Measurements of Stratospheric Water Vapor at Mauna Loa and the Effect of the Hunga Tonga Eruption

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Abstract

The eruption of Hunga Tonga in January 2022 injected an amount of water vapor into the stratosphere that is unprecedented in the satellite era. In the ensuing months Aura Microwave Limb Sounder (MLS) measurements showed that this plume of water vapor spread from its original injection site at 20.50S to Mauna Loa, Hawaii at 19.50N, where an increase was observed in April by the ground-based Water Vapor Millimeter-wave Spectrometer (WVMS) instruments. Interannual variations in water vapor occur over Mauna Loa due to both dynamical variations in the tropical stratosphere and variations in the amount of water vapor crossing the tropical tropopause, and we place the observed stratospheric water vapor increase from Hunga Tonga into context of these other variations that have been observed since 2013.

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Key Points:

A Aura MLS measurements showed that water vapor from the Hunga Tonga eruption spread to 20°N in April 2022

B Ground-based instruments at Mauna Loa observed an increase in the lower stratosphere in April 2022.

C The April 2022 increase in water vapor in the upper stratosphere over Mauna Loa is placed in context of interannual variations since 2013.

Abstract

The eruption of Hunga Tonga in January 2022 injected an amount of water vapor into the stratosphere that is unprecedented in the satellite era. In the ensuing months Aura Microwave Limb Sounder (MLS) measurements showed that this plume of water vapor spread from its original injection site at 20.5ºS to Mauna Loa, Hawaii at 19.5ºN, where an increase was observed in April by the ground-based Water Vapor Millimeter-wave Spectrometer (WVMS) instruments. Interannual variations in water vapor occur over Mauna Loa due to both dynamical variations in the tropical stratosphere and variations in the amount of water vapor crossing the tropical tropopause, and we place the observed stratospheric water vapor increase from Hunga Tonga into context of these other variations that have been observed since 2013.

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 in the satellite era. During the ensuing months this plume of water vapor spread from the original injection site at 20ºS to cover much of the Southern Hemisphere and reached as far as 20ºN, where it was first observed by a ground-based microwave instrument at Mauna Loa, Hawaii in April 2022. These ground-based measurements capable of detecting water vapor at the altitude of the plume have been made since 2013, and we compare the sudden increase in water vapor caused by the arrival of this plume over Mauna Loa with other variations that have occurred over the last decade. This study lays the ground-work for an understanding of the effect of the water vapor injected by the eruption on overall water vapor in the stratosphere in the coming years.

1 Introduction

The eruption of Hunga Tonga on 15 January 2022 injected large amounts of water vapor into the stratosphere, breaking all records for direct injection of water vapor, by a volcano or otherwise, in the satellite era [Millan et al, 2022]. The Hunga Tonga is an undersea volcano located at 20.5ºS, 184.6ºE, and Aura MLS measured water vapor anomalies at altitudes as high as 57 km. While the direct injection of water vapor to 57 km was an impressive event, the injection of a much larger amount of water vapor into the stratosphere (~10-50 km) is likely to have a much more long-lasting effect on water vapor in the middle atmosphere.

Ground-based microwave measurements have been made at the Network for the Detection of Atmospheric Composition (NDACC) site at Mauna Loa, Hawaii (19.5ºN, 204.4ºE) since 1996 by a Water Vapor Millimeter-wave Spectrometer (WVMS) instrument [Nedoluha et al., 2022]. The WVMS instruments are designed primarily for mesospheric (~50-80 km) H_2O measurements, but no significant increase in mesospheric water vapor was detected by the WVMS instruments that could be attributed to Hunga Tonga. While these instruments are focused on mesospheric trend detection, they can be used to measure changes in water vapor in the stratosphere [Nedoluha et al., 2011]. The water vapor injected into the lower and mid- stratosphere (~100-5 hPa, ~10-35 km) by Hunga Tonga represents a unique opportunity to test the ability of the WVMS measurements to detect unusual changes in water vapor in the mid-stratosphere (~10 hPa, ~30 km).

2. Ground-based microwave measurements in the stratosphere

The vertical profile of the water vapor measurements is obtained by measuring near the H_2O emission peak at 22 GHz and making use of the change in pressure broadening with altitude. Retrieving water vapor mixing ratios in the lower stratosphere requires a much broader spectral measurement than is required in the mesosphere. A downward extension of the useful measurement range into the lower stratosphere was accomplished by reducing instrumental baseline artifacts and by replacing the discrete filters on the WVMS instrument with a Fast Fourier Transform (FFT) spectrometer, providing 16,384 channels over a 500 MHz range [Gomez et al., 2012]. Nedoluha et al. [2011] showed that, with an FFT, retrievals had skill down to ~26 km over a five-month period for measurements taken at Table Mountain, California (34.4°N, 242.3°E), and details of the retrieval scheme used here are given therein. The filterbank-based WVMS instrument at Mauna Loa was similarly replaced by a new instrument with an FFT backend in 2013, and it is measurements from this instrument that will be shown here.

The standard WVMS measurement product is retrieved from a ~1 week integration of the spectrum within +/-30 MHz of the H_2O emission peak at 22 GHz. Results from these retrievals from 1992 to 2021 are presented in Nedoluha et al. [2022], where H_2O vertical profiles are shown from 45 km to 80 km. Unlike the standard WVMS retrievals, the retrievals for this study make use of a wider +/-160 MHz spectral measurement centered around the H_2O emission peak at 22 GHz with a much shorter integration period. Useful retrievals in the stratosphere can be obtained in ~6 hours of measurement, but the challenge of such measurements in the lower and mid-stratosphere is that the water vapor retrievals are sensitive to very small changes in the instrumental baseline. Making use of 6-hour retrievals minimizes the possibility that a few bad spectral measurements (as can occur, for example, when there is water in the feedhorn antenna) will affect the retrieved water

vapor for an entire week. While severely contaminated spectra can be identified and removed from the spectral dataset, even slightly contaminated spectra can cause errors in the retrieved water vapor in the stratosphere.

In Figure 1 we show the averaging kernel for a typical WVMS retrieval used in this study. As can be seen, the sensitivity of these 6-hour retrievals drops sharply above ~60 km and they would therefore be inappropriate for mesospheric studies. By comparison, the averaging kernels for the standard weekly retrievals from Mauna Loa show a decrease in sensitivity above ~70 km, and the peak sensitivity at 70 km is ~0.5 [Nedoluha et al., 2022]. It is particularly important for this study to note that the WVMS retrievals, which will be shown down to 28 km, are sensitive to changes in water vapor at altitudes several kilometers below the retrieval altitude.

