Observing and Projecting the Lasting Fate of the Hunga Eruption on Atmospheric Water Vapor and Hydroxyl Radical

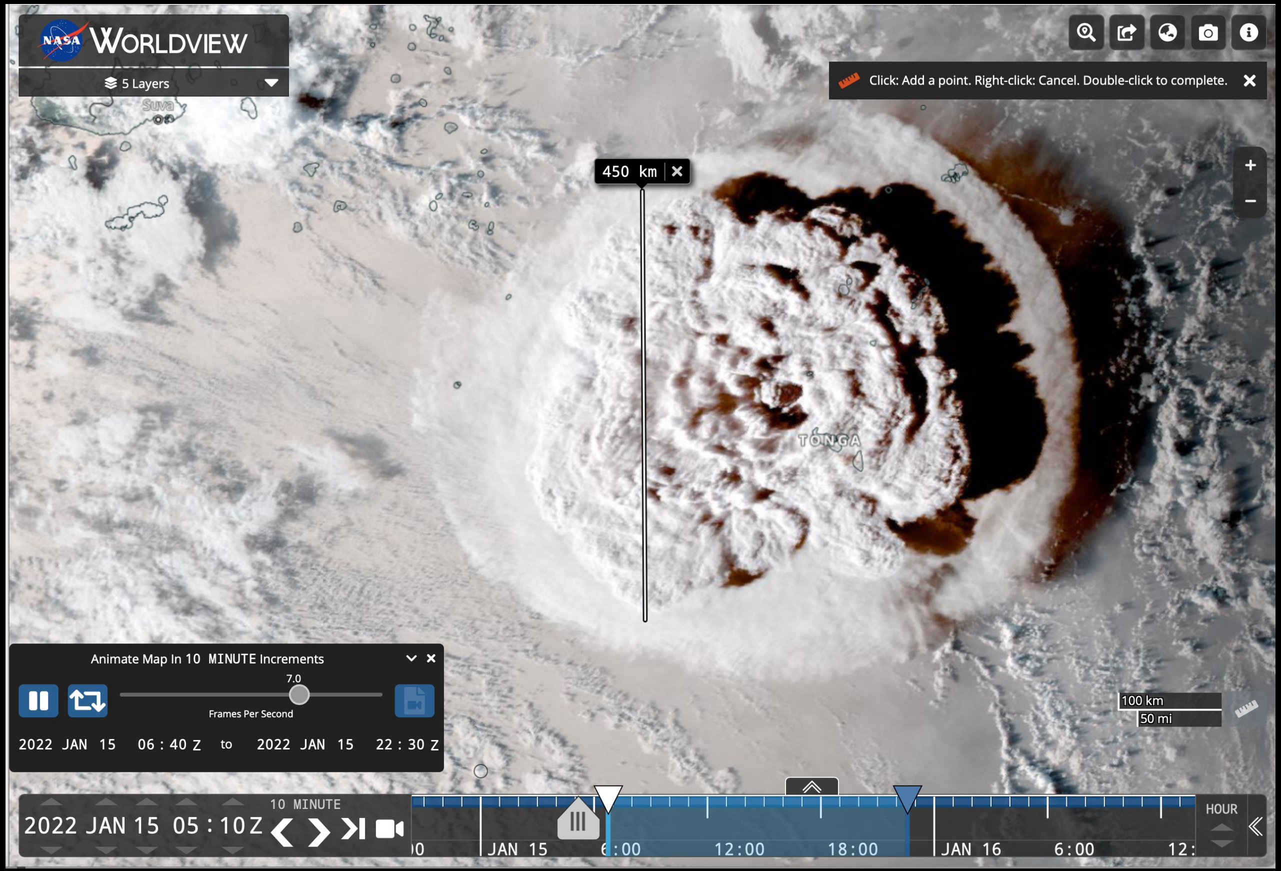
Luke Oman[1], Pete Colarco[1], Qing Liang[1], Steve Steenrod[1,2], Paul Newman[1], Eric Fleming[1,3]

[1]NASA/GSFC, Greenbelt, MD, USA
[2]University of Maryland-Baltimore County, Baltimore, MD USA
[3]Science Systems and Applications, Latham, MD USA

SPARC Workshop
23 Apr. 2024

Hunga Eruption

It is important to properly model the latitudinal extent of the umbrella cloud which is shown in the figure on the right to be about 450-600 km.



For the main eruption we use an equal weighted injection of 6° latitude by 4° longitude between 20-30 km in altitude.

Main eruption: Jan 15, 2022
8-hr (4z-12z) injecting ~600 Tg of H_2O and 0.5 Tg SO_2 in GEOSCCM

Smaller injections are included on Jan. 13th and 14th

GEOS CCM – Goddard Earth Observing System Chemistry Climate Model coupled with the Stratosphere-Troposphere Global Modeling Initiative (GMI) Chemical Mechanism and GOCART Aerosol module

Using both dynamically constrained Replay (GEOS GMI) and Free-running simulations (GEOS CCM, multiple ensembles)

Hunga Water Vapor Perturbation - MLS

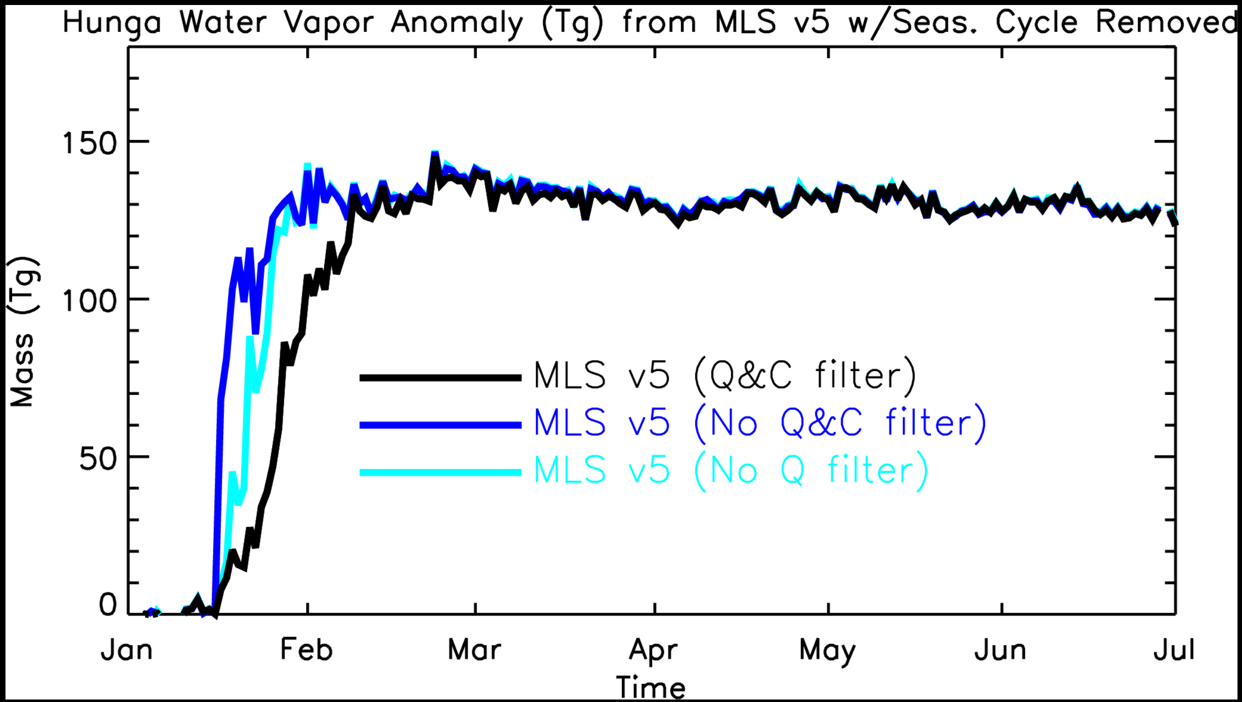
Measurements from MLS show a significant increase in stratospheric water vapor approaching 150 Tg in v5 and possibly close to 170 Tg in v4.2 (not shown)

