

This discussion paper is/has been under review for the journal Geoscientific Model Development (GMD). Please refer to the corresponding final paper in GMD if available.

# A Consistent Prescription of Stratospheric Aerosol for Both Radiation and Chemistry in the Community Earth System Model (CESM1)

R. R. Neely III<sup>1,2</sup>, A. Conley<sup>2</sup>, F. Vitt<sup>2</sup>, and J. F. Lamarque<sup>2</sup>

<sup>1</sup>National Centre for Atmospheric Science (NCAS) and the School of Earth and Environment (SEE), University of Leeds, Leeds, UK

<sup>2</sup>National Center for Atmospheric Research (NCAR), Boulder, Colorado, USA

Received: 27 November 2015 – Accepted: 16 December 2015  
– Published: 21 December 2015

Correspondence to: R. R. Neely III (r.neely@leeds.ac.uk)

Published by Copernicus Publications on behalf of the European Geosciences Union.

**GMDD**

8, 10711–10734, 2015

**Prescribed  
Stratospheric  
Aerosol in CESM1**

R. R. Neely III et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



## Abstract

Here we describe an updated parameterization for prescribing stratospheric aerosol in the Community Earth System Model (CESM1). The need for a new parameterisation is motivated by the poor global response of most models in Coupled Model Inter-comparison Project 5 (CMIP5) to colossal volcanic perturbations to the stratospheric aerosol layer (such as the 1991 Pinatubo eruption or the 1883 Krakatau eruption) in comparison to observations. In particular, the scheme used in the CMIP5 simulations by CESM1 simulated a global temperature decrease by a factor 2 larger than was observed. The new parameterisation takes advantage of recent improvements in historical stratospheric aerosol databases to allow for varying both the mass loading and effective radius of the prescribed aerosol. Simulations utilizing the new scheme are shown to now reproduce the observed global mean temperature response as well as the temperature response of the stratosphere due to local aerosol heating after the 1991 Pinatubo eruption.

## 1 Introduction

Volcanic perturbations to stratospheric aerosol are an essential, but most often ill represented, forcing of the climate system (Solomon et al., 2011; Driscoll et al., 2012; Knutson et al., 2013). Earth's climate system has been perturbed by several colossal (volcanic explosivity index (VEI) of 5 or greater) volcanic eruptions since 1960 (see Fig. 1) (Newhall and Self, 1982). The impact each of these eruptions has had on the global mean surface temperature anomaly is shown in Fig. 1.

Figure 1 compares the Coupled Model Inter-comparison Project 5 (CMIP5) multi-model global mean surface temperature anomaly to three different observationally based datasets (Taylor et al., 2012). The vertical dashed grey lines note the date of colossal volcanic eruptions accounted for in the forcing files utilized in the CMIP5 eruptions. Figure 1 shows that the response to the volcanic forcing in most CMIP5 models

GMDD

8, 10711–10734, 2015

## Prescribed Stratospheric Aerosol in CESM1

R. R. Neely III et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



results in a stronger cooling than was observed for each of the colossal eruptions over the second half of the twentieth century. Notably, the ensemble-mean global mean temperature falls by a further 0.1 °C than what was observed after the eruption of Pinatubo in June of 1991 (which is the best observed of all colossal volcanic eruptions).

5 Stratospheric aerosol is prescribed in several ways with various levels of complexity in global climate models. Most models contributing to CMIP5, including NCAR's Community Climate System Model, version 4 (CCSM4) (Meehl et al., 2012), use a scheme that prescribes a zonal mean, monthly mass of aerosol in the stratosphere (using datasets such as created by Ammann et al., 2003, and Sato et al., 1993). This  
10 mass of aerosol interacts with the model's (1) radiative transfer parameterization to create a stratospheric aerosol optical depth (SAOD) and (2) chemistry parameterization to create a surface area density (SAD) using several underlying assumptions about the size distribution and composition of the volcanic mass. Though adequate, these methods leave much to be desired for accurately modelling the evolution of the aerosol  
15 plumes after these eruptions.

To address the need for a more accurate representation of colossal volcanic eruptions in current climate models, including the Community Atmosphere Model (CAM) and Whole Atmosphere Community Climate Model (WACCM) within the framework of the Community Earth System Model (CESM1) (Neale et al., 2013; Lamarque et al.,  
20 2012; Marsh et al., 2012; Meehl et al., 2013), a new dataset was derived to force models participating in the Chemistry Climate Model Initiative (CCMI) (Eyring and Lamarque, 2012; Eyring et al., 2013). Here we describe the implementation of this dataset in CESM1(CAM4-chem & WACCM) with additional updates in preparation for CCMI Phase 1 simulations (Eyring et al., 2013).

## 25 **2 Summary of CCSM4 original dataset and implementation**

Previous to CESM1, CAM4 was part of the Community Climate System Model (CCSM4). Neale et al. (2010) fully describe the scheme used to specify volcanic erup-

---

**Prescribed  
Stratospheric  
Aerosol in CESM1**

R. R. Neely III et al.

---

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



---

**Prescribed  
Stratospheric  
Aerosol in CESM1**R. R. Neely III et al.

---

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

tions and the stratospheric aerosol layer in CCSM4 (specifically in CAM4.0) and how this interacts with the other parameterizations. For a full description of the model's climate and its response to forcings see Meehl et al. (2012). Here we summarize the main features of the volcanic prescription in CCSM4(CAM4) that have been changed significantly for the update described below so that future studies utilizing the new scheme in CESM1 may account for changes in the model's behaviour compared to simulations conducted for CMIP5.

In CAM4, stratospheric aerosol is treated by prescribing a single zonally averaged species. The prescription consists of a monthly-mean mass ( $\text{kg m}^{-2}$ ) distributed on a predefined meridional and vertical grid. The input time series from 1850 to 2010 is based upon Ammann et al. (2003) that built upon the previous database of Stenchikov et al. (1998). This mass is assumed to be comprised of 75 % sulphuric acid and 25 % water and have a constant log-normal size distribution with a wet effective radius ( $r_{\text{eff}}$  i.e. the third moment divided by the second of the size distribution) of  $0.426 \mu\text{m}$  and a standard deviation ( $\sigma(\ln r)$ ) of 1.25.

