Projecting the Lasting Fate of the Hunga Tonga-Hunga Ha'apai Eruption on the Stratosphere through Connecting Measurements to Models

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SAGE III/ISS Science Team Meeting
12 –13 Sept. 2023

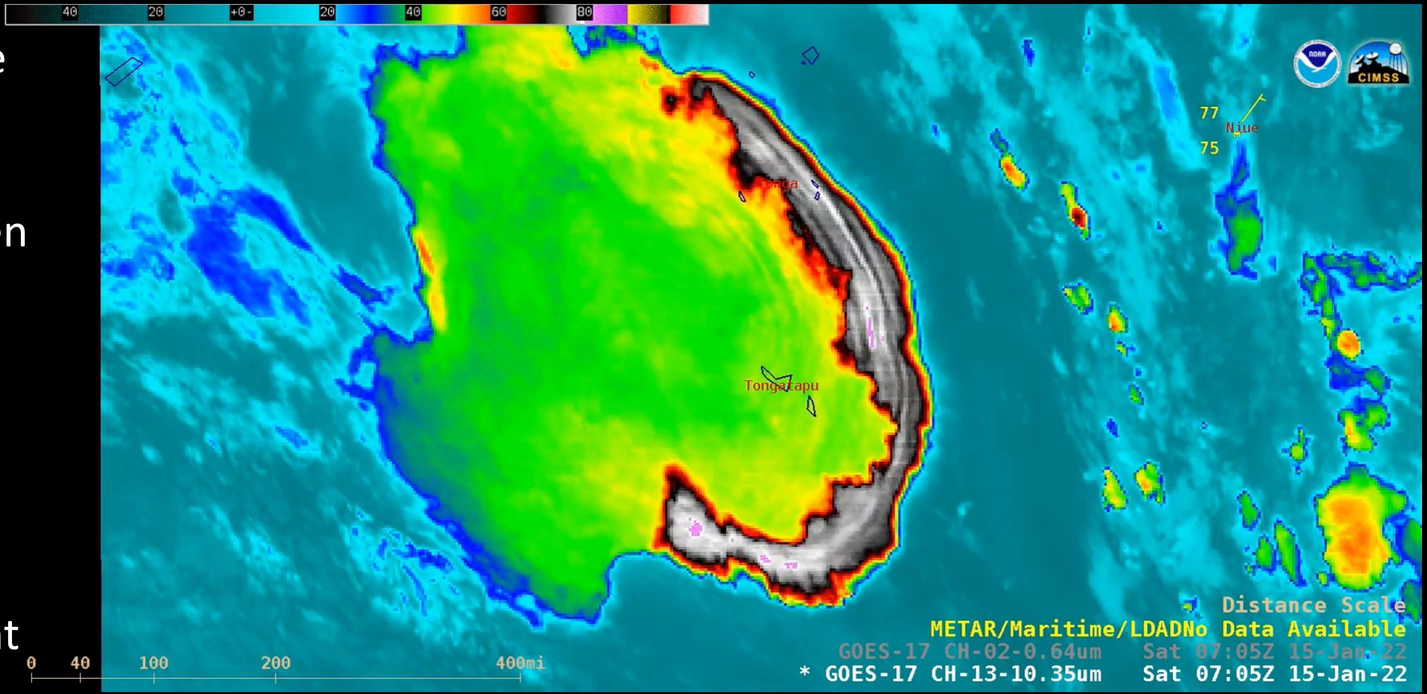
Outline

- Overview of the Hunga Tonga Eruption and Model Initialization
- GEOS CCM/GMI Modeling and Capabilities
- Handling Constituent Injections
- Hunga Tonga Water Vapor Observed by MLS
- Comparisons of MLS and GEOS CCM Modeling
- Water Vapor Loss Processes
- Longer Term Water Vapor Removal Projections
- Changes in Other Constituents
- SO_2 Conversion and Aerosol Evolution
- Other GEOSCCM/GMI Modeling Work of Potential Interest to the SAGE III/ISS Community
- Summary and Future Work

Hunga Tonga - Hunga Ha‘apai Eruption

Submarine Volcano main eruption Jan. 15, 2022
Volcanic cloud reached the Mesosphere (~58 km) – not seen previously in our satellite record
Injecting about 0.5 Tg of SO_2 gas as well as some ash and sulfate aerosol

But the main story is the water vapor injected into the stratosphere
Normally quite dry at about 5 ppmv, measured values of several hundred to ~3000 ppmv were seen between 24-30 km (*Vömel et al., 2022*).



Injections of stratospheric water vapor and sulfate aerosol have very different removal timescales which impacts their fate.

The IR GOES-17 satellite time lapse shows the different phases of the eruption, creating strong gravity waves and record amounts of lightning strikes (not shown)

This large perturbation of a long-lived tracer like water vapor should inform about many dynamical, chemical, and radiative processes in the atmosphere

Hunga Tonga - Hunga Ha‘apai Eruption

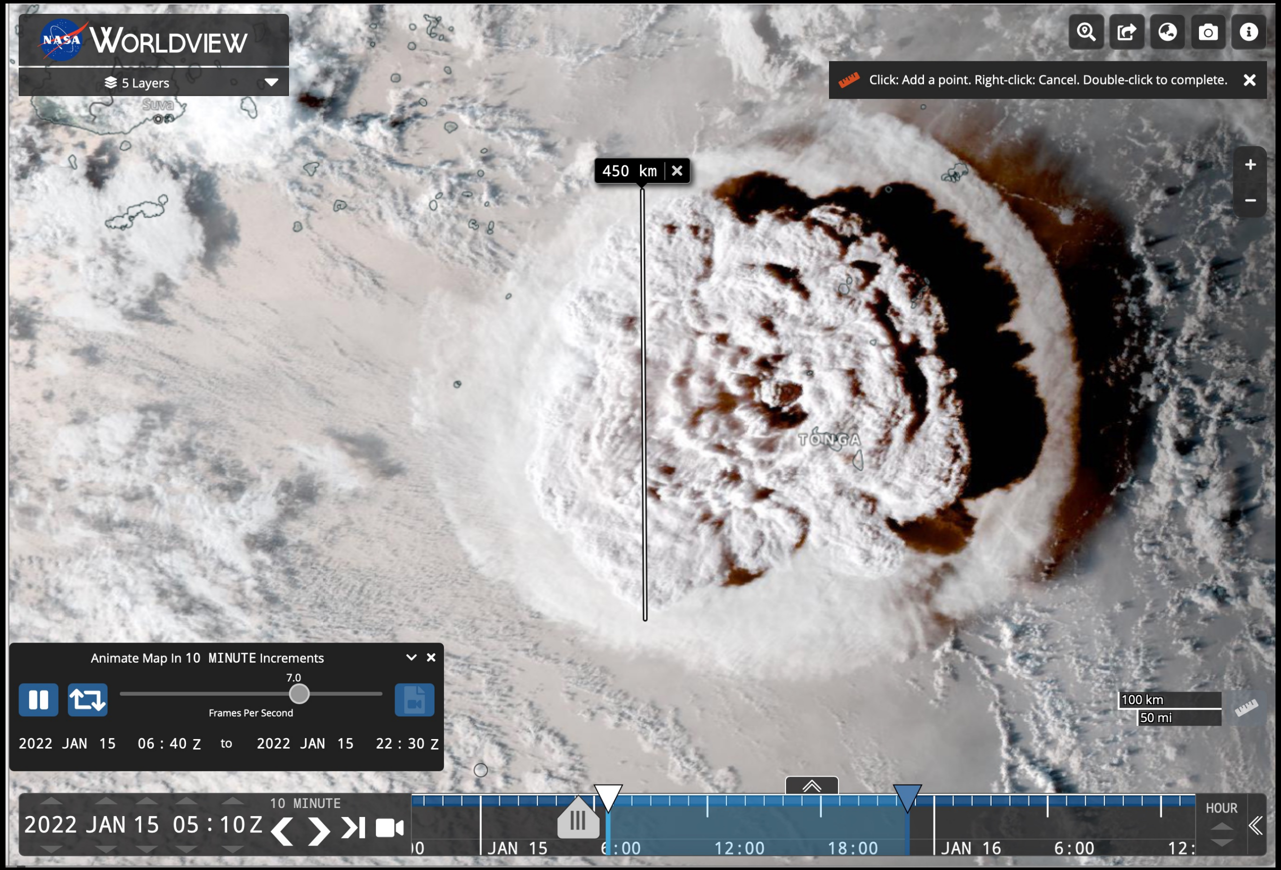
It is important to properly model the latitudinal extent of the umbrella cloud which is shown in the figure on the right to be about 450-600 km.

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



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Using both dynamically constrained Replay and Free-running simulations (multiple ensembles)

GEOS CCM/GMI Modeling and Capabilities

GEOS is the Goddard Earth Observing System and it is the framework GCM maintained by NASA GMAO for our chemical/aerosol modeling capabilities

It can be paired with many options for chemistry and aerosols. For the simulations I will talk about today this includes the Global Modeling Initiative (GMI) Stratosphere-Troposphere Chemical Mechanism and the Goddard Chemistry Aerosol Radiation and Transport (GOCART) bulk aerosol module.

