Authors' Response to Reviews of

HSW-V v1.0: localized injections of interactive volcanic aerosols and their climate impacts in a simple general circulation model

Joseph Hollowed, Christiane Jablonowski, Hunter Y. Brown, Benjamin R. Hillman, Diana L. Bull, and Joseph L. Hart
egusphere-2024-335

RC: ***Reviewer Comment***, AR: Author Response, ☐ Manuscript Text

1. Reviewer #2

1.1. Author Comments

We thank the reviewer for carefully reading our manuscript and providing very constructive suggestions for improvement. Each comment below appears as a reviewer comment (RC) followed by an author response (AR). Closed boxes show text from the manuscript. Red text with strikethrough represents deleted text, and blue text with wavy underlining represents new text. Section numbers refer to those as they appear in the updated manuscript (for example, some Appendix section numbers have changed).

The biggest changes made are in our response to Comment 1, where we added new paragraphs of text, a new appendix section, and a new figure in support of a discussion of the Brewer-Dobson circulation in our model. In our responses to Comment 2 and Comment 11, we have added several new references. The remaining comment responses consist of small edits and clarifications.

1.2. Comment 1

RC: ***My only more general comment relates to the lack of any mention of the Brewer-Dobson circulation (BDC), which is the main process which controls the transport and spread of stratospheric aerosol. Around line 496, some discussion of the tropospheric large scale circulation is present, which may be relevant to the simulations given the rather low injection height used in the "Pinatubo-like" simulations, but the general utility of this model set-up will depend in part on the fidelity of the BDC: in terms of general features like isolation of the tropical pipe, large-scale mixing in the extratropical stratosphere, and polar subsidence. If an assessment of the stratospheric meridional circulation in the HSW model configuration is given in other studies, it would be useful to summarize some of that work in the introduction. If not, maybe the authors can provide some guidance based on their own results.***

AR: We strongly agree that the fidelity of the BDC is relevant to the utility of this model. While we did attempt to introduce some discussion on the global circulation in Section 4.2, as the reviewer has noted, we agree that the focus on the Hadley cell is mostly relevant to the troposphere, and that a broader discussion on the residual circulation in the stratosphere is missing. At least one prior study has shown transformed Eulerian mean (TEM) analysis results for a HSW atmosphere (Yao & Jablonowski, 2016), but we are not aware of a study that shows the residual circulation in particular, and of course none which include our modified HSW implementation near the model top.

To this end, we have performed an analysis to obtain the residual velocity components and streamfunction in the stratosphere, averaged over five years of an HSW run with no volcanic injection present. A new appendix containing a new figure (Appendix B, Figure B1) show the results. Section 4.2 also now includes an extended discussion on the global circulation which references this appendix. Specifically, we show that the global stratospheric circulation is qualitatively consistent with the equinoctial (hemispherically symmetric) state of the BDC in nature. This of course differs from the solstice condition of the BDC which was manifest during the historical Pinatubo event in June of 1991. This difference is important to understand, but does not diminish the utility of our model, in our opinion. Still, we have included a sentence which suggests that the HSW relaxation temperature could, in principle, be replaced with an asymmetric form if desired, which has precedent in prior studies.

The new paragraph in Section 4.2 is as follows:

These conclusions about the mean tropospheric circulation can be expressed more generically for the stratospheric mass transport by way of a transformed Eulerian mean (TEM) analysis. Following the specific TEM framework presented in Gerber and Manzini (2016) based on Andrews et al. (1987), we computed residual velocities in the meridional plane for the HSW atmosphere with no volcanic injections. The five-year average state of the residual velocities between 100 hPa and the the model top near 0.1 hPa are presented in Appendix B. This residual circulation is essentially the HSW analog of the well-known Brewer-Dobson Circulation (BDC), which describes the global mass circulation through the stratosphere (see e.g. Butchart (2014) for a detailed review). Figure B1 shows two symmetric overturning circulation features from equator to pole in each hemisphere, characterized by tropical upwelling, a midlatitude surf zone, and polar subsidence. This symmetry is markedly different from the average residual circulation of the northern-hemisphere summer in nature, which sees a single southward pole-to-pole mass transport in the stratosphere (Butchart, 2014). Thus, the volcanic aerosol distribution as manifest in HSW-V remains primarily in the northern hemisphere, unlike the historical Mt. Pinatubo event. This circulation pattern is much more reminiscent of the equinox condition of the BDC. Specifically, the streamfunction presented in Fig. B1 is in good qualitative agreement with the the observed residual streamfunction during the Spring of 1992 following the historical Mt. Pinatubo eruption (Eluszkiewicz et al., 1996). Similarly, the meridional and vertical residual velocities are in qualitative agreement with those derived from the multi-reanalysis mean presented in Abalos et al. (2021) and reanalysis Springtime means as in Fujiwara et al. (2022) (their Chapter 11). We note that if a solstice condition is desired in the global circulation for future studies with this model, it would be straightforward to replace the HSW equilibrium temperature T_{eq} with a different one designed for that purpose, as in Polvani and Kushner (2002).

