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1 Hunga Tonga-Hunga Ha'apai Volcano Impact Model 2 Observation Comparison (HTHH-MOC) Project: 3 Experiment Protocol and Model Descriptions

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63

64 **Abstract:**

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66 The 2022 Hunga volcanic eruption injected a significant amount of water vapor and a moderate
67 amount of sulfur dioxide into the stratosphere causing observable responses in the climate
68 system. We have developed a model-observation comparison project to investigate the evolution
69 of volcanic water and aerosols, and their impacts on atmospheric dynamics, chemistry, and
70 climate, using several state-of-the-art chemistry climate models. The project goals are: 1.
71 Evaluate the current chemistry-climate models to quantify their performance in comparison to
72 observations; and 2. Understand atmospheric responses in the Earth system after this exceptional
73 event and investigate the potential impacts in the projected future. To achieve these goals, we
74 designed specific experiments for direct comparisons to observations, for example from balloons
75 and the Microwave Limb Sounder satellite instrument. Experiment 1 is a free-running ensemble
76 experiment from 2022 to 2031. Experiment 2 is a nudged-run experiment from 2022 to 2023
77 using observed meteorology. To allow participation of more climate models with varying
78 complexities of aerosol simulation, we include two sets of simulations in Experiment 2:
79 Experiment 2a is designed for models with internally-generated aerosol while Experiment 2b is
80 designed for models using prescribed aerosol surface area density. We take model results from
81 the previously developed Tonga-MIP to fulfill Experiment 3, which focuses on the initial
82 dispersion and microphysical evolution of aerosol and water plumes. Experiment 4 is designed to
83 understand the climate impact on the mesosphere from 2022-2027, for which the experiment
84 design is the same as Experiment 1 but for models that resolve the upper stratosphere and
85 mesosphere.

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88 **1. Introduction and motivations of this project**

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90 The Hunga Tonga-Hunga Ha'apai (HTHH) Impacts activity was established in the World
91 Climate Research Programme (WCRP) Atmosphere Processes And their Role in Climate
92 (APARC) as a limited-term focused cross-activity with a duration of three years. It aims to assess
93 the impacts of the 15 January 2022 Hunga volcanic eruption and produce an assessment to
94 document the Hunga impact on the climate system. The Hunga eruption injected an
95 unprecedented amount of water (H₂O) and moderate sulfur dioxide (SO₂) into the stratosphere
96 (Millan et al., 2022), presenting a unique opportunity to understand the impacts on the
97 stratosphere of a large-magnitude explosive phreatomagmatic eruption. The wide range of
98 satellite observations of the stratospheric water and sulfate plumes, global transport and
99 dispersion of volcanic materials, and unusual chemical and temperature signals are helpful in
100 assessing model representations of stratospheric chemistry, aerosol, and dynamics. For example,
101 the Aura Microwave Limb Sounder (MLS) observed ~150 Tg of water injected by the Hunga
102 eruption (Millan et al., 2022), which slowly decayed due to the polar stratospheric cloud (PSC)
103 dehydration process and stratosphere-troposphere exchange (Fleming et al., 2024; Zhou et al.,
104 2024). Large aerosol optical depth are observed by Ozone Mapping and Profiler Suite (OMPS)
105 (Taha et al., 2022), due to fast formation of sulfate (Zhu et al., 2022) and the high optical
106 efficiency of Hunga aerosol particles (Li et al., 2024). Unlike the stratospheric warming patterns
107 observed from previous large volcanic eruptions (El Chichón in 1982 and Pinatubo in 1991),
108 global stratospheric temperatures decreased by 0.5 to 1.0 K in the first two years following the
109 Hunga eruption, largely due to radiative cooling from injected water vapor (Randel et al., 2024).
110 Satellite observations in June, July, August 2022 reveal reduced lower stratospheric ozone (O₃)
111 over the SH midlatitudes and subtropics, with high levels near the equator, exceeding previous
112 variability. These ozone anomalies coincide with a weakening of the Brewer-Dobson circulation
113 during this period (Wang et al., 2023). Changes in stratospheric winds also influence the
114 mesosphere, leading to a stronger mesospheric circulation and corresponding temperature
115 changes (Yu et al., 2023). These observed phenomena provide a unique opportunity to test the
116 ability of chemistry-climate models to simulate the evolution of volcanic aerosols combined with
117 such a large amount of water vapor, as well as understand how volcanic water vapor and aerosols
118 modify radiative balances and stratospheric ozone.

119 The APARC HTHH Impacts activity aims to provide a benchmark analysis of the
120 eruption impacts so far, and projections of eruption climate impacts over the next few years. To
121 facilitate the success of this activity, we designed a multi-model evaluation project, the Hunga
122 Tonga-Hunga Ha'apai Volcano Impact Model Observation Comparison (HTHH-MOC) Project.
123 The HTHH-MOC provides a foundation for a coordinated multi-model evaluation of global
124 chemistry-climate models' performance in response to the Hunga volcanic eruption. It defines a
125 set of perturbation experiments, where volcanic forcings—injected water vapor and aerosol
126 concentrations—are consistently applied across participating model members. HTHH-MOC
127 aims to assess how reliably global chemistry-climate models simulate the climate responses to
128 this unprecedented volcanic forcing. This project enhances our confidence in attributing and
129 interpreting observations following the Hunga eruption. The scientific questions related to the
130 HTHH-MOC are: How does the Hunga volcanic plumes' transport relate to or impact
131 stratospheric dynamics (such as Brewer-Dobson circulation, polar vortex and the Quasi-Biennial
132 Oscillation) and upper atmosphere? What are the chemical impacts of the Hunga eruption in the
133 stratosphere and mesosphere? What and how long is the radiative effect of the Hunga eruption?
134 Does Hunga impact the tropospheric/surface climate?



