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Modulation of the Northern polar vortex by the Hunga Tonga-Hunga Ha'apai eruption and associated surface response

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Abstract. The January 2022 Hunga Tonga-Hunga Ha'apai (HT) eruption injected sulfur dioxide and unprecedented amounts of water vapor (WV) into the stratosphere. Given the manifold impacts of previous volcanic eruptions, the full implications of these emissions are a topic of active research. This study explores the dynamical implications of the perturbed upper atmospheric composition using an ensemble simulation with the Earth System Model SOCOLv4. The simulations replicate the observed anomalies in the stratosphere and lower mesosphere's chemical composition and reveal a novel pathway linking water-rich volcanic eruptions to surface climate anomalies. We show that in early 2023 the excess WV caused significant negative anomalies in tropical upper-stratospheric/mesospheric ozone and temperature, forcing an atmospheric circulation response that particularly affects the Northern Hemisphere polar vortex (PV). The decreased temperature gradient leads to a weakening of the PV, which propagates downward similarly to sudden stratospheric warmings (SSWs) and drives surface anomalies via stratosphere-troposphere coupling. These results underscore the potential for HT to create favorable conditions for SSWs in subsequent winters as long as the near-stratopause cooling effect of excess WV persists. Our findings highlight the complex interactions between volcanic activity and climate dynamics and offer crucial insights for future climate modeling and attribution.

1 Introduction

The January 15, 2022 eruption of the Hunga Tonga-Hunga Ha'apai (HT) volcano was a unique and unprecedented event in the observational era. It released massive amounts of water vapor (WV) and sulfur dioxide (SO_2) into the stratosphere, far exceeding previous records. This eruption injected between 140 and 150 Tg of WV and 0.4 Tg of SO_2 into the stratosphere, reaching mesosphere levels (Millán et al., 2022; Coy et al., 2022; Xu et al., 2022; Randel et al., 2023). The immediate and subsequent effects of the aerosol and WV plumes have been marked, causing significant anomalies in atmospheric circulation, composition, and temperature (Coy et al., 2022; Yu et al., 2023; Wilmouth et al., 2023).

The radiative impacts of volcanic eruptions, particularly those associated with sulfate aerosols emerging following the SO_2 emissions, are well-known and have been widely studied (Robock, 2000; Marshall et al., 2022). The modulation of dynamical

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processes by volcanic eruptions and potential surface impacts, however, are incompletely understood. Typically, volcanic eruptions cause lower-stratospheric warming, which strengthens the polar vortex (PV) and via stratosphere-troposphere coupling results in surface warming over Eurasia and altered weather patterns in the Northern Hemisphere (Stenchikov et al., 2002). However, in the case of the HT eruption, this pronounced and canonical lower-stratospheric warming has not been identified, and its absence is most likely attributable to lower emissions of SO_2.

Instead, the HT eruption has led to significant anomalies in the stratospheric and lower-mesospheric ozone and temperature, which affected atmospheric circulation and particularly of the Southern Hemisphere (Coy et al., 2022; Wang et al., 2023; Yu et al., 2023; Zhang et al., 2024a). The increased OH concentrations induced by the excess WV from the HT eruption led to ozone depletion and temperature anomalies in the upper stratosphere and lower mesosphere (Fleming et al., 2024).

The excess of WV due to the HT eruption exerts a forcing around the tropical stratopause. Studies on the influence of solar variability (Gray et al., 2010; Kuchar et al., 2015; Mitchell et al., 2015) suggest that such forcing at the stratopause level can also act as a significant modulator of atmospheric dynamics. This raises two main questions: 1) Do similar modulation effects emerge for the HT eruption? and 2) if so, do changes in the tropospheric circulation emerge in response to the increase in WV, similarly to those emerging for uniformly doubling WV in the lower stratosphere (Maycock et al., 2013)?

This study explores a novel pathway by which the HT eruption may have modulated stratospheric and mesospheric conditions and consequently impacted surface climate. Here we use a set of ensemble sensitivity simulations performed with the Earth System model (ESM) SOCOLv4 with and without the HT forcing to analyze the effects of the HT eruption and validate these simulations with observational data (see Section A1 in Appendix). We then assess the statistical significance of the detected effects and examine the mechanisms through which the HT eruption could influence the stratospheric PV in 2023, leading to sudden stratospheric warming (SSW). Finally, we conclude with a summary of the results, a discussion on the general forcing mechanism in the following winters when the HT forcing would persist and an outlook of how these dynamically-induced events could be further explored.

2 Results

We set the scene by illustrating the evolution of the monthly and zonal-mean structure of water vapor, ozone, OH and temperature for the extended winter 2022/2023 in Fig. 1. About ten months after the eruption, the WV inputs of HT have distributed across the middle and upper stratosphere and the mesosphere. In December 2022, the WV plume (panel **A**) is mostly localized around 20 hPa and 45°S, but has already started to disperse into the NH and beyond the stratopause. This distributed HT WV anomaly affects ozone globally, as evidenced by the negative anomalies in the lower mesosphere and positive anomalies in the mid-stratosphere (panel **B**). The positive O_3 anomaly can be attributed to increased conversion of NO_x to the HNO_3 reservoir (see Fig. A4) due to higher abundance of OH (Fleming et al., 2024) as shown in Fig. 1, as well as due to hydrolysis of N_2O_5 on aerosol surfaces (Kinnison et al., 1994). Under elevated aerosol loading (see Fig. A2) the heterogeneous reactions serve as a significant source of chlorine activation and ozone loss in the lower stratosphere, which may include reaction of HCl with HOBr (Zhang et al., 2024b), with HOBr being the product of $BrONO_2$ hydrolysis (see Fig. A5). In the lower mesosphere, the