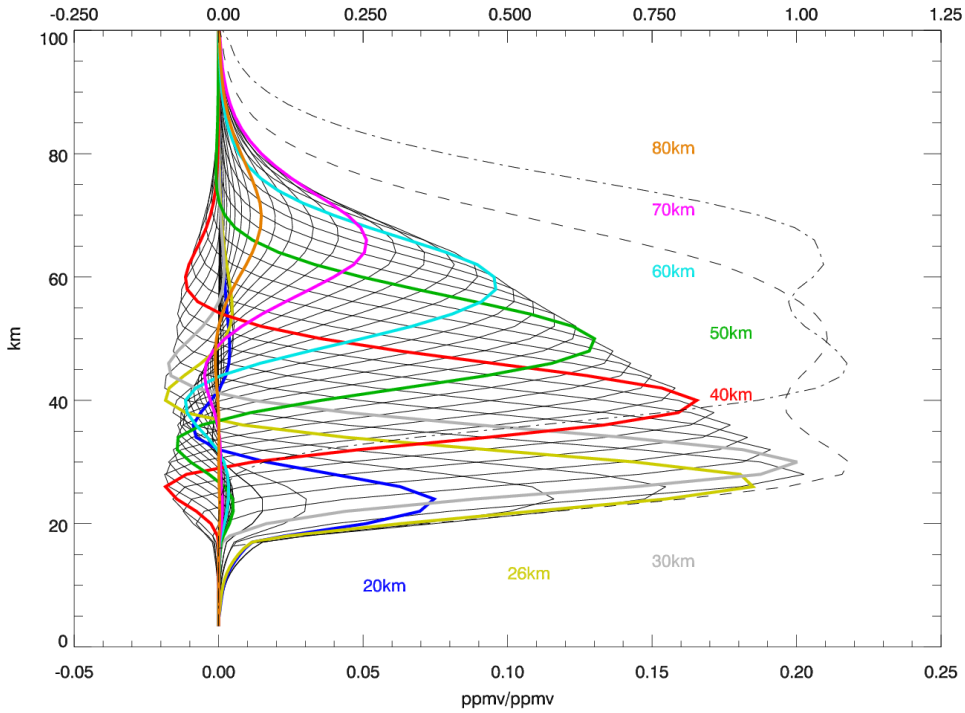

Figure 1- A typical averaging kernel for a 6-hour WVMS retrieval at Mauna Loa. Each solid line represents the sensitivity of the measurement to a perturbation over a 2 km interval and is referenced to the bottom axis. The dashed line shows the sum of the averaging kernels for these retrievals and is referenced to the top axis. The dot-dashed line shows the sum of the averaging kernels for the standard weekly retrievals.

3. WVMS and MLS H_2O measurements near Mauna Loa

Millan et al. [2022] showed the evolution of the H_2O plume from Hunga Tonga through March 2022. The Aura MLS H_2O water vapor product is retrieved from the radiances measured by the radiometers centered near 190 GHz. The v2.2 retrievals were validated by Lambert et al. [2007]. 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. However, Livesey et al. [2021] showed 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]. Further evidence for this drift is supported by drifts relative to other MLS measurement channels. The MLS v5 retrieval removes the drift relative to ACE-FTS, and the MLS team now generally recommends use of these MLS v5 H_2O retrievals. In addition to the temporal difference between Aura MLS v4 and v5 H_2O retrievals, Aura MLS v5 H_2O is also ~5-10% lower than v4 H_2O in the stratosphere and mesosphere. Since the H_2O measurements near Mauna Loa are not as extremely high as was the case near the volcano immediately following the initial eruption, all of the MLS measurements shown here will use the MLS v5 retrieval.

In Figure 2 we show the spread of the high water vapor anomaly from Hunga Tonga as observed by MLS from March to July 2022. As is indicated in the figure, the lower stratospheric high water vapor anomaly does not consistently reach the latitude of the WVMS measurements at Mauna Loa until April. The H_2O anomaly also reaches the latitude of the WVMS measurements at Lauder (at 45.0°S) in May, but, because of the lower altitude and resultant higher tropospheric optical depth at this site (relative to Mauna Loa and Table Mountain) these measurements do not have the lower stratospheric stability required for a reliable detection. The WVMS measurements at Table Mountain (34.4°N) should be able to detect an increase of this magnitude, but the anomaly does not consistently reach that far north during this time period.

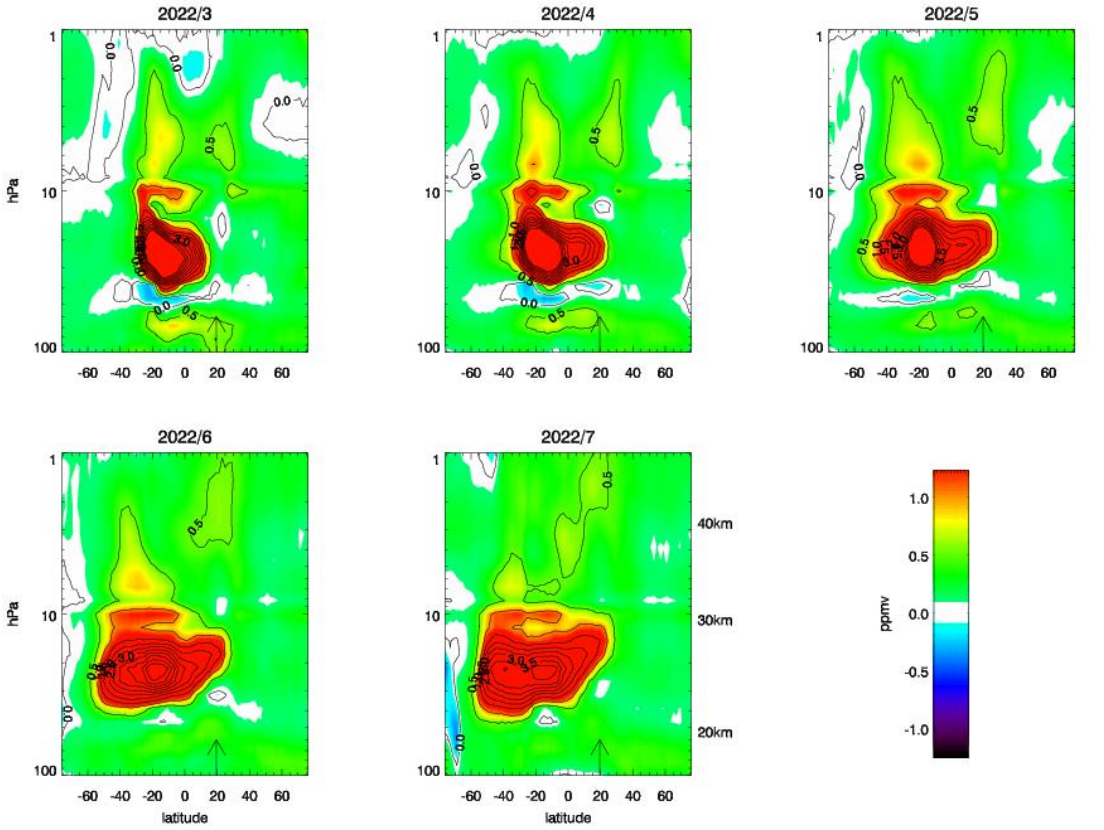

Figure 2- The monthly zonal-median water vapor anomaly relative to the MLS climatology for MLS measurements from March to July 2022. Data is shown on the native MLS pressure levels. Indicated altitudes are approximate. The arrow at 19.5N represents the latitude of the Mauna Loa site.

