The Spread of the Hunga Tonga H_2O Plume in the Middle Atmosphere Over the First Two Years Since Eruption

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Key Points:

- Three ground-based instruments confirm the MLS observation of a >1ppmv increase in H_2O in the lower mesosphere in 2023.
- The MLS H_2O monthly zonal anomaly from 76S-76N and 83-0.1 hPa has, for at least a month, been larger than at any time before the eruption.
- Almost all of the mass of H_2O injected into the stratosphere remains in either the stratosphere or mesosphere 22 months after the eruption.

Abstract

The eruption of Hunga Tonga in January 2022 injected a large amount of water into the stratosphere. Satellite measurements from Aura Microwave Limb Sounder (MLS) show that this water vapor (H_2O) has now spread throughout the stratosphere and into the lower mesosphere, resulting in an increase of >1 ppmv throughout most of this region. Measurements from three ground-based Water Vapor Millimeter Wave Spectrometer (WVMS) instruments and MLS are in good agreement, and show that in 2023 there was more H_2O in the lower mesosphere than at any time since the WVMS measurements began in the 1990's. At Table Mountain, California all WVMS H_2O measurements at 54 km since June 2023, and all of the measurements from Mauna Loa, Hawaii, since the resumption of measurements in September 2023, show larger mixing ratios than any previous measurements. At 70 km several recent ~1 week WVMS retrievals in the last few months show the largest anomalies ever measured. The MLS measurements show that maximum H_2O anomalies have occurred throughout almost all of the stratosphere and lower mesosphere since the eruption. As of November 2023, almost all of the ~140 Tg of water originally injected into the stratosphere by the Hunga Tonga eruption remains in the middle atmosphere at pressures below 83 hPa (altitudes above ~17 km). The eruption occurred during a period when stratospheric H_2O was already slightly elevated above the 2004-2021 MLS average, and the November 2023 anomaly of ~160 Tg represents ~15% of the total mass of H_2O in this region.

Plain Language Summary

The eruption of the undersea Hunga Tonga volcano on 15 January 2022 injected large amounts of water vapor into the stratosphere, breaking all records for direct injection of water vapor

(H_2O) in the satellite era. Water vapor mixing ratios in the stratosphere and lower mesosphere (~20-65km) range from ~2-8 ppmv depending upon height, latitude, and season, and satellite measurements from Aura Microwave Limb Sounder (MLS) show that this water vapor has now spread throughout the stratosphere and into the lower mesosphere, resulting in an increase of >1 ppmv nearly globally throughout this altitude range. The MLS measurements are confirmed at three sites by the ground-based Water Vapor Millimeter Wave Spectrometer (WVMS) instruments, and all of these measurements show that there is more H_2O in the lower mesosphere (~50-65km) than at any time since the WVMS measurements began in the 1990's. At 70 km several WVMS measurements in the last few months show the largest anomalies ever measured. As of November 2023, almost all of the ~140 Tg of water originally injected into the stratosphere by the Hunga Tonga eruption remains in the middle atmosphere at pressures below 83 hPa (altitudes above ~17 km).

1 Introduction

On 15 January 2022, the eruption of the Hunga Tonga undersea volcano injected huge amounts of water vapor (H_2O) into the atmosphere. Measurements showed that a small amount of this H_2O was injected directly into the lower mesosphere (Millan et al., 2022; Carr et al., 2022); however, a much larger quantity was injected into the stratosphere. The early evolution of this stratospheric H_2O plume has been documented in several studies (Millan et al., 2022; Legras et al., 2022; Khaykin et al., 2022; Schoeberl et al., 2022; Nedoluha et al., 2023a). Fleming et al. (2024) have presented some calculations of the effect of this additional H_2O on O_3 and temperature over the next decade.

Nedoluha et al. (2023b) (hereafter N23) documented an increase in mesospheric H_2O in 2022. Measurements from MLS and three ground-based microwave instruments often recorded the highest H_2O mixing ratio anomalies ever seen. N23 concluded that a portion of this increase was caused by some of the H_2O-enriched air from Hunga Tonga that had risen slowly through the stratosphere and into the lower mesosphere. But it was also noted that the observed H_2O increases in 2022 in the lower mesosphere were caused, at least in part, by dynamical conditions that allowed for an anomalous amount of methane (CH_4) oxidation.

In this study we document the further spread of the Hunga Tonga H_2O plume in the stratosphere and the increase in mesospheric H_2O observed in 2023. While the high mesospheric H_2O mixing ratios observed in 2022 were unprecedented, the increase observed in 2023 was much larger and more widespread. We also document the timescales over which the injected H_2O mass spread throughout the middle atmosphere from the January 2022 eruption until November 2023.

2. Ground-based and Satellite Datasets

The WVMS instruments have been making nearly continuous measurements of H_2O in the middle atmosphere since the early 1990's. Measurements are made from the Network for the Detection of Atmospheric Composition Change (NDACC) sites at Table Mountain, California (34.4º N, 242.3º E), Mauna Loa, Hawaii (19.5º N, 204.4º E), and Lauder, New Zealand (45.0º S, 169.7º E). These instruments make spectrally resolved measurements of the 22 GHz H_2O emission line to obtain a vertical profile of H_2O. The vertical resolution in the mesosphere is ~16 km (FWHM).

The standard WVMS measurement product, which will be used in this study, is retrieved from a ~1 week integration of the spectrum within +/-30 MHz of the H_2O emission peak at 22 GHz. The precise time period is determined by variations in conditions at each site. Results from these retrievals from 1992 to 2021 were presented in Nedoluha et al. (2022), where H_2O vertical profiles were shown from 45 km to 80 km.