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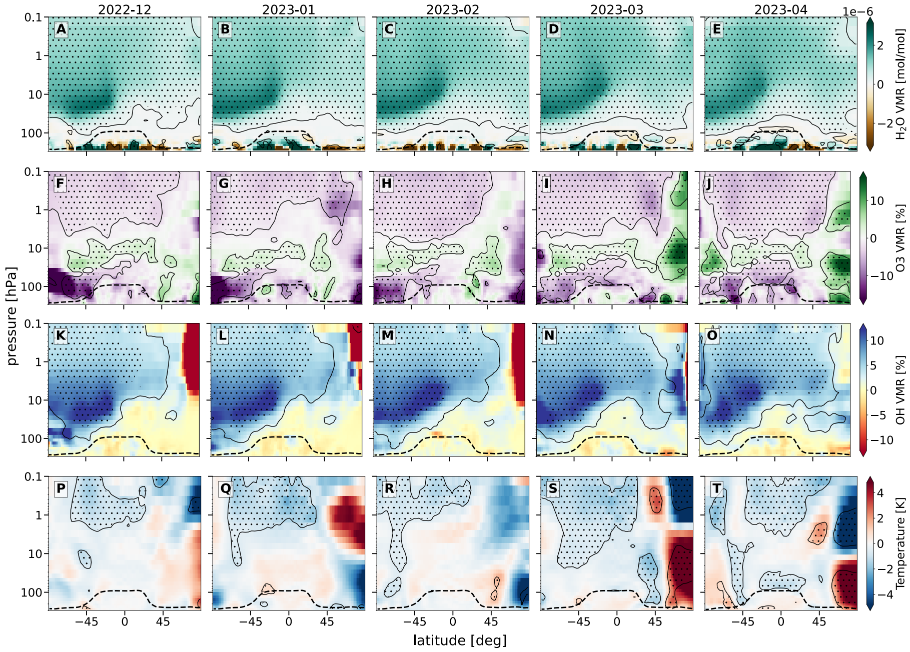

Figure 1. Monthly and zonal-mean structure of water vapor volume mixing ratio (VMR; first row **A–E** in $\mathrm{mol/mol}$), ozone (second row **F–J** in %), OH (third row **K–O** in %) and temperature (fourth row **P–T** in K) anomalies, respectively, for the extended boreal winter 2022/2023. Anomalies are expressed as difference between SOCOL simulation with and without the HT forcing. 2σ statistical significance from t-test is indicated by dots. 1σ FDR correction is indicated by black solid contour lines. Tropopause pressure level is visualized by black dashed line.

negative ozone anomaly is a direct consequence of the chemical pathway initiated by the excess of OH. Note, the significant OH anomalies, similar to those of O_3 and H_2O, at that time do not reach the Northern polar cap. Radiatively-induced anomalies in temperature emerge in our simulations around and beyond the stratopause as consequence of the reduced absorption of ultraviolet radiation by ozone (see Fig. 4.24 in Brasseur and Solomon, 2005).

The negative mesospheric temperature anomaly emerges at the beginning of boreal winter and extends up to 20°N latitude (see Fig. 1**P–T**). The subsequent temporal evolution and propagation towards high latitudes we discuss further below. To illustrate the latitudinal variations, anomalies and impacts in detail, we plot in Fig.2 the evolution of daily temperature profiles during the months JFMAM in 2023 for northern equatorial latitudes (0°–20°N; **A**) and the northern polar cap (60°–90°N; **B**). Here it becomes obvious that the negative mesospheric temperature anomaly persisted at lower latitudes through the whole winter 2022/2023 (see Fig. 2**A**). This is in agreement with the observational estimates from satellites (Fleming et al., 2024) and GPS radio occultation (Veenus and Das, 2023; Stocker et al., 2024). In contrast, at higher latitudes no significant mesospheric temperature anomaly is found (see Fig. 2**B**). This difference between low and high latitudes manifests in a reduced horizontal temperature gradient in the upper stratosphere and the lower mesosphere, which via thermal wind relation, weakens the polar-night jet.