Figure 3 shows water vapor measured by WVMS and Aura MLS (offset by 1 ppmv) near Mauna Loa in the stratosphere (28, 30, 34, and 40 km) from January through July 2022. As noted above, WVMS retrievals become increasingly unstable with decreasing altitude in the lower stratosphere, hence no WVMS retrievals below 28km will be shown here. In Figure 3 the Aura MLS measurements have been convolved with the WVMS averaging kernels and make use of the same local MLS-climatology-based a priori (x_{MLS}^{climo}) that is used in the WVMS retrievals, i.e. $x_{sat}^{conv} = x_{MLS}^{climo} + A_{WVMS} \times (x_{sat}^{meas} - x_{MLS}^{climo})$. The measurements up to 34 km show a sudden increase in water vapor at the beginning of April, with the water remaining elevated from that point onwards.

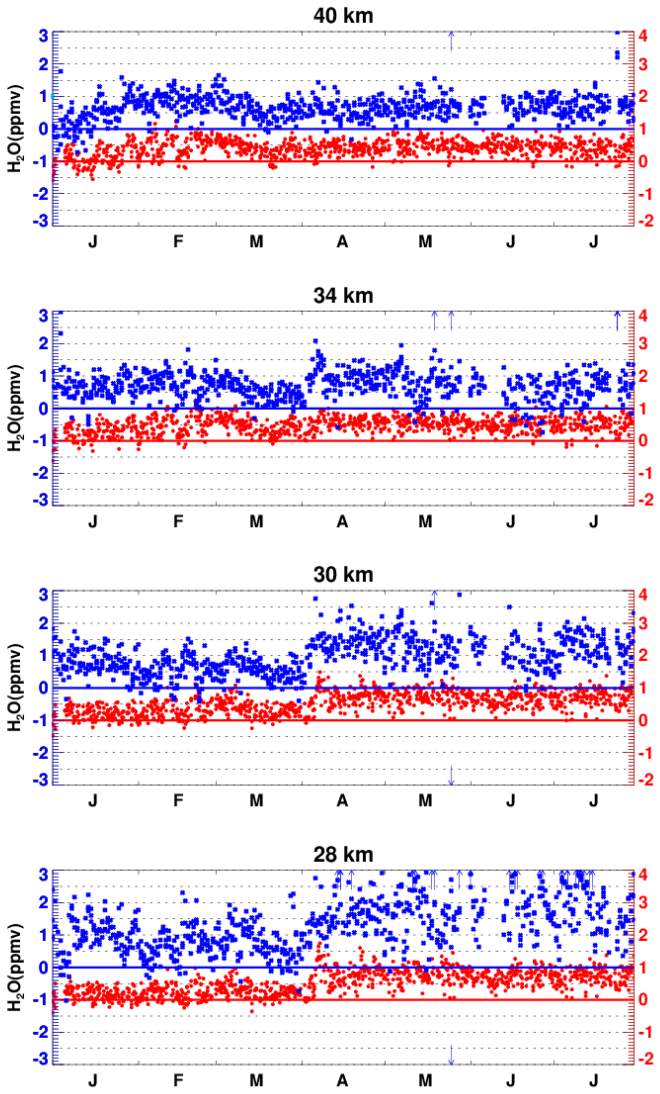

Figure 3 – Water vapor retrieval anomalies for January through July 2022 relative to an MLS-climatology for individual MLS overpasses (red) and 6-hour WVMS measurements (blue). MLS measurements are within +/-2° latitude and +/-10° longitude of Mauna Loa. Note that the y-axes for the two measurement datasets have been offset by 1ppmv to minimize the over plotting of points. Arrows indicate individual measurements outside the axis range. The MLS measurements shown here have been convolved with WVMS averaging kernels.

In Figure 4 we show stratospheric water vapor profiles measured by the WVMS and MLS instruments. Each profile shown is either an average of the three monthly profiles for January through March (JFM), or for May through July (MJJ). For 2022 this separates the three full months before and after the increase in water vapor when the Hunga Tonga arrived over Mauna Loa.

While this study will focus on mixing ratio anomalies, we note that the mixing ratio profiles measured by the two instruments are generally in good agreement. The exception to this is that the WVMS H_2O measurements from ~28-34 km do not increase as rapidly with increasing altitude

as the MLS measurements. This is probably the result of a small but stable instrumental baseline component in the measurement spectrum in this WVMS instrument which affects the lowest retrieved altitudes. To the extent that this baseline component is stable, it should not significantly affect the retrieved H_2O anomalies.

In Figure 4 we show both convolved and unconvolved MLS profiles to help clarify the effects of convolving the MLS profiles to better match the vertical resolution and sensitivity of the WVMS measurements. Surprisingly, the 2022 differences between JFM and MJJ between the WVMS and unconvolved MLS profiles are in better agreement than between the WVMS and convolved MLS profiles. The MLS measurements themselves have a vertical resolution (FWHM of the averaging kernels) of 3-4 km in the altitude range shown [Livesey et al., 2020].

To put the 2022 lower stratospheric increase in perspective from a seasonal variation standpoint we also show the 9-year average of the JFM and MJJ profiles for 2013-2021. The average from both instruments shows a decrease in H_2O from JFM to MJJ from 28 to 48 km (with a small exception near ~30 km in the unconvolved MLS profile). Relative to this 9-year average we see that, in addition to the large H_2O increase below ~34 km from the arrival of the Hunga Tonga plume, the H_2O profile in 2022 has several other unusual features. First, we note that in 2022 water vapor values are higher than average throughout the stratosphere both before and after the arrival of the plume. Second, we note that the H_2O change from JFM to MJJ is different from that of most years at several altitude levels. In 2022 changes from JFM to MJJ can be separated into three altitude regions. Below ~34 km there is an increase, associated with the arrival of increased H_2O in April. From ~34-40 km there is a smaller decrease in H_2O (similar to what is observed in the 9-year average). And from ~40 km to the stratopause there is again an increase from JFM to MJJ that is not seen in the 9-year average. Note that such a growing positive anomaly is also apparent in Figure 2. Unlike the mid-April increase apparent at 28 km, there is, however, no clear event associated with this increase in upper stratospheric H_2O. The profile for 2015 is also shown in Figure 4 because, as will be discussed later, the Quasi-Biennial Oscillation (QBO) phase of this year is very similar to that of 2022.