In CAM4 the stratospheric aerosol mass interacts with the radiative transfer code via the predefined mass-specific extinction, single scattering albedo, and asymmetry parameters. These parameters are calculated using the constants defined above (i.e. all of the aerosol conforms to a log-normal size distribution with a  $r_{\text{eff}}$  of  $0.426 \mu\text{m}$  and  $\sigma(\ln r)$  of 1.25 and the aerosol mass is composed of 75 % sulphuric acid and 25 % water) and are stored in lookup tables for the shortwave and long wave radiative transfer schemes separately (with a single dimension that varies by spectral band) for use by each of the spectral bands in the Community Atmosphere Model Radiative Transfer (CAMRT) parameterization. This information is combined with similar information from other radiatively active species in CAM4 as specified by Neale et al. (2010).

### 3 Summary of CESM1(CAM5) original dataset and implementation

Here we summarize the main features of the stratospheric aerosol prescription in CESM1(CAM5) so that differences may be accounted for between future simulations using the new CESM1 stratospheric aerosol scheme and the previous simulations conducted for CMIP5. For a full discussion of the parameterization used to represent stratospheric aerosol in CESM1(CAM5) please see chapter 4 of Neale et al. (2012).

Like CAM4, CESM1(CAM5) specifies the stratospheric aerosol as a mass mixing ratio of wet sulphate aerosol (i.e. a mixture of 75 % sulphuric acid and 25 % water) to dry air as a function of height, latitude and time. CESM1(CAM5) added the ability to include non-zonally symmetric aerosol as well (i.e. varying by longitude) previous to the present update.

One notable overall improvement of CESM1(CAM5) is the utilisation of the Rapid Radiative Transfer Method for GCMs (RRTMG) (Mlawer et al., 1997; Iacono et al., 2008). For each short-wave band calculation, extinction optical depth, single scattering albedo and asymmetry properties are determined from the aerosol properties according to their size and mass and radius. For each long-wave only absorption optical depth is calculated.

As with CAM4, to interact with the radiative transfer scheme, CESM1(CAM5) calculates mass-specific properties over each spectral band of RRTMG and parameterized a lookup table with  $\mu = \ln(r_g)$  as the dependent variable. This is the main difference between the CAM4 and CAM5 when it comes to representing the impact of stratospheric aerosols. Instead of a one-dimensional look up table (i.e. just varying over spectral band) as CAMRT uses in CAM4, RRTMG utilizes a two-dimensional look up table that varies by  $\mu$  and spectral band. The calculations used to form the look up table assume the size distribution of the aerosol to be a log-normal distribution with a geometric mean radius  $r_g$  that varies as specified and a constant geometric standard deviation  $\sigma_g$ , specified as 1.8 within the assumptions that are used to form the optical parameters file.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Note that for a log-normal distribution, the geometric mean radius  $r_g$  and the median  $r_m$  are equal and the effective radius is related to the geometric radius and geometric standard deviation by  $r_{\text{eff}} = r_g \exp(\frac{5}{2}(\ln \sigma_g)^2)$ . The geometric standard deviation is the exponential of the standard deviation of  $\ln(r)$ . (See Grainger (2015) for full derivations of log-normal aerosol size distribution properties.)

In CESM1(CAM5) the mass-specific aerosol extinction, scattering, and asymmetric scattering are defined as:

$$b_{\text{ext}} = \frac{3}{4\rho r_{\text{eff}}} \int_0^{\infty} Q_{\text{ext}}(r) dL(r) \quad (1)$$

$$b_{\text{sca}} = \frac{3}{4\rho r_{\text{eff}}} \int_0^{\infty} Q_{\text{sca}}(r) dL(r) \quad (2)$$

$$b_{\text{asm}} = \frac{3}{4\rho r_{\text{eff}}} \int_0^{\infty} Q_{\text{exasmt}}(r) dL(r) \quad (3)$$

The mass-specific absorption is defined as the difference of the extinction (Eq. 1) and scattering (Eq. 2):

$$b_{\text{abs}} = \frac{3}{4\rho r_{\text{eff}}} \int_0^{\infty} (Q_{\text{ext}}(r) - Q_{\text{sca}}(r)) dL(r) \quad (4)$$

Where  $L(r)$  is the incomplete gamma function defined as

$$L(r) = \int_0^r r'^2 n(r') dr' / \int_0^{\infty} r'^2 n(r') dr' \quad (5)$$

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



and the density ( $\rho$ ) of the assumed 75%/25% sulfuric acid to water mixture at 215 K is  $1750 \text{ kg m}^{-3}$ .  $Q_{\text{ext}}(r)$ ,  $Q_{\text{sca}}(r)$ ,  $Q_{\text{asm}}(r)$  are the Mie efficiencies parameters obtained from the MIEV0 (Wiscombe, 1996).

Similar to CAM4, CESM(CAM5) uses the time series from 1850 to 2010 from Ammann et al. (2003). This time series does not take advantage of the ability to change  $r_g$  and instead a constant value of 1.25 was assumed in the formation of the optical parameters file even though the model code allowed for this improvement. This original forcing file also does not take advantage of the ability of the model to utilize a zonally asymmetric forcing file.

#### 4 Summary of CESM1(WACCM4) and CESM1(CAM4-chem) original dataset and implementation for chemistry

In CESM1(WACCM4) and CESM1(CAM4-chem), the prescription of volcanic aerosols differs from CCSM4 and CESM1(CAM5) due to the need to specify the surface area density (SAD) of stratospheric aerosol for use in the heterogeneous stratospheric chemistry parameterization. Marsh et al. (2013), building upon Tilmes et al. (2009), fully describes the CESM1(WACCM4) scheme. For details about CESM1(CAM4-chem) see Lamarque et al. (2012). In summary, the stratospheric aerosol surface area density (SAD) is prescribed from a monthly zonal-mean time series derived from observations and is identical to that specified in the CCMVal2 REF-B1 simulations Eyring et al. (2010).