The measurements from Mauna Loa were interrupted on 27 November 2022, by a lava flow which cut power, communications, and road access to the site. Solar panels were flown in and installed by helicopter in September 2023, and these provide sufficient power to operate a single WVMS instrument. The WVMS6, which had been providing the long-term dataset was initially brought back into operation, but the initial performance was unsatisfactory. Since 26 September 2023 the H_2O measurements are therefore being made with the WVMS5 instrument, which had previously been used primarily for experimentation and to validate WVMS6 measurements. The WVMS5 instruments makes use of a new corrugated gaussian horn antenna design developed specifically for WVMS5 by Dr. Jorge Teniente and the Anteral Antenna group (Teniente et al., 2011]. This antenna went through many years of development on WVMS5 to improve the reflectivity (S11) and the H and E plane differences in order to reduce the baseline created by the use of both antenna planes and an absorber bar in the signal-reference measurement (Gomez et al., 2012).

There has been a slight adjustment to the WVMS H_2O retrievals from Lauder that are presented here relative to those shown in N23 which particularly affected the H_2O mixing ratios in July and August 2022. The WVMS retrievals rely upon a background temperature, and in N23 the temperatures for that period were calculated using an MLS climatology of coincident measurements covering the days of the ~1 week WVMS retrieval. Here we have made use of the average of the contemporaneous MLS temperatures taken during the ~1 week WVMS. The difference between climatological and measured temperature is usually small, however the year-to-year mesospheric temperatures near Lauder from June through August are particularly variable. In 2022 these differed by >10K from climatology over several weeks. An incorrect temperature background of 10K causes an error in the retrieved H_2O of ~0.5 ppmv in the mesosphere, and the new WVMS retrievals show variations that are in slightly better agreement with MLS.

The Aura MLS H_2O product is retrieved from the radiances measured by the radiometers centered near 190 GHz. The MLS v4 H_2O retrievals were used in Millan et al. (2022) because of poor fits in v5 retrievals in regions of extremely enhanced H_2O. In this study we use v5 retrievals, but, except in direct comparisons with WVMS measurements, we show monthly zonal medians in order to limit the effect of any problems with MLS measurements when the H_2O values are extremely enhanced. The v5 retrievals are generally recommended by the MLS Team. Livesey et al. (2021) showed that the v5 retrievals remove an upward drift in the MLS v4 H_2O measurements of ~2-4%/decade from ~50 hPa to 0.1 hPa since 2010 relative to the Atmospheric Chemistry Experiment Fourier Transform Spectrometer (ACE-FTS) (Bernath, et al., 2005). Those profile comparisons showed a kink in the relative drift near 10 hPa, a feature that is apparent in plots showing MLS H_2O anomalies relative to climatology near this level.

To compare with H_2O variations in the 1990's we also show observations from the Halogen Occultation Experiment (HALOE). HALOE observed between 2.45 and 10.0 µm using a solar occultation technique which provided measurements in two separate latitude bands on any day (one in sunrise mode and one in sunset mode). A full description of the design and operation is given by Russell et al. (1993). The results shown here use the HALOE third public release v19 retrievals.

3. WVMS, MLS, and HALOE Measurements of H_2O

In Figure 1 we show the monthly zonal median H_2O mixing ratio anomalies in the stratosphere and mesosphere for January to November, 2023. The anomalies are calculated relative to a 2004-2021 MLS-based climatology. The year begins with positive anomalies almost everywhere, with the largest anomalies in the lower stratosphere and in the tropical upper stratosphere. From January through April the strong tropical anomalies spread both northwards and southwards in the upper stratosphere. During this period the anomaly in the tropical lower stratosphere decreases as younger stratospheric air, unperturbed by the Hunga Tonga eruption, rises through the tropopause. Then, in June 2023 mixing ratio anomalies >1 ppmv spread into the northern midlatitude lower mesosphere (~ 1 hPa to 0.1 hPa). By August, the lower mesosphere from ~50S to 50N shows anomalies > 1 ppmv, with actual mixing ratios >8 ppmv throughout most of this region. In October 2023, almost the entire upper stratosphere (10 to 1 hPa) and lower mesosphere shows anomalies > 1 ppmv, with the sole exception being the Northern Hemisphere (NH) upper stratosphere.