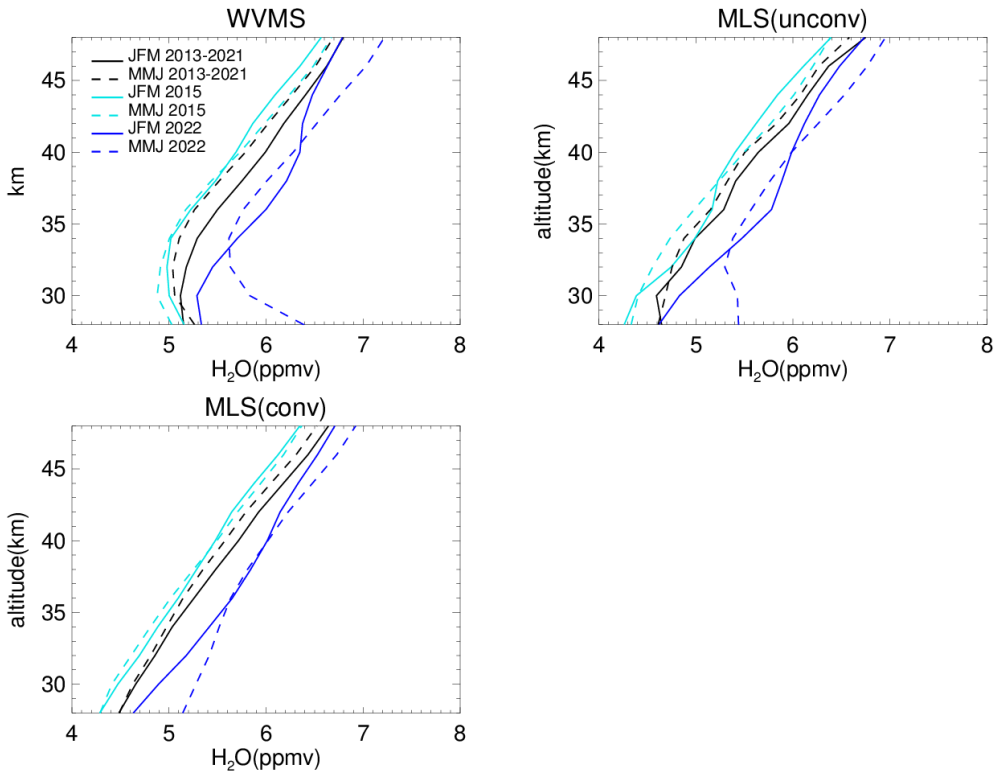

Figure 4- Water vapor profiles over Mauna Loa from WVMS (top left), MLS (top right) and convolved MLS (bottom left) measurements. Profiles are shown for January-March (solid) and May-July (dashed), and are separated between a 2013-2021 average (black), 2015 (cyan), and 2022 (blue).

In Figure 5 we show MLS measurements in the lower stratosphere from January through July near Mauna Loa for all years since 2013. The MLS measurements shown in Figure 5 have not been convolved, and the mixing ratios are shown on the MLS native grid with an approximate altitude to simplify the comparison with other figures.

When compared to the H_2O measured in other years, the increase in H_2O that occurred near Mauna Loa in April 2022 is clearly an unprecedented event. When the anomaly initially arrived, it was confined to ~23km to ~27km. In subsequent months in 2022 the H_2O mixing ratio began to rise at higher altitudes and decrease at the lower altitudes.

While the 2022 post-March H_2O from the Hunga Tonga plume is certainly the largest anomaly, there are other years, especially at the highest level shown in Figure 5 (14 hPa; ~28km) that show daily mixing ratios that are, throughout these seven months, consistently either higher or lower than average. As an example, in 2019 the H_2O mixing ratios shown in Figure 5 are consistently anomalously high. These anomalously high mixing ratios at this level are seen in MLS measurements throughout the northern hemisphere during this period, and there is no indication that this was the result of an unusual injection of H_2O. In this study we will attempt to place the observed stratospheric water vapor increase from Hunga Tonga into the context of these other interannual variations that have been observed since 2013.

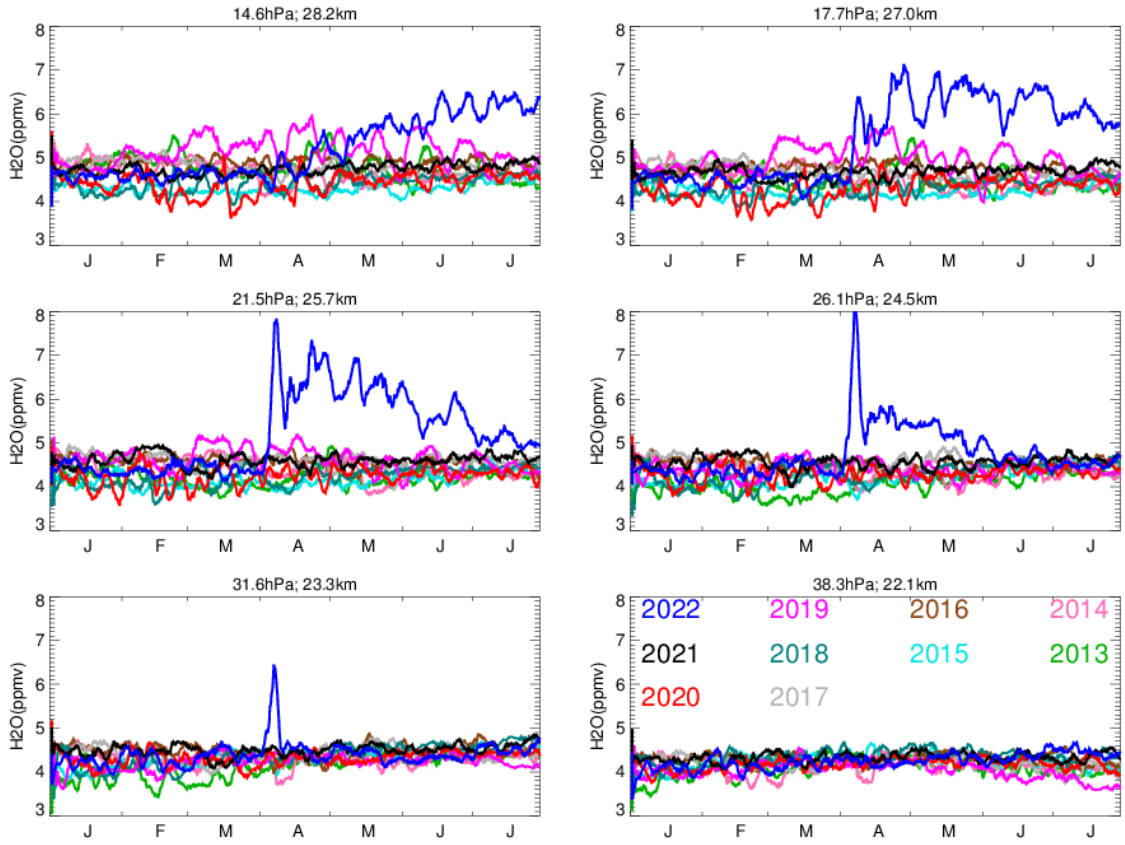

Figure 5- Daily average Aura MLS measurements on the native pressure grid (altitudes are approximate) from January through July of 2013 through 2022 within +/-2° latitude and +/-10° longitude of Mauna Loa.

In Figure 6 we show a comparison of timeseries for the years since 2013 from both WVMS and MLS. The WVMS results shown are medians of 6-hour retrievals within +/-5 days of the date shown. Using medians instead of means minimizes the adverse effect of single retrievals that are corrupted with baseline artifacts. MLS results are +/-5 day averages and are shown for both convolved and unconvolved MLS retrievals. The years 2013 and 2019 are highlighted because these years, along with 2022, show the highest mixing ratios in the mid-stratosphere for much of the time period shown. Mixing ratios for 2015 are also highlighted, and will be further discussed below.

The WVMS and MLS retrievals at 44 km both show lower than average H_2O throughout most of the year in 2019, and higher than average H_2O in 2013 and 2022. There is a large drop in the 44km mixing ratios in February 2019 in the WVMS measurements which shows up with a much smaller amplitude in the MLS measurements. We think this is probably an instrumental artifact in the WVMS measurements caused by baseline instability, but we cannot identify a specific instrumental anomaly.

At 34 km the WVMS measured H_2O mixing ratios for 2013, 2019, and 2022 are unusually large throughout the time period. This differs from the MLS mixing ratios only in that the 2019 MLS

mixing ratios are not high in January and February. While the measured mixing ratios are large in January 2022 in all three datasets, there is no indication that this a result of the Hunga Tonga eruption.

