The possible connection of the large ozone hole in September 2023 with the Hunga Tonga volcanic eruption

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Abstract: Polar stratospheric chemistry is highly sensitive even to minor disruptions in water vapor or temperature. Unusual behavior in temperature and water vapor has been identified in the southern polar winter stratosphere in 2023. The potential correlation between the post-Hunga-Tonga eruption elevation of water vapor (detected in the tropics), temperature changes, and ozone anomalies is under discussion, as these parameters play a crucial role in stratospheric chemistry and dynamics. In the winter of 2023 in the Southern Hemisphere, an unexpected decrease in ozone levels and the emergence of a substantial ozone hole were observed. This event marked one of the most significant ozone decreases in the past 15 years, with an unusually large ozone hole occurring during this period, and it appears to be at least partly associated with the Hunga Tonga eruption.

Plain language summary

The stratosphere holds significant importance within the middle atmosphere. The polar region in the Southern Hemisphere, in particular, experiences unique conditions in terms of both chemistry and dynamics. Even slight changes in certain parameters can lead to substantial alterations in chemistry. Ozone behavior in this region is a frequent subject of study, particularly due to the persistent issue of the ozone hole. While the ozone hole area has been on a decreasing trend over the past two decades, in 2023, it reached its largest extent since 2011. The question arises whether this increase is an isolated occurrence, possibly linked to the Hunga-Tonga eruption and the subsequent rise in water vapor within the polar vortex. This study aims to examine the behavior of water vapor and temperature, crucial parameters in stratospheric chemistry, and to shed light on effects in ozone content.

1. Introduction

The stratosphere, spanning from 15 to 55 km in the atmosphere, is a critical layer in the middle atmosphere with a notable characteristic of being generally dry, especially when compared to the troposphere. Volcanic eruptions, particularly major ones, release gases, including water vapor, and aerosol pollutants into the stratosphere, influencing the atmospheric radiative balance, dynamics, and the entire climate system.

Following a period of volcanic unrest starting from the end of December 2021 and strong explosions on January 14th, 2022, which removed the aerial part of the Hunga Tonga–Hunga Ha'apai (HT) volcano, the submarine volcano violently erupted on January 15th, 2022, at approximately 04:15 UTC. The volcanic ash reached over 30 km, and the transient overshoot even reached the mesosphere (Proud et al., 2022). Various wave signatures have been identified in the upper atmosphere, affecting thermospheric wind, ionospheric equatorial electrojet (Harding et al., 2022; Le et al., 2022), ionospheric plasma drift, Total Electron Content (TEC) (Aa et al., 2022; Themens et al., 2022; Zhang et al., 2022), and including Travelling Ionospheric Disturbances (TIDs) (Chen et al., 2023a, Vadas et al., 2023, Liu et al., 2023a) with their multi-wave structure (Li et al., 2023), as well as signatures at magnetically conjugate locations (Lin et al., 2022; Shinbori et al., 2022). Madonia et al. (2023) described the propagation of corresponding disturbances in the lower and upper atmosphere over the Central Mediterranean area. Liu et al. (2023b) successfully simulated atmospheric and ionospheric responses to the Tonga volcano eruption using the Whole Atmosphere Community Climate Model with thermosphere and ionosphere extension (WACCM-X). Multiple geosphere responses to the Tonga volcanic eruption were reviewed by Chen et al. (2023b).

