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# **Hunga Tonga-Hunga Ha'apai Volcano Impact Model Observation Comparison (HTHH-MOC) Project: Experiment Protocol and Model Descriptions**

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Y.Z. Concept design, Project Administration, Experiment design, data archive, WACCM model setup;

E.A. provides NOAA balloon aerosol and water vapor observations for experiments

E.B. Experiment design, conducts experiments using WACCM6MAM;

A.B. Experiment design, Data archive;

A.J. Experiment 2b prescribed fields preparation;

M.K. provides GloSSAC data for Exp 2b;

T.S. and S.W.: S.W. conducted all MIROC-CHASER experiments, data post-processing, data archive under supervision of T.S., who developed the aerosol microphysics scheme of the model.

X.W. and W.Y. Conducts experiment using WACCM6MAM;

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N.L., S.B. and M.K.: Conducts experiment using IPSL7-STRATAER, data post-processing and archive

M.M. and L.F.. Conducts experiment using IPSL7-STRATAER-REPROBUS, data post-processing and archive

S.R. and S.C. Conducts experiments using IFS-COMPOI

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F.F.Ø., G.K., O.M. contributed to experiment design

C.B. Conducts experiment using EMAC

I.Q., V.A., R.U. and A.K. Model output inspection and evaluation

E.F. Conducts experiments using GSFC2D, data post-processing, and data archive.

D.P. Contributed to experiment design and conducted experiments using CMAM and data post-processing

P.R.C., L.D.O., Q.L., M.M., and S.S. Contributed to experiment design and conducted experiments with the NASA GEOS CCM

H.A. and Y.Y. Conducts experiment using CCSRNIES-MIROC3.2, data post-processing and archive

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## **Abstract:**

The 2022 Hunga volcanic eruption injected a significant amount of water vapor and a moderate amount of sulfur dioxide into the stratosphere causing observable responses in the climate system. We have developed a model-observation comparison project to investigate the evolution of volcanic water and aerosols, and their impacts on atmospheric dynamics, chemistry, and climate. The project goals are: 1. Validate the current chemistry-climate models to have more confidence in their performance; and 2. Understand atmospheric responses in the Earth system after this exceptional event and investigate the potential impact in the projected future. To achieve these goals, we designed specific experiments for direct comparisons to observations, for example from balloons and the Microwave Limb Sounder satellite instrument. Experiment 1 is a free-running ensemble experiment from 2022 to 2031. Experiment 2 is a nudged-run experiment from 2022 to 2023. To allow participation of more climate models with varying complexities of aerosol simulation, we include two sets of simulations in Experiment 2: Experiment 2a is designed for models with internally-generated aerosol while Experiment 2b is designed for models using prescribed aerosol surface area density. We take model results from the previously

developed Tonga-MIP to fulfill Experiment 3, which focuses on the initial dispersion and microphysical evolution of aerosol and water plumes. Experiment 4 is designed to understand the climate impact on the mesosphere from 2022-2027, for which the experiment design is the same as Experiment 1 but for models that resolve the upper stratosphere and mesosphere.

## 1. Introduction and motivations of this project

The Hunga Tonga-Hunga Ha'apai (HTHH) Impacts activity was established in the World Climate Research Programme (WCRP) Atmosphere Processes And their Role in Climate (APARC) as a limited-term focused cross-activity with a duration of three years. It aims to assess the impacts of the 15 January 2022 Hunga volcanic eruption and produce an assessment to document the Hunga impact on the climate system. The Hunga eruption injected an unprecedented amount of water (H<sub>2</sub>O) and moderate sulfur dioxide (SO<sub>2</sub>) into the stratosphere (Millan et al., 2022), presenting a unique opportunity to understand the impacts on the stratosphere of a large-magnitude explosive phreatomagmatic eruption. The wide range of satellite observations of the stratospheric water and sulfate plumes, global transport and dispersion of volcanic materials, and unusual chemical and temperature signals are helpful in assessing model representations of stratospheric chemistry, aerosol, and dynamics. For example, the Aura Microwave Limb Sounder (MLS) observed ~150 Tg of water injected by the Hunga eruption (Millan et al., 2022), which slowly decayed due to the polar stratospheric cloud (PSC) dehydration process and stratosphere-troposphere exchange (Fleming et al., 2024; Zhou et al., 2024). Large aerosol optical depth are observed by Ozone Mapping and Profiler Suite (OMPS) (Taha et al., 2022), due to fast formation of sulfate (Zhu et al., 2022) and the high optical efficiency of Hunga aerosol particles (Li et al., 2024). Unlike the stratospheric warming patterns observed from previous large volcanic eruptions (El Chichón in 1982 and Pinatubo in 1991), global stratospheric temperatures decreased by 0.5 to 1.0 K in the first two years following the Hunga eruption, largely due to radiative cooling from injected water vapor (Randel et al., 2024). Satellite observations in June, July, August 2022 reveal reduced lower stratospheric ozone (O<sub>3</sub>) over the SH midlatitudes and subtropics, with high levels near the equator, exceeding previous variability. These ozone anomalies coincide with a weakening of the Brewer-Dobson circulation during this period (Wang et al., 2023). Changes in stratospheric winds also influence the mesosphere, leading to a stronger mesospheric circulation and corresponding temperature changes (Yu et al., 2023). These observed phenomena provide a unique opportunity to test the ability of chemistry-climate models to simulate the evolution of volcanic aerosols combined with such a large amount of water vapor, as well as understand how volcanic water vapor and aerosols modify radiative balances and stratospheric ozone.

The APARC HTHH Impacts activity aims to provide a benchmark analysis of the eruption impacts so far, and projections of eruption climate impacts over the next few years. To facilitate the success of this activity, we designed a multi-model evaluation project, the Hunga Tonga-Hunga Ha'apai Volcano Impact Model Observation Comparison (HTHH-MOC) Project. The HTHH-MOC provides a foundation for a coordinated multi-model evaluation of global chemistry-climate models' performance in response to the Hunga volcanic eruption. It defines a set of perturbation experiments, where volcanic forcings—injected water vapor and aerosol concentrations—are consistently applied across participating model members. HTHH-MOC aims to assess how reliably global chemistry-climate models simulate the climate responses to

this unprecedented volcanic forcing. This project enhances our confidence in attributing and interpreting observations following the Hunga eruption. The scientific questions related to the HTHH-MOC are: How does the Hunga volcanic plumes' transport relate to or impact stratospheric dynamics (such as Brewer-Dobson circulation, polar vortex and the Quasi-Biennial Oscillation) and upper atmosphere? What are the chemical impacts of the Hunga eruption in the stratosphere and mesosphere? What and how long is the radiative effect of the Hunga eruption? Does Hunga impact the tropospheric/surface climate?

Therefore, the HTHH-MOC project is focused on evaluating global chemistry-climate models regarding the following three science themes: (1) plume evolution, dispersion, and large-scale transport; (2) impacts on stratospheric chemistry and the ozone layer; and (3) radiative forcing from the eruption and surface climate impacts. Besides the HTHH-MOC project, the assessment also includes analysis of observations and models that are not global climate models. In the following paragraph, we describe the HTHH-MOC experiment design and participating models.

## 2. Experiment Design

There are four experiments designed to fulfill the scientific goals. Each experiment includes four kinds of simulations with different volcanic injections, to explore the separate impacts of volcanic water and aerosols during the post-eruption period: a) Control case (no eruption); b) H<sub>2</sub>O (~150 Tg) & SO<sub>2</sub> (0.5 Tg); c) Only H<sub>2</sub>O (~150 Tg). d) Only SO<sub>2</sub> (0.5 Tg). Simulations with the injection of SO<sub>2</sub> only (d) are optional and designed for aerosol-focused models. The SO<sub>2</sub> and water injections are prescribed based on Millan et al. (2022) and Carn et al. (2023). Note that ~150 Tg of water is not the injection amount but the amount retained after the first couple of days. This is because some models form ice particles that fall out of the stratosphere due to large H<sub>2</sub>O supersaturation during the initial injection (Zhu et al., 2022); these models will have to inject more H<sub>2</sub>O to counterbalance the ice formation (see **Table 7**). The only requirement is that the model should have reasonable comparison to the MLS observations for water vapor as shown in **Figure 1**. Aside from retaining ~150 Tg of water, the water vapor enhancement should be near 10 hPa to 50 hPa, and most of the water vapor should be located between 10°N and 30°S by March 2022.

The first experiment (**Exp1**) is a free-running ensemble simulation covering the period from 2022 to 2031. The experiment has been designed to answer questions on: 1. Understanding the long-term evolution of Hunga water vapor and aerosols in free-running models; 2. Quantifying Hunga effects on stratospheric temperatures, dynamics, and transport; 3. Understanding the impact of dynamic changes on ozone chemistry; 4. Quantifying the net radiative forcings; 5. Estimating surface impacts (e.g., temperature, El Niño-Southern Oscillation, monsoon precipitation, etc.). Simulations with free-running meteorology are required to properly understand the impacts of the eruption on atmospheric dynamics and transport processes, and the resulting impacts of those on chemical species (e.g., ozone) and surface climate. Since coupling of the atmosphere with ocean and land processes is required to fully simulate many aspects of the surface impacts, the use of coupled atmosphere, ocean, and land models is recommended. However, since such a fully interactive set up imposes additional computing requirements, an alternative model set up with fixed sea-surface temperatures (SSTs) and sea-ice is also allowed. In that case, the prescribed climatological SSTs and sea-ice data are obtained by averaging SST during the past decade (2012-2021), with the same data imposed in both the H<sub>2</sub>O+SO<sub>2</sub> (b) and control (a) simulations. It is important to note that both initial and

boundary conditions in a model come with uncertainties, and model processes are simplified. Therefore, model simulations are influenced by the characteristics of the model itself and the background state of the atmospheric system (Jones et al., 2016; Brodowsky et al., 2021). To address some of the inherent uncertainties and reduce contribution of interannual variability to the forced response, we use a large ensemble of simulations with slightly varied initial conditions.