At 30 km and 28 km the April 2022 increase in mixing ratio begins to stand out as an unusual step increase in the WVMS retrievals. While there are other jumps and drops in mixing ratio of this magnitude in other years (e.g., there is a particularly large spike in early March, 2015 and there are two large temporary dips in February and March 2018), following these events in other years the mixing ratio returns to near its previous level. We assume that these other events are caused by baseline instabilities related to unusual tropospheric conditions, but, besides the unusual mixing ratios, we have no independent evidence that indicates that this data is problematic. What distinguishes the 2022 data is that the mixing ratios remain high following the April increase.

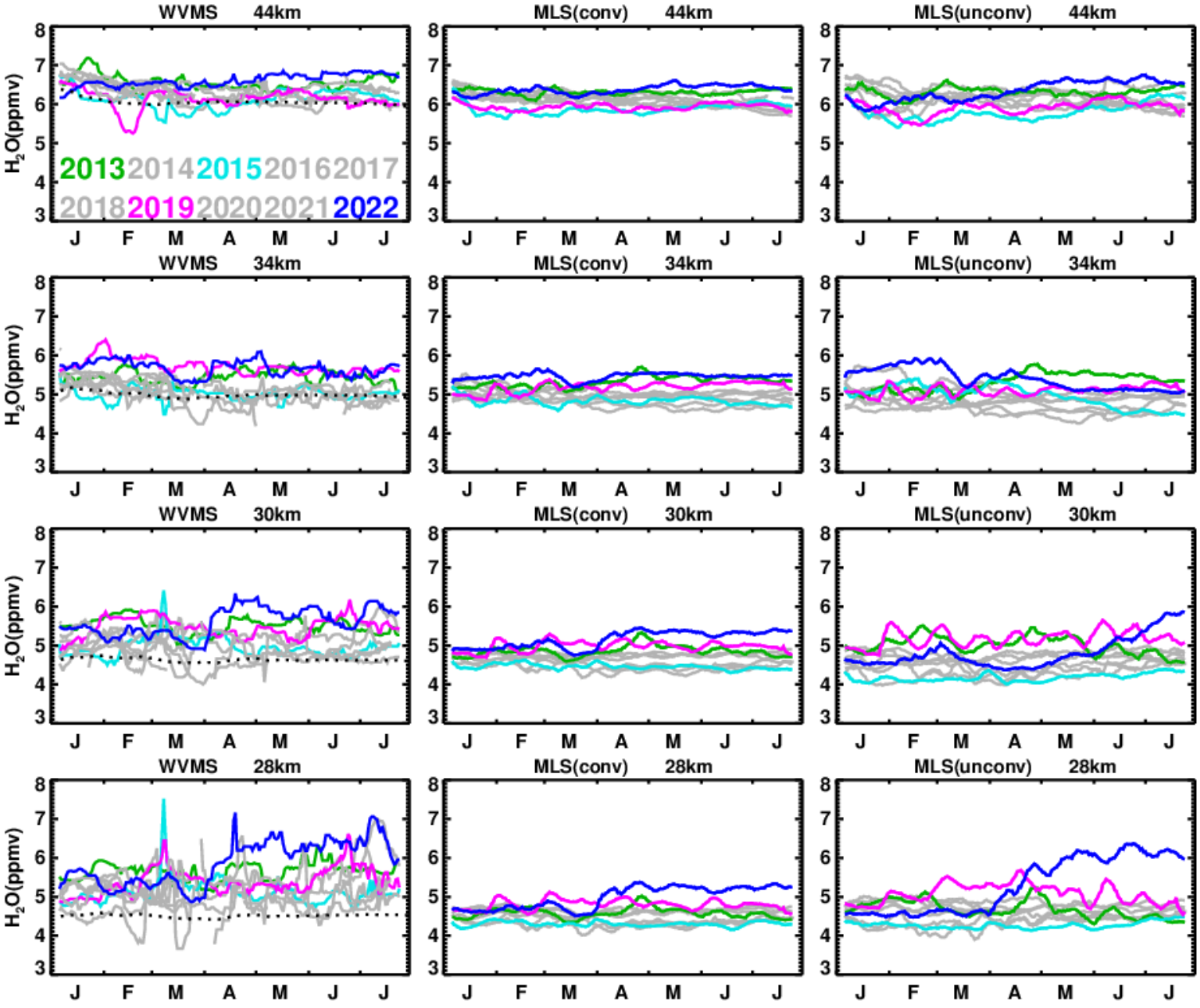

Figure 6- Water vapor measurements with a +/-5 days smoothing at Mauna Loa from January through July of 2013 through 2022. Results are shown for WVMS (left column), MLS-convolved (middle column), and MLS-unconvolved interpolated to WVMS altitudes. Measurements are highlighted for 2013 (green), 2015 (cyan), 2019 (pink), and 2022 (blue).

4. Other geophysical drivers of interannual variations in stratospheric H_2O

In order to understand the effect of the Hunga Tonga eruption on stratospheric H_2O near Mauna Loa we investigate other geophysical factors that are known to cause interannual changes in stratospheric H_2O mixing ratios. Two important factors that drive interannual water vapor

anomalies in the tropical stratosphere are the QBO and the average tropical tropopause temperatures. The QBO affects upwelling [Baldwin et al., 2001], which in turn affects dynamics and thus chemical composition [e.g. Schoeberl et al., 2008; Nedoluha et al., 2015]. In Figure 7 we show the 30 mb zonal wind index for each year since 2013. As we noted above, 2013 and 2019 had unusually high mid-stratospheric H_2O mixing ratios, and the phase of the QBO is quite similar in 2013 and 2019, having strongly positive zonal wind indices for much of the period shown. This suggests that this phase of the QBO is correlated with the large mid-stratospheric H_2O mixing ratios over Mauna Loa observed during those years. The phase of the QBO in 2022 is, however, not similar to that seen in either 2013 or 2019, but it is similar to that of 2015. Comparisons between 2015 and 2022 can therefore help to determine to what extent unusual H_2O variations in 2022 may be related to the phase of the QBO.

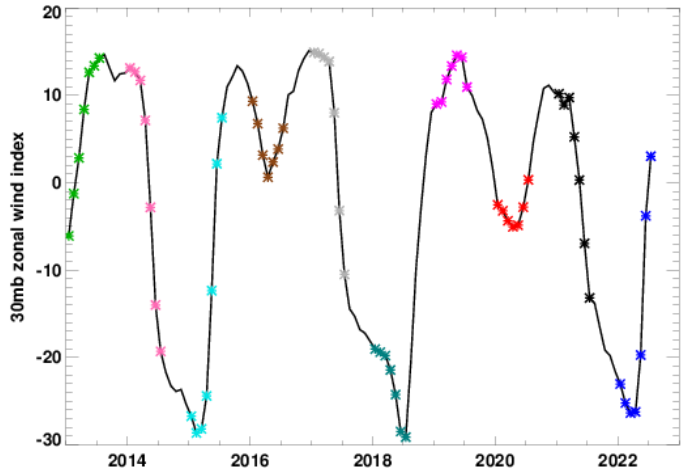

Figure 7- The 30mb monthly zonal wind index from www.cpc.ncep.noaa.gov. The symbols indicate January through July of each year, with the same yearly colors as in Figure 5.

