Clarifying the Fate of Hunga Tonga Water Vapor with a Tagged Tracer Simulation

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1. Motivation: Balancing the HTHH Water Vapor Budget

The explosive Hunga Tonga-Hunga Ha'apai (HTHH) volcanic eruption **injected an unprecedented 150 Tg of water vapor into the stratosphere** in January of 2022, leading to significant local cooling and ozone loss [1]. Previous studies have determined the impact of the volcanic water vapor plume using the difference between model simulations with and without (counterfactual) the HTHH water vapor perturbation. However, mixing with background water vapor and low signal-to-noise ratios limit the usefulness of this approach in precisely diagnosing the radiative forcing and fate of HTHH emissions. **To clarify the relative importance of removal mechanisms, we implement a new volcanic water tracer** in the National Center for Atmospheric Research (NCAR) Community Atmosphere Model (CAM).

2. Model Setup: Tagged Volcanic Water Tracer Development

Adaptation of isotope-enabled CAM

The tagged volcanic tracer developed in this study is based on the isotope-enabled version of CAM, iCAM6 [2]. **Tagged tracers in iCAM6 undergo a parallel water cycle** with optional fractionation effects. Several code modifications were needed to adapt iCAM6 for the tagged volcanic tracer:

- Removal of surface sources of volcanic water (no re-evaporation)
- CFL number calculation in water tracer microphysics was adjusted to enable accurate tracer simulation in a high-top configuration
- Volcanic water registered in WACCM chemistry package, which handles unified Tropospheric, Stratospheric, Mesospheric, and lower Thermospheric (TSMLT) chemistry

Experiment 2a protocol (HTHH Model-Observation Comparison)

Designed to analyze the radiative and chemical impact of HTHH water without dynamical feedbacks, this experiment entails [3]:

- **3-hourly nudging of U, V, and T to MERRA2 reanalysis**
- Prognostic modal aerosols (MAM4 model)
- 150 Tg of H2O and 0.5 Tg of SO2 applied over 6-hour period on **01/15/2022**
- Typically, two simulations (SO2+H2O and control) to determine impact.
- **Only one tagged tracer simulation is needed to determine impact.**

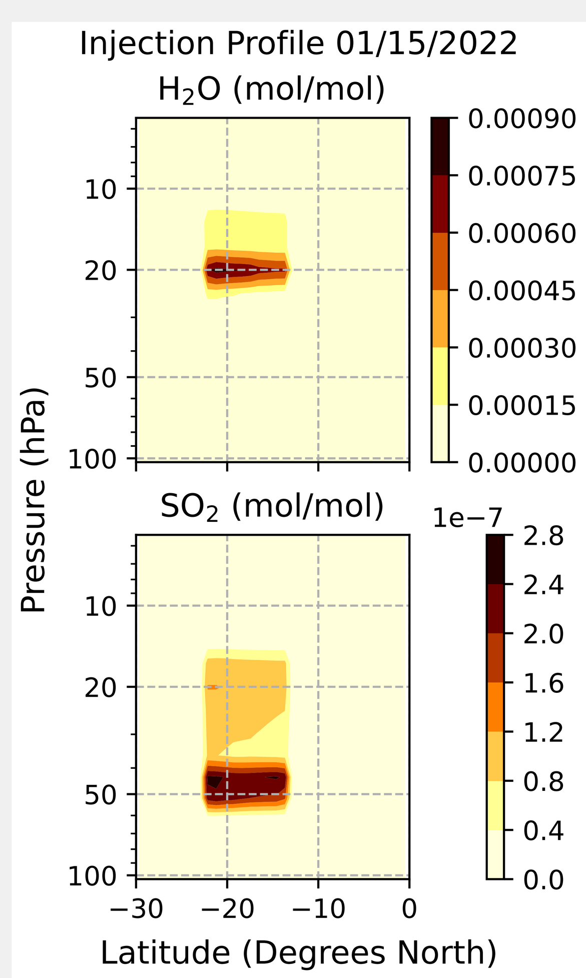

Figure 1. Injection Profile for HTHH H2O and SO2

3. Data for Verification

- Daily and monthly mean H2O vapor mixing ratios are obtained from the **Stratospheric Water and OzOne Satellite Homogenized (SWOOSH)** data set [4], which assimilates Aura MLS measurements.
  - The HTHH water vapor anomaly was calculated by subtracting 2005-2021 climatology from 2022-2023 data.
- Exp. 2a SO2+H2O and control WACCM simulations (not tagged) [5]
  - The HTHH water vapor anomaly is SO2+H2O - control

