ISSRDC

# Earth's upper atmosphere after the Hunga Tonga – Hunga Ha'apai eruption as seen by the Stratospheric Aerosol and Gas Experiment III on the International Space Station (SAGE III/ISS)

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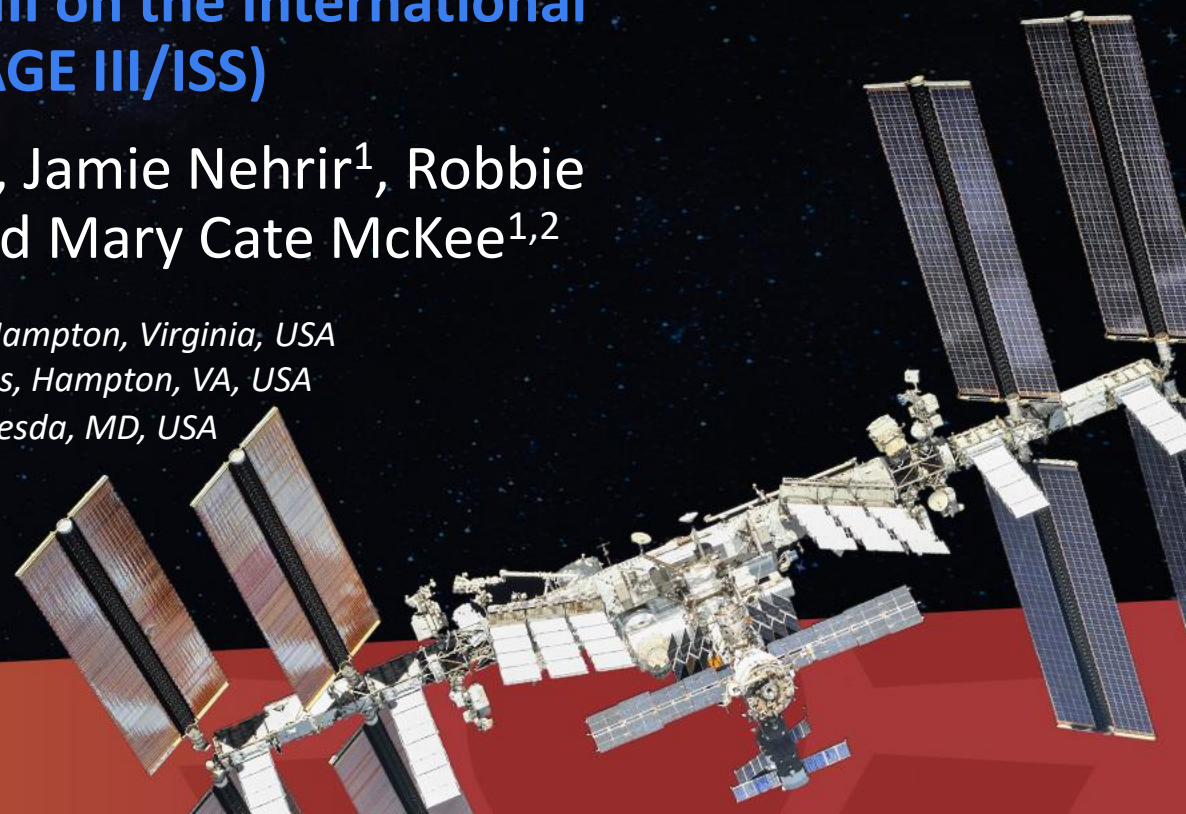

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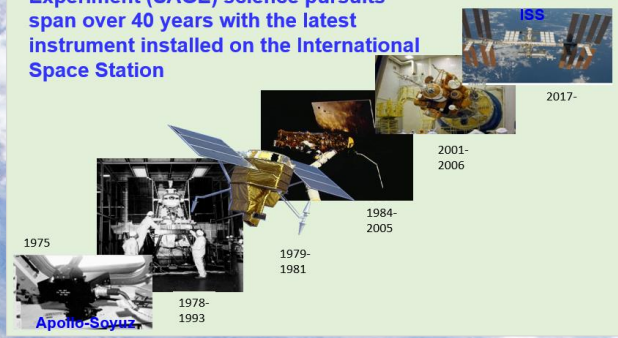
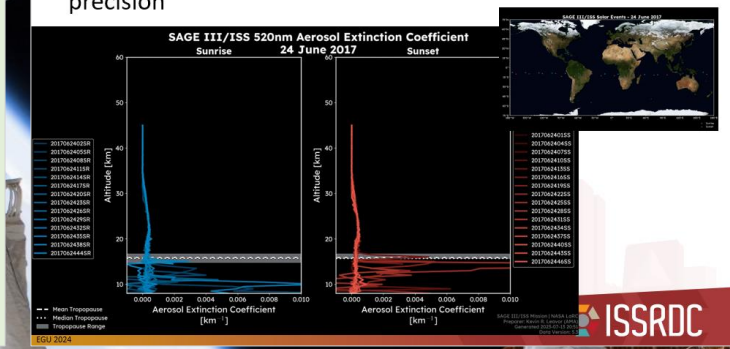
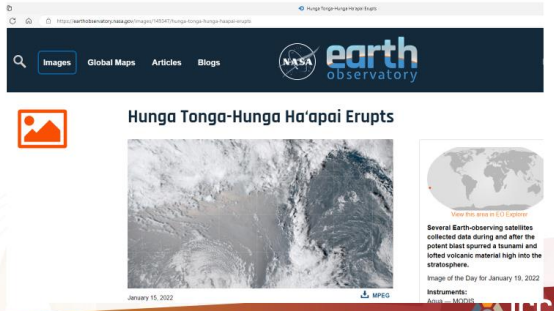
## Stratospheric Aerosol and Gas Experiment (SAGE) science pursuits span over 40 years with the latest instrument installed on the International Space Station

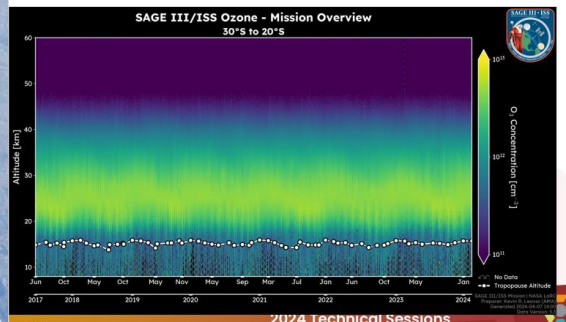



## Validation: Daily data in tropics measures internal precision

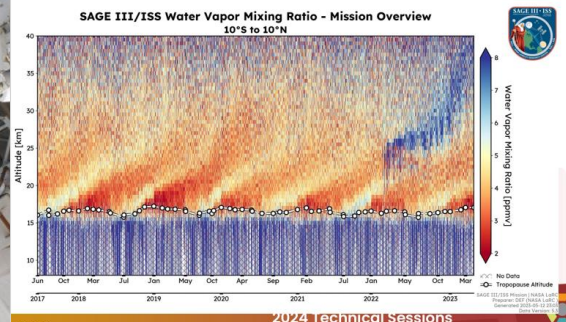


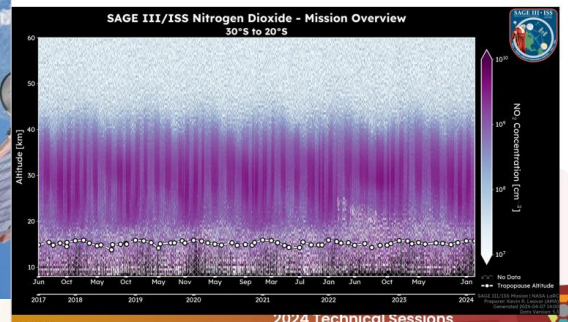

## Ozone ($O_3$)



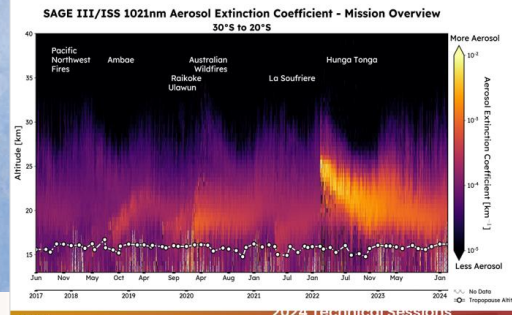

## Water Vapor ($H_2O$)




## Nitrogen Dioxide ($NO_2$)




## Stratospheric Aerosol




## Summary

- **SAGE III/ISS is a collaborative Earth science mission – key element in climate observing system - to study the recovery of the global ozone layer and the evolving climate.**
- **Since June 2017, SAGE III/ISS has documented many natural variations of stratospheric constituents and the historical perturbation by the Hunga volcanic eruption.**
  - **Largest perturbation of $H_2O$ in SAGE II & III records**
  - **Largest $NO_2$ perturbation in SAGE III record**
  - **Aerosol increase from Pinatubo still largest in SAGE record**
- Mission approved through 2026, manifested on ISS through 2030, bridging to future missions observing the stratosphere

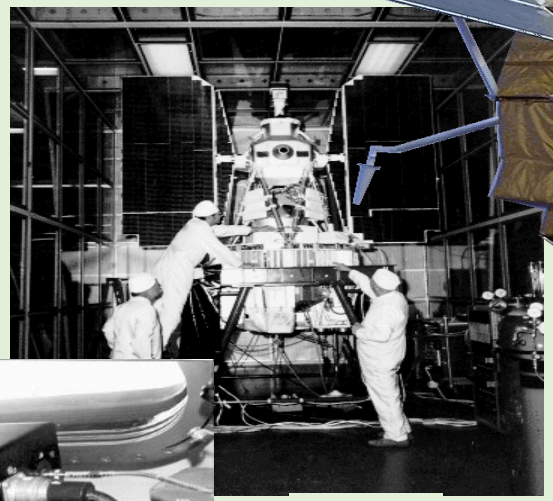


Image Credit: NASA Astronaut Ricky Arnold

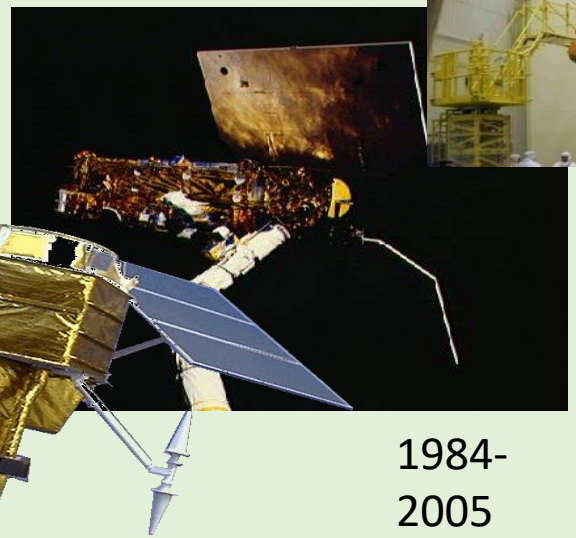
# Stratospheric Aerosol and Gas Experiment (SAGE) science pursuits span over 40 years with the latest instrument installed on the International Space Station

Apollo-Soyuz

1975



1978-
1993



1979-
1981

1984-
2005

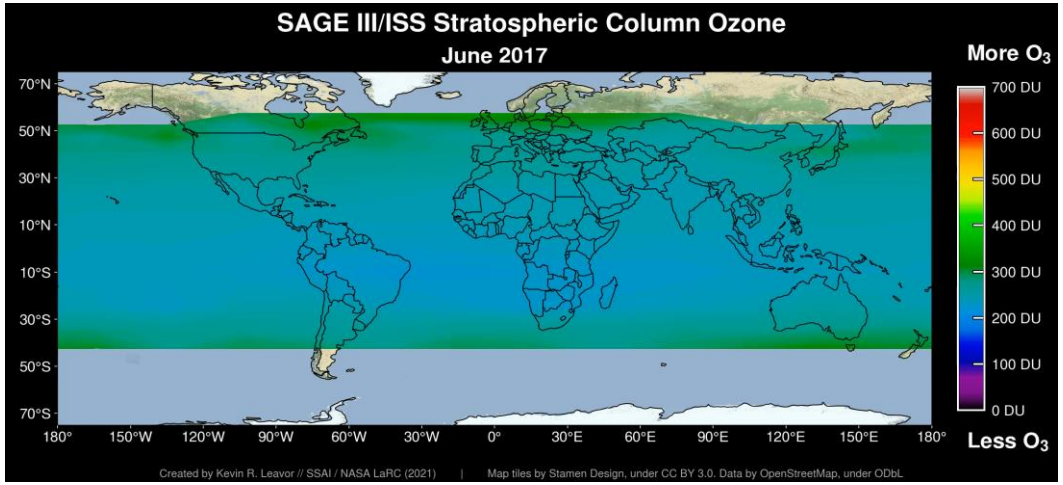
2001-
2006


2017-

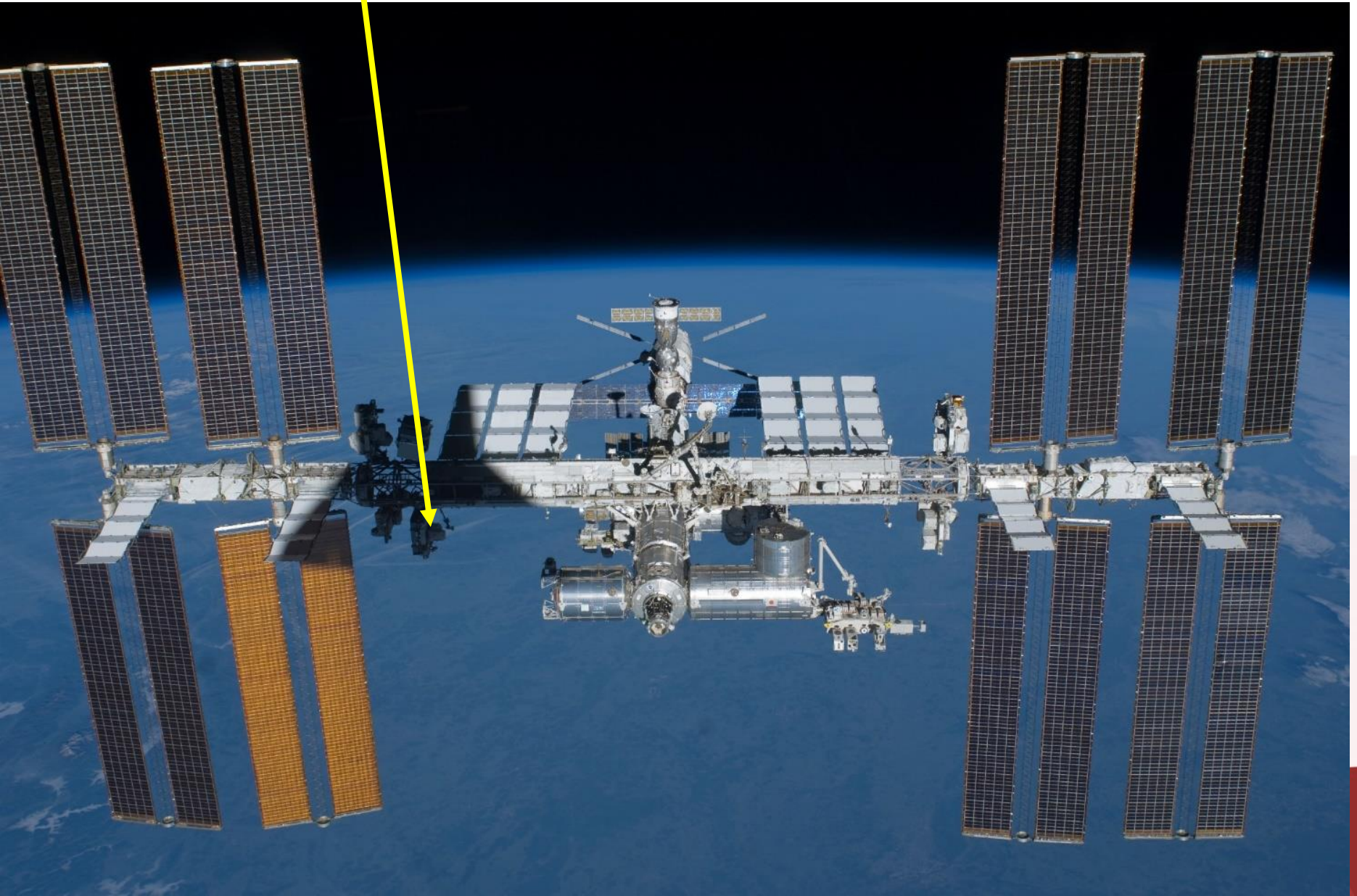
# SAGE III/ISS Overview

- SAGE produces high vertical resolution profiles of aerosols, ozone, water vapor, and other trace gases in the stratosphere and upper troposphere using the very stable occultation technique
- Core element of WMO International Ozone Assessment and WCRP SPARC
- Acquired >60k occultation events Jun 2017-Apr 2023
- ~7 years science mission; approved extended mission 2024-2026, 2027-30 to be reviewed
- Current data products v5.3 (released March 2023)
- ROSES Science Team, 3rd cohort just selected
- 60 peer-reviewed papers using SAGE III/ISS data products, with others in review
- Vibrant internship program with ~5 NIFS students/yr