The mass of aerosol to be used by CAMRT is derived by determining a volume density of sulphate aerosol by assuming a lognormal size distribution with fixed size ( $r_{\text{eff}} = 0.5 \mu\text{m}$ ), width ( $\sigma = 1.25$ ) and number density (Kinnison et al., 2007). The mass of aerosol per unit volume can then be derived given the ratio of  $\text{H}_2\text{O}$  to  $\text{H}_2\text{SO}_4$  within each aerosol droplet as parameterized by Tabazadeh et al. (1997). This differs from CAM4's and CESM1(CAM5) assumed aerosol composition of 75% sulphuric acid and 25% water. However, the optical constants in the radiation parameteriza-

### Prescribed Stratospheric Aerosol in CESM1

R. R. Neely III et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



tion still assume this composition. Besides the determination of mass described above from the SAD input file, the parameterization of stratospheric aerosol in CAMRT in CESM1(WACCM) is the same as in CAM4.

## 5 Implementation of the new prescribed stratospheric aerosol scheme in CESM1

In this work, we have unified the stratospheric aerosol parameterization for both CESM1(CAM4-chem) (tagged in the NCAR code repository as cesm1\_1\_1\_ccmi23), CESM1(WACCM4) (tagged in the NCAR code repository as cesm1\_1\_1\_ccmi30) and CESM1(CAM5) (tagged in the NCAR code repository as cesm1\_1\_1\_ccmi30) to take advantage of the new forcing file prepared for CCMI (Eyring et al., 2013). The new forcing file is derived from the SAGE 4 $\lambda$  dataset that is described by Arfeuille et al. (2013). The main advantage is that the new dataset includes information on the mass, effective radius and surface area density that is all derived from a unified basis of information.

Here we only describe the changes made to the models in order to use the new CCMI forcing file. For the full documentation of CAMRT (the radiation scheme in CAM4 and WACCM4) and RRTMG (utilised in CAM5), which were not modified here, please see Neale et al. (2010, 2012) as noted above. In summary three main changes occurred: (1) the forcing input file (this has the main advantage of updating the stratospheric aerosol masses to reflect the most current observational and modelling studies as well as providing a coherent dataset of aerosol mass, surface area density and radius), (2) CAM4's shortwave radiation scheme has been modified to allow for variations in the effective radius of the aerosol distribution with time as provided by the new forcing file and (3) the optical look up tables for both CAMRT and RRTMG were updated with new Mie calculations.

### Prescribed Stratospheric Aerosol in CESM1

R. R. Neely III et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

## 5.1 Forcing file

For the new implementation of the stratospheric aerosol forcing in CESM1 we utilize the new stratospheric aerosol dataset derived to force models participating in the Chemistry Climate Model Initiative (CCMI) (Eyring and Lamarque, 2012; Eyring et al., 2013).

5 This file was chosen as it provides updated values of aerosol mass loading as well as values for the effective radius and SAD of the aerosol distribution. Thus, the information contained in this dataset can be used by the new stratospheric aerosol parameterization in conjunction with both CESM1's radiative and chemical schemes. This is a significant improvement upon the separate datasets utilised in previous versions of  
10 CESM1.

The new forcing file provides the mass loading, surface area density and size of aerosol from 1960 to 2012. The for original file was modified slightly to form the input file for CESM. The current file version is entitled "CESM\_1949\_2100\_sad\_V2\_c130627.nc" and can be found on the CESM input data  
15 repository. The main difference between this file and the original file is that the monthly-mean values from the minimum in stratospheric aerosol observed in 1998 and 1999 have been used to fill in the years from 1949 to 1959 and from 2012 to 2100. This was done in accordance with the CCMI documentation (Eyring et al., 2013).

To fully implement the new stratospheric SAD file in CESM1(CAM4-chem-  
20 CCMI) and CESM1(WACCM4-CCMI) several modifications were made to the mechanics of how the CESM interacted with volcanic forcing files so that information about the size of the aerosol could be included with the radiation calculation. This resulting code, entitled "prescribed\_strataero.F90" is located in the chemistry utilities of CESM (`{top level directory of model version}/models/atm/cam/src/chemistry/utills/prescribed_strataero.F90`). This file reads  
25 the necessary input parameters and transforms them into the values need by the model. By default, it also masks out any aerosol below the model's tropopause. The code may be easily modified and adapted to input values from other input files.

## GMDD

8, 10711–10734, 2015

### Prescribed Stratospheric Aerosol in CESM1

R. R. Neely III et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



## Prescribed Stratospheric Aerosol in CESM1

R. R. Neely III et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



It should be noted that CESM1 linearly interpolates the input file in time and space to match the time step and spatial grid of the model. As such, this results in differences between the monthly-mean aerosol specified in the input file and the aerosol that the model's other parameterizations actually experience. This is particularly an issue during periods of rapid concentration change. Similar issues have been noted for the specification of ozone in Neely et al. (2014). The best method to counteract errors due to this issue is to specify the aerosol values at the highest temporal cadence available.

## 5.2 Optical properties

As in previous versions of the model, here we assume that the stratospheric aerosol is comprised of a mixture of 75 % sulphuric acid and 25 % water and conforms to a log-normal size distribution. Unlike the previous parameterizations, the distribution has a varying effective radius that is specified by the input file.

As described above, CESM1(CAM5) already provided the necessary mechanism to use this information from the input file. For CESM1(CAM4-chem-CCMI) and CESM1(WACCM4-CCMI) we adapted the shortwave mechanism of CESM1(CAM5) to use both mass and  $r_g$  to look up the mass-specific aerosol extinction, scattering, and asymmetric scattering for each of CAMRT's shortwave bands. In doing this a new optical properties file was determined for CAM4 to allow for the variations in  $r_g$ . This file is entitled "volc\_camRT\_byradius\_sigma1.6\_c130724.nc" and is available for download from CESM's input data repository (access is described below) in the physics properties folder of CAM (/trunk/inputdata/atm/cam/physprops/volc\_camRT\_byradius\_sigma1.6\_c130724.nc).

