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Key Points:

- Antarctic dehydration is a major removal pathway of stratospheric H₂O injected from Hunga Tonga-Hunga Ha'apai (HTHH) eruption
- HTHH H₂O caused small (up to 10 DU) additional chemical ozone depletion in 2023 Antarctic spring
- Model indicates e-folding timescale of 4 years for removal of HTHH H₂O from stratosphere

Supporting Information:

Supporting Information may be found in the online version of this article.

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Antarctic Vortex Dehydration in 2023 as a Substantial Removal Pathway for Hunga Tonga-Hunga Ha'apai Water Vapor

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Abstract The January 2022 eruption of Hunga Tonga-Hunga Ha'apai (HTHH) injected a huge amount (~150 Tg) of water vapor (H₂O) into the stratosphere, along with small amount of SO₂. An off-line 3-D chemical transport model (CTM) successfully reproduces the spread of the injected H₂O through October 2023 as observed by the Microwave Limb Sounder. Dehydration in the 2023 Antarctic polar vortex caused the first substantial (~20 Tg) removal of HTHH H₂O from the stratosphere. The CTM indicates that this process will dominate removal of HTHH H₂O for the coming years, giving an overall e-folding timescale of 4 years; around 25 Tg of the injected H₂O is predicted to still remain in the stratosphere by 2030. Following relatively low Antarctic column ozone in midwinter 2023 due to transport effects, additional springtime depletion due to H₂O-related chemistry was small and maximized at the vortex edge (10 DU in column).

Plain Language Summary Around 150 Tg (150 million tons) of water vapor was injected into the stratosphere during the eruption of Hunga Tonga-Hunga Ha'apai. Water vapor is a greenhouse gas and this increase is expected to have a warming effect in the troposphere, as well causing perturbations in stratospheric chemistry and aerosols. We use an atmospheric model to study the residence time of this excess water vapor and its impact on the recent Antarctic ozone hole. The model performance is evaluated by comparison with satellite measurements. Wintertime dehydration in the Antarctic stratosphere in 2023 is found to be an important mechanism for removal of the volcanic water from the stratosphere. However, the overall removal rate is predicted to be slow; around 25 Tg (17%) is still present in 2030. The direct impact of the excess water vapor on ozone via chemical processes in the Antarctic ozone hole in 2023 is small.

1. Introduction

The eruption on 15th January 2022 of the submarine Hunga Tonga–Hunga Ha'apai (HTHH) volcano (20.54°S, 175.38°W) is recognized as the most explosive in the last 30 years, with emissions reaching up to ~55 km (Carr et al., 2022; Taha et al., 2022). It was unusual due to the huge amount of water vapor (H₂O) injected very high into the stratosphere, along with only small quantities of sulfur dioxide (SO₂), thereby challenging many preconceptions about the atmospheric impacts of volcanic eruptions. This exceptional event is a global experiment allowing us to study, for the first time, a water-rich volcanic eruption. Microwave Limb Sounder (MLS) satellite measurements indicate that around 150 Tg of H₂O was injected, increasing the stratospheric burden by around 10% (Khaykin et al., 2022; Millán et al., 2022; Xu et al., 2022), while the SO₂ injection was only 0.5 Tg. This is expected to generate a very different climate forcing to other satellite-observed SO₂-rich volcanic eruptions, possibly leading to a net warming of the global surface temperature due to the dominant radiative effect of H₂O perturbations (Jenkins et al., 2023; Sellitto et al., 2022), yet remaining highly uncertain as indicated by a recent detailed radiative transfer calculation (Schoeberl et al., 2023).

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The slow spreading of the injected H₂O throughout the stratosphere via the Brewer-Dobson circulation (BDC) (Coy et al., 2022; Manney et al., 2023) is also expected to affect stratospheric chemistry and dynamics. Rapid ozone depletion was observed in the initial plume (Evan et al., 2023; Zhu et al., 2023), along with the rapid formation of a dense aerosol layer as a result of the water vapor injection (Asher et al., 2023; Zhu et al., 2022). In addition, evident processing of chlorine and repartitioning of reactive nitrogen species was observed in the southern tropical stratosphere immediately after the HTHH eruption, which then spread poleward over the following months (Santee et al., 2023). The aerosol layer was transported polewards at lower altitudes than the H₂O enhancement. The excess H₂O caused a strong cooling in the SH mid-latitude stratosphere shortly after the eruption (Schoeberl et al., 2022; Vömel et al., 2022), which in turn strengthened the mid-latitude jet and slowed down the BDC (Coy et al., 2022). When the HTHH H₂O reaches high latitudes with the descent of the BDC, it can affect gas-phase and heterogeneous processes related to polar ozone loss. Determining the timing and longevity of the excess H₂O is thus critically important for assessing the impact on stratospheric ozone recovery and near-term climate change.

