S5 Hunga Tonga-Hunga Ha'apai Volcano Model Intercomparison Project (Tonga-MIP): Experiment Protocol, Model Descriptions, and Result Preview

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This section is based on: Clyne et al. (2024).

Clyne, M., O.B. Toon, T. Sukhodolov, G.W. Mann, S. Dhomse, S. Tilmes, Y. Zhu, P.R. Colarco, K. Tsigaridis, T. Nagashima, T. Sekiya, K. Sudo, and S. Watanabe, 2024: Tonga-MIP: The Hunga Tonga-Hunga Ha'apai Volcano Model Intercomparison Project. In M. Clyne (Ed.), *Modeling the role of volcanoes in the climate system* (Publication No. 31487034, Doctoral dissertation, University of Colorado at Boulder). Publicly Available Content Database. `https://www.proquest.com/dissertations-theses/modeling-role-volcanoes-climate-system/docview/3100397790/se-2`

Preface

Two major modeling efforts arose following the Hunga eruption. The first, designed for model-to-model comparison with the goal of identifying model differences and their causes, was Tonga-MIP. The second, designed to facilitate model-to-measurement comparison with the goal of predicting climate impacts from the eruption, was the Hunga Tonga-Hunga Ha'apai Model Observations Comparison (HTHH-MOC, Supplementary S1). Here, Supplementary S5 has been compiled to provide a brief overview of Tonga-MIP's experimental protocol and participating models, and to indicate where Tonga-MIP and HTHH-MOC differ in their design.

S5.1 Experiment protocol and model descriptions

Tonga-MIP uses a coordinated experimental protocol that requires all participating models to inject specified amounts of volcanic material at the same time in the same location, and over the same duration. Participating models are not allowed to tune their injection parameters for desired results. This is in contrast to the HTHH-MOC design, where models are given guidelines as to how to inject the material into the stratosphere, but asked to tune their injection parameters so that benchmarks comparing to observations in the early months after the eruption would be met – a requirement to accommodate HTHH-MOC's differing needs. In Tonga-MIP, daily average model outputs from January 1st, 2022 through April 30th, 2022 are used to analyze the microphysical evolution of the volcanic cloud. Hunga's massive water injection plays a role in the chemical lifetime of the SO_2 and subsequent stratospheric aerosol effective radius, composition, mass burden, extinction, and optical depth.

To ease prediction of the longer term climate response, the HTHH-MOC experiments inject the volcanic material at altitudes matching observations of the plume after its initial rapid descent. In order to retain the observed 150 Tg of water perturbation in the stratosphere, participating models had to inject unrealistic quantities of water or spread the water injection over a larger area or over a longer duration to accommodate for the lower water saturation vapor pressure at the HTHH-MOC experiments' target altitudes, where temperatures are lower than at slightly higher altitudes. However, when water injections are made at the higher altitudes observed by the Hunga plume, the water is retained in the stratosphere without falling out immediately as ice. The input values for Tonga-MIP's experimental protocol were selected for accurate representation of the observed injection of the volcanic material, whilst remaining obtainable for all models to comply with under the differing constraints of their grid and temporal resolutions. The fuller justification for Tonga-MIP's experimental protocol and explanations of its finer details remain unchanged, and so we refer the reader to Clyne et al. (2024).

Table S5.1 lists the Tonga-MIP experiments. Table S5.2 lists the participating models and references for the configurations used in Tonga-MIP. Table S5.3 lists the stratospheric aerosol and chemistry packages used in each Tonga-MIP model. Table S5.4 lists the requested outputs from participating models to allow consistent analysis via a MIP postprocessing software package for volcanoes (Clyne, 2024).

S5.2 Result preview

Tonga-MIP has enabled identification of modeling decisions regarding size distribution scheme, stratospheric chemistry, aerosol morphology, physical constants, and algorithm solving that impact aerosol microphysics and are causing underlying differences in simulated stratospheric aerosols. Consequences of differences in some of these fundamentals were made more visible under the extreme conditions of the Hunga event. The importance of continuing educated model developments cannot be understated. If science and policy decisions related to solar radiation modification are to be well informed, some of these intermodel differences will need to be resolved. While the preliminary results of Tonga-MIP can be found in Clyne et al. (2024), the analysis still needs to undergo peer review and additional model runs have since been added. Improved analysis is planned for publication in a peer reviewed journal and has been joined by additional coauthors S. Bekki, N. Lebas, M. Marchand, L. Falletti, and J.R. Pierce.