**STRATOSPHERIC OZONE**

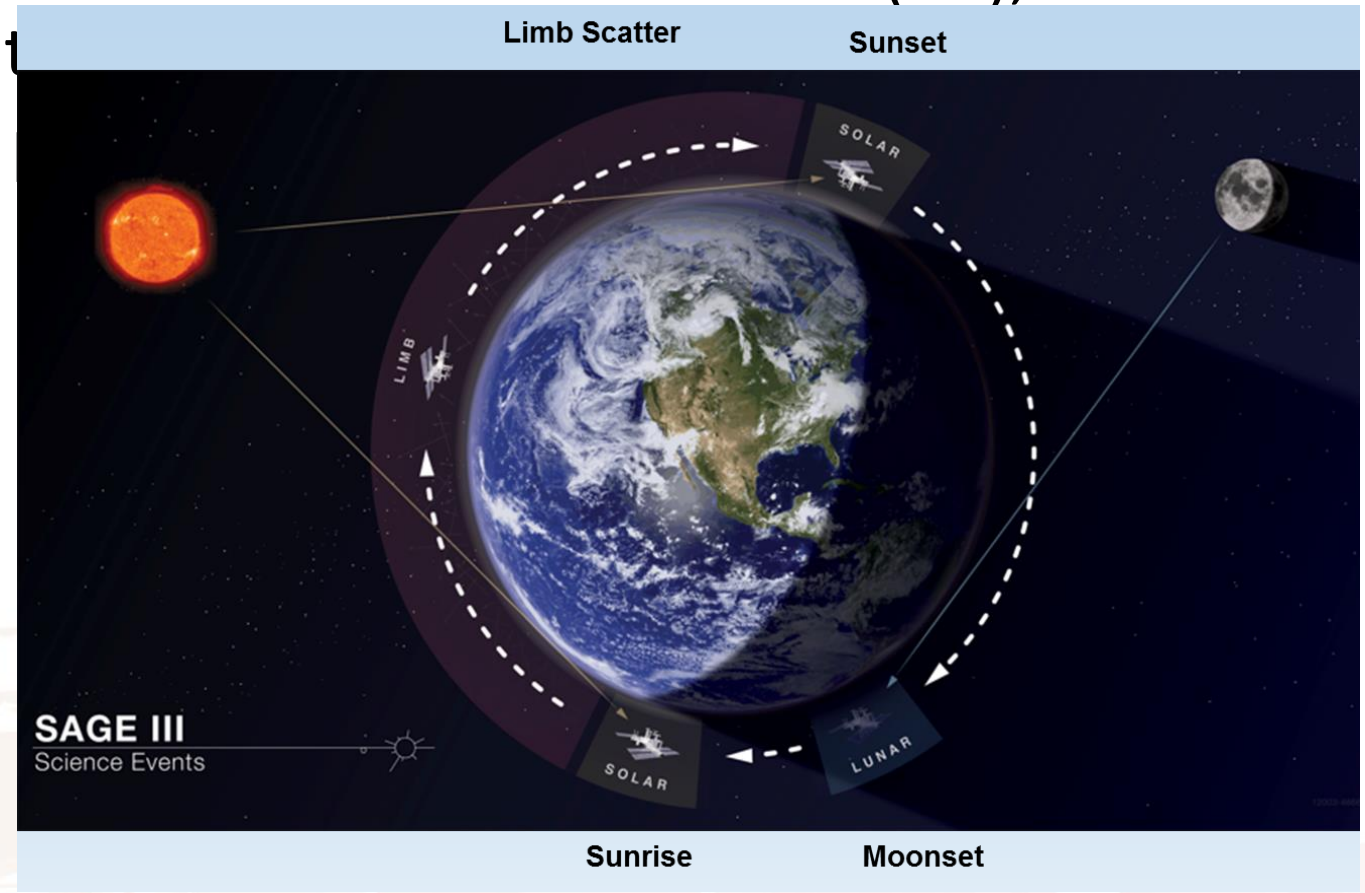



# Location of SAGE III



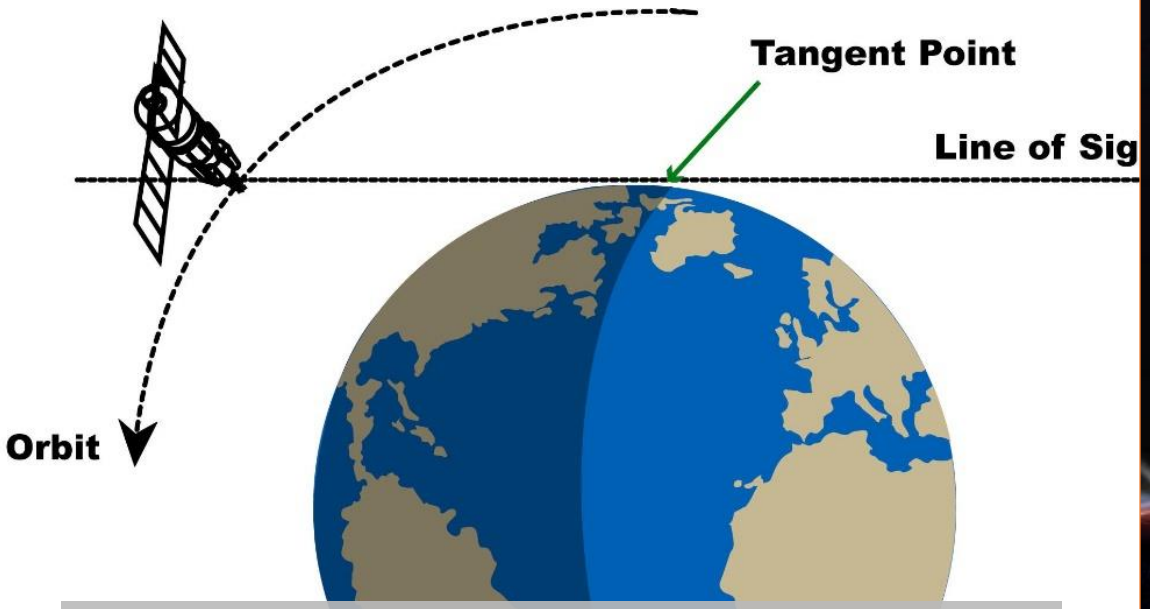
# Science Collection Modes

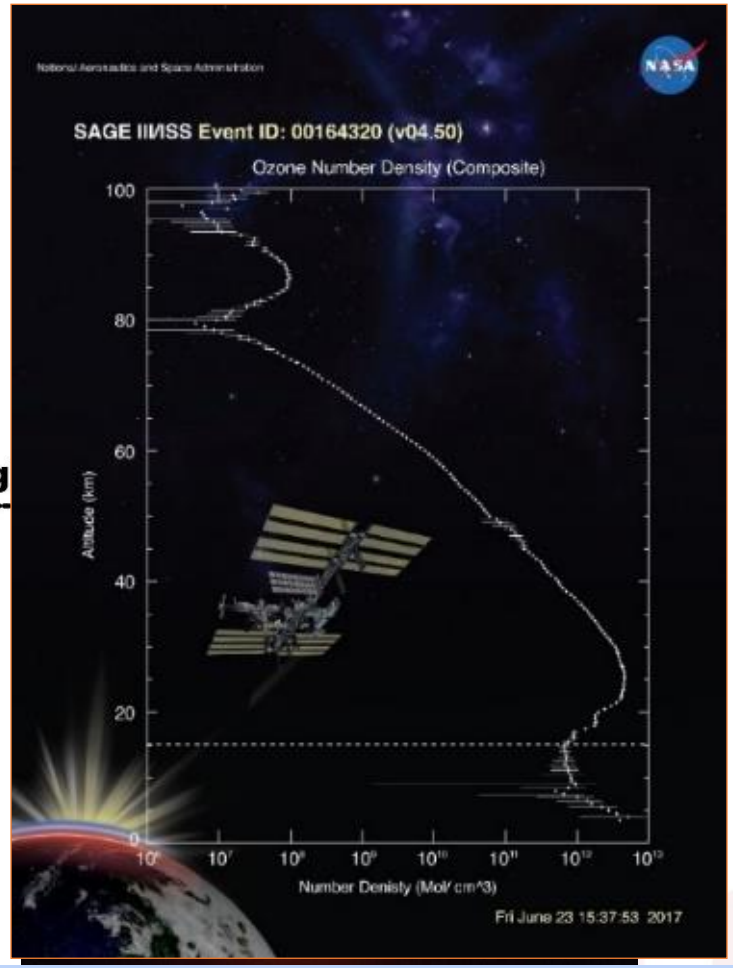
- Operational Modes include: Solar Occultation (SO), Lunar Occultation (LO) & Limb Scat
- Occultation events dictated



# SAGE Technique

**Measurement of Sun while looking above the atmosphere to calibrate the instrument**



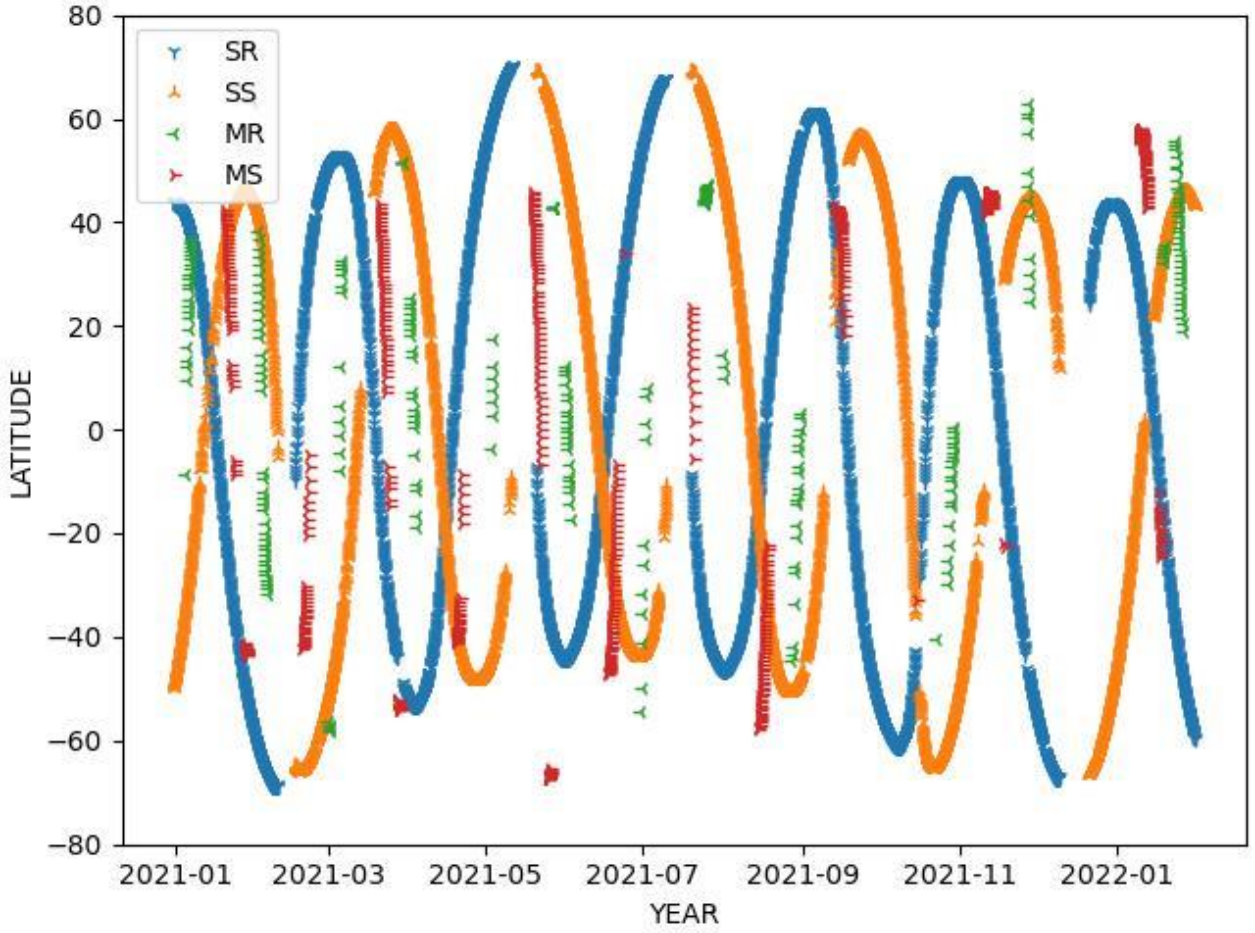




Stable and precise occultation method is ideally suited for long-term measurements.

**Measurement of Sun while looking through the atmosphere to determine altitude and amount of the aerosol or gas**

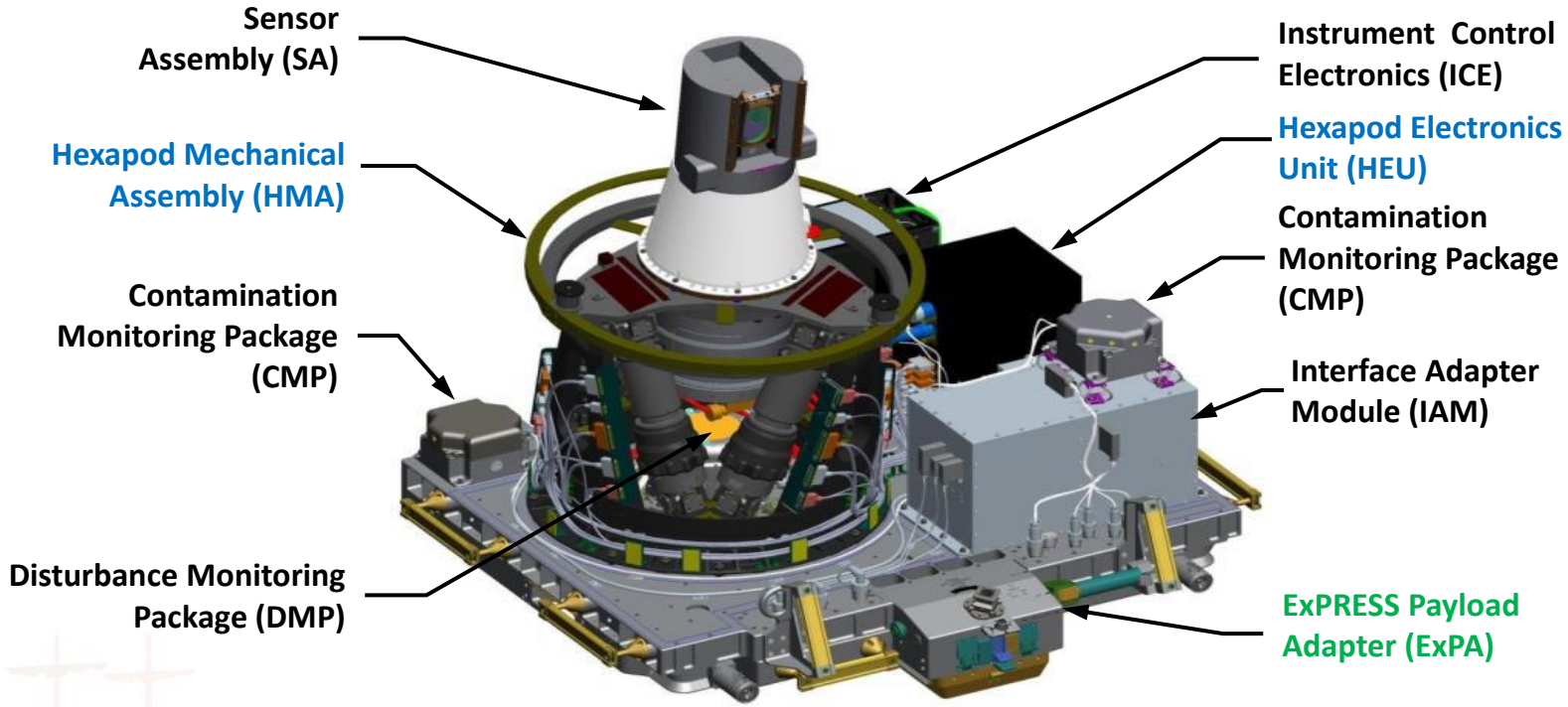
# Spatial-Temporal Sampling

- The 51.6°inclined orbit of the ISS is well-suited for SO
- Provides near-global observations on a monthly cycle with coverage of low and mid-latitudes
- Similar to SAGE II



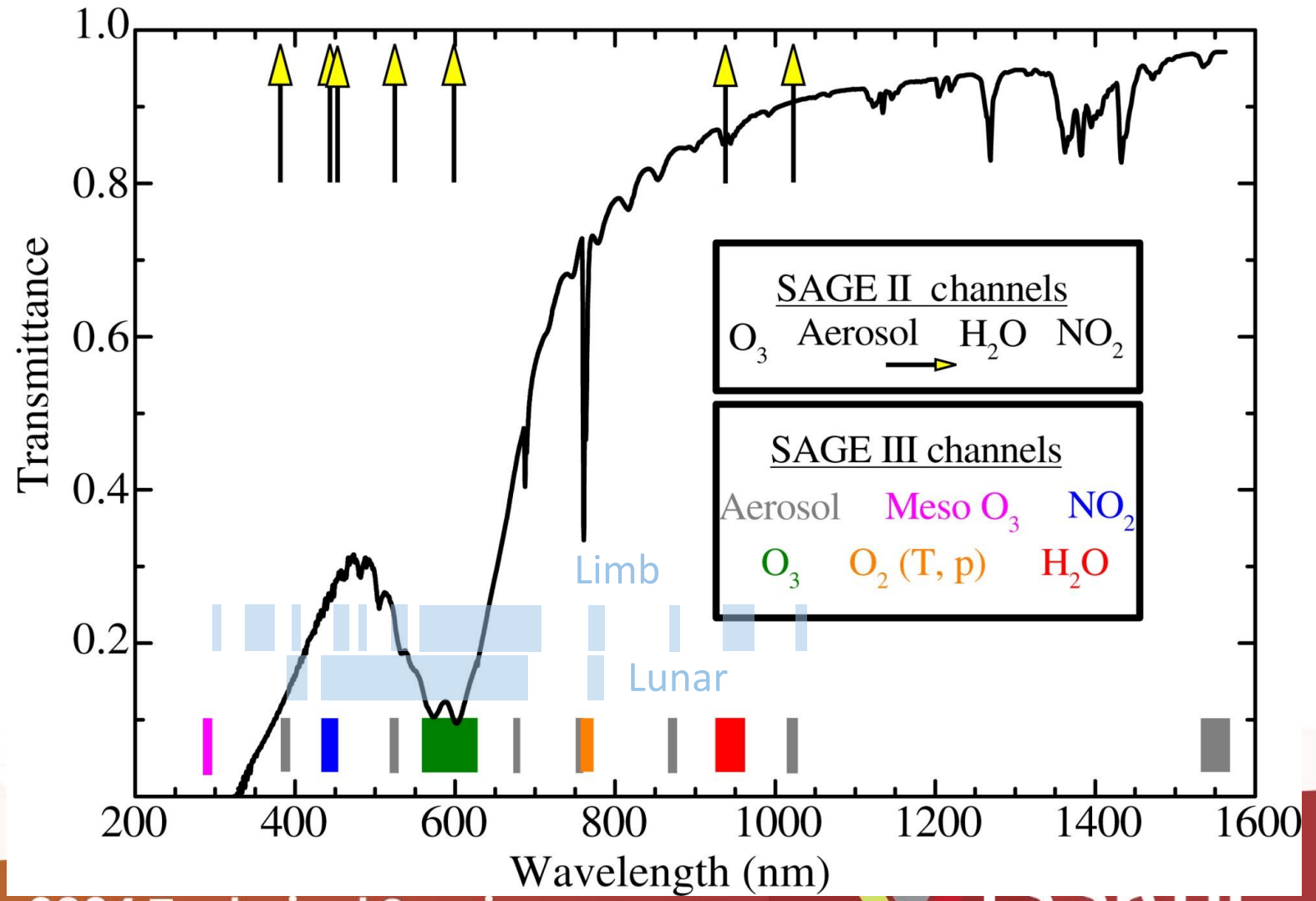
# Payload Key Features:

- Spectrometer covering 290-1030 nm
- Quartz contamination door over telescope aperture
- Scan head azimuth rotation range > 360°
- Hexapod accounts for ISS attitude variation prior to data collection
- DMP records platform attitude variations during data collection
- CMP to guide Operations for limiting contamination to optics

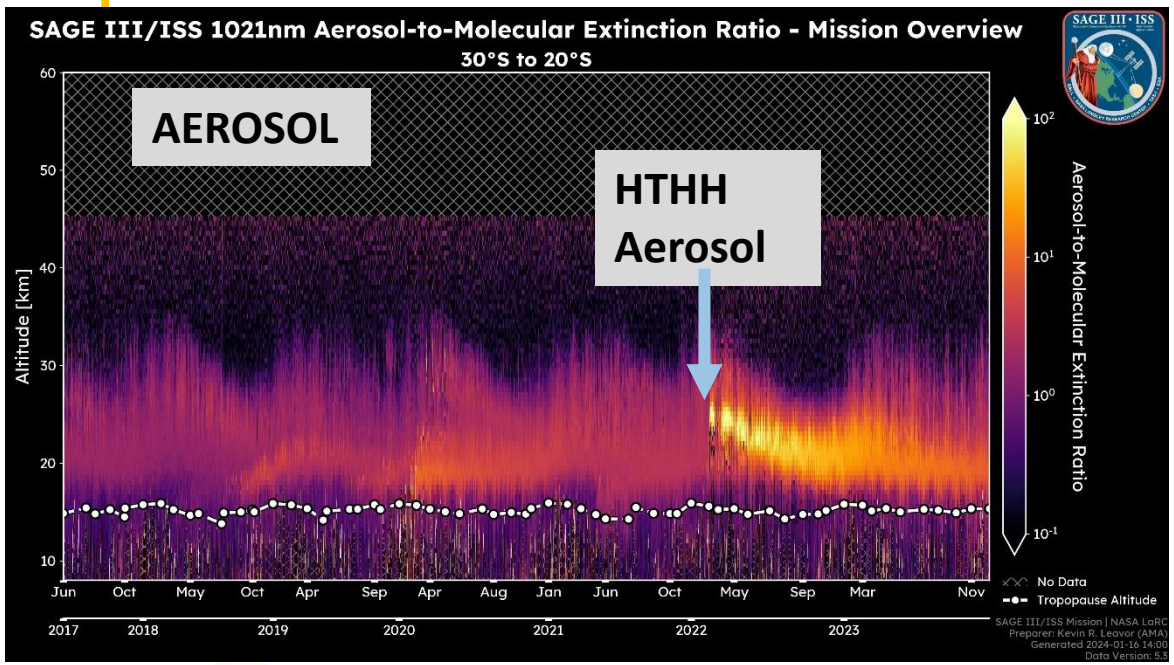


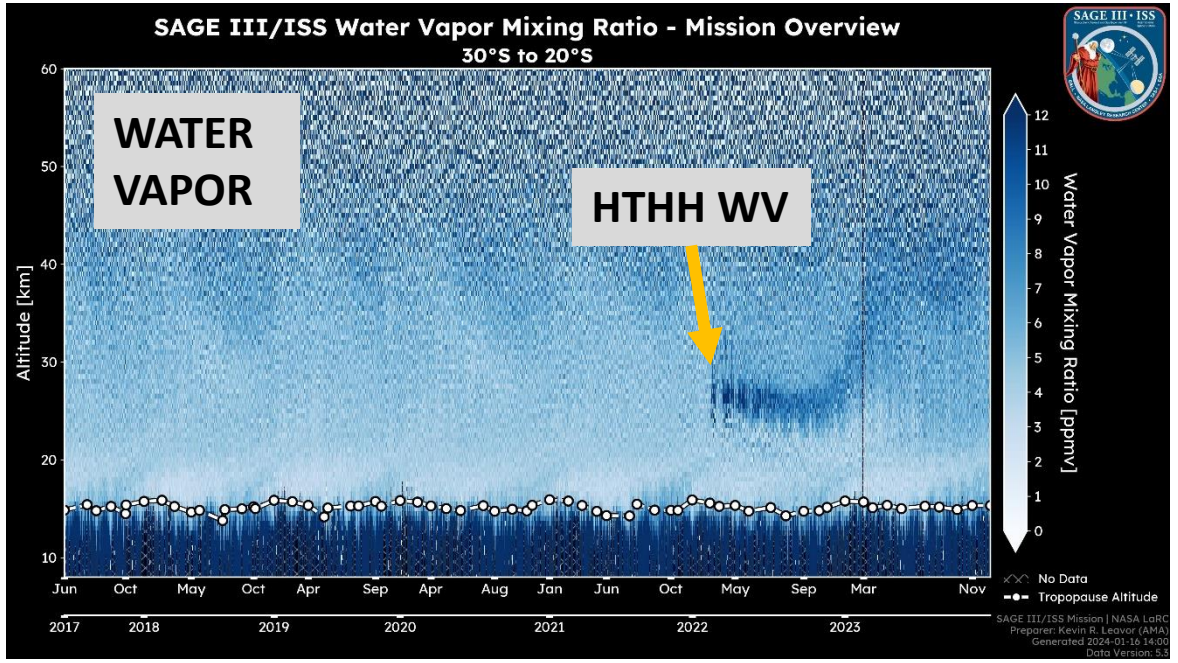
# SAGE Spectral Sampling

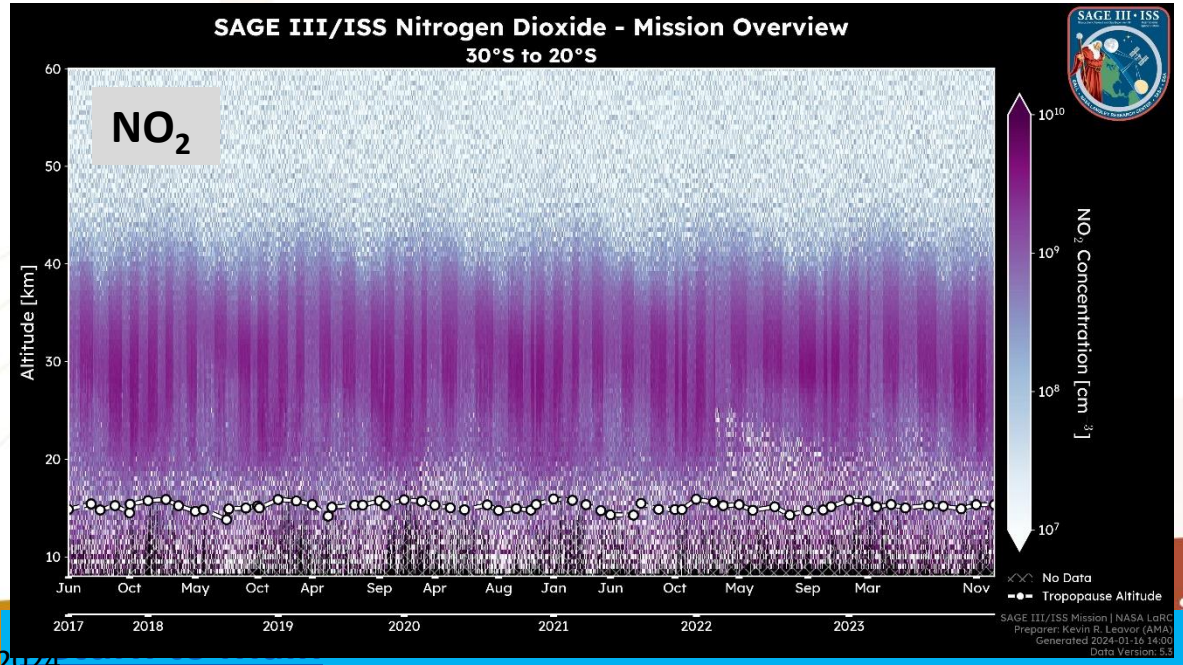
- Spectrometer covering 290-1030 nm, with 2-3nm bandpass
- Diode at ~1550 nm
- **The SAGE III sampling can replicate that of SAGE II, but with improved spectral resolution and an updated algorithm**

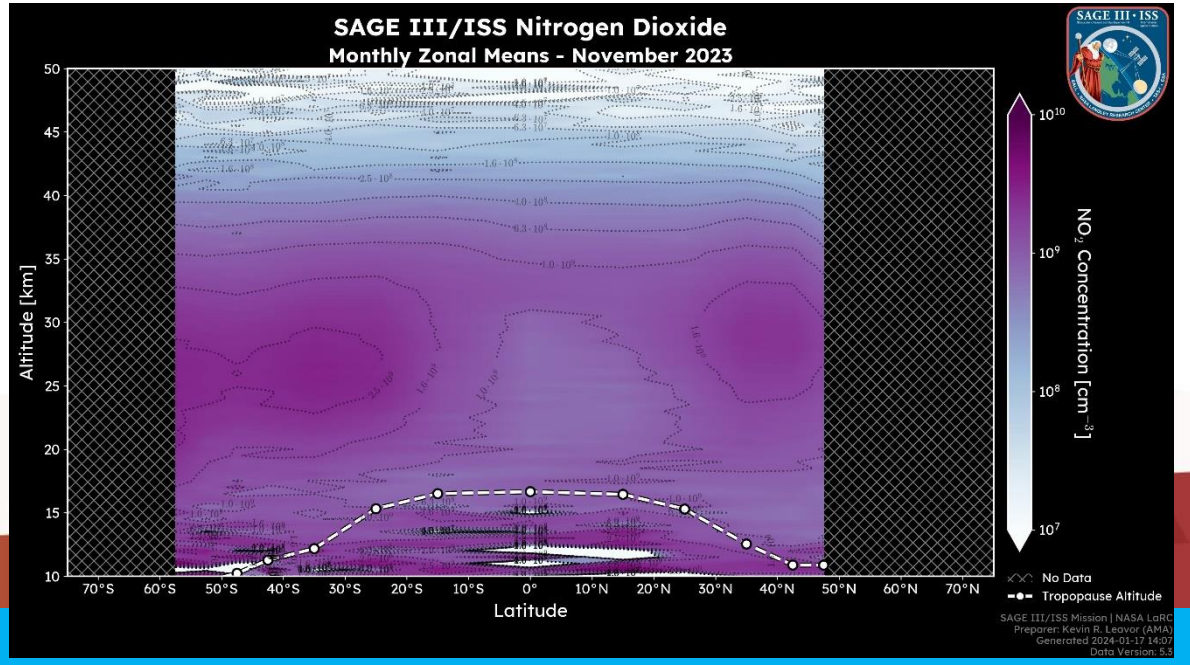


# Sample of Data Products



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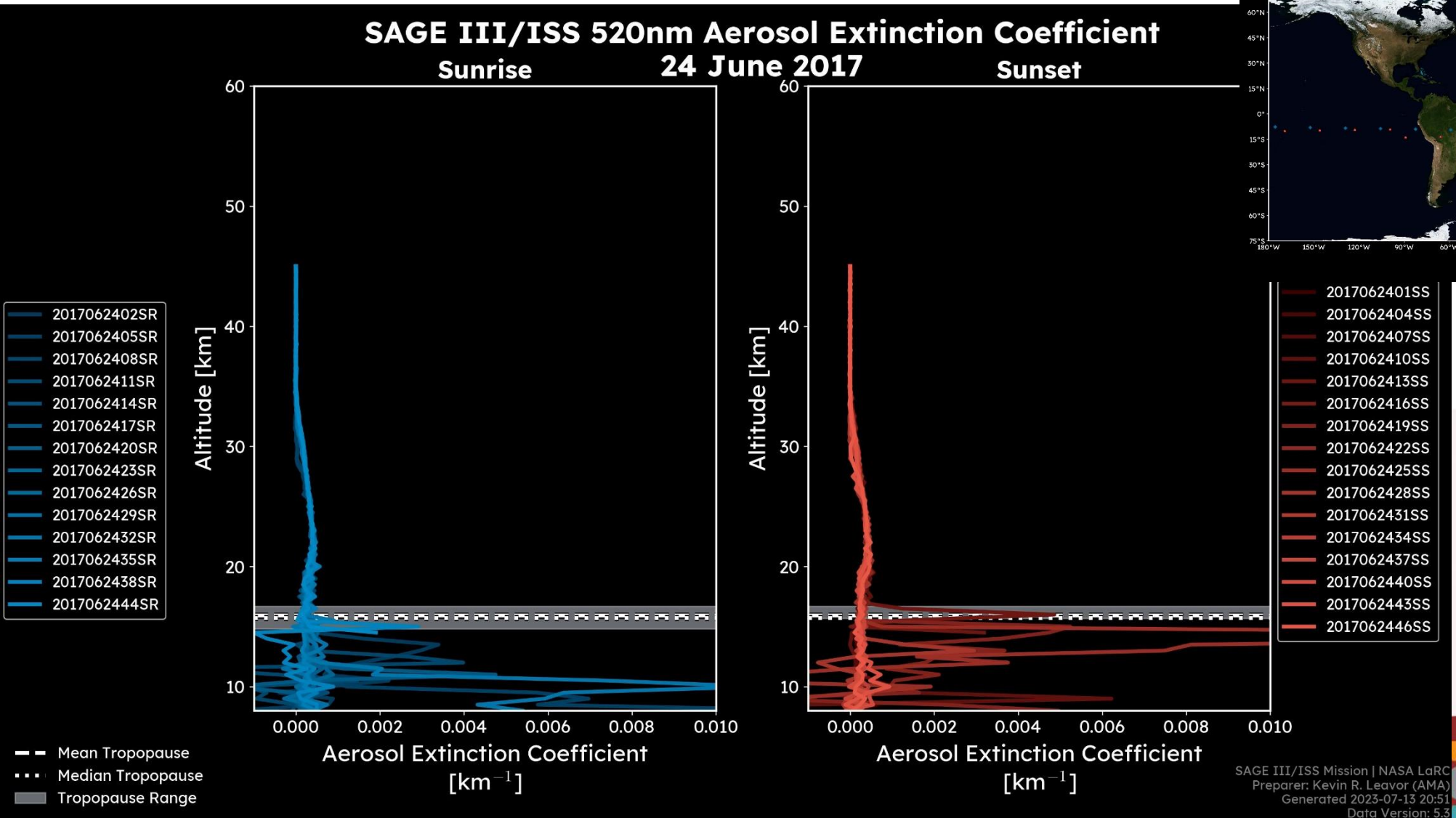
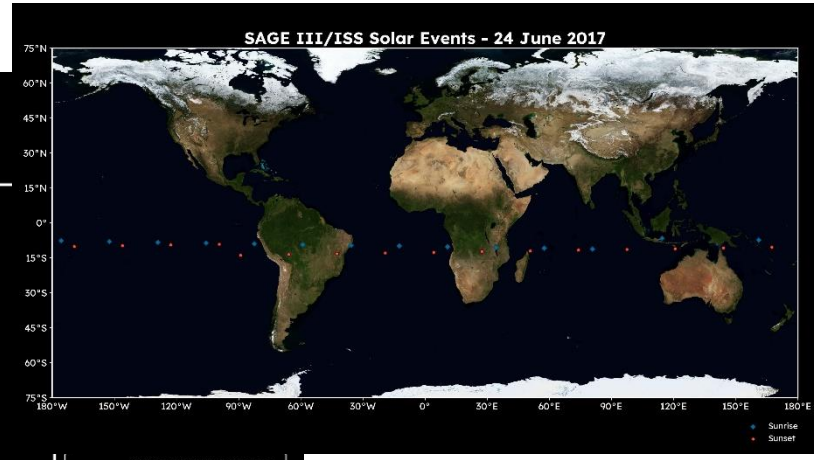
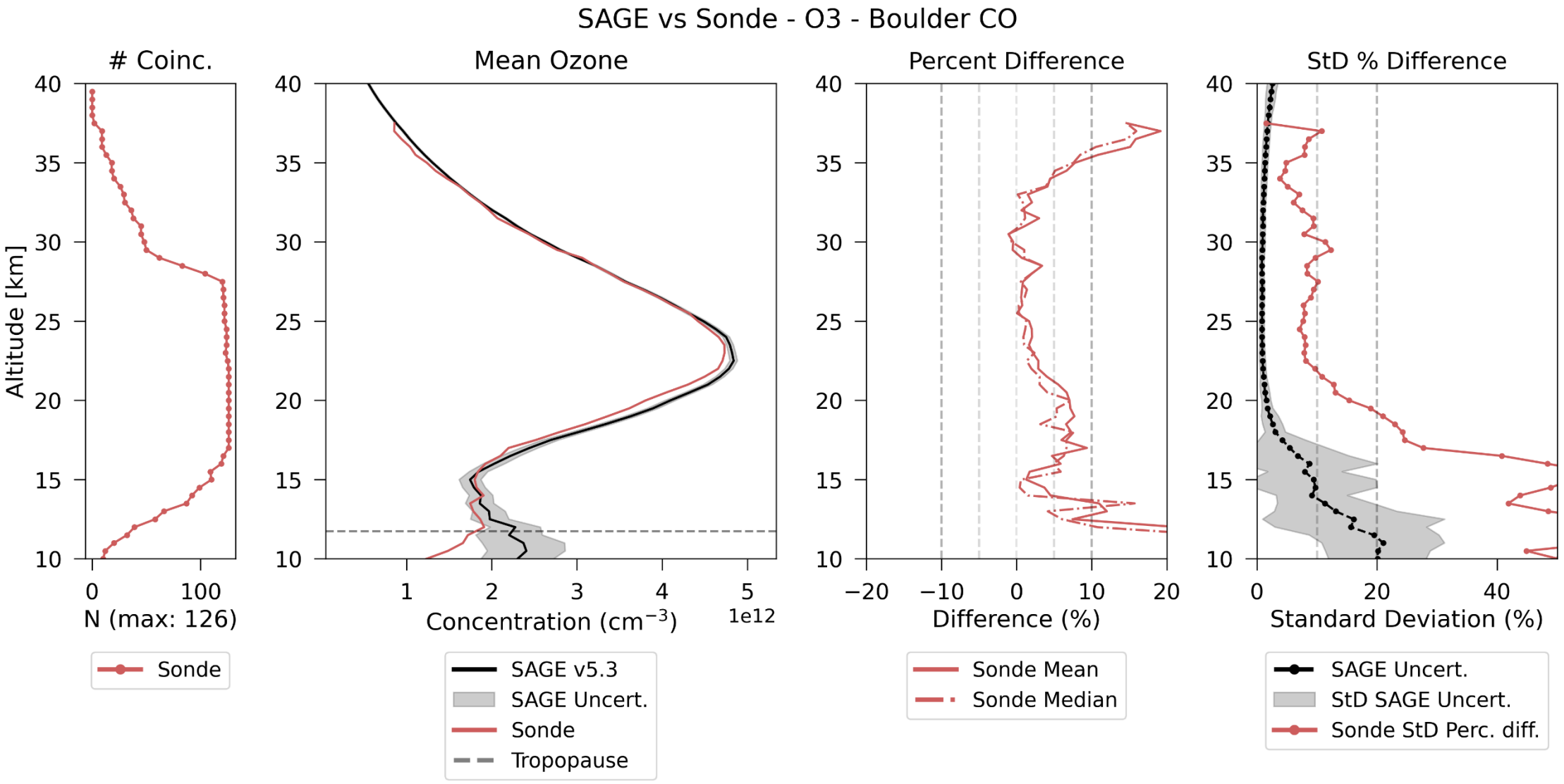