It can be run in many resolutions and configurations :
Resolution: typically 72 levels can be run up to 181 levels and with coupled chemistry ~50 km horizontal resolution but we have a several decade simulation at ~25 km
Configurations: Free Running model (CCM), Chemistry Transport Model (CTM), Replay (constrained dynamics of core variables)

We have a number of simulations available for the community to use and we can make recommendations depending on the needs

New GMI capabilities – Constituent Injections

A fairly recent addition to the modeling capabilities for GMI simulations is that we have added Trace Gas constituent injections like has been done in GOCART (volcanic eruptions, fires)

This work was prompted by the needs that have arisen with the Hunga Tonga Eruption as well as some recent large fire events like the Australian New Years (ANY) fires in 2019/20 and the British Columbia wildfires in 2017

This is available for any GMI species (including water vapor since GMI modifies water vapor from CH_4 oxidation)

Previously for some of the stronger stratospheric injections from large fires we were altering the restart to add in additional constituent injections

You provide the species and amount (kg/s) as well as location (lat x long x alt) and time extent for each date

We prioritized adding this to the modeling capabilities to test with the Hunga Tonga case

Hunga Tonga Water Vapor Perturbation - MLS

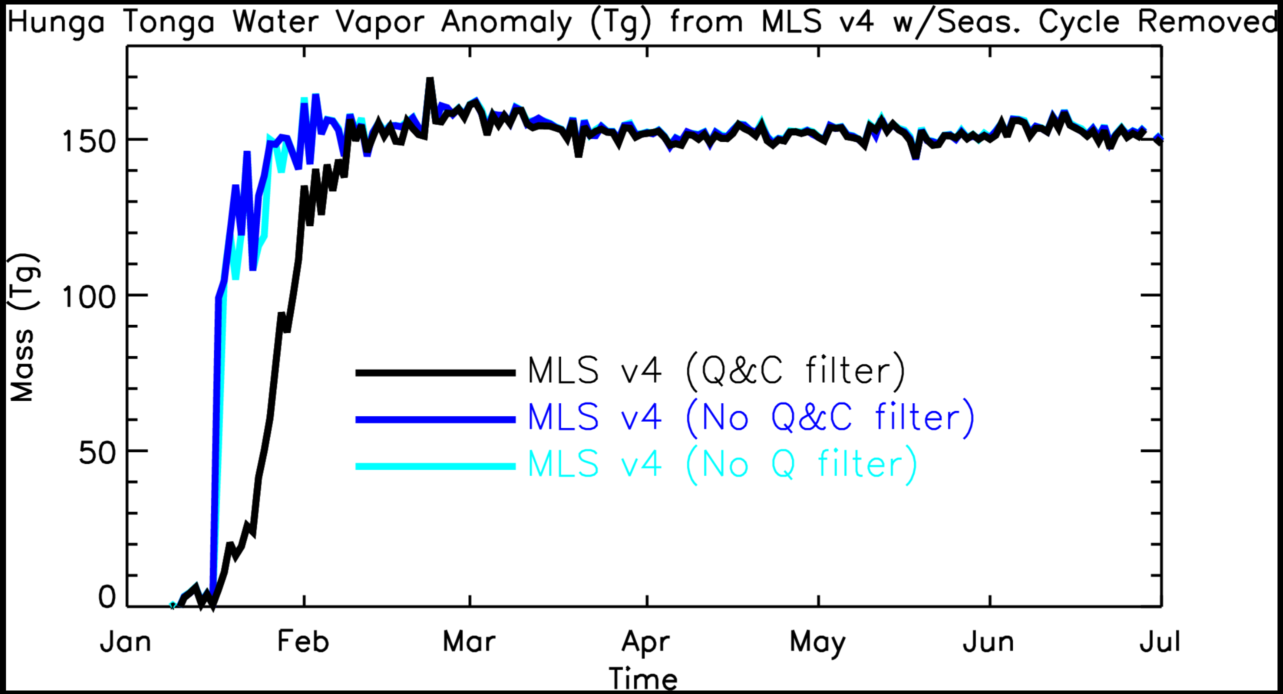
Measurements from MLS show a significant increase in stratospheric water vapor of over 150 Tg possibly close to 170 Tg

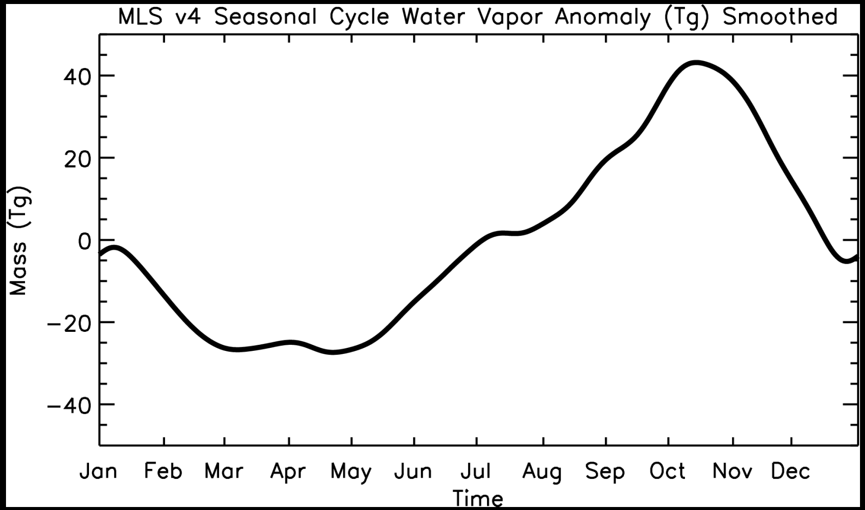
Background stratospheric water vapor is ~1375 Tg (above 100 hPa) so this represent an ~11-12% increase injected over a several hours time.

The figure to the top right shows the calculated water vapor mass (Tg) using the MLS v4.2 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 Team indicated issue with v5 H_2O because of change in T/P algorithm and recommend using v4.2

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

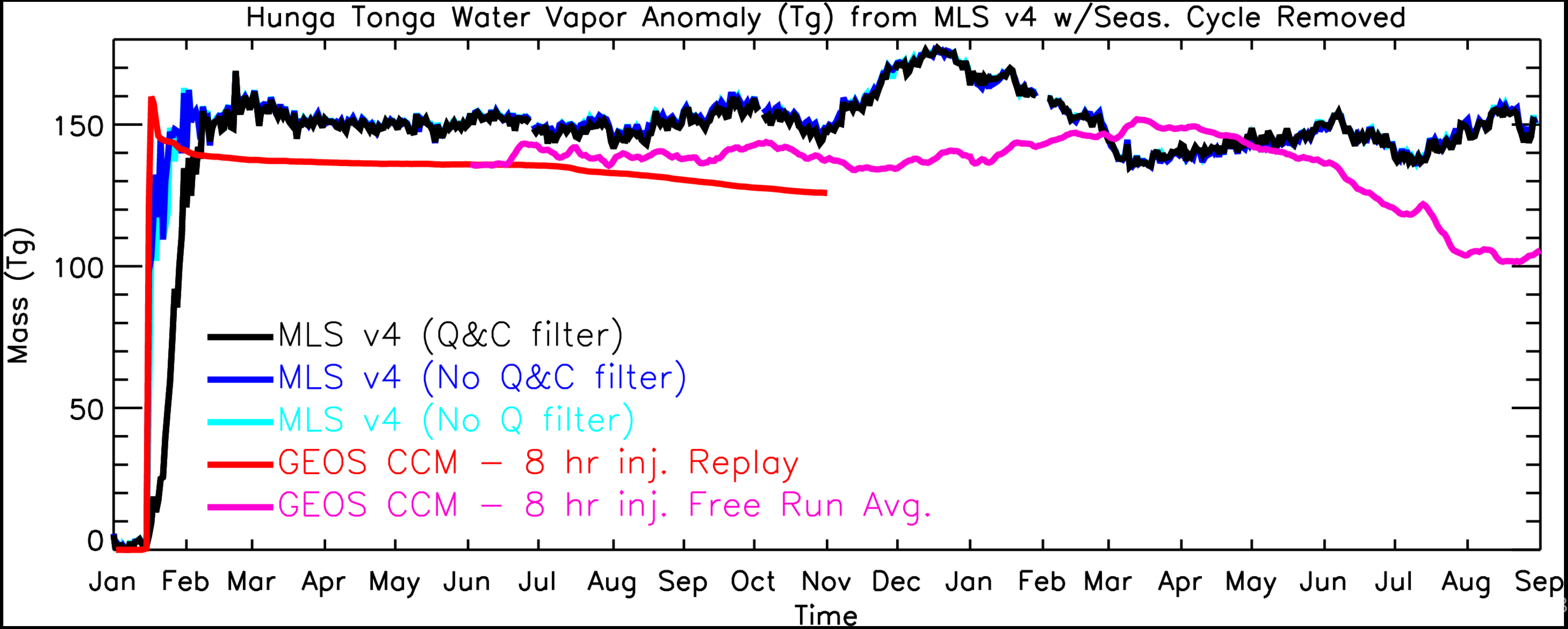




Hunga Tonga Water Vapor Perturbation – MLS and GEOS CCM

We modeled the Hunga Tonga water vapor injection with GEOS CCM coupled to GMI chemistry. The simulations include both replay and an ensemble of free running simulations.

