

Projecting the Lasting Fate of the Hunga Tonga-Hunga Ha'apai Eruption on the Stratosphere through Connecting Measurements to Models

Luke Oman¹, Pete Colarco¹, Qing Liang¹, Steve Steenrod^{1,2}, Paul Newman¹, Eric Fleming^{1,3}, and Ghassan Taha^{1,4}

¹NASA/GSFC, Greenbelt, MD, USA

²University of Maryland-Baltimore County, Baltimore, MD USA

³Science Systems and Applications, Latham, MD USA

⁴Morgan State University, MD, USA

Introduction

On 15th Jan. 2022 the submarine volcano Hunga Tonga-Hunga Ha'apai (HTHH) injected approximately 0.5 Tg of sulfur dioxide into the stratosphere, but more significantly added 150-170 Tg of water vapor to the stratospheric background (an 11-12% perturbation) in a matter of several hours. The sulfur dioxide rapidly converted to sulfate aerosol and along with water vapor, was transported around the Southern Hemisphere sub-tropics into midlatitudes with some transport into the Northern Hemisphere. With a much longer lifetime than sulfate aerosol, measurable water vapor anomalies are likely to persist for the remainder of the decade. Satellite measurements from limb and nadir viewing observing instruments provide the information needed to reasonably initialize the HTHH eruption in the Goddard Earth Observing System (GEOS) model using the "replay" framework coupled to the Global Modeling Initiative (GMI) stratosphere-troposphere chemical mechanism for the recent past and continue the simulations into the future with the free running chemistry climate model (CCM).

Hunga Tonga-Hunga Ha'apai Eruption - Water Vapor

It is important to properly model the latitudinal extent of the umbrella cloud which is shown in the figure to right to be about 450-600 km.

For the main eruption we use an equal weighted injection of 6° latitude by 4° longitude between 20-30 km in altitude.

Main eruption: Jan 15, 2022

8-hr (4z-12z) injecting ~600 Tg of H₂O and 0.5 Tg SO₂ in GEOSCCM

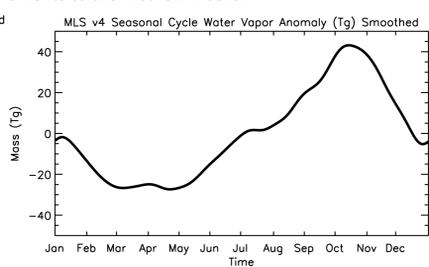
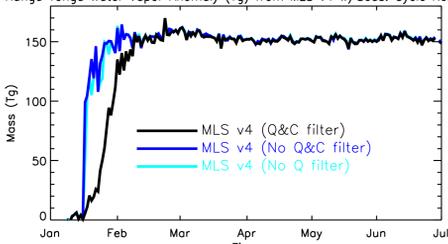
Smaller injections are included on Jan. 13th and 14th

GEOS CCM – Goddard Earth Observing System Chemistry Climate Model coupled with the Stratosphere-Troposphere Global Modeling Initiative (GMI) Chemical Mechanism and GOCART Aerosol module

Measurements from MLS show a significant increase in stratospheric water vapor of over 150 Tg possibly close to 170 Tg. Background stratospheric water vapor is ~1375 Tg (above 100 hPa) so this represents an ~11-12% increase injected over a several hours.

The figure to the top right shows the calculated water vapor mass (Tg) using the MLS v4.2 recommended quality and convergence filtering (black curve) as well as when no quality filter is used (cyan curve) and when no quality and convergence filtering is used (blue curve) which adds measurements to the first few weeks.

Hunga Tonga Water Vapor Anomaly (Tg) from MLS v4 w/Seas. Cycle Removed



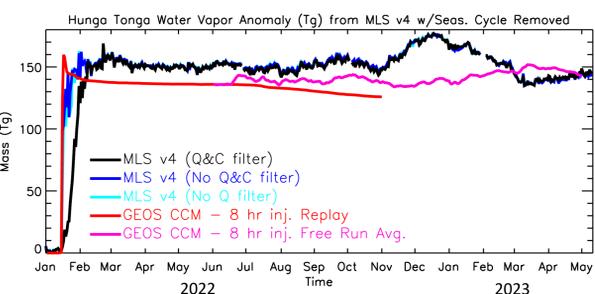
MLS Team indicated an issue with v5 H₂O because of change in T/P algorithm and recommend using v4.2

The remaining difference with the expected injection amount is from under-sampling the plume in the early days. The figure to right above shows the size of the seasonal cycle in water vapor mass which is typically decreasing Jan-Mar

We modeled the Hunga Tonga water vapor injection with GEOS CCM coupled to GMI chemistry. The simulations include both replay and an ensemble of free running simulations.

GEOS CCM with Replay is added to the MLS curves shown in for an 8-hr injection (red, solid curve)

GEOS CCM free running simulations starting in June 2022 (magenta, solid curve)



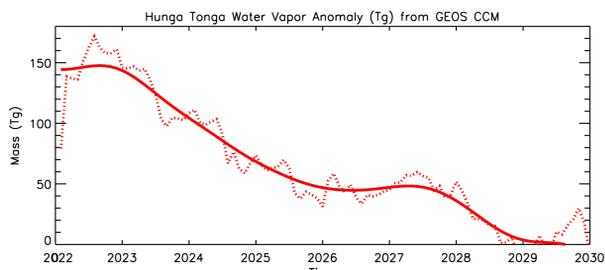
The 8-hr injection runs about 10-15% low but reasonable in comparison to MLS.