135 Therefore, the HTHH-MOC project is focused on evaluating global chemistry-climate
136 models regarding the following three science themes: (1) plume evolution, dispersion, and large-
137 scale transport; (2) impacts on stratospheric chemistry and the ozone layer; and (3) radiative
138 forcing from the eruption and surface climate impacts. Besides the HTHH-MOC project, the
139 assessment also includes analysis of observations and models that are not global climate models.
140 In the following paragraph, we describe the HTHH-MOC experiment design and participating
141 models.
142

143 2. Experiment Design

144 There are four experiments designed to fulfill the scientific goals. Each experiment
145 includes four kinds of simulations with different volcanic injections, to explore the separate
146 impacts of volcanic water and aerosols during the post-eruption period: a) Control case (no
147 eruption); b) H₂O (~150 Tg) & SO₂ (0.5 Tg); c) Only H₂O (~150 Tg). d) Only SO₂ (0.5 Tg).
148 Simulations with the injection of SO₂ only (d) are optional and designed for aerosol-focused
149 models. The SO₂ and water injections are prescribed based on Millan et al. (2022) and Carn et al.
150 (2023). Note that ~150 Tg of water is not the injection amount but the amount retained after the
151 first couple of days. This is because some models form ice particles that fall out of the
152 stratosphere due to large H₂O supersaturation during the initial injection (Zhu et al., 2022); these
153 models will have to inject more H₂O to counterbalance the ice formation (see **Table 7**). The only
154 requirement is that the model should have reasonable comparison to the MLS observations for
155 water vapor as shown in **Figure 1**. Aside from retaining ~150 Tg of water, the water vapor
156 enhancement should be near 10 hPa to 50 hPa, and most of the water vapor should be located
157 between 10°N and 30°S by March 2022.

158 The first experiment (**Exp1**) is a free-running ensemble simulation covering the period
159 from 2022 to 2031. The experiment has been designed to answer questions on: 1. Understanding
160 the long-term evolution of Hunga water vapor and aerosols in free-running models; 2.
161 Quantifying Hunga effects on stratospheric temperatures, dynamics, and transport; 3.
162 Understanding the impact of dynamic changes on ozone chemistry; 4. Quantifying the net
163 radiative forcings; 5. Estimating surface impacts (e.g., temperature, El Niño-Southern
164 Oscillation, monsoon precipitation, etc.). Simulations with free-running meteorology are
165 required to properly understand the impacts of the eruption on atmospheric dynamics and
166 transport processes, and the resulting impacts of those on chemical species (e.g., ozone) and
167 surface climate. Since coupling of the atmosphere with ocean and land processes is required to
168 fully simulate many aspects of the surface impacts, the use of coupled atmosphere, ocean, and
169 land models is recommended. However, since such a fully interactive set up imposes additional
170 computing requirements, an alternative model set up with fixed sea-surface temperatures (SSTs)
171 and sea-ice is also allowed. In that case, the prescribed climatological SSTs and sea-ice data are
172 obtained by averaging SST during the past decade (2012-2021), with the same data imposed in
173 both the H₂O+SO₂ (b) and control (a) simulations. It is important to note that both initial and
174 boundary conditions in a model come with uncertainties, and model processes are simplified.
175 Therefore, model simulations are influenced by the characteristics of the model itself and the
176 background state of the atmospheric system (Jones et al. , 2016; Brodowsky et al., 2021). To
177 address some of the inherent uncertainties and reduce contribution of interannual variability to
178 the forced response, we use a large ensemble of simulations with slightly varied initial
179 conditions.



180 Since some aspects of the response, e.g., impacts on the radiative forcing, may be too
181 noisy from free-running model simulations even with large ensembles, we have also designed the
182 second experiment which uses nudged temperature and meteorology to reduce the contribution
183 of interannual variability and thus isolate chemical changes and their radiative forcing.
184 Experiment 2 (**Exp2**) is a two-year simulation that runs from 2022 to 2023 with nudged winds
185 and/or temperature to answer questions on H₂O and aerosol evolution; quantification of the net
186 radiative forcings; and impacts on mid-latitude and polar ozone chemistry. **Exp2** has two distinct
187 realizations: Experiment 2a (**Exp2a**) and Experiment 2b (**Exp2b**). The models participating in
188 **Exp2a** all have a prognostic aerosol module, but vary in the complexity of their representation of
189 aerosol microphysics (i.e., bulk, modal, or sectional). Models participating in **Exp2b** use
190 prescribed aerosol surface area density (SAD) and radiative properties as input to the models
191 (Jörmann et al., 2024). The prescribed aerosol properties are calculated using Global sSpace-
192 based Stratospheric Aerosol Climatology (GloSSAC; Thomason et al., 2018; Kovilakam et al.,
193 2020, 2023) version 2.22 aerosol data from 1979-2023. Note that for the period after the Hunga
194 eruption, GloSSAC uses the Stratospheric Aerosol and Gas Experiment (SAGEIII/ISS) version
195 5.3 interpolated along the time axis and the Optical Spectrograph and InfraRed Imager System
196 (OSIRIS) version 7.3 to fill in any missing data poleward of 60° N/S due to the unavailability of
197 the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) data since
198 January 2022. Therefore, when conducting analyses north/south of 60° N/S it should be noted that
199 the aerosols may be underestimated due to the OSIRIS instrument retrieval biases. We ask for
200 the models to check their initial chemical fields against MLS to see if the models are qualified to
201 evaluate their ozone chemistry. The nudged runs of **Exp2** enable isolation of the chemical impact
202 of the Hunga eruption from the volcanically induced changes in dynamics by comparing the runs
203 with and without H₂O+SO₂ injection. The net radiative effect anomaly due to water and sulfate
204 aerosol can also be calculated by comparing the control run (a) with the H₂O+SO₂ injection run
205 (b).

206 The third experiment (**Exp3**) is designed to explore the plume evolution between 1 day
207 and up to 1 or 2 months after the eruption, including plume microphysics and chemistry. This
208 experiment is adopted from TongaMIP (designed by Clyne et al., 2024), which has both free-
209 running and nudged simulations to study the Hunga plume during the first three months after the
210 eruption. All models are requested to inject 150 Tg of water but the retaining of the water varies
211 between models, while other experiments here ask to retain ~150 Tg of water in the stratosphere.
212 This is because for other experiments, our goal is to reproduce the long-term observations first
213 and then to understand the Hunga climate impact; while **Exp3** is designed to understand the
214 differences in physics processes (i.e., cloud and aerosol physics and sulfur chemistry) between
215 models, expanding on findings from prior model intercomparison (Clyne et al., 2021; Quaglia et
216 al., 2023) with upgraded and additional models. These experiments are detailed in Clyne et al.
217 (2024).

218 The fourth experiment (**Exp4**) is a free-running ensemble simulation to understand
219 climate impacts on the mesosphere and ionosphere from 2022-2027, such as gravity wave drag,
220 temperature changes, polar mesospheric clouds (PMCs), and atmospheric circulation. This
221 experiment uses the first 5 years of **Exp1** and is limited to the models resolving the upper
222 atmosphere.