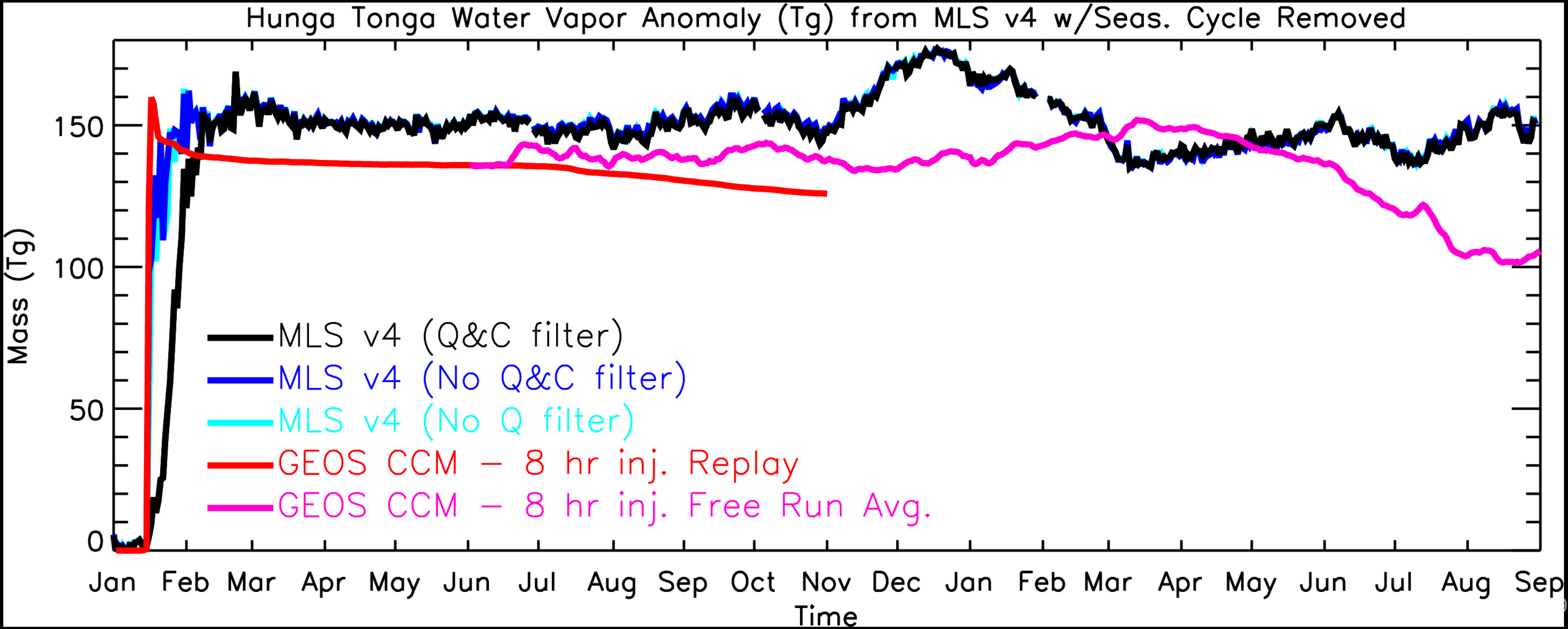
GEOS CCM with Replay is added to the MLS curves shown in for an 8-hr injection (red, solid curve)
GEOS CCM free running simulations starting in June 2022 (magenta, solid curve)



Hunga Tonga 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 and the PDF function used for condensation in the model.

The 8-hr injection runs about 10-15% low but reasonable in comparison to MLS. After almost 20 months the MLS integrated water vapor loss is still in the noise.



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 HT 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 has not had much impact in removing HT water vapor but should become the dominant mechanism after a few years

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

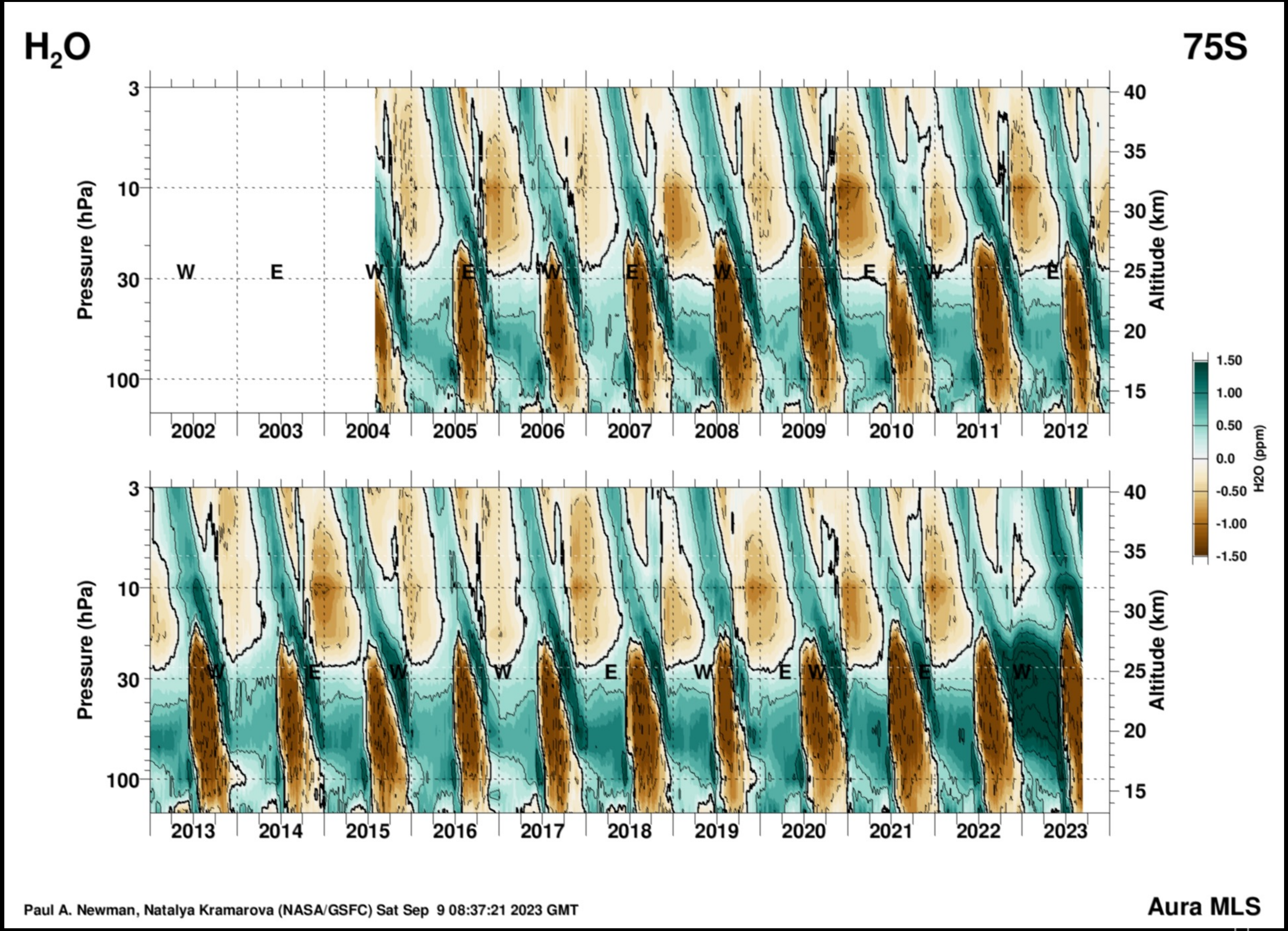
Polar Water Vapor – MLS 75^{o}S

The plot to the right shows the MLS water vapor record at 75^{o}S punctuated by the large increase due to HTE