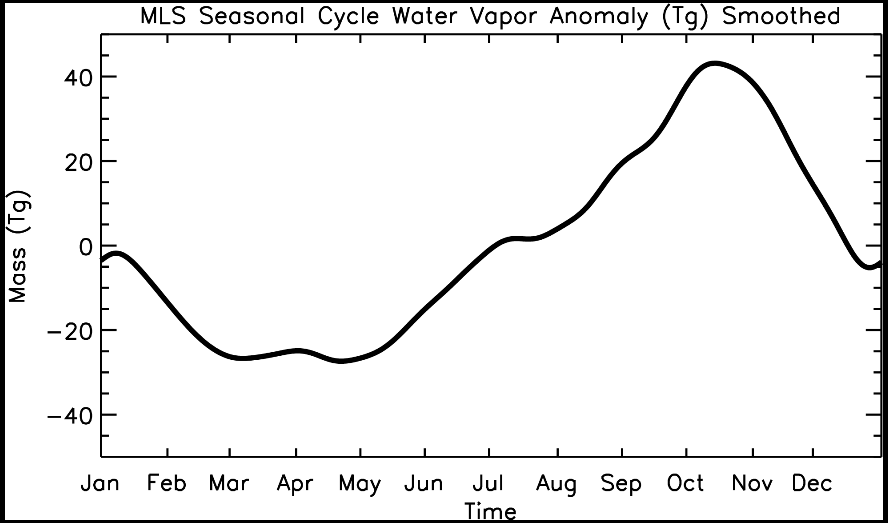
Background stratospheric water vapor is ~1375 Tg (above 100 hPa) so this represent an ~10-12% increase injected over a several hours time.

The figure to the top right shows the calculated water vapor mass (Tg) using the MLS v5 recommended quality and convergence filtering (black curve) as well as when no quality filter is used (cyan curve) and when no quality and convergence filtering is used (blue curve) which adds measurements to the first few weeks.

MLS v4.2 H_2O shows about 15% more total water vapor mass

The remaining difference with the expected injection amount is likely mostly from under-sampling the plume in the early days.

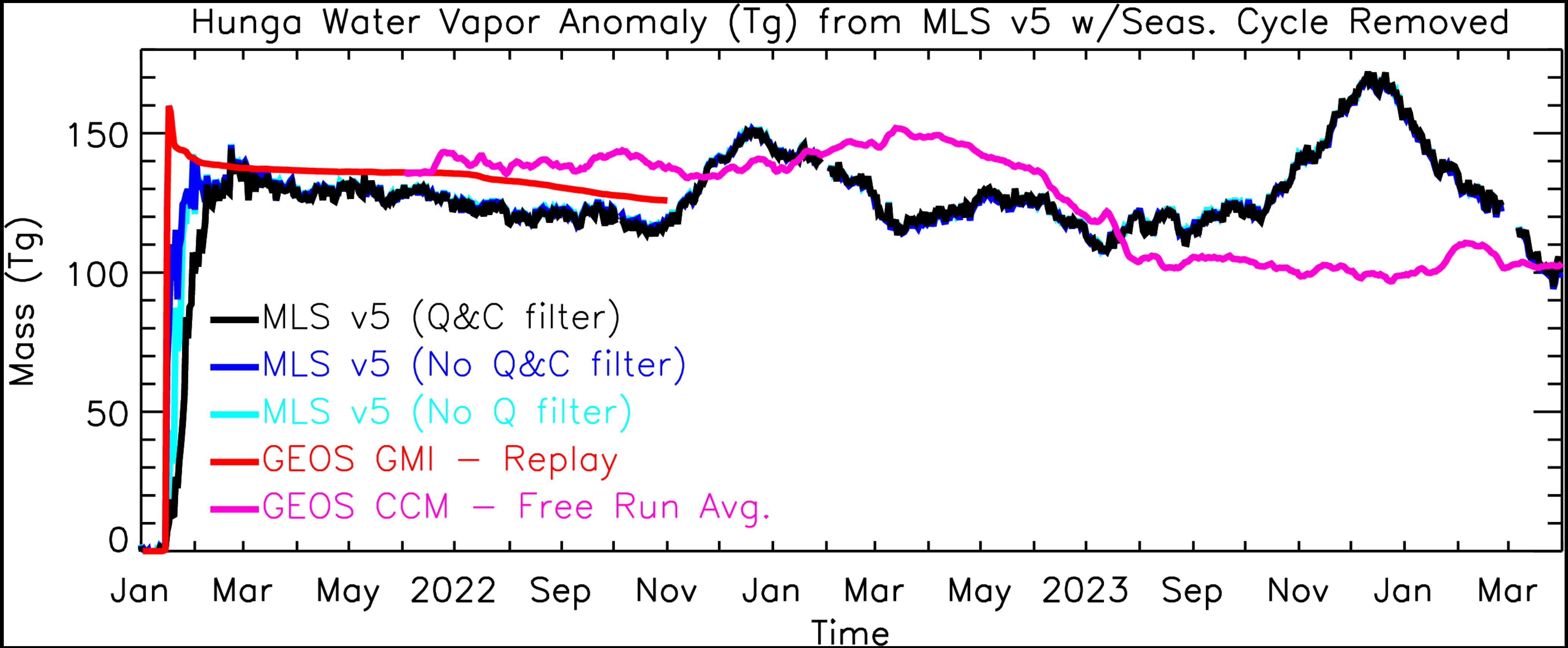




Hunga Water Vapor Perturbation – MLS and GEOS CCM

The majority of the injection is removed by immediate condensation (~75%) and what remains is near saturation, an additional 15% is removed in the first few days with a slower/smaller removal over the subsequent weeks related to moving over a colder part of the atmosphere