223 **Table 1** shows the forcings and emissions data used for all experiments except for
224 Experiment 3 (**Exp3**). **Table 2** shows the settings specific to each experiment. For volcanic
225 injection for **Exp1, 2** and **4**, we recommend the injections of H₂O and SO₂ at 4 UTC on Jan 15,



226 2022. All the models are required to retain a similar amount of water as observed by MLS (~ 150
 227 Tg). The models are recommended to compare with the MLS evolution for validation (**Figure 1**).
 228 The goal is to retain the same amount of water and similar altitude to start with, so we can
 229 analyze the water's impact on the stratosphere and climate. If injecting 25-30 km cannot retain
 230 150 Tg, models can inject higher than 30 km. The SO₂ injection is required to be 0.5 Tg for all
 231 models. The injection locations are not required to be co-injected with H₂O.

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

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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 Exp1 , 2 years for Exp2). recommended references: Volcanic degassing Carn et al. (2017); Eruptive volcanoes (Neely III, & Schmidt (2016) https://archive.researchdata.leeds.ac.uk/96/ 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 ₂ emissions around current levels before beginning to decline by 2050.
Chemical initialization	Stratospheric chemistry fields (such as O ₃ , H ₂ 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.

241 * 5 years is enough to reach sulfate equilibrium in the stratosphere; water may take 7 years (each model
 242 should adjust the spin-up time according to model features). ** Recommended degassing volcanic
 243 emissions injected at the cone altitude, constant flux based on Carn et al. (2017). Database is updated
 244 through 2022 here: <https://doi.org/10.5067/MEASURES/SO2/DATA406>.

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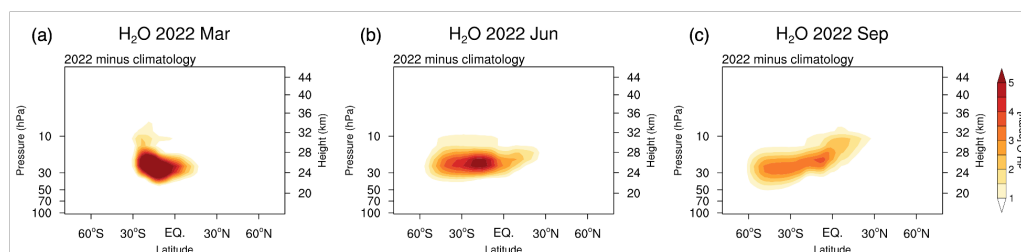
Table 2. Experiment design

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 doesn't generate)	Fixed (climatology = mean of monthly average during the past decade (2012-2021), repeating annually) This applies to spin-up time too.	10-20
	(i.e. nudge until Jan 31)		prescribed		Coupled ocean (optional) initialize with observed ocean state (see section 3 for individual model descriptions)	10-20
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

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Figure 1. Monthly average water vapor perturbation after the Hunga eruption from MLS. Panels (a-c) show the observed dispersion of the H₂O enhancement in 2022 in the months of (a) March, (b) June, and (c) September.

3. Model output

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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.

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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.

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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**.



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

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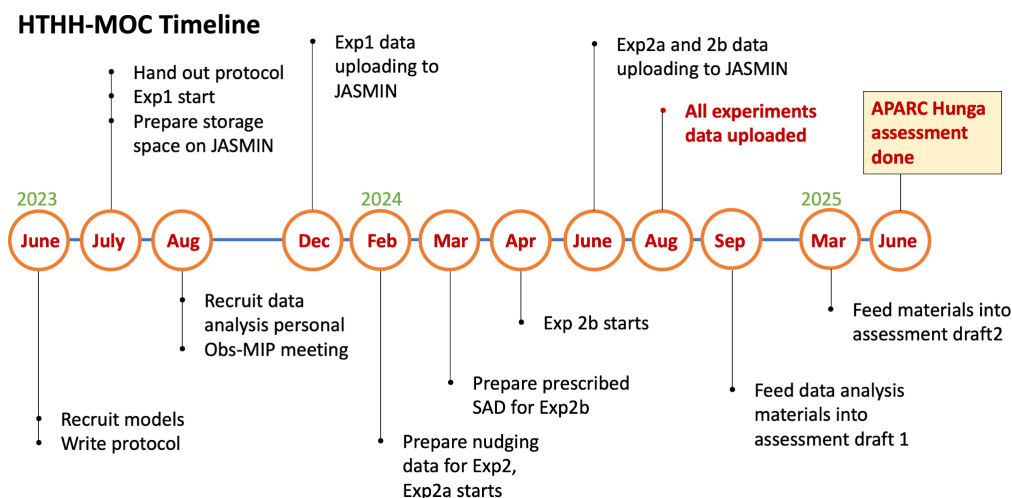
283 4. Model Descriptions and the Hunga Volcanic Injection Specification

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

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

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

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

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300 **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 Jinan Univ.	Pengfei Yu Yifeng Peng	pengfei.yu@colorado.edu pengvf16@lzu.edu.cn
CCSRNIES-MIROC3.2	Akiyoshi et al. (2023), Akiyoshi et al. (2016)	NIES	Yosuke Yamashita Hideharu Akiyoshi	yamashita.yosuke@nies.go.jp hakiyosi@nies.go.jp
CMAM	Jonsson et al. (2004), Scinocca et al. (2008)	CCCma, Environment and Climate Change Canada	David Plummer	david.plummer@ec.gc.ca
EMAC MPIC	Schallock et al. (2023)	MPI-C, -M, DLR	Christoph Brühl	christoph.bruehl@mpic.de
GA4 UM-UKCA	Dhomse et al. (2020)	Univ. Leeds	Graham Mann, Sandip Dhomse	G.W.Mann@leeds.ac.uk , S.S.Dhomse@leeds.ac.uk
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 Cy49R1	Huijnen et al. (GMD, 2016), Rémy et al. (GMD, 2022)	ECMWF and team CAMS2_35	Simon Chabrilat Samuel Rémy	Simon.chabrilat@aeronomie.be sr@hygeos.com
LMZ6.2-LR-STRATAER/LMD Z6.2-LR-STRATAER-REPROBUS	O. Boucher et al. 2020, Marchand et al., 2012	CNRS, Sorbonne Université, IPSL, LATMOS, LOCEAN	Marion Marchand, Slimane Bekki, Nicolas Lebas, Lola Falletti	marion.marchand@latmos.ipsl.fr , slimane.bekki@latmos.ipsl.fr , nicolas.lebas@locean.ipsl.fr , lola.falletti@latmos.ipsl.fr
MIROC-CHASER	Sekiya et al. (2016)	JAMSTEC	Shingo Watanabe, Takashi Sekiya	wnabe@jamstec.go.jp , tsekiya@jamstec.go.jp
MIROC-ES2H	Tatebe et al. (2019), Kawamiya et al. (2020)	JAMSTEC and NIES	Shingo Watanabe, Takashi Sekiya, Tatsuya Nagashima, Kengo Sudo	wnabe@jamstec.go.jp , tsekiya@jamstec.go.jp , nagashima.tatsuya@nies.go.jp , kengo@nagoya-u.jp
SOCOLv4	Sukhodolov et al. (2021)	PMOD/WRC and ETH-Zurich	Timofei Sukhodolov	timofei.sukhodolov@pmodwrc.ch
WACCM6/CARM A	Tilmes et al. (2023)	NCAR	Simone Tilmes Cheng-Cheng Liu Yunqian Zhu Margot Clyne (Exp 3)	tilmes@ucar.edu chengcheng.liu@lasp.colorado.edu yunqian.zhu@noaa.gov margot.clyne@colorado.edu
WACCM6/MAM	Mills et al. (2016)	NCAR	Xinyue Wang Simone Tilmes Jun Zhang Wandi Yu	xinyuew@colorado.edu tilmes@ucar.edu jzhan166@ucar.edu yu44@llnl.gov