4. Tagged Tracer Verification

Global comparison of HTHH water anomaly with observations

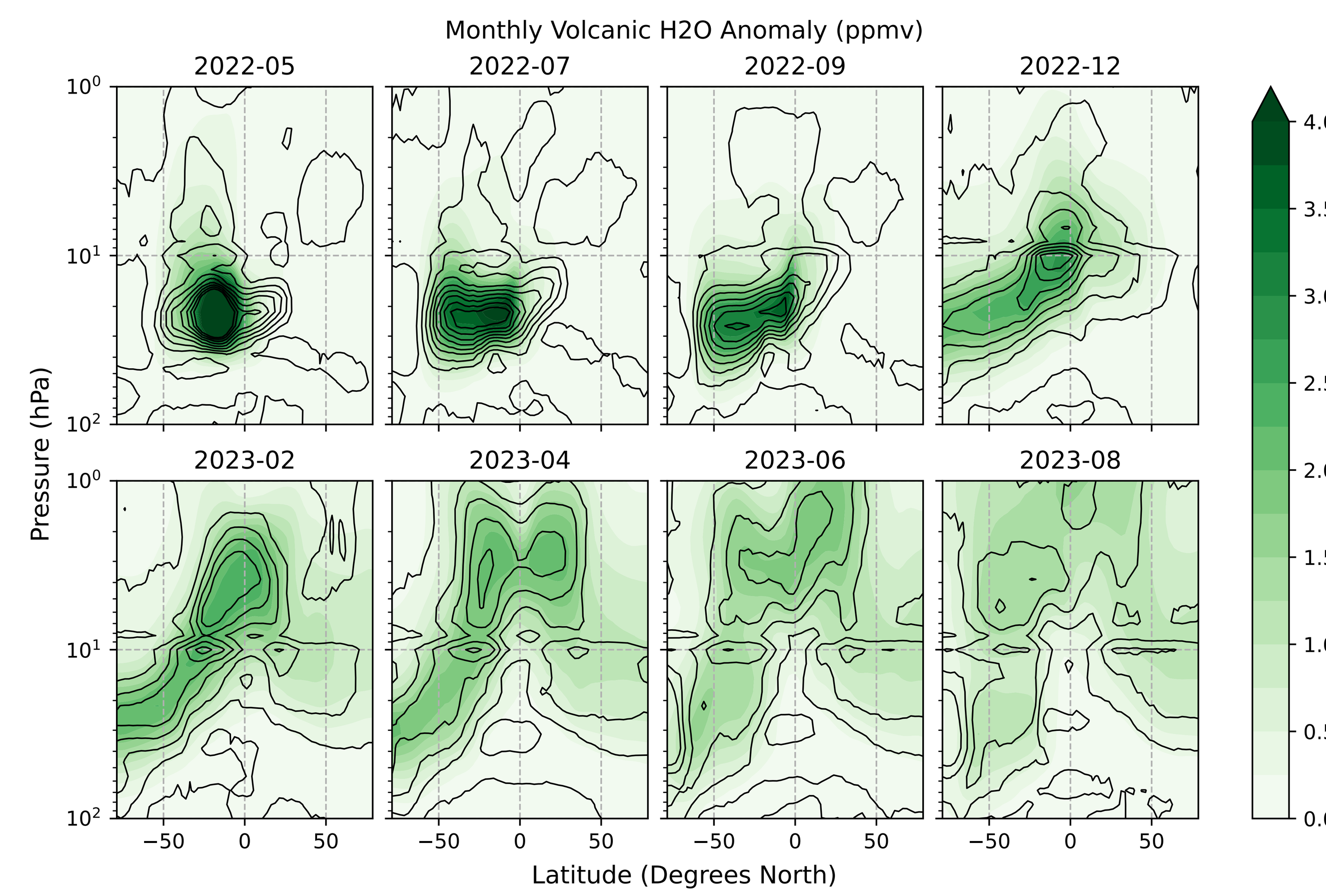

Figure 2. Zonal mean HTHH water vapor anomaly for selected months in 2022-2023 from WACCM tagged simulations (filled contours) and SWOOSH-MLS data (black contours).