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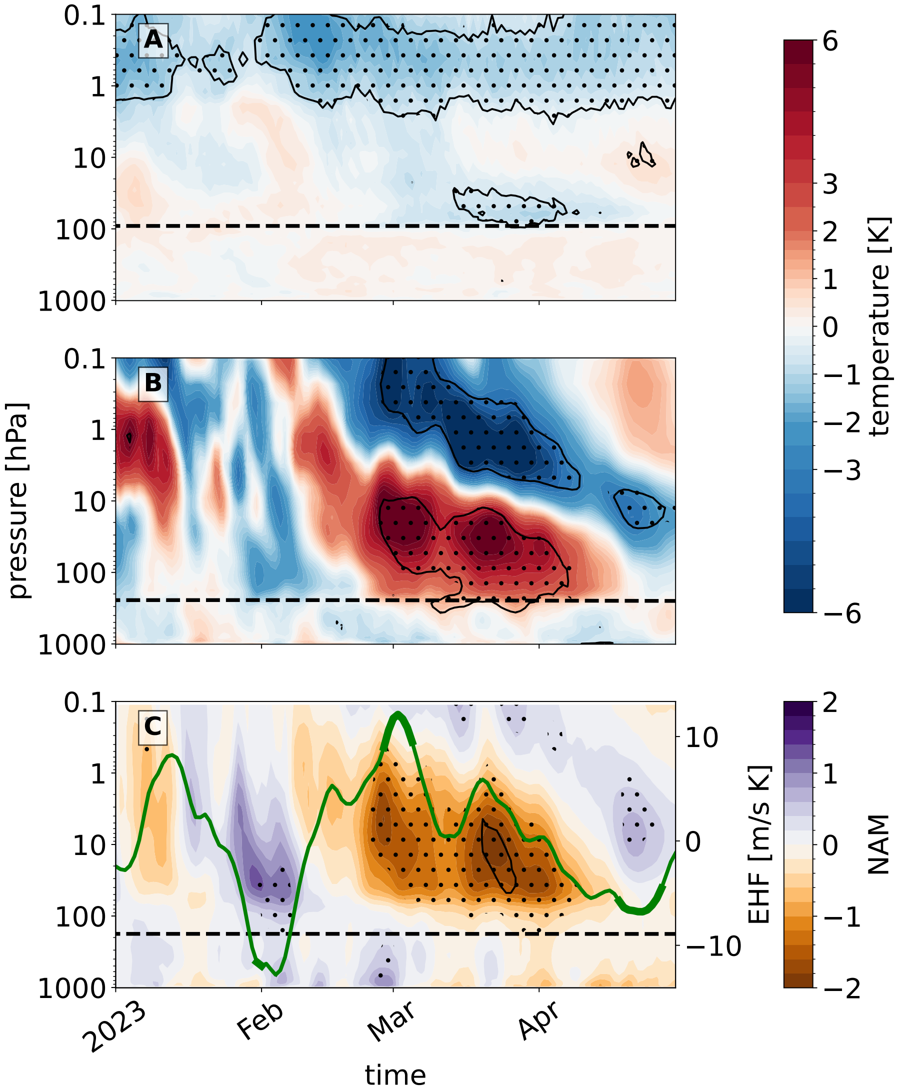

Figure 2. Weighted zonally-averaged temperature averaged over 0°–20°N (**A**) and 60°–90°N (**B**), and Northern Annual Mode (NAM; shading in **C**) and Eddy Heat Flux at 100 hPa averaged over 45°–75°N (EHF in m/s K; green line in **C**) daily anomalies for the months JFMA in 2023. Anomalies are expressed as difference between SOCOL simulation with and without the HT forcing. 2σ statistical significance from t-test is indicated by dots. 1σ FDR correction is indicated by black solid contour lines.

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In consequence, the weakened winds allow more planetary waves (PW) to propagate upwards into the stratosphere (Charney and Drazin, 1961), where they break and dissipate and thereby further weaken the already disturbed stratospheric PV. The slowdown of the winds and associated rise of polar temperature (see Fig. 2**B**) emerges in our simulations as early as February, but is fully evident in March 2023. The stratospheric polar warming connected with the enhanced Brewer-Dobson circulation is directly coupled to the cooling aloft and associated weaker meridional circulation. Further, along with the temperature change we observe (subsequently) increasing concentrations of ozone over the polar cap in March and April (see Fig. 1**S–T** or Fig. 13 in Fleming et al. (2024)). The temperature structure across the upper atmosphere displayed in Fig. 2 resembles the transition from a more positive to a more negative phase of NAM in the stratosphere and lower mesosphere, respectively. Figure 2**C** illustrates how the HT forcing projects on the NAM mode (shading). Along with NAM we provide the eddy heat flux (EHF; green line) at 100 hPa as a proxy for upward propagation of planetary waves (e.g., Newman et al., 2001). The downward phase propagation of negative NAM anomalies documents the wave mean-flow interaction (Baldwin and Dunkerton, 2001), also indicated by Eliassen-Palm flux diagnostics (see Fig. A6). Since the EHF response lags slightly behind NAM, the triggering mechanism appears to be similar to SSWs, and how dynamically-forced anomalies in the upper stratosphere and lower mesosphere may be communicated downward and thus control PWs (Hitchcock and Haynes, 2016).

Turning the focus to lower levels, it becomes apparent that negative NAM anomalies emerge close to the surface ($\sim 1000\,\mathrm{hPa}$) in May, which follow the significant negative NAM anomalies in the stratosphere in the preceding months. This lagged occurence suggests that the propagation of the stratospheric anomalies might drive these tropospheric anomalies via stratosphere-troposphere coupling (Thompson et al., 2005). To further explore this hypothesis, we turn the focus to the analysis of the monthly sea level pressure (SLP in hPa) anomaly in April 2023, which is shown in Fig. 3. Here we identify a positive SLP anomaly in polar and negative SLP anomaly in mid-latitudes. This pattern is characteristic for a negative modulation of the stratospheric PV associated with a poleward shift of the tropospheric jet stream. The canonical temperature pattern with a pronounced cold anomaly in Northern Europe (see Fig. 3**B**) clearly arises for this weak vortex event (Kolstad et al., 2022). Generally, the coupling is independent of the mechanism causing these changes in PV and is present across all timescales (Kidston et al., 2015).