Since some aspects of the response, e.g., impacts on the radiative forcing, may be too noisy from free-running model simulations even with large ensembles, we have also designed the second experiment which uses nudged temperature and meteorology to reduce the contribution of interannual variability and thus isolate chemical changes and their radiative forcing. Experiment 2 (**Exp2**) is a two-year simulation that runs from 2022 to 2023 with nudged winds and/or temperature to answer questions on H<sub>2</sub>O and aerosol evolution; quantification of the net radiative forcings; and impacts on mid-latitude and polar ozone chemistry. **Exp2** has two distinct realizations: Experiment 2a (**Exp2a**) and Experiment 2b (**Exp2b**). The models participating in **Exp2a** all have a prognostic aerosol module, but vary in the complexity of their representation of aerosol microphysics (i.e., bulk, modal, or sectional). Models participating in **Exp2b** use prescribed aerosol surface area density (SAD) and radiative properties as input to the models (Jörmann et al., 2024). The prescribed aerosol properties are calculated using Global sSpace-based Stratospheric Aerosol Climatology (GloSSAC; Thomason et al., 2018; Kovilakam et al., 2020, 2023) version 2.22 aerosol data from 1979-2023. Note that for the period after the Hunga eruption, GloSSAC uses the Stratospheric Aerosol and Gas Experiment (SAGEIII/ISS) version 5.3 interpolated along the time axis and the Optical Spectrograph and InfraRed Imager System (OSIRIS) version 7.3 to fill in any missing data poleward of 60° N/S due to the unavailability of the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) data since January 2022. Therefore, when conducting analyses north/south of 60°N/S it should be noted that the aerosols may be underestimated due to the OSIRIS instrument retrieval biases. We ask for the models to check their initial chemical fields against MLS to see if the models are qualified to evaluate their ozone chemistry. The nudged runs of **Exp2** enable isolation of the chemical impact of the Hunga eruption from the volcanically induced changes in dynamics by comparing the runs with and without H<sub>2</sub>O+SO<sub>2</sub> injection. The net radiative effect anomaly due to water and sulfate aerosol can also be calculated by comparing the control run (a) with the H<sub>2</sub>O+SO<sub>2</sub> injection run (b).

The third experiment (**Exp3**) is designed to explore the plume evolution between 1 day and up to 1 or 2 months after the eruption, including plume microphysics and chemistry. This experiment is adopted from TongaMIP (designed by Clyne et al., 2024), which has both free-running and nudged simulations to study the Hunga plume during the first three months after the eruption. All models are requested to inject 150 Tg of water but the retaining of the water varies between models, while other experiments here ask to retain ~150 Tg of water in the stratosphere. This is because for other experiments, our goal is to reproduce the long-term observations first and then to understand the Hunga climate impact; while **Exp3** is designed to understand the differences in physics processes (i.e., cloud and aerosol physics and sulfur chemistry) between models, expanding on findings from prior model intercomparison (Clyne et al., 2021; Quaglia et al., 2023) with upgraded and additional models. These experiments are detailed in Clyne et al. (2024).

The fourth experiment (**Exp4**) is a free-running ensemble simulation to understand climate impacts on the mesosphere and ionosphere from 2022-2027, such as gravity wave drag,



temperature changes, polar mesospheric clouds (PMCs), and atmospheric circulation. This experiment uses the first 5 years of **Exp1** and is limited to the models resolving the upper atmosphere.

**Table 1** shows the forcings and emissions data used for all experiments except for Experiment 3 (**Exp3**). **Table 2** shows the settings specific to each experiment. For volcanic injection for **Exp1, 2** and **4**, we recommend the injections of H<sub>2</sub>O and SO<sub>2</sub> at 4 UTC on Jan 15, 2022. All the models are required to retain a similar amount of water as observed by MLS (~ 150 Tg). The models are recommended to compare with the MLS evolution for validation (**Figure 1**). The goal is to retain the same amount of water and similar altitude to start with, so we can analyze the water's impact on the stratosphere and climate. If injecting 25-30 km cannot retain 150 Tg, models can inject higher than 30 km. The SO<sub>2</sub> injection is required to be 0.5 Tg for all models. The injection locations are not required to be co-injected with H<sub>2</sub>O.

The data analysis of this project is designed to do inter-model comparisons, as well as inter-experiment comparisons. For example, the comparisons between **Exp2a** and **Exp2b** can help to understand how well we simulate the sulfate SAD and the importance of SAD variation for stratospheric ozone chemistry. Comparing **Exp1** and **Exp2** for the same period can help understand radiative forcing and radiative effects. In addition, large (10-20) member ensembles are requested for free-running simulations to better quantify the role of internal variability in the climate response.

**Table 1. Summary of forcings and emissions data used in each experiment.**

|   |  |
|---|--|
| Spin-up*                                | 5 years nudged runs  |
| Degassing** and eruptive volcano source | Need both degassing and eruptive volcanic input for 5 year spin-up. Degassing continues during the experiment runs (e.g. 10 years for <b>Exp1</b> , 2 years for <b>Exp2</b> ). recommended references: Volcanic degassing Carn et al. (2017); Eruptive volcanoes (Neely III, & Schmidt (2016) <a href="https://archive.researchdata.leeds.ac.uk/96/">https://archive.researchdata.leeds.ac.uk/96/</a> or Carn et al. (2017); Assume no more explosive volcanoes after Hunga. |
| Surface emission                        | Coupled Model Intercomparison Project phase 6 (CMIP6) emissions follow SSP2-4.5 (Gidden et al., 2019), which adopts an intermediate greenhouse gas (GHG) emissions: CO <sub>2</sub> emissions around current levels before beginning to decline by 2050.   |
| Chemical initialization                 | Stratospheric chemistry fields (such as O <sub>3</sub> , H <sub>2</sub> O) at the beginning of 2022 should be compared with MLS observations for validation if the model participates in evaluation of the Hunga stratospheric chemistry impact.   |

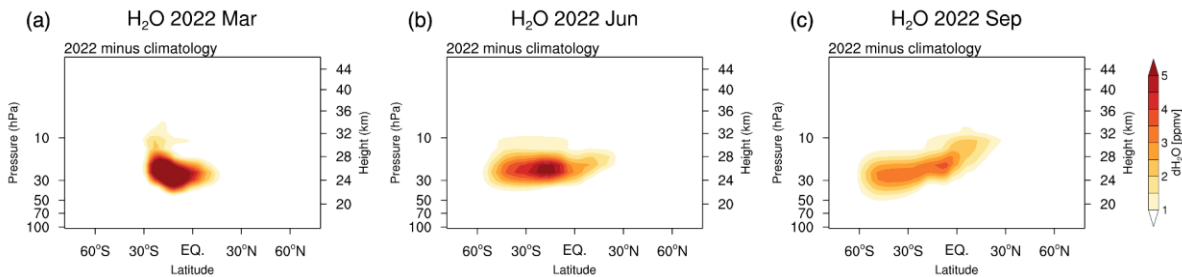
\* 5 years is enough to reach sulfate equilibrium in the stratosphere; water may take 7 years (each model should adjust the spin-up time according to model features). \*\* Recommended degassing volcanic emissions injected at the cone altitude, constant flux based on Carn et al. (2017). Database is updated through 2022 here: <https://doi.org/10.5067/MEASURES/SO2/DATA406>.

**Table 2. Experiment design**

| Experiment | Meteorology                | period             | aerosol treatment          | QBO                                | SST  | Ensemble members |
|------------|----------------------------|--------------------|----------------------------|------------------------------------|--|------------------|
| Exp1       | Free run starts Feb 1.     | 10 years 2022-2031 | model simulated aerosol or | Internal generated (Nudge if model | Fixed (climatology = mean of monthly average during the past decade (2012-2021), repeating annually) | 10-20            |
|            | (i.e. nudged until Jan 31) |                    | prescribed                 | doesn't generate)                  | Coupled ocean (optional) initialize with observed ocean state (see section 3 for                     | 10-20            |



|                   |   |                             |                         |               |               | individual model descriptions) |
|-------------------|---|-----------------------------|-------------------------|---------------|---------------|--------------------------------|
| Exp2a             | Nudged wind only and/or nudged T and wind*  | 2 years 2022-2023           | model simulated aerosol | nudged        | Observed SST  | -                              |
| Exp2b             | Nudged wind only and/or nudged T and wind*  | 2 years 2022-2023           | prescribed              | nudged        | Observed SST  | -                              |
| Exp3 (Tonga -MIP) | Both free run and nudged runs are conducted | 3 months after the eruption | model simulated aerosol | not specified | not specified | -                              |
| Exp4              | same as Exp1                                | 5 years 2022-2027           | same as Exp1            | same as Exp1  | same as Exp1  | same as Exp1                   |



**Figure 1.** Monthly average water vapor perturbation after the Hunga eruption from MLS. Panels (a-c) show the observed dispersion of the H<sub>2</sub>O enhancement in 2022 in the months of (a) March, (b) June, and (c) September.

