Response to Reviewer #1

The authors would like to thank reviewer #1 for their thoughtful comments. Their suggestions have helped to clarify important model parameters as well as experimental results.

1 General Comments

There is some general issue throughout the text incl. the abstract with respect to the name of the volcanic forcing data set. To my understanding GLOSSAC and the CMIP6 Stratospheric Aerosol data set are not the same. The stratospheric aerosol data set for CMIP6 is build on the Global Satellite-based Stratospheric Aerosol Climatology (GloSSAC, Thomason et al., 2018) for the satellite area (from 1980) onwards. The version 3 (Luo, 2017) is based on GloSSAC v1.0 (Thomason et al., 2018), while the revised version v4 for Jan 1991-Dec 1994 (Luo, 2018) is based on the new data set GloSSAC v1.1 (Thomason 2018). So there exist no GLOSSAC version 4. Please check and revise the text carefully with respect to the name convention.

Lines 6-10 of the abstract have been updated to:

"To improve this situation for CMIP6 a two step process was undertaken. First, a combined stratospheric aerosol dataset, the Global Space-based Stratospheric Aerosol Climatology, GloSSAC, was constructed. Next, GloSSAC, along with information from ice-cores and sun photometers, was used to generate aerosol distributions, characteristics and optical properties to construct a consistent stratospheric aerosol forcing dataset for models participating in CMIP6."

In the release note to version 4 of the stratospheric aerosol data set for CMIP6 (Luo, 2018), some first comparison between Stratospheric Aerosol Optical Depth and extinction of version 3 and 4 were already made with similar results as listed in section 2. This should be mentioned.

Thank you, that should be included and this is now discussed on Page 3 Lines 16-17.
"Luo et al., (2018) show the magnitude of these changes at several latitude bins and times for 1020 nm, and the following analysis expands on this at 550 nm in the context of this paper."

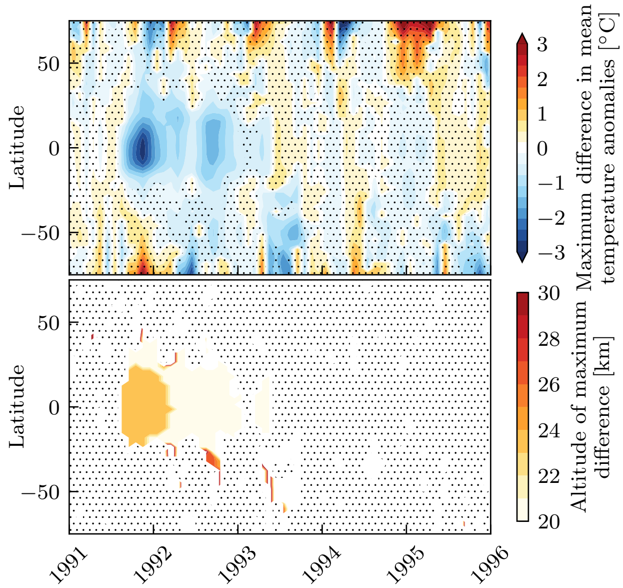
2 Specific Comments

Title: The title is a little bit misleading and need to be changed as the authors consider only the Post Pinatubo episode (1990 -1996) and not the full CMIP6 historical period.

Changed to "Quantifying CanESM5 and EAMv1 sensitivities to Mt. Pinatubo volcanic forcing for the CMIP6 historical experiment"

Page 1, line 20 (also page 12, line 7), "can be as large as 3 C" . Maybe the authors could be more specific here and can give the exact duration and the altitude of this local maximum. If I look at figure 5, I can hardly see a temperature anomaly of 3C. A supplementary lon/lat figure might be helpful here to better illustrate this point.

Thank you, an additional latitude-time figure (Figure 6 in the paper also attached here) has been added to clarify the temperature anomalies and discussed on page 10 Lines 10-13. Hopefully this new figure, along with Figure 5, help clarify the spatial extent and magnitude of the anomalies.



Page 2, line 2, "an estimated 10 Tg of sulfur into the stratosphere." The S emission of Mt Pinatubo is uncertain current estimates range between 5 to 10 Tg S, see for example Timmreck et al. (2018) , p 2583.

Revised to *"the 1991 eruption of Mt. Pinatubo injected an estimated 5-10 Tg of sulfur into the stratosphere (Guo et al., 2014, English et al., 2013, Dhomse et al., 2014, Timmreck et al., 2018)"* on Page 2 Line 2.

Page 2, line 16-18, Please reformulate this sentence as it is a bit misleading. Solomon et al (2011) and Fyfe et al (2013) used an updated version of the Sato et al. (1993) data set which includes the more recent eruption.

We don't think *Solomon et al.,* (2011) used the most recent version of Sato et al., but instead used the *Vernier et al.,* (2011) climatology derived from CALIPSO measurements to extend measurements post-2000. The updated Sato dataset was published in December 2012, and used OSIRIS data as opposed to CALIPSO, so these datasets will differ somewhat. While *Fyfe et al.,* (2013) used the updated Sato climatology, they did so only until 1993 (1998 was also tested), at which point they transitioned to the Vernier dataset.

Page 3, line 7, " an error was found " You can be more specific here and mention that it was a CLAES cloud clearing problem which affected the Pinatubo period mostly in the first months after the eruption , see "Release Notes Stratospheric Aerosol Radiative Forcing and SAD version v4.0.0 1850 - 2016 (Luo, 2018).

Thank you, updated with suggested explanation on Page 3 Lines 7-8.

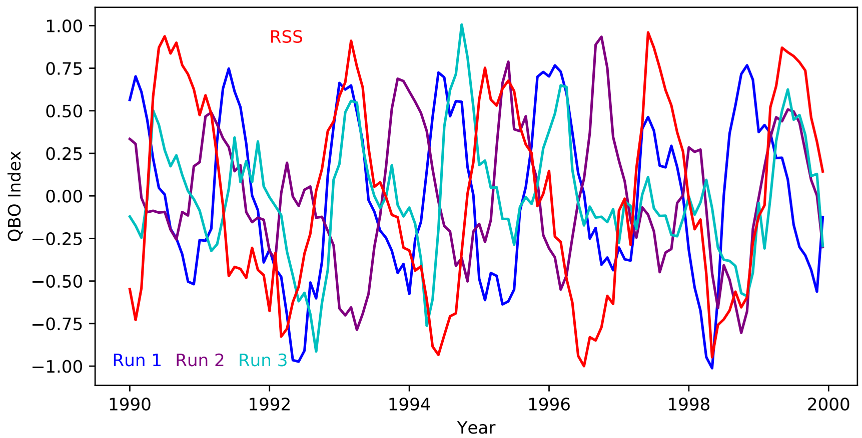
Page 5, line 8, Some information about the vertical resolution in the stratosphere and in the tropical tropopause region in the CanESM5 would be nice

The vertical resolution is approximately 1-2km in the lowermost stratosphere. This has been added to the CanESM5 and EAMv1 model description on Page 7 Line 6.

Page 5, line 17, Same for the EAMv1.

The vertical resolution is approximately 1-2km in the lowermost stratosphere. This has been added to the EAMv1 model description on Page 7 Line 16.

Page 5, line 26, One has to be careful to compare here not apples and oranges. All the cited papers (Minnis et al., 1993; Stenchikov et al., 1998; Ramachandran et al., 2000) show a decrease in net shortwave flux radiation but mention an increase in reflected shortwave radiation.



Thank you, clarified to *"and increases in reflected radiation at the top of the atmosphere"* on Page 7 Line 25.

Page 8, line 8, "three realizations were performed using the EAMv1 model" As the EAMv1 model produces the QBO, I wonder about the QBO in the model. Were the QBO in different phases in the model run and how does they differ from the actual observed phase?

The QBO were in different phases during the eruption, although none matched the observed phasing precisely. The attached figure shows the QBO Index (as calculated from Christy and Drouilhet (1994) for the three EAM simulations and RSS observations, as the observed value from RSS. This is now briefly discussed on Page 7 Lines 17-18.

Christy, J. R., & Drouilhet Jr, S. J. (1994). Variability in daily, zonal mean lower-stratospheric temperatures. Journal of climate, 7(1), 106-120.

Page 12, line 10-11, I wonder if you had a look on possible changes in sea ice in the CanESM5?

We did not look at sea ice specifically, but both the ocean heat content, and temperature outside of the tropics remain unchanged between version. The now included Figure 6 on Page 11 shows this more clearly and discussed on Page 10 Lines 13-15.

Figure 3, The authors might think about to present the flux anomalies in the more common way with negative net short wave flux anomalies and net positive LW anomalies.

Switched throughout to the more common convention.

Response to Reviewer #2

The authors would like to thank reviewer #2 for the thorough review. In particular, mention of the upcoming of GloSSAC v2 is an important point, and the notes on model and experimental description have hopefully helped to clarify results.