3 Discussion and summary

The January 2022 Hunga Tonga-Hunga Ha'apai volcanic eruption significantly modified the radiative balance, photochemistry, and dynamics of the stratosphere and lower mesosphere, as has been extensively documented (Coy et al., 2022; Sellitto et al., 2022; Jenkins et al., 2023; Santee et al., 2023). Here we add to the discussion of HT effects by illustrating for the first time the dynamical stratosphere-troposphere-surface coupling in the NH following the eruption. We show in a series of ESM sensitivity simulations how the WV input propagated upward and poleward, and thereby impacted the stratospheric PV and contributed to the emergence of SSW in boreal winter 2022/2023 and subsequent surface SLP anomalies. Similarly, the HT eruption induced a marked warming anomaly in the Arctic region, with temperatures rising by up to 2 K near the North Pole in early 2022 (Bao et al., 2023).

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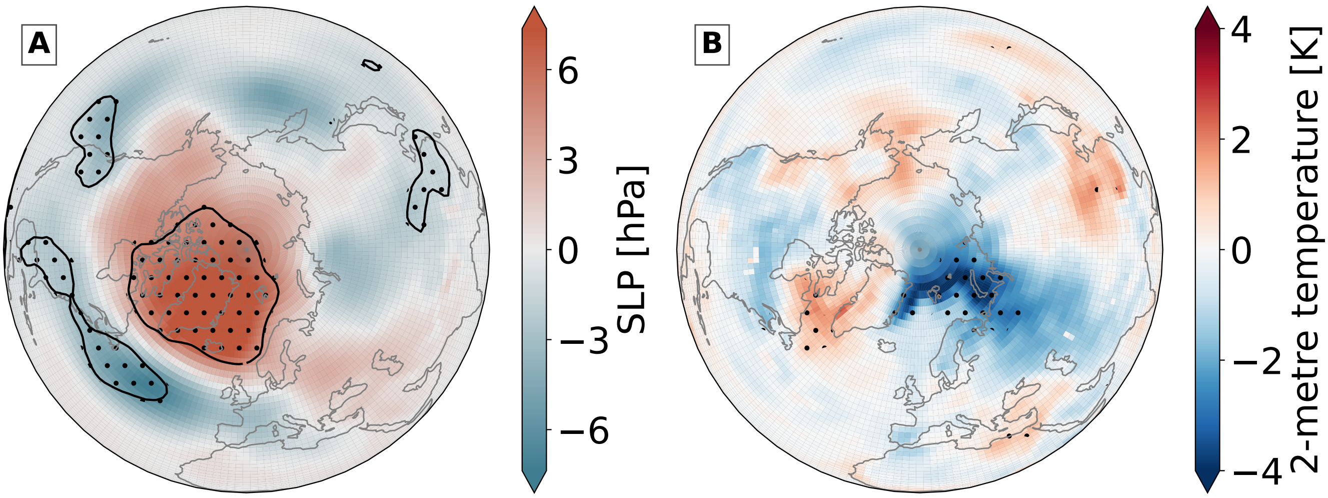

Figure 3. Sea level pressure (**A**; SLP in hPa) and surface air temperature (**B**; in K) monthly anomaly in April 2023. Anomalies are expressed as difference between SOCOL simulation with and without the HT forcing. 2σ statistical significance from t-test is indicated by dots. 1σ FDR correction is indicated by black solid contour lines.

Our results thereby illustrate how anomalies in OH, nitrogen species, and O_3, induced in the stratosphere and lower mesosphere due to excess of WV after the HT eruption, influence upper atmosphere dynamics via alteration of temperature gradients, and thereby lead to the emergence of a negative NAM anomaly at upper levels during the winter-spring transition that manifests by April 2023 in SLP. We begin our attribution in the upper stratosphere and lower mesosphere, where increased OH concentrations induce a negative ozone anomaly. In consequence, our set of sensitivity simulations illustrates a radiatively-induced temperature response in equatorial latitudes up to 20°N latitude, which leads to a reduced horizontal hemispheric temperature gradient. This alteration of the temperature gradient is associated with weaker winds via the thermal wind relation. As weaker winds emerge in the stratosphere (negative NAM anomaly) we find that the anomaly propagates with time downward illustrating the wave mean-flow interaction similarly as during SSWs. This mechanism provides in summary a chain of processes which could have contributed to the observed SSW during the winter 2022/2023. We note that the causal link cannot be entirely established on the one hand due to internal stratospheric variability driving SSWs (Baldwin et al., 2021) and on the other the free-running ocean set up of our simulations. However, all things equal our results clearly show that HT has provided favorable conditions for the emergence of late winter NH SSWs in 2023.

For the first time since records began in the mid 20th century, three SSW-like events have been detected during the extended winter 2023/2024. Ineson et al. (2024), using a large model ensemble, showed that such event series has a return period of about 250 years. Our model-projected forcing during that winter was weaker due to a quicker WV dissipation from the stratosphere. Thus, we do not detect any significant dynamical responses. However, in principle the mechanism suggested above should be valid for the following winters as well if the lower-mesospheric temperature cooling would be persistent and strong enough due to the excess of WV. This mechanism establishes a novel pathway how water-rich volcanic eruptions can indirectly impact the

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surface climate via downward propagation of the dynamical perturbation from the stratosphere and lower mesosphere. Thereby it adds to the manifestations of stratosphere-troposphere coupling on various timescales. Future work should vet the proposed mechanism, ideally within multi-model inter-comparison projects, and explore whether the HT forcing also contributed to the disruption of the stratospheric PV during the following winters.