To create the new optical lookup table for CAM4, a new set of Mie efficiency terms needed to be determined for a range of wavelengths and size parameters appropriate for the CAMRT and the new aerosol input file. The index of refraction is based on the assumption of a 75 to 25 % mixture of sulphuric acid and water at 293 K. Data for this was compiled from the GEISA spectroscopic database (<http://ether.ipsl.jussieu.fr>).

## Prescribed Stratospheric Aerosol in CESM1

R. R. Neely III et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



The specific data used was originally reported by Biermann et al. (2000). The data file used in the optical calculations is entitled “volcsulfrefind75-25.mat” and is available by contacting the lead author. The file is organized by the real and imaginary parts of the index of refraction and contains both the original data and fit parameters used to create the final data set that evenly spans the desired spectrum region. The parameters used in the final Mie calculation are “realind”, “imind”, “realmicron” and “immicron”.

All Mie calculations were done using the “MATLAB Functions for Mie Scattering and Absorption” developed by Mätzler (2002). The code used to create the CESM1(CAM4-chem-CCMI) and CESM1(WACCM4-CCMI) optical properties may be found in Sect. S1 of the Supplement. A similar method was used to also update the optical properties file for CESM1(CAM5). The new optical properties file for CESM1(CAM5) is entitled “volc\_camRRTMG\_byradius\_sigma1.6\_c130724.nc” and is available from CESM’s input data repository (/trunk/inputdata/atm/cam/physprops/volc\_camRRTMG\_byradius\_sigma1.6\_c130724.nc). This code is attached in Supplement Sect. S2. The main difference between the two versions is which spectral bands are used. This is a direct consequence of the different bands used by CAMRT versus RRTMG. In addition, only the shortwave parameters were updated in CESM1(CAM4-chem-CCMI) and CESM1(WACCM4-CCMI) while both the shortwave and longwave were updated in CESM1(CAM5). The reason for only adjusting the shortwave parameters in CAMRT for CAM4 are purely historical due to the complex entanglement of the different species in the longwave parameterization CAMRT. It was also thought that little improvement would have been made.

## 6 Results from the new CESM1 stratospheric aerosol parameterization

In Fig. 2 we document the resulting global SAOD between 1960 and 2000 produced by the new prescribed stratospheric aerosol parameterization (referred to as New CESM1). This is in comparison to the SAOD resulting from the parameterization used by CCSM4 and the latest version of the observationally based Sato et al. (1993)

dataset. Several differences are apparent in comparison. In general, the peak global mean SAOD after each major eruption is reduced in CESM1 compared to both the CCSM4 specification and the results of Sato et al. (1993). The one exception to this is the 1963 Agung eruption in which the Sato et al. (1993) results show an even more reduced, though broader, peak than CESM1 and CCSM4. Between the Agung eruption in 1963 and the 1974 Fuego eruption, there are many significant differences between the three SAOD time series. Notably, the CESM1 SAOD does not peak in 1968 as the other two data do and the Sato et al. (1993) show higher levels of aerosol throughout the period. The reasons for these differences are due to the underlying assumptions about the eruptions included in the creation of the forcing file. Though several moderate eruptions (VEI 4) are known to have occurred in this period (Stothers, 2001; Bauer, 1979; Hofmann et al., 1992; Langmann, 2013; Sato et al., 1993), measurements are sparse and, without further investigation, the correct representation of these perturbations to the stratospheric aerosol burden is highly uncertain. After Fuego, outside of periods perturbed by volcanic eruptions, CCSM4 and CESM1 display similar levels of background SAOD while Sato et al. (1993) seems not to account for background stratospheric aerosol (the impact of this exclusion of background stratospheric aerosol is full discussed in Solomon et al., 2011).

To examine the impact of the new stratospheric forcing on climate, we performed an experiment that compared 5 ensemble members of CESM1(CAM5) with the new stratospheric aerosol parameterization versus 5 members using the original parameterization over the period influenced most strongly by 1991 Mt. Pinatubo eruption. Each of the 5 members in the respective ensembles used different initial ocean states and atmospheric initial conditions that were derived from the original five CESM1(CAM5) CMIP5 simulations. The differences between the two ensembles shown here highlights the improvement the new scheme has on CESM1's ability to simulate the climate response to a colossal volcanic eruption.

In Fig. 3 we show the impact on top of atmospheric net radiative flux. A significant reduction is seen at the peak of the stratospheric aerosol perturbation in late 1991.

**Prescribed  
Stratospheric  
Aerosol in CESM1**

R. R. Neely III et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Notably, outside the period of highest aerosol loading after the eruption (i.e. the second half of 1991), there is very little difference in the net radiative flux between the two ensembles.

In Fig. 4, the global annual mean temperature (i.e. the response to the differences in the simulated forcing's in Fig. 3) is shown for each of the 2 ensembles in comparison to observations from the GISS Surface Temperature Analysis (GISTEMP) (Hansen et al., 2010; GISTEMP Team, 2015). For the original forcing parameterization, the difference between the model and analysis record is similar to Fig. 1 while the new parameterization simulates a trend that follows the observed record within the variability of the model runs and error estimate of the analysis. The most significant improvement is observed in the 1992 global annual temperature. As in Fig. 1, the original CCSM4 parameterization causes the simulated ensemble mean, global mean temperature anomaly to drop  $\sim 0.4^\circ\text{C}$ . This is double the observed decrease in temperature of  $\sim 0.2^\circ\text{C}$ . In comparison, the new parameterization simulates a decrease in ensemble mean global mean temperature of  $\sim 0.25^\circ\text{C}$ , though the variability of the run completely overlaps with the observational range.

In addition to the improvements found in the global surface temperature response, the new stratospheric aerosol scheme drastically improves the CESM1(CAM5)'s performance in representing stratospheric heating after the volcanic eruption. This is shown in Fig. 5 where we compare the 50 hPa anomaly for the two ensembles against the Radiosonde Innovation Composite Homogenization (RICH) (Haimberger et al., 2008). This is notable as the previous stratospheric aerosol scheme caused heating that was over seven times the observed anomaly and had significant implications for changes in stratospheric dynamics and chemistry. In the new scheme, the simulated stratospheric heating is at most double the observed anomaly.