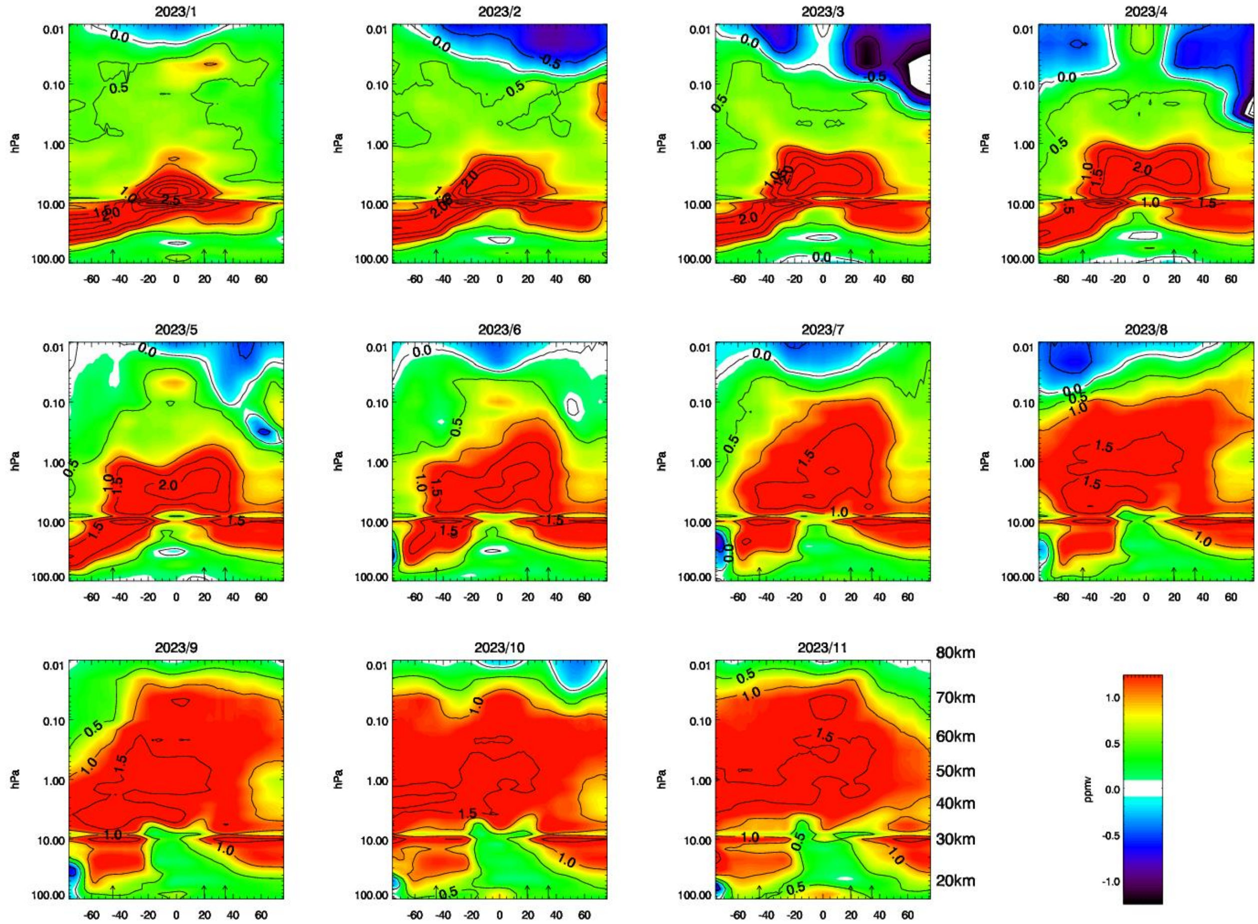

Figure 1– The monthly zonal-median H_2O anomaly relative to a 2004-2021 MLS climatology for MLS measurements from January to November 2023 for latitudes 75°S to 75°N. Data is shown on the native MLS pressure levels. Indicated altitudes are approximate. The arrows indicate the latitudes of the WVMS sites. Contours are in 0.5 ppmv intervals up to 2 ppmv, and in 1 ppmv intervals for larger H_2O mixing ratio anomalies.

In Figure 2 we show MLS nitrous oxide (N_2O) measurements (not anomalies) with contours of H_2O anomalies superimposed. Like N_2O, CH_4 has a sharply decreasing vertical gradient in the upper stratosphere, and CH_4 measurements from the HALOE instrument in the early 1990's showed a similar "rabbit ear" structure in latitudinal variation in April (Randel et al., 1998). High N_2O values are indicative of younger air, and Figure 2 shows that in 2023 this rising younger air brings with it H_2O-enriched air from the Hunga Tonga plume. In April both the H_2O anomaly and the N_2O mixing ratios in the upper stratosphere are slightly higher in the Southern Hemisphere (SH) than NH midlatitudes. From May through June, with the beginning of Boreal summer, this hemispheric asymmetry is reversed, and the H_2O anomalies >1.75 ppmv begin to enter the NH lower mesosphere.

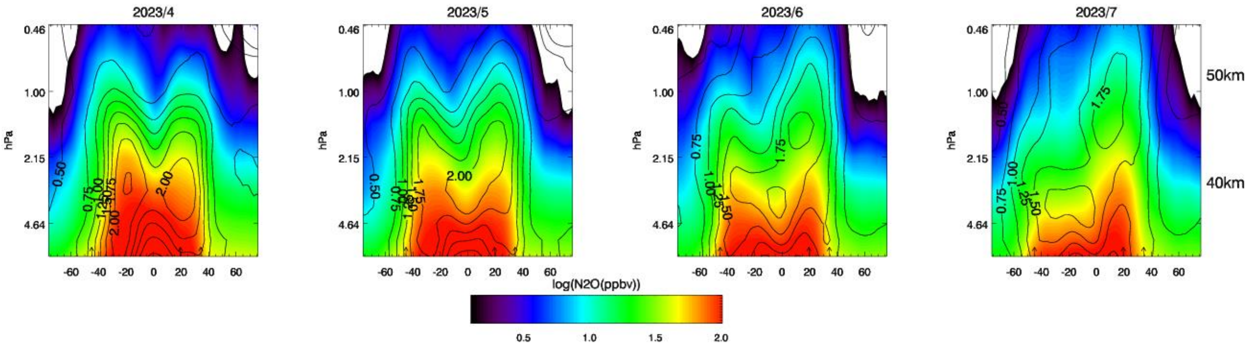

Figure 2- The monthly zonal-median N_2O mixing ratios (colors) and H_2O mixing ratio anomalies (lines) as measured by MLS from April through July 2023 for 75°S to 75°N. The indicated altitudes are approximate.

In Figure 3 we show WVMS and coincident MLS H_2O measurements near the WVMS sites from January 2022 through November 2023. The MLS measurements are an average over a coincident time period (usually ~1 week) within ±2° latitude, ±30° longitude of the WVMS sites, and are convolved with WVMS averaging kernels appropriate to each site (e.g., Nedoluha et al., 2022). The H_2O increase at 54 km is first observed at Table Mountain and Mauna Loa, and then slightly later at Lauder.