This injection is reasonable in comparison to MLS. After over 2 years only relatively small losses have occurred and the MLS integrated water vapor is difficult to distinguish with remaining natural variability (mainly QBO related)



Stratospheric Water Vapor Removal Mechanisms

Polar Dehydration – Operating seasonally, centered in the winter season in the respective hemispheres, driven by condensation at cold temperatures. It is a much larger water vapor removal mechanism in the SH than the NH. Each polar cap represents less than 1/16th of the global area

This dominates at first with Hunga as the water vapor is largely in the SH and makes into the polar region in 2023

Folding back into the troposphere – Stratosphere-Troposphere Exchange of Mass/Water is the dominant loss process once the water vapor is in the lower stratosphere extratropics.

Currently the vast majority is above this region so it has not had much impact in removing HT water vapor but should become the dominant mechanism after a few years and has just made it below 85 hPa in 2024

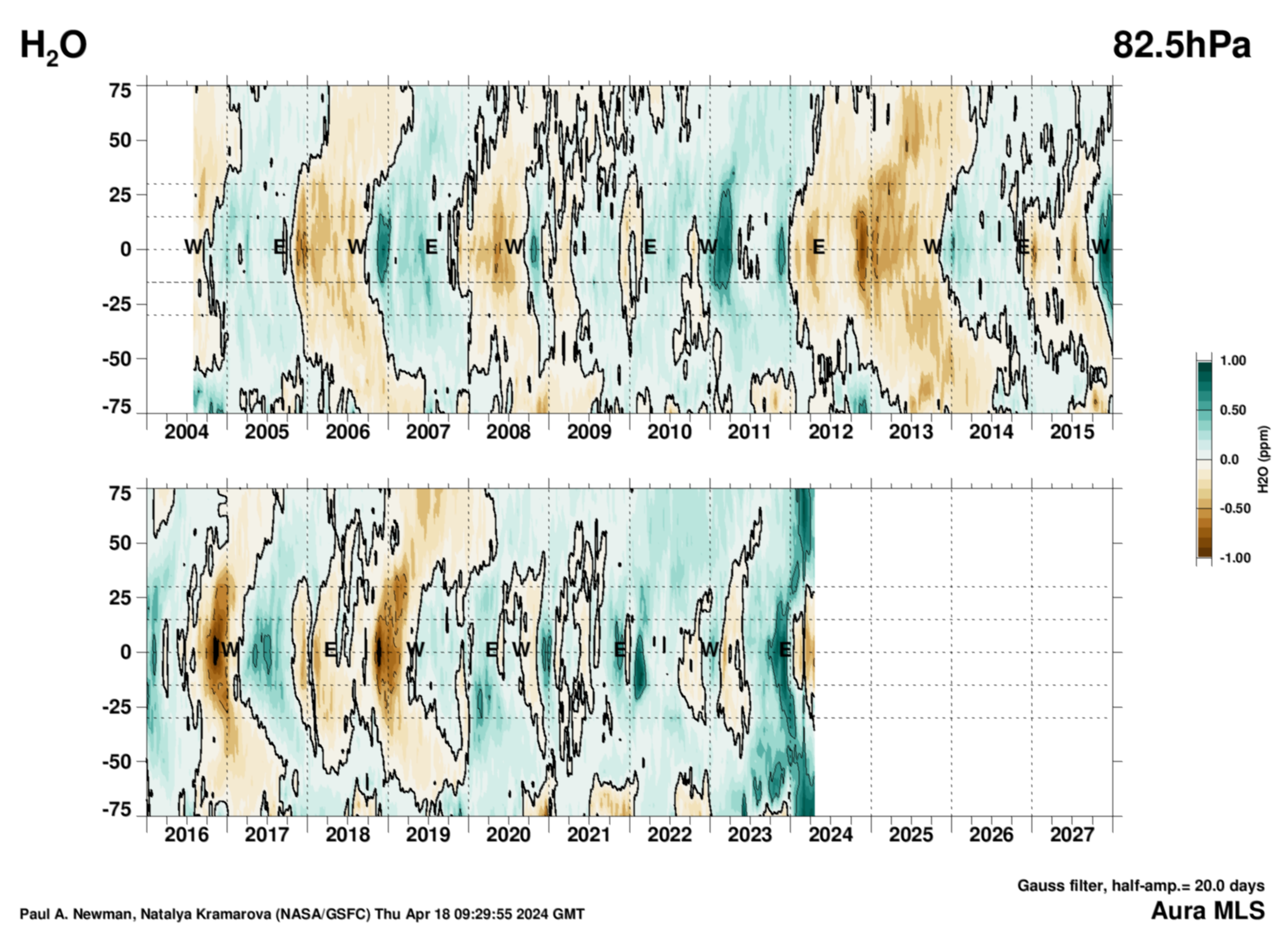
Water Vapor Photodissociation – O_2 Schumann-Runge and Lyman-alpha photolysis – Operating at the shortest wavelengths of light mostly above the stratopause - ~1% atmospheric mass at these altitudes make it a slow and more minor loss mechanism

Lower Stratospheric Water Vapor from MLS

The plot to the right shows the MLS water vapor record at 82.5 hPa with latitude with some enhancements at higher latitudes by the Hunga eruption just showing up in 2024

This plot does have the seasonal cycle removed

Suggesting little contribution of STE loss process as of present, this is expected to change going forward



Water Vapor and Impact on SO_2 lifetime

Simulations with GEOS CCM show a significant impact from the water vapor injection on the evolution of the SO_2 injection