HTHH water vapor anomalies calculated using MLS data and the WACCM tagged volcanic tracer exhibit a very similar temporal evolution characterized by **upward and poleward spreading with the Brewer-Dobson circulation**

Regional comparison: Southern Hemisphere polar vortex

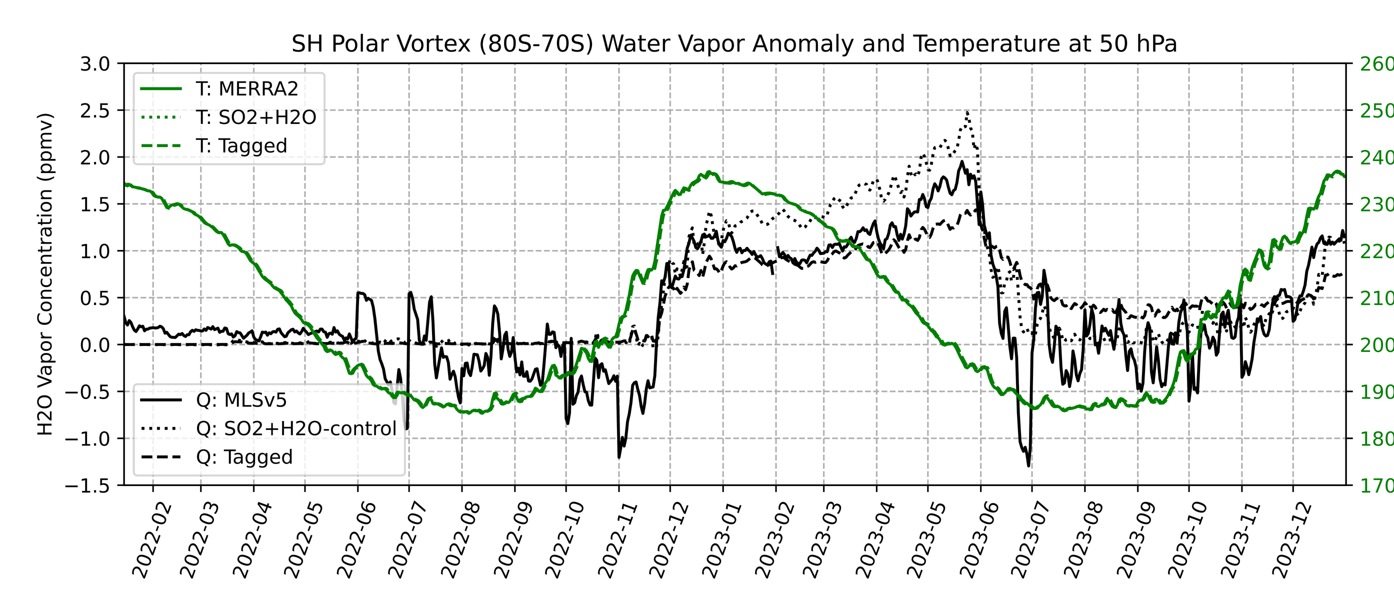

Figure 3. Southern hemisphere polar vortex-averaged HTHH water vapor anomaly from MLSv5 (black, solid), WACCM counterfactual (black, dotted), and WACCM tagged (black, dashed), and average temperature (green, line styles as before).

HTHH plume dehydration aligns temporally in simulations and observations and is of similar magnitude.

Key Takeaways

- Tagged volcanic tracer captures observed HTHH plume evolution well
- Antarctic vortex dehydration followed by precipitation confirmed as major removal mechanism of HTHH water

Future work

- HTHH water vapor radiative forcing
- Update iCAM6 model code to enable a direct comparison between counterfactual and tagged approaches
- Implementation of tagged water thermodynamic tendencies **(passive -> active)**

