RESPONSE TO THE REVIEWERS' COMMENTS

REVIEWER 1

This manuscript analyzes data from multi-model ensemble simulations using 5 chemistry-climate models, to assess the impacts of the 2022 Hunga eruption on the ozone layer, which injected unprecedented amount of water vapor and modest amounts of aerosol precursors. This is a result from an international collaboration activity, the Hunga Tonga–Hunga Ha'apai Volcano Impact Model Observation Comparison (HTHH-MOC) project, and the simulation protocol is explained by Zhu et al. (Geosci. Model Dev., https://doi.org/10.5194/gmd-18-5487-2025, 2025).

In the manuscript, the changes in ozone, aerosols, water vapor, NO2, ClOx, BrOx, temperature, and zonal wind, with respect to the control simulations without any injection, are analyzed and discussed in detail. The interpretation of the simulation results seems to me mostly very reasonable. I think that the manuscript can be accepted for publication in Atmospheric Chemistry and Physics after considering the following few points.

We thank the reviewer for the positive review and helpful comments that have improved the manuscript. We analyze the individual points below in blue.

Figure 1(a) (and Figure S1(a)): Why does the GEOSCCM panel not have any dotted region?

Thank you for spotting this. This was because the aerosol SAD diagnostic we used in GEOSCCM included only sulfate aerosol from the Hunga eruption and no other contribution from background aersols. Hence the SAD value in the control simulation, and its variability (standard deviation), was close to 0. As such, the standard error we used for the diagnosis of the statistical significance, $i.e. \sqrt{\frac{\sigma_1^2}{n_1}+\frac{\sigma_2^2}{n_2}}$, is always small and determined only by the variability in the Hunga aerosol forcing. Hence the Hunga forcing was always detectable over the variability driven entirely by its own variability.

To make the GEOSCCM results more consistent with the results of the other two models, we have now changed this panel for GEOSCCM to include sulfate SAD changes from both volcanic and non-volcanic sources. While this does not affect the derived Hunga response, it does allow to better account for the role of background aerosol SAD variability and, as the result, some regions now appear as non-statistically significant (i.e. as in the other two models).

Lines 197-201: It is not clear whether the negative tropospheric ozone anomalies are due to the negative lower stratospheric ozone anomalies or due to reduced amount of stratosphere-to-troposphere transport. Please clarify in the text.

As suggested, we have clarified this by adding: "In the nudged simulations (Fig. S3), the corresponding tropospheric O3S changes are much smaller than in the free-running simulations, suggesting the reduced transport has the dominant role in driving this response (see also Section 3.3), as opposed to just reduced lower stratospheric ozone levels."

Regarding the paragraph starting from Line 189: I feel that the cause-result relationship described here for temperature and zonal wind anomalies is not very clear to me. Is the following understanding of mine correct? If so, could you rewrite the text more clearly?

The main causes for the temperature anomalies are composition changes (that affect radiative heating/cooling distribution) and meridional circulation changes probably due mainly to natural variability. The zonal wind anomalies are primarily the immediate response (on monthly time scales) to the temperature anomalies through the thermal wind relationship, as it is a very strong constraint. Of course, changes in the zonal wind distribution would influence the meridional circulation through changes in the Rossby wave propagation, and changes in the meridional circulation would change the ozone distribution and thus influence temperature through radiative process; but these two may be considered as secondary.

(The main point here is that zonal wind anomalies could be just a reflection of the temperature anomalies through the thermal wind relationship.)

We agree that there is a strong two-way coupling between the temperature and circulation changes, and we revised the text to make that even more clear.

Section 3.4. Its title is "Radiative impacts . . .", but do the authors actually mean "Temperature impacts on ozone photochemistry"? This is because at Lines 345-347, the authors write about temperature dependence in the ozone chemistry. This might seem rather picky, but I think that the temperature anomalies here are probably due to both the radiative cooling due to increased water vapor and the changes in the meridional circulation (i.e. ascent anomalies), the latter of which is probably mainly due to natural variability. Note that ascent anomalies would result in both (1) adiabatic cooling and (2) less lower stratospheric ozone that leads to less solar heating on ozone there. If so, "Temperature impacts" rather than "Radiative impacts" would be more appropriate.

We agree with the reviewer, and as suggested we have changed “radiative impacts” to “temperature impacts” in the title of Section 3.4.

Lines 386-387: Could you clarify the causes of the cooling anomalies? More longwave cooling due to increased water vapor is one cause, but ascent anomalies (if they exist) lead to adiabatic cooling and less ozone and less solar heating on ozone.

We agree and have rephrased:

“The simulations show modest chemical ozone changes driven by anomalous chemical processing on aerosol surfaces and water-induced stratospheric cooling, including chlorine, bromine and nitrogen repartitioning. These changes manifest as ozone decreases in the lower stratosphere and ozone increases in the middle stratosphere. These chemical changes occur alongside dynamical contributions from altered circulation and ozone transport.”

To: “The simulations show modest chemical ozone changes driven by anomalous chemical processing - including chlorine, bromine and nitrogen repartitioning - on aerosol surfaces and stratospheric cooling from water-induced longwave emissions. These changes manifest as ozone decreases in the lower stratosphere and ozone increases in the middle stratosphere. These chemical changes occur alongside dynamical contributions from altered circulation, adiabatic heating/cooling and ozone transport.”