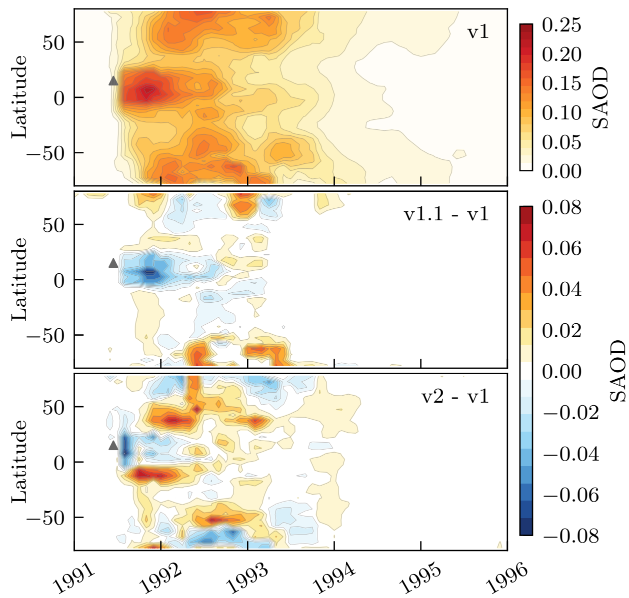
1 Major Comments

The GloSSAC dataset version 2.0 was advertised at the 2019 American Geophysical Union Fall Meeting (Thomason et al. 2019, see reference list at the end) which I guess some of the authors are aware about, but this newer version is never mentioned in the manuscript. Given the main objective of the manuscript, I think the fact that a newer version exists should at the very least be discussed? I attach a plot briefly comparing global mean SAOD in v1.0, v1.1 and v2.0, which is a modified version of Figure S1 in Aubry et al. (2020) (see reference list at the end). For the Pinatubo period, v2.0 has larger SAOD than v1.0, whereas v1.1 has smaller SAOD than v1.0. Differences between v2.0 and v1.0 also tend to be more important than those between v1.1 and v1.0. Using v2.0 instead of v1.1 would thus likely change many of the results presented in this study, even though I would expect the conclusions that using any of these GloSSAC versions cause changes in the Pinatubo climate response that are small compared to the natural variability.

I recommend that the authors at least make the reader aware that a version 2.0 of the GloSSAC dataset exists and discuss differences between version 1.1 and 2.0. Adding a SI figure similar to the nice figure 1 but showing GloSSAC v1.0, v1.1 and v2.0 would be useful. In support of this discussion, I think that the authors should reproduce figure 3 and 4 using GloSSAC v2.0. I believe this should have a relatively low computational cost given that these are 5-year AMIP simulation(s)? It would provide a first test of the differences caused by using the newest GloSSAC version in terms of radiative forcing. I believe it would additionally be a very useful contribution to further quantifying how uncertainties in stratospheric aerosol datasets - which are very challenging to build - translate in terms of radiative forcing uncertainty. Repeating the other simulations (e.g. the fully coupled CanESM simulations) with GloSSAC 2.0 would be fantastic if computational cost allows it.

I understand that the time of creation of the GloSSAC v2.0 version likely was very close to the time at which simulations for this study were conducted, and I am also not entirely sure whether the v2.0 version has been officially released (the dataset webpage still seems to mention v1.1: https://eosweb.larc.nasa.gov/project/glossac/glossac). However, given that this newer update has been advertised to the scientific community and is available (at least upon request), I believe that the authors should at the very least make the reader aware of v2.0 and discuss the differences with v1.1.

Thank you, and we agree that the new GloSSAC v2 will be an important addition to the climate record and should be noted. We now discuss version 2 with updated references and include a supplemental figure comparing the glossac versions in the same manor as the forcing datasets (also attached here). Please see Page 5 lines 1-7 and Supplemental Figure S1 of the revised manuscript.
A more complete analysis including radiative forcing differences would indeed be very interesting; however,



at the time of writing the optical properties and climatologies that are derived from GloSSAC v2 (and used as the inputs to the climate models) have not yet been produced. Conversion from GloSSAC to climate forcing files is a detailed process with many variables, making any use of v2 in climate studies a comparison of both the GloSSAC version and conversion steps needed to translate the GloSSAC data into climate model input. Additionally, we have updated the manuscript to hopefully clarify the difference between the underlying GloSSAC dataset and the derived CMIP climatology.

2 Other Comments

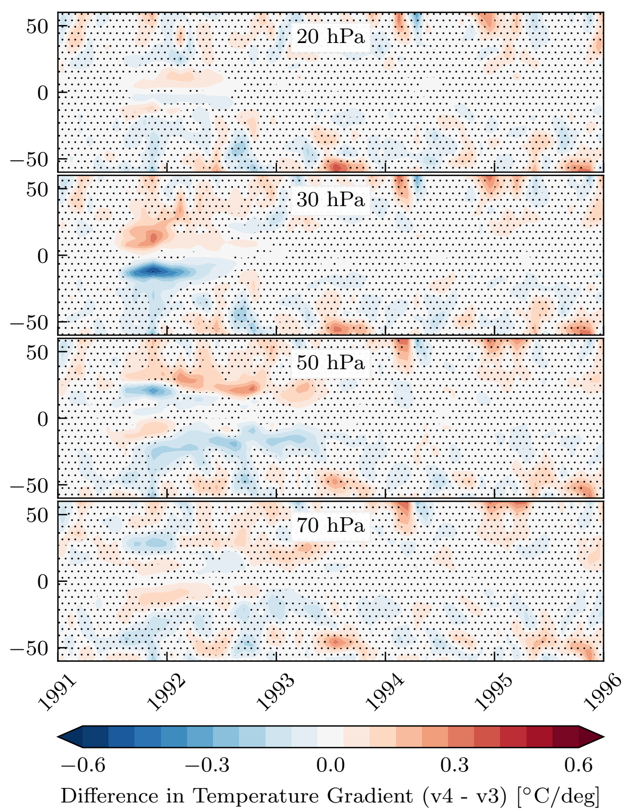
The authors mention that there is no apparent difference in El Nino Southern Oscillation (ENSO) states in the 2 years following the Pinatubo eruption, but I don't think the North Atlantic Oscillation (NAO) response is mentioned anywhere? Given that changes in stratospheric temperature response are significant and much larger in the tropics, I think it would be very valuable to show/mention whether using the new aerosol dataset affects the response of : i) the meridional temperature gradient in the stratosphere; ii) the polar vortex strength (during winter) and iii) the winter NAO phase.

i) A figure showing the meridional temperature gradient at 4 pressure levels is attached. Dotted regions indicate where no statistically significant change has occurred. Significant differences in temperature gradients are not present outside of the tropics or at levels other than 20, 30, and 50 hPa.

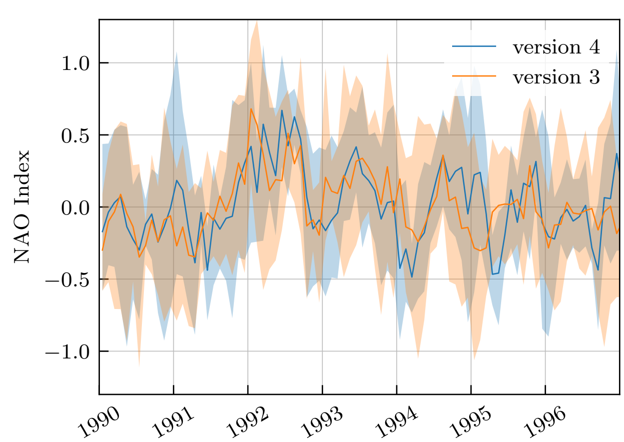
ii)Although the polar vortex strength was not looked at specifically, the temperature gradient outside of 30°S-30°N is unaffected by the changes in aerosol, so no changes to the polar vortex are expected. This is now noted on Page 10 Line 13. Further investigation into the effects of additional parameters would certainly be interesting, but likely require larger ensembles as no significant effects are noticeable in either temperature outside of the tropics, ocean heat content, ENSO or NAO (see next point) in the current ensembles.

iii)NAO was investigated and no significant change was found between version 3 and version 4 of the forcing datasets. The attached figure shows the NAO index between 1990 and 1996. Lines indicate ensemble means and shaded areas indicate 10 and 90^{th} percentiles. That no change is seen in the NAO index is now also mention on Page 13 Lines 1-2.

I find the manuscript very clear, concise and pleasant to read except for the presentation of the experimental design (and to a lesser extent, for the models). The reader discovers along



20 hPa
30 hPa
50 hPa
70 hPa
50
0
−50
1991
1992
1993
1994
1995
1996
−0.6
−0.3
0.0
0.3
0.6
Difference in Temperature Gradient (v4 - v3) [°C/deg]



version 4
version 3
NAO Index
1.0
0.5
0.0
−0.5
−1.0
1990
1991
1992
1993
1994
1995
1996

the way which simulation set-up was used for which parts, with often a lack of details. For example, section 3.1 suggests that CanESM5 was used in fully coupled mode, but then in section 4.1 it is used in AMIP mode and it is not clear how many simulations were conducted. In section 4.2, the coupled version is used and the number of ensemble member is specified, but it is not clear how initial conditions were sampled. Overall, I would prefer to see all details of experimental design in a section 3.3 clearly presenting the model setup used (for both CanESM and EAMv1) for different diagnostic, the number of ensemble members, and how initial conditions were sampled. (a table could be useful here). It would also be nice to harmonize a bit the model description, e.g. describe the model resolution in similar units (degree vs km) so that the reader can easily compare them, and give information about ability to simulate QBO for both model in their respective sections.

Thank you, section 3 has been revised to include more detail on experiment setup as well as provide a more complete overview of the models. See Page 6, lines 1-23 and Table 1.

3 Specific Comments

Page 1, line 14 and 18: I believe the abstract would read a bit better if you directly mentioned that you used two different models, and then the main results from the two models.