The new appendix is as follows:

Appendix B: Residual Circulation of the modified Held-Suarez-Williamson atmosphere

A discussion of the residual circulation of the HSW atmosphere was presented in Section 4.2. Figure B1 shows the vertical and meridional components of the residual velocity in the meridional plane from 100 hPa to 0.1 hPa averaged over five years of integration of a HSW run with no volcanic injections, after a five-year spinup period. Also shown is the residual circulation mass streamfunction. The meridional residual velocity, vertical residual velocity, and residual velocity sreamfunction are exactly the forms presented as Eq. A6, A7, and A8 of Gerber and Manzini (2016), respectively.

The residual vertical and meridional velocities agree qualitatively well with those computed from

Springtime averages of reanalysis data as presented in Fujiwara et al. (2022) (their Figures 11.12 and 11.15). A curious feature of the HSW residual velocities are the sign reversals in both residual velocity components, as well as the streamfunction, in the polar stratosphere near 10-30 hPa. These features appear in some, but not all, of the Springtime reanalysis results of Fujiwara et al. (2022) in the meridional residual velocity, though not in the vertical residual velocity.

The new figure is below:

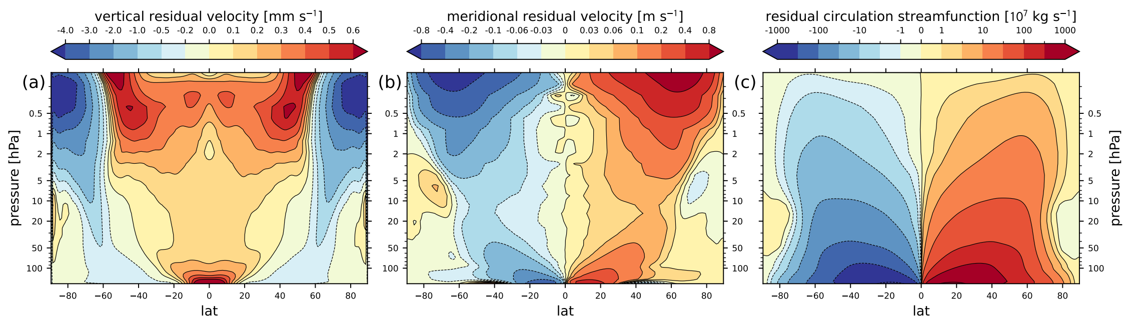

Figure B1. Stratospheric residual circulation of the HSW atmosphere averaged over five years, after a five-year spinup period. The vertical scale extends from 100 hPa to the model top near 0.1 hPa. **(a)** The vertical residual velocity in mm s^{-1}. Contours are irregularly spaced. **(b)** The meridional residual velocity in m s^{-1}. Contours are irregularly spaced. **(c)** The residual streamfunction in units of 10^7 kg s^{-1}. Contours unlabeled on the colorbar are three times their neighboring contour toward zero. That is, the positive contours are 1, 3, 10, 30, 100 . . .

In addition, a small change was made to Section 2.2:

As there are no seasonal variations present, each hemisphere eternally varies about this winter-like steady state, which is qualitatively representative of observations (Fleming et al., 1990)~~, while the~~ . At the same time, the global circulation, and thus mass transport, is characterized by symmetric thermally-direct ~~circulation~~ circulations (Hadley cells) ~~is more~~ in the troposphere, and symmetric residual streamfunction cells in the stratosphere, consistent with equinox states in nature (see discussion in Sect. 4.2 and Appendix B).

1.3. Comment 2

RC: ***Line 29: there are of course many different stratospheric aerosol models used by groups around the world. Therefore it could be here widen the scope of references on such model beyond one single model. A possibility might be to include a reference to a study which includes multi-model comparison (e.g., Clyne et al., 2021) and/or a model-focused review paper (e.g., Timmreck, 2012).***

AR: We have added a citation to Clyne et al., 2021 alongside the existing citation to Zanchettin et al., 2016, which seemed appropriate. We have also reworded the final sentence of this paragraph and added a citation to the Timmreck, 2012 paper. We thank the reviewer for bringing these works to our attention.