The Tonga underwater volcano's exceptional eruption injected an unprecedented amount of water vapor directly into the stratosphere (Carr et al., 2022; Millán et al., 2022; Xu et al., 2022) and substantially increased the water vapor concentration in the mesosphere in 2022 (Nedoluha et al., 2023). While the initial injection plume at 20°S reached the upper stratosphere (Carr et al., 2022, Millán et al.,2022) showed that after three months, this excess water vapor settled near the 20 hPa altitude in a latitude band from 30°S to 5°N. These water vapor fingerprints in the mentioned latitudes have been analyzed by (Schoeberl et al., 2022), and they align with climatological expectations. This perturbation moisture is expected to remain in the stratosphere for 2 to 3 years if there are no major thermodynamic or photochemical sinks. The main impact of water vapor is its radiative activity in the infrared range, contributing to the total radiative cooling in the stratosphere, which is otherwise dominated by the effects of carbon dioxide and ozone (e.g., Gille & Lyjak, 1986). These significant perturbations in water vapor are expected to increase the amount of radiation lost to space, locally cooling the stratosphere (Schoeberl et al., 2022; Sellitto et al., 2022).

Using Modern-Era retrospective Analysis for Research and Application, Version 2 (MERRA-2) and MERRA-2 Stratospheric Composition Reanalysis of Aura Microwave Limb Sounder (MLS), Coy et al. (2022) observed that the excess water vapor significantly cooled the stratosphere (near 20 km) at midlatitudes of the Southern Hemisphere (SH), affecting the circulations at these altitudes. As a result, strong westerly winds were generated above the temperature anomaly, producing changes in the meridional circulation. Wang et al. (2022) found a large-scale SH stratospheric cooling, equatorward shift of the Antarctic polar vortex, and slowing of the Brewer-Dobson circulation associated with a substantial ozone reduction in the SH winter midlatitudes as a consequence of the HT volcanic eruption. On the other hand, Manney et al. (2023) observed no clear evidence of the HT volcanic eruption influence on the 2022 Antarctic vortex or its composition due to the strong transport barrier at its edge. The 2022 Antarctic polar vortex was near average; the vortex was large, strong, and long-lived but not exceptionally so. Also several studies used ERA5 for Hunga-Tonga eruption analyses (Wright et al., 2022 or Wang et al., 2023)

Our study aims to study water vapor concentration and temperature impact on stratospheric chemistry, with a focus mainly on the southern stratospheric total columnar ozone during the first two SH winters after the HT eruption. Winds in the stratosphere soon carried the excess water vapor around the globe to all longitudes and spread the water vapor in latitude to some extent. Since water vapor can affect chlorine activation during specific temperature conditions, we can see during the SH winter 2023 evidence of very large and unpredicted ozone hole.

2. Results and discussion

We use ERA5 (ECMWF Re-Analysis) of ECMWF (European Centre for Medium-Range Weather Forecasts); they can be downloaded from ERA5 link to examine temperature, water vapor, and ozone characteristics throughout the study period, spanning from January 2022 to October 2023. This timeframe encompasses two Southern Hemisphere (SH) winters following the eruption of the Hunga Tonga–Hunga Ha'apai (HT) volcano. Our analysis focused on monthly mean values of temperature and water vapor at 10 hPa, a critical altitude where we anticipate significant impacts on atmospheric dynamics and chemistry because and for example a huge amount of ozone (ozone layer) in the mid regions of the stratosphere occurs Additionally, we investigated monthly mean total column ozone levels in the SH polar region. We focus on the second SH winter in 2023, as it provides an opportunity to detect potential effects of the HT eruption within the SH polar vortex. This is relevant, because Manney et al. (2023) found no effect of the first winter in the SH polar vortex; the vortex was established too early to allow penetration of the HT produced extra water vapor inside the vortex.