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

Smaller feature of lower stratospheric moistening from PSC reevaporation



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Aura MLS

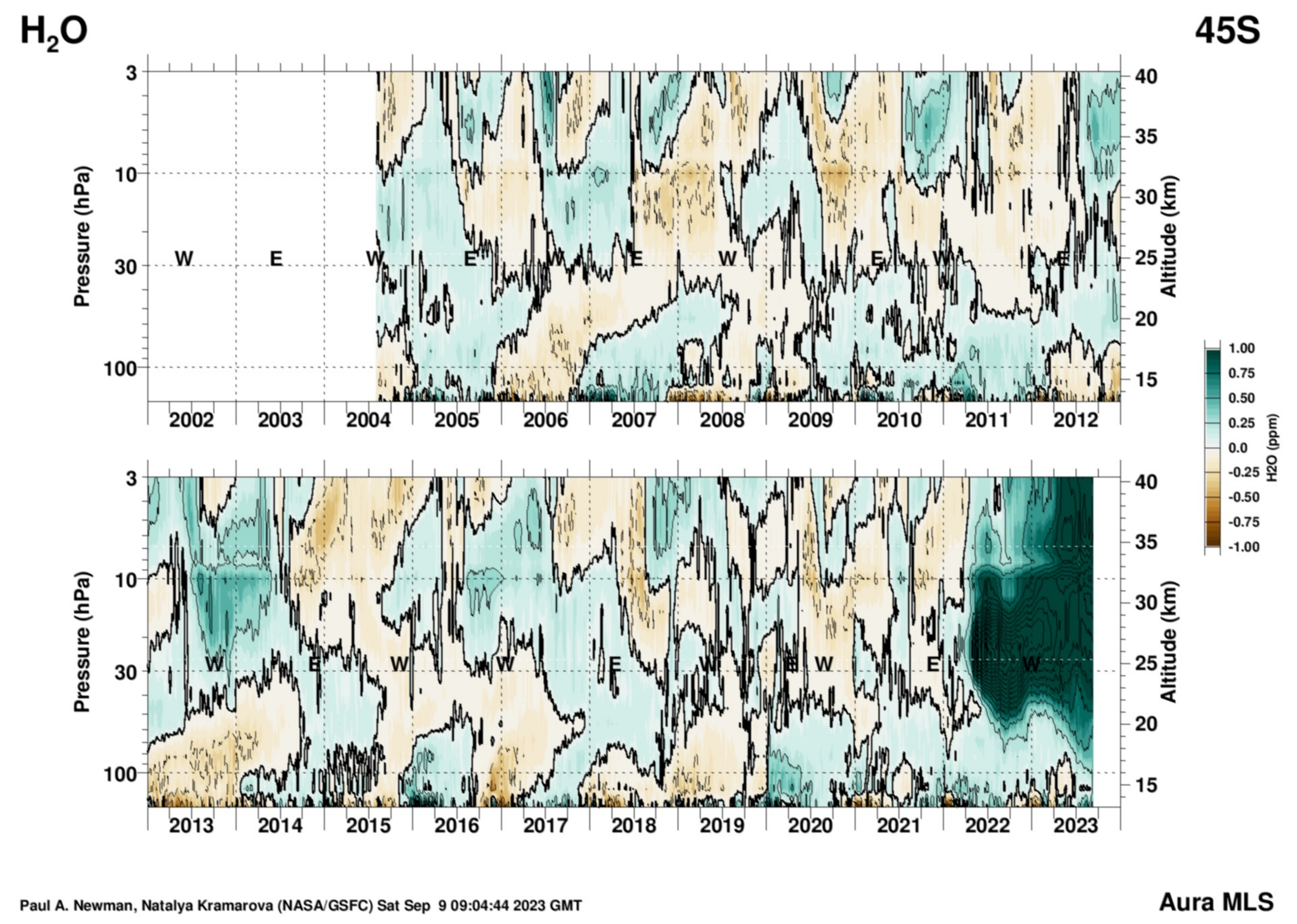
Mid-latitude Water Vapor – MLS 45^{o}S

The plot to the right shows the MLS water vapor record at 45^{o}S with the much more visible punctuation by the HTE

This plot does have the seasonal cycle removed

At these latitudes initially the water vapor is spreading into the region around 20-30 hPa but after a few months it is enhancing the background from 50-5 hPa

By 2023 the water vapor enhancement 1-2 ppmv is extended to at least 3 hPa



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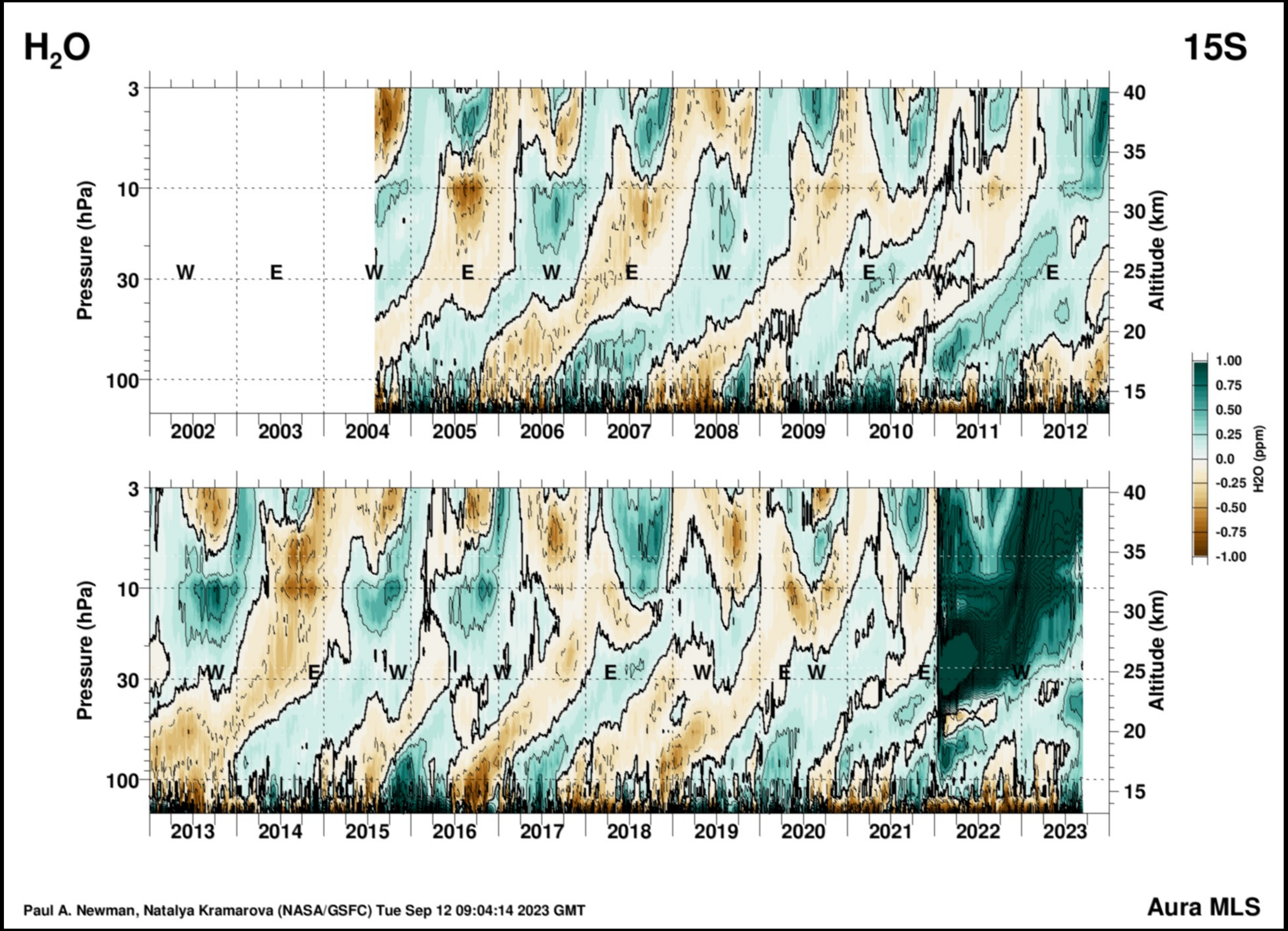
Tropical Water Vapor – MLS 15^{o}S

The plot to the right shows the MLS water vapor record at 15^{o}S 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.



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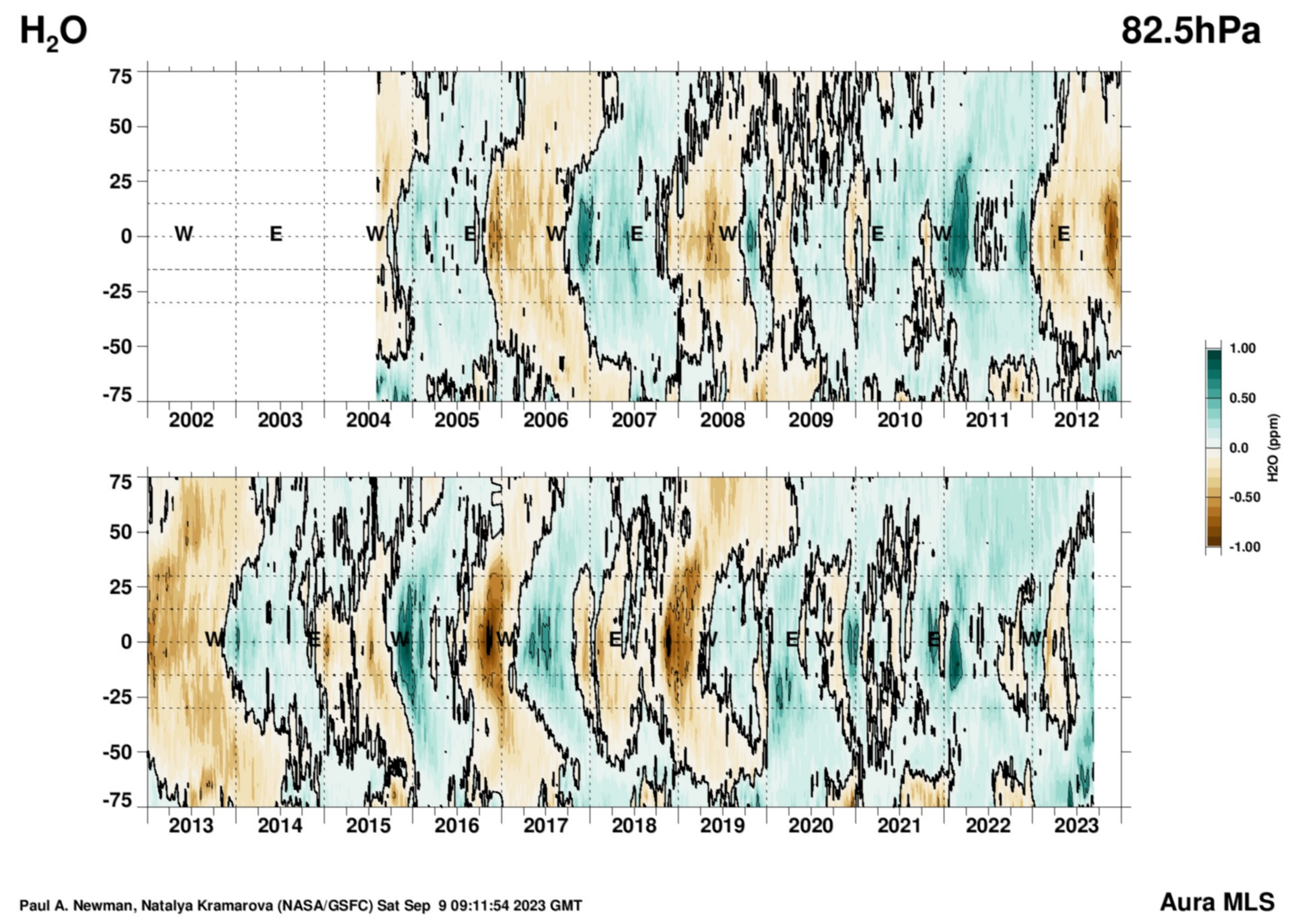
Lower Stratospheric Water Vapor