Water vapor can affect processes that drive stratospheric ozone in many ways. One important example is the formation of polar stratospheric clouds (PSCs), which initiate ozone-depleting heterogeneous chemistry. Sedimentation of ice PSCs irreversibly changes the H₂O amount in the polar vortex, and affects the ozone-depletion processes via dehydration and denitrification (e.g., Fahey et al., 2001; Feng et al., 2011; Kelly et al., 1989; Tabazadeh et al., 2000). Dehydration in Antarctic winter has long been observed (e.g., Kelly et al., 1989; Rosenlof et al., 1997; Tomikawa et al., 2015; Vömel et al., 1995), but its representation by models can vary when applying PSC schemes with different complexity. If we use the HTHH water transport and its dehydration at polar regions as metrics to test a model's stratospheric transport and PSC processes, we can then predict the longevity of the excess H₂O by calculating its annual removal amount.

In this paper we use an off-line 3-D chemical transport model (CTM) to simulate the spatio-temporal evolution of the injected H₂O with the results showing good agreement with MLS measurements in terms of plume spread and removal of HTHH H₂O from the stratosphere. We estimate the longevity of the excess H₂O and the amount that may remain in the stratosphere over the coming decade. We also diagnose the direct chemical impact of the increased H₂O on stratospheric ozone through gas-phase and heterogeneous chemistry (e.g., PSCs and aerosols). The impacts are simulated with specified realistic post-eruption meteorology but hence do not account explicitly for dynamical feedbacks. Our CTM setup nonetheless provides useful constraints on changes seen in more complex coupled radiative-dynamical-chemical models (Wang et al., 2023).

2. Model and Observations

The TOMCAT/SLIMCAT CTM (Chipperfield, 1999, 2006) was run at a horizontal resolution of 2.8° × 2.8° and 32 levels from the surface to about 60 km forced with European Centre for Medium-Range Weather Forecasts (ECMWF) ERA5 meteorology (Hersbach et al., 2020). The model uses a detailed gas-phase stratospheric chemistry scheme, and a simplified PSC scheme for the simulation of heterogeneous chemistry based on the assumption of thermodynamic equilibrium between PSC particles, including liquid aerosol, solid nitric acid trihydrate, and/or solid ice particles (Groß et al., 2018), and the gas phase (e.g., Feng et al., 2011, 2021). In this scheme, ice particles with assumed radius of 10 μm sediment with a fall velocity of 1,500 m/day. A control simulation (**Control**) without treatment of HTHH was integrated from 1980 to October 2023. Output from run **Control** for 1 January 2022 was used to initialise a run (**HT**) until 31 October 2023 with the injection of 150 Tg of H₂O into the low-mid stratosphere at southern subtropical latitudes. We experimented with the timing of the model H₂O injection between January 15th and April 1st. A later injection date, when the plume is already well spread longitudinally and latitudinally (e.g., early April), overcomes inconsistencies between the initial plume dynamics and the coarse resolution CTM. Thus, the additional H₂O was injected on April 1st between 22 km (36 hPa) and 26 km (20 hPa) altitude (peaking at 24 km) and between latitudes 2°S and 28°S with a constant mixing ratio at each level, corresponding to the location of the bulk of the observed plume (see below). The model used here employs a climatological distribution of H₂O in the troposphere, so that any excess H₂O transported to this region is removed from the model. Injection of H₂O into the stratosphere assumes a constant annual mean value with no seasonal cycle. The runs used background fields for stratospheric sulfuric acid aerosols with no enhancement due to HTHH. The magnitude and impact of the HTHH SO₂ on polar ozone depletion is uncertain (Wang et al., 2023) and in this study we focus on H₂O alone.