Page 1 Lines 14-20 have been updated to
"This study uses two models, the Canadian Earth System Model version 5 (CanESM5), and Energy Exascale Earth System Model (E3SM) Atmosphere Model version 1 (EAMv1) to estimatethe difference in instantaneous radiative forcing in simulated post-Pinatubo climate response when using version 4 instead of version 3. Differences in temperature, precipitation, and radiative forcings are generally found to be small compared to internal variability. An exception to this is differences in monthly temperature anomalies near 24 km altitude in the tropics, which can be as large as 3° C following the eruption of Mt. Pinatubo."

Page 1, line 22: replace "leading to a cooling effect" by "leading to a surface cooling effect"

Thank you, updated on Page 1 Line 22.

Page 2, line 1: I find the formulation "multiplying the impact on climate" a bit confusing; maybe replace by something like "which in turn strengthens this surface cooling"

Changed as suggested on Page 1 Line 23

Page 2, line 2: as you give a range of radiative forcing you could give a range on the injected sulfur mass, which is still a major source of uncertainty.

Updated on Page 2 line to
"For example, the 1991 eruption of Mt. Pinatubo injected an estimated 5-10 Tg of sulfur into the stratosphere (Guo et al., 2004, English et al., 2013, Dhomse et al., 2014)"

Page 2, line 5: I would avoid expressions like "equally impressive"; maybe replace by "There was also a significant impact on oceans, "?

Updated Page 2 line 4 as suggested.

Page 2, line 8: More recent references you may consider to add are Stocker et al. (2019) (they use GloSSAC) and Schmidt et al. (2018)

Thank you, added on Page 2 Lines 8-9.

Page 2, section 2 title: "The Stratospheric Aerosol Dataset" reads a bit funny; maybe say "The CMIP6 Stratospheric Aerosol Dataset" ?

Updated on Page 2 Line 26.

Page 3, line 7: I think it would be neat to briefly describe what kind of error it was, in one or two sentences?

Agreed, this has been added on Page 3 Lines 7-8.

Page 3, Figure 1: this relates to my main comment, but I think having a similar figure for GloSSAC v2.0 would be nice, and I really think you have to mention and discuss this newer update.

Thank you, and we agree that GloSSAC v2 should be mentioned. Supplemental Figure S1 is now included (and attached below) and v2 is discussed on Page 5 Lines 1-7.

Page 4, line 4: do you mean optical thickness? If so please clarify

Thank you, corrected on Page 4 Line 4/5.

Page 5, sections 3.1 and 3.2: could you give the rough vertical resolution at the altitude of the Pinatubo plume for both models?

Vertical resolutions of CanESM5 (1.5km) and EAMv1 (1-2km) in the lowermost stratosphere have been added to the model description sections. See Page 7 Lines 6 and 16 respectively.

Page 5, lines 8 and 17: to ease the model comparison, could you give the horizontal resolution either in degree or km or both?

Horizontal model resolution now specified in both km and degrees on Page 7 lines 5 and 15.

Page 5, line 20: could you clarify whether the version you use includes this modified parameterization?

The parameterization was not included in this version. This has been clarified in the manuscript as: "*While the QBO can be greatly improved by modifying parameterized convectively generated gravity waves (Richter et al., 2019) this is not included in the current simulations.*", on Page 7 lines 18-19.

Page 5, section 3.1: could you provide in this section some information on the model capability to simulate the QBO, like you do for EAMv1 in section 3.2? You could then remove it from Page 9 line 15.

Added to CanESM5 description on Page 7 line 8 and removed from Page 9.

Section 4.1: it is very hard to understand which model(s) was used to conduct simulation to diagnose radiative forcing (I understand it's CanESM5 from the caption of Figure 3?). Please clarify. I think having a section 3.3 with summary of experimental design would greatly help as highlighted in one of my main comments.

Thank you, hopefully this is addressed in the updated section 3 (See Page 6, lines 1-23) and Table 1.

Page 6, line 1: Section 3.1 gives the impression CanESM5 is used in fully-coupled mode; I'd prefer if you clarified earlier that you use it in AMIP mode to quantify changes in radiative forcing. Similarly, you say "simulations": how many? How were initial conditions sampled?

See previous note.

Page 6, line 5: Would shortwave/longwave be a more standard terminology than solar/thermal?

Perhaps, the cited literature mentions both shortwave/infrared/longwave and solar/thermal radiation, so we have chosen to go with the latter convention.

Page 6, Figure 3: even though the point of the paper is not to compare the model with observations, I think it would be neat to show some on this figure (e.g. from ERBE)

We agree this would be an interesting comparison. However, the volcanic signal is clear in this analysis only because the radiation calculation is ran with and without stratospheric aerosols, so is not possible with observational datasets.

Page 7, line 3-5: just a personal preference but I think this should be in the figure caption only, not in the main text.

Agreed, removed from main text.

Page 7, line 5-9: given the reduction in heating rate is mostly in the tropic, an immediate question coming to mind whether it affects the meridional temperature gradient, winter polar vortex strength, and winter NAO response?

See note above for more details, but the meridional temperature gradient is also unaffected outside of the tropics. This is now noted on Page 10 Line 13.

Page 7, Figure 4: clarify in the legend that these results are from CanESM?

Thank you, now clarified in the caption as *"instantaneous heating rates from CanESM5 model runs"*.

Page 8, line 1-9: I wish it was clear before that coupled simulation were used to diagnose climate response and AMIP simulations for radiative forcing. Here you specify ensemble size, and you are clear about which model you use (in contrast with section 4.1), but I think you should briefly mentioned how initial conditions were sampled. (and again instead of mentioning it here I would rather have a section 3.3 devoted to the experimental design)

Agreed, Hopefully Section 3 now more clearly explains experimental setup and what simulations were used for which analysis.

Page 9, line 1-2: It's nice that you show comparison with observations here.

Page 9, lines 11-13: Although the changes highlighted are small, they slightly improve consistency with observations? I think it's worth highlighting explicitly? That being said I would expect a stronger temperature response if you used the version 2.0 of GloSSAC... I really think this should be discussed.

We certainly agree it's an interesting question, and now discuss the changes to GloSSAC v2. However, the assumptions involved in translating from GloSSAC extinction values to optical properties integrated over model bands are not trivial, and make this difficult to answer until that process is performed in a comparable way to that done for CMIP6 models. At the time of writing we are unaware of when that process will be performed, or of a paper describing the details which are required to reproduce it.

Page 10, line 5-6: You may consider including a more recent citation for ENSO response to volcanism such as Khodri et al. (2017)

Thank you, this reference has been added on Page 12 Line 5.

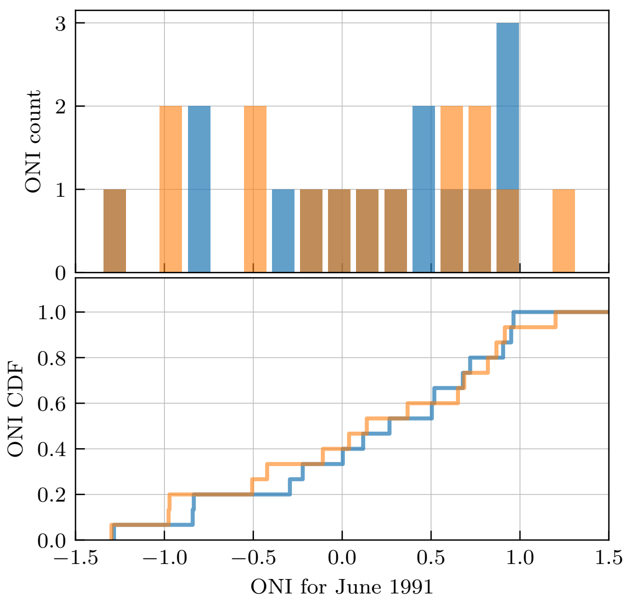
Page 10, line 6: changes in volcanic forcing before the eruption are only from January 1991 onwards, and are of magnitude smaller than 0.01 in terms of SAOD, is that correct? I find this clear shift to a La-Nina like state quite impressive given the really small changes applied for just 5 months

That is correct that the changes are much small. However, the shift to La-Nina states is also small and not clear statistically with an ensemble size of 15. The attached figure shows the ENSO state of the 15 ensemble members for June 1991. Therefore, We don't think there is any reason to suspect the slight change in ENSO phasing is anything other internal variability.

Page 11, line 1-4: It's nice to comment on ENSO but given the changes in tropical stratospheric temperature you find, I am really curious to know if the winter NAO response is affected, or at least the winter polar vortex.

See above plot and comment for more details, but the NAO and temperature of the higher latitudes is unaffected by the changes in aerosol.

Page 12: Conclusions are clear and concise.


ONI count
3
2
1
0
ONI CDF
1.0
0.8
0.6
0.4
0.2
0.0
−1.5
−1.0
−0.5
0.0
0.5
1.0
1.5
ONI for June 1991

Response to Reviewer #3

The authors would like to thank reviewer #3 for their comments. We have updated the model and experimental descriptions as per your suggestions and think this made for a much clearer manuscript.

1 General Comments

This manuscript presents the changes in simulated climate response (where climate is intended as temperature and precipitation) occurring when an error in the CMIP6 stratospheric aerosol forcing database in the post-Pinatubo period is corrected. The authors conclude that the correction does not significantly impact temperatures and precipitations (although there are changes in tropical stratospheric temperatures). This manuscripts presents the results in a straightforward manner. The scientific significance is fair, in the sense that the scope of the manuscript is pretty limited, but it presents one of those results that should be documented in peer-review journals in view of the importance of the CMIP6 simulations.