The plot to the right shows the MLS water vapor record at 82.5 hPa with latitude with no significant enhancements by the HTE yet apparent

This plot does have the seasonal cycle removed

Suggesting no significant contribution of STE loss process as of present, this is expected to change going forward



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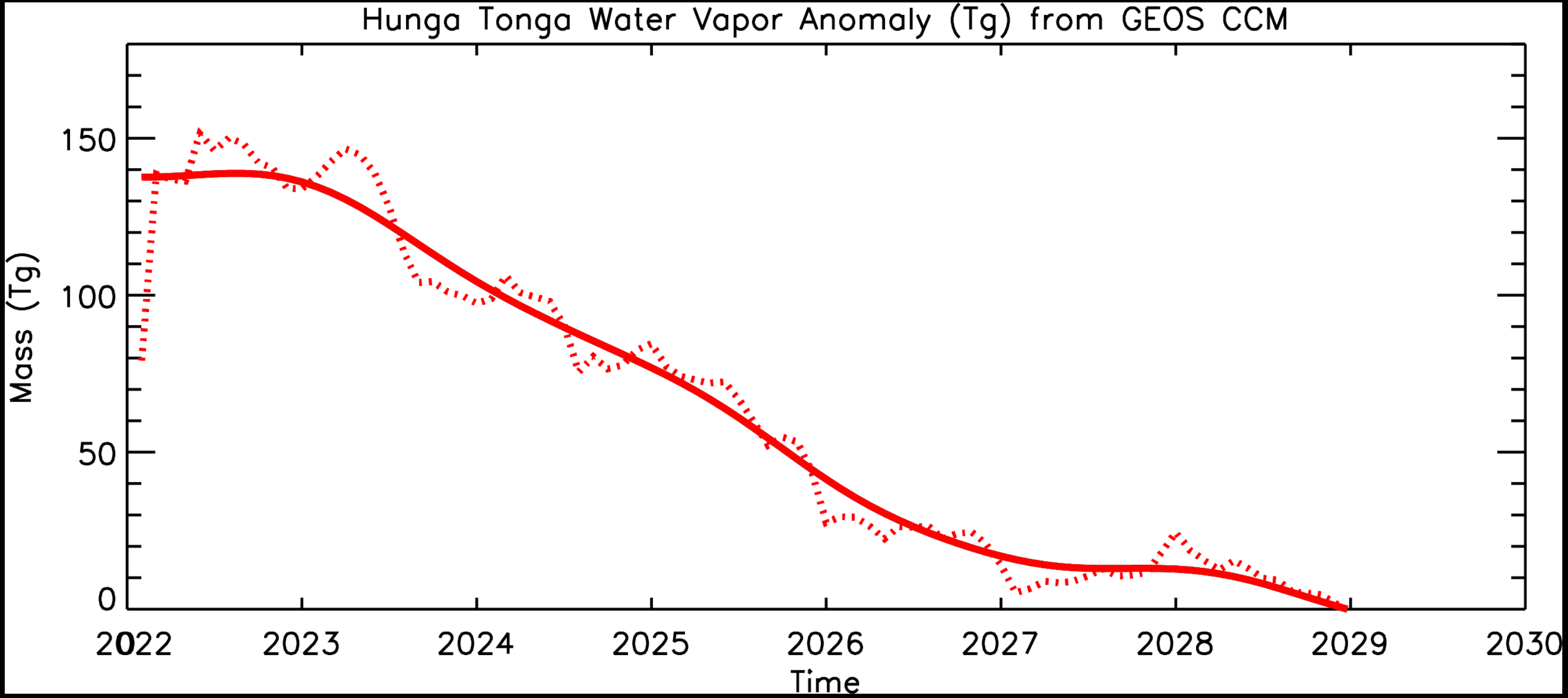
Longer-Term Hunga Tonga Water Vapor Evolution

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 HTE 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 so this is likely a lower end estimate