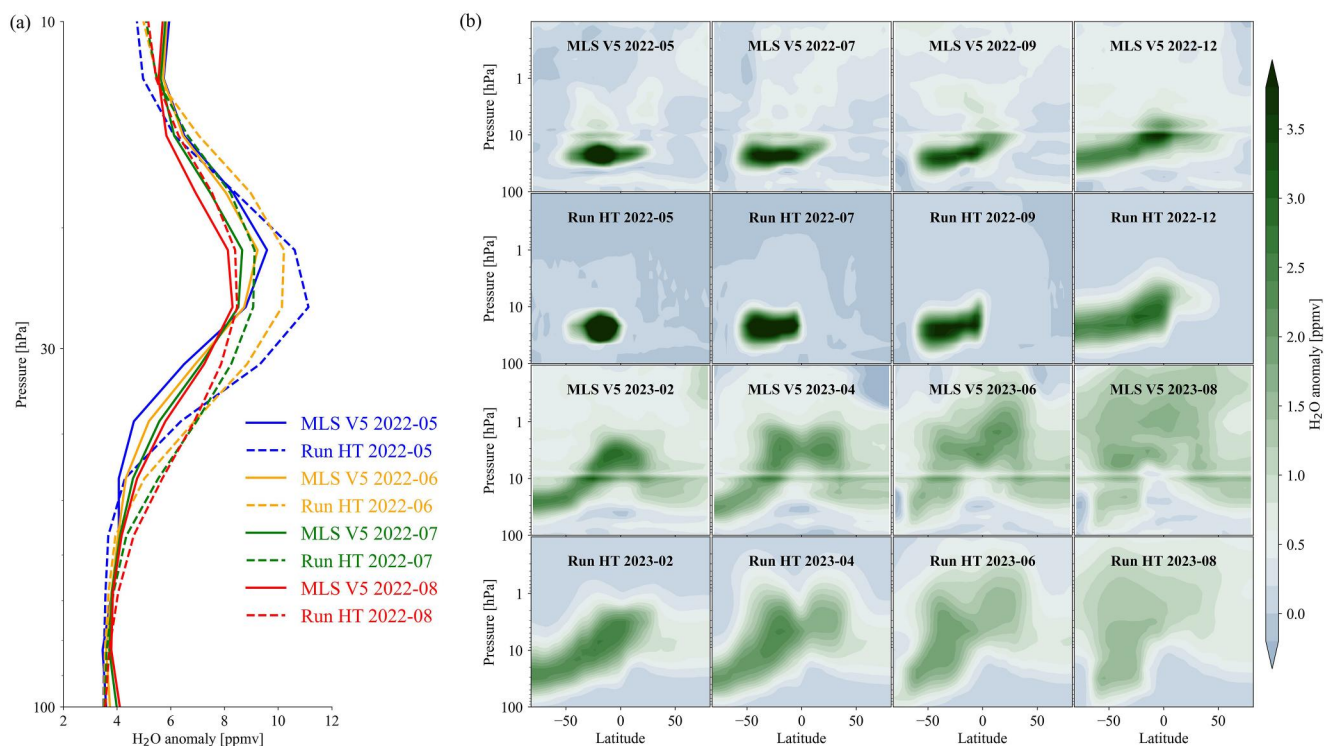


Figure 1. Water vapor (H₂O) profile and evolutions after the HTHH eruption. (a) Zonal mean H₂O anomaly profiles (ppmv) between 40°S and 20°S from May to September 2022 from Microwave Limb Sounder (MLS) v5 observations (solid lines) and run HT (dashed lines). (b) Zonal mean latitude-pressure cross sections of H₂O anomalies observed by MLS v5 and simulated by model run HT from May 2022 to August 2023.

To test the possible future evolution of the HTHH H₂O three further model runs were performed. These were integrated from 1 January 2023 until 2030 using repeating ERA-5 meteorology for 2022. Run **Con_2022** was essentially an extension of run **Control**; run **HT_2022** was an extension of **HT**; run **HT_2022 ns** was the same as run **HT_2022** but had sedimentation of PSC particles turned off. The experiments are summarized in Table S1 in Supporting Information S1.

The modeled results are compared to satellite measurements of H₂O from MLS (Waters et al., 2006) and total column ozone from the Ozone Monitoring Instrument (Levelt et al., 2006) on the NASA Aura satellite, and the Infrared Atmospheric Sounding Interferometer (IASI) (Siddans et al., 2018) on MetOp-B satellite.

MLS H₂O anomalies are calculated as deviations from the climatology of 2005–2021. The model anomalies are calculated as differences between runs **HT** and **Control** to obtain the HTHH H₂O. The stratospheric total mass of H₂O is estimated as the global (80°S–80°N) sum of the stratospheric column over each 5° latitude band from MLS volume mixing ratio measurements on pressure levels. For this study, we use MLS version 4 (v4) and version 5 (v5) products for the H₂O mass, but focus on v5 for analysis of long-term transport.