I do not have any major comment, except for the description of the models and simulations. The descriptions of the models report very few characteristics, but there is no remarks on why these two models were chosen. It is not clear if they were the models available, or if they were chosen because their characteristics complement each other. There should be some concluding remark in the section about model description that contrast the two models against each other and make clear in which respect the results are expected or could differ, given the different characteristics. A table could also be useful, where columns report items such as "interactive SSTs" or "stratospheric chemistry".

Additionally, there is not initial description of the simulations. The simulations are introduced where they are analyzed, but it would be useful to have right after the model description a section where all simulations are presented.

Thank you, Section 3 has been updated with a description of the simulations and why the particular models were chosen has been added. Please see Page 6 lines 1-21, and table 1 in the revised manuscript.

Quantifying ~~multi-model~~ CanESM5 and EAMv1 sensitivities to Mt. Pinatubo volcanic forcing for the CMIP6 historical experiment

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Abstract. Large volcanic eruptions reaching the stratosphere have caused marked perturbations to the global climate including cooling at the Earth's surface, changes in large-scale circulation and precipitation patterns and marked temporary reductions in global ocean heat content. Many studies have investigated these effects using climate models, however uncertainties remain in the modelled response to these eruptions. This is due in part to the diversity of forcing datasets that are used to prescribe the distribution of stratospheric aerosols resulting from these volcanic eruptions, as well as uncertainties in optical property derivations from these datasets. To ~~reduce these uncertainties in the Coupled Model Intercomparison Project 6 (~~improve this situation for CMIP6 ~~) a~~ a two step process was undertaken. First, a combined stratospheric aerosol dataset, the Global Space-based Stratospheric Aerosol Climatology, GloSSAC (1979-2016), was constructed. ~~Along~~ Next, GloSSAC, along with information from ice-cores and sun photometers, ~~GloSSAC~~ was used to generate aerosol distributions, characteristics and optical properties ~~and construct a~~ to construct a more consistent stratospheric aerosol forcing dataset for models participating in CMIP6. This "version 3" of the stratospheric aerosol forcing has been endorsed for use in all contributing CMIP6 simulations. Recent updates to the underlying GloSSAC from version 1 to version 1.1 affected the 1991 to 1994 period and necessitated an update to the stratospheric aerosol forcing from version 3 to version 4. As version 3 remains the official CMIP6 input, quantification of the impact on radiative forcing and climate is both relevant and timely for interpreting results from experiments such as the CMIP6 historical simulations. This study uses two models, the Canadian Earth System Model version 5 (CanESM5), and Energy Exascale Earth System Model (E3SM) Atmosphere Model version 1 (EAMv1) to estimate the difference in instantaneous radiative forcing in simulated post-Pinatubo climate response when using version 4 instead of version 3. Differences in temperature, precipitation, and radiative forcings are generally found to be small compared to internal variability. ~~To further elucidate sensitivities that are representative of the CMIP6 model suite, additional simulations are performed using the Energy Exascale Earth System Model (E3SM) Atmosphere Model version 1 (EAMv1), which also indicates that the impact of the update to GloSSAC version 4 on climate are relatively minor.~~ An exception to this is differences in ~~temperature anomalies in the stratosphere~~monthly temperature anomalies near 24 km altitude in the tropics, which can be as large as 3°C following the eruption of Mt. Pinatubo.

1 Introduction

The stratosphere holds a layer of aerosols consisting primarily of sulfuric acid and water that impact climate in a variety of ways (Kremser et al., 2016). Most importantly, this stratospheric aerosol layer scatters incoming light leading to a surface cooling effect. Scattering in the atmosphere can be greatly enhanced by volcanic eruptions, ~~multiplying the impact on climate~~which in turn strengthens this surface cooling. For example, the 1991 eruption of Mt. Pinatubo injected an estimated ~~10~~5-10 Tg of sulfur into the stratosphere ~~(Guo et al., 2004)~~(Guo et al., 2004; English et al., 2013; Dhomse et al., 2014; Timmreck et al., 2018) , resulting in a peak top-of-atmosphere radiative forcing of roughly 3-4 Wm^{-2} (Ramachandran et al., 2000; Hansen et al., 1992), and cooled global temperatures by a few tenths of a degree Celsius (Robock and Mao, 1995; Thompson and Solomon, 2009). ~~The~~ There was also a significant impact on oceans~~was equally impressive~~, with global ocean heat content decreasing by 3×10^{22} J, and sea level decreasing by 5 mm (Church et al., 2005). Over the last two decades a number of smaller volcanic eruptions have also injected sulfur dioxide into the stratosphere (Vernier et al., 2011). These eruptions have had a small but discernible effect on global temperature ~~(Solomon et al., 2011; Fyfe et al., 2013; Haywood et al., 2014; Santer et al., 2014)~~ (Solomon et al., 2011; Fyfe et al., 2013; Santer et al., 2014; Schmidt et al., 2018; Stocker et al., 2019).

Issues remain in characterizing the radiative forcing caused by changes in stratospheric aerosols and the climate responses that result. General circulation models, for example, often overestimate the stratospheric warming response following the eruption of Mount Pinatubo (Lanzante and Free, 2008; Gettelman et al., 2010). The impact of smaller, post-Pinatubo volcanic eruptions on surface cooling needs better quantification (Santer et al., 2014), and large uncertainties remain in characterizing the response of the upper troposphere and lower stratosphere to volcanic eruptions (Ridley et al., 2014; Andersson et al., 2015). Such uncertainties in the climate response to volcanic eruptions result in part from differences in the stratospheric aerosol datasets that are prescribed in general circulation models (GCMs). GCMs participating in the Fifth Coupled Model Intercomparison Project (CMIP5) (Taylor et al., 2012; Driscoll et al., 2012) used stratospheric aerosol datasets from Ammann et al. (2003) and Sato et al. (1993), while post-CMIP5 simulations (Solomon et al., 2011; Fyfe et al., 2013) have used datasets that include recent eruptions (Vernier et al., 2011). To avoid a diversity of stratospheric aerosol datasets, and their associated forcings, a homogenized stratospheric aerosol time series was developed for use with CMIP6 (Durack et al., 2018).

This stratospheric aerosol dataset will help reduce uncertainties that have resulted from differing stratospheric aerosol assumptions (e.g., in CMIP5). While modelling centres were performing simulations for CMIP6 an update was made to this dataset that affected the stratospheric aerosol loading of the Pinatubo eruption. Although the updates are not CMIP6 endorsed, and forcing should remain consistent across models, the changes to aerosol loading can be substantial. To estimate the potential effect of these changes on CMIP6 results we characterize the impact of this dataset update on the global climate using two general circulation models.

2 The CMIP6 Stratospheric Aerosol Dataset

For CMIP6 experiments the stratospheric aerosol forcing dataset post-1980 was constructed in a two step process. First, data from multiple satellite instruments was compiled into a continuous extinction record at 525 nm that spans the entire period.

Extinction measurements at other visible and near-infrared wavelengths are available for portions of the record, but do not span its entirety. This composes the Global Satellite-based Stratospheric Aerosol Climatology, or GloSSAC (Thomason et al., 2018). The second step is deriving the asymmetry factor, single scattering albedo and extinction at the wavelengths required for radiative transfer calculations in climate models (Luo, 2018a). This was done by deriving a particle size distribution from the measurement periods where multiple wavelengths are available (1985-2005) and extrapolating to periods where they are not (pre-1985 and post-2005). This composes the IACETH-SAGE3lambda-3-0-0 dataset available from input4MIPs. Luo (2018a) then used the particle size distributions to compute the optical parameters at the wavelength bands of participating models. In this way, the optical properties required for each participating model's radiative transfer scheme are consistent with the underlying extinction and particle size climatology. As of May 31, 2016 these were available from `ftp://iacftp.ethz.ch/pub_read/luo/CMIP6` and represented version 3 stratospheric aerosol datasets used for CMIP6, herein referred to as version 3, or 'v3' for brevity.

After publication of these datasets an error was found in the GloSSAC processing involving the cloud clearing in the CLAES data, necessitating an update ~~to version~~ in GloSSAC from version 1 to version 1.1, and subsequent update in the CMIP6 forcing dataset from version 3 to version 4 (Luo, 2018b). The update was published August 27, 2018 and is available from `ftp://iacftp.ethz.ch/pub_read/luo/CMIP6_SAD_radForcing_v4.0.0`. As it is not yet officially CMIP endorsed it is not currently available from input4MIPs. Changes to the data processing primarily affected only a subset of the satellite measurements which contributed to the January 1991 to December 1994 period, so data outside of this range remains the same between version 3 and version 4.

Of most direct consequence to GCM experiments is the stratospheric aerosol optical depth (SAOD), calculated as the vertical integral of aerosol extinction from the tropopause to the top of the atmosphere, or in this case to the top of the dataset at 40 km. Luo (2018b) show the magnitude of these changes at several latitude bins and times for 1020 nm, and the following analysis expands on this at 550 nm in the context of this paper. The top panel in Figure 1 shows the monthly SAOD at 550 nm from the version 3 dataset. The impact of the Mount Pinatubo eruption on SAOD is largest in the tropics, but a substantial amount of aerosol is transported to the extra-tropics in both hemispheres in ensuing months, and global SAOD values remain elevated over background for several years. The bottom panel shows the SAOD differences between version 3 and version 4. The peak Pinatubo-induced SAOD values are smaller in version 4, but v4 exhibits modest increases at other locations, reducing globally averaged differences and potentially offsetting climate differences between versions. Fractional differences show a very similar pattern with differences in the thickest part of the plume reaching 20%, and differences nearer the poles reaching 50% for short periods of time.