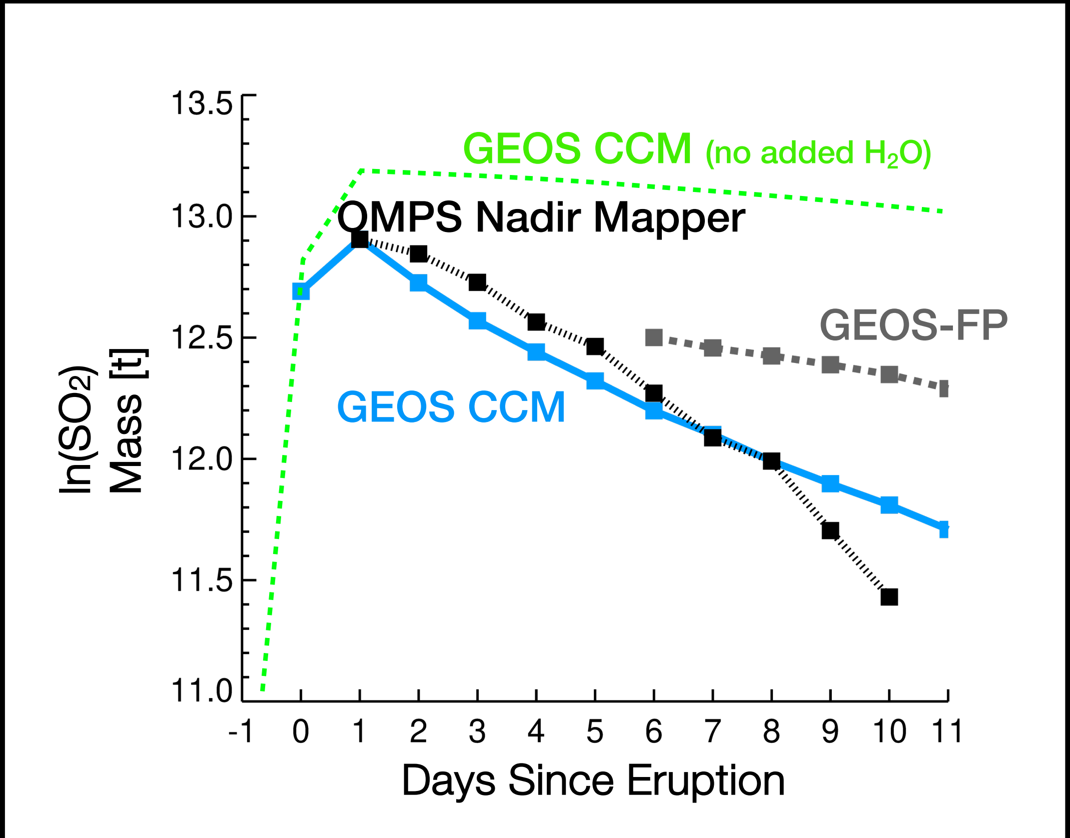
The lifetime of Hunga SO_2 is significantly reduced to 6-8 days and compares well with the model simulation that includes the enhanced water vapor injection and would have remained much longer with background water vapor

The large increase in water vapor increased OH radical speeding up the conversion of SO_2 into sulfate aerosol

The black curve show OMPS_NM SO_2 evolution

The solid blue curve shows GEOS CCM with the added water vapor injection compared to a much slower SO_2 decay with background stratospheric water vapor (dotted green)

The dotted gray curve is from GEOS-FP run at very high resolution but only background water vapor



Southern Hemisphere Change in Water Vapor and OH

GEOSCCM Modeled SH change in Water Vapor (%) for the 4 years following the Hunga Eruption

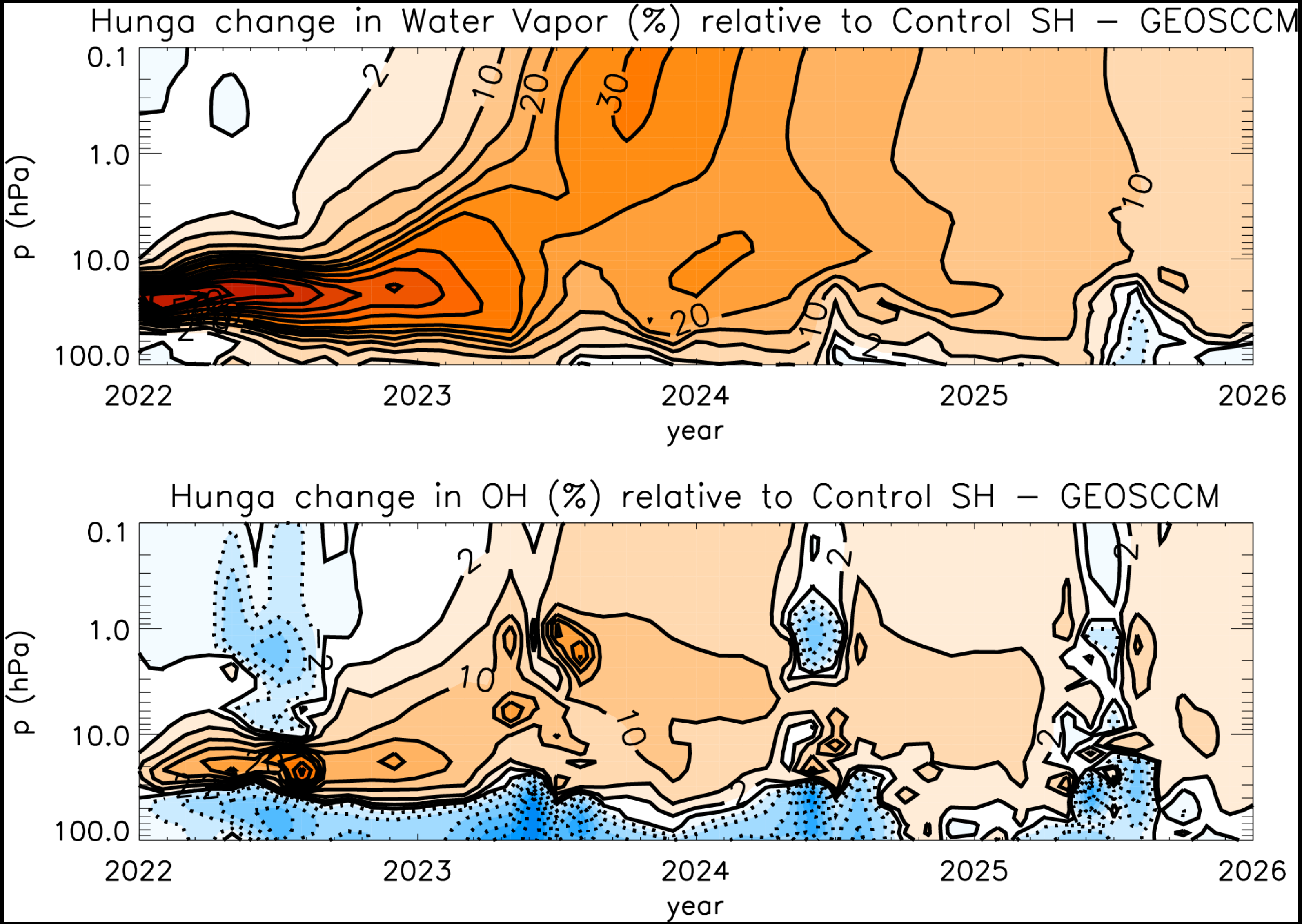
4 ensemble members of each

Up to 60% change in water vapor around 20-30 hPa in the first few months

After 1 year more vertically spread and typically 10-30% above background and already some in the lower most stratosphere