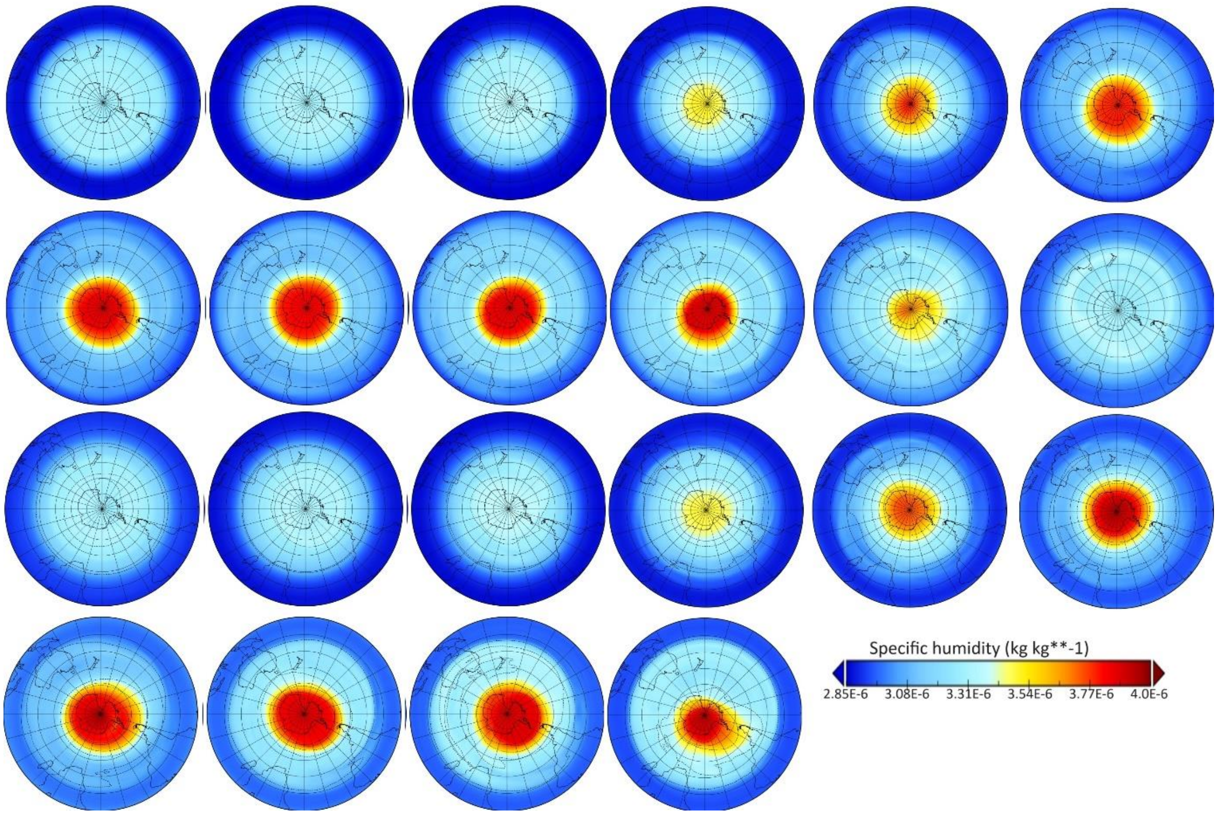

Figure 1 Specific humidity at 10 hPa from ERA5 reanalysis. SH is displayed for each month from January 2022 till October 2023.

Figure 1 shows specific humidity at 10 hPa from January 2022 to October 2023, displaying Southern Hemisphere (SH) for each month. A consistent pattern emerges, with an observed increase in water vapor (WV) during polar winters. This trend is notably evident in both the SH winters of 2022 and 2023.

Interestingly, higher specific humidity values are observed in the SH polar region during July, August, and September 2023. In 2022 the maximum values of the monthly mean reach about 3.7 E-6 while in 2023 they reach about 4.1E-6, which is about 10 % increase. Notably, the region of increased water vapor is more extensive in September 2023 compared to 2022. This observation is probably associated with the injection of water vapor by the Hunga Tonga–Hunga Ha'apai (HT) eruption and its subsequent transport from lower latitudes because there is usually increase in winter but it is much smaller and remains very short time (only few days instead of weeks or months).

The next parameter closely tied to ozone and water vapor is temperature presented in Figure 2. The outcomes are particularly evident at 10 hPa, spanning from January 2022 to October 2023. Notably, the Northern Hemisphere (NH) exhibits nearly identical patterns during the past two winters, while the Southern Hemisphere (SH) displays distinct behavior, particularly in July, August, and October 2023.