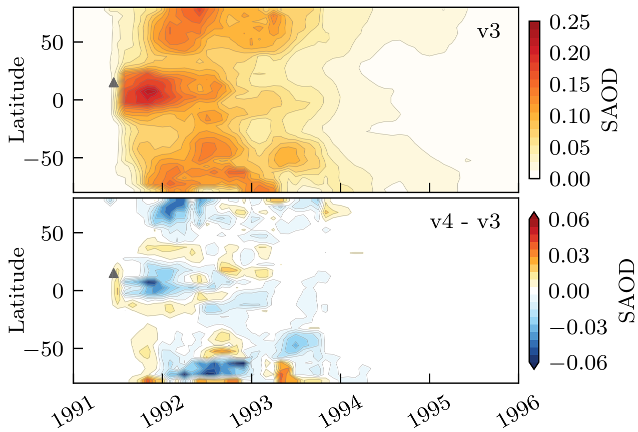

Figure 1. The top panel shows aerosol optical depth in the stratosphere (SAOD) at 550 nm from the v3 dataset. The bottom panel shows the absolute difference between the versions, computed as v4 − v3, during this same time period. The triangle marks the Pinatubo eruption at 14°N on June 15, 1991.

However, when looking at SAOD alone, decreases in extinction at higher altitudes can be offset by increases nearer the tropopause, reducing the apparent differences. This can be seen in Figure 2, which shows the difference in extinction at 550 nm as a function of altitude and time for the global average and three latitude bands that showed large changes in SAOD. The most prominent differences between v3 and v4 are evident in the tropics where the main aerosol plume has been reduced in optical thickness by up to 50%. Conversely, altitudes below the main plume have increased extinction. While the increase extends to the ground, most of these altitudes are below the tropopause, and so are not considered in climate simulations (CMIP6 simulations are recommended to use stratospheric aerosols only above the tropopause (Thomason et al., 2018)). The solid gray lines in Figure 2 indicate the monthly averaged thermal tropopause from NCEP1 reanalysis data (Kalnay et al., 1996).

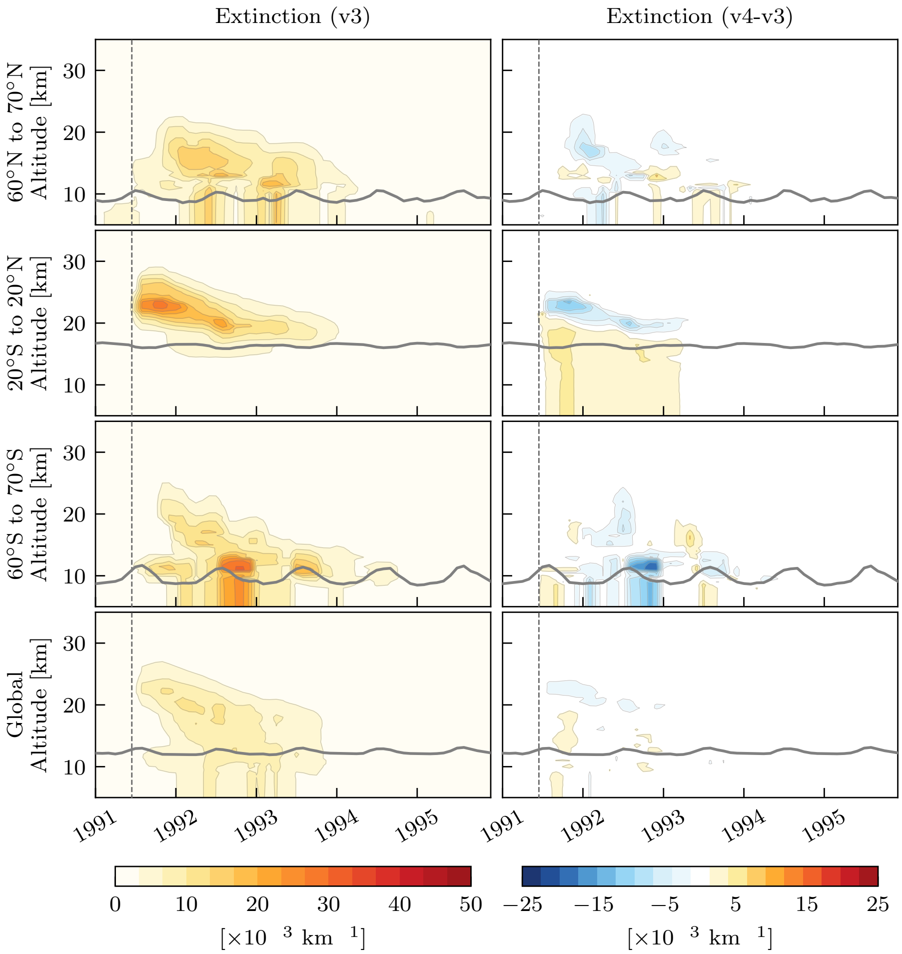

Figure 2. The left column shows the version 3 extinction at 550 nm in four latitude bands. The right column shows the change in extinction when the newer version 4 data product is used (v4-v3). The solid gray lines show the monthly NCEP1 thermal tropopause and the dashed line indicates the date of the Pinatubo eruption.

3 ~~Models~~

2.1 ~~CanESM5~~

It is worth highlighting here that since the creation of the version 4 stratospheric aerosol dataset updates to the underlying GloSSAC dataset have continued, with version 2 now available (Kovilakam et al., 2020). Figure S1 shows the changes in stratospheric aerosol optical depth between GloSSAC versions 1, 1.1 and 2. While these recent updates to GloSSAC have not been incorporated into the CMIP6 stratospheric aerosol forcing dataset, the magnitude of the differences between GloSSAC version 1 and version 2 are at least as large in magnitude (although very different in distribution) to the differences between version 1 and version 1.1 of GloSSAC (Aubry et al., 2020). This makes it likely that future updates to stratospheric aerosol forcing will result in climate effects of comparable magnitude to those seen in this study.

The

3 Experimental Setup

This paper looks at three types of impacts caused by changes to the stratospheric aerosol forcing; from the immediate radiative and heating differences, to short term temperature effects, to longer-term changes represented by ocean heat content. Table 1 shows the three experiments, the models used for each, and whether they were ran in atmosphere-ocean coupled mode (ESM) or uncoupled with prescribed ocean temperatures (AMIP). The analysis uses two models, the Canadian Earth System Model version 5 (CanESM5) was used to evaluate the effect of the change from version 3 which has a relatively coarse resolution that enables simulation of large ensembles in a fully coupled ocean-atmosphere mode, and the E3SM Atmosphere Model version 1 (EAMv1) which is used to verify effects in higher resolution models, albeit with smaller statistics.

Simulations for examining impacts on radiative forcing and heating rates were performed with CanESM5 in atmosphere-only mode using sea-surface temperature and sea-ice prescribed by observations for the period 1990-1999 following the AMIP protocol (Gates et al., 1999). For this analysis one simulation spanning from 1989 to 2014 was performed with the version 3 forcing data and a second with the version 4. Since only differences in instantaneous quantities are explored in this analysis a larger ensemble was not performed.

To explore the climate response to volcanic forcing, transient historical experiments were performed with CanESM5 following the methodologies set forth for CMIP6 (Eyring et al., 2016) using the version 3 aerosol climatology and all standard forcings. Simulations using version 4 of the aerosol dataset on the post-Pinatubo instantaneous radiative forcing and climate simulated by this model . stratospheric aerosol data were performed with the same protocol by branching new simulations off of CanESM5 historical simulations at the end of 1989. This was done for 15 realizations, with simulations using version 4 data run until 2014. In addition, three realizations were performed using the EAMv1 model. As with the CanESM5 simulations, we consider both version 3 and 4 of the volcanic aerosol dataset, performing three simulations with each version, using the CMIP6 protocols for the period 1990-1999. The reason for not using the coupled E3SM, and the reduction in ensemble size is the considerably higher computational cost of E3SM and EAMv1 compared to CanESM5. Additionally, as explained later, the coupled and uncoupled response in CanESM5 is very comparable, indicating the use of a fully coupled model is not generally necessary.

3.1 CanESM5

We provide here a brief description of CanESM5 but a more through thorough overview of the components and properties of CanESM5 is given in Swart et al. (2019). The atmospheric component of CanESM5, the Canadian Atmospheric Model version 5 (CanAM5) is a spectral model employing T63 triangular truncation with physical tendencies calculated on a 128×64 (∼2.81° or approximately 300 km at the equator) horizontal linear grid. CanAM5 has 49 unevenly spaced vertical levels up to ∼0.1 hPa, with a vertical resolution of approximately 1.5 km near 25 km altitude. The physical ocean component of CanESM5

Table 1. Models and model configurations used in this analysis.

Experiment	Model	Mode	Ensemble size (v3 + v4)
Radiative Forcing	CanESM5	AMIP	2 (1 + 1)
Temperature	CanESM5	ESM	30 (15 + 15)
	EAMv1	AMIP	6 (3 + 3)
Ocean Heat Content	CanESM5	ESM	(15 + 15)

is based on NEMO version 3.4.1 (Madec and Imbard, 2012) and has 45 levels with approximately 6 m resolution in the upper ocean increasing to ∼250 m in the lower ocean, and a horizontal resolution of approximately 1°. CanAM5 does not simulate a QBO.