3. Evaluation of the Model Post-Eruption Stratospheric Transport

We first assess the model performance for the H₂O transport after eruption. Figure 1a shows the H₂O anomaly profiles after the HTHH injection in model run **HT** (dashed line), compared with MLS measurements (solid line). The two are in good agreement, both showing the positive water vapor anomaly of 8–11 ppmv peaking between 30 hPa and 10 hPa from April to September. While the injected total mass in the model is consistent with MLS, the simulation has slightly larger peak anomalies and smaller horizontal extent after injection. The simulated plume spread is in very good agreement with the observations through August 2023 (Figure 1b and Movie S1), in particular regarding the characteristics and behavior of the excess H₂O at the mixing barriers in the stratosphere, including the polar vortex edge and the subtropics. Around 4–6 months after the eruption, the excess H₂O moves into the Southern Hemisphere (SH) mid-latitudes within the shallow branch of the BDC. However, it does not intrude into the 2022 Antarctic polar vortex due to the strong polar night jet. Only after the breakdown of the

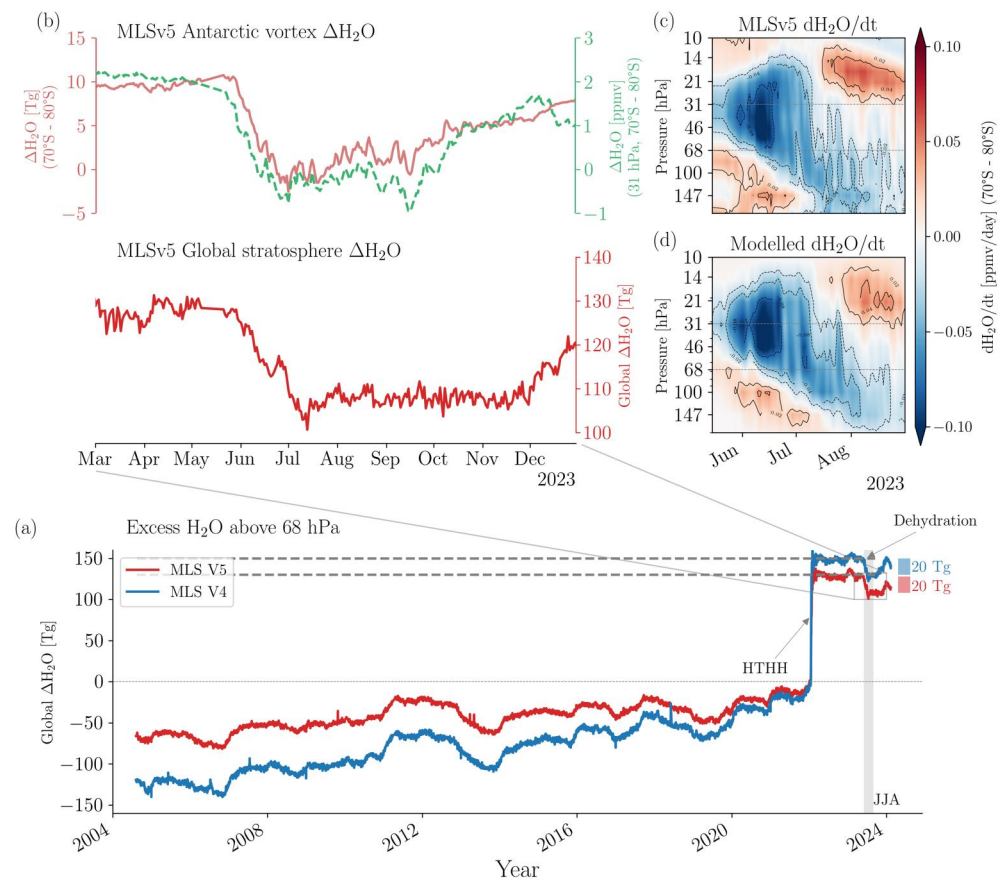


Figure 2. Microwave Limb Sounder (MLS) observed and TOMCAT simulated dehydration of the Antarctic polar vortex. (a) Time series of observed excess global H₂O mass (Tg) above 68 hPa from MLS v4 and v5. The gray bar marks the months of June, July and August 2023. (b) A zoomed segment shows MLS v5 observed dehydration in March–December 2023, represented by the excess H₂O mass (Tg) above 68 hPa for the whole globe and SH polar cap (80°S–70°S), along with H₂O mixing ratio (ppmv) anomalies at 31 hPa. (c) MLS v5 observed daily tendencies of mean SH polar cap H₂O mixing ratio (ppmv/day) with a 30-day smoothing from June to August in 2023. (d) Same as (c) but for TOMCAT simulated (run HT) daily tendencies.