In July 2023, we observe lower temperatures (around 15K) in the SH polar region than in 2022. This aligns with the increase of water vapor during this month (Figure 1) as water vapor is a radiative cooler. Conversely, October reveals a significantly warmer polar region, with temperature differences reaching up to 12 K. Intriguingly, this rise in temperature is not accompanied by a substantial decrease in water vapor, which might typically explain such variations. Hence, our exploration leads us to the search for the other parameter influencing temperature dynamics, which is ozone.

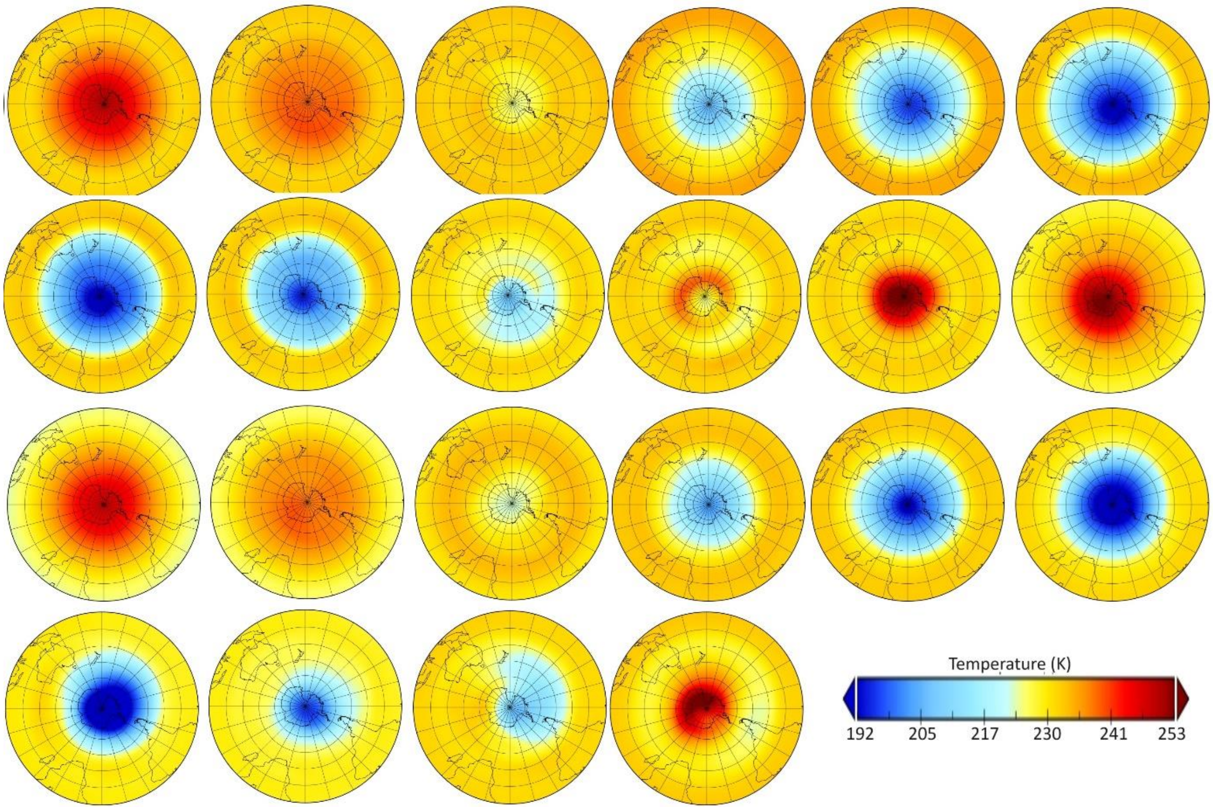

Figure 2 Temperature at 10 hPa from ERA5 reanalysis. SH is displayed for each month from January 2022 till October 2023.