The gap in the WVMS data from Mauna Loa is the result of the cut in power and communications caused by the eruption of Mauna Loa. As noted in Section 2, there are two WVMS instruments at Mauna Loa, with the primary timeseries provided by the WVMS6 instrument. However, since there was some difficulty with the restart of WVMS6, and since the solar panels only provide sufficient power for one instrument, the post-Mauna Loa eruption measurements are currently being provided by WVMS5. Before the Mauna Loa eruption WVMS5 and WVMS6 were in good agreement, as can be seen in Figure 3.

Figure 3 shows the large mid-2023 increase in H_2O in the lower mesosphere observed by WVMS and coincident MLS measurements at Lauder, Mauna Loa, and Table Mountain. Some of the WVMS measurements are biased slightly high relative to the MLS measurements, but the magnitude of the observed increase in lower mesospheric H_2O is in good agreement. As was noted in N23 the H_2O mixing ratios at 54 km were already at record-high levels by the end of 2022. However, based on an analysis of coincident N_2O measurements and the phase of quasi-biennial oscillation (QBO), it was shown that a significant component of the observed increase in the lower mesosphere was probably caused by dynamical variations (slower ascent) unrelated to Hunga Tonga. In 2023, however, there was a much larger increase in lower mesospheric H_2O, and the MLS N_2O measurements do not indicate that this is a period of unusually slow ascent that would lead to an increase in H_2O. This increase can therefore only be ascribed to the Hunga Tonga plume.

The H_2O anomalies at 70 km in Figure 3 also show an increase throughout much of 2023, but dynamical variations cause much larger anomaly variations at this altitude than in the lower mesosphere. As was noted in N23, the large increase in anomalous H_2O mixing ratio observed over Lauder in 2022 was coincident with a large decrease in anomalous carbon monoxide (CO). Similar variations in H_2O and CO occurred in 2015 during a similar phase of the QBO. N23 therefore concluded that a significant portion of the 2022 upper mesospheric increase over Lauder was probably not caused by Hunga Tonga.

In late 2022 there was a decrease in H_2O at 70 km at both Mauna Loa and Table Mountain, followed in subsequent months by an increase of comparable magnitude. At Lauder there was a sharp increase in 70 km H_2O at the end of 2023. The two measurements of H_2O anomalies >1 ppmv at 70 km at Mauna Loa in November 2023 are the only such measurements since those WVMS observations began in 1996. Similarly, the 16-23 September 2023 WVMS measurements at Table Mountain which shows an anomaly of >1.5 ppmv is the only such measurement since observations began in 1992, while the second largest anomaly (1.2 ppmv) occurred during the 31 October to 6 November 2023 retrieval. Thus, the MLS and WVMS measurements suggest that increase H_2O from Hunga Tonga is affecting H_2O values in the upper mesosphere as well. This increase in H_2O occurs during a period when solar irradiance is increasing and thus causing increased photodissociation of H_2O (and hence lower H_2O mixing ratios) in the mesosphere. The Lyman-α solar irradiance in 2023 is higher than at any time since the maxima during solar cycle 23 which peaked in 2001-2002 (lasp.colorado.edu/lisird/data/composite_lyman_alpha).