Antarctic polar vortex in November 2022 did the H₂O reach the pole (see also Manney et al. (2023)). The subtropical transport barrier in 2022 summer, favored by weak wave forcing in the easterly phase of the Quasi-Biennial Oscillation, confines the excess H₂O to the Northern Hemisphere (NH), until the transition to westerlies at the end of 2022. This also explains the improvement of the model in 2023 compared with 2022 in representing the H₂O transport across the equator. H₂O enters the deep branch of the BDC in 2023, ascending from the tropics and descending into the high latitudes in the SH. The model reproduces well the timing of the HTHH-injected H₂O penetrating the polar vortex, and the altitudes of the H₂O plume. This indicates the model has a good representation of both the poleward horizontal H₂O transport by the shallow branch of the BDC and the ascent of the water-enriched air to high levels by the deep branch of the BDC.

4. Dehydration in 2023 Antarctic Winter

Figure 2a shows the time evolution series of total excess stratospheric H₂O mass above 68 hPa observed by the MLS. After the enhancement of the stratospheric H₂O mass by ~150 Tg after HTHH injection in January 2022, the amount of excess H₂O remained steady until a sudden drop of ~20 Tg from June to July 2023. This strong dehydration is also seen in the time series of the Antarctic H₂O mass and mixing ratio at 31 hPa (Figure 2b). First, the excess H₂O rose to its highest and unprecedented level at the end of May 2023 in this 20-year record, when the HTHH-injected H₂O entered the Antarctic stratosphere via the deep branch of the BDC. Then, a striking drop in H₂O occurred within just 3 months from June to August 2023. The H₂O anomaly fell from 2.5 ppmv to close to

zero in August 2023. The amplitude of this stratospheric dehydration is also unprecedented in the observational record since 2004. The fact that the H₂O anomaly returns to essentially zero in August, like the previous years, shows that the vortex H₂O is controlled by the local polar temperatures (so that water vapor remaining in the gas-phase is determined by its saturation vapor pressure) and is not affected by additional volcanic injection; that is, ice PSC processes effectively cancel out the in-vortex impact of the additional HTHH water vapor by the end of Austral winter. Note that the model has a good representation of H₂O inside the Antarctic polar vortex core in winter/spring 2023 (Figure S1 in Supporting Information S1).

Figures 2c and 2d show the daily tendencies of the H₂O mixing ratio inside the Antarctic vortex observed by MLS v5 and simulated by the model. The dramatic dehydrated areas above 68 hPa are clearly seen in the lower stratosphere in June 2023 with the largest rate of H₂O decrease of 0.19 ppmv/day. This led to a fast transition of the lower stratosphere from anomalously wet conditions to dry in the Antarctic vortex core. The region of strong dehydration is in good agreement with the vertical domain of PSCs that are usually observed between 15 and 25 km. The strong dehydration is accompanied by an increase in H₂O mixing ratio below, indicating enriched H₂O below the dehydrated region. This dehydration and rehydration below are visible until August. Importantly, we see a clear descent of the rehydration over time, causing water originating from higher altitudes to accumulate initially in the polar lowermost stratosphere. The dehydrated and rehydrated air carries on descending throughout winter forced by the BDC with ultimately H₂O being irreversibly removed from the stratosphere. This is supported by observed significant positive anomalies below the tropopause in the Antarctic in September (Figure S2 in Supporting Information S1). The recovery of the global H₂O mass in late 2023, however, appears to be largely due to the enhancement of the tropical entry (Figure S3 in Supporting Information S1) probably caused by the slowdown of the BDC. Based on the good agreement between the model simulation and MLS data, the observed dehydration and rehydration below can only be linked to the sedimentation of the ice PSC particles, evaporation at lower levels and descent of this rehydrated air with the BDC. The important consequence is that a substantial amount of HTHH H₂O is removed from the stratosphere during the austral winter.