Code and data availability. SWOOSHv2.7 data can be downloaded from https://csl.noaa.gov/groups/csl8/swoosh/. A-RIP data can be downloaded from https://www.jamstec.go.jp/ridinfo/. M2-SCREAM can be downloaded from https://acdisc.gesdisc.eosdis.nasa.gov/opendap/hyrax/M2SCREAM/GMAO_M2SCREAM_INST3_CHEM.1/. GloSSAC data can be downloaded from https://asdc.larc.nasa.gov/project/GloSSAC. All analysis scripts will be made available on zenodo.com upon acceptance. Similarly, we will make the post-processed simulation data openly available via data.mendeley.com. Any direct access to full simulation data can be arranged by contacting the authors.

Appendix A: Methods

A1 SOCOLv4 simulations

We use a set of ensemble sensitivity simulations performed with the Earth System model SOCOLv4 (Sukhodolov et al., 2021), which comprises comprehensive stratospheric chemistry and sulfate aerosol microphysics, to assess the impacts of the HT eruption on stratospheric composition and dynamics. SOCOLv4 is used in a T63 horizontal resolution ($1.9° \times 1.9°$) and a vertical resolution of 47 vertical levels (till ∼0.01 hPa), with the boundary conditions following the recommendations of the Model Intercomparison Project Phase 6 (CMIP6; Eyring et al., 2016). The quasi-biennial oscillation (QBO) is not self-generated with the employed vertical resolution, and therefore it is nudged in the model. Since the simulations expand into the future, instead of the actual QBO observational data we used the same data but shifted back by 16 years, allowing to keep the QBO phase during the eruption that is similar to the observed one. The SOCOL model is widely used for process analyses in stratospheric research and has contributed to the recent Chemistry-Climate Model Initiative (CCMI; Morgenstern et al., 2022; Friedel et al., 2023) and interactive stratospheric aerosol model intercomparison (ISA-MIP Quaglia et al., 2023; Brodowsky et al., 2024) among others.

Our set of simulations comprises an ensemble of transient simulations with and without HT forcing. We perform a 5-year spin-up prior to the HT eruption, so that by the date of the event the ocean is already in a random state, contributing to the noise level in the ensemble. In January 2022 we then branch out two ensembles, one with and one without the HT forcing. Both ensembles comprise 10 ensemble members. Note, WV freezing around the emission region was switched off for several days to avoid artifacts and mimic the estimated magnitude ($\sim 150\,\mathrm{Tg}$) of the WV forcing by Millán et al. (2022) and M2-SCREAM (see Fig. A1**A**). The M2-SCREAM WV anomaly is within the ensemble spread, however this spread is quite wide, suggesting that the WV plume evolution could have been strongly modulated by the background dynamical conditions. Also, the modeled WV anomaly shows a more pronounced seasonal cycle.

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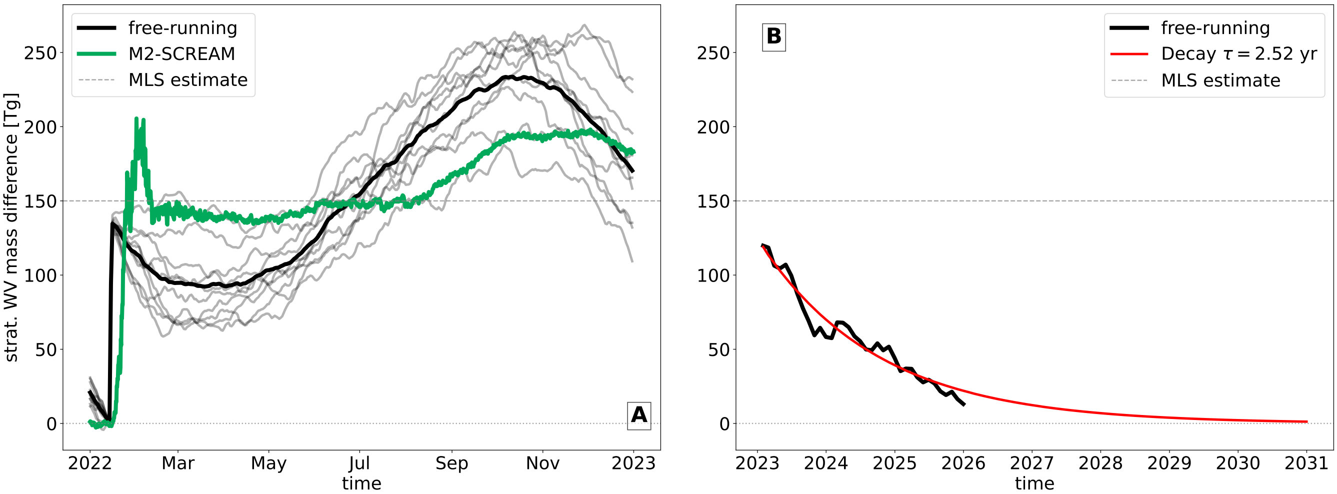

Figure A1. (A) Anomalous daily integrated stratospheric water vapor during January 2022 for the free-running (black line) SOCOLv4 simulations and M2-SCREAM (green line) with respect to January 14, 2022. **(B)** Anomalous monthly integrated stratospheric water vapor for the free-running SOCOLv4 simulations (black line) for the period 2023-2025 and the corresponding fitted decay (red line) with e-folding time τ of 2.52 years. Horizontal dotted line represent the estimated magnitude after the HT eruption by Millán et al. (2022).