# SAGE comparison vs. in-situ: $O_3$



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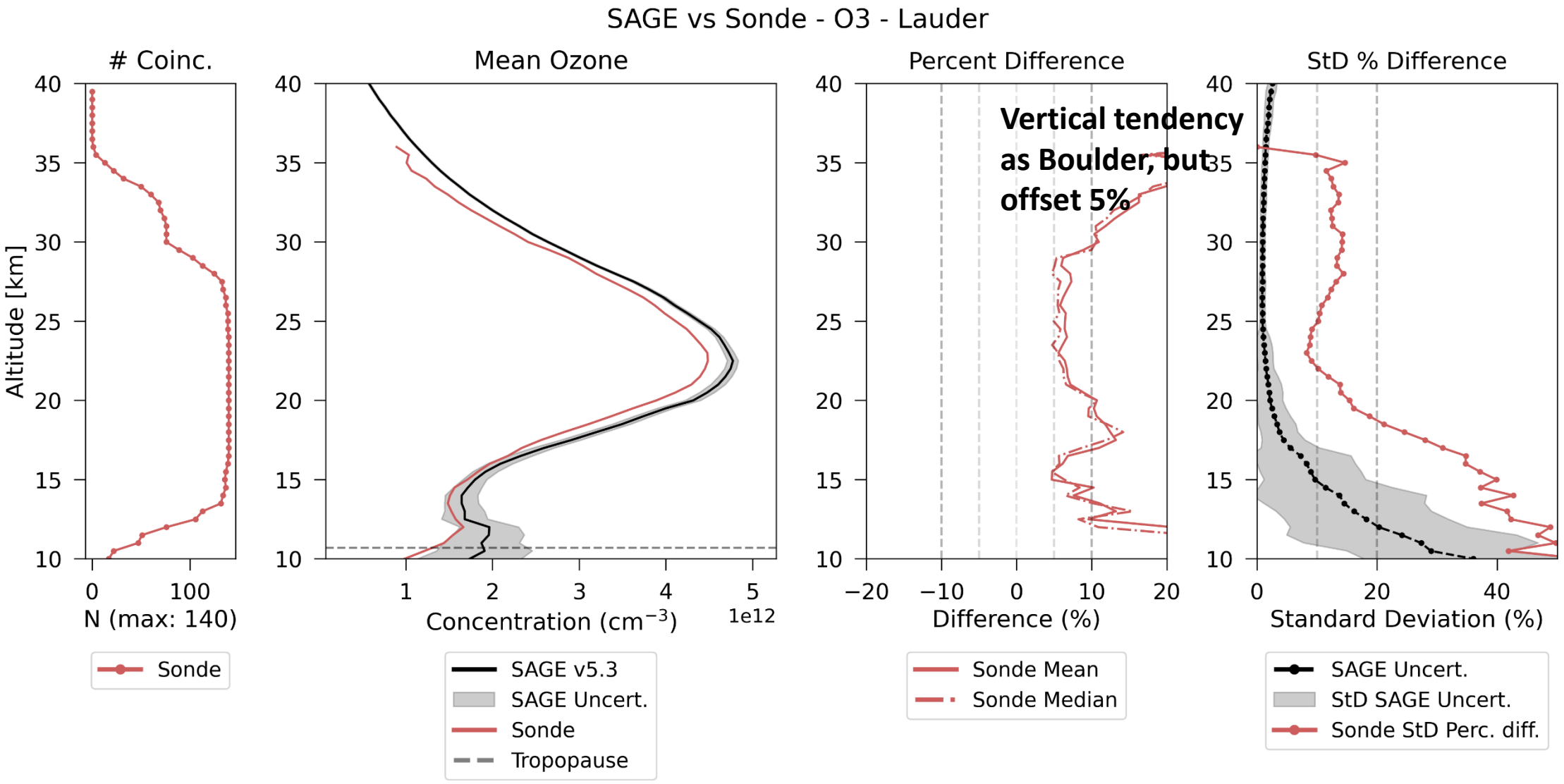
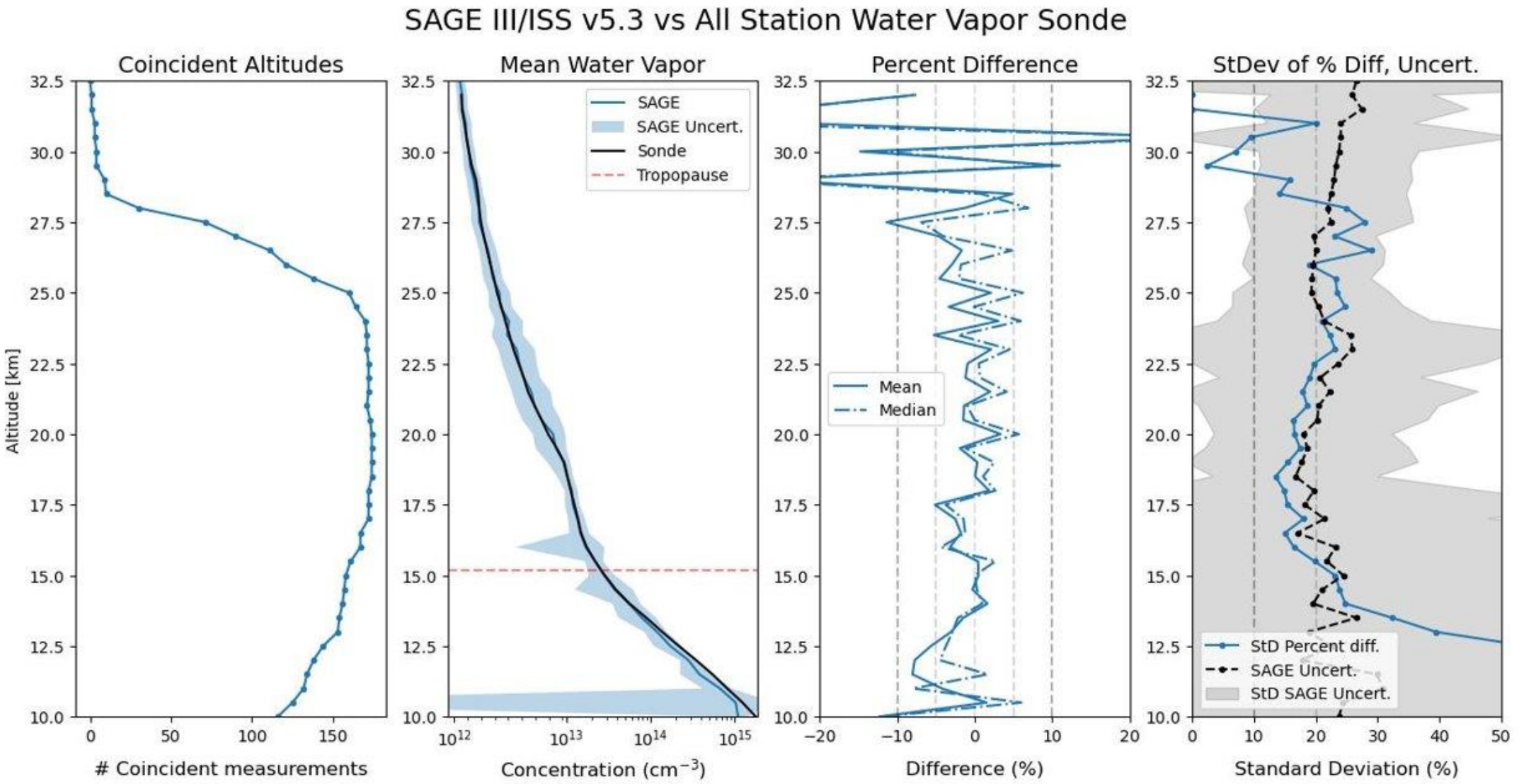
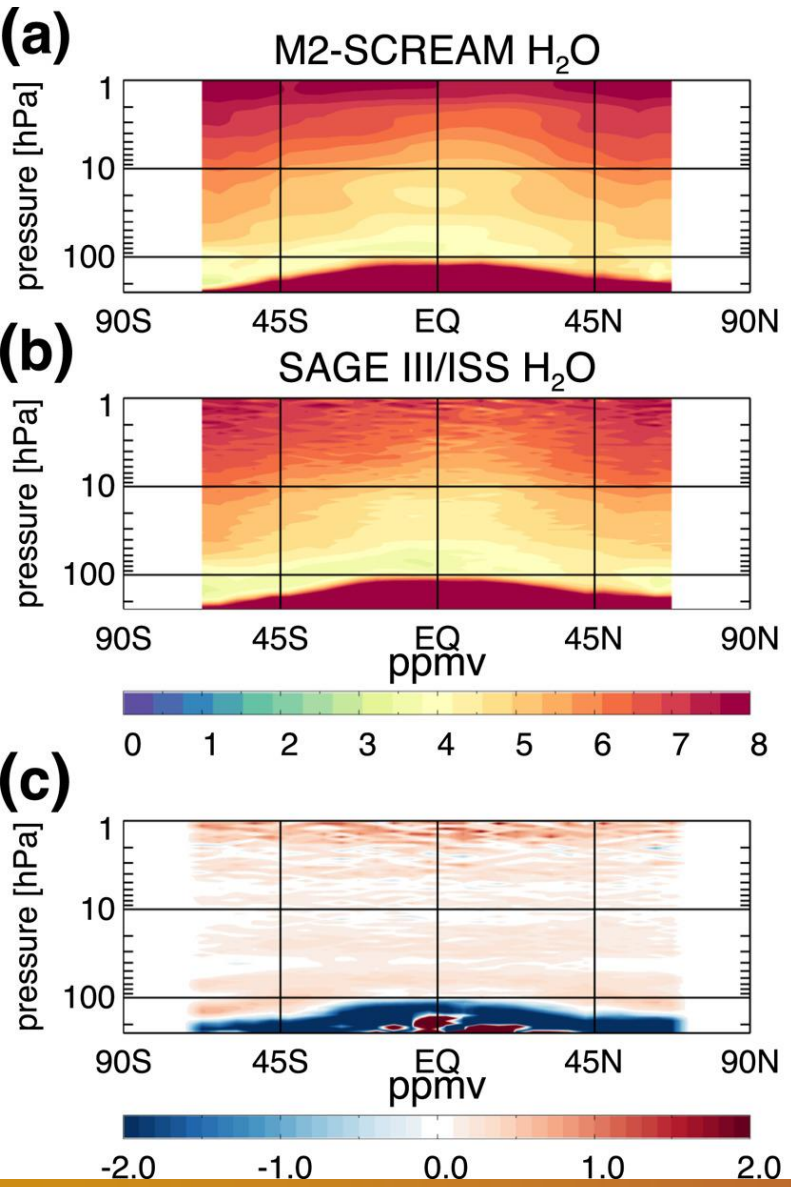
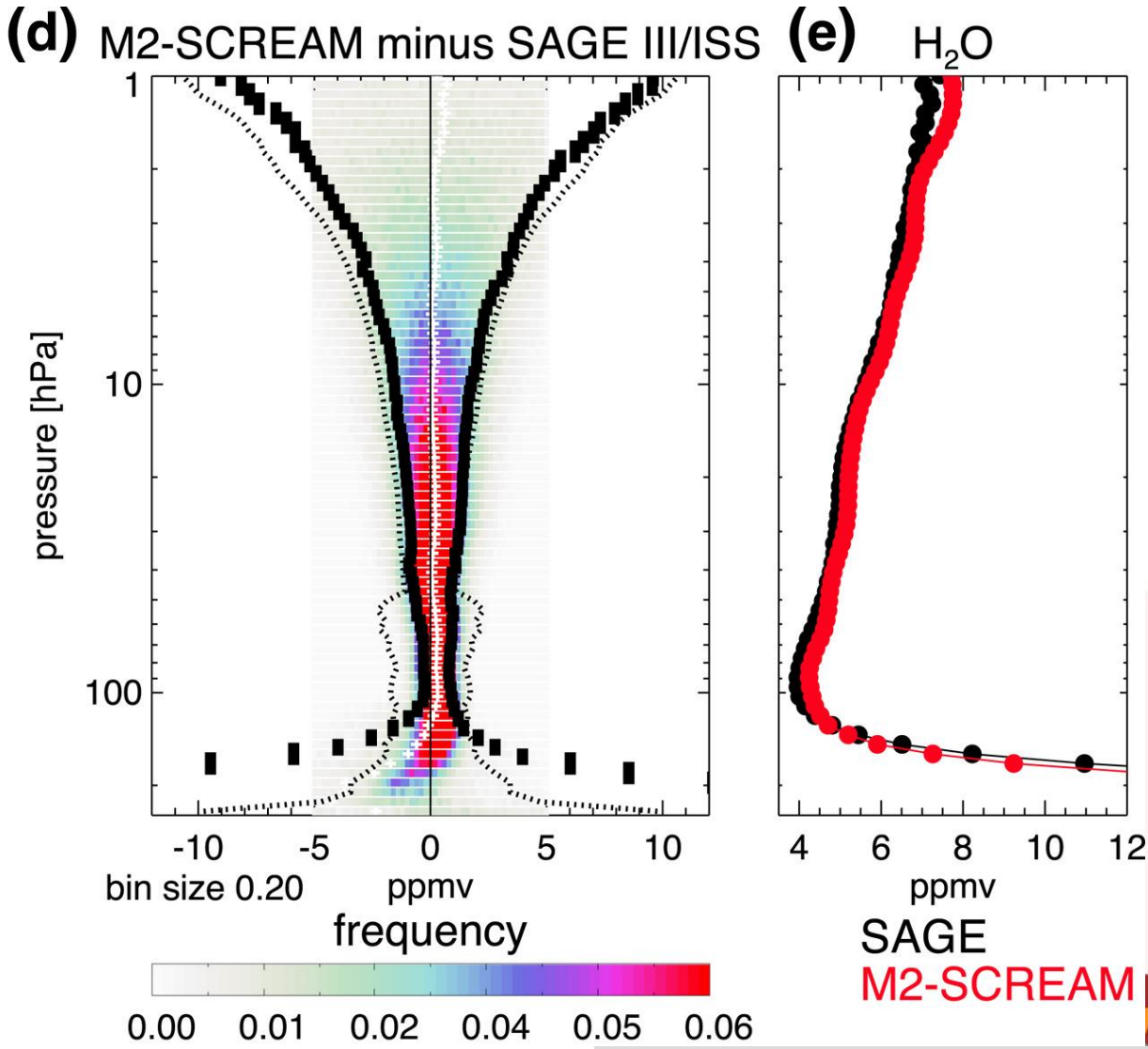


# Very Good Comparisons with $H_2O$ Sondes



# Very Good Agreement with M2-SCREAM (MLS)







**2018**

**SAGE v5.2**
**MLS v4.2**

[Wargan et al. (2023)], *M2-SCREAM: A Stratospheric Composition Reanalysis of Aura MLS Data With MERRA-2 Transport*

