

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

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## 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 H<sub>2</sub>O, we find peak radiative forcing of +0.12 W/m<sup>2</sup> from the water vapor greenhouse effect, partially offset by aerosol cooling of -0.15 W/m<sup>2</sup>. The H<sub>2</sub>O-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 H<sub>2</sub>O shows radiative forcing scaling approximately linearly at  $8 \times 10^{-4}$  W/m<sup>2</sup>/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 H<sub>2</sub>O 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 H<sub>2</sub>O 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  $\sim 0.3$  W/m<sup>2</sup> per ppmv increase [5]. Aerosol optical depth from SO<sub>2</sub> oxidation produces shortwave scattering with forcing  $\Delta F_{\text{aer}} \approx -0.1 \times m_{\text{SO}_2}$  W/m<sup>2</sup> per Tg.

**HOx Chemistry.** Photolysis of excess H<sub>2</sub>O produces OH and HO<sub>2</sub> (HOx) radicals that catalyze ozone destruction via  $\text{OH} + \text{O}_3 \rightarrow$

**Table 1: Modeled response to the Hunga Tonga eruption (150 Tg H<sub>2</sub>O, 0.4 Tg SO<sub>2</sub>).**

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

**Table 2: Sensitivity of peak H<sub>2</sub>O radiative forcing, surface temperature, and ozone loss to injection mass (SO<sub>2</sub>=0).**

H <sub>2</sub> O (Tg)	RF (W/m <sup>2</sup> )	$\Delta T_s$ (K)	O <sub>3</sub> 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 H<sub>2</sub>O enhancement.

**Dynamical Transport.** Vertical diffusion with eddy diffusivity  $K_{zz} = 0.1$  m<sup>2</sup>/s governs the transport, combined with Brewer–Dobson upwelling. The H<sub>2</sub>O 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 H<sub>2</sub>O injection with 0.4 Tg SO<sub>2</sub>.

### 3.2 Sensitivity Analysis

Table 2 shows peak radiative forcing and ozone loss as functions of H<sub>2</sub>O injection mass for the SO<sub>2</sub>-free case.

Radiative forcing scales approximately linearly with injection mass at  $8 \times 10^{-4}$  W/m<sup>2</sup>/Tg. Ozone loss exhibits a sub-linear relationship consistent with the square-root dependence of HOx production on H<sub>2</sub>O concentration.

### 3.3 Aerosol–Water Vapor Competition

Including SO<sub>2</sub> co-injection of 0.5 Tg reduces peak surface warming from +0.038 K to +0.022 K for a 150 Tg H<sub>2</sub>O case, demonstrating partial cancellation. The aerosol cooling peaks within 3–6 months

while the H<sub>2</sub>O 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/m<sup>2</sup> 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<sub>x</sub> 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

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