## GMDD

8, 10711–10734, 2015

### Prescribed Stratospheric Aerosol in CESM1

R. R. Neely III et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



## 7 Summary

Here we describe the new prescribed stratospheric aerosol parameterization for CESM1. This work represents a significant improvement in the representation of stratospheric aerosols in CESM1 as it unifies the treatment between the chemical and radiative transfer parameterizations within all atmospheric models under the larger CESM1 umbrella. We have shown that it robustly and consistently improves the representation of stratospheric aerosol and resulting climatic response, especially after colossal volcanic eruptions. Specifically, we have shown that the new scheme accurately reproduces the observed global temperature response to the 1991 Pinatubo eruption. Though not explicitly shown, the new scheme described here also has a significant improvement on the accuracy of representation of background stratospheric aerosol in CESM1.

This scheme may also be easily adapted to other stratospheric aerosol forcings, such as those used in geoengineering experiments, by simply changing the masses, radii and SAD of the input file as has been done in Xia et al. (2015). Here we have focused on the technical specification of the new implementation of prescribed stratospheric aerosol in CESM1 and the impact this new specification has on the global radiation budget. As mentioned, the implementation also includes improvements to CESM1's specified stratospheric aerosol SAD. The impact the new SAD forcing has on the chemical parameterization of CESM1 is described in Tilmes et al. (2015).

### Code and input data availability

Released CESM code is made available through a subversion repository. The code may be downloaded by following the specific "User's Guide" for each model version after registering as a CESM user. For more information please see: <https://www2.cesm.ucar.edu/models/current>.

In addition to the latest CESM code, the latest version of the data used to create the optical parameters file as well as the final optical parameters files for CAM4 and

GMDD

8, 10711–10734, 2015

## Prescribed Stratospheric Aerosol in CESM1

R. R. Neely III et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



CAM5 and stratospheric aerosol forcing file for CESM may be found within the input data repository (<https://svn-ccsm-inputdata.cgd.ucar.edu/trunk/inputdata/>). Access to this repository is managed similarly to the CESM code repository and instructions for downloading data may also be found under each model's "User Guide" at <https://www2.cesm.ucar.edu/models/current>.

The scripts used to create the optical parameters for are attached in the supplement. All questions about these scripts should be directed to the lead author.

**The Supplement related to this article is available online at doi:10.5194/gmdd-8-10711-2015-supplement.**

*Acknowledgements.* We thank Daniel Marsh, Rolando Garcia, Sean Santos and Michael Mills for their assistance in developing the new volcano parameterization. CESM is sponsored by the National Science Foundation (NSF) and the US Department of Energy (DOE). Administration of the CESM is maintained by the Climate and Global Dynamics Division (CGD) at the National Center for Atmospheric Research (NCAR). Computing resources were provided by the Climate Simulation Laboratory at NCAR's Computational and Information Systems Laboratory (CISL), sponsored by the National Science Foundation and other agencies. Ryan R. Neely III was supported by the National Center for Atmospheric Research's Advanced Study Program (NCAR ASP) during this work.

## References

- Ammann, C. M., Meehl, G. A., Washington, W. M., and Zender, C. S.: A monthly and latitudinally varying volcanic forcing dataset in simulations of 20th century climate, *Geophys. Res. Lett.*, 30, 1657, doi:10.1029/2003GL016875, 2003.
- Arfeuille, F., Luo, B. P., Heckendorn, P., Weisenstein, D., Sheng, J. X., Rozanov, E., Schraner, M., Brönnimann, S., Thomason, L. W., and Peter, T.: Modeling the stratospheric warming following the Mt. Pinatubo eruption: uncertainties in aerosol extinctions, *Atmos. Chem. Phys.*, 13, 11221–11234, doi:10.5194/acp-13-11221-2013, 2013.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



## Prescribed Stratospheric Aerosol in CESM1

R. R. Neely III et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Biermann, U. M., Luo, B.-P., and Peter, T.: Absorption spectra and optical constants of binary and ternary solutions of  $\text{H}_2\text{SO}_4$ ,  $\text{HNO}_3$ , and  $\text{H}_2\text{O}$  in the mid infrared at atmospheric temperatures, *J. Phys. Chem. A*, 104, 783–793, doi:10.1021/jp992349i, 2000.

Driscoll, S., Bozzo, A., Gray, L. J., Robock, A., and Stenchikov, G.: Coupled Model Intercomparison Project 5 (CMIP5) simulations of climate following volcanic eruptions, *J. Geophys. Res.*, 117, D17105, doi:10.1029/2012JD017607, 2012.

Eyring, V. and Lamarque, J.-F.: Global chemistry-climate modeling and evaluation, *Eos Trans. AGU*, 93, 539–539, doi:10.1029/2012EO510012, 2012.

Eyring, V., Cionni, I., Bodeker, G. E., Charlton-Perez, A. J., Kinnison, D. E., Scinocca, J. F., Waugh, D. W., Akiyoshi, H., Bekki, S., Chipperfield, M. P., Dameris, M., Dhomse, S., Frith, S. M., Garny, H., Gettelman, A., Kubin, A., Langematz, U., Mancini, E., Marchand, M., Nakamura, T., Oman, L. D., Pawson, S., Pitari, G., Plummer, D. A., Rozanov, E., Shepherd, T. G., Shibata, K., Tian, W., Braesicke, P., Hardiman, S. C., Lamarque, J. F., Morgenstern, O., Pyle, J. A., Smale, D., and Yamashita, Y.: Multi-model assessment of stratospheric ozone return dates and ozone recovery in CCMVal-2 models, *Atmos. Chem. Phys.*, 10, 9451–9472, doi:10.5194/acp-10-9451-2010, 2010.