### 3. Model output

The model output covers variables based on the Chemistry-Climate Modeling Initiative (CCMI) output list with some additions specific to this study. The detailed list is provided in the **Supplementary Excel Table**. We have requested that all models generate the same variable names, units, ordering of dimensions (longitude from 0°E to 360°E; latitude from 90°S to 90°N; pressure levels from 1000 hPa to 0.03 hPa or altitude from 0 meter to 85,000 meter), and file name structure (e.g. ‘variable\_domain\_modelname\_experimentname.nc’ or ‘domain\_modelname\_experimentname.variable.nc’). The examples of Experiment\_name are: HTHHMOC-Exp1, HTHHMOC-Exp1and4. The example file names are: Monthlymean\_WACCM6MAM\_HTHHMOC-Exp1and4-NoVolc-fixedSST.ensemble001.O3.nc or O3\_Dailymean\_WACCM6MAM\_HTHHMOC-Exp1and4-H2Oonly-fixedSST.ensemble001.nc.

The 3D model output is requested on both model levels (hybrid pressure or height) and interpolated to CMIP6 plev39 grid (plev39: 1000, 925, 850, 700, 600, 500, 400, 300, 250, 200, 170, 150, 130, 115, 100, 90, 80, 70, 50, 30, 20, 15, 10, 7, 5, 3, 2, 1.5, 1.0, 0.7, 0.5, 0.4, 0.3, 0.2,

0.15, 0.1, 0.07, 0.05, 0.03 hPa) and for Mesospheric analysis (**Exp4**) adding 0.02, 0.01, 0.007, 0.005, 0.003, 0.001 above the plev39 grid.

Monthly mean output is requested for all variables for both **Exp1** and **Exp4**, with some fields (specified in the Excel sheet) as daily mean. Some of the fields requested as daily means are specified, either as surface fields or at reduced number of pressure levels. Daily mean output is requested for all variables for **Exp2**.

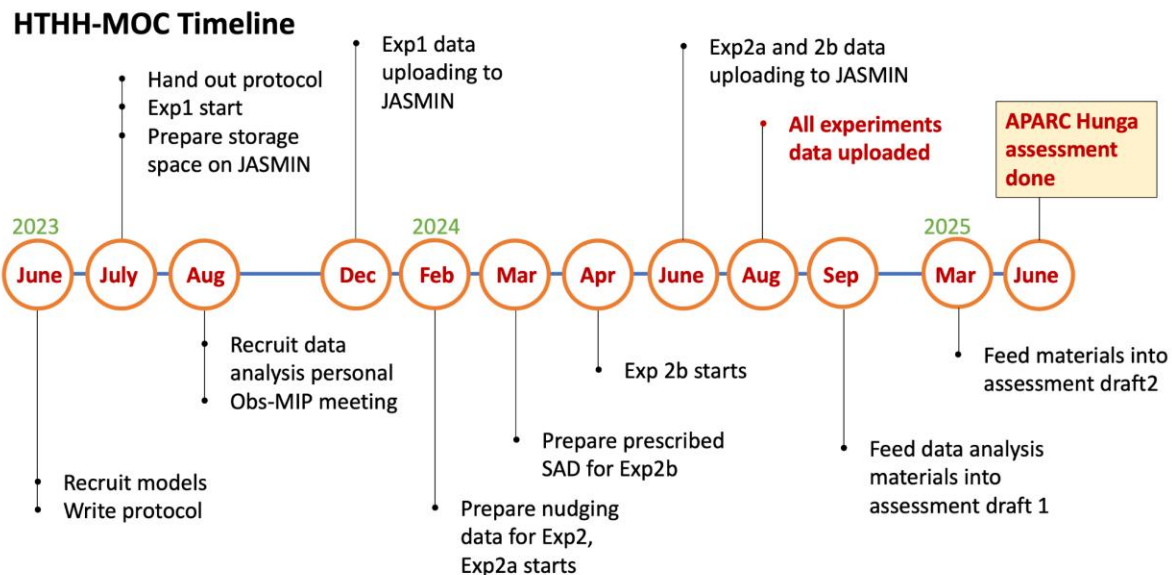
The model output (~33 TB) is archived at the JASMIN workspace (jasmin.ac.uk). JASMIN provides large storage space and compute facilities to facilitate the data archiving and post data analysis of this project. This reduces the need for data transfers and allows reproducible computational workflows. Seddon et al (2023) described the facility in detail. Our next phase is to publicly release the data by transferring the data to the Centre for Environmental Data Analysis (CEDA) archiving system.

#### 4. Model Descriptions and the Hunga Volcanic Injection Specification

As part of the three-year Hunga Impact activity, this project is highly time-sensitive. We designed the timeline for each experiment (**Figure 2**) to facilitate the completion of the 2025 Hunga Impact assessment. However, the JASMIN workspace will remain open for the uploading of modeling data after the deadline denoted in **Figure 2** until 2025.

This paper only includes model descriptions for those models that submitted the output following the assessment timeline. The model setup follows the protocols listed in Section 2 unless specified below. **Tables 4-7** provide key information on the participant models, which are detailed described in the following paragraphs for each model.

Three models participated only in **Exp3** (Tonga-MIP) and not in the other experiments: for the descriptions of these three models (MIROC-ES2H, SOCOLv4, and GA4 UM-UKCA) we refer to Clyne et al. (2024).



**Figure 2.** The timeline designed for HTHH-MOC in order to cooperate with the APARC HTHH Impact assessment.

**Table 4. Participating models and contact information**

| Model name   | Description reference paper                         | Institutions (that develop the model)                       | Primary contact (who runs the model)  | Emails   |
|--|---|---|---|--|
| CAM5/CARMA   | Yu et al. (2015)                                    | CU Boulder<br>Jinan Univ.                                   | Pengfei Yu<br>Yifeng Peng   | <a href="mailto:pengfei.yu@colorado.edu">pengfei.yu@colorado.edu</a><br><a href="mailto:pengyf16@lzu.edu.cn">pengyf16@lzu.edu.cn</a>   |
| CCSRNIES-<br>MIROC3.2                                      | Akiyoshi et al. (2023),<br>Akiyoshi et al. (2016)   | NIES  | Yousuke Yamashita<br>Hideharu Akiyoshi                                      | yamashita.yosuke@nies.go.jp<br>hakiyosi@nies.go.jp   |
| CMAM   | Jonsson et al. (2004),<br>Scinocca et al. (2008)    | CCCma,<br>Environment and Climate Change Canada             | David Plummer   | david.plummer@ec.gc.ca   |
| EMAC MPIC  | Schallock et al. (2023)                             | MPI-C, -M,<br>DLR   | Christoph Brühl   | christoph.bruehl@mpic.de   |
| GA4 UM-UKCA  | Dhomse et al. (2020)                                | Univ. Leeds   | Graham Mann,<br>Sandip Dhomse   | <a href="mailto:G.W.Mann@leeds.ac.uk">G.W.Mann@leeds.ac.uk</a> ,<br><a href="mailto:S.S.Dhomse@leeds.ac.uk">S.S.Dhomse@leeds.ac.uk</a>   |
| GEOSCCM  | Nielsen et al. (2017)                               | NASA  | Peter Colarco   | peter.r.colarco@nasa.gov   |
| GEOS/CARMA   | Nielsen et al. (2017)                               | NASA  | Parker Case   | parker.a.case@nasa.gov   |
| GSFC2D   | Fleming et al. (2020)                               | NASA  | Eric Fleming  | eric.l.fleming@nasa.gov  |
| IFS-COMPO<br>Cy49R1  | Huijnen et al. (GMD, 2016), Rémy et al. (GMD, 2022) | ECMWF and team<br>CAMS2_35                                  | Simon Chabrilat<br>Samuel Rémy  | Simon.chabrilat@aeronomie.be<br>sr@hygeos.com  |
| IPSLCM7-<br>STRATAER/<br>IPSLCM7-<br>STRATAER-<br>REPROBUS | O. Boucher et al. 2020,<br>Marchand et al., 2012    | CNRS,<br>Sorbonne Université,<br>IPSL,<br>LATMOS,<br>LOCEAN | Marion Marchand,<br>Slimane Bekki,<br>Nicolas Lebas,<br>Lola Falletti       | marion.marchand@latmos.ipsl.fr,<br><a href="mailto:slimane.bekki@latmos.ipsl.fr">slimane.bekki@latmos.ipsl.fr</a> ,<br><a href="mailto:nicolas.lebas@locean.ipsl.fr">nicolas.lebas@locean.ipsl.fr</a> ,<br><a href="mailto:lola.falletti@latmos.ipsl.fr">lola.falletti@latmos.ipsl.fr</a>    |
| MIROC-CHASER   | Sekiya et al. (2016)                                | JAMSTEC   | Shingo Watanabe,<br>Takashi Sekiya  | wnabe@jamstec.go.jp,<br>tsekiya@jamstec.go.jp  |
| MIROC-ES2H   | Tatebe et al. (2019),<br>Kawamiya et al. (2020)     | JAMSTEC and<br>NIES   | Shingo Watanabe,<br>Takashi Sekiya,<br>Tatsuya Nagashima,<br>Kengo Sudo     | wnabe@jamstec.go.jp,<br>tsekiya@jamstec.go.jp,<br><a href="mailto:nagashima.tatsuya@nies.go.jp">nagashima.tatsuya@nies.go.jp</a> ,<br>kengo@nagoya-u.jp  |
| SOCOLv4  | Sukhodolov et al. (2021)                            | PMOD/WRC<br>and ETH-<br>Zurich                              | Timofei Sukhodolov  | timofei.sukhodolov@pmodwrc.ch  |
| WACCM6/CARM<br>A   | Tilmes et al. (2023)                                | NCAR  | Simone Tilmes<br>Cheng-Cheng Liu<br>Yunqian Zhu<br>Margot Clyne-<br>(Exp 3) | <a href="mailto:tilmes@ucar.edu">tilmes@ucar.edu</a><br><a href="mailto:chengcheng.liu@lasp.colorado.edu">chengcheng.liu@lasp.colorado.edu</a><br><a href="mailto:yunqian.zhu@noaa.gov">yunqian.zhu@noaa.gov</a><br><a href="mailto:margot.clyne@colorado.edu">margot.clyne@colorado.edu</a> |
| WACCM6/MAM   | Mills et al. (2016)                                 | NCAR  | Xinyue Wang<br>Simone Tilmes<br>Jun Zhang<br>Wandi Yu                       | xinyuew@colorado.edu<br>tilmes@ucar.edu<br>jzhan166@ucar.edu<br>yu44@llnl.gov  |