OH generally increases but by a smaller percentage especially early on with higher amounts of aerosols present

Decreases seen below 40 hPa



Southern Hemisphere Change in Water Vapor and OH

GEOSCCM Modeled SH change in Water Vapor (%) for the 4 years following the Hunga Eruption

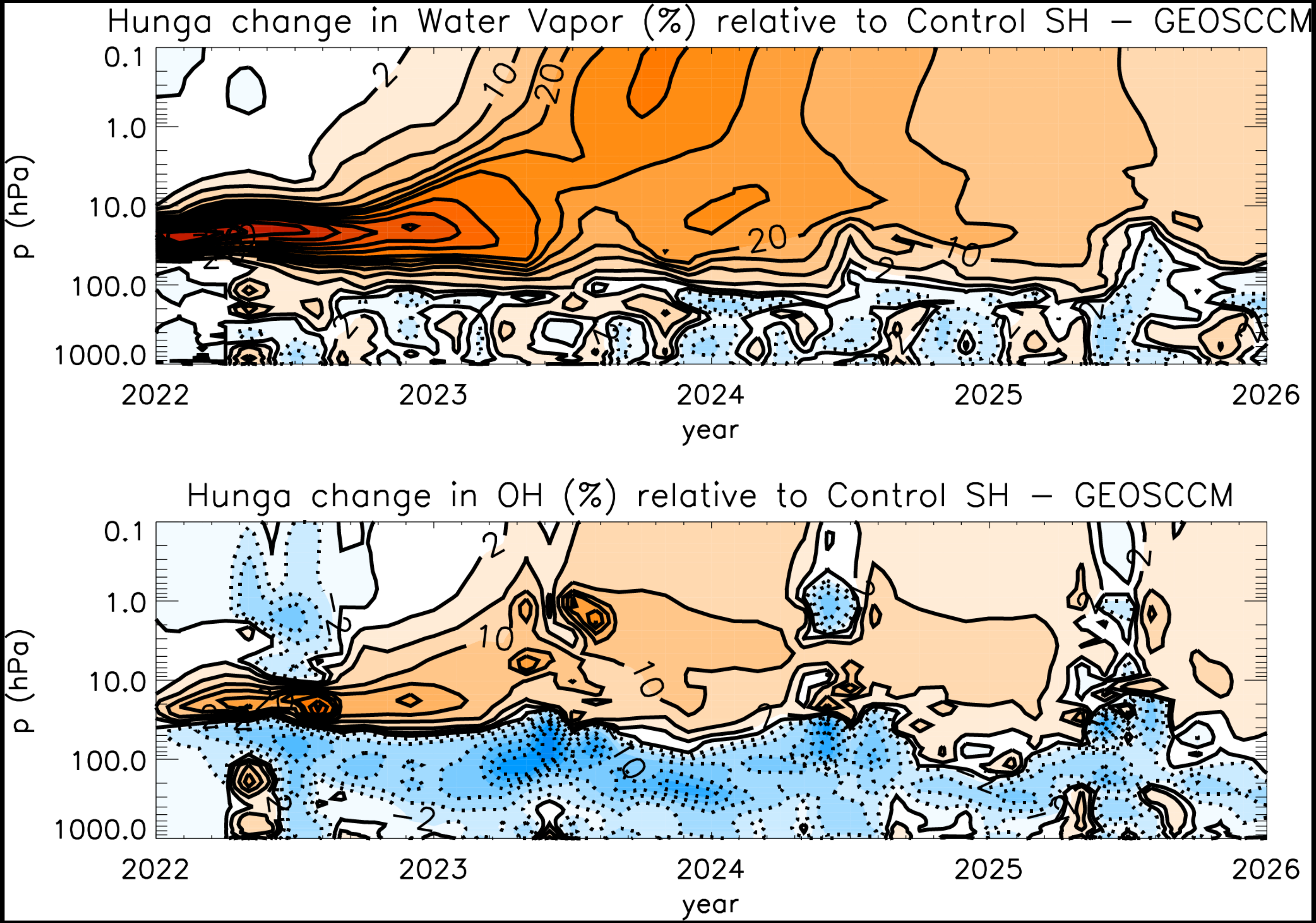
4 ensemble members of each

Up to 60% change in water vapor around 20-30 hPa in the first few months

After 1 year more vertically spread and typically 10-30% above background and already some in the lower most stratosphere

OH generally increases but by a smaller percentage especially early on with higher amounts of aerosols present

Decreases seen below 40 hPa extending into the troposphere



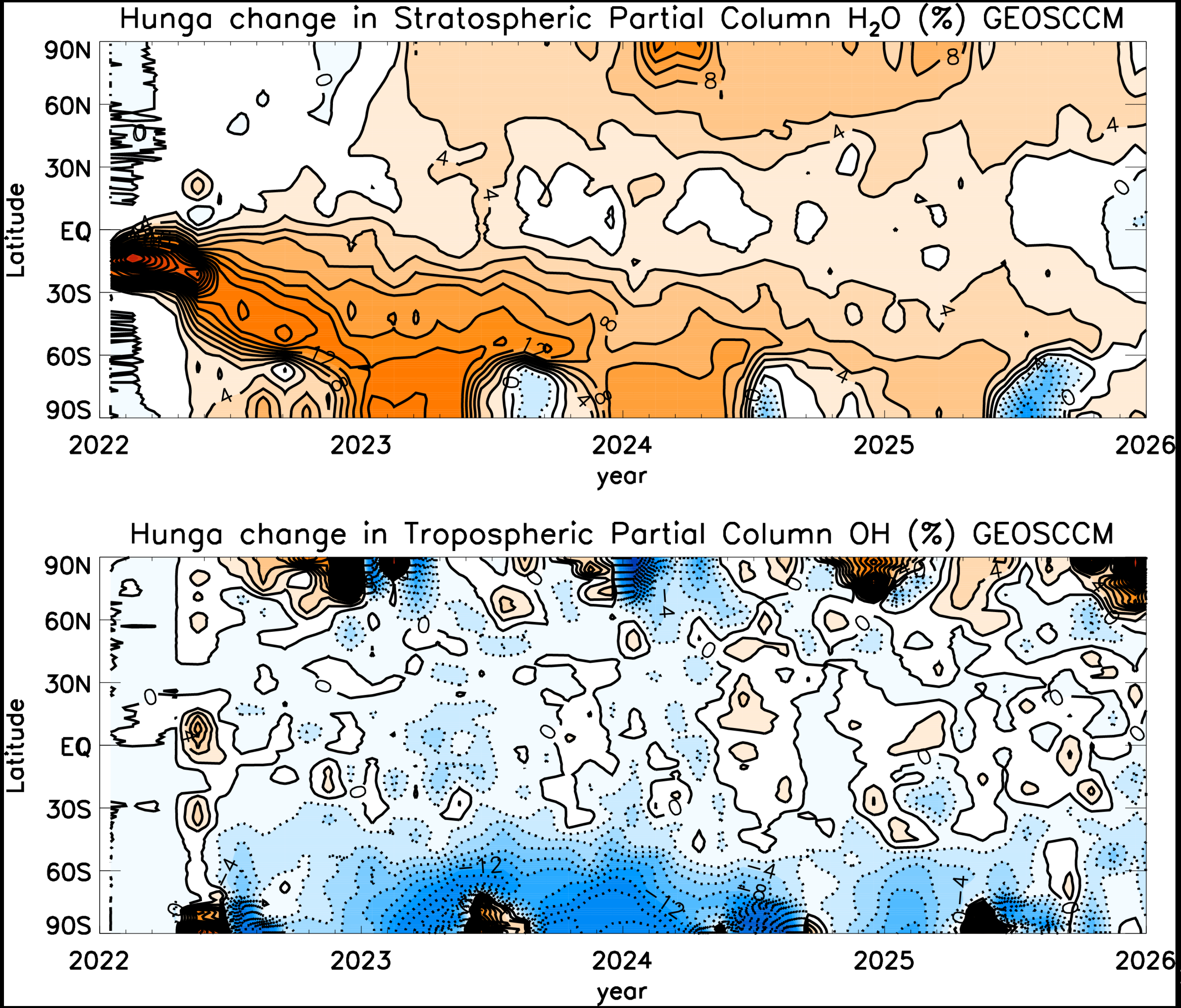
Hunga Impacted Stratospheric H_2O and Tropospheric OH