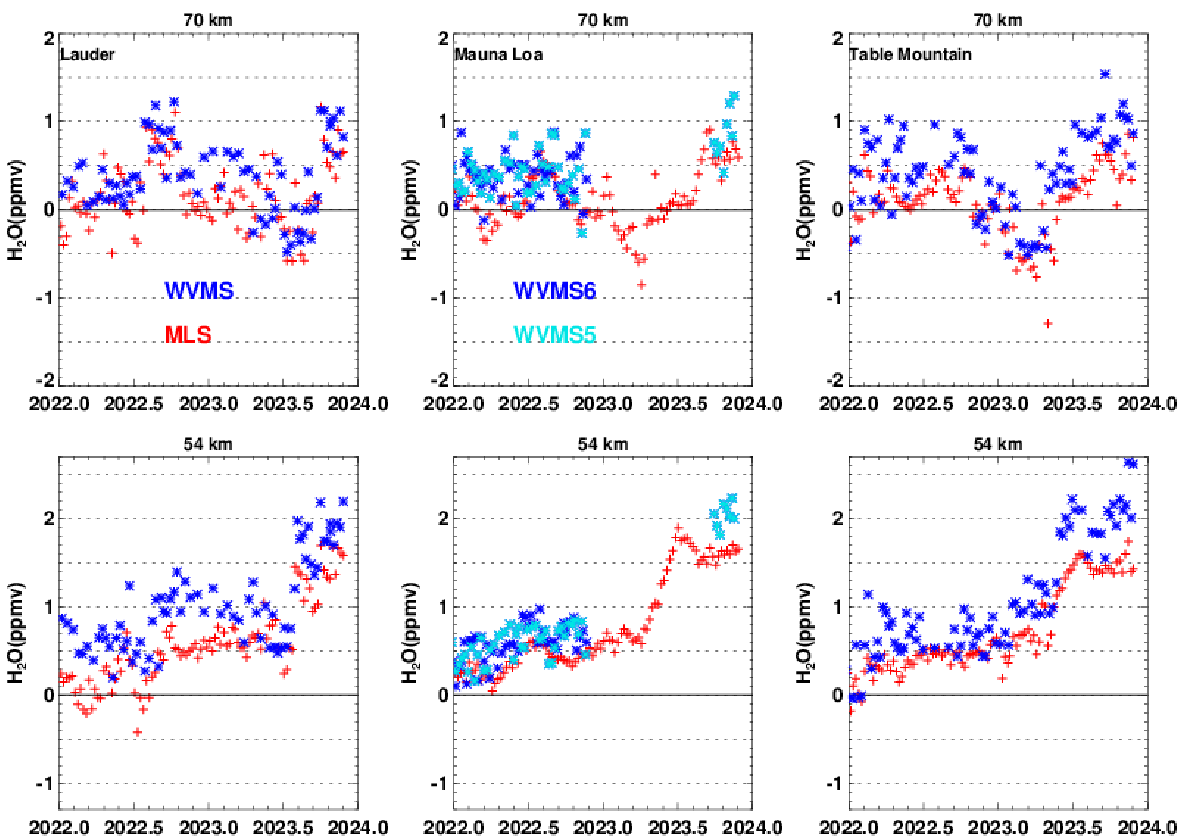

Figure 3- WVMS H_2O anomalies (blue and cyan; see text) and coincident MLS measurements (red) at three WVMS sites. The MLS measurements have been convolved with WVMS averaging kernels. The anomalies are calculated relative to an MLS 2004-2021 H_2O climatology.

To put the recent lower mesospheric increase into a multidecadal context we show in Figure 4 the H_2O timeseries at 54 km at the three WVMS sites since 1991. At Table Mountain all of the ~weekly 54 km WVMS H_2O measurements since June 2023, and all of the measurements from Mauna Loa since the resumption of measurements in September 2023, show larger anomalies relative to the MLS climatology, and also larger absolute mixing ratio values, than any previous measurements. Near Lauder there are strong latitudinal gradients in mesospheric H_2O from June through August (coincident with the temperature gradients mentioned in Section 2), and this can cause a large weekly H_2O anomaly that is comparable to the increase caused by Hunga Tonga. Also, the WVMS measurements from Lauder are inherently noisier due to the high tropospheric opacity at the site. But the presence in both WVMS and MLS measurements of anomalies consistently more than 0.9 ppmv above the instrumental average since mid-July 2023 is unprecedented.

The timeseries shown in Figure 4 allows for comparison of the H_2O variations following the Hunga Tonga eruption with the gradual increase seen in the early 1990's in measurements from HALOE, and from the WVMS instruments at Lauder and Table Mountain (Evans et al.,1998; Nedoluha et al., 1998a). Nedoluha et al. (2003) showed an increase of ~0.4 ppmv in upper stratospheric and lower mesospheric measurements from HALOE from 1991-1995, with a significant fraction of that increase driven by increased CH_4 oxidation caused by dynamical variations (Nedoluha et al. 1998b). When compared to the 1990's H_2O increase near the stratopause, the change in H_2O from the Hunga Tonga plume is both much larger and occurs over a much shorter period.