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**Table 5. Participating models for each experiment.**

| Model names                       | Exp1                    | Exp1/4<br>(coupled ocean) | Exp2a    | Exp2b    | Exp3<br>(Tonga-MIP) | Exp4                   |
|-----------------------------------|-------------------------|---------------------------|----------|----------|---------------------|------------------------|
| CAM5/CARMA                        |                         |                           | <b>X</b> |          |                     |                        |
| CCSRNIES-<br>MIROC3.2             |                         |                           |          | <b>X</b> |                     |                        |
| CMAM                              | <b>X</b> (H2O-<br>only) |                           |          |          |                     | <b>X</b><br>(H2O-only) |
| EMAC MPIC                         |                         |                           | <b>X</b> |          |                     |                        |
| GA4 UM-UKCA                       |                         |                           |          |          | <b>X</b>            |                        |
| GEOSCCM                           | <b>X</b>                |                           | <b>X</b> |          | <b>X</b>            |                        |
| GEOS/CARMA                        |                         |                           | <b>X</b> |          |                     |                        |
| GSFC2D                            | <b>X</b>                |                           |          | <b>X</b> |                     | <b>X</b>               |
| IFS-COMPO                         |                         |                           | <b>X</b> |          |                     |                        |
| IPSLCM7-<br>STRATAER              |                         |                           | <b>X</b> |          | <b>X</b>            |                        |
| IPSLCM7-<br>STRATAER-<br>REPROBUS |                         |                           | <b>X</b> |          | <b>X</b>            |                        |
| MIROC-<br>CHASER                  | <b>X</b>                |                           | <b>X</b> |          |                     |                        |
| MIROC-ES2H                        |                         |                           |          |          | <b>X</b>            |                        |
| SOCOLv4                           |                         |                           |          |          | <b>X</b>            |                        |
| WACCM6/CAR<br>MA                  |                         |                           | <b>X</b> |          | <b>X</b>            |                        |
| WACCM6/MA<br>M                    | <b>X</b>                | <b>X</b>                  | <b>X</b> |          | <b>X</b>            | <b>X</b>               |

**Table 6. Model resolutions and schemes used for experiments except for Exp3 (Tonga-MIP)**

| Model names           | Horizontal resolution | nlevels | Model Top   | Vertical resolution in the stratosphere | Aerosol scheme           | Specified dynamic source | QBO for free fun             | Chemistry package (tropospheric chemistry included?) |
|-----------------------|-----------------------|---------|-------------|---|--------------------------|--------------------------|------------------------------|--|
| CAM5/CARM<br>A        | ~2 deg                | 56      | 45 km       | 1-4 km                                  | CARMA sectional(20 bins) | GEOS5                    | -                            | MOZART (yes)   |
| CCSRNIES-<br>MIROC3.2 | T42                   | 34      | 0.01 hPa    | 1-3 km                                  | None                     | MERR A-2                 | nudged                       | full strat; no tropo                                 |
| CMAM                  | T47                   | 80      | 0.00 06 hPa | 0.8 - 2.5 km                            | None                     | ERA5                     | nudged                       | stratospheric + methane-NOx in troposphere           |
| EMAC MPIC             | T63                   | 90      | 0.01 Pa     | 0.5km in LS                             | GMXE, modal              | ERA-5                    | Internal but slightly nudged | MECCA, simplified troposphere                        |
| GEOSCCM               | c90 (~1               | 72      | 0.01        | ~1 km                                   | GOCA                     | MERR                     | Internal                     | GMI (yes)  |

|                                   |                               |     |                                |               |                                 |                             |                       |   |
|-----------------------------------|-------------------------------|-----|--------------------------------|---------------|---------------------------------|-----------------------------|-----------------------|---|
|                                   | deg)                          |     | hPa                            |               | RT<br>(Bulk)                    | A-<br>2/GEOS<br>-FP         | generated             |   |
| GEOS/CARMA                        | c90 (~1<br>deg)               | 72  | 0.01<br>hPa                    | ~1 km         | CARMA<br>(sectional<br>24 bins) | MERR<br>A-<br>2/GEOS<br>-FP | Internal<br>generated | GMI (yes)                                 |
| GSFC2D                            | 4°                            | 76  | .002<br>hPa<br>(~<br>92<br>km) | 1km           | Prescri<br>bed<br>only          | MERR<br>A-2                 | Internal<br>generated | full strat;<br>partial trop               |
| IFS-COMPO                         | T <sub>L</sub> 511<br>(~40km) | 137 | 0.01<br>hPa                    | 0.5-1.5<br>km | Bulk                            | ERA5                        | -                     | BASCOE<br>(strato) + CB05<br>(tropo)      |
| IPSLCM7-<br>STRATAER              | 2.5° ×<br>1.3°                | 79  | 80k<br>m                       | 1-5 km        | S3A(sect<br>ional 36<br>bins)   | ERA5                        | Internal<br>generated | No  |
| IPSLCM7-<br>STRATAER-<br>REPROBUS | 2.5° ×<br>1.3°                | 79  | 80k<br>m                       | 1-5 km        | S3A(sect<br>ional 36<br>bins)   | ERA5                        | Internal<br>generated | REPROBUS                                  |
| MIROC-<br>CHASER                  | T85                           | 81  | 0.00<br>4<br>hPa               | 0.7-1.2<br>km | MAM<br>3                        | MERR<br>A-2                 | Internal<br>generated | troposphere-<br>stratosphere<br>chemistry |
| WACCM6/CA<br>RMA                  | ~1 deg                        | 70  | 140<br>km                      | 1-2 km        | Sectional<br>(20 bins)          | MERRA-<br>2                 | Internal<br>generated | MOZART (yes)                              |
| WACCM6/MA<br>M                    | ~1 deg                        | 70  | 140<br>km                      | 1-2 km        | MAM4                            | MERRA-<br>2                 | Internal<br>generated | MOZART (yes)                              |

**Table 7. Hunga volcanic injection profile for experiments except for Exp3 (Tonga-MIP)**

| Model names                   | Data and duration    | H <sub>2</sub> O amount (left after a week) | H <sub>2</sub> O altitude          | H <sub>2</sub> O location/area | SO <sub>2</sub> amount     | SO <sub>2</sub> altitude     | SO <sub>2</sub> location/area   |
|-------------------------------|----------------------|---|------------------------------------|--------------------------------|----------------------------|------------------------------|---------------------------------|
| CAM5<br>/CAR<br>MA            | Jan 15,<br>6 hrs     | 150 Tg<br>(~135 Tg)                         | 25-35 km                           | 22-14°S, 182-<br>186°E         | 0.5 Tg                     | 20-28 km                     | 22-14°S,<br>182-186°E           |
| CCSR<br>NIES-<br>MIRO<br>C3.2 | Jan 15,<br>instantly | 150 Tg<br>(~150 Tg)                         | 12.0-27.6 hPa                      | 181.4–187.0°E,<br>14.0–22.3°S  | -                          | -                            | -                               |
| CMA<br>M                      | Feb 20,<br>5 days    | 150 Tg<br>(~150 Tg)                         | near 25.5 km                       | zonally average                | -                          | -                            | -                               |
| EMAC<br>MPIC                  | Jan 16,<br>12hrs     | 136 Tg<br>(~130 Tg)                         | Gaussian<br>centered at<br>21.5hPa | 23-19°S, 177-<br>173°W         | 0.4 Tg<br>based<br>on obs. | 23-27 km<br>based on<br>obs. | 30°S-5°N,<br>90-120°W<br>(330°) |
| GEOS<br>CCM                   | Jan 15,<br>6 hrs     | 750 Tg<br>(~150 Tg)                         | 25-30 km                           | 22-14°S, 182-<br>186°E         | 0.5 Tg                     | 25-30 km                     | 22-14°S,<br>182-186°E           |
| GEOS/<br>CARM<br>A            | Jan 15,<br>6 hrs     | 750 Tg<br>(~150 Tg)                         | 25-30 km                           | 22-14°S, 182-<br>186°E         | 0.5 Tg                     | 25-30 km                     | 22-14°S,<br>182-186°E           |