GEOSCCM simulates reduced tropospheric OH in response to the Hunga eruption

Decreases develop overtime during late 2022 and by 2024 there are 5-25% decreases in tropospheric OH mainly poleward of 30°S

Matches a similar pattern in stratospheric sulfate optical depth

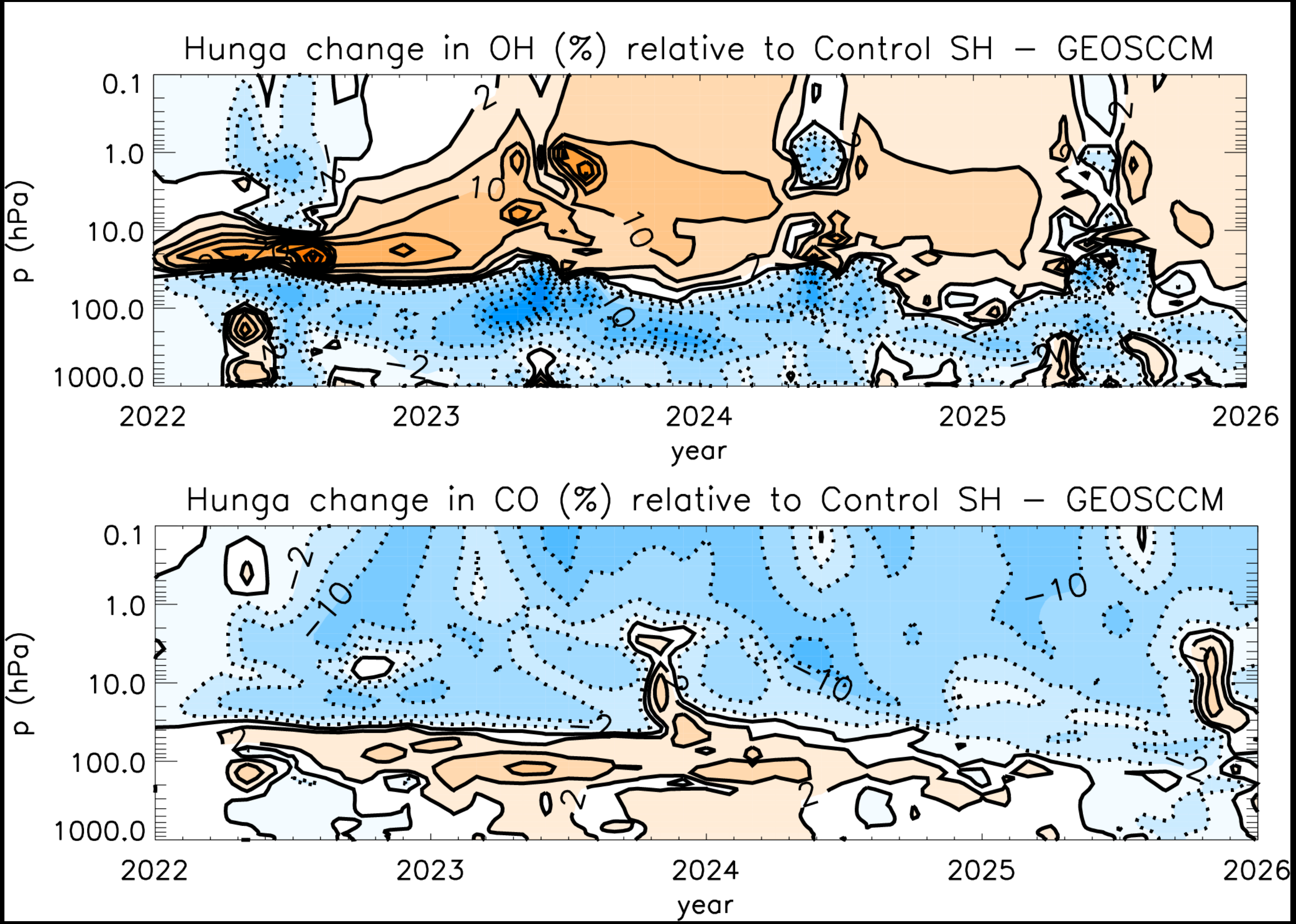
What are the implications to species impacted by OH?