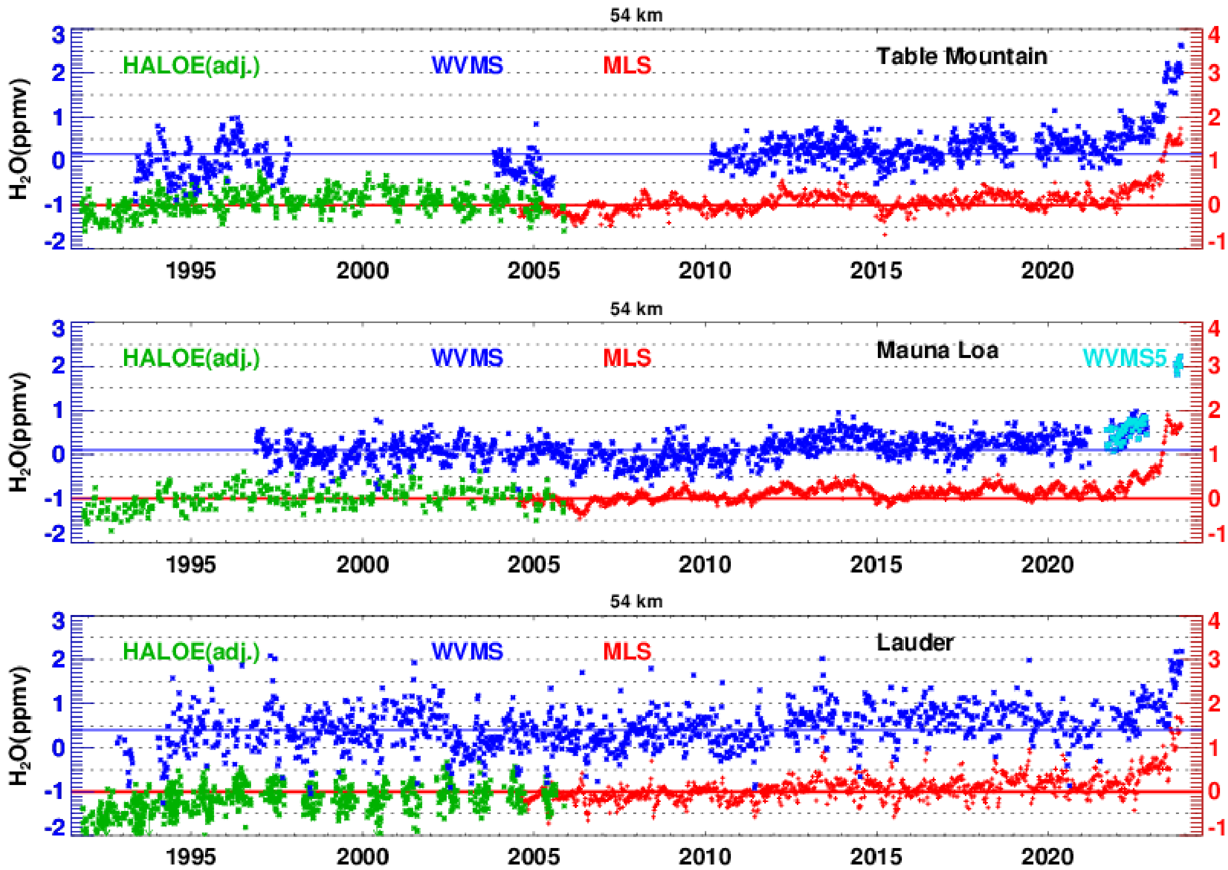

Figure 4- H_2O anomalies at 54 km from WVMS (blue and cyan; see text), HALOE (green) and MLS (red) at, or coincident with, the three WVMS sites. The HALOE and MLS measurements have been convolved with WVMS averaging kernels. The satellite measurements are referenced to the right-hand axis which, to prevent overplotting of data, is offset by 1 ppmv from the axis for the WVMS measurements. The measurements from HALOE have been adjusted to create an unbiased time series relative to MLS. The blue line shows the average WVMS offset from the MLS climatology.

4. The Spread and Persistence of the Hunga Tonga H_2O Plume

In Figure 5 we show the variation of the mass of H_2O in the stratosphere from 83 hPa to 0.1 hPa since the beginning of 2021 (latitudes from 75°S to 75°N represent ~97% of the global area). As in previous plots, the values shown are calculated from monthly zonal mixing ratio anomalies from the 2004-2021 climatology, but for Figure 5 these values are integrated over the indicated pressure range and area to provide a mass. The typical annual variation measured by MLS over this entire pressure range and latitude region, which comes almost entirely from the lowermost altitudes, is ~30-40 Tg. As was shown in Nedoluha et al. (2023a) the 365-day mean 100 hPa tropopause temperature was ~0.5 K to 0.9 K above the 42-year mean in 2021. The high average tropopause temperature during 2021 is probably the primary reason why the mass of H_2O in the 83 hPa to 31 hPa level is ~25 Tg above the 2004-2021 climatological value. The value in this level in 2021 is not unusual, but is comparable to the highest levels measured since 2004.

The average mass of H_2O from 83 hPa to 0.1 hPa and 75°S to 75°N in 2021 in the MLS measurements was 1096 Tg. Initial calculations of additional stratospheric H_2O mass from the MLS measurements range from ~130 to 150 Tg (Millan et al. (2022), Xu et al. (2022), and Khaykin et al. (2022)), consistent with the increase shown in Figure 5. Results are shown both from zonal median and zonal mean anomalies, and the results are nearly identical except in the months immediately following the eruption when the plume had not yet spread evenly over all longitudes.

Wilmouth et al., (2023), using 2021 as a background, found that, through the end of 2022, the global H_2O enhancement from 100 hPa to 1.2 hPa, referenced to 2021, had decreased slightly, from 145 Tg to 135 Tg. Figure 5 also shows that there has been only a slight decrease in the total amount of H_2O above 83 hPa during the almost two years after the eruption. While the anomaly in H_2O in the 31 hPa to 10 hPa region is now only ~1/2 as large as immediately after the eruption, a significant fraction of this mass has risen to altitudes with pressures below 10 hPa.

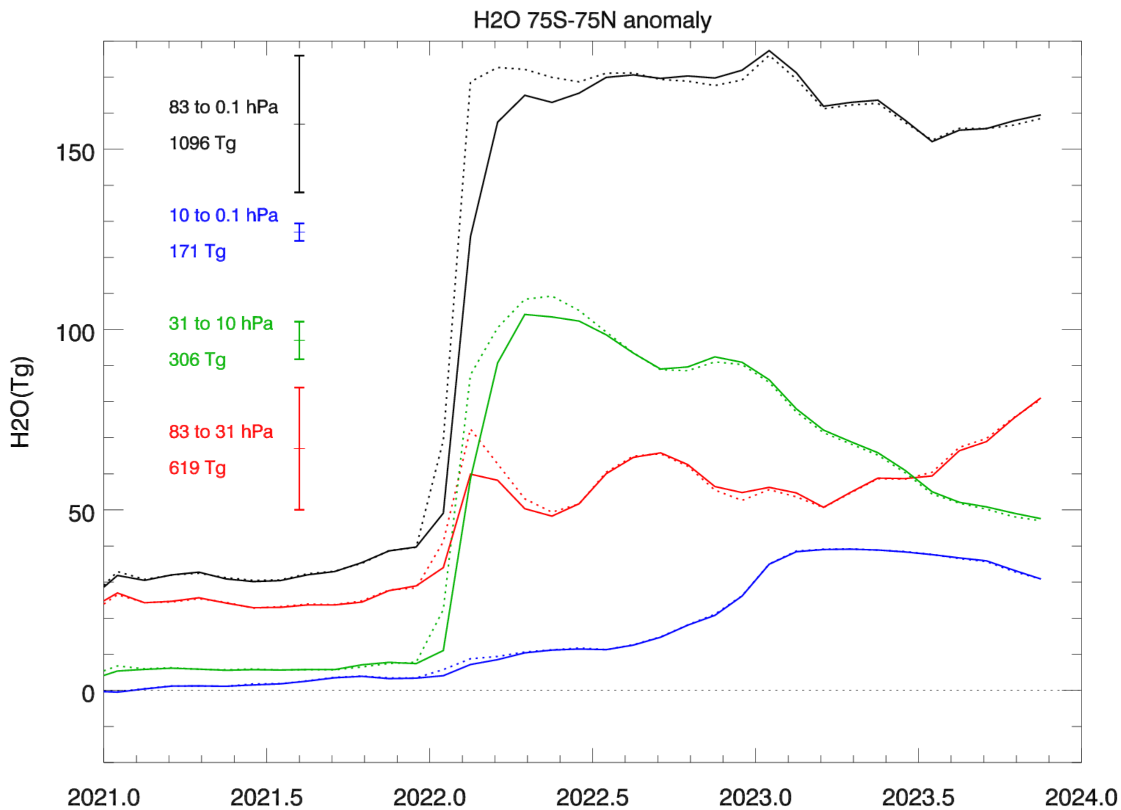

Figure 5- The monthly H_2O mass anomaly from 82 hPa to 0.1 hPa as measured by MLS from 75°S to 75°N. Results are shown both as calculated from the zonal median anomalies (solid) and zonal mean anomalies (dotted). The error bars indicate the standard deviation of the monthly mass anomaly over the indicated pressure ranges for MLS measurements from 2004 through January 2022. Also shown in the labels is the mean of the 2021 H_2O mass in each pressure layer.