Southern Hemisphere Change in Water Vapor and OH

GEOS CCM Modeled SH change in Water Vapor (%) for the 4 years following the HTE

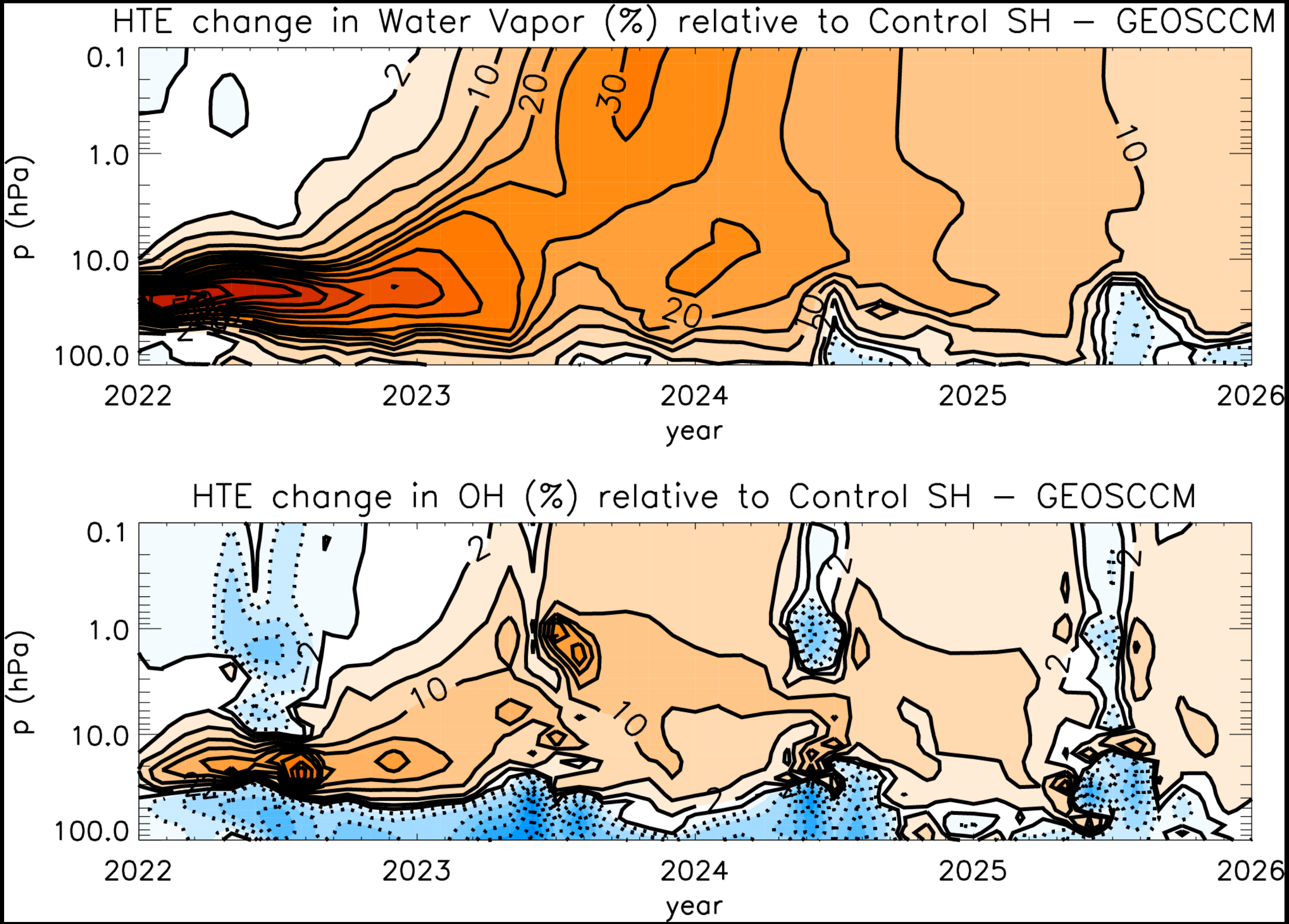
4 ensemble members of each

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



Water Vapor and Impact on SO_2 lifetime

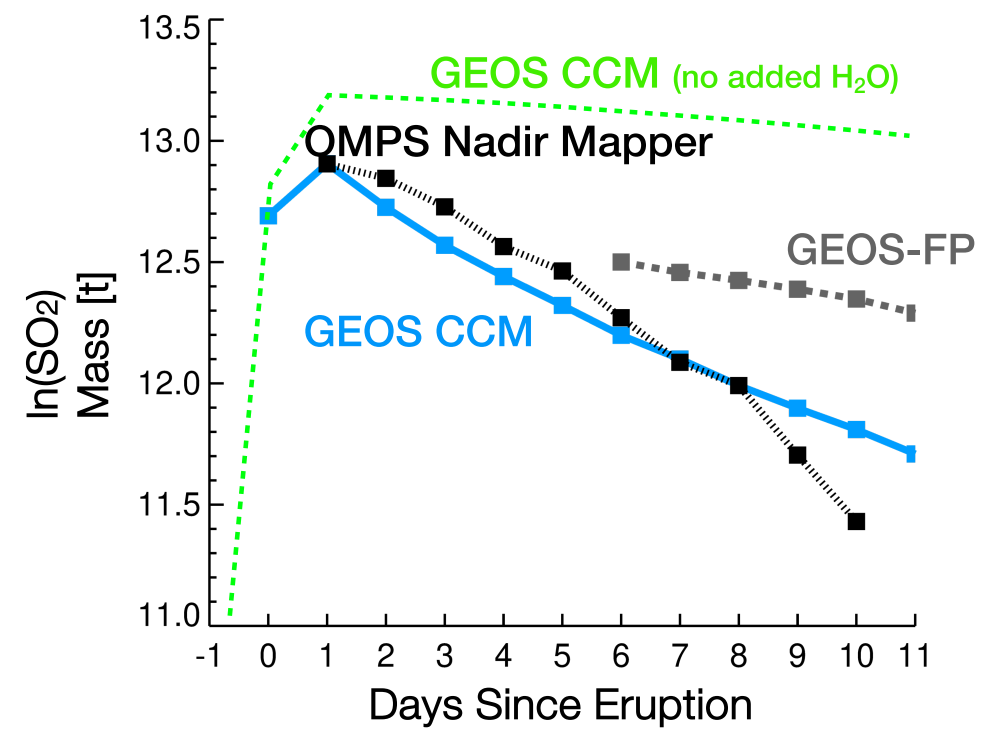
Simulations with GEOS CCM show a significant impact from the water vapor injection on the evolution of the SO_2 injection

The lifetime of Hunga Tonga 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 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



HTHH Sulfate Aerosols – Modeled vs OMPS-LP

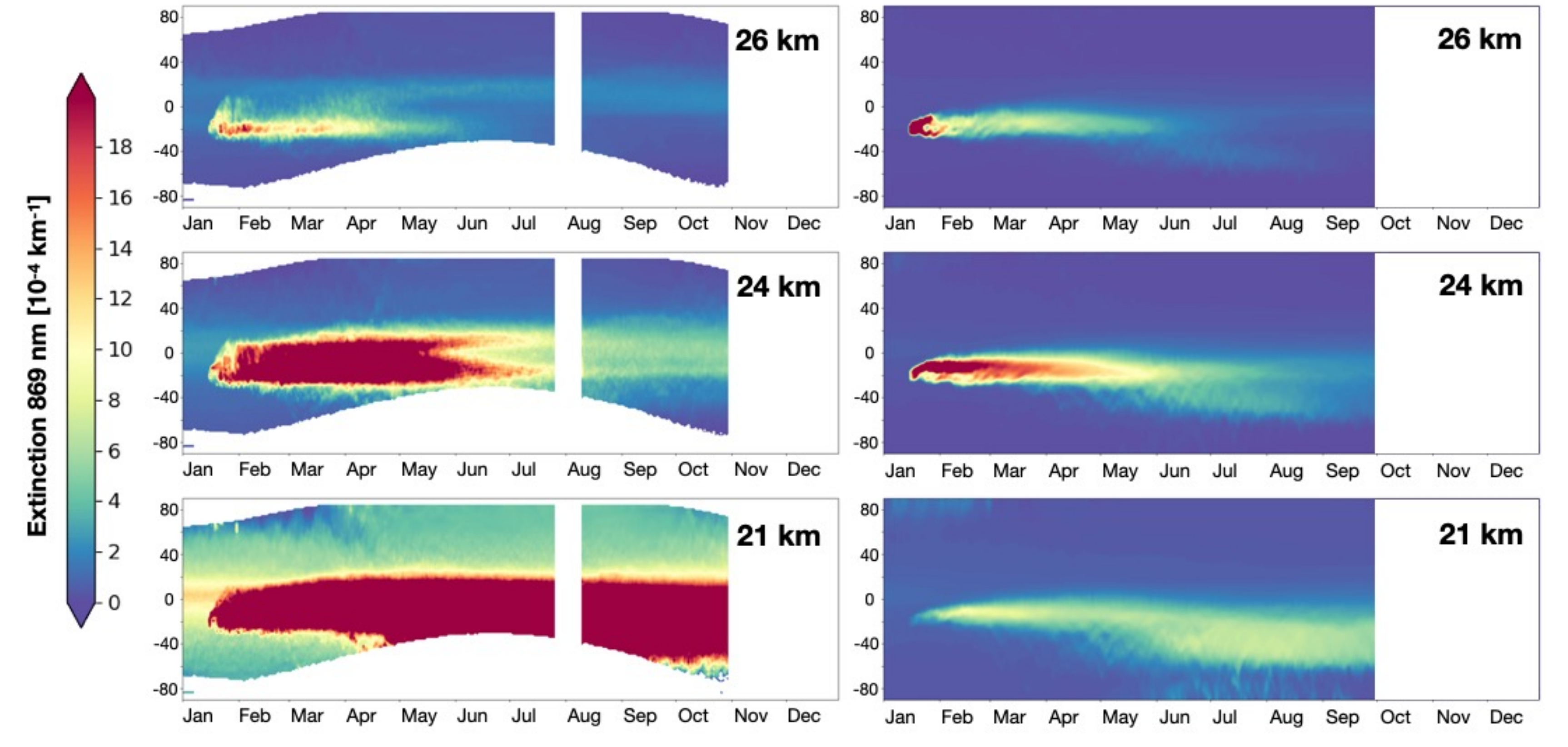
Simulated aerosol profile is similar in spatial extent to OMPS LP observations, but underestimates magnitude of the sulfate extinction especially at lower altitudes

Missing microphysics or direct sulfate injections?

Mass Extinction Efficiency of background stratospheric sulfate-sized particles ~1/2 the Mass Extinction Efficiency (MEE) of larger (Pinatubo-like) sulfate aerosols

Our initial simulation were done with the GOCART bulk aerosol module but present work is looking at a microphysical aerosol model

OMPS LP **GEOS CCM**



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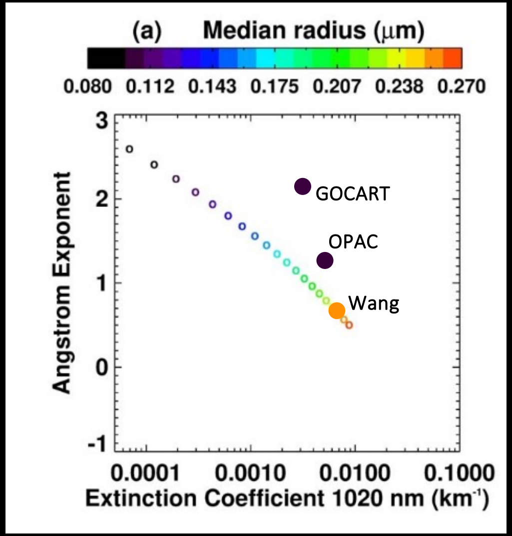
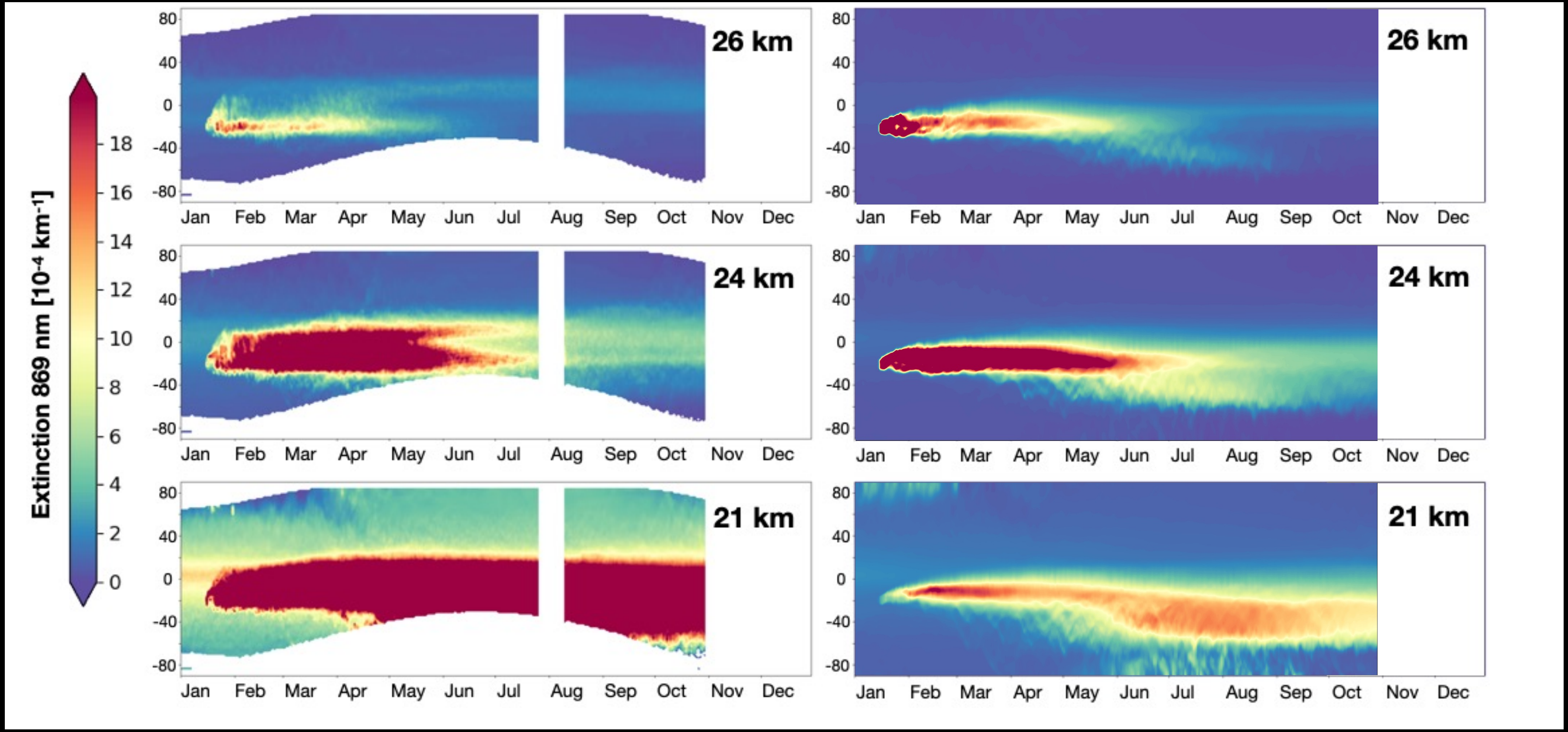


