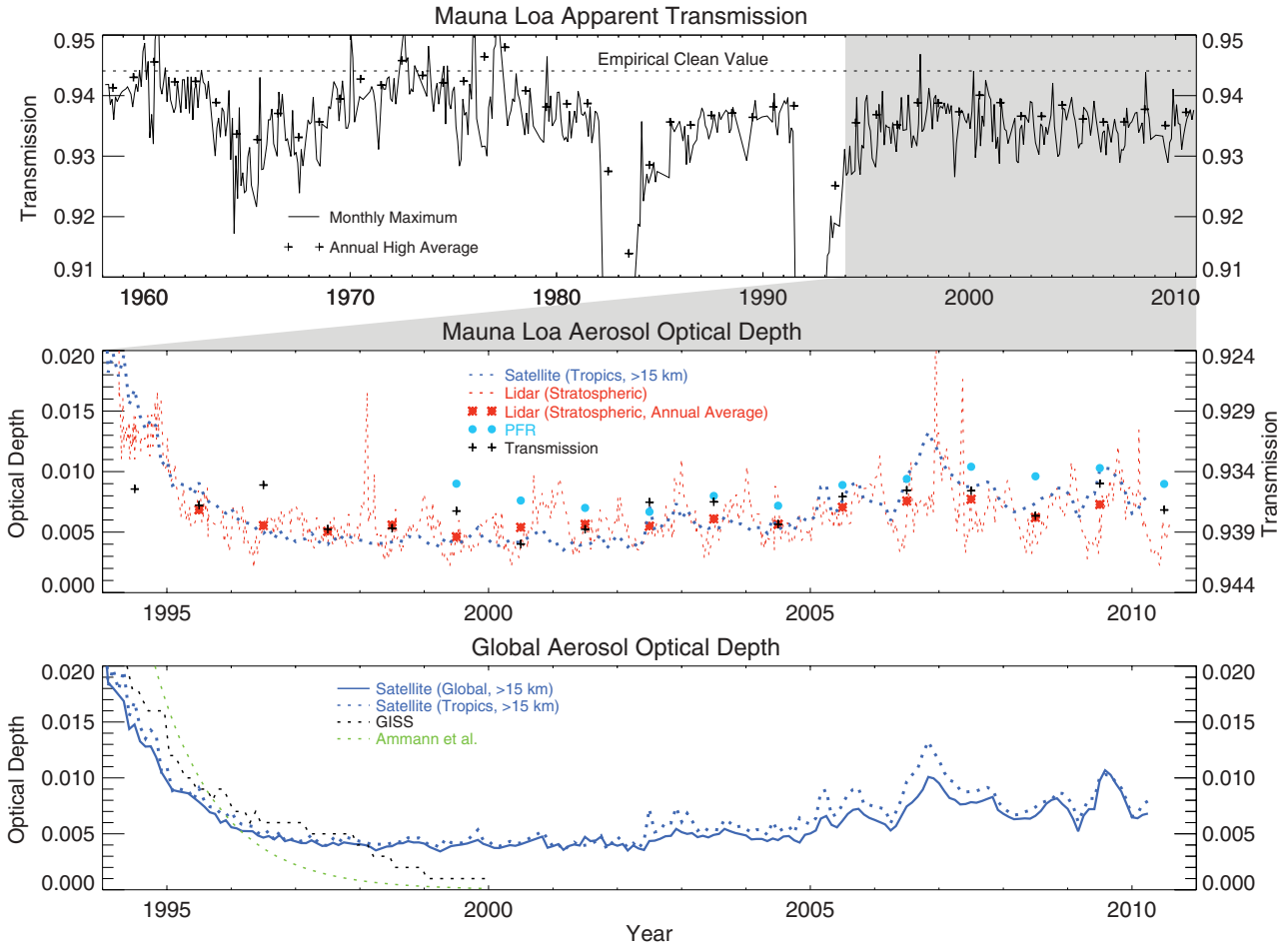