The excess H_2O in the 83 to 31 hPa layer has also increased since early 2023. Figure 1 suggests that there is some increase in this layer from descending air from the Hunga Tonga plume, but about ½ of the increase since March 2023 occurs in the 20°S-20°N region, so this suggests an increase H_2O entering the stratosphere through the tropical tropopause. Dessler et al. (2014), using trajectory calculations, showed a close correlation between MLS H_2O anomalies and Modern-Era Retrospective analysis for Research and Applications (MERRA) temperatures in this region. Figure 6 shows MERRA2 temperatures at 100 hPa from 10°S-10°N. These are consistently well above the long-term average from the beginning of 2021 onwards, and there is a further increase in 2023, suggesting that some of the increase in the lower layer shown in Figure 5 is probably the result of an increase in H_2O entering the stratosphere. The H_2O anomaly above 83 hPa in November 2023 was ~160 Tg, which represents an excess of ~15% over the average amount of H_2O measured in this region by MLS from 2004-2021.

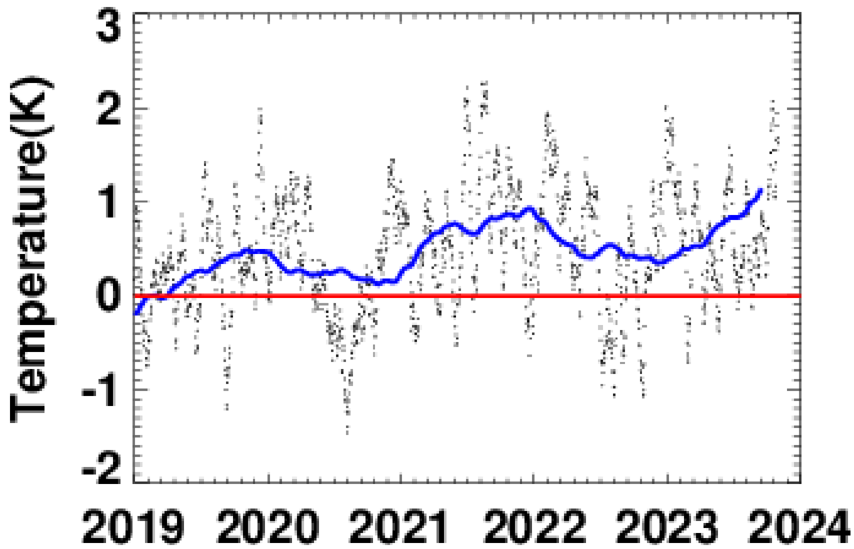

Figure 6- Daily anomalies in 100 hPa temperature from 10°S-10°N from MERRA2 relative to a 1980-present average. The blue line is from a 365-day smoothing.

In Figure 7 we show a measure of the rate of spread of the H_2O plume. As in Figure 1, a zonal monthly median has been calculated from monthly MLS data in 2° latitude bins, and a monthly climatology has been subtracted. Figure 7 then shows the month in which the H_2O mixing ratio anomaly at each latitude and pressure reaches a maximum value. The unprecedented global effect of the Hunga Tonga eruption is apparent in that, for nearly every location up to 0.1 hPa, the monthly maximum zonal median H_2O anomaly has occurred in the months since January 2022. This statement is also true for the maximum absolute H_2O mixing ratio.

During the first two months after the eruption, the increased H_2O in the plume causes sufficient radiative cooling and to significantly perturb the vertical velocity (Randel et al. 2023; Niemeier et al., 2023). Niemeier et al. (2023) show that this velocity perturbation decreases in subsequent months. There is also gradual CH_4 oxidation that occurs in the stratosphere which increases H_2O mixing ratios. H_2O is therefore not a perfectly non-interacting tracer. Nevertheless, especially in the upper stratosphere and mesosphere where the radiative cooling effects are small, Figure 7 can provide timescales for the transport of a tracer from the Hunga Tonga injection site at ~20-30 hPa and 20.5°S. Qualitatively, the timescale at which the month of maximum anomaly rises in the tropics from 10 hPa to 1 hPa is comparable to the residual vertical velocity and the change in modal age-of-air for the tropical pipe region in the Goddard Earth Observing System Chemistry-Climate Model shown in Li et al. (2012)

Figure 7 shows that the plume spread quickly in the tropics in the low and mid-stratosphere, as was previously noted by Schoeberl et al. (2023). It was first clearly observed in early April by WVMS measurements at Mauna Loa (19.5°N) at 28 km, using a non-standard retrieval technique that provided sensitivity in the mid-stratosphere (Nedoluha et al., 2023a). But the ascent into the mid-stratosphere took much longer, with the maximum H_2O anomalies in the mid-stratosphere in the tropics not occurring until almost a year after the eruption.