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Table 5. Participating models for each experiment.

Model names	Exp1	Exp1/4 (coupled ocean)	Exp2a	Exp2b	Exp3 (Tonga-MIP)	Exp4
CAM5/CARMA			X			
CCSRNIES- MIROC3.2				X		
CMAM	X (H2O- only)					X (H2O-only)
EMAC MPIC			X			
GA4 UM-UKCA					X	
GEOSCCM	X		X		X	
GEOS/CARMA			X			
GSFC2D	X			X		X
IFS-COMPO			X			
LMDZ6.2-LR- STRATAER			X		X	
LMDZ6.2-LR- STRATAER- REPROBUS			X		X	
MIROC- CHASER	X		X			
MIROC-ES2H					X	
SOCOLv4					X	
WACCM6/CAR MA			X		X	
WACCM6/MA M	X	X	X		X	X

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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 run	Chemistry package (tropospheric chemistry included?)
CAM5/CARM A	~2 deg	56	45 km	1-4 km	CARMA sectional(20 bins)	GEOS5	-	MOZART (yes)
CCSRNIES- MIROC3.2	T42	34	0.01 hPa	1-3 km	None	MERRA-2	nudged	full strat; no tropo
CMAM	T47	80	0.06 hPa	0.8 - 2.5 km	None	ERA5	nudged	stratospheric + methane-NOx in troposphere
EMAC MPIC	T63	90	0.01 hPa	0.5km in LS	GMXE, modal	ERA-5	Internal but slightly nudged	MECCA, simplified troposphere



GEOSCCM	c90 (~1 deg)	72	0.01 hPa	~1 km	GOCA RT (Bulk)	MERR A-2/GEOS-FP	Internal generated	GMI (yes)
GEOS/CARMA	c90 (~1 deg)	72	0.01 hPa	~1 km	CARMA (sectional 24 bins)	MERR A-2/GEOS-FP	Internal generated	GMI (yes)
GSFC2D	4°	76	.002 hPa (~92 km)	1km	Prescribed only	MERR A-2	Internal generated	full strat; partial trop
IFS-COMPO	T1,511 (~40km)	137	0.01 hPa	0.5-1.5 km	Bulk	ERA5	-	BASCOE (strato) + CB05 (tropo)
LMDZ6.2-LR-STRATAER	2.5° × 1.3°	79	80k m	1-5 km	S3A(sectional 36 bins)	ERA5	Internal generated	No
LMDZ6.2-LR-STRATAER-REPROBUS	2.5° × 1.3°	79	80k m	1-5 km	S3A(sectional 36 bins)	ERA5	Internal generated	REPROBUS
MIROC-CHASER	T85	81	0.004 hPa	0.7-1.2 km	MAM 3	MERR A-2	Internal generated	troposphere-stratosphere chemistry
WACCM6/CARMA	~1 deg	70	140 km	1-2 km	Sectional (20 bins)	MERRA-2	Internal generated	MOZART (yes)
WACCM6/MAM	~1 deg	70	140 km	1-2 km	MAM4	MERRA-2	Internal generated	MOZART (yes)

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

Model names	Data and duration	H ₂ O amount (left after a week)	H ₂ O altitude	H ₂ O location/area	SO ₂ amount	SO ₂ altitude	SO ₂ location/area
CAM5/CARMA	Jan 15, 6 hrs	150 Tg (~135 Tg)	25-35 km	22-14°S, 182-186°E	0.5 Tg	20-28 km	22-14°S, 182-186°E
CCSRNIES-MIROC3.2	Jan 15, instantly	150 Tg (~150 Tg)	12.0-27.6 hPa	181.4–187.0°E, 14.0–22.3°S	-	-	-
CMAM	Feb 20, 5 days	150 Tg (~150 Tg)	near 25.5 km	zonally average	-	-	-
EMAC MPIC	Jan 16, 12hrs	136 Tg (~130 Tg)	Gaussian centered at 21.5hPa	23-19°S, 177-173°W	0.4 Tg based on obs.	23-27 km based on obs.	30°S-5°N, 90-120°W (330°)
GEOSCCM	Jan 15, 6 hrs	750 Tg (~150 Tg)	25-30 km	22-14°S, 182-186°E	0.5 Tg	25-30 km	22-14°S, 182-186°E



GEOS/CARMA	Jan 15, 6 hrs	750 Tg (~150 Tg)	25-30 km	22-14°S, 182-186°E	0.5 Tg	25-30 km	22-14°S, 182-186°E
GSFC2D	use MLS H ₂ O profile until March 1	~150 Tg (~150 Tg)	-	zonally average	-	-	-
IFS-COMPO	Jan 15, 3 hrs	190 Tg (~150 Tg)	25-30 km	400 km by 200 km centered 20°S and 175°W	0.5 Tg	25-30 km	400 km by 200 km centered 20°S and 175°W
LMDZ6.2-LR-STRATAER	Jan 15, 1 day	150 Tg (~150 Tg)	Gaussian centered at 27.5 km and standard deviation of 2.5 km	22°-14°S, 182-186°E	0.5 Tg	Gaussian centered at 27.5 km and standard deviation of 2.5 km	22-14°S, 182-186°E
LMDZ6.2-LR-STRATAER-REPROBUS	Jan 15, 1 day	150 Tg (~150 Tg)	Gaussian centered at 27.5 km and standard deviation of 2.5 km	22-14°S, 182-186°E	0.5 Tg	Gaussian centered at 27.5 km and standard deviation of 2.5 km	22-14°S, 182-186°E
MIROC-CHASER	Jan 15 4 UTC, 6 hours	186 Tg (~150 Tg)	25-30 km	22-14°S, 182-186°E	0.5 Tg	25-30 km	22-14°S, 182-186°E
WACCM6/CARMA	Jan 15, 6 hours	150 Tg (~135 Tg)	25-35 km	22-14°S, 182-186°E	0.5 Tg	20-28 km	22-14°S, 182-186°E
WACCM6/MAM	Jan 15, 6 hours	150 Tg (~150 Tg)	25-35km	22-6°S, 182.5 -202.5°E	0.5 Tg	26.5-36 km	22-6°S, 182.5 -202.5°E