Hunga Tonga-Hunga Ha'apai Erupts

https://earthobservatory.nasa.gov/images/149347/hunga-tonga-hunga-haapai-erupts

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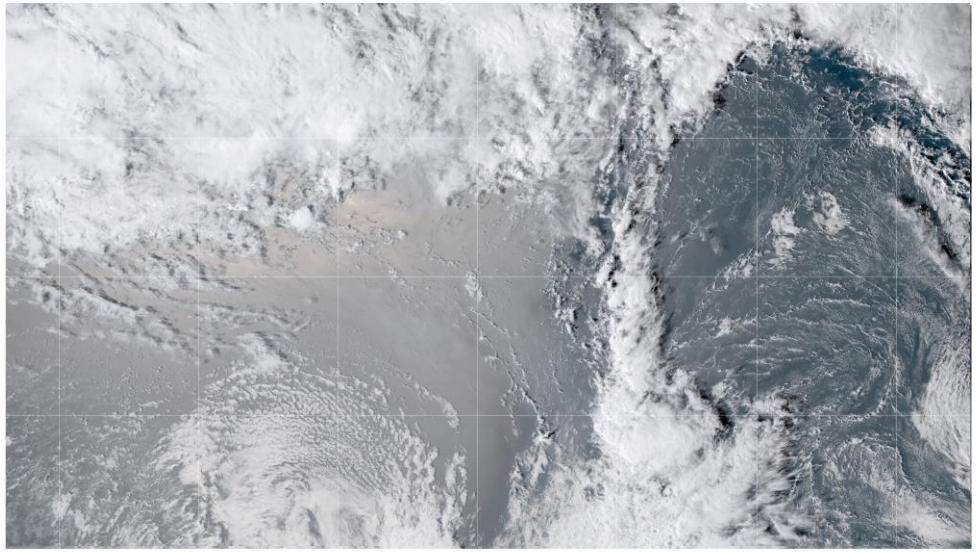
NASA earth observatory

# Hunga Tonga-Hunga Ha'apai Erupts



January 15, 2022

MPEG

View this area in EO Explorer

**Several Earth-observing satellites collected data during and after the potent blast spurred a tsunami and lofted volcanic material high into the stratosphere.**

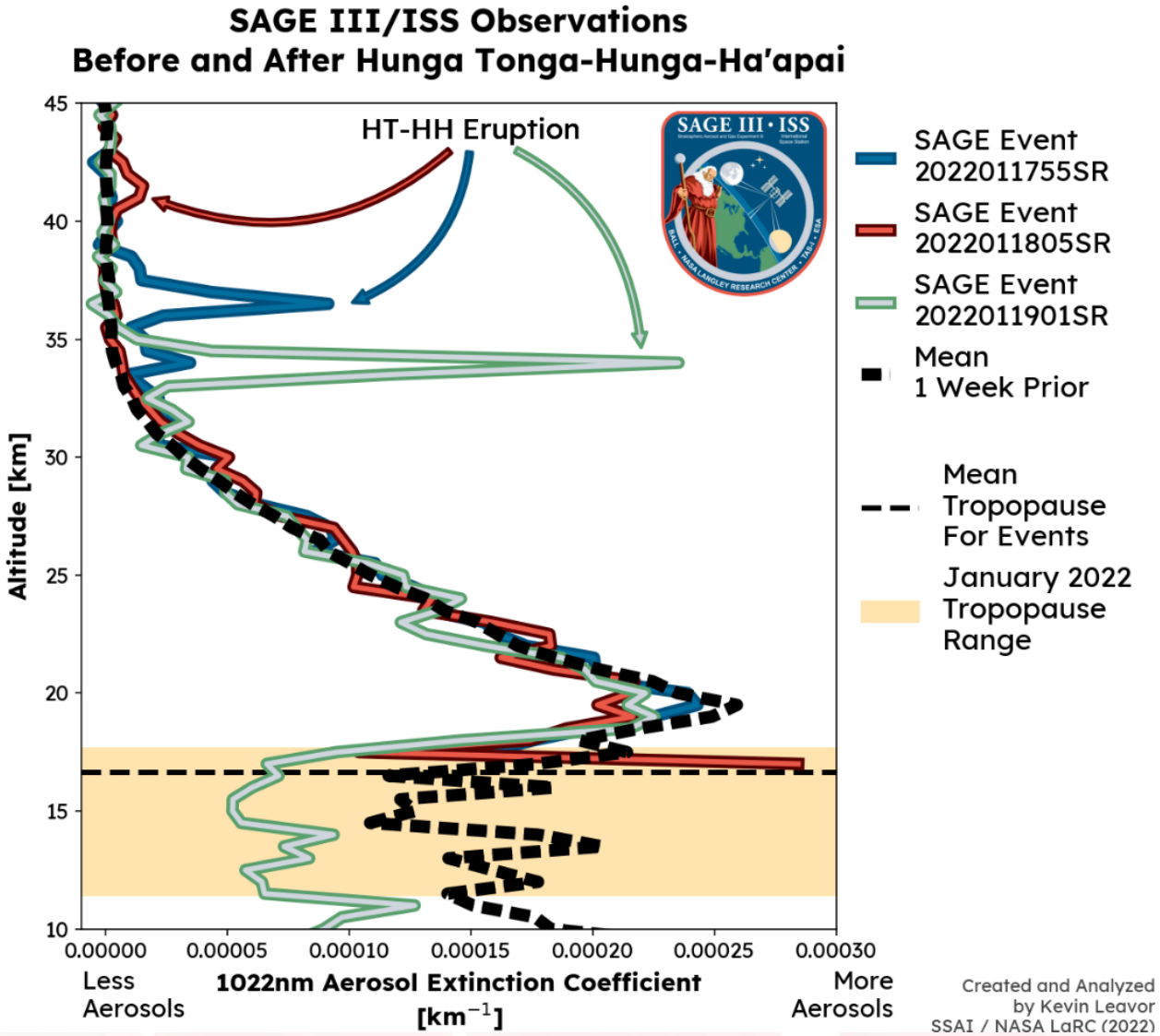
Image of the Day for January 19, 2022

**Instruments:**

Aqua — MODIS

# Early profiles from SAGE

- Following the spectacular mid-January 2022 eruptions of the undersea Hunga Tonga-Hunga Ha'apai volcano, SAGE III/ISS observed significant increases in stratospheric aerosols and water vapor, and decreases in stratospheric ozone, resulting from the eruption.
- Within days after the eruption, SAGE III observations moved into the latitude of Tonga and the instrument detected dramatically enhanced, very concentrated layers of stratospheric aerosol particles as high as 42 km in altitude.
- Because SAGE III observations also passed through the region just one week prior to the eruption, NASA scientists observed the direct impacts to Earth's stratosphere in the science data.

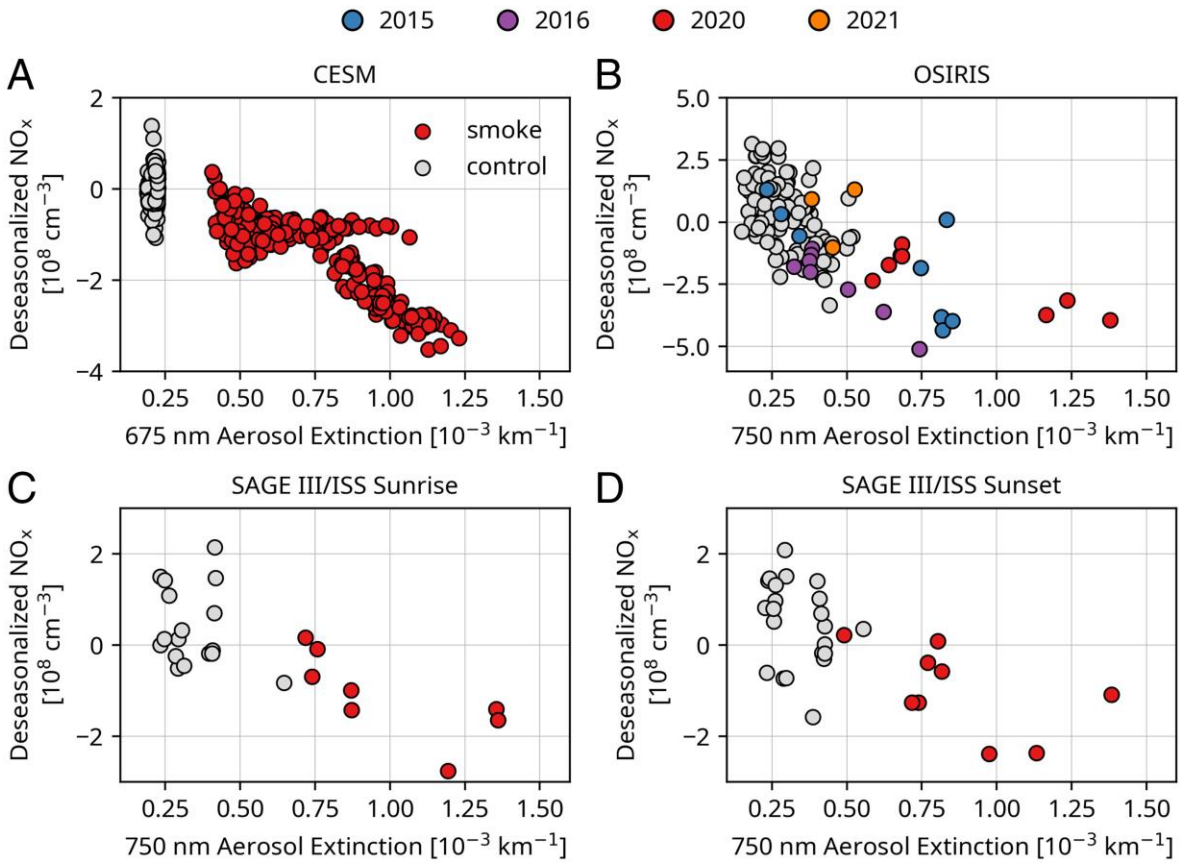


# Smoke & Stratospheric Ozone Destruction

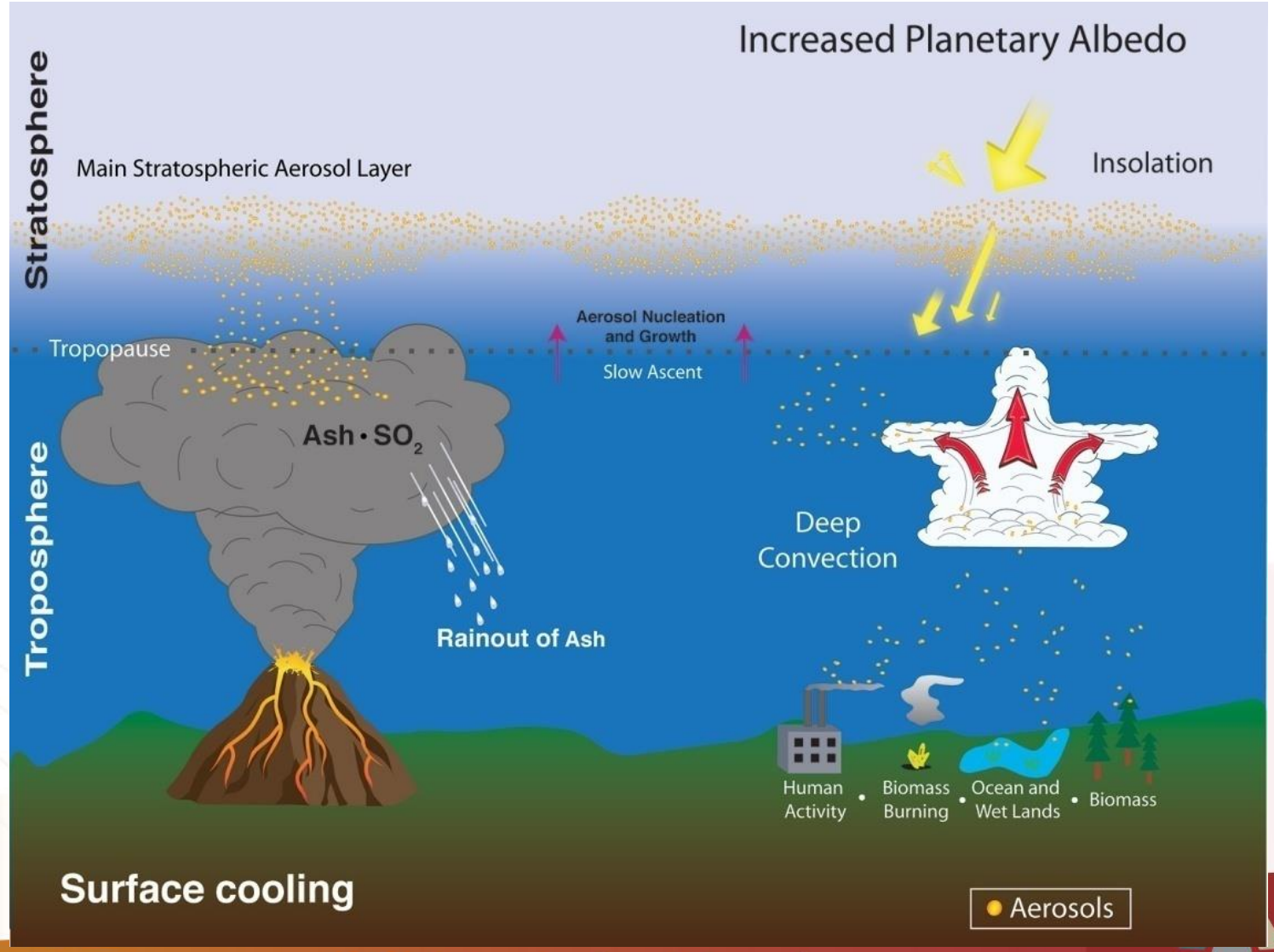
- Solomon et al. (2022) closely examined stratospheric composition following the Australian New Year (2020) fires by combining concurrent measurements of aerosol and $NO_2$ with CESM model calculations.
- Decline in $NO_2$ with increasing particle concentrations is a marker for surface chemistry that contributes to mid-lat. ozone depletion.
- Decreases in mid-lat. SH ozone up to 8 DU were observed after ANY fires/prior to Ant. Ozone hole

June 20, 2023

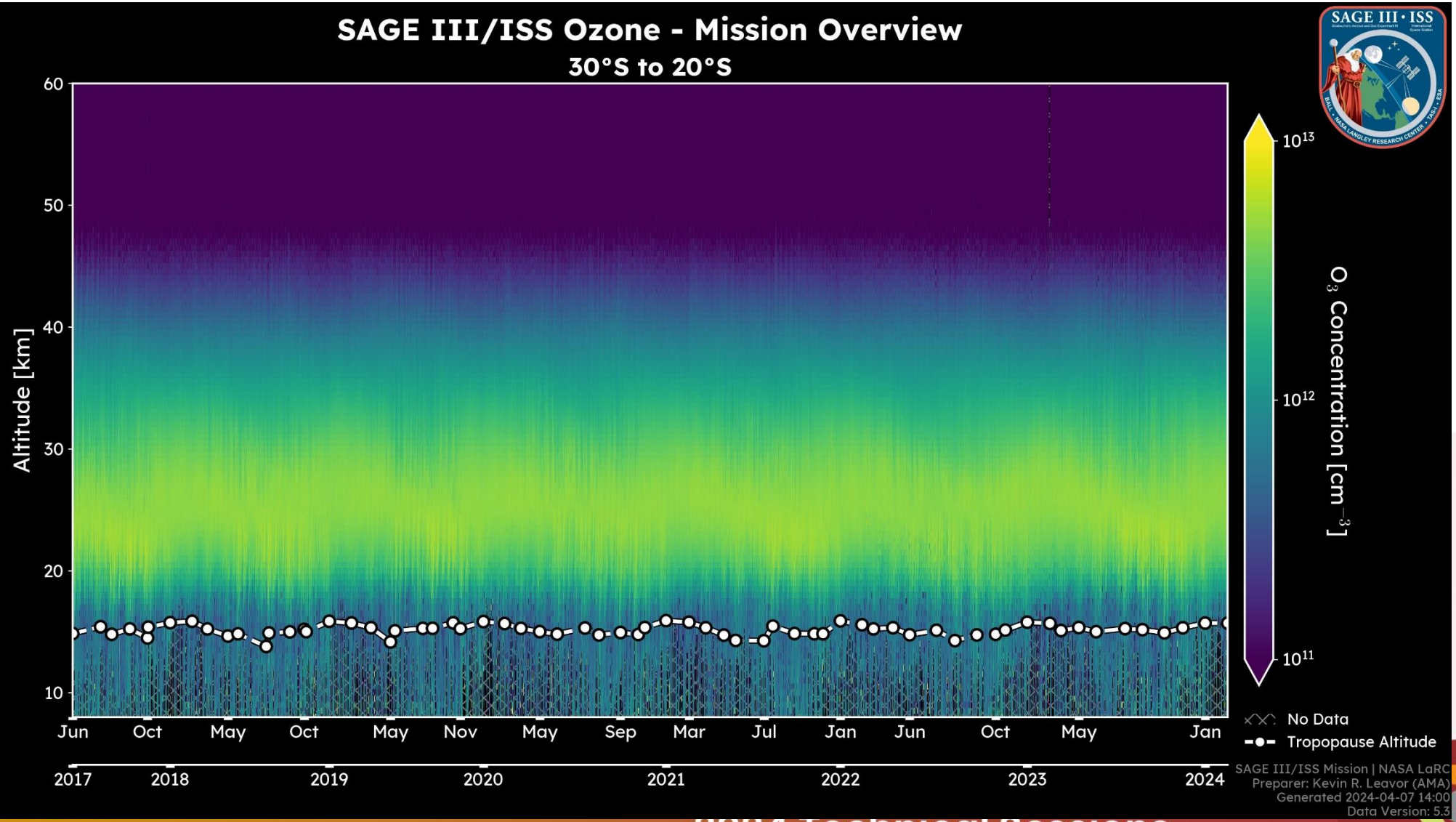
- Increasing wildfire activity in a warming world may slow the recovery of the ozone layer.