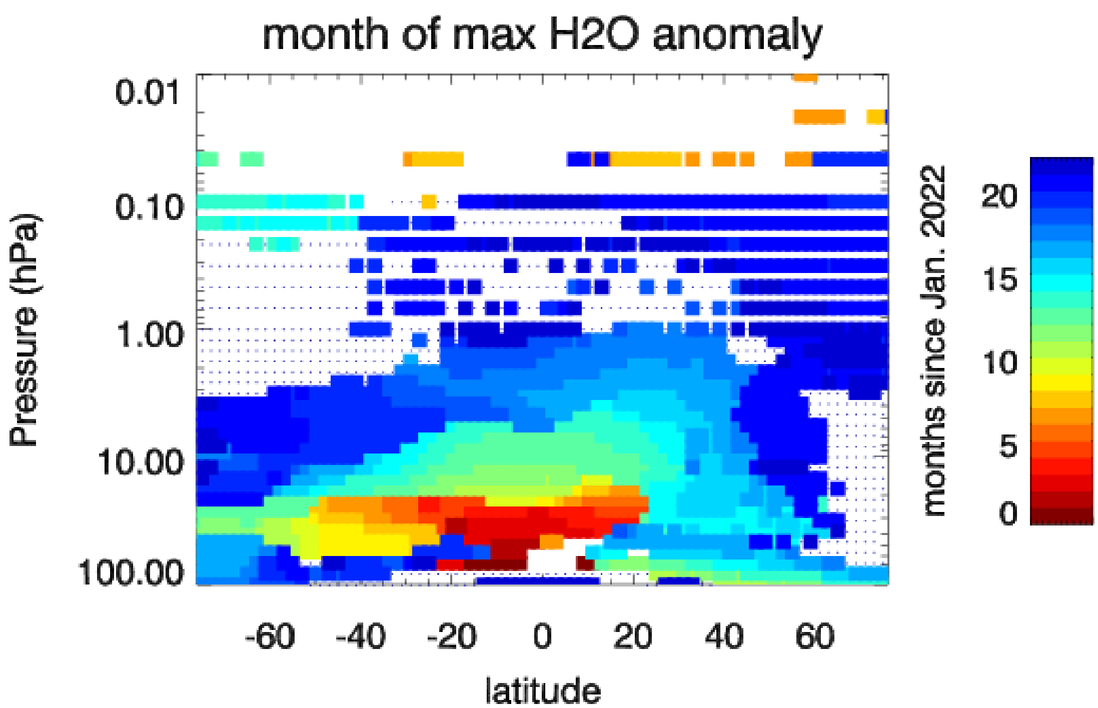

Figure 7- The number of months after the eruption of Hunga Tonga that the zonal median MLS H_2O anomaly reached its maximum value. Small dots indicate that the maximum occurred in the last month shown (November 2023). Results are shown for all MLS pressure levels from 100 to 0.01 hPa and in 2 degree latitude increments. Regions with no symbol (primarily in the upper mesosphere) indicate that the maximum H_2O anomaly occurred before January 2022.

The asymmetry in the evolution of the SH and NH tropics, shown in Figure 2, is also apparent in Figure 7. There is a maximum in SH tropical upper stratosphere at 20S at 1.8 hPa in March 2023, but not until September does the maximum reach 1 hPa. By contrast, the maximum in the NH tropics at 1.8 hPa occurs in May, but it reaches 1 hPa and enters the mesosphere soon thereafter.

There are at least two regions where the month of maximum H_2O occurs during this time period, but is unrelated to the Hunga Tonga plume. The maxima in H_2O in the SH upper mesosphere in August 2022, and at the highest northern latitudes in February and March 2022, are primarily caused by unusual dynamical conditions, as is evidenced by unusually low CO mixing ratios, as was shown in N23.

5. Summary

While the high mesospheric H_2O mixing ratios observed in 2022 were unprecedented, the increase observed in 2023 was much larger and more widespread. By October 2023 large (>1ppmv) anomalies were observed throughout the lower mesosphere by Aura MLS and by three WVMS instruments. At Table Mountain all WVMS H_2O measurements at 54 km since June 2023, and all of the measurements from Mauna Loa since the resumption of measurements in September 2023, show larger mixing ratios than any previous measurements. At 70 km several WVMS measurements in the last few months from Table Mountain and Mauna Loa show the largest anomalies ever measured at these sites.

The MLS measurements allow for the tracking of the spread of the Hunga Tonga plume throughout the middle atmosphere, and maximum H_2O anomaly values have occurred throughout almost all of the stratosphere and lower mesosphere since the eruption. These measurements also show that, as the water vapor spread, the total mass anomaly in the stratosphere and lower mesosphere (82 hPa to 0.1 hPa) remained nearly constant, so that, 22 months after the eruption, almost all of the water injected into the middle atmosphere during the Hunga Tonga eruption remains in the middle atmosphere.

6. Acknowledgments

We thank G. Rose, M. Kotkamp, M. Brewer, J. Robinson, and P. Wang for their efforts to maintain and calibrate the WVMS instruments at Mauna Loa, Table Mountain, and Lauder. This work was supported by the NASA Earth Sciences Division Upper Atmosphere Research Program and by the Office of Naval Research. Work at the Jet Propulsion Laboratory, California Institute of Technology, was carried out under a contract with the National Aeronautics and Space Administration. We thank M. Heney for making the daily GMA:GEOS5 temperature data at each site available in a convenient form.

7. Data Availability Statement

WVMS weekly retrievals are available on the NDACC data server at https://www-air.larc.nasa.gov/missions/ndacc/data.html#. MLS v5 data are available at https://disc.gsfc.nasa.gov/datasets?page=1&keywords=ML2H2O_005. HALOE v19 data are available at disc.gsfc.nasa.gov/datasets?keywords=HALOE. GEOS temperature data are available at https://gmao.gsfc.nasa.gov/GMAO_products/. Lyman-alpha timeseries based on work of Machol et al. (2019).

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