According to the fitted decay, we project the stratospheric WV burden to represent an enhanced forcing over the next years and only return to pre-HT background values by 2031. The excess of stratospheric WV is removed by sedimentation of PSCs within the SH PV and transported to higher latitudes of both hemispheres via the Brewer-Dobson circulation (BDC). The combination of these processes leads to an exponential decay of the WV burden with an estimated e-folding time of ∼2.5 years based on the fitted period of 2023–2025 (see Fig. A1**B**). Our decay estimate is in agreement with Fleming et al. (2024), who used a free-running 2D model, but about half of the estimate provided by Zhou et al. (2024), who estimated an e-folding time scale of 4 years using a chemical transport model with perpetual ERA5 meteorology.

Furthermore, we use data from SWOOSH for daily H_2O (Davis et al., 2016) and GloSSAC for monthly mean Surface Area Density (SAD; NASA/LARC/SD/ASDC, 2023) to validate SOCOLv4 anomalies (see Figs. A2 vs. A3). Note, we retrieve SAD fields using extinction coefficients on all 4 GloSSAC wavelengths (Jörimann et al., 2024). The SAD background in GloSSAC is a bit higher in higher latitudes compared to SOCOLv4, since for GloSSAC we used the 1999-2004 climatology representative for the volcanically quiescent conditions, while for SOCOL we used the difference between experiments with and without HT. The aerosol plume evolves in a similar spatio-temporal manner, i.e. towards the SH and lower pressure levels. The WV plume extends horizontally, firstly towards the SH PV and then across the equator according to climatology of the residual circulation. During the boreal winter 2023, the WV anomaly is spread across all latitudes from middle stratosphere upward in both SWOOSH and SOCOLv4. The reduction of water in SOCOLv4 starts to be apparent in the end of 2023 in contrast to SWOOSH where the WV anomaly sustains its values. This highlights a deficiency of our model as the anomalous water dissipates faster from the stratosphere, which is related to a stronger BDC and numerical diffusion. This caveat has been already

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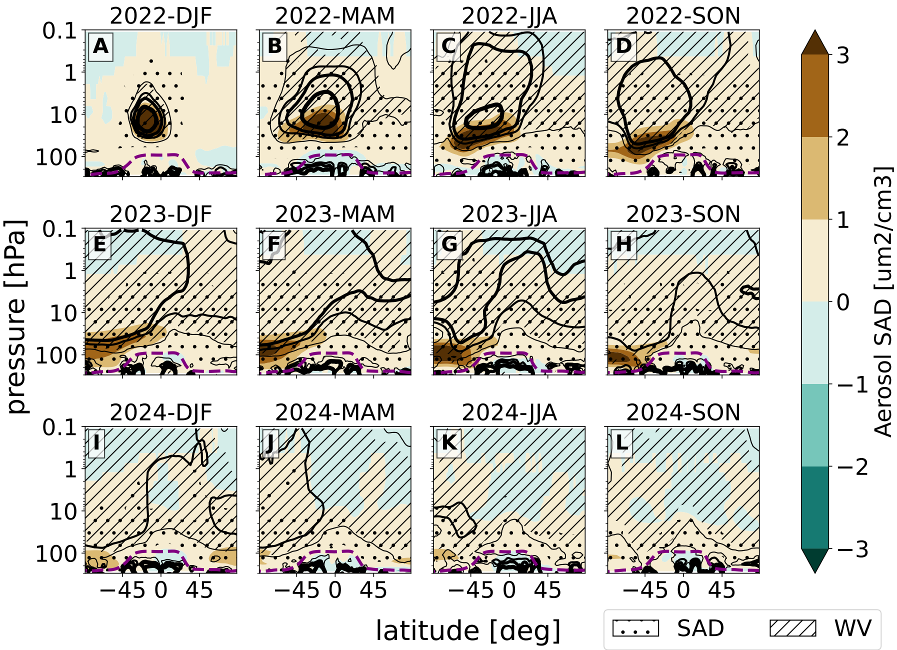

Figure A2. Seasonal and zonal-mean structure of Surface Area Density (SAD; shading in $\mu m^2/cm^3$) and Water Vapour (WV; solid contour lines: $0.1, 0.5, 1, 3\,mol/mol$) volume mixing ratio. Anomalies are expressed as difference between SOCOLv4 simulation with and without the HT forcing. 2σ statistical significance from t-test is indicated by dots and hatching in case of SAD and WV, respectively. Tropopause pressure level is visualized by purple dashed lines

reported (Sukhodolov et al., 2021) but could be addressed in future simulation with higher vertical resolution (Brodowsky et al., 2021). Nevertheless, during late 2022 and early 2023 the model is in a good agreement with observations in terms of the WV and aerosol forcing.

A2 Calculation of anomalies

Throughout our analysis we evaluate significance fields using the minimum local p-values from Student's t-test with global test statistics using the False Detection Rate (FDR) methodology (Wilks, 2006), first described by Benjamini and Hochberg (1995) and later promoted by Wilks (2016) in the atmospheric sciences. All illustrations in Section 2 show differences between simulations with and without HT forcing. For significance regions we show in addition to the dots indicating local p-values < 0.05, boundaries of p-values < 0.32 corrected for FDR.