Figure 3 presents the results for the total columnar ozone content up from 500 hPa, offering insights into its behavior in the Southern Hemisphere (SH) polar and higher latitudes. If we look on the behavior in 2022, there is a typical decrease of ozone in August and September, which is replaced by slow increase in November and December. However, a closer examination of ozone dynamics in 2023 reveals some intriguing differences. The ozone decrease initiates earlier, in June, persisting until September. In August there is unusual area of higher values around the polar vortex and September, in particular, showcases a pronounced gradient between the polar vortex region and higher latitudes, with a substantial decrease in the center of polar vortex—from 180 DU in 2022 to approximately 140 DU in 2023. Additionally, the ozone hole's spatial extent in 2023 compared to that of 2022 which is not in agreement with trend of decreasing area of ozone hole prediction. Moreover, there is almost no ozone hole observed in October 2023 (see also ozonewatch link), while normal behavior is that the increase of ozone concentration occurs in November-December. This unpredictability raises questions about whether the distinct temperature and water vapor behaviors in September and October influenced this drastic change in ozone distribution. This unusual behavior is confirmed also by NASA observations (see ozonewatch link).

According to (Rosenlof, 2018) heterogeneous chlorine activation needs very dry conditions in the polar stratosphere, very low temperatures (below ∼195 K) (e.g. Solomon, 1999; Shi et al., 2001). This situation can be found in June and July 2023, when there is more WV and temperature is significantly lower than normal (it drops under 195K). In previous years the temperature is higher than 195K during this period and that is why chlorine activation did not occur. Moreover, Robrecht et al. (2019) studied relation of water vapor, temperature and ozone connection. They show that even small increase of water vapor (10 % increase) above background values would allow chlorine activation at higher temperatures (200–205 K). The observed increase of water vapor in 2023 together with temperature below 200 K and strong polar vortex helps to establish good conditions for larger ozone loss in September 2023 in polar region. Unusual increase of temperature in October 2023 is probably connected with substantial increase of ozone values. According to observations showed in ozonewatch, the area of ozone hole (almost 25 mil km^2) is the biggest one in August and September 2023 since 2011 (except for 2019 when strong warming occurred). This observation also shows that in August and September 2023 we can find the lowest amount of ozone from 2009. On the other hand, in October 2023 ozone hole is one of the smallest in several years.