5. Long-Term Decay of HTHH Water Vapor

To clarify the mechanism for the removal of the HTHH injected H₂O, we compare simulations **HT_2022**, **HT_2022 ns** and **Con_2022**. Figure 3a shows the total burden of gas-phase H₂O summing over all model levels (with constant tropical input to the stratosphere) projected by TOMCAT simulation through 2030 for these runs. The annual cycle for run **Con_2022**, with a decrease in austral winter and increase afterward, is related to the annual cycle of its sinks and sources, the dehydration inside the polar vortex in June to August, and the tape recorder signal with enhanced H₂O from the tropical troposphere to the stratosphere that has maximum enhancement around September. A similar annual cycle exists in run **HT_2022**. The differences between the two runs is because the dehydration is stronger for run **HT_2022**, causing a decreasing year-to-year difference between them. In contrast, the run **HT_2022 ns** does not show this strong dehydration and annual cycle, with a slower decay throughout the following years. Here, the H₂O decay is caused by the stratosphere-to-troposphere transport where stratospheric air with HTHH-injected H₂O slowly descends into the troposphere at high latitudes via the deep branch of the BDC and is replaced by air from the troposphere with H₂O values determined by tropopause temperatures.

Figure 3b shows the differences in the total burden of H₂O mass between the HTHH perturbed runs and the control run. The excess H₂O, once injected into the stratosphere, is removed in an almost step-like fashion during austral winter starting in 2023. The amount of H₂O removal, around 20 Tg in 2023, is in very good agreement with the MLS-observed value, supporting the TOMCAT representation of the HTHH H₂O transport and removal. The modeled e-folding lifetime for the removal of the excess H₂O is around 4 years (half-life of ~2.8 years) from the point at which removal starts (over a year after the eruption), so that ~25 Tg remains in the stratosphere at 2030. The longevity of the HTHH injected H₂O thus exceeds 7 years. Comparing the simulated H₂O mass in the stratosphere between runs **HT_2022** and **HT_2022 ns**, it can be seen that PSC sedimentation plays a key role in the removal of the HTHH H₂O. Without PSC sedimentation, the decline of H₂O mass is much slower so that only around 50 Tg H₂O is removed by 2030, accounting for ~38% of the total removal in run **HT_2022** by that time. The H₂O removal without PSC sedimentation will involve the residual circulation returning from the stratosphere to the troposphere. The dehydration due to the sedimentation of ice PSC particles thus accounts for more than 60% of the modeled total removal over this period, serving as a main removal pathway of the HTHH H₂O. It is worth noting that PSC sedimentation is also important for the removal of background (non-volcanic) H₂O. Without PSC