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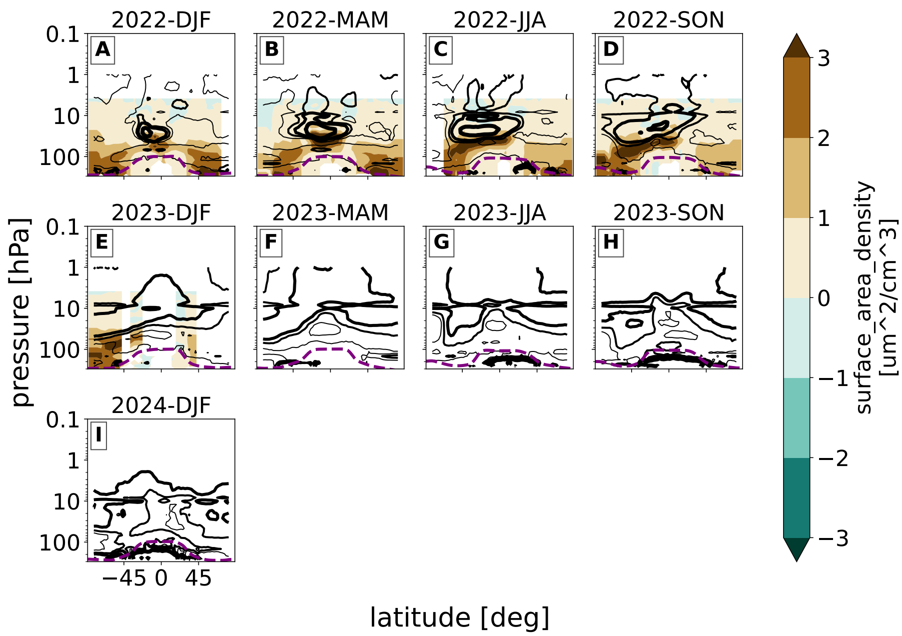

Figure A3. easonal and zonal-mean structure of Surface Area Density (SAD; shading in $\mu m^2/cm^3$) and Water Vapour (WV; solid contour lines: $0.1, 0.5, 1, 3\,mol/mol$) volume mixing ratio. SAD and WV anomalies in GloSSAC and SWOOSH are expressed as difference with respect to climatology for the period 1999–2004 and 1984–2023, respectively. Tropopause pressure level is visualized by purple dashed line

A3 Calculation of Northern Annual Mode

180 The Northern Annular Mode (NAM) was calculated at each pressure level as the first Empirical Orthogonal Function (EOF) of the daily, latitude weighted, zonal mean zonal wind poleward of the NH (Gerber et al., 2008). The NAM index was defined as the Principal Component time series associated with the first EOF and standardized.

A4 Eliassen-Palm flux diagnostics

The response of resolved waves is investigated using the Eliassen-Palm flux diagnostics (EPF; Andrews and McIntyre, 1987).
185 EP fluxes are computed and scaled following Jucker (2021). The EPF convergence serves as an indicator of wave dissipation and the EPF divergence (EPFD) indicates sourcing.

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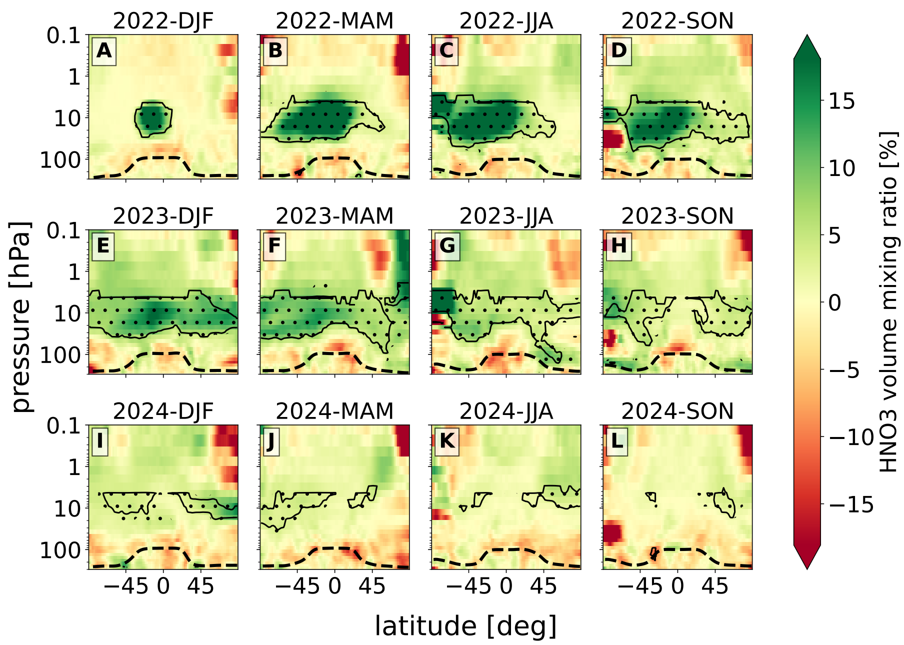

Figure A4. Seasonal and zonal-mean structure of HNO_3 volume mixing ratio (**A–L** in %). Anomalies are expressed as difference between SOCOLv4 simulation with and without the HT forcing. 2σ statistical significance from t-test is indicated by dots. 1σ FDR correction is indicated by black solid contour lines. Tropopause pressure level is visualized by black dashed line