Eyring, V., Lamarque, J.-F., Hess, P., Arfeuille, F., Bowman, K., Chipperfield, M. P., Duncan, B., Fiore, A., Gettelman, A., Giorgetta, M. A., Granier, C., Hegglin, M., Kinnison, D., Kunze, M., Langematz, U., Luo, B., Martin, R., Matthes, K., Newman, P. A., Peter, T., Robock, A., Ryerson, T., Saiz-Lopez, A., Salawitch, R., Schultz, M., Shepherd, T. G., Shindell, D., Stähelin, J., Tegtmeier, S., Thomason, L., Tilmes, S., Vernier, J.-P., Waugh, D. W., and Young, P. J.: Overview of IGAC/SPARC Chemistry-Climate Model Initiative (CCMI) Community Simulations in Support of Upcoming Ozone and Climate Assessments, *SPARC Newsletter No. 40*, 48–66, 2013.

Grainger, R. G.: Some Useful Formulae for Aerosol Size Distributions and Optical Properties, available at: <http://eodg.atm.ox.ac.uk/user/grainger/research/aerosols.pdf>, last access: 2 October 2015.

GISTEMP Team: GISS Surface Temperature Analysis (GISTEMP): NASA Goddard Institute for Space Studies, available at: <http://data.giss.nasa.gov/gistemp/>, last access: 11 November 2015.

Haimberger, L., Tavalato, C., and Sperka, S.: Towards elimination of the warm bias in historic radiosonde temperature records – Some new results from a comprehensive intercomparison of upper air data, *J. Climate*, 21, 4587–4606, 2008.

## Prescribed Stratospheric Aerosol in CESM1

R. R. Neely III et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



- Hansen, J., Ruedy, R., Sato, M., and Lo, K.: Global surface temperature change, *Rev. Geophys.*, 48, RG4004, doi:10.1029/2010RG000345, 2010.
- Iacono, M. J., Delamere, J. S., Mlawer, E. J., Shephard, M. W., Clough, S. A., and Collins, W. D.: Radiative forcing by long-lived greenhouse gases: Calculations with the AER radiative transfer models, *J. Geophys. Res.-Atmos.*, 113, D13103, doi:10.1029/2008JD009944, 2008.
- Jones, P. D., New, M., Parker, D. E., Martin, S., and Rigor, I. G.: Surface Air Temperature and its Changes Over the Past 150 Years, *Rev. Geophys.*, 37, 173–199, 1999.
- Kinnison, D. E., Brasseur, G. P., Walters, S., Garcia, R. R., Marsh, D. R., Sassi, F., Harvey, V. L., Randall, C. E., Emmons, L., Lamarque, J.-F., Hess, P., Orlando, J. J., Tie, X. X., Randel, W., Pan, L. L., Gettelman, A., Granier, C., Diehl, T., Niemeier, U., and Simmons, A. J.: Sensitivity of chemical tracers to meteorological parameters in the MOZART-3 chemical transport model, *J. Geophys. Res.*, 112, D20302, doi:10.1029/2006JD007879, 2007.
- Knutson, T. R., Zeng, F., and Wittenberg, A. T.: Multimodel Assessment of Regional Surface Temperature Trends: CMIP3 and CMIP5 Twentieth-Century Simulations, *J. Climate*, 26, 8709–8743, doi:10.1175/JCLI-D-12-00567.1, 2013.
- Lamarque, J.-F., Emmons, L. K., Hess, P. G., Kinnison, D. E., Tilmes, S., Vitt, F., Heald, C. L., Holland, E. A., Lauritzen, P. H., Neu, J., Orlando, J. J., Rasch, P. J., and Tyndall, G. K.: CAM-chem: description and evaluation of interactive atmospheric chemistry in the Community Earth System Model, *Geosci. Model Dev.*, 5, 369–411, doi:10.5194/gmd-5-369-2012, 2012.
- Marsh, D. R., Mills, M. J., Kinnison, D. E., Lamarque, J.-F., Calvo, N., and Polvani, L. M.: Climate change from 1850 to 2005 simulated in CESM1 (WACCM), *J. Climate*, 26, 1–65, doi:10.1175/jcli-d-12-00558.1, 2012.
- Mätzler, C.: MATLAB functions for Mie scattering and absorption, *IAP Res. Rep.*, 8, 2002.
- Meehl, G. A., Washington, W. M., Arblaster, J. M., Hu, A., Teng, H., Tebaldi, C., Sanderson, B., Lamarque, J. F., Conley, A., Strand, W. G., and White III, J. B.: Climate system response to external forcings and climate change projections in CCSM4, *J. Climate*, 25, 3661–3683, doi:10.1175/JCLI-D-11-00240.1, 2012.
- Meehl, G. A., Washington, W. M., Arblaster, J. M., Hu, A., Teng, H., Kay, J. E., Gettelman, A., Lawrence, D. M., Sanderson, B. M., and Strand, W. G.: Climate change projections in CESM1(CAM5) compared to CCSM4, *J. Climate*, 26, 6287–6308, doi:10.1175/JCLI-D-12-00572.1, 2013.