|   |   |                      |  |  |        |  |  |
|---|---|----------------------|--|--|--------|--|--|
| GSFC<br>2D                                    | use<br>MLS<br>H <sub>2</sub> O<br>profile<br>until<br>March 1 | ~150 Tg<br>(~150 Tg) | -  | zonally average                                | -      | -  | -  |
| IFS-<br>COMP<br>O                             | Jan 15,<br>3 hrs  | 190 Tg<br>(~150 Tg)  | 25-30 km   | 400 km by 200<br>km centered<br>20°S and 175°W | 0.5 Tg | 25-30 km   | 400 km by<br>200 km<br>centered<br>20°S and<br>175°W |
| IPSLC<br>M7-<br>STRA<br>TAER                  | Jan 15,<br>1 day  | 150 Tg<br>(~150 Tg)  | Gaussian<br>centered at 27.5<br>km and standard<br>deviation of 2.5<br>km                            | 22°-14°S, 182-<br>186°E                        | 0.5 Tg | Gaussian<br>centered at<br>27.5 km<br>and<br>standard<br>deviation of<br>2.5 km                            | 22-14°S,<br>182-186°E                                |
| IPSLC<br>M7-<br>STRA<br>TAER-<br>REPR<br>OBUS | Jan 15,<br>1 day  | 150 Tg<br>(~150 Tg)  | at 27.5 km<br>altitude using a<br>Gaussian<br>distribution and<br>standard<br>deviation of 2.5<br>km | 22-14°S, 182-<br>186°E                         | 0.5 Tg | at 27.5 km<br>altitude<br>using a<br>Gaussian<br>distribution<br>and<br>standard<br>deviation of<br>2.5 km | 22-14°S,<br>182-186°E                                |
| MIRO<br>C-<br>CHAS<br>ER                      | Jan 15<br>4 UTC,<br>6 hours                                   | 186 Tg<br>(~150 Tg)  | 25-30 km   | 22-14°S, 182-<br>186°E                         | 0.5 Tg | 25-30 km   | 22-14°S,<br>182-186°E                                |
| WAC<br>CM6/<br>CARM<br>A                      | Jan 15,<br>6 hours  | 150 Tg<br>(~135 Tg)  | 25-35 km   | 22-14°S, 182-<br>186°E                         | 0.5 Tg | 20-28 km   | 22-14°S,<br>182-186°E                                |
| WAC<br>CM6/<br>MAM                            | Jan 15,<br>6 hours  | 150 Tg<br>(~150 Tg)  | 25-35km  | 22-6°S, 182.5 -<br>202.5°E                     | 0.5 Tg | 26.5-36 km   | 22-<br>6°S, 182.5 -<br>202.5°E                       |

#### 4.1 CAM5/CARMA

The atmospheric component of the Community Atmosphere Model version 5 (CAM5) (Lamarque et al., 2012) is the atmospheric component of the Community Earth System Model, version 1 (CESM1.2.2, Hurrell et al., 2013), with a top at around 45 km. CAM5 has a horizontal resolution of 1.9° latitude × 2.5° longitude, utilizing the finite volume dynamical core (Lin & Rood, 1996). The model has 56 vertical levels, with a vertical resolution ~1 km in the upper troposphere and lower stratosphere. The modeled winds and temperatures were nudged to the 3-hour Goddard Earth Observing System 5 (GEOS-5) reanalysis data set (Molod et al., 2015) every time step (30 min) by 1% (i.e., a 50 h Newtonian relaxation time scale). The aerosol is interactively simulated using a sectional aerosol microphysics model, the Community Aerosol and Radiation Model for Atmospheres (CARMA, Yu et al., 2015). The model uses the Model for Ozone and Related Chemical Tracers (MOZART) chemistry that is used for both tropospheric (Emmons et al., 2010) and stratospheric chemistry (English et al., 2011; Mills et al., 2016). The

volcanic emissions from continuously degassing volcanoes uses the emission inventory RCP8.5 and FINNv1.5. No volcanic eruptions except the Hunga 2022 eruption are included.

The initial volcanic injection altitude and area are determined by validating the water and aerosol transportation in months shown in **Figure 1** following the tests in Zhu et al. (2022), Wang et al. (2023) and Zhang et al. (2024). In these simulations, the H<sub>2</sub>O is injected at 25 to 35 km altitude and SO<sub>2</sub> injected at 20 to 28 km altitude. The injection latitude ranges from 22°S to 14°S, and longitude ranges from 182°E to 186°E (Zhu et al., 2022). The initial injection of H<sub>2</sub>O is 150 Tg, with ~ 135 Tg left after the first week following the eruption.

#### 4.2 CCSRNIES-MIROC3.2

The Center for Climate System Research/National Institute for Environmental Studies - Model for Interdisciplinary Research on Climate version 3.2 Chemistry Climate Model (CCSRNIES-MIROC3.2 CCM) (Akiyoshi et al. 2023) was developed based on versions 3.2 of the MIROC atmospheric general circulation model (AGCM), incorporating a stratospheric chemistry module that was developed at National Institute for Environmental Studies (NIES) and the University of Tokyo. The model has a horizontal resolution of T42 (2.8° latitude × 2.8° longitude) and 34 vertical levels, with a vertical resolution ~1 km in the lower stratosphere/upper troposphere and ~3 km in the upper stratosphere and mesosphere. The top level is located at 0.01 hPa (approximately 80 km).

The chemistry in the CCSRNIES-MIROC3.2 CCM is a stratospheric chemistry module including 42 photolysis reactions, 142 gas-phase chemical reactions and 13 heterogeneous reactions for multiple aerosol types (Akiyoshi et al., 2023). Tropospheric chemistry is not included, but the stratospheric chemistry scheme is used for both the troposphere and mesosphere.

In the CCSRNIES-MIROC3.2 CCM, only **Exp2b** can be performed. The atmospheric temperature and horizontal winds are nudged toward Modern-Era Retrospective analysis for Research and Applications Version 2 (MERRA-2) reanalysis (Gelaro et al., 2017) with a 1-day relaxation using instant values at 6-hour interval (Akiyoshi et al., 2016). The HadISST data is used during the simulation.

The CCSRNIES-MIROC3.2 CCM does not have any microphysics scheme for volcanic aerosols. The surface area and spectral optical parameters of extinction, single scattering albedo, and asymmetric factor for Hunga aerosols were prescribed in the model from the GloSSAC version 2.22 aerosol data (Jörmann et al., 2024). H<sub>2</sub>O was injected instantly on 15 January 2022 at the 12 grids of the model in the region 181.4°E–187.0°E in longitude, 14.0°S–22.3°S in latitude, and 12.0 hPa–27.6 hPa in pressure level. A uniform number density of  $1.709 \times 10^{15}$  molecules/cm<sup>3</sup> H<sub>2</sub>O was injected in each of the 12 grids which amounts to ~150 Tg.

#### 4.3 CMAM

The Canadian Middle Atmosphere Model (CMAM) is based on a vertically extended version of CanAM3.1, the third generation Canadian Atmospheric Model (Scinocca et al., 2008). Compared to the standard configuration of CanAM3.1, for CMAM the model top was raised to 0.0006 hPa (approximately 95 km) and the parameterization of non-orographic gravity wave drag (Scinocca, 2003) and additional radiative processes important in the middle atmosphere (Fomichev et al., 2004) have been included. The gas-phase chemistry includes a comprehensive description of the inorganic Ox, NO<sub>x</sub>, HO<sub>x</sub>, ClO<sub>x</sub> and BrO<sub>x</sub> families, along with CH<sub>4</sub>, N<sub>2</sub>O, six chlorine containing halocarbons, CH<sub>3</sub>Br and, to account for an additional 5 ppt of bromine from



short-lived source gases,  $\text{CH}_2\text{Br}_2$  and  $\text{CHBr}_3$  (Jonsson et al., 2004). A prognostic description of, and associated heterogeneous chemical reactions on water ice PSCs (PSC Type II) and liquid ternary solution (PSC Type Ib) particles is included, although gravitational settling (dehydration/denitrification) is not calculated and species return to the gas phase when conditions no longer support the existence of PSC particles.