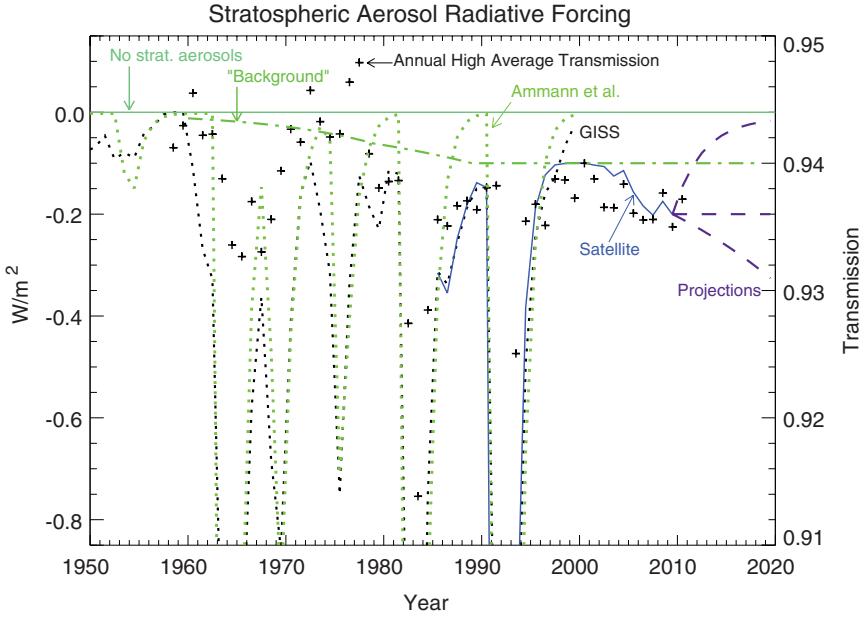