Hunga OH changes Impact Carbon Monoxide

Carbon Monoxide (CO) is significantly influenced by OH concentrations and we see the model projecting 5-15% decreases in the upper atmosphere at pressures lower than about 40 hPa

Below that level we see the decreases in OH correspond to increases in CO around 2-10% over the first few years

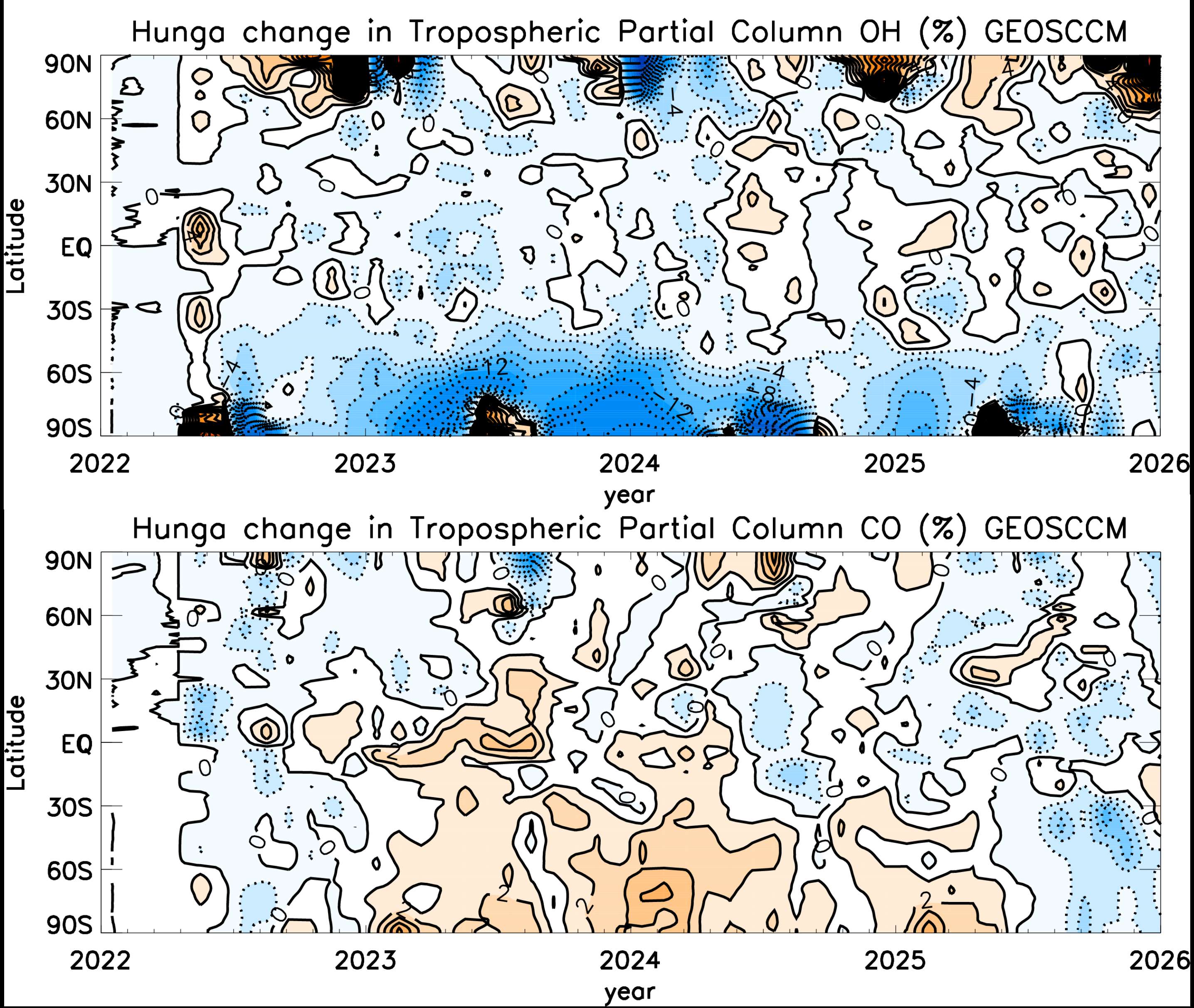


Hunga Tropospheric OH and CO Changes By Latitude

The changes we saw in tropospheric OH over the mid-high latitude SH produce some increased Tropospheric Partial Column CO peaking in early 2024 at 2-5% increase

We also looked at CH_4 but really needs to be assessed with CH_4 emissions and not the mixing ratio boundary conditions that are typically used including in these simulations

Addition species impacted by OH are also effected like NMVOCs



Summary

- Hunga increased the background stratospheric water vapor by at least 10% in several hours time and is likely to be distinguishable from the previous background for much of this decade with the slow removal mechanisms

- The large water vapor injection significantly enhanced mid-stratospheric (and above) OH and is critical to get the very short lifetime of SO_2 that was observed for the Hunga eruption

- Modeling suggests a reduction in OH below, at pressure greater than 40 hPa, with the largest decreases in the SH mid-high latitudes (5-25% integrated over the troposphere)

- The changes in the OH radical impact other gases like CO with decreases in the upper atmosphere and increases in the troposphere