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311

312 4.1 CAM5/CARMA

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



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

327 The initial volcanic injection altitude and area are determined by validating the water and
328 aerosol transportation in months shown in **Figure 1** following the tests in Zhu et al. (2022), Wang
329 et al. (2023) and Zhang et al. (2024). In these simulations, the H₂O is injected at 25 to 35 km
330 altitude and SO₂ injected at 20 to 28 km altitude. The injection latitude ranges from 22°S to 14°S,
331 and longitude ranges from 182°E to 186°E (Zhu et al., 2022). The initial injection of H₂O is 150
332 Tg, with ~ 135 Tg left after the first week following the eruption.

333

334 **4.2 CCSRNIES-MIROC3.2**

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

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

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

353 The CCSRNIES-MIROC3.2 CCM does not have any microphysics scheme for volcanic
354 aerosols. The surface area and spectral optical parameters of extinction, single scattering albedo,
355 and asymmetric factor for Hunga aerosols were prescribed in the model from the GloSSAC version
356 2.22 aerosol data (Jörmann et al., 2024). H₂O was injected instantly on 15 January 2022 at the 12
357 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
358 hPa–27.6 hPa in pressure level. A uniform number density of 1.709×10¹⁵ molecules/cm³ H₂O was
359 injected in each of the 12 grids which amounts to ~150 Tg.

360

361 **4.3 CMAM**

362 The Canadian Middle Atmosphere Model (CMAM) is based on a vertically extended
363 version of CanAM3.1, the third generation Canadian Atmospheric Model (Scinocca et al., 2008).
364 Compared to the standard configuration of CanAM3.1, for CMAM the model top was raised to
365 0.0006 hPa (approximately 95 km) and the parameterization of non-orographic gravity wave
366 drag (Scinocca, 2003) and additional radiative processes important in the middle atmosphere
367 (Fomichev et al., 2004) have been included. The gas-phase chemistry includes a comprehensive
368 description of the inorganic Ox, NO_x, HO_x, ClO_x and BrO_x families, along with CH₄, N₂O, six
369 chlorine containing halocarbons, CH₃Br and, to account for an additional 5 ppt of bromine from
370 short-lived source gases, CH₂Br₂ and CHBr₃ (Jonsson et al., 2004). A prognostic description of,



371 and associated heterogeneous chemical reactions on water ice PSCs (PSC Type II) and liquid
372 ternary solution (PSC Type Ib) particles is included, although gravitational settling
373 (dehydration/denitrification) is not calculated and species return to the gas phase when
374 conditions no longer support the existence of PSC particles.

375 The simulations for the HTHH-MOC simulations were performed at T47 spectral
376 resolution (approximately 3.8° resolution on the linear transform grid used for the model
377 physics), with 80 vertical levels giving a vertical resolution of approximately 0.8 km at 100 hPa,
378 increasing to 2.3 km above 0.1 hPa. The CMAM does not internally generate a QBO, so the
379 zonal winds in the equatorial region were nudged towards a dataset based on observed variations
380 up to December 2023, constructed using the method of Naujokat (1986) and extended into the
381 future by repeating a historical period that is congruent with the observed QBO in late 2023.
382 Water vapor from the Hunga eruption was added as a zonally average perturbation to the model
383 water over five days from 00 UTC on February 20, 2022. The spatial distribution of the anomaly
384 was designed to reproduce the water vapor anomaly observed in mid-February by the The
385 Atmospheric Chemistry Experiment - Fourier Transform Spectrometer (ACE-FTS) (Bernath et
386 al., 2005) satellite (Patrick Sheese, personal communication), with a maximum value of 13.3
387 ppm at 17°S and 25.5 km and producing an anomaly of ~ 150 Tg H_2O in the stratosphere.
388

389 4.4 EMAC MPIC

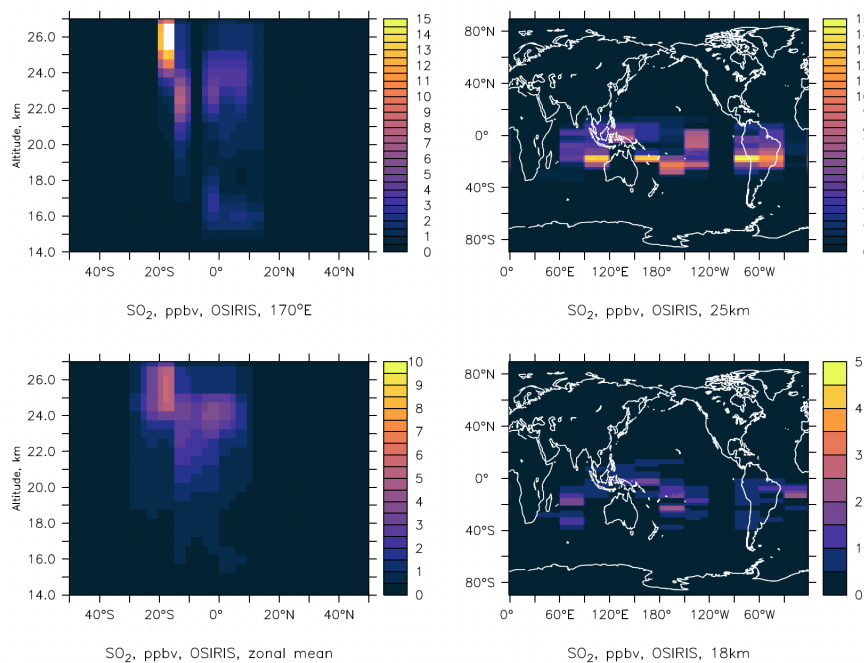
390 The chemistry-climate model EMAC (ECHAM5/MESSy Atmospheric Chemistry)
391 consists of the European Centre Hamburg general circulation model (ECHAM5) and the
392 Modular Earth Submodel System (MESSy) (e.g., Jöckel et al., 2010). Here we use the version of
393 Schallock et al. (2023) in horizontal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