Much of the injection is removed by immediate condensation (~75%) and what remains is near saturation, an additional 15% is removed in the first few days with a slower/smaller removal over the subsequent weeks possibly related to moving over a colder part of the atmosphere and the PDF function used for condensation in the model.

We are continuing these simulations to look at the evolution of water vapor in the stratosphere and the time scales for removal.

A difference in water vapor in a pair of GEOS CCM is shown below as red (dotted curve) and after smoothing (red solid curve) suggesting a 3-4 year e-folding time scale for removal.

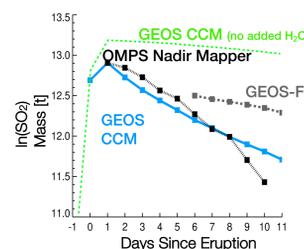
With no significant reaction loss pathways the main removal mechanism is through polar dehydration and transport back into the troposphere through the large-scale BD circulation and tropopause folding.



Hunga Tonga-Hunga Ha'apai Eruption – SO₂ and Aerosols

GEOS CCM shows a significant impact from the water vapor injection on the evolution of the SO₂ injection.

The lifetime of Hunga Tonga SO₂ is significantly reduced to 6-8 days and compares well with the model simulation that includes the enhanced water vapor injection and would have remained much longer with background water vapor



The black curve shows OMPS_NM SO₂ evolution.

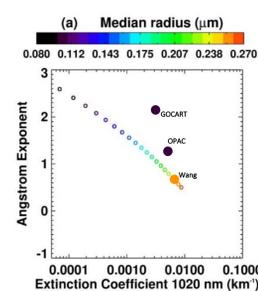
The solid blue curve shows GEOS CCM with the added water vapor injection compared to a much slower SO₂ decay with background stratospheric water vapor (dotted green).

The dotted gray curve is from GEOS-FP run at very high resolution but only background water vapor.

Simulated aerosol profile is similar in spatial extent to OMPS LP observations, but underestimates magnitude of the sulfate extinction especially at lower altitudes.

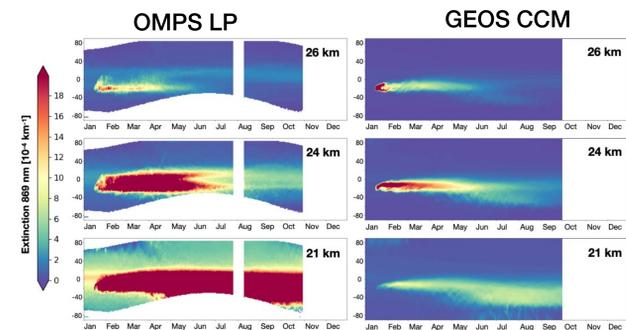
What could be causing the difference?
Missing microphysics or direct sulfate injections?

Mass Extinction Efficiency of background stratospheric sulfate-sized particles ~1/2 MEE of larger (Pinatubo-like) sulfate aerosols



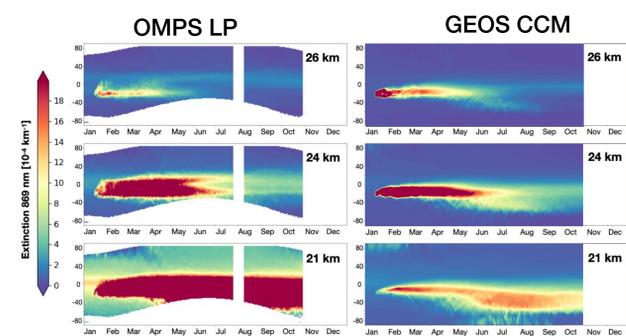
Wang et al., 2023

Some remaining differences related to the slightly higher extinction at the higher levels and still too low at lower levels would be partially addressed by the larger observed aerosol size than was assumed causing greater fall velocities. This would reduce extinction at higher levels and increase it at lower levels.



Using results from Wang et al. 2023 the optical properties table was changed to reflect the new information related to Angstrom Exponent and mass extinction efficiency.

As a post processing step the new tables were provided to update the aerosol extinction coefficient. Showing an overall better agreement with OMPS LP measurements.



Discussion and Future Work

- Hunga Tonga increased the background stratospheric water vapor by about 11-12% in several hours
- This water vapor has a 3-4 year e-folding time scale for removal, mainly by polar dehydration and removal by transport back into the troposphere
- Having a collocated water vapor injection is critical to get the very short lifetime of SO₂ that was observed due to enhanced OH concentrations
- A sizable (5-10) ensemble of simulations is going to be necessary to distinguish some of the impacts from natural variations
- Revisiting the optical properties of sulfate aerosol in our model is helpful to comparisons with OMPS-LP but differences remain

While OMPS-NM and OMPS-LP will continue to provide information about SO₂ and aerosols along with more limited trace gas information (like O₃) with the continued plan for JPSS satellites, we are losing important trace gas information like H₂O and other species with the nearing end of Aura. It is going to be very important to be able to fully track the fate and transport of Hunga Tonga impacts which will likely affect stratospheric composition over the remainder of this decade.

Acknowledgements

We would like to thank the NASA MAP program for supporting this work, the GEOS CCM, and GMI development and NASA NCCS for computing resources.