Extra Slides

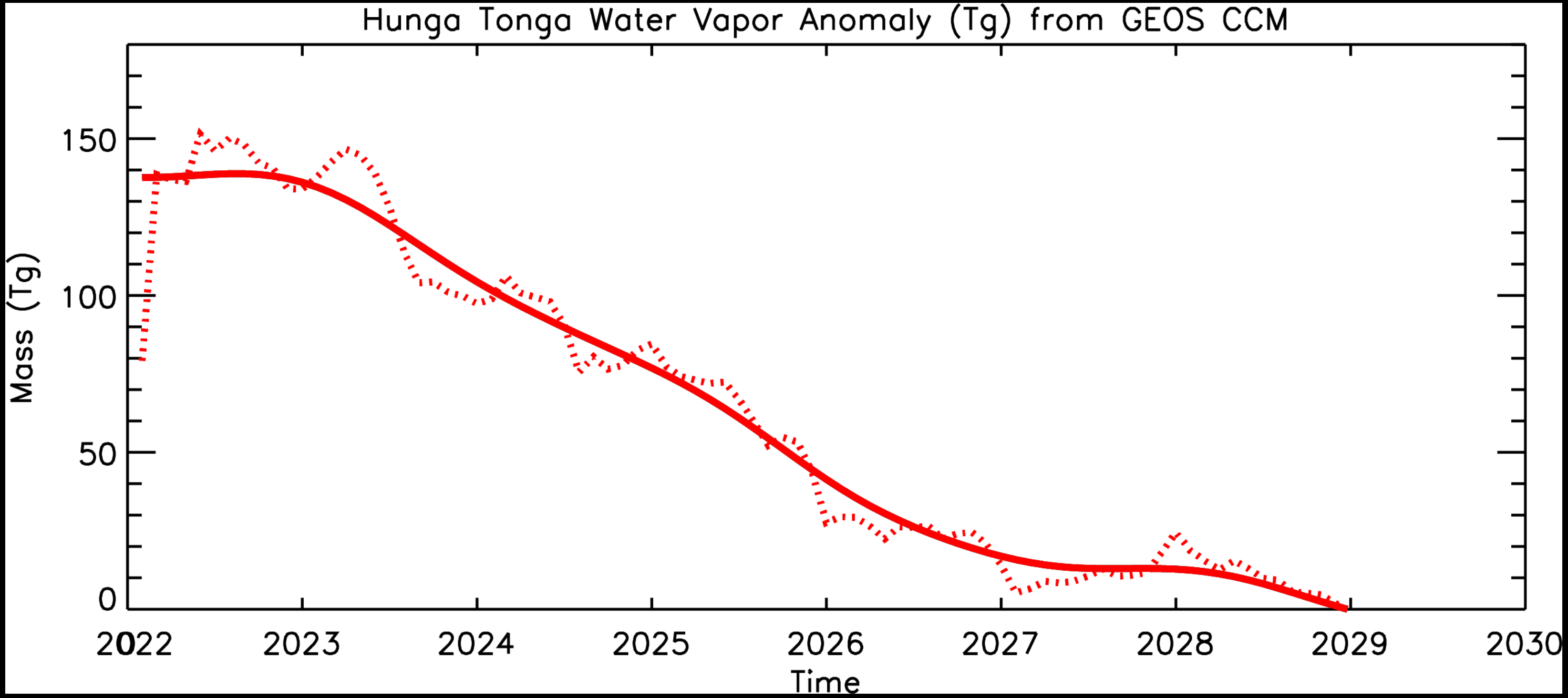
Longer-Term Hunga Water Vapor Evolution

We have continued a series of simulations (4 members) to look at the evolution of water vapor in the stratosphere and the time scales for removal.

A difference in water vapor from GEOS CCM simulations with and without Hunga eruption is shown in red (dotted curve) and after smoothing (red solid curve) suggesting a 3-4 year e-folding time scale for removal.

With no significant reaction loss pathways the main removal mechanism is through polar dehydration and transport back into the troposphere through the large-scale BD circulation and tropopause folding

Model tends to have too fast overturning circulation and more quickly mixes to the lowermost stratosphere, so this is likely a lower end estimate

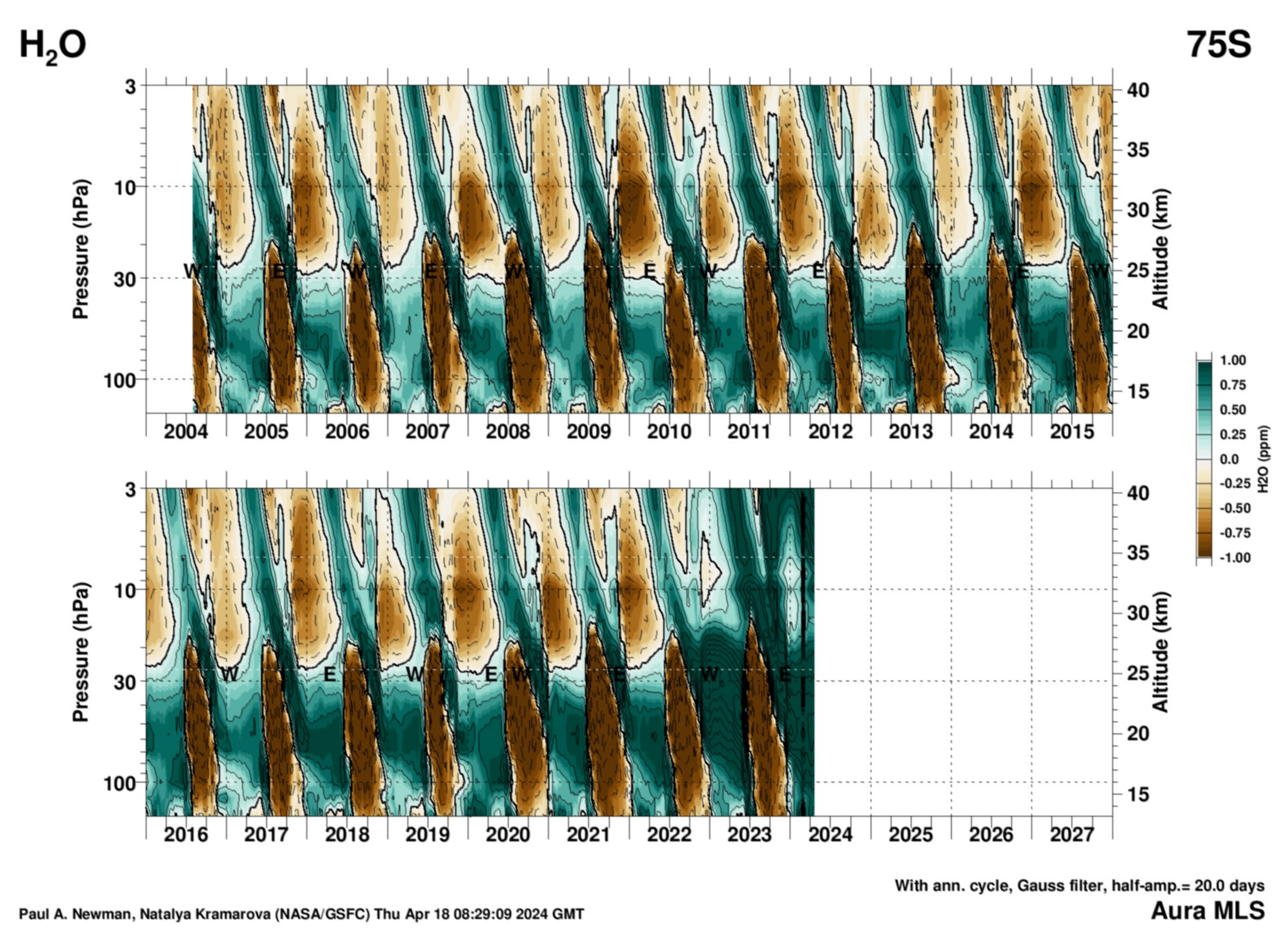


Polar Water Vapor – MLS 75°S

The plot to the right shows the MLS water vapor record at 75°S punctuated by the large increase due to Hunga

This plot does not have the seasonal cycle removed so the strong dehydration during polar winter is shown which at least initially is the largest loss process

Also shown is the seasonal water vapor enhancement from the poleward and downward transport of higher water vapor from CH_4 oxidation



Tropical Water Vapor – MLS 15ºS

The plot to the right shows the MLS water vapor record at 15ºS with similar but smaller anomalies in the NH tropics

This plot does have the seasonal cycle removed

In the tropics you can see the gradual clearing out of the high water vapor anomalies as the more normal tropically dehydrated amounts are being advected upwards.