3.2 EAMv1

In addition to CanESM5, we also consider simulations from version 1.0 of the Energy Exascale Earth System Model (E3SM) (Golaz et al., 2019). In particular, we employ the E3SM Atmosphere Model version 1 (EAMv1) (Rasch et al., 2019) using prescribed sea surface temperature (SST) and sea ice concentrations as boundary conditions. SST and sea ice fields are from HadISST version 1.1.3 (Durack and Taylor, 2017) as described in Hurrell et al. (2008). The model solves the atmospheric primitive equations using a continuous Galerkin spectral finite element method and has a horizontal resolution of approximately 100 km (or 1°) at the equator. EAMv1 has 72 unevenly spaced vertical levels with a model top at ∼0.1 hPa, and vertical resolution of approximately 1-2 km in the lower stratosphere. EAMv1 employs a linearized ozone chemistry scheme (Hsu and Prather, 2009). ~~Although~~ In the realizations used here, EAMv1 produces a quasi-biennial oscillation (QBO) ~~, it~~ that tends to be too ~~strong and~~ frequent compared to ~~observations and~~ observation, but does sample a variety of states during the eruption period. While the frequency and strength of the QBO can be greatly improved by modifying parameterized convectively generated gravity waves (Richter et al., 2019)~~. As with the CanESM simulations, we consider both version 3 and 4 of the volcanic aerosol dataset, performing three simulationswith each version~~, the improvement is not included in the current simulations.

4 Results

4.1 Radiative Forcing

Volcanic aerosols absorb near-infrared and thermal radiation, heating the stratosphere, while simultaneously cooling the troposphere due to scattering of visible and near-infrared radiation. The magnitude of this effect has been investigated in numerous studies, with marked decrease in radiation at the surface (Dutton and Christy, 1992) and tropopause (Hansen et al., 1992), and increases in reflected radiation at the top of the atmosphere (Minnis et al., 1993; Stenchikov et al., 1998; Ramachandran et al., 2000). For this work, radiative forcing is computed as the instantaneous net ~~outgoing~~ incoming flux at the top of the atmosphere for solar wavelengths (less than 4 microns) and thermal wavelengths (greater than 4 microns). Net total radiative forcing is calculated as the sum of the solar and thermal components.

~~Simulations were performed in atmosphere-only mode using sea-surface temperature and sea-ice prescribed by observations for the period 1990-1999 following the AMIP protocol (Gates et al., 1999). For this configuration~~ For the CanESM5 AMIP used here an additional, diagnostic, atmospheric radiative transfer calculation is performed in which the stratospheric aerosol is zeroed out. The difference between the two computations ~~then~~ gives the instantaneous radiative forcing due to the presence of the stratospheric aerosols. Figure 3 shows the solar, thermal and net stratospheric aerosol radiative forcings from the version 3 and version 4 aerosol datasets for the global average and three latitude bands. The thermal forcing from the Pinatubo eruption peaks at approximately ~~-2.5~~2.5 Wm^{-2} in the tropics and ~~-1.5~~1.5 Wm^{-2} globally. Solar forcing is larger, peaking at nearly ~~6 and 3.7~~ -6 and -3.7 Wm^{-2} for the tropics and global averages, respectively. Polar regions can also have large solar forcing during the summer months, but the smaller geographic area and seasonal cycle due to reduced solar insolation in the winter lead to only a small impact globally. Differences in radiative forcing between version 3 and 4, shown as the shaded gray region, are much smaller, with net forcing differences peaking at 0.44 Wm^{-2} in the tropics and 0.11 Wm^{-2} globally. While maximum forcing differences in the SH polar regions are larger than the tropics (up to 1 Wm^{-2}), the relatively small area contributes little to the global averages.

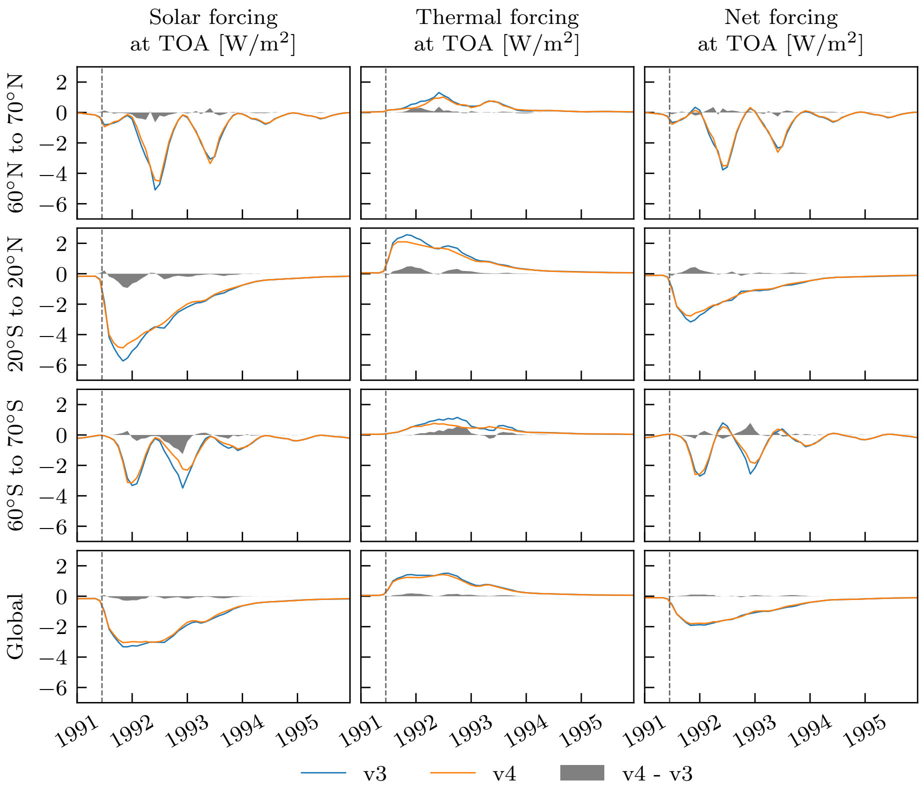

Figure 3. The left column shows the instantaneous solar radiative forcing at the top of atmosphere due to stratospheric aerosols in CanESM5. The blue line shows the forcing from version 3, the orange from version 4, and the gray shaded region indicates the difference in forcing between the two datasets (v4 -v3). The center column shows the instantaneous thermal radiative forcing at top of atmosphere, and the right column shows the instantaneous net radiative forcing at top of atmosphere. Each row shows the results for a different latitude band.

The absorption of both solar and thermal radiation heats the stratosphere in regions of enhanced aerosol loading (Kinne et al., 1992; Kinnison et al., 1994; Stenchikov et al., 1998; Andersen et al., 2001). Figure 4 shows the vertical distribution of instantaneous heating rates due to stratospheric aerosols computed using version 3 of the aerosol dataset. ~~Tropical heating rates have been scaled by a factor of 1/3 so that tropical and extratropical heatings rates can be compared on the same color axis.~~ The largest heating rate of 0.5°C/day in the tropics near 24 km is seen approximately 6 months after the eruption, and contributes to a globally averaged instantaneous heating rate of 0.2°C/day, with increases over background that last until early 1994. The differences in instantaneous heating rates from version 3 to version 4 are also shown in Figure 4. At times, heating rates have been reduced in version 4 by almost half where extinction is largest, with slight increases in heating rates closer to the tropopause. This result is consistent with the differences between the aerosol datasets (Figure 2).

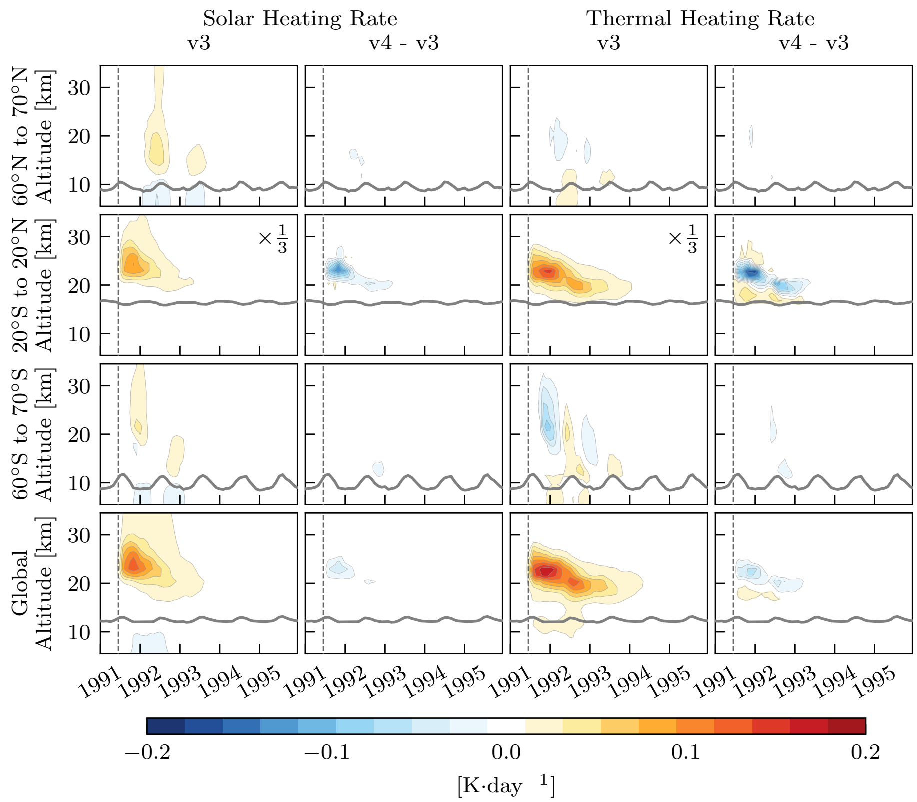

Figure 4. Instantaneous heating rates from CanESM5 model runs. The left column shows the instantaneous solar heating rate due to stratospheric aerosols using the version 3 forcing dataset. The second column shows the change in the instantaneous solar heating rate when version 4 is used instead. The third and fourth columns show the same, expect for the instantaneous thermal heating rates. The gray lines denote the tropopause, and dashed lines indicate the date of the Pinatubo eruption. Note that the v3 instantaneous heating rates in the tropics have been multiplied by 1/3 for visual representation.