An unusual feature that 2015 and 2022 do have in common that is shown in Figure 4 is that, whereas in most years the H_2O mixing ratio in the mid- and upper stratosphere decreases from JFM to MJJ, in 2015 and 2022 there is an increase in mixing ratios above 40 km from JFM to MJJ. The variations in water vapor in the tropical stratosphere are caused both by variations in the amount of water vapor entering the stratosphere from the troposphere, and by dynamical variations. The dynamical variations in H_2O at any particular location are the result of variations in the fraction of CH_4 that has been oxidized. In general, for air parcels ascending unusually slowly (quickly) there is more (less) time for the CH_4 in these unusually old (young) air parcels to oxidize, and hence the H_2O mixing ratio at that particular location will be unusually high (low). Water vapor mixing ratios in the upper stratosphere are particularly sensitive to this dynamical variation. The unusual increasing H_2O from JFM to MJJ in the upper stratosphere above Mauna Loa could therefore be caused by unusual dynamics. If this were the case we would also expect other dynamically sensitive variables to show unusual mixing ratios in this region.

While MLS does not measure CH_4, Figure 8 shows that in the upper stratosphere the N_2O anomaly as measured by MLS at 1.46hPa (~45km) is positive in January and negative in July in both 2015

and 2022. This indicates that the air over Mauna Loa at 1.46hPa in January is unusually young, while in July air at this location and pressure level it is unusually old. This is consistent with an increase in the H_2O anomaly in this region over this period due to the oxidation of CH_4. We therefore conclude that at least some of the unusual increase in H_2O in the upper stratosphere at Mauna Loa following that the eruption of Hunga Tonga could be caused by unusual dynamical variations and not directly by additional H_2O entering the stratosphere The WVMS and MLS measurements do both show, however, that the increase in 2022 is somewhat larger than that in 2015, so we cannot completely discount the possibility that some portion of this upper stratospheric increase in H_2O may be the result of additional H_2O from the eruption.

We also show 2015 and 2022 N_2O variations at 4.6 hPa (~36 km) both to emphasize that 2015 and 2022 are dynamically similar at this altitude as well, and to illustrate that at this level a dynamically driven anomalous increase in H_2O would not be expected. From ~34 km to ~40 km there is a decrease in H_2O from JFM to MJJ 2022 in the unconvolved MLS measurements, and this decrease is very similar to that observed in 2015, suggesting that this is a dynamically driven variation. The WVMS 2022 retrievals show a similar decrease, but only a smaller decrease in 2015, while the convolved MLS measurements show very little decrease in this range.

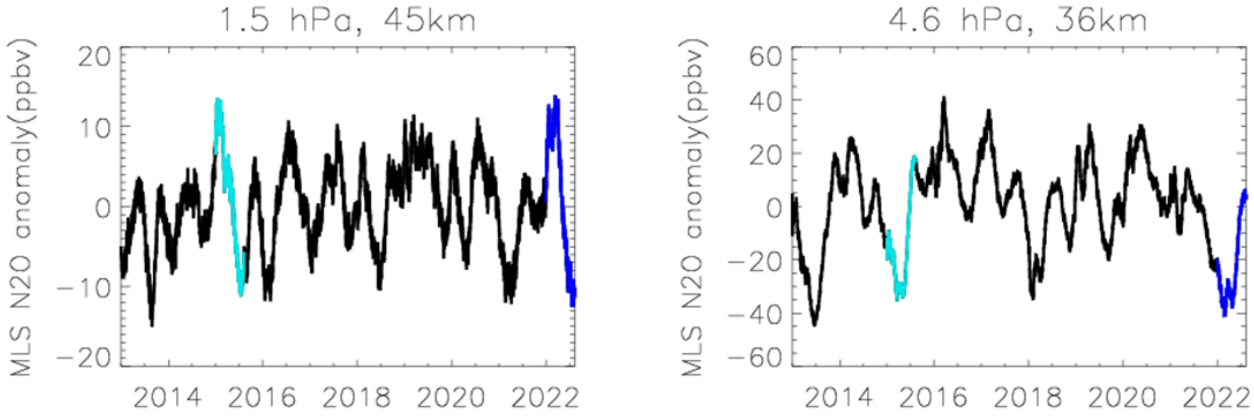

Figure 8- The anomaly from an MLS climatology for N2O over Mauna Loa. Results are shown for 1.46 hPa and 4.6 hPa on the native MLS pressure grid, which corresponds to altitudes of ~45 km and ~36 km. January through July are highlighted for 2015 (cyan) and 2022 (blue).

While the phase of the QBO and the associated dynamical anomalies indicated by the N_2O measurements seem to explain at least some of the unusual upper stratospheric H_2O observed at Mauna Loa in 2022, there remains the question as to why, even before the Hunga Tonga eruption, mixing ratios in 2022 up to ~45 km are above average both in JFM and in MJJ, while in 2015 for those same periods the mixing ratios are below average throughout the stratosphere near Mauna Loa.

As noted above, the other key geophysical factor that affects interannual H_2O variations is tropical tropopause temperature. The mixing ratio of water vapor that crosses from the troposphere into the stratosphere is determined by H_2O saturation mixing ratio where the air crosses the cold point tropopause in the tropics. Seidel and Randel [2006] showed that in the tropics 100 hPa corresponds

approximately to the tropopause level pressure, and Tegtmeier et al. [2020] showed in a number of reanalyses (including MERRA2) that changes in 100 hPa temperatures were very similar to those at the cold point level, so in Figure 9 we show tropical (10ºS-10ºN) temperature anomalies at 100 hPa in the 7 years preceding the beginning of 2015 and 2022 respectively. The temperatures are from MERRA2 and the anomalies are relative to a 1980-present baseline. The precise relationship between cold point tropopause temperature and H_2O saturation mixing ratios (and hence H_2O entering the stratosphere) depends upon the exact temperature and pressure, with Fueglistaler and Haynes [2005] giving a value of ~0.5 ppmv/K, Seidel et al. [2001] ~0.6 ppmv/K, and Nedoluha et al. [1998] ~0.7 ppmv/K.

Schoeberl et al. [2005] (their Figure 2) calculated from model spectra that, while the mean age of air at 30km and 18ºN is ~3 years, much of the air is much younger, as is clear from the mid-stratospheric measurements of the H_2O plume shown here. We estimate from their figure that ~70% of the air has been in the stratosphere for <3 years. The difference in 100 hPa temperature between 2020-2022 as compared to 2013-2015, or between 2019-2021 as compared to 2012-2014, is ~0.7 K. If we combine this with the sensitivity of saturation mixing ratio to pressure we estimate that the changes in tropical tropopause temperature lead to an increase in stratospheric H_2O over Mauna Loa of ~0.3 to 0.4 ppmv between 2022 and 2015.