## Prescribed Stratospheric Aerosol in CESM1

R. R. Neely III et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



- Mlawer, E., Taubman, S., Brown, P., Iacono, M., and Clough, S.: Radiative transfer for inhomogeneous atmospheres: RRTM, a validated correlated-k model for the longwave, *J. Geophys. Res.*, 102, 16663–16682, 1997.
- Morice, C. P., Kennedy, J. J., and Rayner, N. A.: Quantifying uncertainties in global and regional temperature change using an ensemble of observational estimates: The HadCRUT4 data set, *J. Geophys. Res.*, 117, D08101, doi:10.1029/2011jd017187, 2012.
- Neale, R. B., Richter, J., Conley, A., Lauritzen, P. H., Gettelman, A., Williamson, D., Rasch, P., Vavrus, S., Taylor, M., Collins, W., Zhang, M., and Lin, S. J.: Description of the NCAR Community Atmosphere Model (CAM4.0), Tech. Rep. NCAR/TN-485+STR, National Center for Atmospheric Research, Boulder, CO, USA, 2010.
- Neale, R. B., Gettelman, A., Lauritzen, P. H., Park, S., Williamson, D., Conley, A., Garcia, R., Kinnison, D., Lamarque, J.-F., Marsh, D., Mills, M., Smith, A., Tilmes, S., Vitt, F., Morrison, H., Cameron-Smith, P., Collins, W., Iacono, M. J., Easter, R., Ghan, S., Liu, X., Rasch, P., and Taylor, M.: Description of the NCAR Community Atmosphere Model (CAM5.0), Tech. Rep. NCAR/TN-486+STR, National Center for Atmospheric Research, Boulder, CO, USA, 2012.
- Neale, R. B., Richter, J., Park, S., Lauritzen, P. H., Vavrus, S. J., Rasch, P. J., and Zhang, M.: The Mean Climate of the Community Atmosphere Model (CAM4) in Forced SST and Fully Coupled Experiments, *J. Climate*, 26, 5150–5168, doi:10.1175/JCLI-D-12-00236.1, 2013.
- Neely, R. R. I., Marsh, D. R., Smith, K. L., Davis, S. M., and Polvani, L. M.: Biases in southern hemisphere climate trends induced by coarsely specifying the temporal resolution of stratospheric ozone, *Geophys. Res. Lett.*, 41, 8602–8610, doi:10.1002/2014GL061627, 2014.
- Newhall, C. and Self, S.: The Volcanic Explosivity Index (VEI) – an Estimate of Explosive Magnitude for Historical Volcanism, *J. Geophys. Res.*, 87, 1231–1238, doi:10.1029/jc087ic02p01231, 1982.
- Sato, M., Hansen, J., McCormick, P., and Pollack, J.: Stratospheric Aerosol Optical Depths, 1850–1990, *J. Geophys. Res.*, 98, 22987–22994, doi:10.1029/93jd02553, 1993.
- Smith, T. M., Reynolds, R. W., and Peterson, T. C.: Improvements to NOAA’s historical merged land-ocean surface temperature analysis (1880–2006), *J. Climate*, 21, 2283–2296, doi:10.1175/2007JCLI2100.1, 2008.
- Solomon, S., Daniel, J. S., Neely, R. R., Vernier, J. P., Dutton, E. G., and Thomason, L. W.: The Persistently Variable “Background” Stratospheric Aerosol Layer and Global Climate Change, *Science*, 333, 866–870, doi:10.1126/science.1206027, 2011.

## Prescribed Stratospheric Aerosol in CESM1

R. R. Neely III et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Stenchikov, G. L., Kirchner, I., Robock, A., Graf, H.-F., Antuña, J. C., Grainger, R. G., Lambert, A., and Thomason, L.: Radiative forcing from the 1991 Mount Pinatubo volcanic eruption, *J. Geophys. Res.*, 103, 13837, doi:10.1029/98JD00693, 1998.

Taylor, K. E., Stouffer, R. J., and Meehl, G. A.: An Overview of CMIP5 and the Experiment Design, *B. Am. Meteorol. Soc.*, 93, 485–498, doi:10.1175/BAMS-D-11-00094.1, 2012.

Tilmes, S., Garcia, R. R., Kinnison, D. E., Gettelman, A. and Rasch, P. J.: Impact of geo-engineered aerosols on the troposphere and stratosphere, *J. Geophys. Res.-Atmos.*, 114, D12305, doi:10.1029/2008JD011420, 2009.

Tilmes, S., Lamarque, J.-F., Emmons, L. K., Kinnison, D. E., Marsh, D., Garcia, R. R., Smith, A. K., Neely, R. R., Conley, A., Vitt, F., ValMartin, M., Tanimoto, H., and UCI team: Representation of the Community Earth System Model (CESM) CAM4-chem within the Chemistry-Climate Model Initiative (CCMI), *Geosci. Model Dev. Discuss.*, in preparation, 2015.

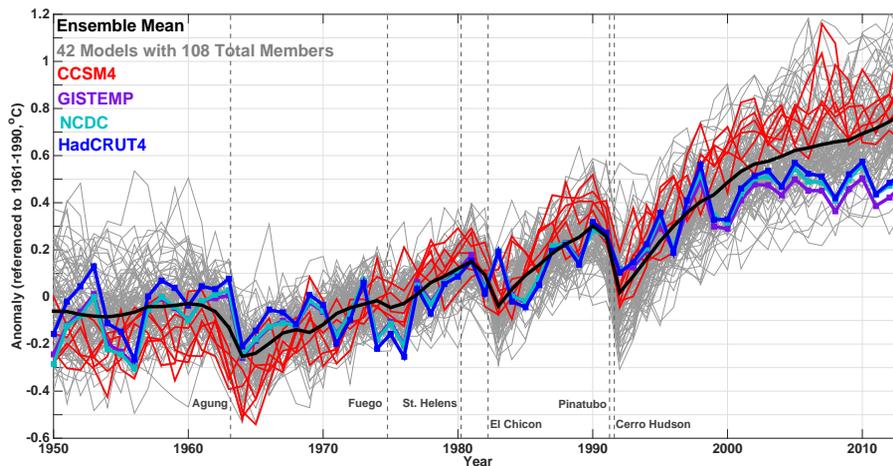
Tabazadeh, A., Toon, O. B., Clegg, S. L., and Hamill, P.: A new parameterization of H<sub>2</sub>SO<sub>4</sub>/H<sub>2</sub>O Atmospheric implications, *Geophys. Res. Lett.*, 24, 1931–1934, doi:10.1029/97gl01879, 1997.

Wiscombe, W. J.: Mie scattering calculations: Advances in technique and fast, vector-speed computer codes, Technical Report Tech. Note, NCAR/TN-140+STR, NCAR, 1996.

Xia, L., Robock, A., Tilmes, S., and Neely III, R. R.: Stratospheric sulfate geoengineering enhances terrestrial gross primary productivity, *Atmos. Chem. Phys. Discuss.*, 15, 25627–25645, doi:10.5194/acpd-15-25627-2015, 2015.