The simulations for the HTHH-MOC simulations were performed at T47 spectral resolution (approximately  $3.8^\circ$  resolution on the linear transform grid used for the model physics), with 80 vertical levels giving a vertical resolution of approximately 0.8 km at 100 hPa, increasing to 2.3 km above 0.1 hPa. The CMAM does not internally generate a QBO, so the zonal winds in the equatorial region were nudged towards a dataset based on observed variations up to December 2023, constructed using the method of Naujokat (1986) and extended into the future by repeating a historical period that is congruent with the observed QBO in late 2023. Water vapor from the Hunga eruption was added as a zonally average perturbation to the model water over five days from 00 UTC on February 20, 2022. The spatial distribution of the anomaly was designed to reproduce the water vapor anomaly observed in mid-February by the The Atmospheric Chemistry Experiment - Fourier Transform Spectrometer (ACE-FTS) (Bernath et al., 2005) satellite (Patrick Sheese, personal communication), with a maximum value of 13.3 ppm at  $17^\circ\text{S}$  and 25.5 km and producing an anomaly of  $\sim 150$  Tg  $\text{H}_2\text{O}$  in the stratosphere.

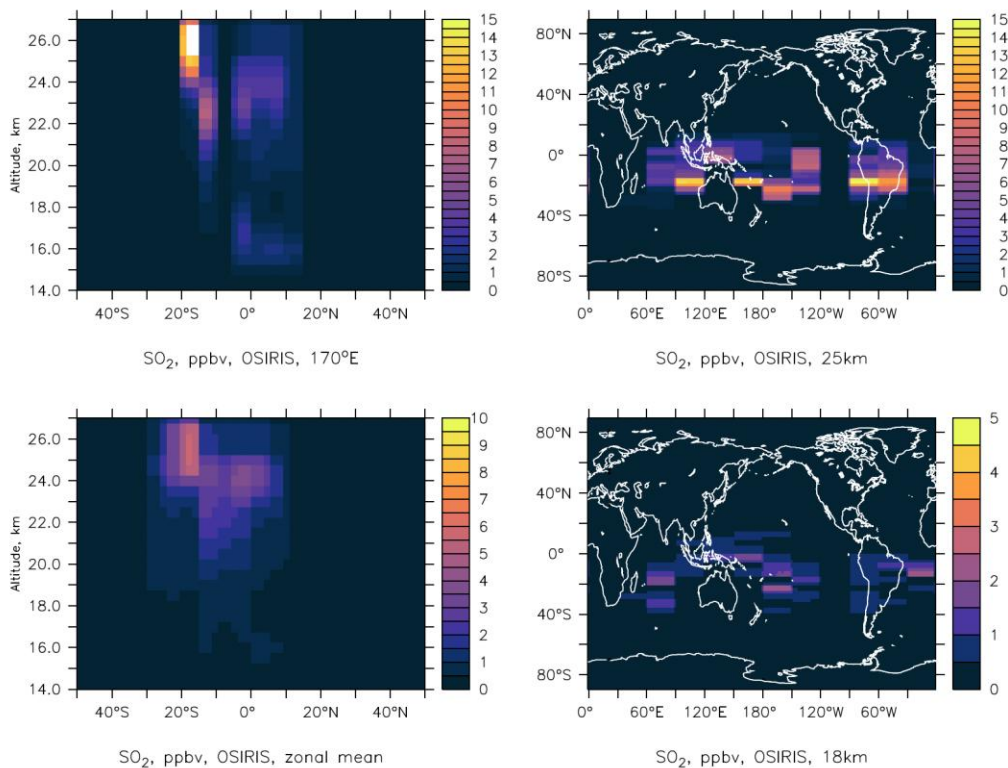
#### 4.4 EMAC MPIC

The chemistry-climate model EMAC (ECHAM5/MESSy Atmospheric Chemistry) consists of the European Centre Hamburg general circulation model (ECHAM5) and the Modular Earth Submodel System (MESSy) (e.g., Jöckel et al., 2010). Here we use the version of Schallock et al. (2023) in horizontal resolution T63 ( $1.87^\circ \times 1.87^\circ$ ) with 90 levels between the surface and 0.01 hPa.

Vorticity, divergence, and temperatures between boundary layer and 100 hPa are nudged to the reanalysis ERA5 (Hersbach et al., 2020), as well as surface pressure. SSTs and sea ice cover are prescribed by ERA5 data. The model can generate an internal QBO but for comparison with observations it was slightly nudged to the Singapore data compiled by Free University of Berlin and Karlsruhe Institute of Technology.

The model contains gas-phase and heterogeneous chemistry on PSCs and interactive aerosols. Surface mixing ratios of chlorine- and bromine-containing halocarbons and other long-lived gases are nudged to Advanced Global Atmospheric Gases Experiment (AGAGE) observations. The microphysical modal aerosol module contains four soluble and three insoluble modes for sulfate, nitrate, dust, organic and black carbon, and aerosol water (Pringle et al., 2010). The instantaneous radiative forcing by tropospheric and stratospheric aerosols can be calculated online by multiple calls of the radiation module. Volcanoes injecting material into the stratosphere are considered as in Schallock et al. (2023) using the perturbations of stratospheric  $\text{SO}_2$  observed by the Michelson Interferometer for Passive Atmospheric Sounding (MIPAS) and aerosol extinction observed by OSIRIS. This method, based typically on data of a 10-day period, distributes the injected  $\text{SO}_2$  over a larger volume than typical point source approaches using the same integrated mass (see also Kohl et al., 2024). For Hunga this method has the disadvantage that  $\text{H}_2\text{O}$  and  $\text{SO}_2$  are not co-injected since  $\text{H}_2\text{O}$  is injected in 12 hours in a slab consisting of four horizontal boxes and a Gaussian vertical distribution centered at 21.5 hPa. For **Exp2a** we continue the 30-year transient simulation presented in Schallock et al. (2023) with and without Hunga Tonga. The simulated  $\text{H}_2\text{O}$ -perturbation is consistent with **Figure 1**. The  $\text{SO}_2$  injection is

derived based on the extinction from the OSIRIS observation averaged over about 10 days (**Figure 3**) (Bruehl et al., 2023).



**Figure 3.** The  $\text{SO}_2$  perturbation from Hunga derived from extinction observed by OSIRIS (averaged over about 10 days, i.e. including several snapshots of the westward moving plume).

#### 4.5 GEOSCCM

The NASA Goddard Earth Observing System Chemistry-Climate Model (GEOSCCM) is based on the GEOS Earth system model (Reinecker et al. 2008, Molod et al. 2015). For the HTHH-MOC experiments the model is run on a cubed-sphere horizontal grid at a C90 resolution (~100 km) with 72 vertical hybrid-sigma levels from the surface to 0.01 hPa (~80 km). Dynamics are solved using the finite-volume dynamical core (Putman and Lin, 2007). Deep and shallow convection are parameterized using the Grell-Freitas (2014) and Park-Bretherton (2009) schemes, respectively, and moist physics is from Bacmeister et al. (2006). The turbulence parameterization is based on the non-local scheme of Lock et al. (2000). Shortwave and longwave radiative fluxes are computed in 30 bands using the Rapid Radiative Transfer Model for GCMs (RRTMG, Iacono et al. 2008).

Stratospheric and tropospheric chemistry are from the Global Modeling Initiative (GMI) mechanism (Duncan et al., 2007; Strahan et al., 2007; Nielsen et al., 2017), updated here to include reactions for sulfur species. The GMI mechanism in GEOSCCM has been extensively evaluated for its stratospheric ozone-related photochemistry and transport in various model intercomparisons, including Stratosphere-troposphere Processes and their Role in Climate (SPARC) Chemistry Climate Model Validation (CCMVal), CCMVal-2, and the CCMi (SPARC-CCMVal, 2010; Eyring et al., 2010, 2013; Morgenstern et al., 2017). Aerosol species are simulated by the Goddard Chemistry, Aerosol, Radiation, and Transport, second generation

(GOCART-2G), module (Collow et al. 2024), which includes a sectional approach for dust (five bins), sea salt (five bins), and nitrate (three bins), and a bulk approach for sulfate (dimethyl sulfide, SO<sub>2</sub>, methanesulfonic acid, and SO<sub>4</sub><sup>2-</sup>) aerosol and carbonaceous species (hydrophobic and hydrophilic modes of “white” and “brown” organics and black carbon).

For the GEOSCCM simulations performed with the GOCART-2G module we use the nominal GOCART-2G sulfate mechanism, updated here to use the online hydroxyl (OH) radical, nitrate (NO<sub>3</sub>) radical, and hydrogen peroxide (H<sub>2</sub>O<sub>2</sub>) from the GMI mechanism instead of climatological fields provided from offline files (Collow et al., 2024). While not a full coupling to the GMI sulfur cycle it nevertheless allows the GOCART-2G sulfate mechanism to have the impact of the Hunga water vapor perturbation on the oxidants. A second “instance” of the GOCART-2G sulfate mechanism is run that is specifically for the volcanic SO<sub>2</sub> and resultant sulfate from the Hunga eruption. This allows us to track the eruptive volcanic aerosol separately from the nominal sulfate instance that sees mainly tropospheric sources. We assign this volcanic instance optical properties consistent with SAGE retrievals of the sulfate aerosol properties, using an effective radius of 0.4 microns. We find that 750 Tg of H<sub>2</sub>O is needed in the initial injection to provide a residual ~150 Tg of water in the stratosphere after a week. All other injection parameters follow the protocol. The model spinup was performed by “replaying” to the MERRA-2 meteorology (Gelaro et al. 2017), and is used throughout the **Exp2a** results.