**Fig. 2.** Apparent transmission observed at Mauna Loa (**top**). Monthly values are determined from the highest transmission observed in each month that contained at least 10 observations. The annual values represent the mean of the 10 most transparent days of each year. Aerosol optical depths for Mauna Loa stratospheric lidar (**middle**) and ground-based optical depth data (for the 10 cleanest days from the Precision Filter Radiometer, see text) are also shown, along with tropical satellite data. The annual apparent transmission values are also plotted in the middle panel for comparison (+). (**Bottom**) Comparison of 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 to 50°S from satellite data discussed in the text. The satellite data are integrated from 15 to 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*), whereas that derived here from satellite observations is shown in the solid blue curve (*17*, *25*); + symbols represent the Mauna Loa apparent transmission observations as in Fig. 2 (scale at right). The dash-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 to 2020, continues to increase in magnitude at 5%/year, or decays back to the assumed 1960 level with a 3-year time constant.



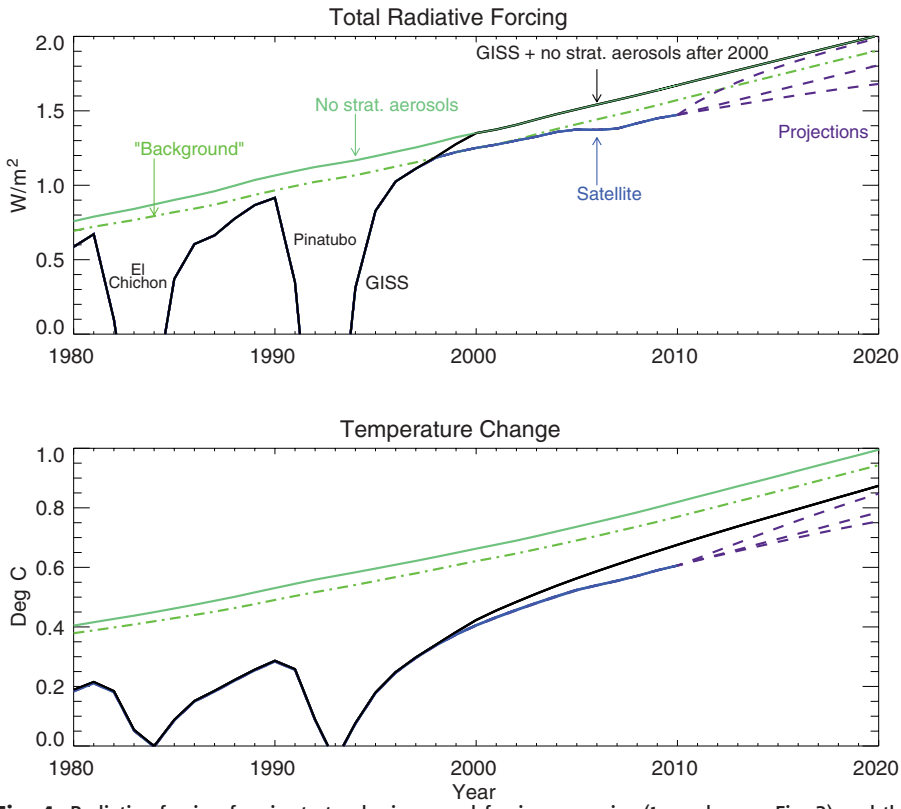



**Fig. 4.** Radiative forcing for six stratospheric aerosol forcing scenarios (**top**, also see Fig. 3) and the resulting change in global average temperature since preindustrial times as calculated by the Bern earth system model of intermediate complexity (**bottom**). Scenarios include: no stratospheric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

ilar 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. 3) over the past 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 by the Intergovernmental Panel on Climate Change (*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 that of $CO_2$, is not affected by the model TCR. Although it is 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*) was used to provide a baseline model scenario against which test cases, including different stratospheric aerosol radiative forcing changes for the past and future, were compared. Figure 4 shows that the observed increase in stratospheric aerosol since the late 1990s caused a global cooling of about −0.07°C as 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. Although 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 to 2010, the observed stratospheric aerosol radiative forcing from satellites yields about 10% less sea-level rise from thermal expansion than obtained when a background near zero is assumed as in (*26*), about 0.16 cm versus 0.186 cm; the data presented in Fig. 3 provide a basis for further study of these effects since 1960. In summary, although the values of radiative forcing due to the changing stratospheric aerosol amounts are small as compared to, for example, colossal eruptions or tropospheric pollution aerosol, they 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 because 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 an opportunity to document the importance of changes in background stratospheric aerosols 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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**Acknowledgments:** The satellite aerosol observations were analyzed by J.P.V. during his fellowship through the NASA Postdoctoral Program at Langley Research Center, administrated by Oak Ridge Associated Universities. It is also a part of his Ph.D. thesis financed by the Centre National de la Recherche Scientifique at LATMOS/Université de Versailles St Quentin. The CALIPSO data were made available at the ICARE data center (www-icare.univ-lille1.fr/). The authors also acknowledge help from A. Hauchecorne, J. P. Pommereau, J. Pelon, and A. Garnier in the analysis of the GOMOS and CALIPSO data sets; J. Barnes for Mauna Loa lidar data; and C. Wehrli for Precision Filter Radiometer data. Funding has also been provided by the Atmospheric Composition and Climate Program of NOAA's Climate Program. Helpful discussions with J. Gregory and D. M. Murphy are gratefully acknowledged.

**Supporting Online Material**

www.sciencemag.org/cgi/content/full/science.1206027/DC1
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Fig. S1
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24 March 2011; accepted 29 June 2011
Published online 21 July 2011;
10.1126/science.1206027