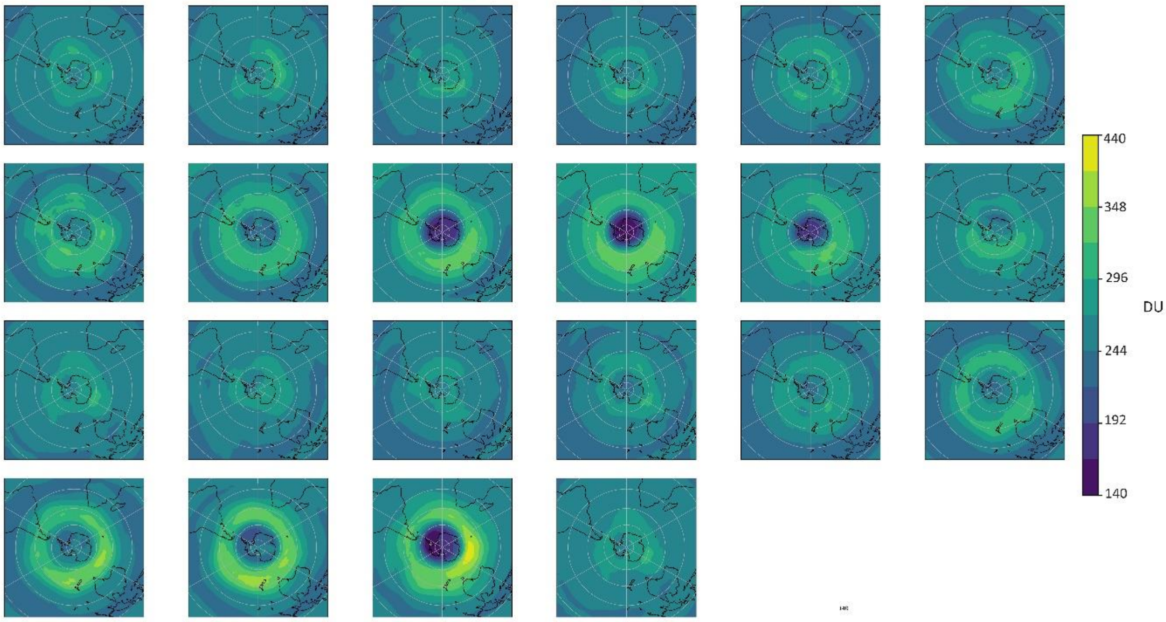

Figure 3 Total column ozone from ERA5 reanalysis. SH is displayed for each month from January 2022 till October 2023.

3. Conclusions

It is noteworthy that water vapor in connection with temperature behavior plays very important role in ozone dynamics, as it can lead to the formation of Polar Stratospheric Clouds (PSCs) and significantly impact the stratosphere's radiative balance. Despite considerable perturbations in midlatitudes (HT eruption in January 2022), observational evidence for the 2022 Antarctic stratospheric polar vortex indicates fairly typical chemical processing, with no clear signs of dynamical vortex disturbances. That is why there is no visible changes in SH polar chemistry and ozone behavior. However, the behavior observed in 2023 deviates from the patterns observed in 2022, adding an intriguing layer to our understanding of these complex atmospheric interactions. There is evident, that water vapor is not the only driver for ozone and chemistry changes while there are definitely important roles of other chemical species from the eruption and possible impact of different stratospheric phenomena but it plays very important role as it is visible in 2023.

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Open Research

Ozonewatch: **https://ozonewatch.gsfc.nasa.gov/meteorology/SH.html**
ERA5: https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-pressure-levels-monthly-means?tab=form (accessed 10.10.2023)

References

Aa, E., Zhang, S.-R., Erickson, P. J., Vierinen, J., et al., 2022. Significant ionospheric hole and equatorial plasma bubbles after the 2022 Tonga volcano eruption. Space Weather, **20**, e2022SW003101, https://doi.org/10.1029/2022SW003101.

Carr, J. L., Horvath, A., Wu, D. L., Friberg, M. D., 2022. Stereo plume height and motion retrievals for the record-setting Hunga Tonga-Hunga Ha'apai eruption of January 15th

2022. Geophys. Res. Lett., 49(9), e2022GL098131, https://doi.org/10.1029/2022GL098131.

Chen, P., Xiong, M., Wang, R., Yao, Y., Tang, F., Chen, H., Qiu, L., 2023a. On the ionospheric disturbances in New Zealand and Australia following the eruption of the Hunga-Tonga – Hunga Ha'apai volcano on January 15th, 2022. Space Weather, 21(4), e2022SW003294, https://doi.org/10.1029/2022SW003294.

Chen, C.-H., Sun, Y.-Y., Zhang, X., Wang, F., Lin, K., Gao, Y., Tang, C.-C., Liu, J., Huang, R., Huang, Q., 2023b. Far-field coupling and interactions in multiple geospheres after the Tonga volcano eruption. Surv. Geophys., 44(3), 587-601, https://doi.org/10.1007/s10712-022-09753-w.

Coy, L., Newman, P. A., Wargan, K., Partyka, G., Strahan, S. E., Pawson, S., 2022. Stratospheric circulation changes associated with the Hunga Tonga-Hunga Ha'apai eruption. Geophys. Res. Lett., 49, e2022GL100982, https://doi.org/10.1029/2022GL100982.

Gille, J. C., Lyjak, L. V., 1986. Radiative heating and cooling rates in the middle atmosphere. J. Atmos. Sci., 43(20), 2215–2229, https://doi.org/10.1175/1520 0469(1986)043<2215:RHACRI>2.0.CO;2.