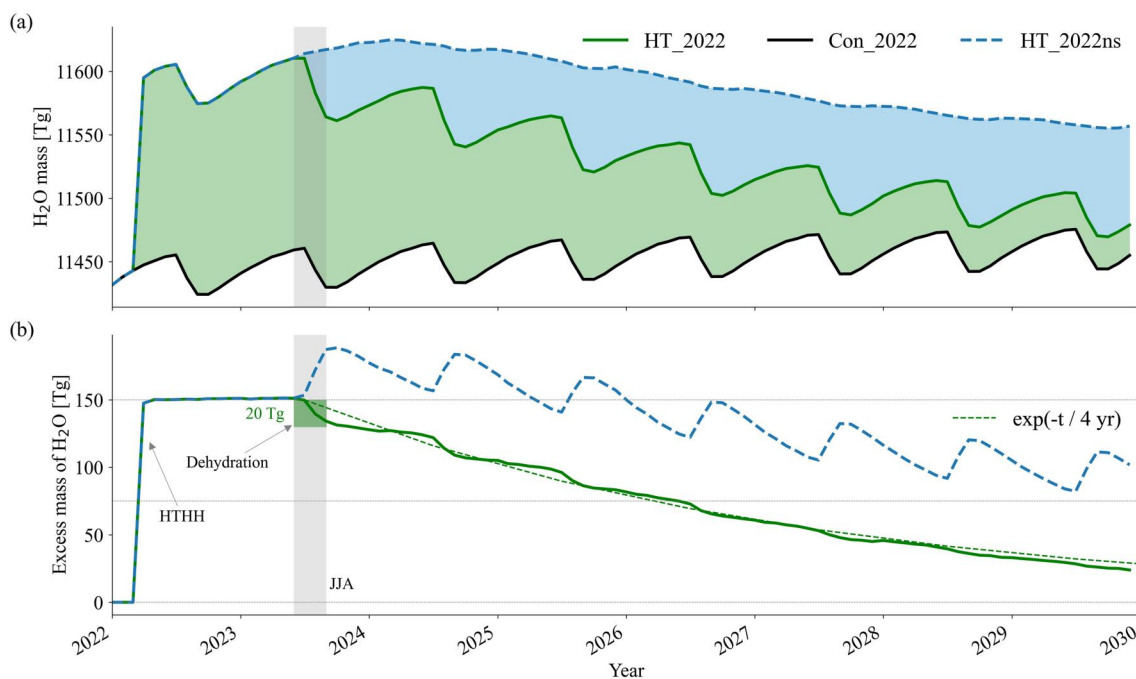


Figure 3. TOMCAT projections of the decay rate of the excess H₂O. (a) Time series of simulated total abundance of H₂O over all model levels (with tropospheric mixing ratios limited to the constant stratospheric input value) for runs **Con_2022**, **HT_2022**, and **HT_2022 ns**. Gray shading indicates the austral winter (JJA) 2023. (b) Differences (Tg) in panel (a) with respect to control run **Con_2022** for runs **HT_2022** and **HT_2022 ns**. The dotted curve illustrates exponential decay with timescale of 4 years starting in July 2023. A horizontal dotted line indicates 75 Tg, 50% of the initial injection.

sedimentation (run **HT_2022 ns**) the stratospheric total H₂O burden would increase slightly during austral winter under the effect of the positive anomalies in H₂O at the tropical tropopause (Gilford & Solomon, 2017). In the model PSC sedimentation removes ~30 Tg of background H₂O each austral winter.

6. Ozone Depletion Due To the Increased H₂O

We now quantify the impact of the additional H₂O on Antarctic ozone through October 2023 and compare with previous years (Figure 4). In 2022, there is negligible modeled chemical impact on the total column ozone at high SH latitudes (65°S–90°S), consistent with the failure of HTHH H₂O to penetrate into the Antarctic polar vortex. In contrast, in 2023 it reached the pole before the vortex formation and thus caused a direct impact. Interestingly, in mid-winter 2023, before the onset of substantial chemical ozone depletion, modeled column ozone is smaller than other modeled years since 1980. This apparent earlier start of the ozone hole was observed by IASI. However, the small difference (10 DU) between model runs **HT** and **Control** shows that this early onset was dynamically driven rather than a chemical impact of the enhanced H₂O. The HTHH injection has been found to be linked to a stable and colder-than-normal vortex, with a slowdown of the BDC (Wang et al., 2023); our CTM may be capturing this effect via the specified ERA5 meteorology but here we cannot quantify it. An unusual transport of ozone-poor air from the upper stratosphere to the lower stratosphere, indicated by the increase of age-of-air in the stratosphere (Figure S4 in Supporting Information S1), can lead to an anomalous decrease of ozone at lower altitudes.

Meanwhile, an earlier formation of the PSCs can lead to more extensive heterogeneous processing and ozone depletion (see Figures S5 and S6 in Supporting Information S1). However, the strong dehydration due to the sedimentation of ice PSC particles (see above) limits the impact of the additional H₂O in the core of the polar vortex. From June to September, an additional depletion of ozone up to 10 DU (around 4% of the background) due to the injected H₂O occurs at the vortex edge, a region of available sunlight and where ozone loss is not saturated. While the modeled mean column ozone in 2023 is outside the range of previous years in June and July, by September and October it is no longer an outlier. Hence, possible early indications of record low springtime ozone did not occur.