Prescribed forcing approaches might be chosen for their computational affordability, though they are also used to facilitate climate model intercomparisons by standardizing the forcing scheme (Zanchettin et al., 2016; Clyne et al., 2021).

. . .

~~A review of these~~ Reviews of the wide array of modeling choices for volcanic forcings ~~is presented in~~ made by different ESMs are presented in Timmreck (2012) and Marshall et al. (2022).

1.4. Comment 3

RC: ***Line 150: Reference here to the HSW "forcing set" seems like a different definition of "forcing" as the term is applied to volcanic aerosol forcing.***

AR: We appreciate the comment from the reviewer and have considered alternative language here. Ultimately, we feel that this usage of "forcing" is correct and consistent with the literature. It may be true that these are different kinds of forcings from a physical perspective; the volcanic aerosol forcing refers to a real physical process being modeled, while the "HSW forcing" refers to an "artificial" process of relaxation toward the reference temperature profile. Still, they are treated identically on paper (mathematically) and in the model, as they both refer to an additive term to the temperature tendency at each model timestep.

For what it's worth, we have replaced a few occurrences of the term "forcing set" in a few sections, since this sounds more specific but was used inconsistently. Beyond this, we did not replace the general usage of "HSW forcing" throughout the rest of the manuscript. The changes were as follows:

- Line 91: replaced "forcing set" with "scheme".
- Line 107: replaced "forcing set" with "set of forcing functions".
- Line 152: "HSW frocing set" was replaced with "HSW atmosphere".
- Line 628: "forcing set" was replaced with "parameterizations".
- Line 708: "forcing set" replaced with "configuration".

1.5. Comment 4

RC: ***Line 222: "timestep n"?***

AR: The word "time" was replaced with "timestep" in this sentence.

1.6. Comment 5

RC: ***Line 289: I guess it should be "either absorption or scattering" or "absorption and scattering", the latter being more generally accurate.***

AR: We agree. The sentence was changed as follows:

A single aerosol species ~~can~~ contributes to extinction of transmitted radiation by ~~either~~ absorption and scattering,. . .

1.7. Comment 6

RC: ***Line 300: Probably useful to specify you refer specifically to the SW AOD here. There is also a LW AOD even if it isn't directly considered.***

AR: We decided that this sentence is unnecessary, and instead added a new sentence to the end of this section which specifies that all further references of the AOD refer specifically to the shortwave AOD. The changes are as follows:

> b_{LW} will be used for the extinction of longwave (LW) radiation, which is assumed to be entirely absorption, and b_{SW} will be used for the extinction of shortwave (SW) radiation, which is assumed to be entirely scattering:
>
> $$b_{\text{LW}} \equiv (b_e \text{ for the longwave band}),$$
> $$b_{\text{SW}} \equiv (b_e \text{ for the shortwave band}).$$
>
> ~~The remainder of this subsection will only discuss b_{SW}. The longwave extinction b_{LW} will be used in Sect. 3.4.1 for the local heating by longwave absorption, but does not contribute to the total column AOD.~~
>
> ...
>
> For a column with a model top at z_{top}, the dimensionless SW AOD τ at a height z is obtained by
>
> ...
>
> We also define a shorthand for the cumulative SW AOD at the surface as $\tau_i \equiv \tau(z=0)$. After summing over k for this case, we have the usual result (Petty, 2006) that each remaining term is just the total column mass burden M_i of the tracer, scaled by the mass extinction coefficient b_{SW} and column area a_i,
>
> $$\tau_i = \sum_k b_{\text{SW}} \frac{q_{i,k}\Delta p_{i,k}}{g} = \sum_k b_{\text{SW}} \frac{q_{i,k} m_{atm,i,k}}{a_i} = b_{\text{SW}} \frac{M_i}{a_i}. \tag{23}$$
>
> Hereafter, "AOD" will refer specifically to the column-integrated SW AOD defined in Eq. (23).

1.8. Comment 7

RC: ***Line 328: It would be good to be explicit about ignoring heating from near-IR solar radiation which was shown by Stenchikov et al. (1998) to be a contributing factor to the total aerosol heating.***

AR: We thank the reviewer for raising this issue; we did not appreciate the difference between near-IR and LW heating, and/or did not describe carefully enough the tuning process. In fact we do tune our heating rates (by way of the LW mass extinction coefficients) to those presented in Stenchikov et. al. (1998) as "total" heating rates (their Figure 10, bottom row), as is described in Appendix C3. In other words, our tuning is implicitly accounting for the near-IR contribution, though we do not name it as such. We have added an explicit mention of this fact in Appendix C3 as follows:

> From observations by previous modeling studies (Stenchikov et al., 2021; Ramachandran et al., 2000; Stenchikov et al., 1998), we expect monthly-mean zonal-mean values for the stratospheric heating rate during month three post-injection to approach $\Delta T = 0.3$ K day^{-1} in the tropics. Note that in the

works cited for this figure, this is the *total* heating rate due to contributions of visible, near-infrared, and infrared radiation. In this work, though we refer to this heating effect specifically as "longwave", we are tuning to the *total* heating rate of 0.3 K day^{-1}.