Gordon, A. E., Cavallo, S. M., Novak, A. K., 2023. Evaluating Common Characteristics of Antarctic Tropopause Polar Vortices. *J. Atmos. Sci.*, ***80***, 337–352, https://doi.org/10.1175/JAS-D-22-0091.1.

Harding, B. J., Wu, Y.-J. J., Alken, P., et al., 2022. Impacts of the January 2022 Tonga volcanic eruption on the ionospheric dynamo: ICON-MIGHTI and swarm observations of extreme neutral winds and currents. Geophys. Res. Lett., 49(9), e2022GL098577, https://doi.org/10.1029/2022gl098577.

Le, G., Liu, G., Yizengaw, E., Englert, C. R., 2022. Intense equatorial electrojet and counter electrojet caused by the January 15th 2022 Tonga volcanic eruption: Space-and ground-based observations. Geophys. Res. Lett., 49(11), e2022GL099002, https://doi.org/10.1029/2022gl099002.

Li, X., Ding, F., Yue, X., Mao, T., Xiong, B., Song, Q., 2023. Multiwave structure of travelling ionospheric disturbances excited by the Tonga volcanic eruption observed by a dense GNSS network in China. Space Weather, 21(2), e2022SW003210, https://doi.org/10.1029/2022SW003210.

Lin, J.-T., Rajesh, P. K., Lin, C. C. H., et al., 2022. The rapid conjugate appearance of the giant ionospheric lamb wave signatures in the Northern Hemisphere after Hunga-Tonga

volcano eruptions. *Geophys. Res. Lett.*, **49**(8), e2022GL098222. https://doi.org/10.1029/2022GL098222.
Liu, L., Morton, Y. J., Cheng, P.-H., Amores, A., Wright, C. J., Hoffmann, L., 2023a. Concentric travelling ionospheric disturbances (CTIDs) triggered by the 2022 Tonga volcanic eruption. J. Geophys. Res. Space Phys., 128(2), e2022JA030656, https://doi.org/10.1029/2022JA030656
Liu, H.-L., Wang, W., Huba, D., Lauritzen, P. H., Vitt, F., 2023b. Atmospheric and ionospheric responses to Hunga-Tonga volcano eruption simulated by WACCM-X. Geophysical Research Letters, 50(10), e2023GL103682, https://doi.org/10.1029/2023GL103682.
Madonia, P., Bonaccorso, A., Bonforte, A., et al., 2023. Propagation of perturbations in the lower and upper atmosphere over the Central Mediterranean, driven by the January 15th 2022 Hunga-Tonga – Ha'apai volcano explosion. Atmosphere, 14(1), #65, https://doi.org/10.3390/atmos14010065.
Manney, G. L., Santee, M. L., Lambert, A., et al., 2023. Siege in the southern stratosphere: Hunga Tonga-Hunga Ha'apai water vapor excluded from the 2022 Antarctic polar vortex. Geophys. Res. Lett., 50, e2023GL103855, https://doi.org/10.1029/2023GL103855.
Millán, L., Santee, M. L., Lambert, A., et al., 2022. The Hunga Tonga-Hunga Ha'apai hydration of the stratosphere. Geophys. Res. Lett., 49(13), e2022GL099381, https://doi.org/10.1029/2022GL099381.
Nedoluha, G.E., Gomez, R.M., Boyd, I., Neal, H., Allen, D.R., Lambert, A., Livesey, N.J., 2023. Mesospheric water vapor in 2022. J. Geophys. Res. Atmos., 128, e2023JD039196, https://doi.org/10.1029/2023JD039196.
Proud, S. R., Prata, A., Schmauss, S., 2022. The January 2022 eruption of the Hunga Tonga-Hunga Ha'apai volcano reached the mesosphere. Earth and Space Science Open Archive, 11. https://doi.org/10.1002/essoar.10511092.1.
Robrecht, S., Vogel, B., Grooß, J. U., Rosenlof, K., Thornberry, T., Rollins, A., ... & Müller, R. (2019). Mechanism of ozone loss under enhanced water vapour conditions in the mid-latitude lower stratosphere in summer. Atmospheric chemistry and physics, 19(9), 5805-5833.
Rosenlof, Karen H. Changes in water vapor and aerosols and their relation to stratospheric ozone. Comptes Rendus Geoscience 350.7 (2018): 376-383.