4.2 Climate Response

The radiative heating rates induced by volcanic eruptions translate to substantial warming in tropical stratospheric temperature anomalies in CMIP5 models, ranging from 2°C to nearly 10°C in the tropical stratosphere (Douglass and Knox, 2005; Driscoll et al., 2012; Arfeuille et al., 2013).

To explore the climate response to volcanic forcing, transient historical experiments were performed with CanESM5 following the methodologies set forth for CMIP6 (Eyring et al., 2016) using the version 3 aerosol climatology and all standard forcings. Simulations using version 4 of the stratospheric aerosol data were performed with the same protocol by branching new simulations off of CanESM5 historical simulations at the end of 1989. This was done for 15 realizations, with simulations using version 4 data run until 2014. In addition, three realizations were performed using the EAMv1 model. As with the CanESM5 instantaneous radiative forcing calculations, these simulations were performed using the CMIP6 protocols (but for the AMIP experiment) for the period 1990-1999.

The ensemble mean CanESM5 stratospheric temperature anomalies following the Pinatubo eruption are shown in the left column of Figure 5. Temperature anomalies up to 7°C are seen in the tropics near 24 km, where the extinction, and solar heating rates are largest. The stratosphere also exhibits a long-term stratospheric cooling, but linearly detrending the record still results in a maximum temperature anomaly of 6°C, and does not change differences seen between version 3 and version 4. The structure of the global averaged temperature anomaly largely follows the evolution of the tropical temperatures, but peaks at approximately 3°C, which results because temperature anomalies outside of the tropics are considerably smaller. When using version 4 of the stratospheric aerosol data the peak temperature anomalies in the tropics are reduced by just over 2°C, and peak global anomalies are reduced by 0.8°C. The stratospheric temperature response in the polar regions can differ by 2-4°C, depending on the version of the SAOD used, but these differences are considerably smaller than the between-realization variability, which has a standard deviation of 6°C in these regions. Increases in stratospheric temperature as modelled by EAMv1 are similar in magnitude (see Figure ??S2). However, with only three ensemble members, temperature differences compared to version 4 are not statistically significant at the 95% level.

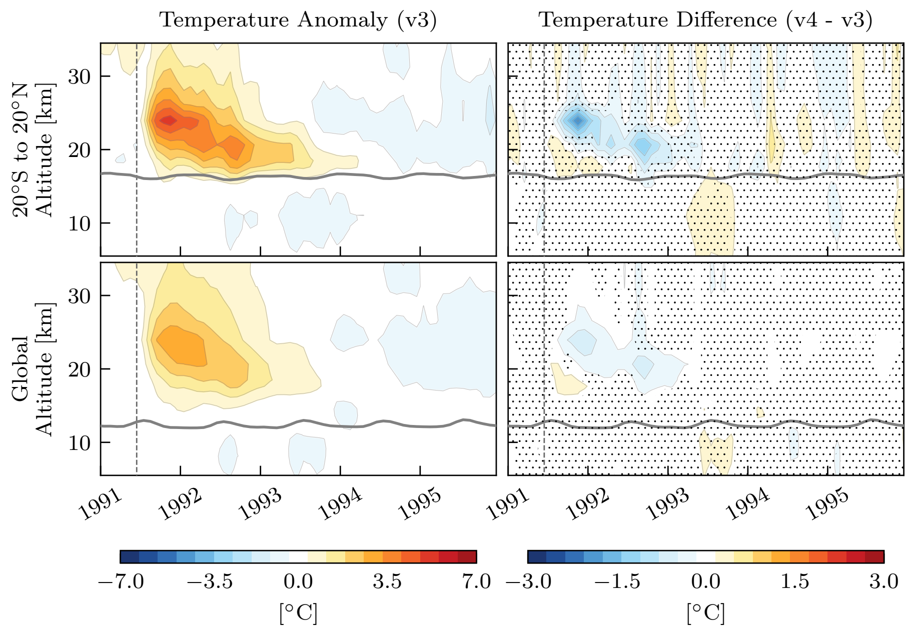

Figure 5. The left column shows the monthly temperature anomalies averaged over all CanESM5 ensemble members with version 3 forcing for 20°S to 20°N (top) and the global average (bottom). The right column shows the difference in temperature when using the version 3 and version 4 datasets. Stippling marks the regions where differences are not significantly different from zero at the 95% confidence level. Anomalies are computed using the simulation period of 1990 through 1999.

Figure 6 shows the same data as a function of latitude and time. The top panel indicates the maximum difference in temperature anomalies at any altitude, with the bottom panel indicating the altitude at which the difference occurs. No temperature differences outside of approximately 30°S to 30°N are evident, nor are changes in the temperature gradient (not shown).

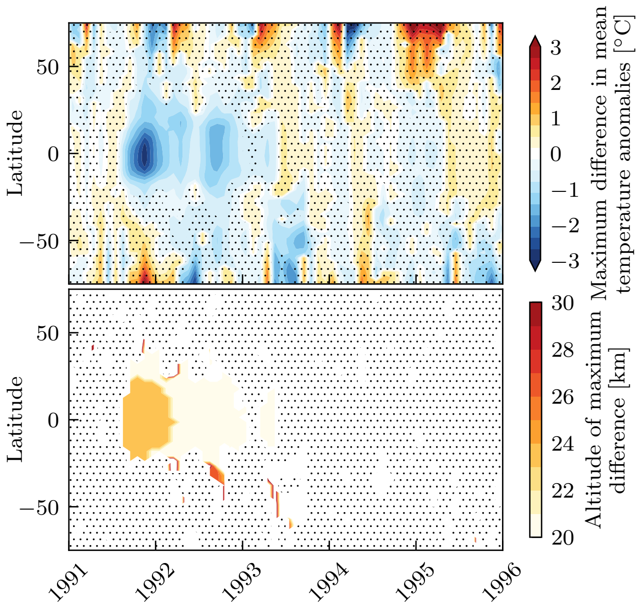

Figure 6. The top panel shows the maximum difference in monthly temperature anomalies at any altitude as a function of latitude and time. Stippling marks the regions where differences are not significantly different from zero at the 95% confidence level. The bottom panel shows the altitude at which the maximum occurs.

For observational comparisons data from the Remote Sensing Systems (RSS) microwave temperature record (Mears and Wentz, 2009; Mears and Wentz, 2009) is used. The RSS datasets are composed of measurements from the Microwave Sounding Units and Advanced Microwave Sounding Units which provide temperature information for several deep atmospheric layers. For this study, the temperature of the lower stratosphere (TLS) and temperature of the lower Troposphere (TLT) products are used. TLS is a weighted average from approximately 10 to 30 km, with a peak sensitivity at 17.4 km and 75% of the contribution coming from between 14 to 22 km. TLT data is from below 10 km with over 75% of the signal from below 5.5 km including a 10-15% contribution from the surface (Mears and Wentz, 2017). Comparable temperature records from CanESM5 and EAMv1 are computed by applying RSS weighting functions to model temperatures. Since TLT includes a significant contribution from the surface, the weighting function depends on the surface type (land or ocean) to account for surface emissivity differences.

Figure 7 shows TLS and TLT anomalies simulated by CanESM5 and EAMv1 using version 3 and version 4 of the dataset in blue and orange respectively, as well as the RSS measurements in black. TLS anomalies are smaller in version 4 by up to 0.5°C in the tropics and 0.25°C globally, but modelled TLS values still remain approximately 1°C above measured values when globally averaged. This model-observational difference in stratospheric temperature has also been noted in other GCMs (Lanzante and Free, 2008; Gettelman et al., 2010). EAMv1 stratospheric temperatures in the tropics show increased variability when compared to CanESM5 due to the quasi-biennial oscillation, which is not present in CanESM5. Tropospheric temperature differences arising from changes to the aerosol dataset are smaller than in the stratosphere for both models. EAMv1 results exhibit much smaller variability between ensemble members in the lower troposphere due to specified sea surface temperatures, and do not show a significant difference between versions 3 and 4. CanESM5 differences in TLT of approximately 0.2°C in the tropics and 0.1°C globally are present in 1993, but result primarily from a change in the phase of the El Niño Southern Oscillation (ENSO) between version 3 and version 4 runs.