5. Budget Analysis: HTHH H_2O Removal Mechanisms

Antarctic vortex dehydration

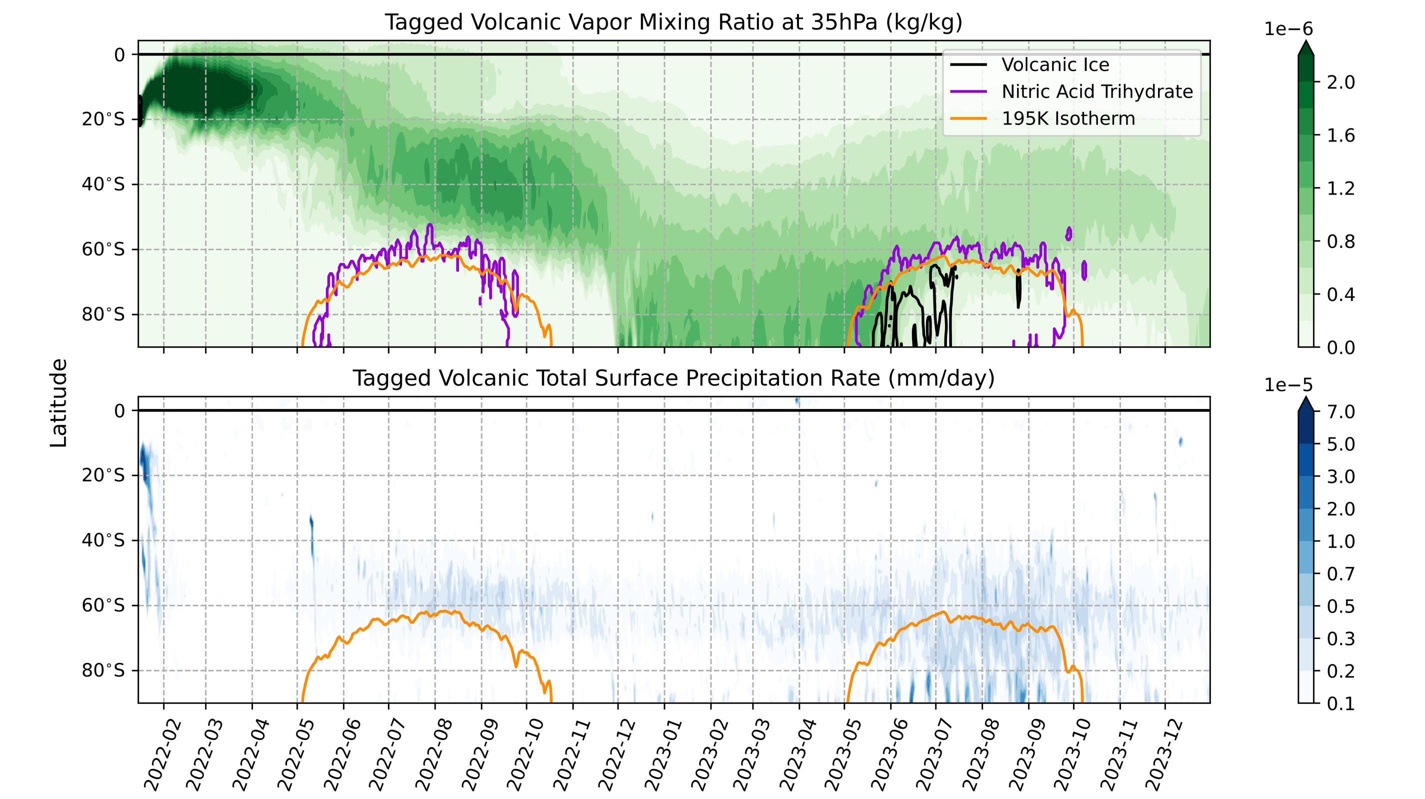

Figure 4. 35 hPa tagged volcanic water vapor anomaly (top) and total volcanic precipitation rate (bottom) for the first two years after the HTHH eruption. Also shown are the **35hPa** 195K isotherm (orange), zero contour for nitric acid trihydrate (magenta), and 2×10^{-8}kg/kg mixing ratio for volcanic cloud ice (black).

Volcanic vapor in the SH polar vortex freezes in polar stratospheric clouds (PSCs) and descends with the Brewer-Dobson circulation, later **exiting the system as precipitation in the form of snow**.