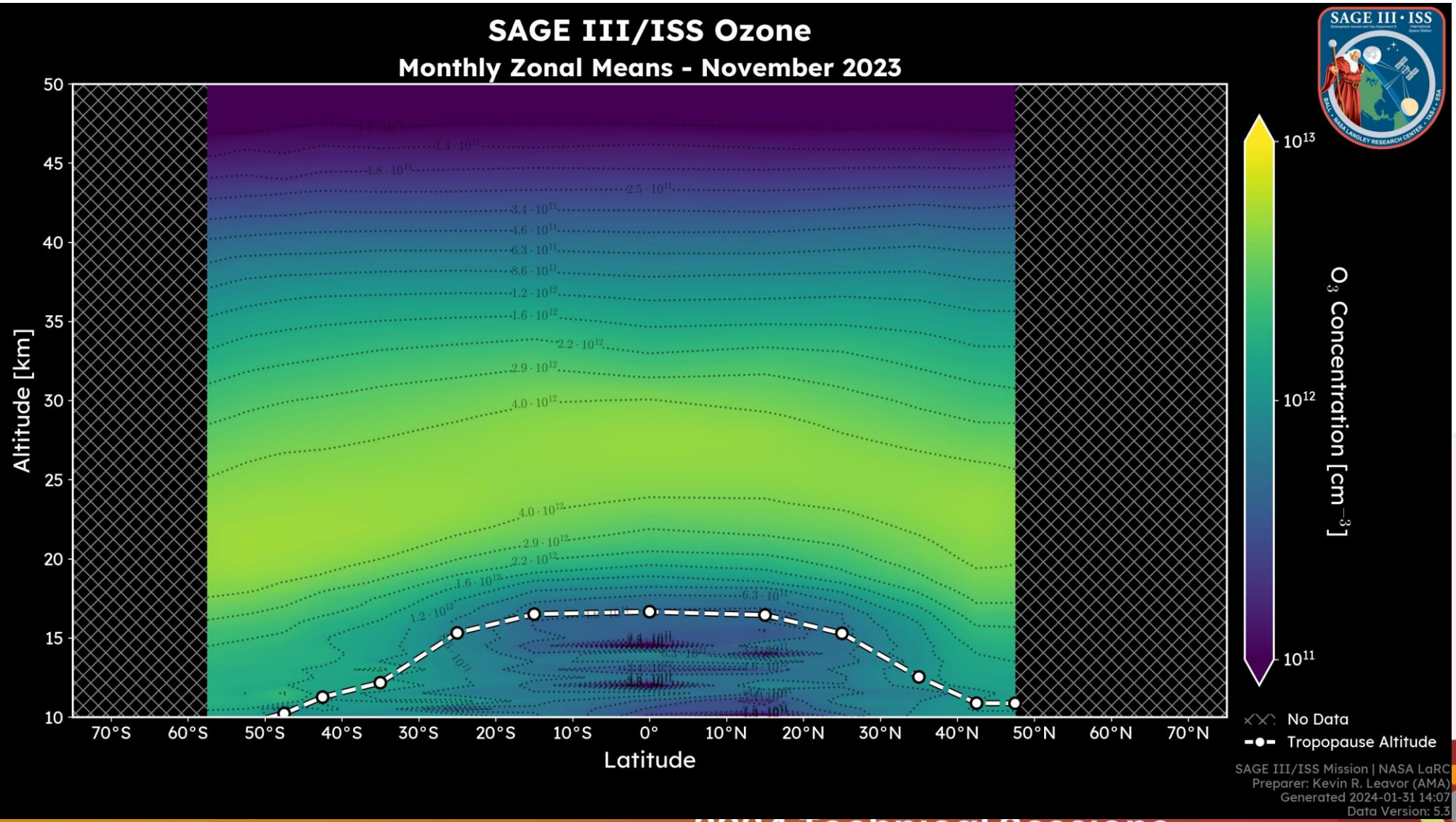
# The Stratospheric Aerosol Layer



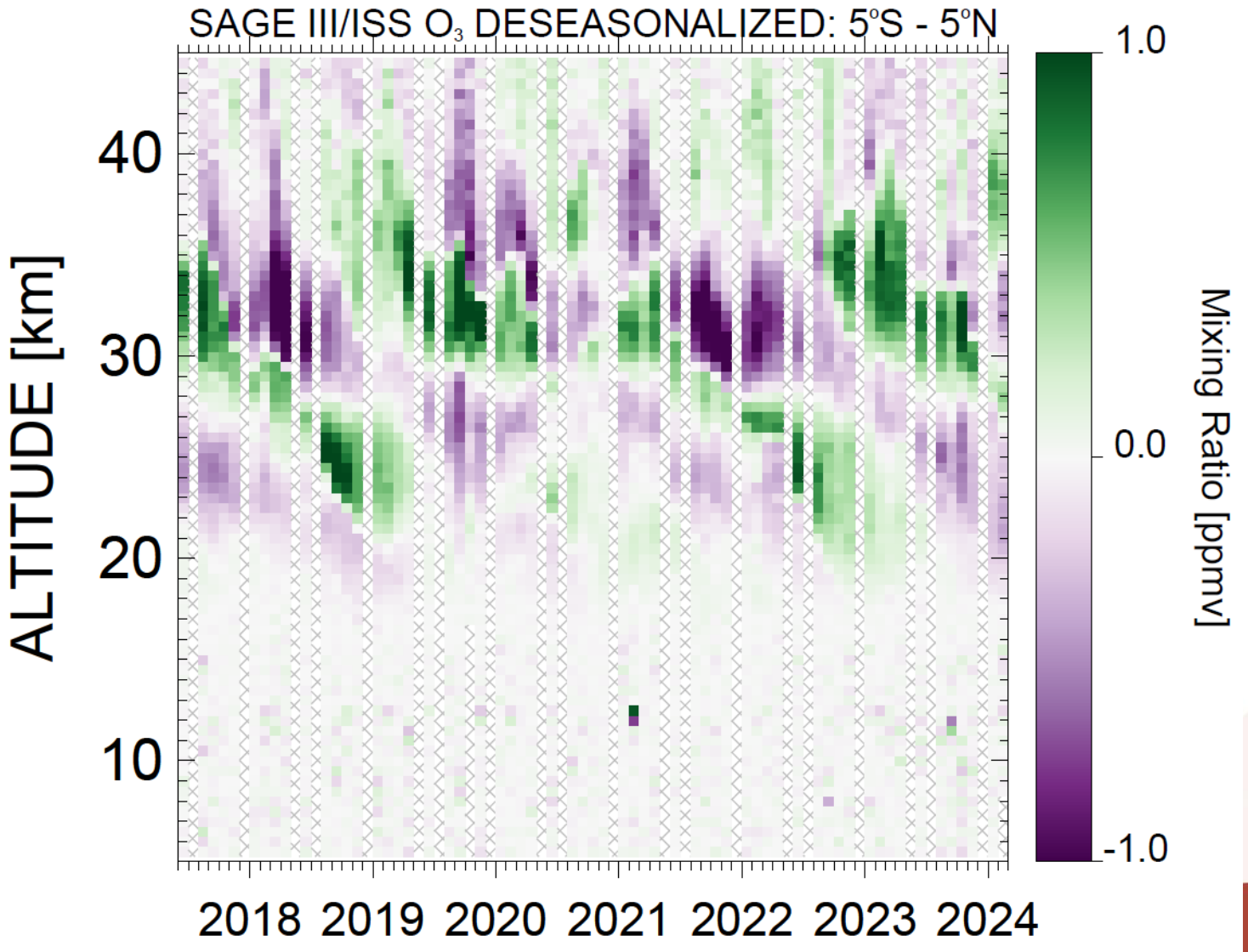
# Ozone ($O_3$)


SAGE III/ISS Ozone - Mission Overview
30°S to 20°S
SAGE III • ISS
Altitude [km]
60
50
40
30
20
10
Jun
Oct
May
Oct
May
Nov
May
Sep
Mar
Jul
Jan
Jun
Oct
May
Jan
2017
2018
2019
2020
2021
2022
2023
2024
$10^{13}$
$10^{12}$
$10^{11}$
$O_3$ Concentration [$cm^{-3}$]
No Data
Tropopause Altitude
SAGE III/ISS Mission | NASA LaRC
Preparer: Kevin R. Leavor (AMA)
Generated 2024-04-07 14:00
Data Version: 5.3

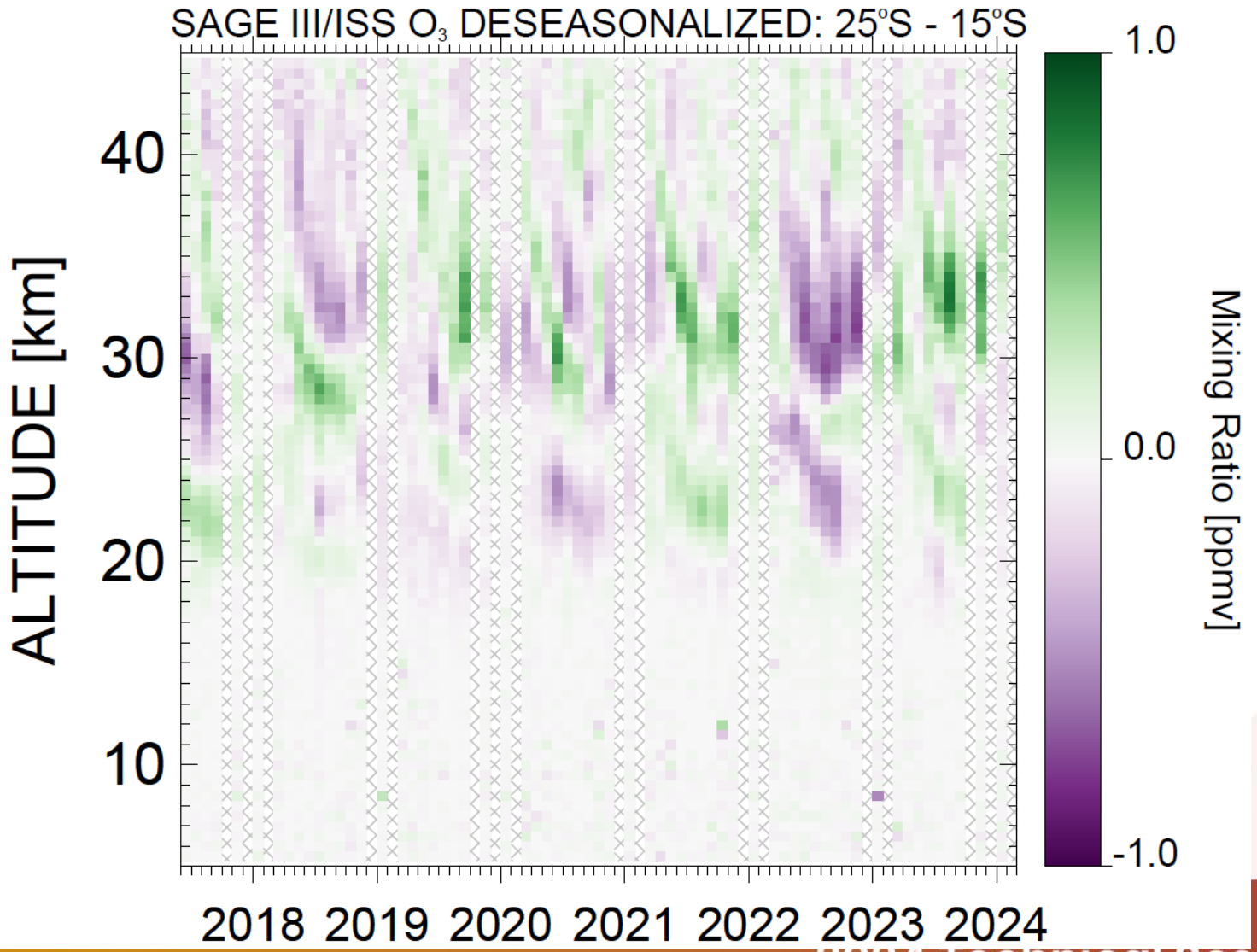
# $O_3$ Latitude vs. Altitude



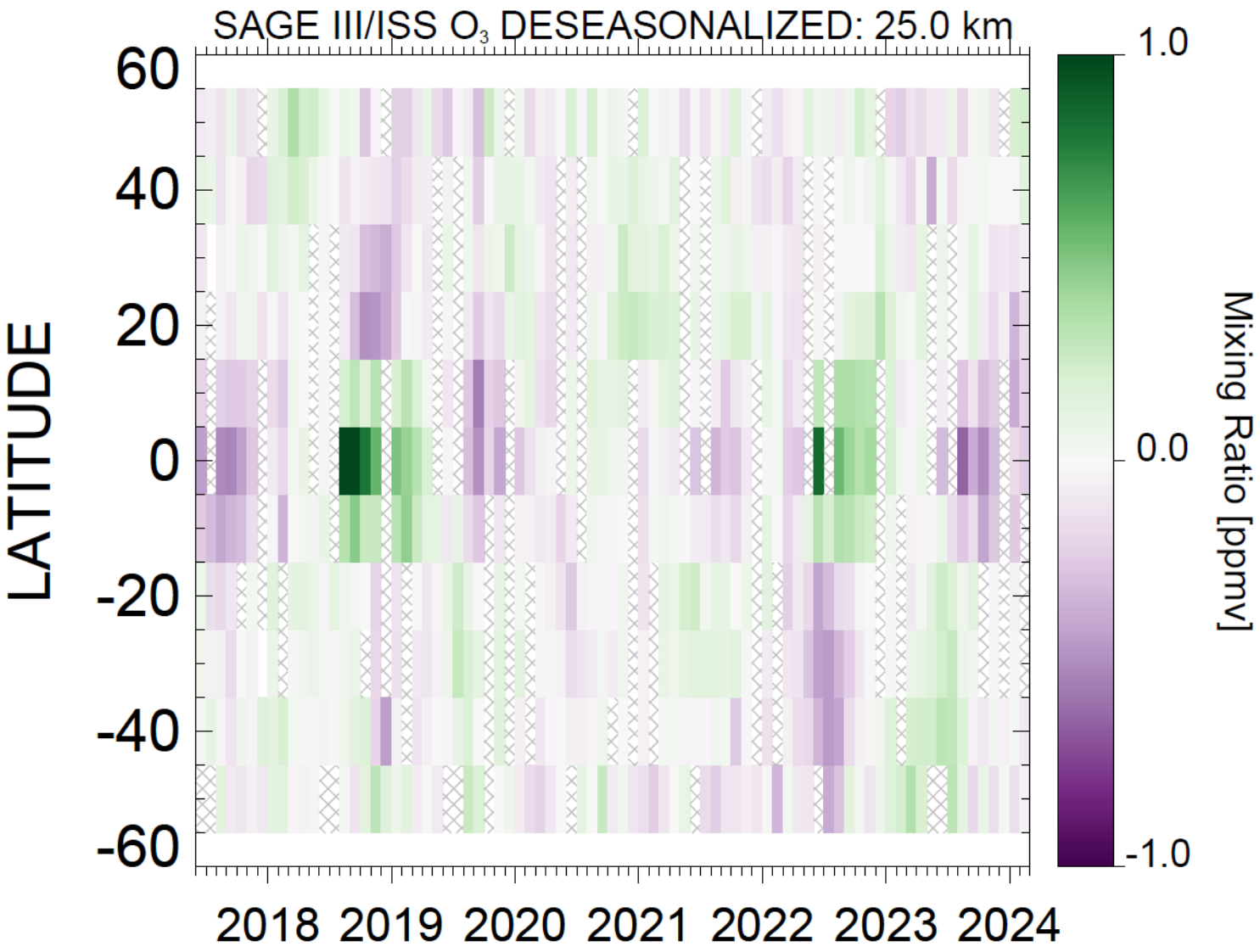
# Remove seasonal average to see propagating variations



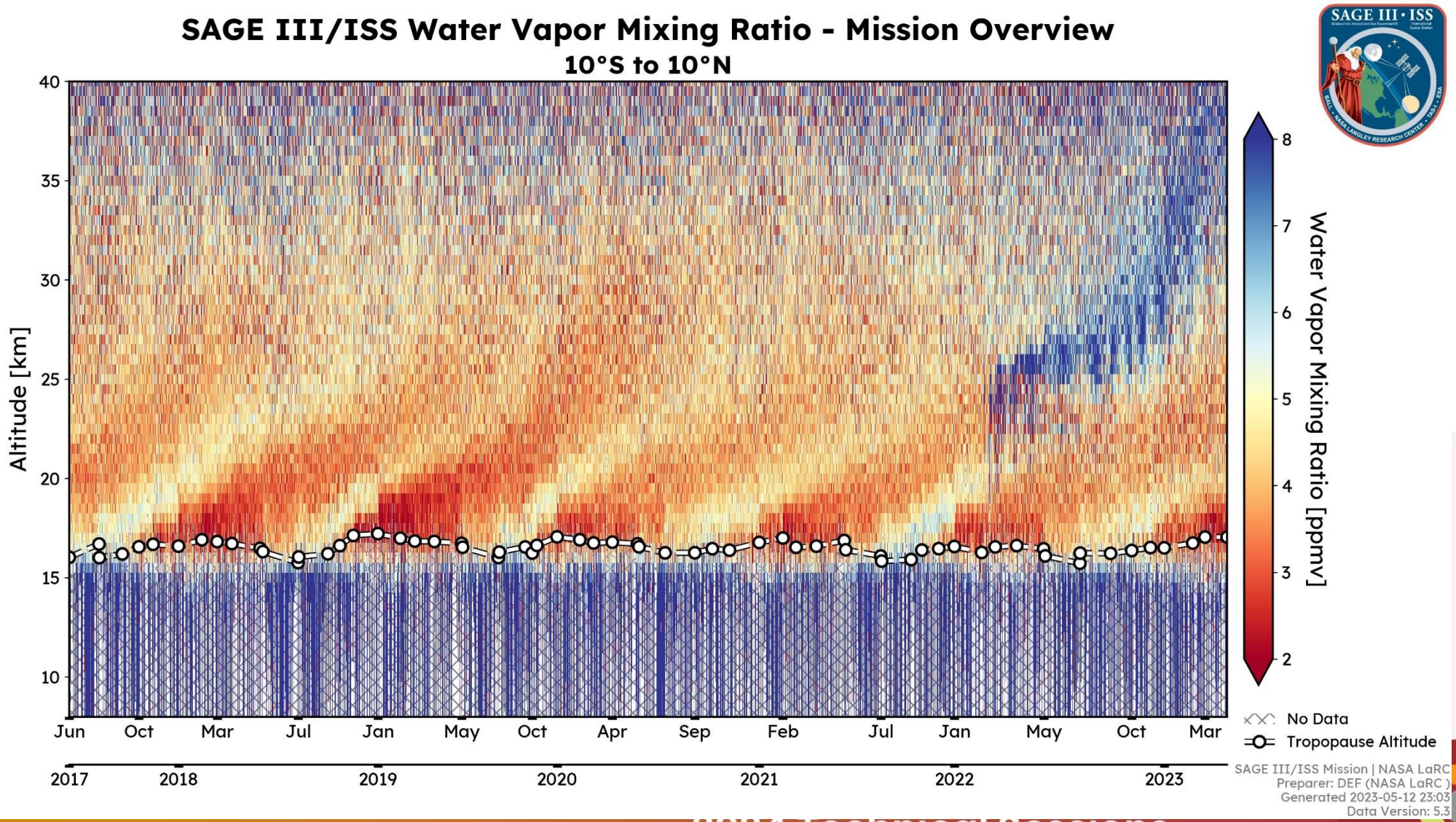
# Variations within Hunga eruption latitude