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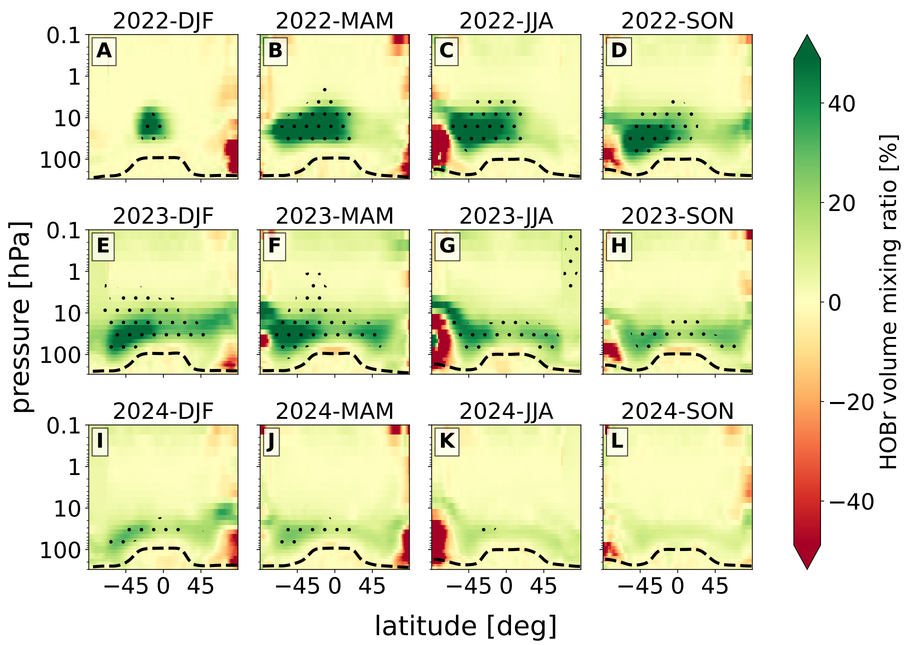

Figure A5. Seasonal and zonal-mean structure of HOBr volume mixing ratio (**A–L** in %). Anomalies are expressed as difference between SOCOLv4 simulation with and without the HT forcing. 2σ statistical significance from t-test is indicated by dots. 1σ FDR correction is indicated by black solid contour lines. Tropopause pressure level is visualized by black dashed line

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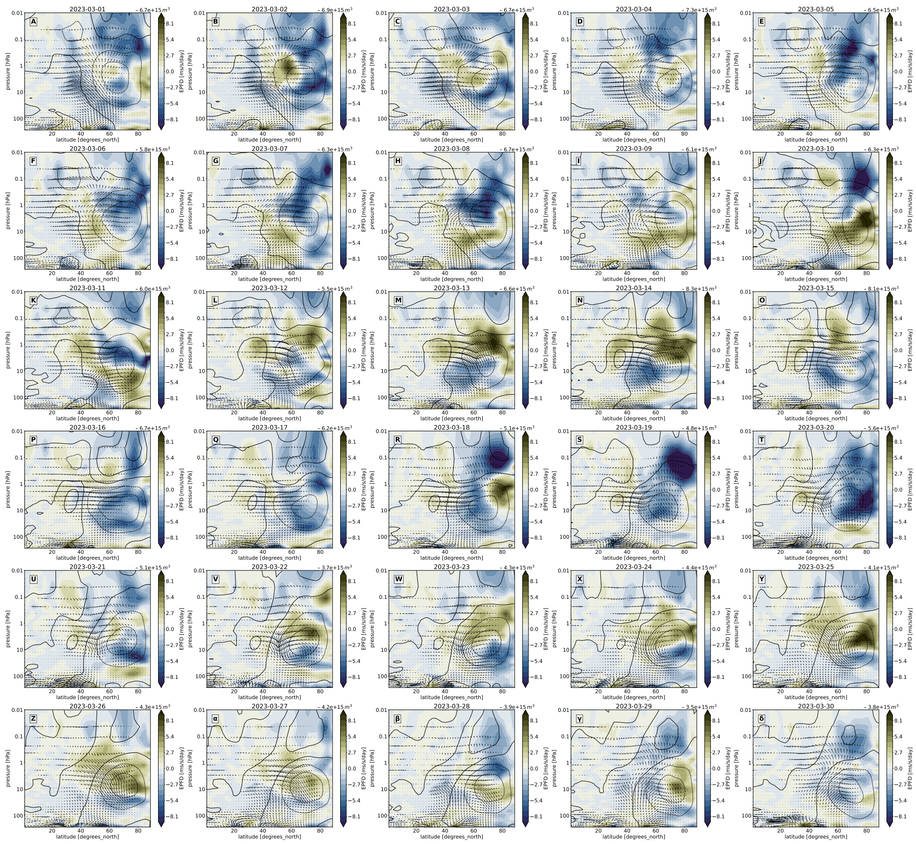

Figure A6. Daily anomalies of the Eliassen-Palm flux (EPF; arrows; in $(\mathrm{m^2/s^2};\mathrm{hPa\,m/s^2})$) and its divergence (EPFD; shading; in $\mathrm{m\,s^{-1}\,day^{-1}}$) and zonal mean zonal wind (solid (positive) and dashed (negative) contours; in $\mathrm{m/s}$) in March 2023.

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Author contributions. AK and TS designed the study. TS set up and carried out the model simulations. AK analysed the data. AK, TS and AJ curated the data. AK compiled the manuscript with inputs of all other authors.

Competing interests. The authors declare that they have no conflict of interest.

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