Wang et al., 2023

OMPS LP

GEOS CCM

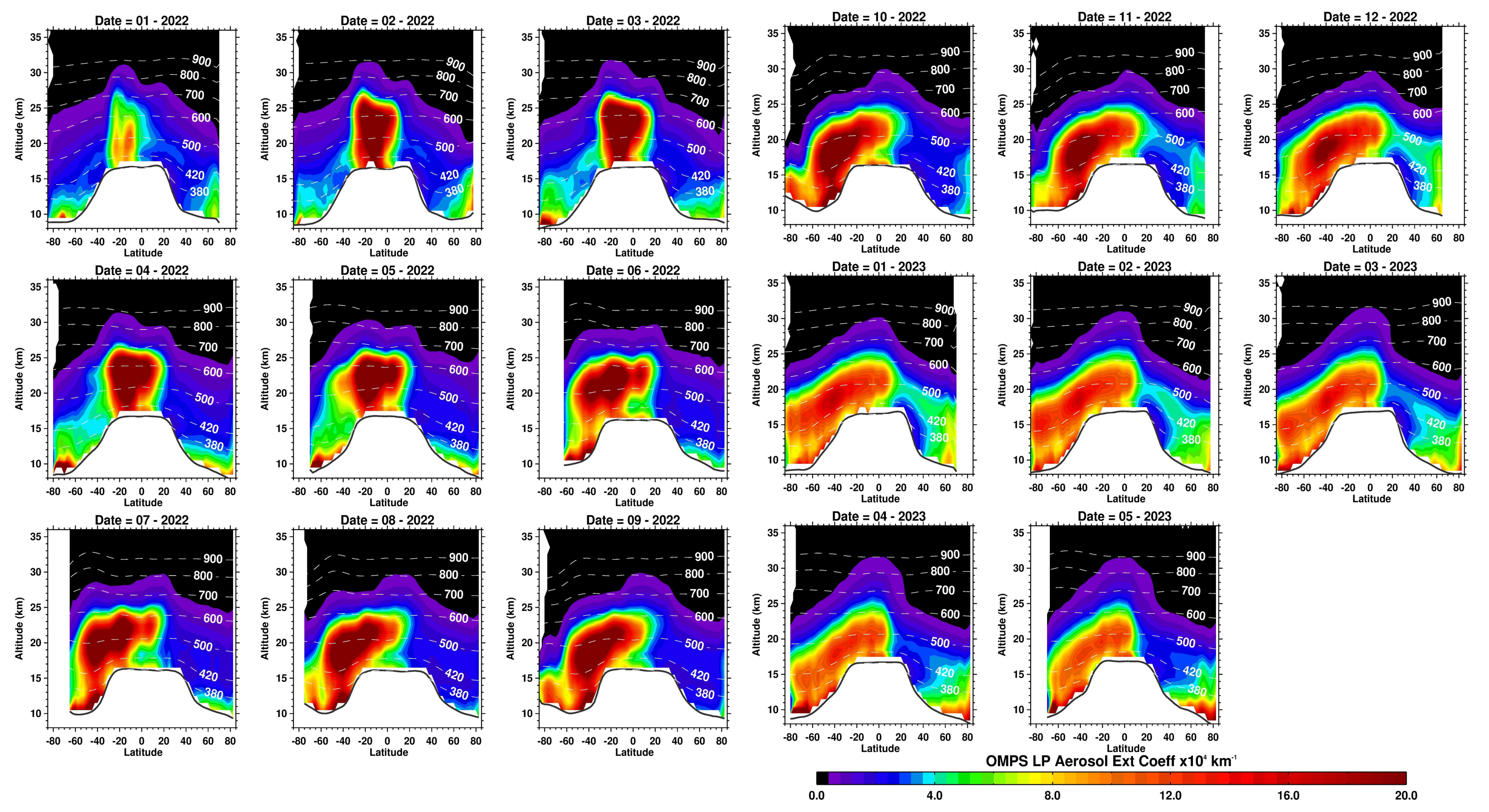


Aerosol Extinction Evolution - Monthly Zonal Mean

Initially largely confined to the tropics with some spread to higher latitudes in the lower stratosphere

Some aerosols made it into the polar vortex in the first winter in the lower most stratosphere

By the end of fall 2023 the SH polar vortex has aerosols well mixed in



Diurnal Cycle Scaling Factors from GEOS GMI

We developed diurnal scaling factors using output from the GEOS GMI model

Applying scaling factors allows us to account for differences between instruments due to different sampling times

The 3D model accounts for seasonal, latitudinal, and altitude differences in the diurnal cycle

We have created profile scaling factors for O_3, NO_2, and NO_3 (recent addition)

If you would like to use them, please contact me Luke Oman (luke.d.oman@nasa.gov) or Sarah Strode (sarah.a.strode@nasa.gov)

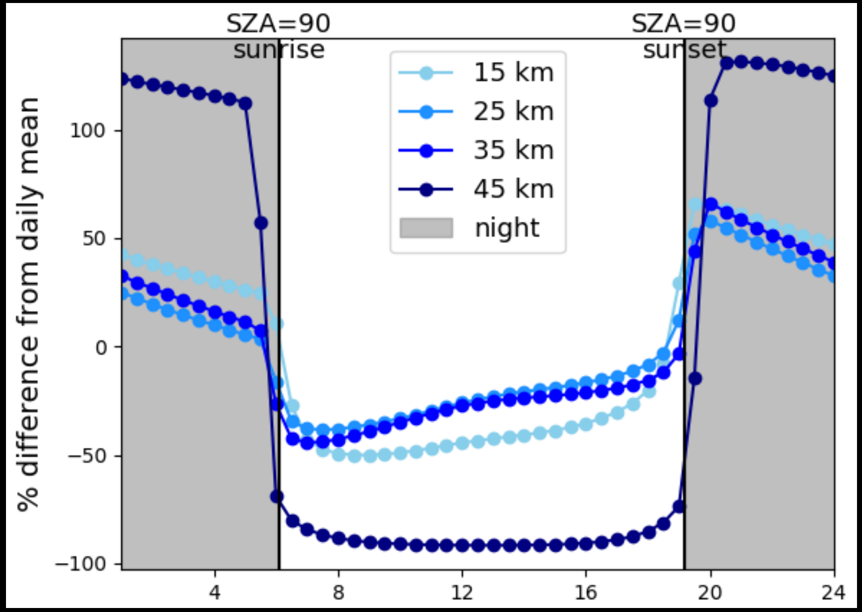
Diurnal Cycle Factors

- Photochemistry drives large diurnal variability in NO_2
- Diurnal variability matters for O_3 at some altitudes
- Accounting for diurnal variability improves the comparability of SAGE III/ISS observations with observations from other times of day, such as MLS
- Previous studies have used box modeling to account for diurnal variability in NO_2

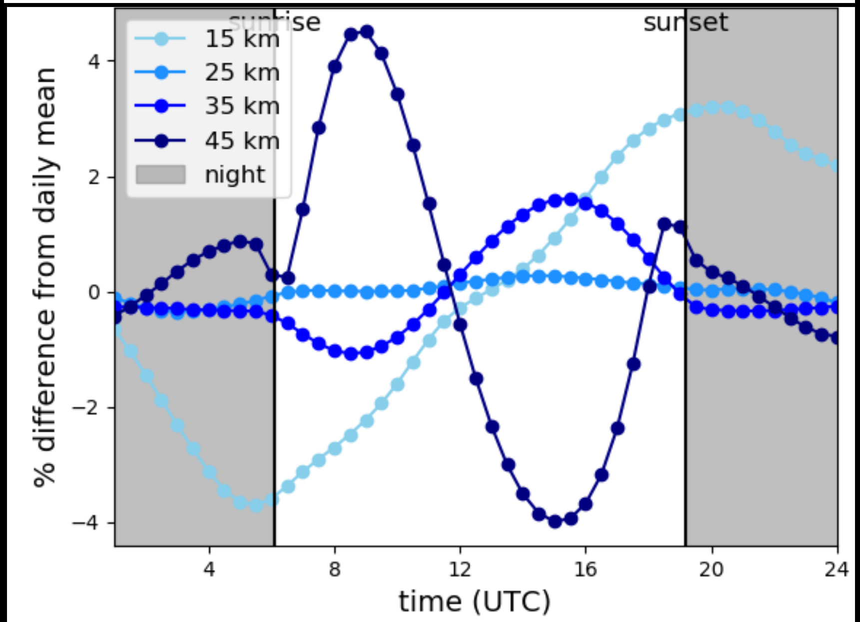
Strode, S. A., G. Taha, L.D. Oman, R. Damadeo, D. Flittner, M. Schoeberl, C.E. Sioris, and R. Stauffer, 2022: SAGE III/ISS ozone and NO_2 validation using diurnal scaling factors, *Atmos. Meas. Tech.*, 15, 6145–6161, https://doi.org/10.5194/amt-15-6145-2022.