Table S5.1: *(Reprinted from Clyne et al., 2024). Tonga-MIP experiments. There is also a control run without the volcano. Eruption duration: 6 hours starting at 0400 UTC January 15th. Horizontal area: [22°S, 14°S], [182°E, 186°E]. SO_2 mass injected: 0.5 Tg.*

Exp. Name	**LowAlt**	**LowAltH_2O**	**HighAlt**	**HighAltH_2O**	**LowAltH_2O Free Running**	**HighAltH_2O Free Running**
Altitude SO_2	25–30 km	25–30 km	30–35 km	30–35 km	25–30 km	30–35 km
H_2O Mass injected	X	150 Tg	X	150 Tg	150 Tg	150 Tg
Altitude H_2O	X	25–30 km	X	30–35 km	25–30 km	30–35 km
Nudging	Specified Dynamics	Specified Dynamics	Specified Dynamics	Specified Dynamics	Free Running	Free Running

Table S5.2: *Participating models and references for the configurations used in Tonga-MIP (adapted from Clyne et al., 2024).*

Model	**Horizontal resolution (lat × lon)**	**Model top (levels)**	**Specified dynamics source**	**Reference paper**
CESM2-WACCM6-MAM4	0.95° × 1.25°	4.5×10^{-6} hPa (70)	GEOS5	Tilmes et al. (2023)
CESM2-WACCM6-CARMA	0.95° × 1.25°	4.5×10^{-6} hPa (70)	GEOS5	Tilmes et al. (2023)
GA4 UM-UKCA	1.25° × 1.875°	85 km (85)	ERA5	Dhomse et al. (2020)
SOCOLv4	1.9° × 1.9°	0.01 hPa (47)	ERA5	Sukhodolov et al. (2021)
MIROC ES2H	2.8° × 2.8°	0.004 hPa (81)	MERRA-2	Tatebe et al. (2019) and Kawamiya et al. (2020)
GEOS-V GOCART GMI[a]	Cubed sphere 90×90×6 (1°)	0.01 hPa (72)	MERRA-2 / GEOS-FP	Nielsen et al. (2017)
IPSLCM7[b] LMDZ-STRATAER-REPROBUS	1.3° × 2.5°	0.03 hPa (79)	ERA5	—

[a]) GEOS-V has comprehensive microphysics when configured with CARMA (Case et al., 2023), but not when configured with GOCART.

[b]) IPSLCM7 is a new development since the CMIP6 version of the IPSL-CM6A-LR climate model described in Boucher et al. (2020). The IPSLCM7 version still uses the atmospheric general circulation model LMDZ (Hourdin et al., 2020), now version 6.2, and couples with stratospheric aerosol chemistry and microphysics modules STRATAER and REPROBUS (see Table S V.3).

Table S5.3: *Overview of stratospheric aerosol and chemistry packages used in each Tonga-MIP model (adapted from Clyne et al., 2024).*

Model	Aerosol size distribution	Aerosol package	Reference	Chemistry package	Reference
CESM2-WACCM6-MAM4	modal	MAM4	Liu et al., 2016	WACCM6	Gettelman et al. (2019)
CESM2-WACCM6-CARMA	sectional	CARMA	Tilmes et al. (2023)	WACCM6	Gettelman et al. (2019)
GA4 UM-UKCA	modal	GLOMAPv8.2	Mann et al. (2010)	StratTrop	Archibald et al. (2020)
SOCOLv4	sectional	AER	Sukhodolov et al. (2021)	MEZON	Egorova et al. (2003)
MIROC ES2H	modal	SPRINTARS6.0	Sekiya et al. (2016)[a]	CHASER4.0	Sudo and Akimoto (2007) and Sudo et al. (2002)
GEOS-V GOCART GMI	bulk	GOCART	Colarco et al., 2010	GMI	Duncan et al. (2007)
IPSLCM7 LMDZ-STRATAER-REPROBUS	sectional	STRATAER[b]	—	REPROBUS	Marchand et al., 2012

[a]) The Spectral Radiation Transport Model for Aerosol Species (SPRINTARS; Takemura et al., 2000; Takemura et al., 2002; Takemura et al., 2005; Takemura et al., 2009) is developed for modal size distribution in Sekiya et al. (2016).

[b]) STRATAER is an improved version of the Sectional Stratospheric Sulfate Aerosol module (S3A; Kleinschmitt et al., 2017) used in IPSL-CM6A-LR, and is still under development.

Table S5.4: *Requested outputs from participating models to allow consistent analysis via the Tonga-MIP postprocessing package for volcanoes (Clyne, 2024). All data are provided clearly labeled with units included in the metadata. Units related by powers of 10 are acceptable. Variables marked with an asterisk (*) in the help description are not required if unavailable.*