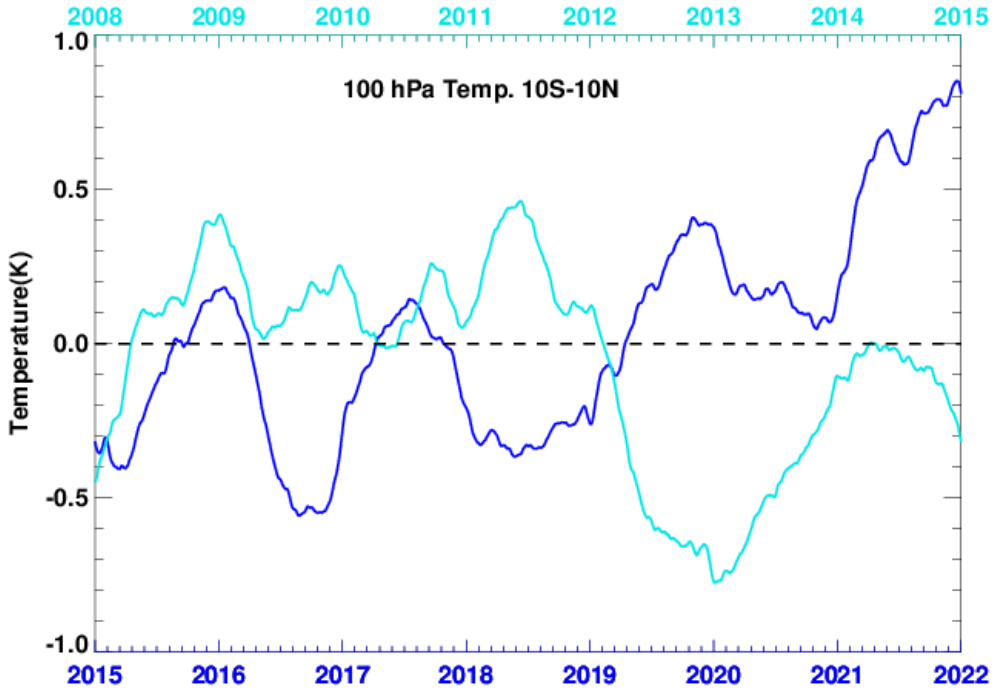

Figure 9 - Tropical tropopause temperature anomalies from MERRA2 at 100 hPa from 10ºS to 10ºN. Temperatures are shown from the 7 years before 2015 (cyan) and the 7 years before 2022 (blue). The data has been smoothed over 365 days and the point at 2022.0 includes temperatures through June 30 2022.

Increasing anthropogenic CH_4 emission will also cause some increase in H_2O over this 7-year period. The increase in CH_4 for the 7 years from 2015 to 2021 during this period is ~0.08 ppmv (gml.noaa.gov/ccgg/trends_ch4/) [Lan et al., 2022]. Above the stratopause where CH_4 is fully

oxidized each additional CH_4 molecule will produce two H_2O molecules and this would increase H_2O by ~0.15 ppmv. Measurements of CH_4 from HALOE [cf. Remsberg, 2015] show that, in the mid-stratosphere over Mauna Loa, the CH_4 mixing ratio is ~1 ppmv, while at the stratopause it is ~0.3 ppmv. Lan et al. [2022] show that ~1.9 ppmv CH_4 is emitted at the surface, hence ~1/2 of the CH_4 has been oxidized in the mid-stratosphere over Mauna Loa and ~85% at the stratopause, contributing ~0.08 ppmv and ~0.14 ppmv to the observed H_2O increase at these respective altitudes. The average difference of H_2O at 28 km and 48 km in JFM 2022 as compared to JFM 2015 is +0.48 ppmv for the WVMS measurements and +0.45 ppmv for the MLS measurements (both convolved and unconvolved), and is therefore approximately consistent with the combined effects of increased tropical tropopause temperatures and increased anthropogenic CH_4 emission.

Given that 2015 and 2022 started with very different amounts of stratospheric H_2O over Mauna Loa, we cannot ascribe the high H_2O mixing ratios observed in 2022 entirely to the Hunga Tonga eruption. The similar QBO phases of these two years does, however, lead to similar dynamical changes, and below ~34km there was no increase observed in H_2O during the first seven months of 2015. Hence, there is no reason to suggest that any of the observed H_2O increase at Mauna Loa during 2022 below ~34km to anything other than the Hunga Tonga plume.

While we have focused here on changes in H_2O over Mauna Loa, we can apply some of the dynamical conclusions to other latitudes in the tropics. Figure 10 shows the N_2O anomaly for June 2022, which looks very similar to that for June 2015. In the upper stratosphere at latitudes near Mauna Loa the negative N_2O anomaly indicates slowly rising air and, as was discussed above, this indicates a region in which more CH_4 oxidation has taken place because the air is unusually old, and hence H_2O will generally be anomalously high. This region is well correlated with the region of increased H_2O shown in Figure 2.

In contrast to the upper stratospheric negative N_2O anomaly over Mauna Loa, near 10 hPa the positive N_2O anomaly in the northern tropics indicates that air in this region is rising unusually rapidly, while, in contrast, the air in the southern tropics is rising unusually slowly. This is consistent with Figure 2, which shows that the peak of the water vapor anomaly rises rapidly in the tropics north of the equator, but not south of the equator. While slowly rising air generally results in increased H_2O, in this case the standard photochemically driven anti-correlation between N_2O and H_2O is overwhelmed in the northern tropics by the effect of the rising plume of young and very large H_2O mixing ratio air from Hunga Tonga.

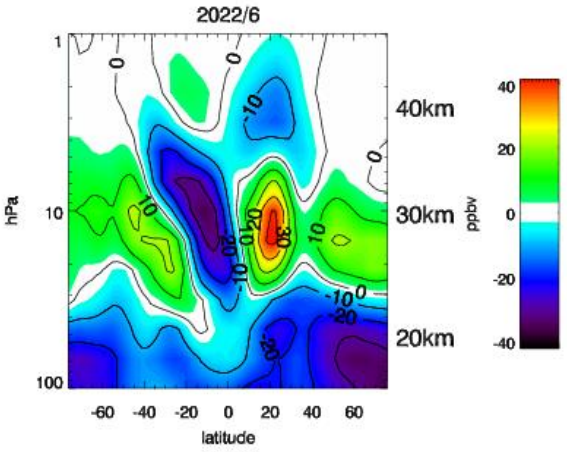

Figure 10 – The June zonal-median N2O anomaly (in ppbv) relative to the MLS climatology for MLS measurements from 2004-2021.

5. Discussion

As noted by Millan et al. [2022] the eruption of Hunga Tonga at 20.5ºS in January 2022 injected unprecedented amounts of H_2O into the stratosphere. The WVMS measurements at Mauna Loa (19.5ºN) are most accurate and stable in the mesosphere, but, following instrumental improvements made in 2012, it is possible to usefully retrieve H_2O in the stratosphere as well. Three months after the Hunga Tonga eruption the WVMS measurements at Mauna Loa observed a sudden increase at the lowest reliable retrieval altitude 28km. This provided an interesting test of the ability of the WVMS measurements to retrieve unusual H_2O variations in the stratosphere.

Interannual variations in water vapor in the tropical stratosphere are caused by a number of geophysical factors unrelated to volcanic emissions. Some years show unusually high water vapor because of dynamical variations related to the QBO. Comparisons between 2015 and 2022 are particularly instructive because the months from January to July during these years are dynamically similar in the stratosphere above Mauna Loa. Changes in H_2O caused by dynamical variations during these months should therefore be similar. However, while dynamical variations that can cause changes in H_2O are similar in 2015 and 2022, the stratospheric H_2O observed before the eruption was much higher in 2022. This can be attributed to higher tropical tropopause temperatures in the previous years, and, to a smaller extent, to increased anthropogenic CH_4 emission over that seven year interval.