#### 4.6 GEOS/CARMA

A second configuration of the GEOSCCM, coupled to the sectional aerosol microphysics package CARMA, also simulated the eruption (GEOS/CARMA). This configuration is the same as above except for the aerosol package and its coupling to the GMI chemistry mechanism. For this version of GEOSCCM, we use the configuration of CARMA described in Case et al. (2023). This configuration uses 24 size bins, spread logarithmically in volume between 0.25nm and 6.7µm in radius and simulates the nucleation, condensational growth, evaporation, coagulation, and settling of sulfate aerosols in these simulations following the mechanism of English et al. (2013). For these simulations, CARMA is fully coupled to the GMI sulfur cycle by the production (i.e., oxidation of SO<sub>2</sub>, evaporation of sulfate aerosols) and loss (i.e., nucleation and condensation of sulfate aerosols) of sulfuric acid (H<sub>2</sub>SO<sub>4</sub>) vapor. Optical properties for the CARMA aerosols are calculated based on the interactively calculated aerosol size distribution. The same injection parameters for GEOSCCM described above are used by this configuration. This model configuration contributed to **Exp2a** and “replayed” to MERRA-2 meteorology as above.

#### 4.7 GSFC2D

The NASA/Goddard Space Flight Center two-dimensional (2D) chemistry-climate model (GSFC2D) has a domain extending from the surface to ~92 km (0.002 hPa). The model has 76 levels, with 1 km vertical resolution from the surface to the lower mesosphere (60 km) and 2 km resolution above (60–92 km). The horizontal resolution is 4° latitude, and the model uses a 2D (latitude–altitude) finite volume dynamical core (Lin & Rood, 1996) for advective transport. The model has detailed stratospheric chemistry and reduced tropospheric chemistry, with a diurnal cycle computed for all constituents each

day (Fleming et al., 2024). The model uses prescribed zonal mean surface temperature as a function of latitude and season based on a multi-year average of MERRA-2 data (Gelaro et al., 2017). Zonal mean latent heating, tropospheric water vapor, and cloud radiative properties as a function of latitude, altitude, and season are also prescribed (Fleming et al., 2020).

For the free-running simulations, the model planetary wave parameterization (Bacmeister et al., 1995; Fleming et al., 2024) uses lower boundary conditions (750 hPa, ~2 km) of geopotential height amplitude and phase for zonal wave numbers 1-4. These are derived as a function of latitude and season using: 1) a 30-year average (1991-2020) of MERRA-2 data for the standard yearly-repeating climatological-dynamics simulations ("Clim-NoQBO"); and 2) individual years of MERRA-2 data (1980-2020) randomly rearranged in time to generate interannual variations in stratospheric dynamics ("ensemble1", "ensemble2", ... "ensemble10"). For the inter-annually varying dynamics simulations, the model includes an internally generated QBO (Fleming et al., 2024).

For experiments that include the Hunga volcanic aerosols, the simulations go through the end of 2023, using prescribed aerosol properties for 2022-2023 from both the GloSSAC data set and derived from the OMPS-LP data (Taha et al., 2021, 2022). For experiments that include the Hunga H<sub>2</sub>O injection, Aura/MLS observations are used to derive a daily zonal mean Hunga water vapor anomaly in latitude-altitude, which is added to the baseline H<sub>2</sub>O (no volcano) through the end of February 2022. This combined water vapor field is then fully model computed starting 1 March 2022 through the end of 2031.

For **Exp2b**, the model zonal mean temperature and transport fields are computed from the MERRA-2 reanalysis data. These are input into the model and used as prescribed fields (no nudging is done).

#### 4.8 IFS-COMPO

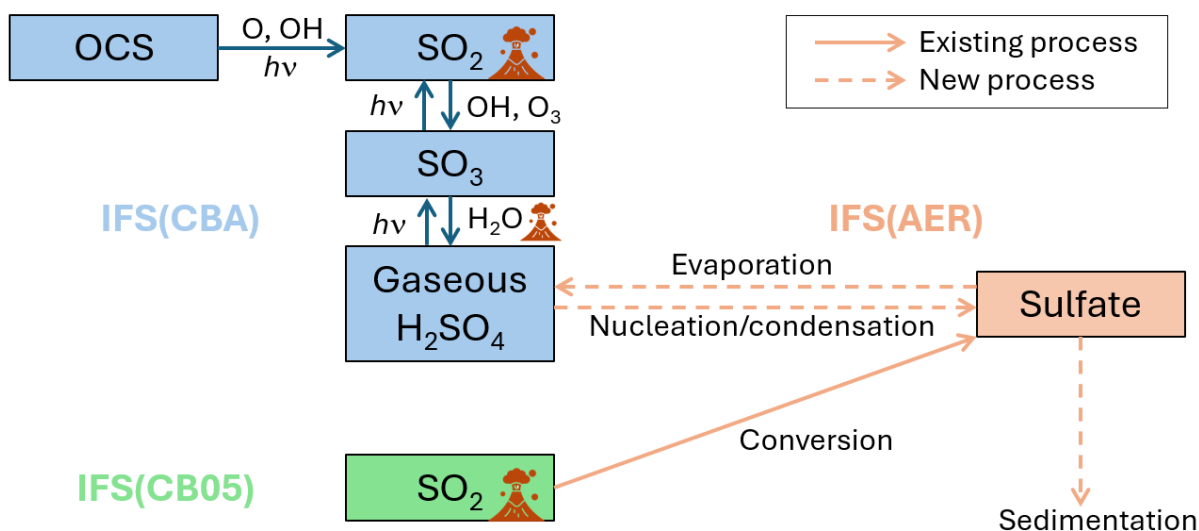
The Copernicus Atmosphere Monitoring Service (CAMS) provides daily global analysis and 5-day forecasts of atmospheric composition (aerosols, trace gases, and GHGs) (Peuch et al. 2022). CAMS is coordinated by the European Centre for Medium Range Weather Forecasts (ECMWF) and uses, for its global component, the Integrated Forecasting System (IFS), with extensions to represent aerosols, trace, and GHGs, being called "IFS-COMPO" (also previously known as "C-IFS", Flemming et al. 2015). IFS-COMPO is composed of IFS(AER) for aerosols, as described in Remy et al. (2022) while the atmospheric chemistry is based on the chemistry module as described in Williams et al. (2022) for the troposphere (IFS-CB05) and Huijnen et al. (2016) for the stratosphere (IFS-CBA). The stratospheric chemistry module of IFS-COMPO is derived from the Belgian Assimilation System for Chemical Observations (BASCOE, Errera et al 2019). IFS-COMPO stratospheric chemistry is used since the operational implementation of cycle 48R1 on June 27, 2023 (Eskes et al., 2024).

The aerosol component of IFS-COMPO is a bulk aerosol scheme for all species except sea salt aerosol and desert dust, for which a sectional approach is preferred, with three bins for

each of these two species. Since the implementation of operational cycle 48R1 in June 2023, the prognostic species are sea salt, desert dust, organic matter (OM), black carbon (BC), sulfate, nitrate, ammonium, and secondary organic aerosols (SOA).

For **Exp2a**, cycle 49R1 IFS-COMPO has been used, which will become operational for CAMS production in November 2024, at a resolution of TL511 (~40 km grid cell) over 137 model levels from surface to 0.01 hPa. Cycle 49R1 IFS-COMPO integrates a number of updates of tropospheric and stratospheric aerosols and chemistry. The most relevant aspect for this work concerns the representation of stratospheric aerosols, which has been revisited with the implementation of a coupling to the stratospheric chemistry through a simplified stratospheric sulfur cycle including nucleation/condensation and evaporation processes, as shown in **Figure 4**. Direct injection of water vapor into the stratosphere is expected to enhance the nucleation and condensation of sulfate through the reaction with  $\text{SO}_3$  and production of gas-phase  $\text{H}_2\text{SO}_4$ .

The volcanic injection takes place between 3 and 6 UTC on January 15, 2022, with a uniform vertical distribution between 25 and 30 km of altitude, over a rectangular region of 400 km (latitude) x 200 km (longitude) centered on the coordinates of the Hunga volcano. The injected quantities are 0.5 Tg  $\text{SO}_2$  and 190 Tg  $\text{H}_2\text{O}$ .



**Figure 4.** Architecture of the stratospheric extension of IFS(AER) and its coupling with IFS(CBA) and IFS(CB05), with existing and new processes implemented in cycle 49R1 of IFS-COMPO.  $h\nu$  represents photolysis and the volcano symbols represent direct injections by volcanic eruptions. Sedimentation is indicated as a new process because it has been revisited.

#### 4.9 IPSLCM7-STRATAER and IPSLCM7-STRATAER-REPROBUS

The Institut Pierre-Simon Laplace Climate Modelling Centre (IPSL CMC, see <https://cmc.ipsl.fr>) has set up a new version of its climate model in the runup of CMIP6. Further description of the IPSL-CM6A-LR climate model can be found in Boucher et al. (2020) and in Lurton et al. (2020). New development of the model is now ongoing to prepare the IPSLCM7 version.