# Viviparity and K-Selected Life History in a Mesozoic Marine Plesiosaur (Reptilia, Sauropterygia)

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**Viviparity is known in several clades of Mesozoic aquatic reptiles, but evidence for it is lacking in the Plesiosauria. Here, we report a Late Cretaceous plesiosaur fossil consisting of a fetus preserved within an adult of the same taxon. We interpret this occurrence as a gravid female and unborn young and hence as definitive evidence for plesiosaur viviparity. Quantitative analysis indicates that plesiosaurs gave birth to large, probably single progeny. The combination of viviparity, large offspring size, and small brood number differs markedly from the pattern seen in other marine reptiles but does resemble the K-selected strategy of all extant marine mammals and a few extant lizards. Plesiosaurs may have shared other life history traits with these clades, such as sociality and maternal care.**

Viviparity, or birthing live young, is common among reptiles, having evolved over 80 times among extant clades (*1*). Live birth has also been documented in several groups of Mesozoic aquatic reptiles, including ichthyosaurs (*2*), mosasauroids (*3*), choristoderans (*4*), and nothosaur-grade sauropterygians (*5*). However, to date no evidence exists for viviparity in the sauropterygian clade Plesiosauria, despite an excellent fossil record and a collection history spanning almost 200 years. This lack of evidence for viviparity is enigmatic given that plesiosaurs were large animals whose bodies lacked a firm connection between the appendicular and axial skeleton, a condition impeding the terrestrial nesting required in an oviparous amniote (*5*–*7*). Viviparity was documented recently in basal, amphibious eosauropterygian clades (*5*), even though these clades have shorter and less intense collecting histories. However, the single published claim of plesiosaur embryonic material (*8*) was shown to be misinterpreted shrimp burrows (*9*), and until now no pregnant plesiosaur fossil has been reported. In this paper, we present fossil evidence of a gravid plesiosaur; furthermore, analysis of the fetus demonstrates that plesiosaurs exhibited a reproductive pattern unique among marine reptiles.

LACM 129639 (Natural History Museum of Los Angeles County) was discovered in 1987 by Charles Bonner on the Bonner Ranch in Logan County (Kansas, USA) at the base of the Pierre Shale [Sharon Springs Member, Campanian (*10*)]. The fossil consists of the largely articulated skeletal remains of two plesiosaur individuals, an adult and a juvenile displaying features at very early stages of development (Fig. 1). The adult is a large, short-necked plesiosaur referable to *Polycotylus latippinus* Cope, complete save for the head and anterior 16 cervical vertebrae. Measurement of the adult vertebral column allows a confident length estimate of 470 cm (*11*). The juvenile consists of a mass of poorly ossified and largely disarticulated bones spilled from the body cavity of the adult, intermingled with phalanges of the adult right fore-paddle (Fig. 2).

Some ambiguity exists concerning the original orientation of the fossil because no quarry map was kept of the excavation. However, a confident reassembly was possible on the basis of the position of elements within each jacket, with subsequent evaluation and validation by the original excavator, Charles Bonner (Fig. 1) (*11*). Of the 12 jackets, three contain a mixture of adult and juvenile elements (Fig. 2). The elements of the juvenile pelvis are near life position, and the juvenile right pubis and left ischium are adhered to the visceral (internal) surface of the adult right coracoid by gypsum and matrix. The presence of phalanges from the right forelimb in the two jackets containing the balance of the juvenile material indicates that their original position was in the vicinity of the right forelimb. The position of this limb relative to the thorax was established on the basis of the location of the pectoral girdle and an associated paddle bone in the thorax jacket. The rest of the mount was laid out in approximate articulation, and the resulting mount was certified as accurate by the original excavator (*11*).

Multiple lines of evidence indicate that the juvenile specimen is an in situ fetus. First, the partially articulated fetal pelvis adhered to the visceral surface of the right adult coracoid establishes that the juvenile was both articulated and within the adult body cavity at the time of deposition, before burial (Fig. 2). Second, both specimens are referable to the same species, *P. latippinus*, on the basis of their possession of that taxon's distinctive humerus. This humerus has a shaft that is narrow and strongly curved relative to other plesiosaurs and also possesses four discrete facets on its distal edge for articulation with the radius, ulna, and two additional ossifications (*11*–*13*). Third, the juvenile skeleton is poorly ossified and displays numerous embryonic

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