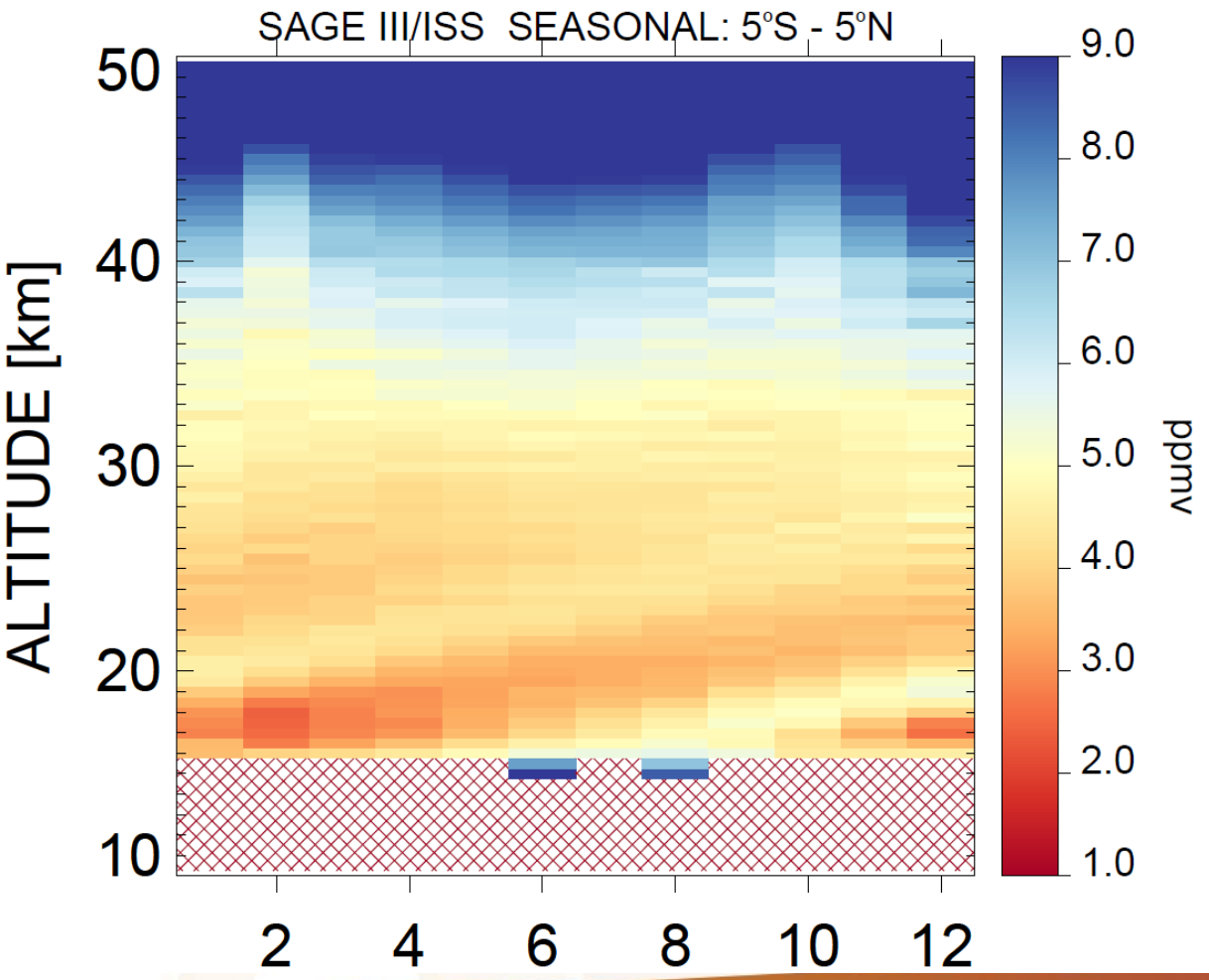
# Ozone Anomalies at 25 km

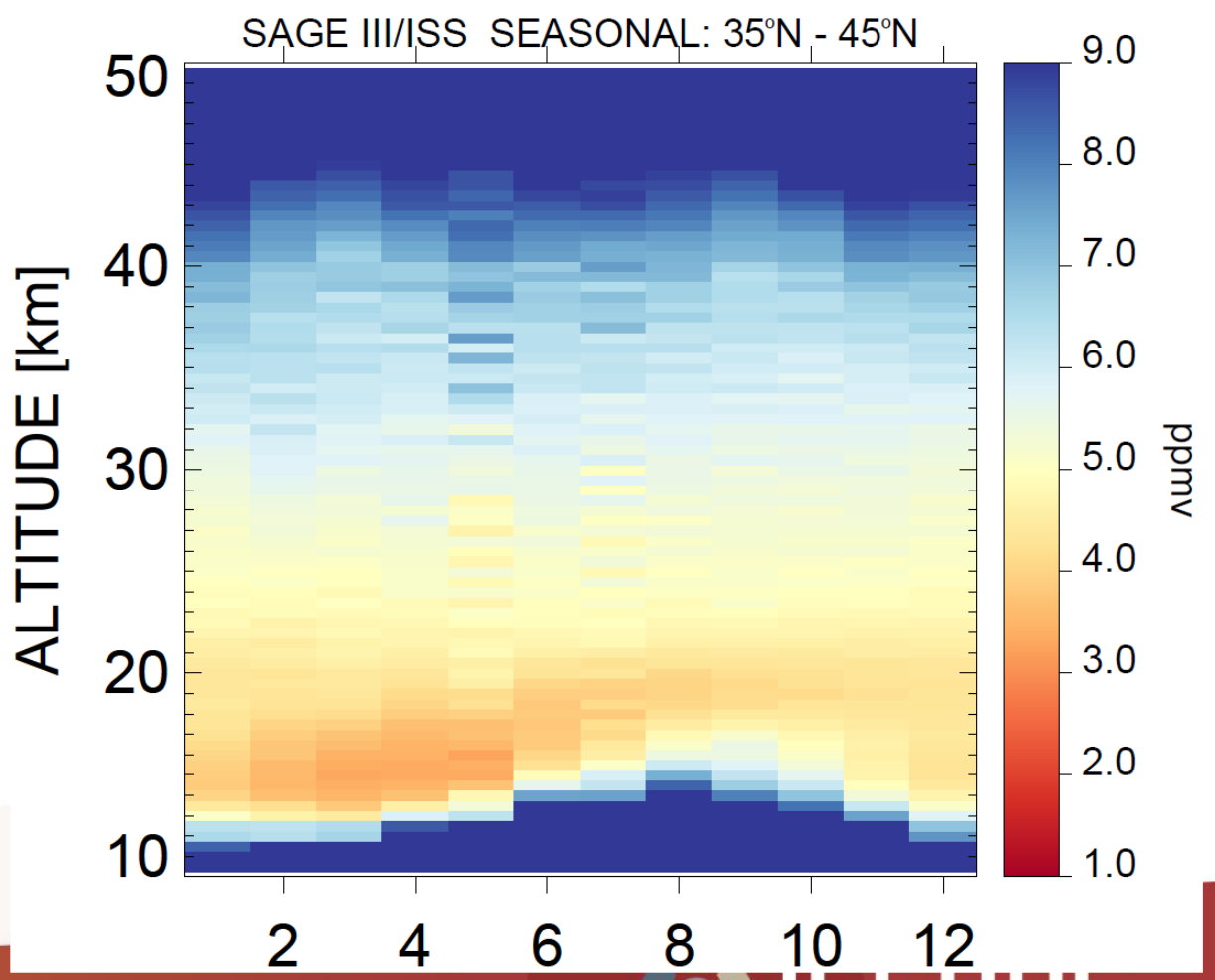


# Water Vapor ($H_2O$)

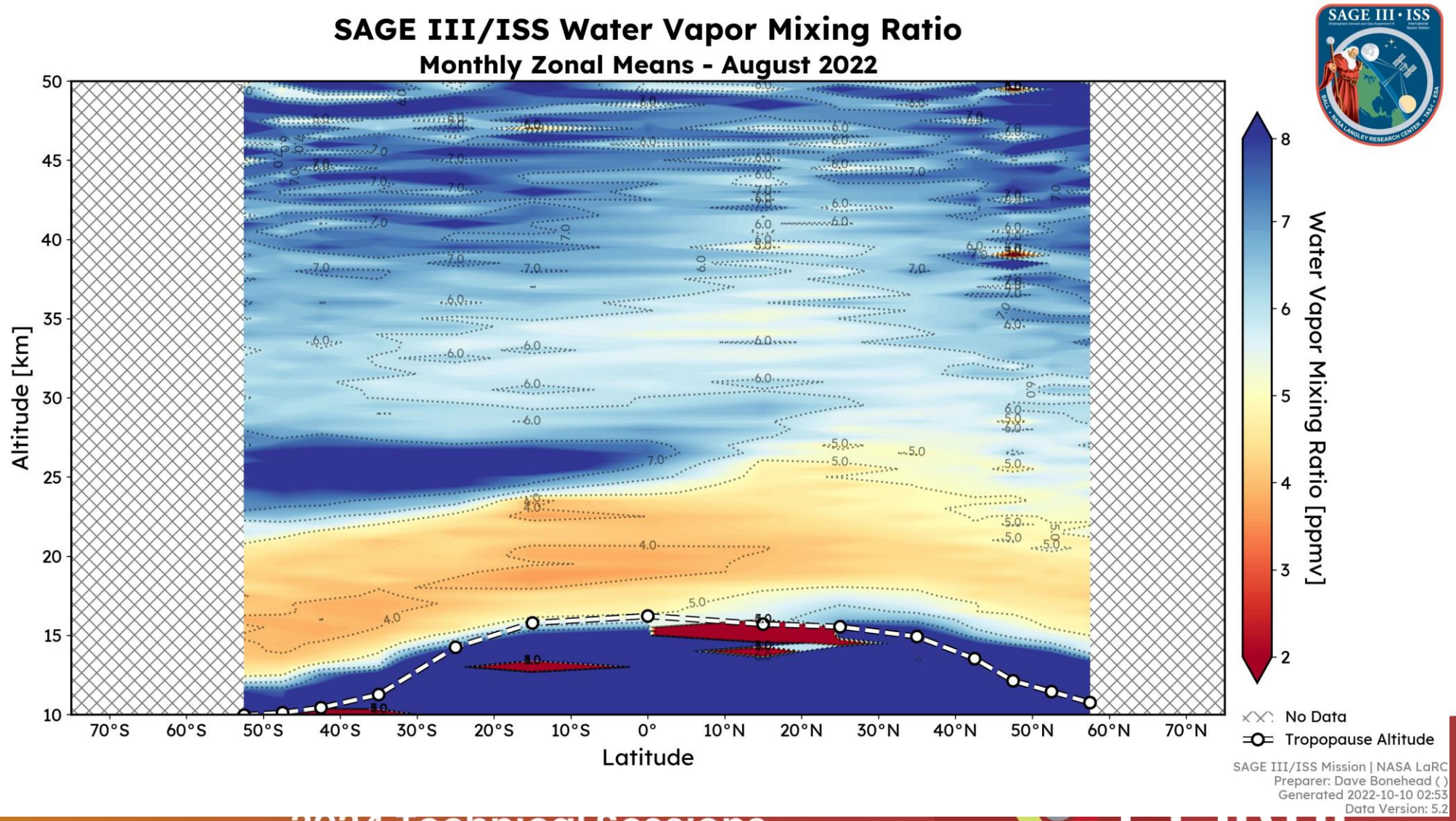


# $H_2O$ Seasonal Cycle



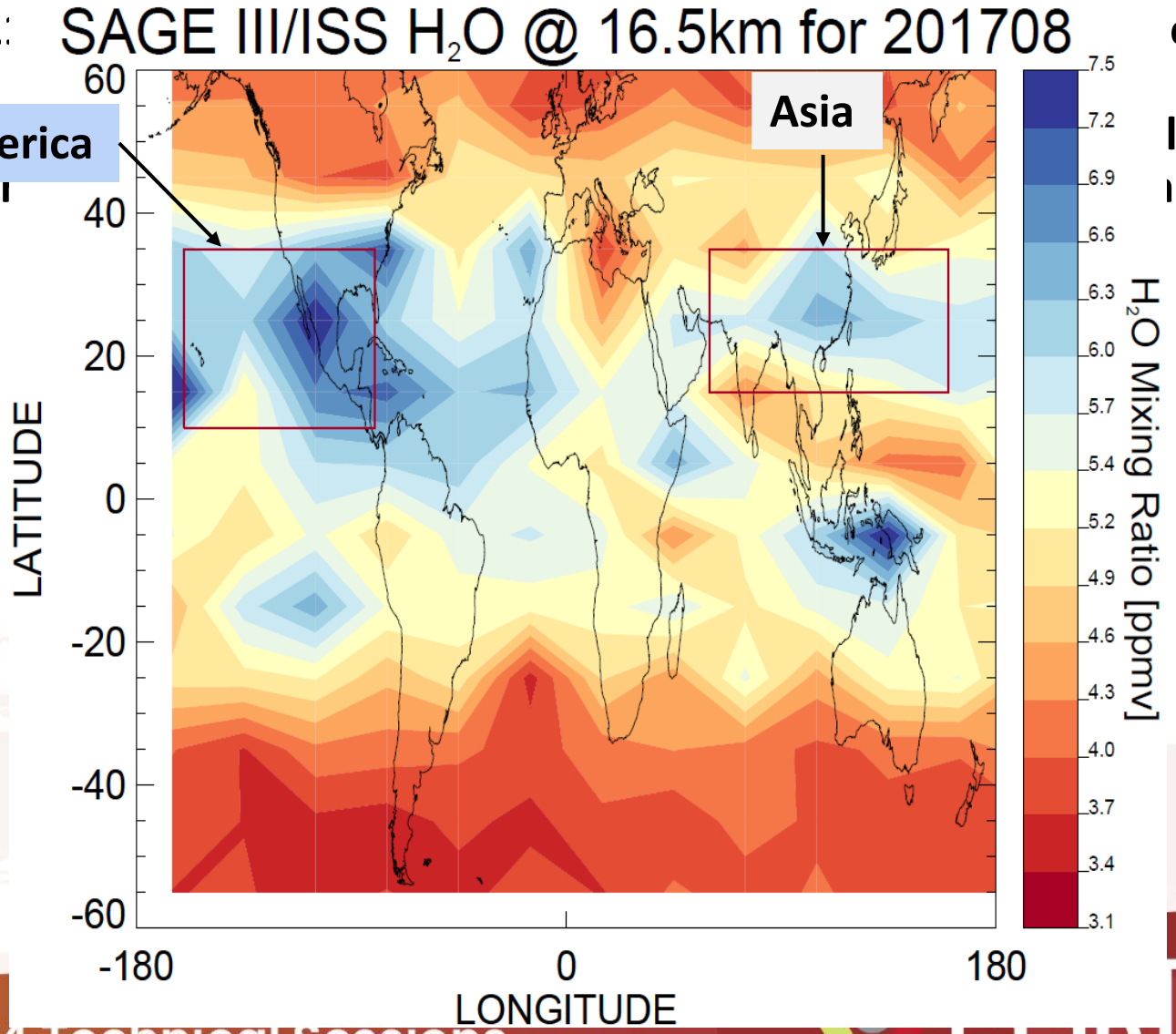



# $H_2O$ Monthly Zonal Mean

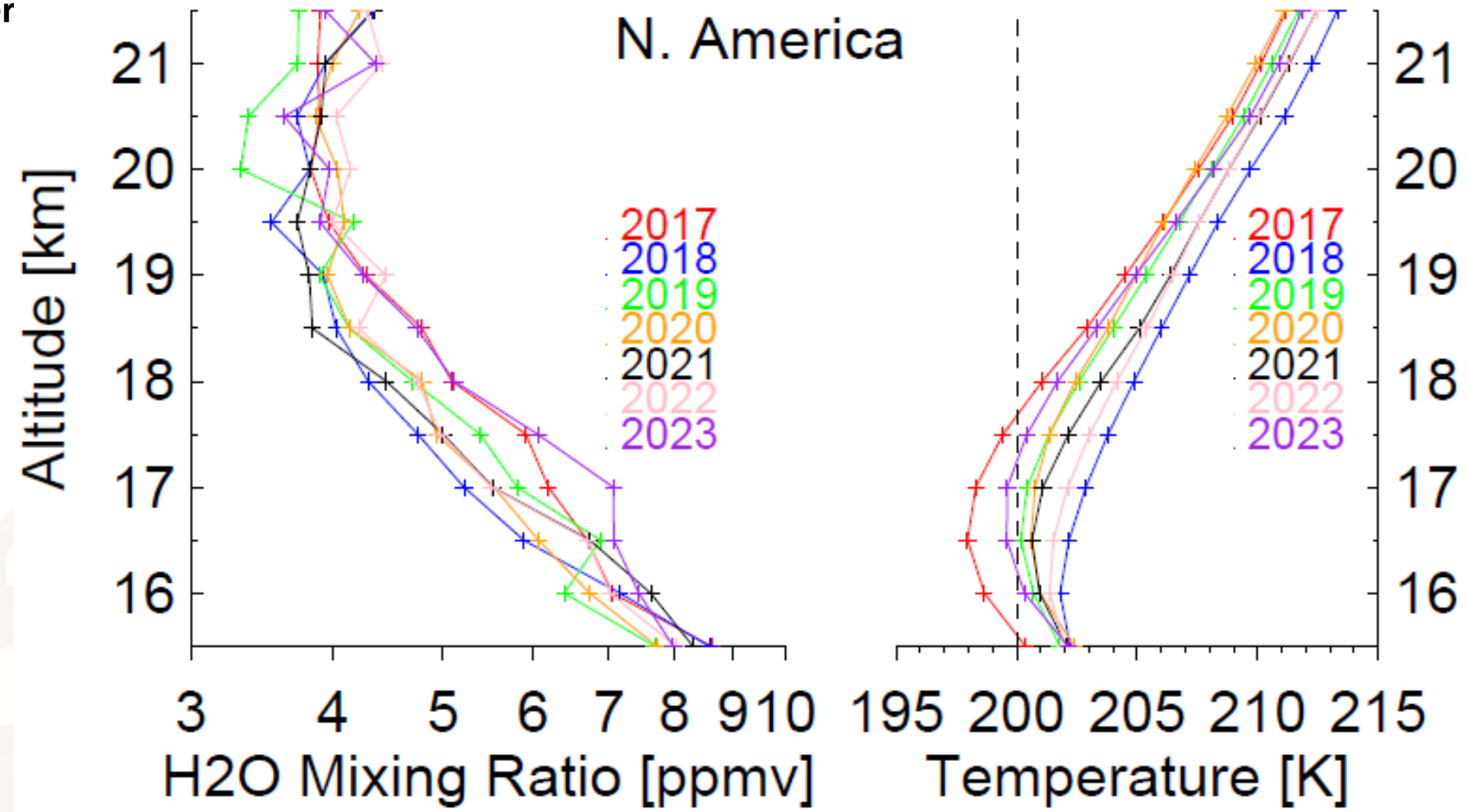


# Summer Monsoon

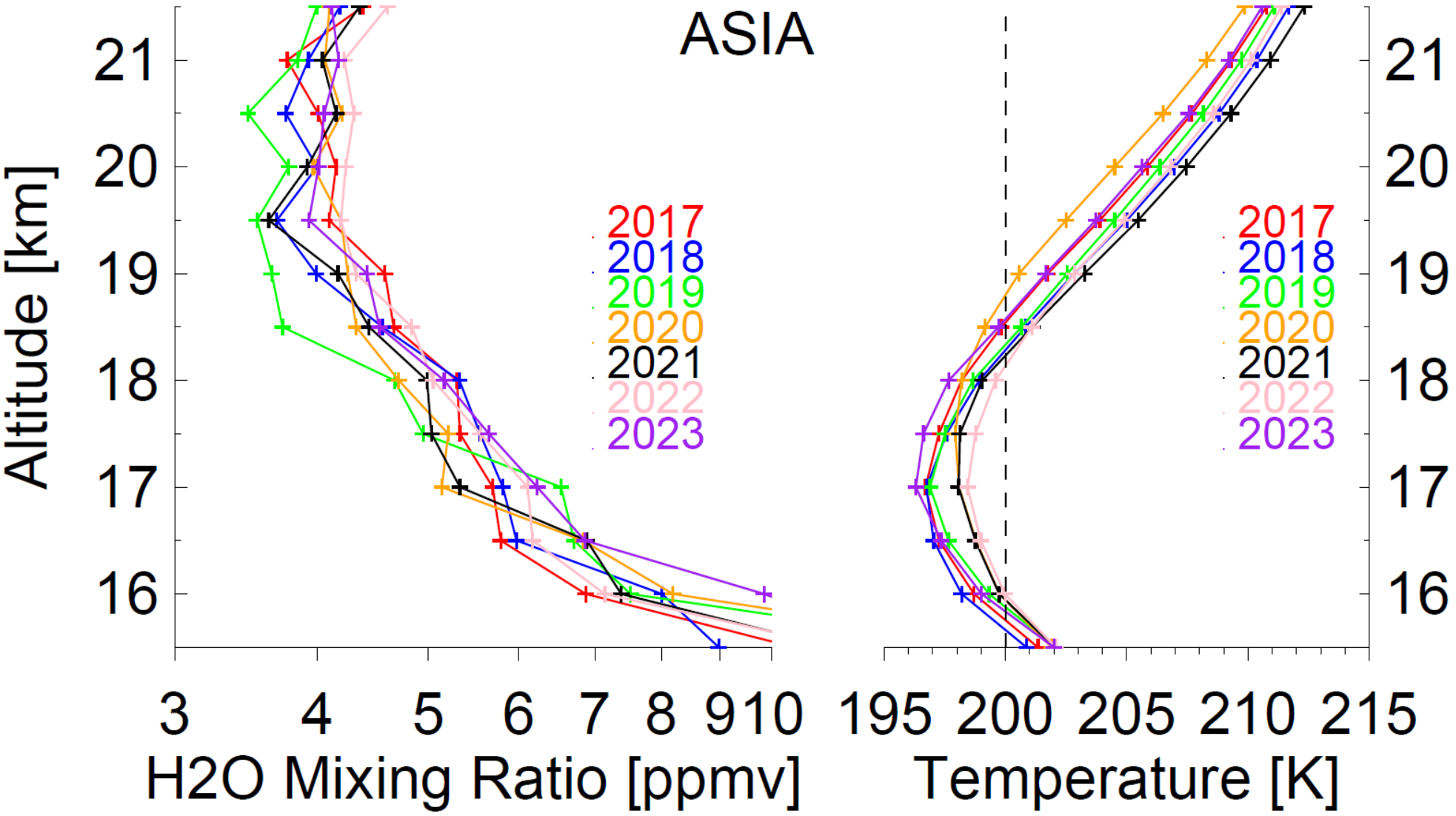
- **Revisiting the work of Park et al. (202 Northern Hemisphere and associated America. For N. American mor warmer years are associated with a dr a driver in SWV as it is in the tropics.**