Stratosphere-troposphere exchange

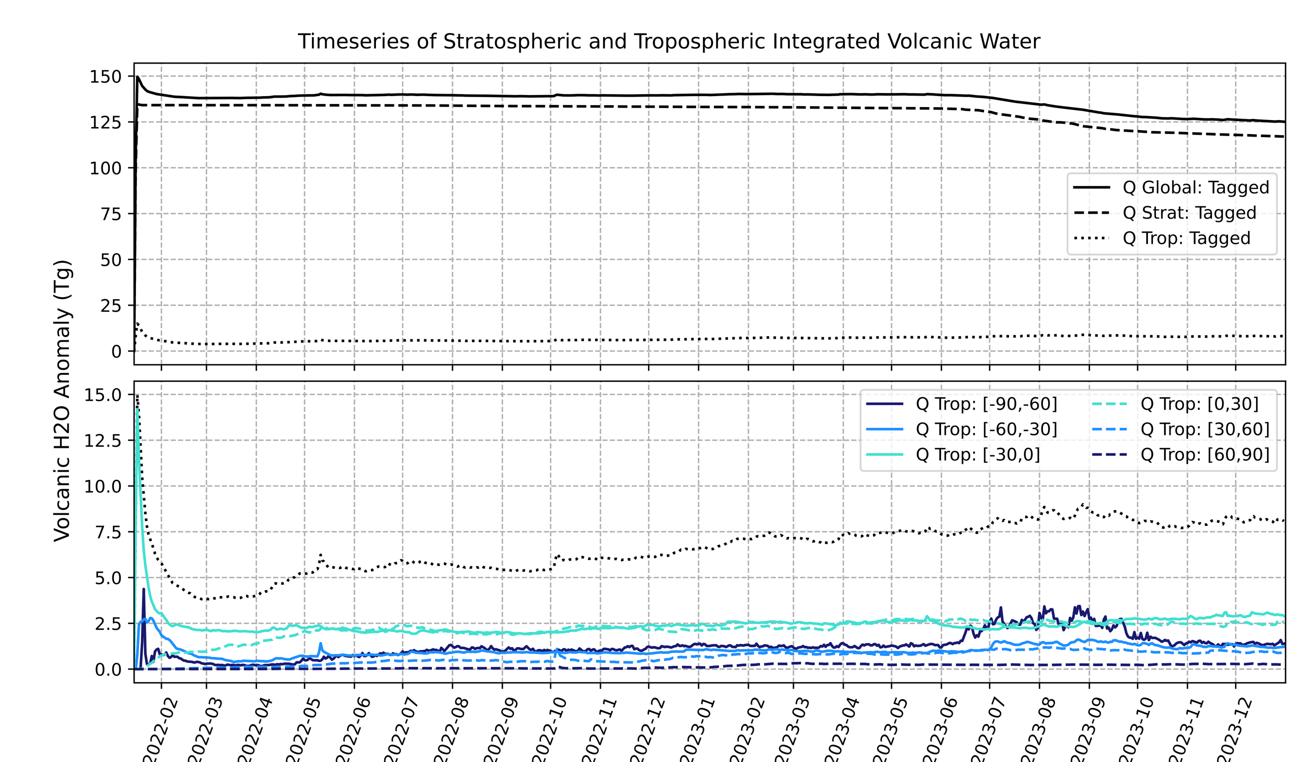

Figure 5. (Top) Timeseries of global- (solid), stratospheric- (dashed), and tropospheric-integrated (dotted) tagged volcanic water (all types). (bottom) Timeseries of tropospheric volcanic water integrated over various latitude bounds.

A large portion of the descending volcanic ice sublimates, as evidenced by the spike in tropospheric integrated water from 90-60S around August 2022 (phase breakdown not shown). **Before this point, there is little change in stratospheric anomaly.**

References

[1] Xinyue Wang et al. "Stratospheric Climate Anomalies and Ozone Loss Caused by the Hunga Tonga-Hunga Ha'apai Volcanic Eruption". (2023). DOI: 10.1029/2023JD039480.

[2] Jesse Nusbaumer et al. "Evaluating hydrological processes in the Community Atmosphere Model Version 5 (CAM5) using stable isotope ratios of water". (2017). DOI: 10.1002/2016MS000839.

[3] Yunqian Zhu et al. "Hunga Tonga–Hunga Ha'apai Volcano Impact Model Observation Comparison (HTHH-MOC) project: experiment protocol and model descriptions". (2025). DOI: 10.5194/gmd-18-5487-2025.

[4] Sean M. Davis et al. "The Stratospheric Water and Ozone Satellite Homogenized (SWOOSH) database: a long-term database for climate studies". (2016). DOI: 10.5194/essd-8-461-2016.

[5] Jun Zhang et al. "Chemistry Contribution to Stratospheric Ozone Depletion After the Unprecedented Water-Rich Hunga Tonga Eruption". (2024). DOI: 10.1029/2023GL105762.

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