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

400 The model contains gas-phase and heterogeneous chemistry on PSCs and interactive
401 aerosols. Surface mixing ratios of chlorine- and bromine-containing halocarbons and other long-
402 lived gases are nudged to Advanced Global Atmospheric Gases Experiment (AGAGE)
403 observations. The microphysical modal aerosol module contains four soluble and three insoluble
404 modes for sulfate, nitrate, dust, organic and black carbon, and aerosol water (Pringle et al.,
405 2010). The instantaneous radiative forcing by tropospheric and stratospheric aerosols can be
406 calculated online by multiple calls of the radiation module. Volcanoes injecting material into the
407 stratosphere are considered as in Schallock et al. (2023) using the perturbations of stratospheric
408 SO_2 observed by the Michelson Interferometer for Passive Atmospheric Sounding (MIPAS) and
409 aerosol extinction observed by OSIRIS. This method, based typically on data of a 10-day period,
410 distributes the injected SO_2 over a larger volume than typical point source approaches using the
411 same integrated mass (see also Kohl et al., 2024). For Hunga this method has the disadvantage
412 that H_2O and SO_2 are not co-injected since H_2O is injected in 12 hours in a slab consisting of
413 four horizontal boxes and a Gaussian vertical distribution centered at 21.5 hPa. For **Exp2a** we
414 continue the 30-year transient simulation presented in Schallock et al. (2023) with and without
415 Hunga Tonga. The simulated H_2O -perturbation is consistent with **Figure 1**. The SO_2 injection is



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



418
419 **Figure 3.** The SO₂ perturbation from Hunga derived from extinction observed by OSIRIS
420 averaged over about 10 days, i.e., including several snapshots of the westward moving plume.
421 Note that the colorbars are not the same in each panel.

422
423

424 4.5 GEOSCCM

425 The NASA Goddard Earth Observing System Chemistry-Climate Model (GEOSCCM) is
426 based on the GEOS Earth system model (Reinecker et al. 2008, Molod et al. 2015). For the
427 HTHH-MOC experiments the model is run on a cubed-sphere horizontal grid at a C90 resolution
428 (~100 km) with 72 vertical hybrid-sigma levels from the surface to 0.01 hPa (~80 km).
429 Dynamics are solved using the finite-volume dynamical core (Putman and Lin, 2007). Deep and
430 shallow convection are parameterized using the Grell-Freitas (2014) and Park-Bretherton (2009)
431 schemes, respectively, and moist physics is from Bacmeister et al. (2006). The turbulence
432 parameterization is based on the non-local scheme of Lock et al. (2000). Shortwave and
433 longwave radiative fluxes are computed in 30 bands using the Rapid Radiative Transfer Model
434 for GCMs (RRTMG, Iacono et al. 2008).

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



442 simulated by the Goddard Chemistry, Aerosol, Radiation, and Transport, second generation
443 (GOCART-2G), module (Collow et al. 2024), which includes a sectional approach for dust (five
444 bins), sea salt (five bins), and nitrate (three bins), and a bulk approach for sulfate (dimethyl
445 sulfide, SO₂, methanesulfonic acid, and SO₄²⁻) aerosol and carbonaceous species (hydrophobic
446 and hydrophilic modes of “white” and “brown” organics and black carbon).

447 For the GEOSCCM simulations performed with the GOCART-2G module we use the
448 nominal GOCART-2G sulfate mechanism, updated here to use the online hydroxyl (OH) radical,
449 nitrate (NO₃) radical, and hydrogen peroxide (H₂O₂) from the GMI mechanism instead of
450 climatological fields provided from offline files (Collow et al., 2024). While not a full coupling
451 to the GMI sulfur cycle it nevertheless allows the GOCART-2G sulfate mechanism to have the
452 impact of the Hunga water vapor perturbation on the oxidants. A second “instance” of the
453 GOCART-2G sulfate mechanism is run that is specifically for the volcanic SO₂ and resultant
454 sulfate from the Hunga eruption. This allows us to track the eruptive volcanic aerosol separately
455 from the nominal sulfate instance that sees mainly tropospheric sources. We assign this volcanic
456 instance optical properties consistent with SAGE retrievals of the sulfate aerosol properties,
457 using an effective radius of 0.4 microns. We find that 750 Tg of H₂O is needed in the initial
458 injection to provide a residual ~150 Tg of water in the stratosphere after a week. All other
459 injection parameters follow the protocol. The model spinup was performed by “replaying” to the
460 MERRA-2 meteorology (Gelaro et al. 2017), and is used throughout the **Exp2a** results.

461

462 **4.6 GEOS/CARMA**

463 A second configuration of the GEOSCCM, coupled to the sectional aerosol microphysics
464 package CARMA, also simulated the eruption (GEOS/CARMA). This configuration is the same
465 as above except for the aerosol package and its coupling to the GMI chemistry mechanism. For
466 this version of GEOSCCM, we use the configuration of CARMA described in Case et al. (2023).
467 This configuration uses 24 size bins, spread logarithmically in volume between 0.25nm and
468 6.7µm in radius and simulates the nucleation, condensational growth, evaporation, coagulation,
469 and settling of sulfate aerosols in these simulations following the mechanism of English et al.
470 (2013). For these simulations, CARMA is fully coupled to the GMI sulfur cycle by the
471 production (i.e., oxidation of SO₂, evaporation of sulfate aerosols) and loss (i.e., nucleation and
472 condensation of sulfate aerosols) of sulfuric acid (H₂SO₄) vapor. Optical properties for the
473 CARMA aerosols are calculated based on the interactively calculated aerosol size distribution.
474 The same injection parameters for GEOSCCM described above are used by this configuration.
475 This model configuration contributed to **Exp2a** and “replayed” to MERRA-2 meteorology as
476 above.