As well as in Section 3.5 as follows:

> The longwave attenuation mechanism of the model is tuned to produce realistic stratospheric heating rates by sulfate aerosols. The mass extinction coefficient b_{LW} for sulfate is instrumental in tuning the long-term mean temperature anomalies. We note that while we refer to this heating mechanism specifically as a "longwave attenuation", the tuning process implicitly accounts for heating contributions from the near-infrared radiation as well (see Appendix C3)...

1.9. Comment 8

RC: ***Line 446: missing "we" in sentence***

AR: This sentence was reworded and moved to the end of the section as follows:

> ~~In Sect.4.2, only show results from an HV ensemble, though we encourage future experiments to present their ensemble generation methods in these terms.~~
>
> ...
>
> For the purposes of the present work, the model results of Sect. 4.2 are shown only for a HV ensemble. We encourage future studies using this model to present their ensemble generation methods in these terms.

1.10. Comment 9

RC: ***Fig. 7 caption describes time axis as "time since eruption" which appears inaccurate.***

AR: This sentence in the caption was reworded as follows:

> ~~Time values are shown as days since eruption~~The eruption occurs at day 180.

1.11. Comment 10

RC: ***Fig. 8 caption: the black marker should be said to denote the time and latitude of injection.***

AR: This was corrected by replacing "vertical center" with "latitude".

1.12. Comment 11

RC: ***Line 558: here and/or in introduction, it would be useful to make reference to the work of DallaSanta et al., (2019) who used a model hierarchy to investigate the dynamical impacts of volcanic forcing, using a much simpler prescribed aerosol forcing.***

AR: We thank the reviewer for bringing this paper to our attention. It will be a very valuable citation and reference for this current manuscript as well as future work. We have added a reference to DallaSanta et al. (2019) in both Section 1 as follows:

Simpler techniques prescribe radiative aerosol properties directly from an external dataset or analytic forms (e.g., see DallaSanta et al. (2019); Toohey et al. (2016); Eyring et al. (2013); Gao et al. 25 (2008); Kovilakam et al. (2020)).

and in Section 5 as follows:

This work is a new addition to an idealized AGCM model hierarchy that can be used to study phenomena in isolation. Examples of this model hierarchy include Sheshadri et al. (2015) and Hughes and Jablonowski (2023) who studied the effects of topography on the atmospheric flow, or Polvani and Kushner (2002) and Gerber and Polvani (2009) who assessed polar jets and hemispheric asymmetry. Other idealized configurations focus on simple moist flows with moisture feedbacks (Frierson et al., 2006; Thatcher and Jablonowski, 2016), tropical cyclones (Reed and Jablonowski, 2012), tracer-based cloud micro-physics (Frazer and Ming, 2022; Ming and Held, 2018), age-of-air tracers (Gupta et al., 2020), the Madden-Julian oscillation (MacDonald and Ming, 2022), or climate-change forcing (Butler et al., 2010). In addition, this work builds upon previous idealizations of volcanism using simpler prescribed forcing approaches. This includes Toohey et al. (2016) who provide a set of zonally-symmetric volcanic aerosol optical properties tuned to observational data, and DallaSanta et al. (2019) who subjected a set of atmospheric models of increasing complexity to a prescribed aerosol forcing in the form of controlled solar dimming, and steady, zonally uniform lower-stratospheric temperature tendencies.

1.13. Comment 12

RC: ***Line 566: A stratovolcano is a particular type of volcano, not one that produces injections of sulfur to the stratosphere.***

AR: This was corrected by replacing “stratovolcano eruptions" with “volcanic eruptions".

1.14. Comment 12

RC: ***Line 588: a little copy editing required***

AR: This sentence was edited as follows:

The three implementations exhibit no difference in tropopause structure. Above the tropopause, the HS model approaches a constant temperature near 200 K, while W98 and ~~our work are consistent~~the modified HSW forcings share a lapse rate of approximately 2.6 K km^{-1} until ~~above~~ 2 hPa , where they diverge.

We also moved this paragraph to the end of Appendix A1, rather than the end of Appendix A, where it was out-of-place.