Schoeberl, M. R., Wang, Y., Ueyama, R., Taha, G., Jensen, E., Yu, W., 2022. Analysis and impact of the Hunga Tonga-Hunga Ha'apai stratospheric water vapour plume. Geophys. Res. Lett., 49(20), e2022GL100248, https://doi.org/10.1029/2022GL100248.

Sellitto, P., Podglajen, A., Belhadji, R., et al., 2022. The unexpected radiative impact of the Hunga Tonga eruption of January 15th, 2022. Res. Square. https://doi.org/10.21203/rs.3.rs-1562573/v1.

Shi, Q., Jayne, J. T., Kolb, C. E., Worsnop, D. R., and Davidovits, P.: Kinetic model for reaction of $ClONO_2$ with H_2O and HCl and HOCl with HCl in sulfuric acid solutions, J. Geophys. Res., 106, 24259–24274, https://doi.org/10.1029/2000JD000181, 2001

Shinbori, A., Otsuka, Y., Sori, T., Nishioka, M., Perwitasari, S., Tsuda, T., Nishitani, N., 2022. Electromagnetic conjugacy of ionospheric disturbances after the 2022 Hunga Tonga-Hunga Ha'apai volcanic eruption as seen in GNSS-TEC and SuperDARN Hokkaido pair of radars observations. Earth Plan. Space, 74(1), 106, https://doi.org/10.1186/s40623-022-01665-8.

Solomon, Susan. "Stratospheric ozone depletion: A review of concepts and history." *Reviews of geophysics* 37.3 (1999): 275-316.

Themes, D. R., Watson, C., Žagar, N., et al., 2022. Global propagation of ionospheric disturbances associated with the 2022 Tonga volcanic eruption. Geophys. Res. Lett., 49(7), e2022GL098158, https://doi.org/10.1029/2022gl098158.

Vadas., S. L., Becker, E., Figueiredo, C., Bossert, K., Harding, B. J., Gasque, L. C., 2023. Primary and secondary gravity waves and large-scale wind changes generated by the Tonga volcanic eruption: Modeling and comparison with ICON-MIGHTI winds. *J.* Geophys. Res. Space Phys., 128(2), e2022JA031138, https://doi.org/10.1029/2022JA031138.

Wang, X., Randel, W., Zhu, Y., et al., 2022. Stratospheric climate anomalies and ozone loss caused by the Hunga Tonga volcanic eruption. ESS Open Archive . November 24, 2022, doi: 10.1002/essoar.10512922.1.

Wright, C. J., Hindley, N. P., Alexander, M. J., Barlow, M., Hoffmann, L., Mitchell, C. N., ... & Yue, J. (2022). Surface-to-space atmospheric waves from Hunga Tonga–Hunga Ha'apai eruption. *Nature*, *609*(7928), 741-746.

Xu, J., Li, D., Bai, Z., Tao, M., & Bian, J., 2022. Large amounts of water vapour were injected into the stratosphere by the Hunga Tonga-Hunga Ha'apai volcano eruption. Atmosphere, *13*(6), 912. https://doi.org/10.3390/atmos13060912

Zhang, S.-R., Vierinen, J., Aa, E., Goncharenko, L. P., Erickson, P. J., Rideout, W., et al., 2022. 2022 Tonga volcanic eruption induced global propagation of ionospheric disturbances *via* Lamb waves. Frontiers in Astronomy and Space Sciences, **9**. https://doi.org/10.3389/fspas.2022.871275