477

478 **4.7 GSFC2D**

479 The NASA/Goddard Space Flight Center two-dimensional (2D) chemistry-climate model
480 (GSFC2D) has a domain extending from the surface to ~92 km (0.002 hPa). The model has 76
481 levels, with 1 km vertical resolution from the surface to the lower mesosphere (60 km) and 2 km
482 resolution above (60-92 km). The horizontal resolution is 4° latitude, and the model uses a 2D
483 (latitude-altitude) finite volume dynamical core (Lin & Rood, 1996) for advective transport. The
484 model has detailed stratospheric chemistry and reduced tropospheric chemistry, with a diurnal
485 cycle computed for all constituents each day (Fleming et al., 2024). The model uses prescribed
486 zonal mean surface temperature as a function of latitude and season based on a multi-year
487 average of MERRA-2 data (Gelaro et al., 2017). Zonal mean latent heating, tropospheric water



488 vapor, and cloud radiative properties as a function of latitude, altitude, and season are also
489 prescribed (Fleming et al., 2020).

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

499 For experiments that include the Hunga volcanic aerosols, the simulations go through the
500 end of 2023, using prescribed aerosol properties for 2022-2023 from both the GloSSAC data set
501 and derived from the OMPS-LP data (Taha et al., 2021, 2022). For experiments that include the
502 Hunga H₂O injection, Aura/MLS observations are used to derive a daily zonal mean Hunga
503 water vapor anomaly in latitude-altitude, which is added to the baseline H₂O (no volcano)
504 through the end of February 2022. This combined water vapor field is then fully model computed
505 starting 1 March 2022 through the end of 2031.

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

509

510 **4.8 IFS-COMPO**

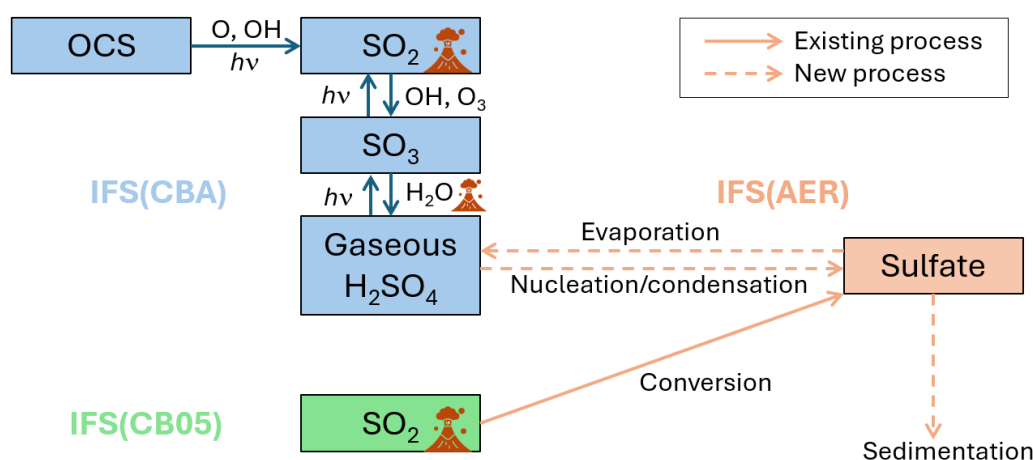
511 The Copernicus Atmosphere Monitoring Service (CAMS) provides daily global analysis
512 and 5-day forecasts of atmospheric composition (aerosols, trace gases, and GHGs) (Peuch et al.
513 2022). CAMS is coordinated by the European Centre for Medium Range Weather Forecasts
514 (ECMWF) and uses, for its global component, the Integrated Forecasting System (IFS), with
515 extensions to represent aerosols, trace, and GHGs, being called "IFS-COMPO" (also previously
516 known as "C-IFS", Flemming et al. 2015). IFS-COMPO is composed of IFS(AER) for aerosols,
517 as described in Remy et al. (2022) while the atmospheric chemistry is based on the chemistry
518 module as described in Williams et al. (2022) for the troposphere (IFS-CB05) and Huijnen et al.
519 (2016) for the stratosphere (IFS-CBA). The stratospheric chemistry module of IFS-COMPO is
520 derived from the Belgian Assimilation System for Chemical ObErvations (BASCOE, Errera et al
521 2019). IFS-COMPO stratospheric chemistry is used since the operational implementation of cycle
522 48R1 on June 27, 2023 (Eskes et al., 2024).

523 The aerosol component of IFS-COMPO is a bulk aerosol scheme for all species except sea
524 salt aerosol and desert dust, for which a sectional approach is preferred, with three bins for each
525 of these two species. Since the implementation of operational cycle 48R1 in June 2023, the
526 prognostic species are sea salt, desert dust, organic matter (OM), black carbon (BC), sulfate,
527 nitrate, ammonium, and secondary organic aerosols (SOA).

528 For **Exp2a**, cycle 49R1 IFS-COMPO has been used, which will become operational for
529 CAMS production in November 2024, at a resolution of TL511 (~40 km grid cell) over 137 model
530 levels from surface to 0.01 hPa. Cycle 49R1 IFS-COMPO integrates a number of updates of
531 tropospheric and stratospheric aerosols and chemistry. The most relevant aspect for this work
532 concerns the representation of stratospheric aerosols, which has been revisited with the
533 implementation of a coupling to the stratospheric chemistry through a simplified stratospheric



534 sulfur cycle including nucleation/condensation and evaporation processes, as shown in **Figure 4**.
535 Direct injection of water vapor into the stratosphere is expected to enhance the nucleation and
536 condensation of sulfate through the reaction with SO_3 and production of gas-phase H_2SO_4 .
537 The volcanic injection takes place between 3 and 6 UTC on January 15, 2022, with a
538 uniform vertical distribution between 25 and 30 km of altitude, over a rectangular region of 400
539 km (latitude) x 200 km (longitude) centered on the coordinates of the Hunga volcano. The injected
540 quantities are 0.5 Tg SO_2 and 190 Tg H_2O .
541



542 **Figure 4.** Architecture of the stratospheric extension of IFS(AER) and its coupling with IFS(CBA)
543 and IFS(CB05), with existing and new processes implemented in cycle 49R1 of IFS-COMPO. $h\nu$
544 represents photolysis and the volcano symbols represent direct injections by volcanic eruptions.
545 Sedimentation is indicated as a new process because it has been revisited.
546
547
548

549 4.9 LMDZ6.2-LR-STRATAER and LMDZ6.2-LR-STRATAER-REPROBUS

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

555 The IPSLCM7 climate model is using the general circulation model named LMDZ for
556 *Laboratoire de Météorologie Dynamique-Zoom* (Hourdin et al., 2006). The LMDZ version used
557 for this study is based on a regular horizontal grid with 144 points regularly spaced in longitude
558 and 142 in latitude, corresponding to a resolution of $2.5^\circ \times 1.3^\circ$. The model has 79 vertical layers
559 and extends up to 80 km, which makes it a “high-top” model. The model shows a self-generated
560 quasi-biennial oscillation (QBO) whose period has been tuned to the observed one for the
561 present-day climate (Boucher et al., 2020).