## Prescribed Stratospheric Aerosol in CESM1

R. R. Neely III et al.



**Figure 1.** Global annual mean surface temperature anomalies from 1950 to 2013 referenced to the mean taken from 1961 to 1990. Light grey lines represent the 108 model members that contributed to the RCP4.5 scenario of CMIP5. The black line represents the multi-model ensemble mean. The members contributed by NCAR’s CCSM4 are highlighted in red. Three observational based datasets have been included for comparison: the GISS Surface Temperature Analysis (GISTEMP) in purple (Hansen et al., 2010; GISTEMP Team, 2015), NOAA’s National Climatic Data Center’s global surface temperature anomalies in teal (Jones et al., 1999; Smith et al., 2008) and global anomalies from the Hadley Centre of the UK Met Office (HADCRUT4) in blue (Morice et al., 2012).

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

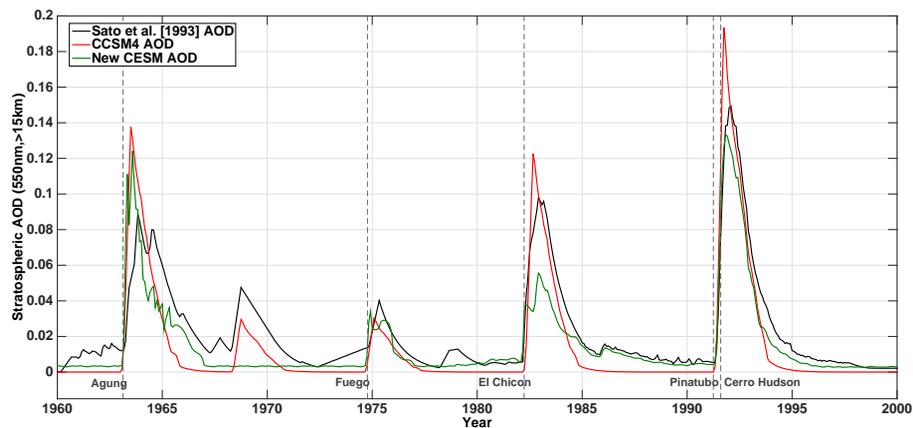
Printer-friendly Version

Interactive Discussion



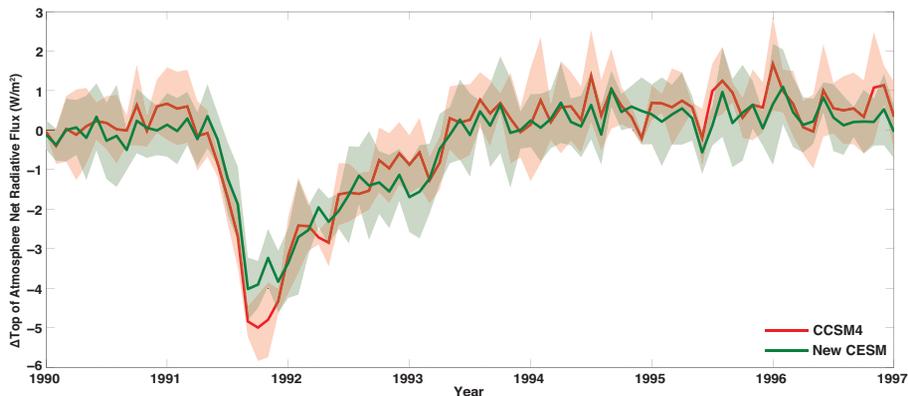
## Prescribed Stratospheric Aerosol in CESM1

R. R. Neely III et al.



**Figure 2.** Globally average Stratospheric AOD integrated from above 15 km. The red line represents the forcing used in CCSM4 simulations. The green line represents the new AOD determined from the SAGE 4 $\lambda$  volcanic aerosol forcing file. For comparison, the latest AOD from the Sato et al. (1993) forcing dataset is shown in black.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)



**Figure 3.** Global, monthly, ensemble, mean change in the top of atmosphere radiative flux due to the simulated Mt. Pinatubo eruption in June of 1991. Each Old and New volcanic ensemble member is differenced from a simulation (not shown) conducted with identical initial conditions but with no stratospheric AOD forcing. Shaded regions represent  $\pm 1\sigma$  standard deviation of the ensemble.

**Prescribed  
Stratospheric  
Aerosol in CESM1**

R. R. Neely III et al.

[Title Page](#)

[Abstract](#)   [Introduction](#)

[Conclusions](#)   [References](#)

[Tables](#)   [Figures](#)

[⏪](#)   [⏩](#)

[◀](#)   [▶](#)

[Back](#)   [Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

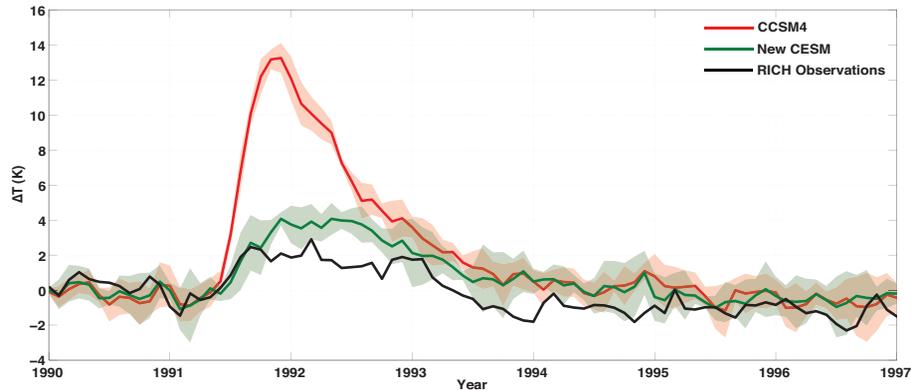
[Interactive Discussion](#)





## Prescribed Stratospheric Aerosol in CESM1

R. R. Neely III et al.



**Figure 5.** Tropical, monthly, ensemble, mean temperature anomaly at 50 hPa due to the simulated Mt. Pinatubo eruption in June of 1991. Anomalies are referenced to the 1990 annual mean in each ensemble member. Shaded regions represent  $\pm 1\sigma$  standard deviation of the ensemble. The RICH data observations come from Haimberger et al. (2008).

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)