While H_2O mixing ratios over Mauna Loa in 2022 were already unusually high even before the arrival of the plume from Hunga Tonga, the sudden increase in H_2O with the arrival or the plume brought H_2O mixing ratios to even higher levels. The observed increase with the arrival of the plume brought an unprecedented increase over Mauna Loa that remained present from May through July. MLS measurements showed that the peak of the mixing ratio ascended during this period over the northern tropics, but showed much less of an altitude change in the southern tropics. This change in ascent rate seems to be related to the QBO phase. While much of this study has been focused on putting the H_2O changes within the context of other geophysically driven interannual variations in H_2O observed at Mauna Loa, we do emphasize that we only observed the very northern edge of an H_2O plume that, at the end of July 2022, covered latitudes from ~60ºS to

20ºN. As portions of this plume rise during the next few years it will be of great interest to measure the effect of the eruption on global H_2O at the stratopause and above.

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7. Data Availability Statement

WVMS six-hour retrievals (GN2022.SIX.HOURLY) are available on the NDACC data server at www-air.larc.nasa.gov/missions/ndacc/data.html#. MLS v5 data are available at disc.gsfc.nasa.gov/datasets?page=1&keywords=ML2H2O_005. GEOS temperature data are available at gmao.gsfc.nasa.gov/GMAO_products/.

8. References

Baldwin et al. (2001), The Quasi-Biennial Oscillation, Reviews of Geophysics, 39, 179-229, 2001.

Bernath,P.F.,McElroy,C.T.,Abrams,M.C.,Boone,C.D.,Butler, M., Camy-Peyret, C., Carleer, M., Clerbaux, C., Coheur, P.-F., Colin, R., DeCola, P., DeMazière, M., Drummond, J. R., Dufour, D., Evans, W. F. J., Fast, H., Fussen, D., Gilbert, K., Jennings, D. E., Llewellyn, E. J., Lowe, R. P., Mahieu, E., McConnell, J. C., McHugh, M., McLeod, S. D., Michaud, R., Midwinter, C., Nassar, R., Nichitiu, F., Nowlan, C., Rinsland, C. P., Rochon, Y. J., Rowlands, N., Semeniuk, K., Simon, P., Skelton, R., Sloan, J. J., Soucy, M.-A., Strong, K., Tremblay, P., Turnbull, D., Walker, K. A., Walkty, I., Wardle, D. A., Wehrle, V., Zander, R., and Zou, J.: Atmospheric Chemistry Experiment (ACE): Mission overview (2005), Geophys. Res. Lett., 32, L15S01, https://doi.org/10.1029/2005GL022386, 2005.

Fueglistaler, S., and P. H. Haynes (2005), Control of interannual and longer-term variability of stratospheric water vapor, J. Geophys. Res., 110, D24108, doi:10.1029/2005JD006019.

Gomez, R. M., G. E. Nedoluha, H. L. Neal, and I. S. McDermid (2012), The fourth-generation Water Vapor Millimeter-Wave Spectrometer, Radio Sci., 47, RS1010, doi:10.1029/2011RS004778.

Lambert, A., et al. (2007), Validation of the Aura Microwave Limb Sounder stratospheric water vapor and nitrous oxide data products, J. Geophys. Res., 112, D24S36, doi:10.1029/2007JD008724.

Lan, X., K.W. Thoning, and E.J. Dlugokencky (2022): Trends in globally-averaged CH4, N2O, and SF6 determined from NOAA Global Monitoring Laboratory measurements. Version 2022-09, https://doi.org/10.15138/P8XG-AA10

Livesey, N. J., et al. (2020), EOS MLS Version 5.0x Level 2 and 3 data quality and description document, Tech. Rep., Jet Propulsion Laboratory, available at: https://mls.jpl.nasa.gov/eos-aura-mls/data-documentation.

Livesey, N. J., et al. (2021), Investigation and amelioration of long-term instrumental drifts in water vapor and nitrous oxide measurements from the Aura Microwave Limb Sounder (MLS) and their implications for studies of variability and trends, Atmos. Chem. Phys., 21, 15409–15430, 2021.

Millán, L., Santee, M. L., Lambert, A., Livesey, N. J., Werner, F., Schwartz, M. J., et al. (2022). The Hunga Tonga-Hunga Ha'apai Hydration of the Stratosphere. Geophysical Research Letters, 49, e2022GL099381. https://doi.org/10.1029/2022GL099381.

Nedoluha, G. E., Bevilacqua, R. M., Gomez, R. M., Siskind, D. E., Hicks, B. C., and Russell III, J. M. (1998): Increases in middle atmospheric water vapor as observed by HALOE and the groundbased Water Vapor Millimeter-wave Spectrometer from 1991–1997, J. Geophys. Res., 103, 3531–3542, 1998.

Nedoluha, G. E., R. M. Gomez, B. C. Hicks, J. Helmboldt, R. M. Bevilacqua, A. Lambert, Ground-based Microwave Measurements of Water Vapor from the mid-Stratosphere to the Mesosphere, J. Geophys. Res., 116, doi:10.1029/2010JD014728, 2011.

Nedoluha, G. E., D. E. Siskind, A. Lambert, and C. Boone, The decrease in mid-stratospheric tropical ozone since 1991, Atmos. Chem. Phys., 15, 4215–4224, 2015, doi:10.5194/acp-15-4215-2015.

Nedoluha, Gerald E., R. Michael Gomez, Ian Boyd, Helen Neal, Douglas R. Allen, David Siskind, Alyn Lambert, and Nathaniel J. Livesey, Measurements of Mesospheric Water Vapor from 1992 to 2021 at three stations from the Network for the Detection of Atmospheric Composition Change, J. Geophys. Res., in revision 2022.

Remsberg, E. E., Methane as a diagnostic tracer of changes in the Brewer–Dobson circulation of the stratosphere, Atmos. Chem. Phys., 15, 3739–3754, 2015, doi:10.5194/acp-15-3739-2015.

Schoeberl, M. R., A. R. Douglass, B. Polansky, C. Boone, K. A. Walker, and P. Bernath (2005), Estimation of stratospheric age spectrum from chemical tracers, J. Geophys. Res., 110, D21303, doi:10.1029/2005JD006125.

Schoeberl, M. R., et al. (2008), QBO and annual cycle variations in tropical lower stratosphere trace gases from HALOE and Aura MLS observations, J. Geophys. Res., 113, D05301, doi:10.1029/2007JD008678.

Seidel, D. J., R. J. Ross, J. K. Angell, and G. C. Reid (2001), Climatological characteristics of the tropical tropopause as revealed by radiosondes, J. Geophys. Res., 106, D8, 7857-7878, 2001.

Seidel, D. J., and W. J. Randel (2006), Variability and trends in the global tropopause estimated from radiosonde data, J. Geophys. Res., 111, D21101, doi:10.1029/2006JD007363.

Tegtmeier, S., et al. (2020), Temperature and tropopause characteristics from reanalyses data in the tropical tropopause layer, Atmos. Chem. Phys., 20, 753–770, 2020.