562 The aerosol is interactively simulated in the STRATAER module using a sectional
563 scheme with 36 size bins. STRATAER is an improved version of the Sectional Stratospheric
564 Sulfate Aerosol (S3A) module (Kleinschmitt et al., 2017). It now takes into account the
565 photolytic conversion of H_2SO_4 into SO_2 in the upper stratosphere (Mills et al., 2005). The size-



566 dependent composition of H₂SO₄/H₂O aerosols is now computed iteratively to ensure that the
567 surface tension, density, and composition are consistent in the calculation of the Kelvin effect.
568 The surface tension, density, H₂SO₄ vapor pressure, and nucleation rates are calculated based on
569 Vehkamäki et al. (2002). The version of the LMDZ6.2-LR-STRATAER atmospheric model used
570 in the HTHH Impact project accounts for the stratospheric H₂O source from methane oxidation.
571 The chemistry is simulated using the REPROBUS (*REactive Processes Ruling the Ozone*
572 *BUDget in the Stratosphere*) chemistry module that includes 55 chemical species and a
573 comprehensive description of the stratospheric chemistry (Marchand et al., 2012, Lefèvre et al.,
574 1994, Lefèvre et al., 1998).

575 For **Exp2a**, the H₂O and SO₂ is injected at 27.5 km altitude using a Gaussian distribution
576 and standard deviation of 2.5 km. The injection latitude ranges from 22°S to 14°S, and longitude
577 ranges from 182°E to 186°E. The injections of H₂O and SO₂ are 150 Tg and 0.5 Tg, respectively.

578

579 **4.10 MIROC-CHASER**

580 The Model for Interdisciplinary Research On Climate - CHEMical Atmospheric general
581 circulation model for Study of atmospheric Environment and Radiative forcing (MIROC-
582 CHASER) version 6 (Seikiya et al. 2016) is a chemistry climate model, with a top at around 0.004
583 hPa. The present version of MIROC-CHASER is built on MIROC6 (Tatebe et al. 2019) and has a
584 spectral horizontal resolution of T85 (1.4° latitude × 1.4° longitude). The model has 81 vertical
585 levels, with a vertical resolution 0.7 km in the lower stratosphere, ~1.2 km in the upper
586 stratosphere, and ~3 km in the lower mesosphere. In the free-running simulations, the model
587 generates QBO internally. The ensemble members have different initial conditions (January 1,
588 2022), which are generated using slightly different nudging relaxation time during the spin-up.
589 The aerosols are interactively simulated using a three-mode modal aerosol module (Seikiya et al.
590 2016). The chemistry uses comprehensive troposphere-stratosphere chemistry (Watanabe et al.
591 2011). The volcanic emission from continuously degassing volcanoes uses the emission inventory
592 of Fioletov et al. (2022). For the explosive volcanic eruptions during the spin-up time, explosive
593 volcanic emissions follow Carn (2022).

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

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

599 The initial volcanic injection altitude and area are not tuned but follow the experimental
600 protocol. For **Exp1** and **Exp2a**, the H₂O and SO₂ are injected at 25 to 30 km altitude. The injection
601 latitude ranges from 22°S to 14°S, and longitude ranges from 182°E to 186°E. The initial injection
602 of H₂O is 186 Tg, with ~150 Tg left after the first week following the eruption. The large initial
603 H₂O injection is necessary to keep 150 Tg in the stratosphere as requested by the experimental
604 protocol, because a large amount of ice clouds generates and falls to the troposphere soon after the
605 eruption.

606

607 **4.11 WACCM6/MAM4**

608 The Whole Atmosphere Community Climate Model version 6 (WACCM6; Gettelman et
609 al. 2019) is the high-top version of the atmospheric component of the Community Earth System
610 Model, version 2 (CESM2), with a top at around 140 km. WACCM6 has a horizontal resolution
611 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 μm in radius for the pure sulfate group that sulfate homogeneous nucleation occurs in, and ranges from 0.05 to 8.7 μm 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



655 simulations, the H₂O is injected to 25 to 35 km altitude following Zhu et al. (2022), while the SO₂
656 is injected 82% of the total mass to 26.5-28 km and 18% to 28-36 km altitude. The injection latitude
657 ranges from 22°S to 6°S, and longitude ranges from 182.5°E to 202.5°E.

658

659 **5. Summary**

660 A multi-model observation comparison project is designed to evaluate the impact of the
661 2022 Hunga eruption. Four experiments are designed to cover various research interests for this
662 eruption, including sulfate and water plume dispersion and transport, dynamical and chemical
663 responses in the stratosphere, and climate impact. The project will not only benefit the Hunga
664 Impact assessment, but also benchmark the model performance on simulating stratospheric
665 explosive volcanic eruption events. These events have a potentially large impact on the Earth
666 system, especially on the stratospheric ozone layer and radiative balance.

667

668

669 **Code/Data availability**

670 GloSSAC: DOI (10.5067/GloSSAC-L3-V2.2).

671

672 **Author Contributions:**

673 Y.Z. Concept design, Project Administration, Experiment design, data archive, WACCM models
674 setup;

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

676 E.B. and S.T. and J.Z. Experiment design, conducts experiments using WACCM6MAM;

677 A.B. Experiment design, Data archive;

678 A.J. Experiment 2b prescribed fields preparation;

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

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

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

684 Z.Z. Conducts experiment using WACCM6MAM, WACCM6MAM data post-processing, data
685 archive;

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

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

689 S.R. and S.C. Conducts experiments using IFS-COMPO

690 M.C. Experiment design, Tonga-MIP lead;

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

692 C.B. Conducts experiment using EMAC

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

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

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

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

699 P.C. and P.R.C. Contributed to experiment design and conducted experiments with the NASA
700 GEOS CARMA model



701 H.A. and Y.Y. Conducts experiment using CCSRNIES-MIROC3.2, data post-processing and
702 archive
703 D.V. contributed to experiment design and assisted E.B. with variables request
704 W.R. and P.N. concept design
705 G.M. concept design and in charge of JASMIN data archiving
706 P.Y. and Y.P. conduct experiments using CAM5CARMA and data post-processing
707 S.T. and C.-C. L. conduct experiments using WACCM6CARMA and data post-processing
708

709 **Competing interests**

710 We declare at least one of the co-authors is on the editorial board of GMD.

711

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746



747

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