Line 395: It would be nice that the authors clarify a little bit more what are the dynamical processes here. They could be meridional circulation, zonal wind, transport (in particular, of ozone). Or, radiative processes are also included in this term implicitly?

We agree with the review but note that the dynamical processes are clarified earlier on in the same paragraph already, and that sentence has been now expanded following the reviewer’s comment above (“These chemical changes occur alongside dynamical contributions from altered circulation, adiabatic heating/cooling and ozone transport.”). Since we would like to avoid repetition within the same paragraph, we have decided to not re-state which dynamical processes are included on this line.

REVIEWER 2

General comments: The manuscript investigate uncertainties regarding the extent to which the unprecedented injection of water vapor into the stratosphere, alongside with aerosol precursors influenced the stratospheric ozone layer. The authors claim that the chemical contribution was as important as the dynamical contribution in determining the overall ozone response to the Hunga eruption in the southern extra-tropics, with anomalous chemical (chlorine, bromine and nitrogen) processing on aerosol surfaces under. The manuscript is well written and contains some interesting material, which should be published. I recommend publication after minor revisions of the following minor and specific points:

We thank the reviewer for the positive review and helpful comments that have improved the manuscript. We analyze the individual points below in blue.

Minor comments:

1. Recently the APARC HTHH report has been published and it is nice overview about the effort that scientists have put into the evaluation of HTHH impact. This report needs to be discussed.

We agree and have added a reference to the report in the introduction section: “The effort was undertaken in support of the recent APARC (Atmospheric Processes and their Role in Climate) Hunga Volcanic Eruption Atmospheric Impacts Report (APARC, 2025), which summarized the current scientific understanding of the eruption’s effects on the atmosphere and climate.”

2. It is important to consider that significant variability in wave and vortex dynamics in mid and high latitudes requires large ensembles to negate their impact on the ensemble means. While an ensemble size of 10 is larger than in most previous single model volcanic studies, it may still be insufficient for unambiguously identifying significant high-latitude responses to volcanic forcing. This introduces additional uncertainty to the response. Ideally, we would compare the difference in the HTHH response between 3 and 10 members in order to test the uncertainties associated with sample size. However, a more accurate result would require an ensemble size of over 50 members

We agree that understanding the role of interannual variability and ensemble size on the Hunga response is very important. We note, however, the manuscript already includes discussion and analysis of this in Section 3.3 and Figure 8 (restated here below). We have now modified the text slightly to make it even more clear this analysis constitutes part of the manuscript:

“**Below we focus on the contribution of** the large natural interannual variability characterizing the extra-tropical stratosphere. As shown in Bednarz et al. (2025) using the 30-member WACCM-MAM ensemble, the forced dynamical response to the Hunga eruption in both hemispheres is likely relatively weak compared to interannual variability. The role such large interannual variability plays in the diagnosed ozone response to Hunga is illustrated in Fig. 8 (again using the 30-member WACCM-MAM ensemble), exemplified by the Antarctic total column ozone response in September-October-November 2023. A total column ozone response of ~20 DU was diagnosed from the model based on all 30 members (black solid line), with half of it attributed to chemical changes (black dashed line**; as given by the corresponding nudged simulations**) and half to dynamical changes. **However, and importantly,** a very large spread of potential ozone responses **spanning both positive and negative values** is found if only a small subset of the ensemble is used for the diagnosis (blue and red lines). This suggests that (i) large model ensembles are needed to confidently diagnose the forced ozone response to the eruption, and (ii) such forced response is unlikely to be detectable in the observational record, which essentially constitutes just one realization.”

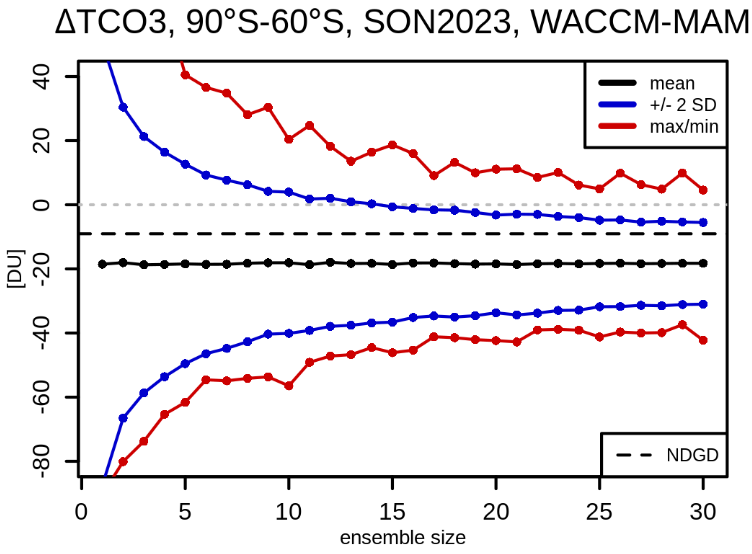
ΔTCO3, 90°S-60°S, SON2023, WACCM-MAM

Figure 8. Detectability of the September-October-November (SON) 2023 Antarctic total column ozone (TCO3) response in the free-running simulation with the simultaneous injection of SO_2 and H_2O in WACCM-MAM. Results obtained by randomly subsampling each ensemble with replacement to obtain 2000 artificial ensembles each of different ensemble size. Black lines denote the mean response, and blue and red lines indicate the ±2 standard deviation and the maximum/minimum ranges, respectively, of the possible responses. The dashed black line denotes the response obtained from the corresponding nudged simulation.