Diurnal cycles at 0E, 40N for April 2018

NO_2



O_3



Summary and Future Work

- Hunga Tonga increased the background stratospheric water vapor by ~11-12% in several hours time
- This water vapor has a 3-4 year e-folding time scale for removal, mainly by polar dehydration and removal by transport back into the troposphere
- Having a collocated water vapor injection is critical to get the very short lifetime of SO_2 that was observed due to enhanced OH concentrations
- An ensemble of simulations is necessary to distinguish some of the impacts and minimize natural variations
- Still work to be done to understand the optical properties of sulfate aerosol in the case of Hunga Tonga and how to best represent with bulk aerosol modules

Current and Future Work

- Revisiting the optical properties of sulfate aerosol in our model is helpful to comparisons with OMPS-LP but differences remain

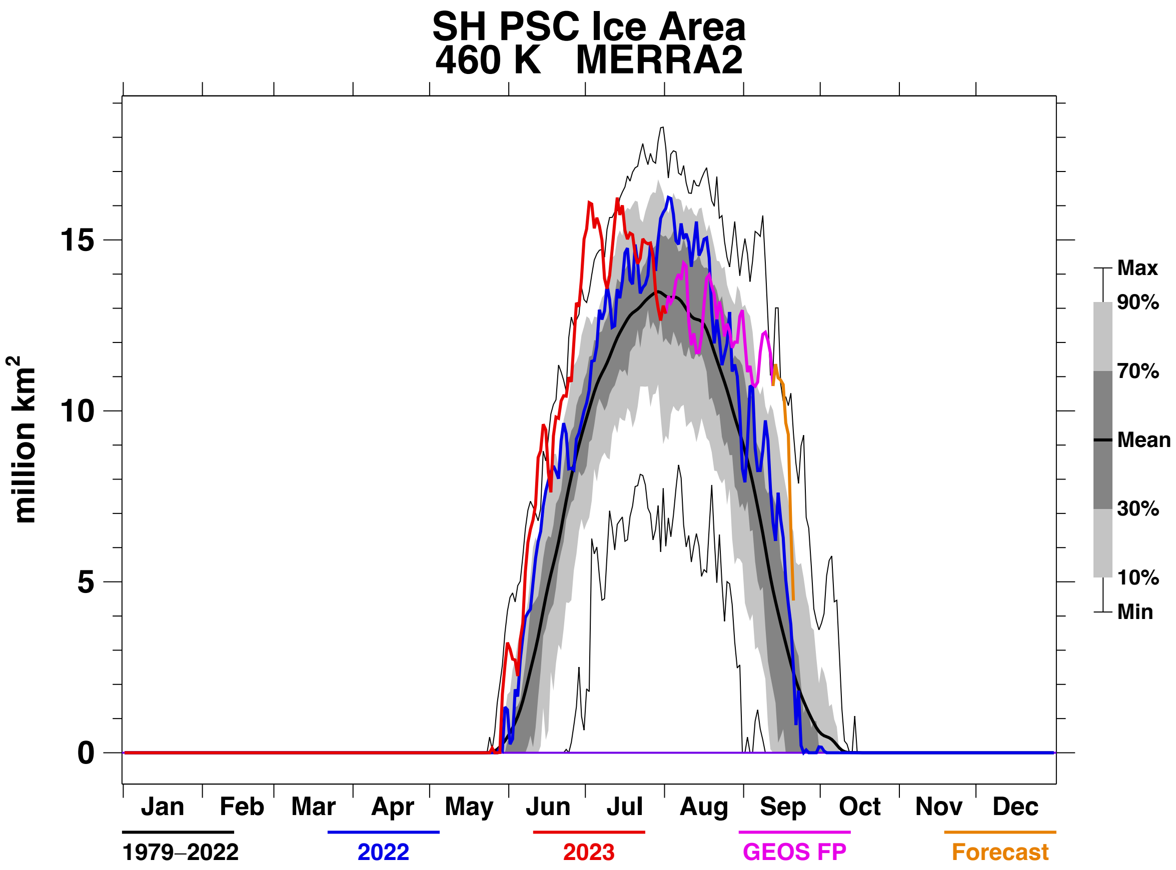
- Current work is adding microphysical aerosol model simulations to better understand the aerosol growth and evolution and those results could feedback to high fidelity bulk aerosol model simulation

- Higher vertical resolution simulations to improve the transport and circulation strength

- Are there other injections that should be also considered, some preliminary work with TROPOMI suggests some direct sulfate aerosol injection, also record lightning production ~192,000 lightning strikes in 11 hours many at altitudes (20-30 km) which don’t typically experience lighting strikes creating NOx

Extra Slides

Southern Hemisphere – Polar Stratospheric Clouds and Ozone


SH PSC Ice Area
460 K MERRA2

P. Newman (NASA), L. Lait (SSAI), S. Pawson (NASA)

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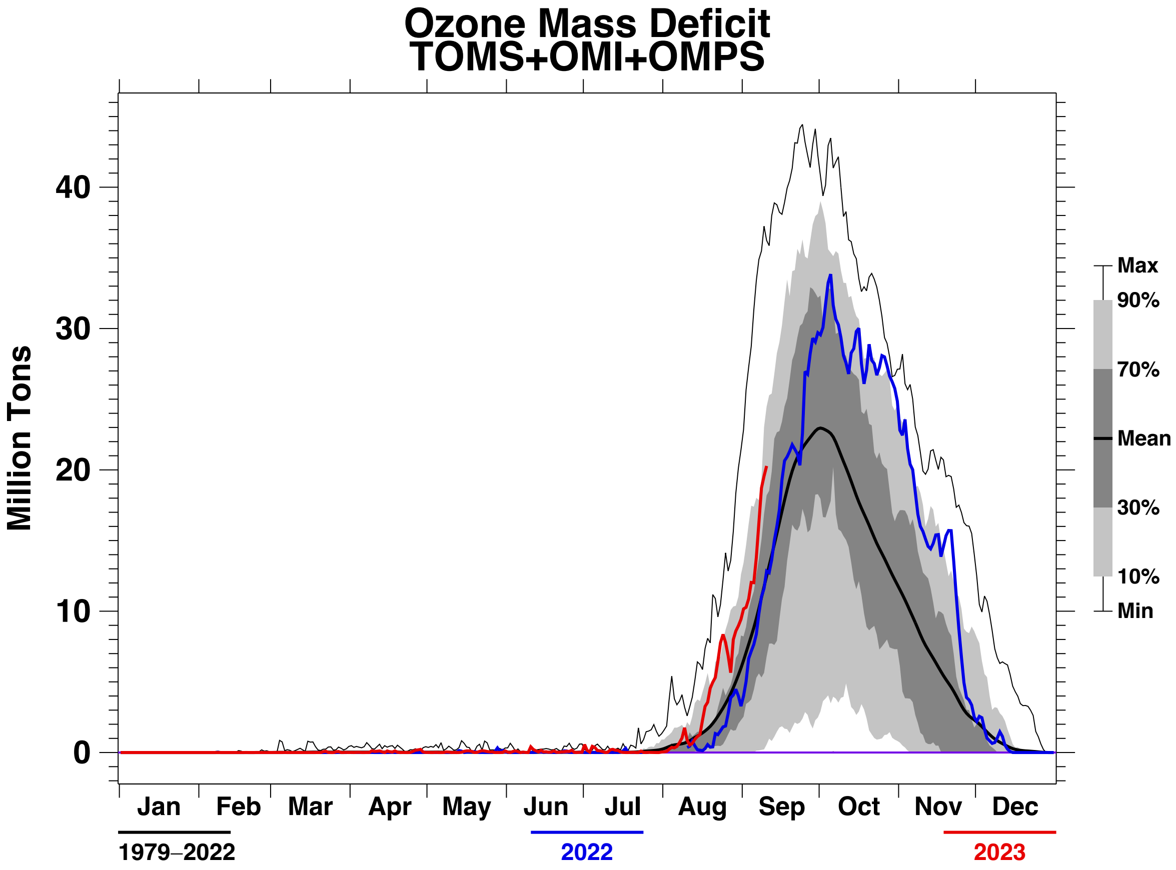
Ozone Mass Deficit
TOMS+OMI+OMPS

P. Newman (NASA), L. Lait (SSAI), R. McPeters (NASA), S. Pawson (NASA)

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* PSC Ice Area based on climatological water vapor of 5 ppm