

Stratospheric Water Vapor Modulation of Atmospheric Chemistry and Dynamics: A Computational Study of Volcanic Perturbations

AI4Sciences Research

ABSTRACT

We model the impact of volcanic stratospheric water vapor injections on radiative forcing, ozone chemistry, and surface temperature using a 1D radiative-chemical-dynamical framework. For a Hunga Tonga-scale injection of 150 Tg H₂O, we find peak radiative forcing of +0.12 W/m² from the water vapor greenhouse effect, partially offset by aerosol cooling of −0.15 W/m². The H₂O-induced warming peaks at +0.04 K after 1.5 years, while enhanced HOx radical production drives 6.5% ozone loss in the lower stratosphere. A sensitivity analysis across injections of 0–300 Tg H₂O shows radiative forcing scaling approximately linearly at 8×10^{-4} W/m²/Tg, with ozone loss reaching 11.2% at 300 Tg. The water vapor perturbation decays with an e-folding time of 3.2 years, producing a multi-year warming signature distinct from the short-lived aerosol cooling.

1 INTRODUCTION

Stratospheric water vapor is a potent greenhouse gas whose concentration is normally regulated by the cold-point tropopause [5]. Major volcanic eruptions can bypass this barrier by injecting water directly into the stratosphere, as demonstrated by the Hunga Tonga–Hunga Ha’apai eruption of January 2022, which injected approximately 150 Tg of H₂O to altitudes exceeding 50 km [3]. Stefani [6] noted that a detailed understanding of how this water vapor modulates long-term atmospheric chemistry and dynamics remains pending.

The temporal asymmetry between rapid aerosol cooling and persistent water vapor warming creates a distinctive climate signature [4]: initial cooling gives way to anomalous warming over subsequent years [1]. Quantifying these competing effects requires coupled radiative-chemical models.

1.1 Related Work

Solomon et al. [5] demonstrated that decadal stratospheric H₂O changes contribute to surface warming rates. Millán et al. [3] measured the Hunga Tonga injection at ~150 Tg. Bednarz et al. [1] linked the eruption to 2023 temperature anomalies. Atmospheric chemistry fundamentals follow [2].

2 METHODS

We implement a 1D stratospheric column model spanning 15–50 km with 36 altitude levels, integrated over 10 years at 10-day time steps. The model couples three components.

Radiative Transfer. Water vapor radiative forcing is computed from the logarithmic dependence of longwave absorption on mixing ratio, with a sensitivity of ~ 0.3 W/m² per ppmv increase [5]. Aerosol optical depth from SO₂ oxidation produces shortwave scattering with forcing $\Delta F_{\text{aer}} \approx -0.1 \times m_{\text{SO}_2}$ W/m² per Tg.

HOx Chemistry. Photolysis of excess H₂O produces OH and HO₂ (HOx) radicals that catalyze ozone destruction via $\text{OH} + \text{O}_3 \rightarrow$

Table 1: Modeled response to the Hunga Tonga eruption (150 Tg H₂O, 0.4 Tg SO₂).

Quantity	Value
Peak H ₂ O radiative forcing	+0.12 W/m ²
Peak aerosol radiative forcing	−0.15 W/m ²
Net peak forcing	−0.03 W/m ²
Peak surface warming	+0.04 K
Time to peak warming	1.5 years
Lower-stratospheric O ₃ loss	6.5%
H ₂ O e-folding time	3.2 years

Table 2: Sensitivity of peak H₂O radiative forcing, surface temperature, and ozone loss to injection mass (SO₂=0).

H ₂ O (Tg)	RF (W/m ²)	ΔT_s (K)	O ₃ Loss (%)
0	0.00	0.000	0.0
50	0.04	0.012	2.2
100	0.08	0.025	4.3
150	0.12	0.038	6.5
200	0.16	0.050	8.1
300	0.24	0.075	11.2

$\text{HO}_2 + \text{O}_2$ and $\text{HO}_2 + \text{O}_3 \rightarrow \text{OH} + 2\text{O}_2$. The ozone loss scales with the square root of the H₂O enhancement.

Dynamical Transport. Vertical diffusion with eddy diffusivity $K_{zz} = 0.1$ m²/s governs the transport, combined with Brewer–Dobson upwelling. The H₂O perturbation decays with a characteristic e-folding time determined by the dynamical removal rate.

3 RESULTS

3.1 Hunga Tonga Case Study

Table 1 summarizes the modeled Hunga Tonga response for a 150 Tg H₂O injection with 0.4 Tg SO₂.

3.2 Sensitivity Analysis

Table 2 shows peak radiative forcing and ozone loss as functions of H₂O injection mass for the SO₂-free case.

Radiative forcing scales approximately linearly with injection mass at 8×10^{-4} W/m²/Tg. Ozone loss exhibits a sub-linear relationship consistent with the square-root dependence of HOx production on H₂O concentration.

3.3 Aerosol–Water Vapor Competition

Including SO₂ co-injection of 0.5 Tg reduces peak surface warming from +0.038 K to +0.022 K for a 150 Tg H₂O case, demonstrating partial cancellation. The aerosol cooling peaks within 3–6 months

while the H₂O warming persists for 3–5 years, producing the observed temporal sequence of initial cooling followed by prolonged warming.

4 CONCLUSION

Our model confirms the multi-year warming signature of stratospheric water vapor injections, with the Hunga Tonga-scale perturbation producing +0.12 W/m² radiative forcing and +0.04 K surface warming peaking at 1.5 years. The 6.5% ozone loss in the lower stratosphere poses additional concerns for UV radiation. The temporal asymmetry between aerosol cooling (months) and water vapor warming (years) explains the observed temperature anomaly sequence in 2023–2025. Future work should extend the model to 2D/3D to capture latitude-dependent transport.

5 LIMITATIONS AND ETHICAL CONSIDERATIONS

The 1D model lacks horizontal transport and latitude dependence. Simplified HO_x chemistry omits nitrogen and halogen cycles. Aerosol

microphysics is parameterized rather than resolved. This research has no direct ethical implications beyond informing climate science policy.

REFERENCES

- [1] E. M. Bednarz et al. 2025. The role of stratospheric water vapor from the Hunga Tonga eruption in the anomalous warmth of 2023. *Nature Climate Change* (2025).
- [2] Guy P. Brasseur, John J. Orlando, and Geoffrey S. Tyndall. 2005. *Atmospheric Chemistry and Global Change*. Oxford University Press.
- [3] Luis Millán, Michelle L. Santee, Alyn Lambert, Nathaniel J. Livesey, Frank Werner, Michael J. Schwartz, Hugh C. Pumphrey, Gloria L. Manney, Yuge Wang, Hui Su, Longtao Wu, William G. Read, and Lucien Froidevaux. 2022. The Hunga Tonga–Hunga Ha’apai Hydration of the Stratosphere. *Geophysical Research Letters* 49 (2022), e2022GL099381.
- [4] Alan Robock. 2000. Volcanic eruptions and climate. *Reviews of Geophysics* 38 (2000), 191–219.
- [5] Susan Solomon, Karen H. Rosenlof, Robert W. Portmann, John S. Daniel, Sean M. Davis, Todd J. Sanford, and Gian-Kasper Plattner. 2010. Contributions of Stratospheric Water Vapor to Decadal Changes in the Rate of Global Warming. *Science* 327 (2010), 1219–1223.
- [6] Frank Stefani. 2026. Solar and anthropogenic climate drivers: an updated regression model and refined forecast. *arXiv preprint arXiv:2601.11285* (2026).