Short name	Long name	Units	Dimensions	Help description
Dimensions				
lev	Vertical gridbox level pressure	hPa	[lev]	
ilev	Pressure at grid level interface	hPa	[ilev] = [lev] + 1	* not required if unavailable
lat	Latitude	degrees north	[lat]	
lon	Longitude	degrees east	[lon]	
time	Time dimension	days since run start	[time]	e.g., "days since 2022-01-01 00:00:00"
Variables				
date	Date corresponding to time dimension	YYYYMMDD or YYYY-MM-DD	[time]	
AREA	Horizontal area of grid box	m^2	[time,lat,lon]	Only need one instance in time
MASS	Mass of grid box	kg	[time,lev,lat,lon]	* Can be substituted with density (DENS) if MASS unavailable
TROP_P	Tropopause pressure	Pa	[time,lat,lon]	
TROP_Z	Tropopause altitude	m	[time,lat,lon]	
T	Temperature	K	[time,lev,lat,lon]	
PBLH	Planetary Boundary Layer height	m	[time,lat,lon]	
PS	Surface pressure	Pa	[time,lat,lon]	
Z3	Geopotential height	m	[time,lev,lat,lon]	* not required if unavailable
OH	OH mixing ratio	mol/mol	[time,lev,lat,lon]	
O_3	Ozone mixing ratio	mol/mol	[time,lev,lat,lon]	
SO	SO mixing ratio	mol/mol or kg/kg	[time,lev,lat,lon]	Dry mixing ratio; * not required if unavailable
SO_2	Sulfur dioxide mixing ratio	mol/mol or kg/kg	[time,lev,lat,lon]	Dry mixing ratio
SO_3	SO_3 mixing ratio	mol/mol or kg/kg	[time,lev,lat,lon]	Dry mixing ratio; * not required if unavailable
H_2SO_4	Sulfuric acid mixing ratio	mol/mol or kg/kg	[time,lev,lat,lon]	Dry mixing ratio
SO_4	Sulfate aerosol dry mixing ratio	kg/kg or mol/mol	[time,lev,lat,lon]	If multiple modes, provide each with description
WTPER	H_2SO_4 weight percent	%	[time,lev,lat,lon]	Weight percent in wet sulfate aerosol (H_2O–H_2SO_4)
SO_2_CHML	SO_2 chemical loss rate	$/cm^3/s$	[time,lev,lat,lon]	* not required if unavailable, but preferred
EXTINCTUV	Aerosol extinction 350 nm	1/m or 1/km	[time,lev,lat,lon]	
EXTINCT	Aerosol extinction 550 nm	1/m or 1/km	[time,lev,lat,lon]	
EXTINCTNIR	Aerosol extinction 1020 nm	1/m or 1/km	[time,lev,lat,lon]	
SAD_AERO	Aerosol surface area density	cm^2/cm^3 or $\mu m^2/cm^3$ or $\mu m^2/\mu m^3$	[time,lev,lat,lon]	

Table S5.4 (continued)

Short name	**Long name**	**Units**	**Dimensions**	**Help description**
REFF_AERO	Aerosol effective radius (wet)	cm or μm	[time,lev,lat,lon]	
dgnumwet	Aerosol mode wet diameter (each mode)	m	[time,lev,lat,lon]	Provide for each mode if modal model
num_ax	Mode number mixing ratio	1/kg	[time,lev,lat,lon]	Provide for each mode if modal model
AODUV	Aerosol optical depth 350 nm	none	[time,lat,lon]	Total column
AODUVst	Stratospheric AOD 350 nm	none	[time,lat,lon]	Column from tropopause to TOA; * not required if unavailable
AODVIS	Aerosol optical depth 550 nm	none	[time,lat,lon]	Total column; * not required if unavailable
AODVISst	Stratospheric AOD 550 nm	none	[time,lat,lon]	Column from tropopause to TOA; * not required if unavailable
AODNIR	Aerosol optical depth 1020 nm	none	[time,lat,lon]	Total column; * not required if unavailable
AODNIRst	Stratospheric AOD 1020 nm	none	[time,lat,lon]	Column from tropopause to TOA; * not required if unavailable
H_2O	Water vapor mixing ratio	mol/mol	[time,lev,lat,lon]	
FLDS	Downwelling longwave flux at surface	W/m^2	[time,lat,lon]	* not required if unavailable
FLNS	Net longwave flux at surface	W/m^2	[time,lat,lon]	* not required if unavailable
FLNR	Net longwave flux at tropopause	W/m^2	[time,lat,lon]	* not required if unavailable
FLNT	Net longwave flux at top of model	W/m^2	[time,lat,lon]	* not required if unavailable
FLUT	Upwelling longwave flux at top of model	W/m^2	[time,lat,lon]	* not required if unavailable
FSDS	Downwelling solar flux at surface	W/m^2	[time,lat,lon]	* not required if unavailable
FSNS	Net solar flux at surface	W/m^2	[time,lat,lon]	* not required if unavailable
FSNR	Net solar flux at tropopause	W/m^2	[time,lat,lon]	* not required if unavailable
SOLIN	Solar insolation (TOA downwelling)	W/m^2	[time,lat,lon]	* not required if unavailable
FSNT	Net solar flux at top of model	W/m^2	[time,lat,lon]	* not required if unavailable
FSUTOA	Upwelling solar flux at top of model	W/m^2	[time,lat,lon]	* not required if unavailable

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