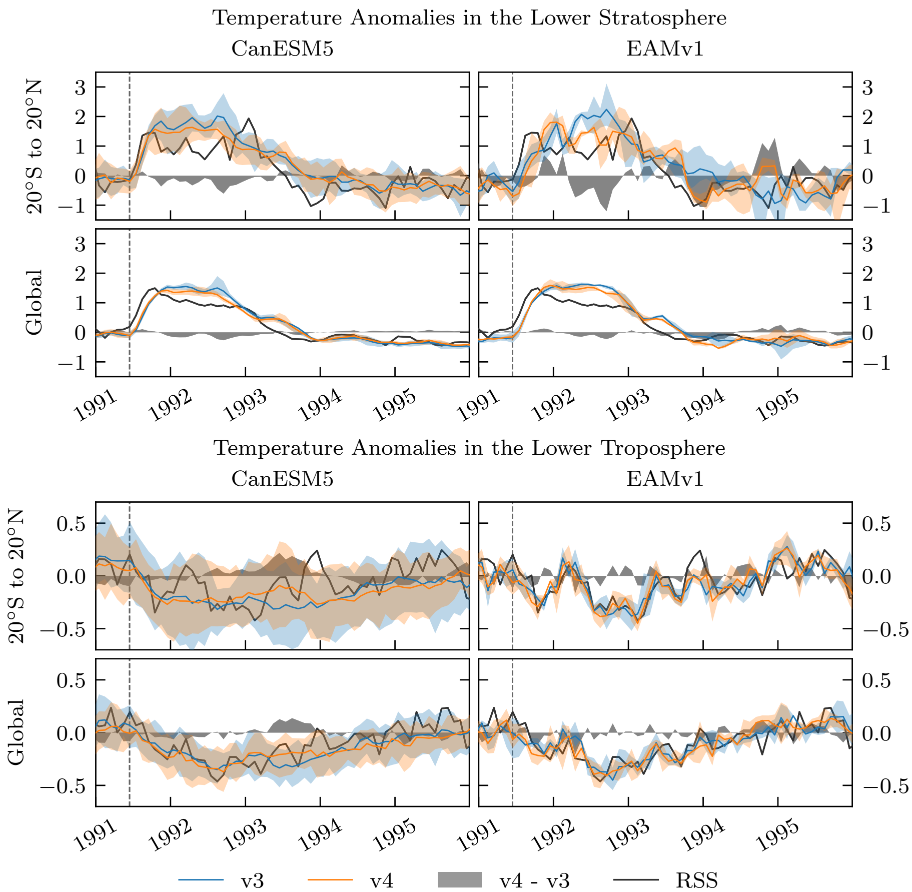

Figure 7. Temperature anomalies in the lower stratosphere (top two rows) and lower troposphere (bottom two rows) in the tropics and globally averaged. The left column shows results from CanESM5 and the right column EAMv1. Solid blue lines show the mean temperature anomaly using the version 3 dataset and orange show the same using version 4. The blue and orange shaded regions show the 10th and 90th percentiles for version 3 and 4 respectively for the CanESM5 ensemble and the max/min range for the EAMv1 ensemble. The gray region shows the mean difference between simulations using version 3 and version 4. The black line shows the RSS observations and the dashed line marks the eruption of Pinatubo on June 15th, 1991. Anomalies are computed using the simulation period of 1990 through 1999.

While large eruptions may increase the likelihood and magnitude of El Niño events ~~(Adams et al., 2003; Mann et al., 2005; Emile-Geay e~~ (Adams et al., 2003; Mann et al., 2005; Emile-Geay et al., 2008; Khodri et al., 2017), the response is heavily model dependent (Predybaylo et al., 2017). Due to non-zero changes in the volcanic forcing before the eruption, the version 3 and version 4 ensembles are not in ~~the same internal state~~ identical internal states on June 16th when Pinatubo erupts, with the version 4 ensemble tending slightly to more La Niña-like states. This can have a marked effect on the climate response ~~(Pausata et al., 2016; Zanchettin et al.~~

(Lehner et al., 2016; Pausata et al., 2016; Zanchettin et al., 2019). However, there is no apparent difference in ENSO states in the 2 years following the eruption when initial conditions are taken into account. Similar investigation of the North Atlantic Oscillation (NAO) shows no significant impact on the phase or magnitude. Additionally, changes to the aerosol forcing do not have a significant impact on ocean heat content, as shown in Figure 8. As such, changes to atmospheric temperatures in CanESM5 AMIP runs (not shown) show comparable changes to coupled runs, and therefore the AMIP runs from the EAMv1 model are expected to be a good representation of results from the coupled model.

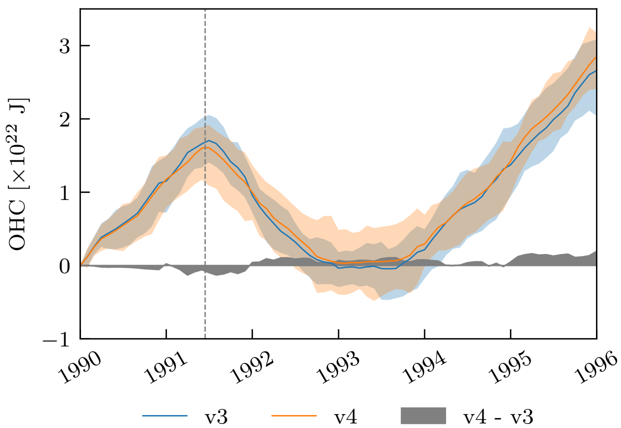

Figure 8. Monthly deseasonalized ocean heat content relative to January 1990. The blue line shows OHC using the version 3 aerosol forcing while the orange line indicates results when using version 4. The shading indicates the 10^{th} and 90^{th} percentiles of the data.

In addition to temperature responses, several studies have noted a decrease in global precipitation following the Pinatubo eruption (Robock and Liu, 1994; Broccoli et al., 2003; Gillett et al., 2004; Barnes et al., 2016). The CanESM5 ensemble mean shows a global precipitation decrease of 0.05 mm/day one year after the eruption, consistent with previous studies. However, this is similar for both the version 3 and version 4 datasets, and differences in precipitation due to the change in stratospheric aerosols are not statistically significant. These results are summarized in Figure 9 that shows the changes in climate response when using version 3 and version 4 aerosols averaged for two years following the Pinatubo eruption. For CanESM5, with results shown as the box and whisker plots, the largest differences in temperatures between aerosol datasets occur near 24 km and are statistically significant from zero at the 95% confidence level, as are the changes in the TLS. Changes in lower tropospheric temperatures are not statistically significant between versions, nor are changes in precipitation. EAMv1 results are shown as individual points, and indicate similar responses to those seen in CanESM5.

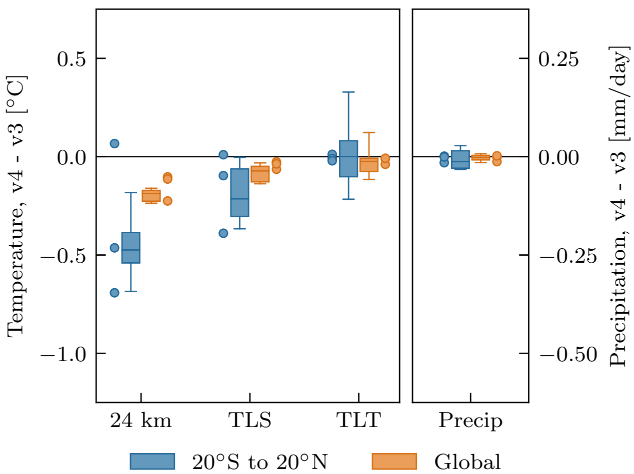

Figure 9. Difference in temperature and precipitation levels between version 3 and version 4 for the 2 years following the Pinatubo eruption. Boxes show the interquartile range of the CanESM5 data from the 15 member ensemble, and whiskers mark the 10^{th} and 90^{th} percentiles. Individual markers show the values from each of the three EAMv1 ensemble realizations.

5 Conclusions

Since publication of the version 3 stratospheric aerosol dataset recommended for CMIP6, updates included in version 4 have resulted in extinction differences as large 50% in the aerosol plume of the Pinatubo eruption. When these datasets are used in CanESM5 it is found that using version 4 instead of version 3 caused reductions in the instantaneous top-of-atmosphere radiative fluxes up to 0.44 W/m^2 in the tropics approximately 6 months following the eruption and maximum differences in instantaneous radiative heating rates of 0.2 °C/day in the tropics. The substantial change in stratospheric heating rates at specific altitudes following the eruption results in significant temperature response differences of up to 3°C. Over deeper layers and larger spatial scales the impact is less pronounced with only the TLS showing statistical significance. As a result, the impact on global precipitation rates is also small. Temperatures in the lower stratosphere, between approximately 14 and 22 km, are decreased by 0.2°C with no statistically significant change in the lower troposphere. Similarly, precipitation rates and changes to the ENSO index are not substantial enough to be distinguished from unforced internal model variability. Based on results from two models participating in CMIP6, we find that the impact of the update from version 3 to version 4 of the stratospheric aerosol dataset is relatively small for the fields considered of radiative forcing, temperature, and precipitation. This indicates that while there is a known forcing issue in the v3 stratospheric aerosol dataset, this does not undermine the utility of the CMIP6 historical ensemble to quantify the anthropogenic-forced impact on the climate. Use of the new SAOD dataset may, however, affect quantities not considered in this study, and its impact may be model dependent, so modelling groups interested in the post-Pinatubo response may want to assess the impact of the new SAOD dataset in their models.

~~Same as Figure 5, except using data from EAMv1 ran in AMIP mode.~~

Code and data availability. The CanESM5 model code is available at https://gitlab.com/cccma/canesm. CanESM5 model data and analysis code is available at 10.5281/zenodo.3524445. The E3SM project, code, simulation configurations, model output, and tools to work with the output are described at the E3SM website (https://e3sm.org). Instructions on how to get started running E3SM and its components are available at the E3SM website (https://e3sm.org/model/running-e3sm/e3sm-quick-start). All model codes may be accessed on the GitHub repository (at https://github.com/E3SM-Project/E3SM)

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Competing interests. The authors declare that they have no conflict of interest.

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