The IPSLCM7 climate model is using the general circulation model named LMDZ for *Laboratoire de Météorologie Dynamique-Zoom* (Hourdin et al., 2006). The LMDZ version used

for this study is based on a regular horizontal grid with 144 points regularly spaced in longitude and 142 in latitude, corresponding to a resolution of  $2.5^\circ \times 1.3^\circ$ . The model has 79 vertical layers and extends up to 80 km, which makes it a “high-top” model. The model shows a self-generated quasi-biennial oscillation (QBO) whose period has been tuned to the observed one for the present-day climate (Boucher et al., 2020).

The aerosol is interactively simulated in the STRATAER module using a sectional scheme with 36 size bins. STRATAER is an improved version of the Sectional Stratospheric Sulfate Aerosol (S3A) module (Kleinschmitt et al., 2017). It now takes into account the photolytic conversion of  $\text{H}_2\text{SO}_4$  into  $\text{SO}_2$  in the upper stratosphere (Mills et al., 2005). The size-dependent composition of  $\text{H}_2\text{SO}_4/\text{H}_2\text{O}$  aerosols is now computed iteratively to ensure that the surface tension, density, and composition are consistent in the calculation of the Kelvin effect. The surface tension, density,  $\text{H}_2\text{SO}_4$  vapor pressure, and nucleation rates are calculated based on Vehkamäki et al. (2002). The version of the IPSLCM7-LMDZ atmospheric model used in the HTHH Impact project accounts for the stratospheric  $\text{H}_2\text{O}$  source from methane oxidation. The chemistry is simulated using the REPROBUS (*REactive Processes Ruling the Ozone BUdget in the Stratosphere*) chemistry module that includes 55 chemical species and a comprehensive description of the stratospheric chemistry (Marchand et al., 2012, Lefèvre et al., 1994, Lefèvre et al., 1998).

For **Exp2a**, the  $\text{H}_2\text{O}$  and  $\text{SO}_2$  is injected at 27.5 km altitude using a Gaussian distribution and standard deviation of 2.5 km. The injection latitude ranges from  $22^\circ\text{S}$  to  $14^\circ\text{S}$ , and longitude ranges from  $182^\circ\text{E}$  to  $186^\circ\text{E}$ . The injections of  $\text{H}_2\text{O}$  and  $\text{SO}_2$  are 150 Tg and 0.5 Tg, respectively.

#### 4.10 MIROC-CHASER

The Model for Interdisciplinary Research On Climate - Chemical Atmospheric general circulation model for Study of atmospheric Environment and Radiative forcing (MIROC-CHASER) version 6 (Sekiya et al. 2016) is a chemistry climate model, with a top at around 0.004 hPa. The present version of MIROC-CHASER is built on MIROC6 (Tatebe et al. 2019) and has a spectral horizontal resolution of T85 ( $1.4^\circ$  latitude  $\times$   $1.4^\circ$  longitude). The model has 81 vertical levels, with a vertical resolution 0.7 km in the lower stratosphere,  $\sim 1.2$  km in the upper stratosphere, and  $\sim 3$  km in the lower mesosphere. In the free-running simulations, the model generates QBO internally. The ensemble members have different initial conditions (January 1, 2022), which are generated using slightly different nudging relaxation time during the spin-up. The aerosols are interactively simulated using a three-mode modal aerosol module (Sekiya et al. 2016). The chemistry uses comprehensive troposphere-stratosphere chemistry (Watanabe et al. 2011). The volcanic emission from continuously degassing volcanoes uses the emission inventory of Fioletov et al. (2022). For the explosive volcanic eruptions during the spin-up time, explosive volcanic emissions follow Carn (2022).

For **Exp1** fixed SST simulations, the model uses the observed SST from 10-year climatological mean from 2012 to 2021.

For **Exp2a**, the atmospheric temperature and winds are nudged to MERRA-2 reanalysis with a 12-hour relaxation using 3-hour meteorology. The observed SST uses the NOAA  $1/4^\circ$  Daily Optimum Interpolation Sea Surface Temperature (OISST) from 2022 to 2023 (Huang et al. 2020).

The initial volcanic injection altitude and area are not tuned but follow the experimental protocol. For **Exp1** and **Exp2a**, the  $\text{H}_2\text{O}$  and  $\text{SO}_2$  are injected at 25 to 30 km altitude. The injection latitude ranges from  $22^\circ\text{S}$  to  $14^\circ\text{S}$ , and longitude ranges from  $182^\circ\text{E}$  to  $186^\circ\text{E}$ . The

initial injection of H<sub>2</sub>O is 186 Tg, with ~150 Tg left after the first week following the eruption. The large initial H<sub>2</sub>O injection is necessary to keep 150 Tg in the stratosphere as requested by the experimental protocol, because a large amount of ice clouds generates and falls to the troposphere soon after the eruption.

#### 4.11 WACCM6/MAM4

The Whole Atmosphere Community Climate Model version 6 (WACCM6; Gettelman et al. 2019) is the high-top version of the atmospheric component of the Community Earth System Model, version 2 (CESM2), with a top at around 140 km. WACCM6 has a horizontal resolution of 0.9° latitude × 1.25° longitude, utilizing the finite volume dynamical core (Lin & Rood, 1996). The model has 70 vertical levels, with a vertical resolution ~1 km in the lower stratosphere, ~1.75 km in the upper stratosphere, and ~3.5 km in the upper mesosphere and lower thermosphere (Garcia et al., 2017). In the free-running simulations, the model generates QBO internally (Mills et al., 2017; Gettelman et al. 2019). The ensemble members differ in the last date of nudging (from January 27 to February 5, 2022). The aerosol is interactively simulated using a four-mode modal aerosol module (MAM4; Liu et al., 2012, 2016; Mills et al., 2016), in which we used the Vehkamäki nucleation scheme (Vehkamäki et al., 2002). The chemistry uses comprehensive troposphere-stratosphere-mesosphere-lower-thermosphere (TSMLT) chemistry (Gettelman et al. 2019). The volcanic emissions from continuously degassing volcanoes use the emission inventory of Andres and Kasgnoc (1998). For the explosive volcanic eruptions during the spin-up time, explosive volcanic emissions follow Mills et al. (2016) and Neely III and Schmidt (2016) with updates until 2022.

For **Exp1** and **Exp4** with the coupled ocean simulation, the ocean and sea-ice are initialized on January 3, 2022 with output from a standalone ocean model forced by atmospheric state fields and fluxes from the Japanese 55-year Reanalysis (Tsujino et al., 2018). To accurately simulate the early plume structure and evolution, the winds and temperatures in WACCM are nudged toward the Analysis for Research and Applications, MERRA-2 meteorological data (Gelaro et al., 2017) throughout January 2022. After February 1, 2022, the model is free-running to capture fully-coupled variability. For the fixed SST simulation, the model uses the 10-year climatology SST from 2012 to 2021.

For **Exp2**, the atmospheric temperature and winds are nudged to MERRA-2 reanalysis with a 12-hour relaxation using 3-hour meteorology (Davis et al., 2022). The observed SST uses 10-year climatological mean from 2012 to 2021.

The initial volcanic injection altitude and area are the same as described for section 4.1 CAM5/CARMA.

#### 4.12 WACCM6/CARMA

WACCM6/CARMA only performed **Exp2** and used a configuration similar to WACCM6/MAM4 with the same horizontal and vertical resolution, SSTs, and meteorological nudging. Differences compared to WACCM6/MAM4 are the chemistry and aerosol configuration used. WACCM6/CARMA used the middle atmosphere chemistry with limited chemistry in the troposphere and comprehensive chemistry in the stratosphere, mesosphere and



lower thermosphere (Davis et al., 2022). Furthermore, we use the Community Aerosol and Radiation Model for Atmospheres (CARMA, Tilmes et al. 2023, based on Yu et al., 2015 with some updates) as the aerosol module, in which we used the Vehkamäki nucleation scheme (Vehkamäki et al., 2002). CARMA defines 20 mass bins and tracks the dry mass of the particles and assumes particle water is in equilibrium with the environmental water vapor. The approximate radius ranges from 0.2 nm to 1.3  $\mu\text{m}$  in radius for the pure sulfate group that sulfate homogeneous nucleation occurs in, and ranges from 0.05 to 8.7  $\mu\text{m}$  in the mixed group that tracks all major tropospheric aerosol types (i.e. black carbon, organic carbon, sea salt, dust, sulfate).

The initial volcanic injection altitude and area are determined by validating the water and aerosol transportation in the first six months against MLS and OMPS observations. In these simulations, the  $\text{H}_2\text{O}$  is injected to 25 to 35 km altitude following Zhu et al. (2022), while the  $\text{SO}_2$  is injected 82% of the total mass to 26.5-28 km and 18% to 28-36 km altitude. The injection latitude ranges from 22°S to 6°S, and longitude ranges from 182.5°E to 202.5°E.

## 5. Summary

A multi-model observation comparison project is designed to evaluate the impact of the 2022 Hunga eruption. Four experiments are designed to cover various research interests for this eruption, including sulfate and water plume dispersion and transport, dynamical and chemical responses in the stratosphere, and climate impact. The project will not only benefit the Hunga Impact assessment, but also benchmark the model performance on simulating stratospheric explosive volcanic eruption events. These events have a potentially large impact on the earth system, especially on the stratospheric ozone layer and radiative balance.

## Data Availability

GloSSAC: DOI (10.5067/GloSSAC-L3-V1.0).

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