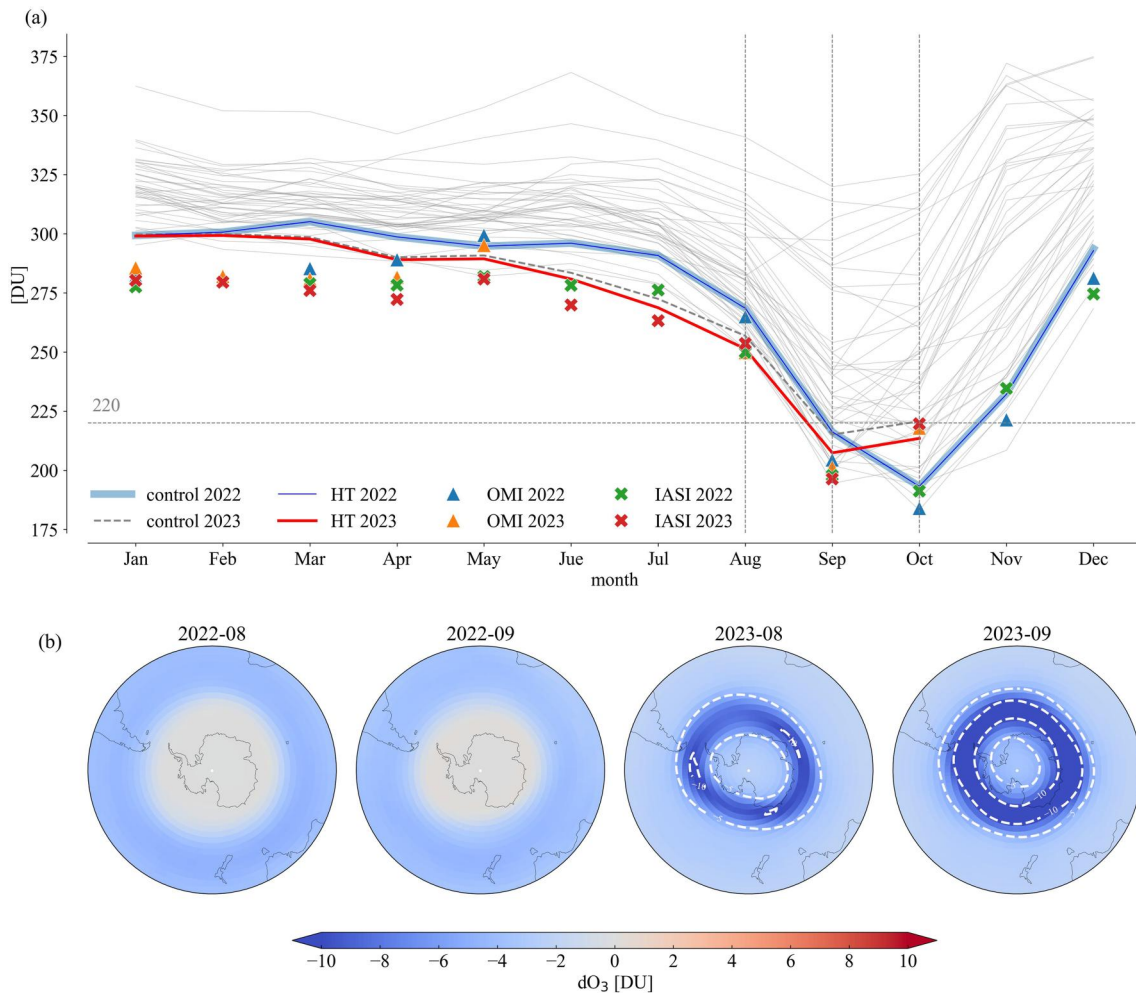


Figure 4. Stratospheric ozone changes after HTHH. (a) Time series of the mean total column ozone (DU) at SH high-latitudes (65°S–90°S), comparing run **Control** in 2022 (bold blue), 2023 (dashed gray) and years 1980–2021 (gray) with run **HT** in 2022 (thin navy) and 2023 (solid red), and with Ozone Monitoring Instrument (triangle), and Infrared Atmospheric Sounding Interferometer (cross) satellite observations in 2022 and 2023. (b) Modeled monthly mean difference in column ozone (DU) between runs **HT** and **Control** for August and September in 2022 and 2023.

Model runs **Con_2022** and **HT_2022** can be used to estimate the longer term impact of the HTHH H₂O over the next 5 years (Figure S7 in Supporting Information S1). The largest column depletion occurs at the edge of the Antarctic vortex in 2023 at 10 DU (see also Figure 4). The impact on the Antarctic ozone hole then decreases in subsequent years as the HTHH H₂O decays. Other large impacts on column ozone occur in the SH midlatitudes in 2022 and, to a lesser extent, the Arctic winter/spring. Interestingly, the impact on the Arctic maximizes in winter 2024/25 due to the spread of the HTHH H₂O, but note that these runs use repeating 2022 meteorology. In reality Arctic ozone loss is dominated by meteorological variability.

7. Summary and Discussion

Near-term projections of the HTHH climate impacts depend strongly on the estimation of the transport and longevity of the injected water vapor. Here we show that the Antarctic ice PSC sedimentation is likely a major removal pathway from the stratosphere for the HTHH-injected H₂O. This PSC sedimentation is partly responsible for a small estimated impact on chemical loss in the 2023 Antarctic vortex. Nevertheless, there are many other potential chemical, microphysical and radiative impacts of H₂O (and initial SO₂) in the stratosphere. The projected long residence time of the HTHH H₂O means that we can expect it to influence the atmosphere for many years. Many more modeling and observational studies are needed to quantify these impacts further.

Data Availability Statement

The v4 and v5 MLS water vapor data is available at Lambert et al. (2015, 2020), respectively. IASI ozone data (Siddans et al., 2018) can be downloaded from the Aeris portal. OMI total column ozone product is available at Veefkind (2012). TOMCAT model data is available at Zhou (2023).

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