- **For N. American monsoon, August 2017 remains moister/cooler than other years, while warmer years are associated with a drier as it is in the tropics.**

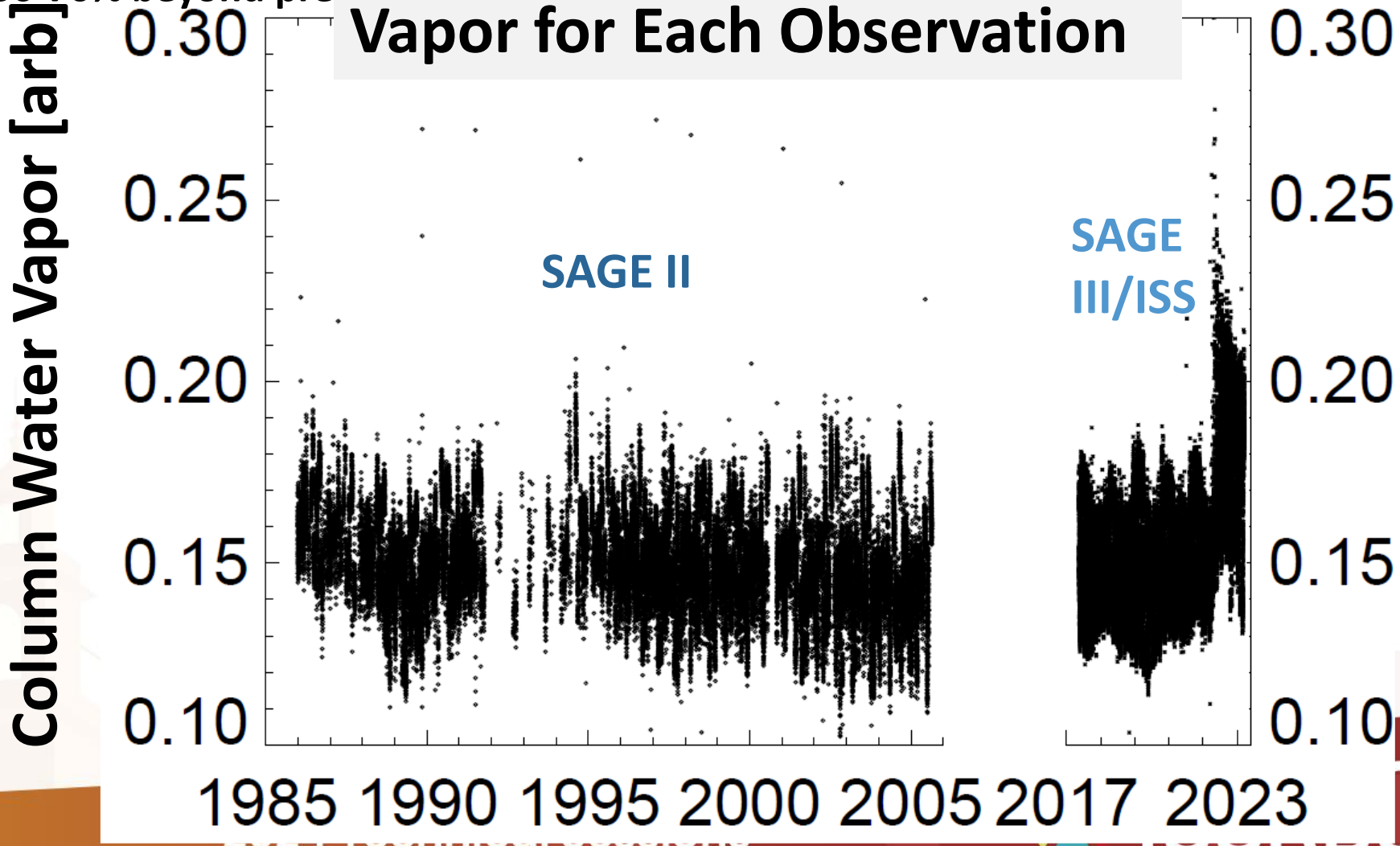


# Asia Shows Little Year-to-Year Variation

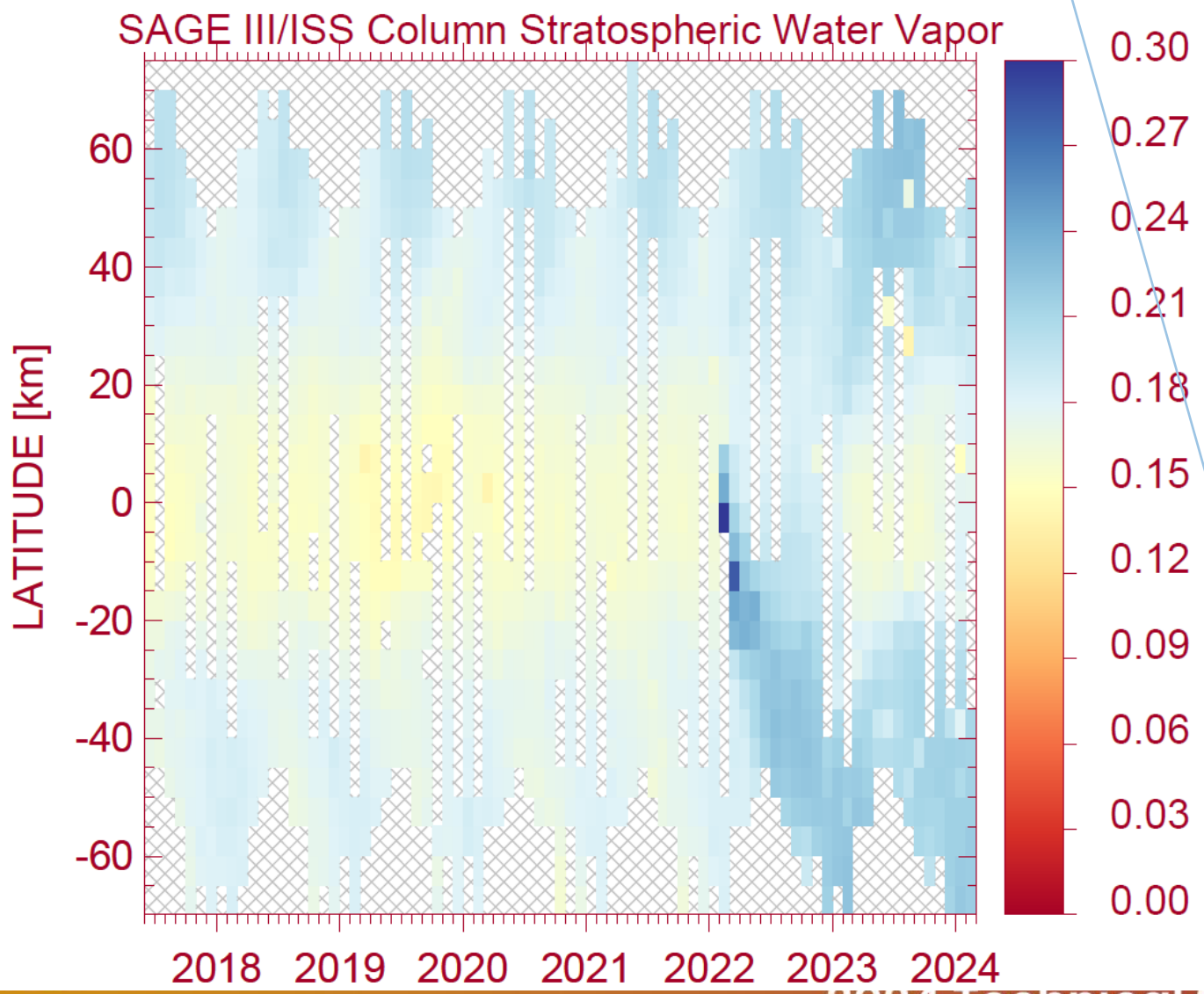


# HTHH Strat. $H_2O$ Largest in Satellite Era

- **Mid-stratospheric water vapor column … water vapor layer has increased 50-70% beyond pre**

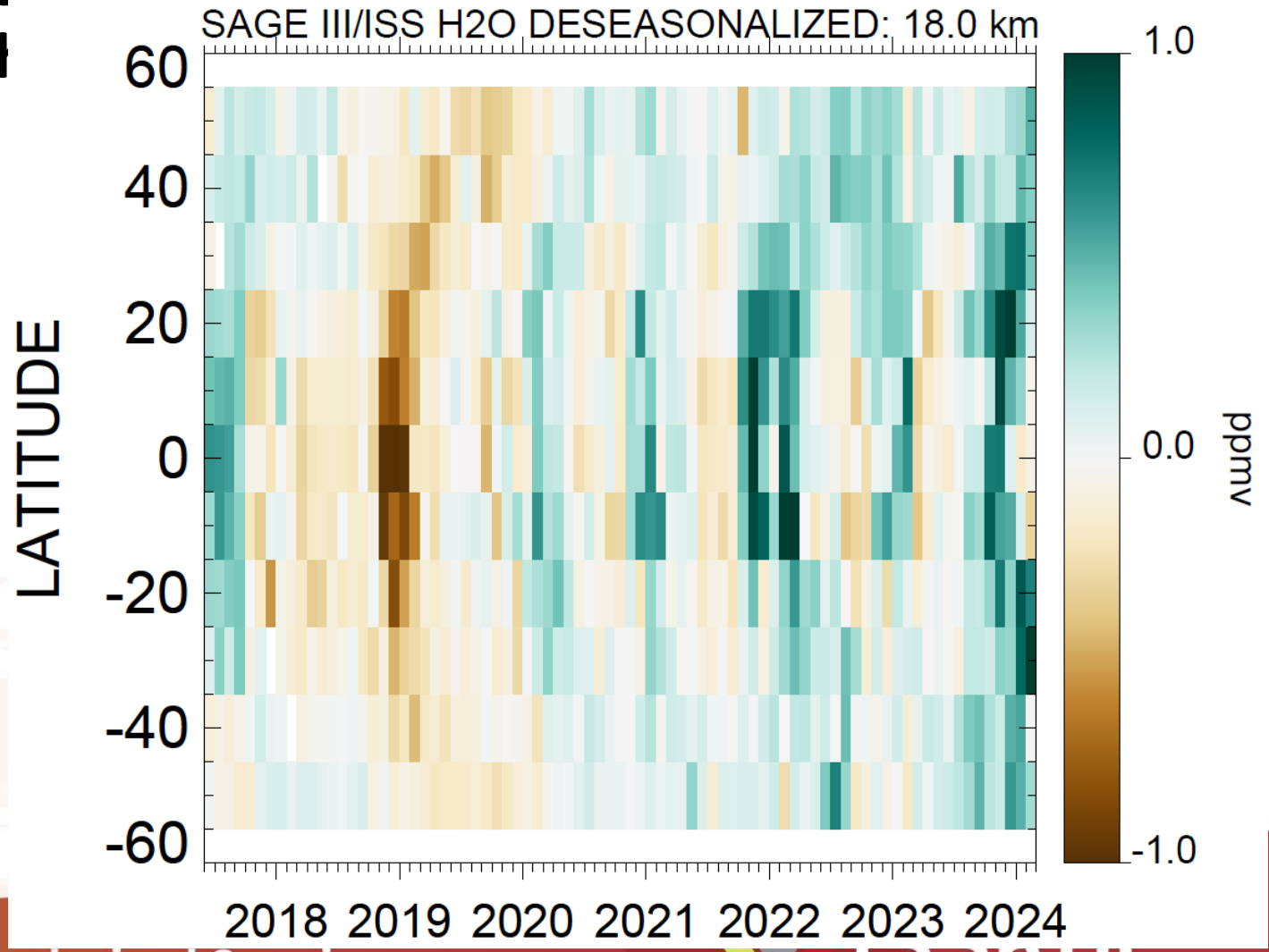


# Hunga Eruption



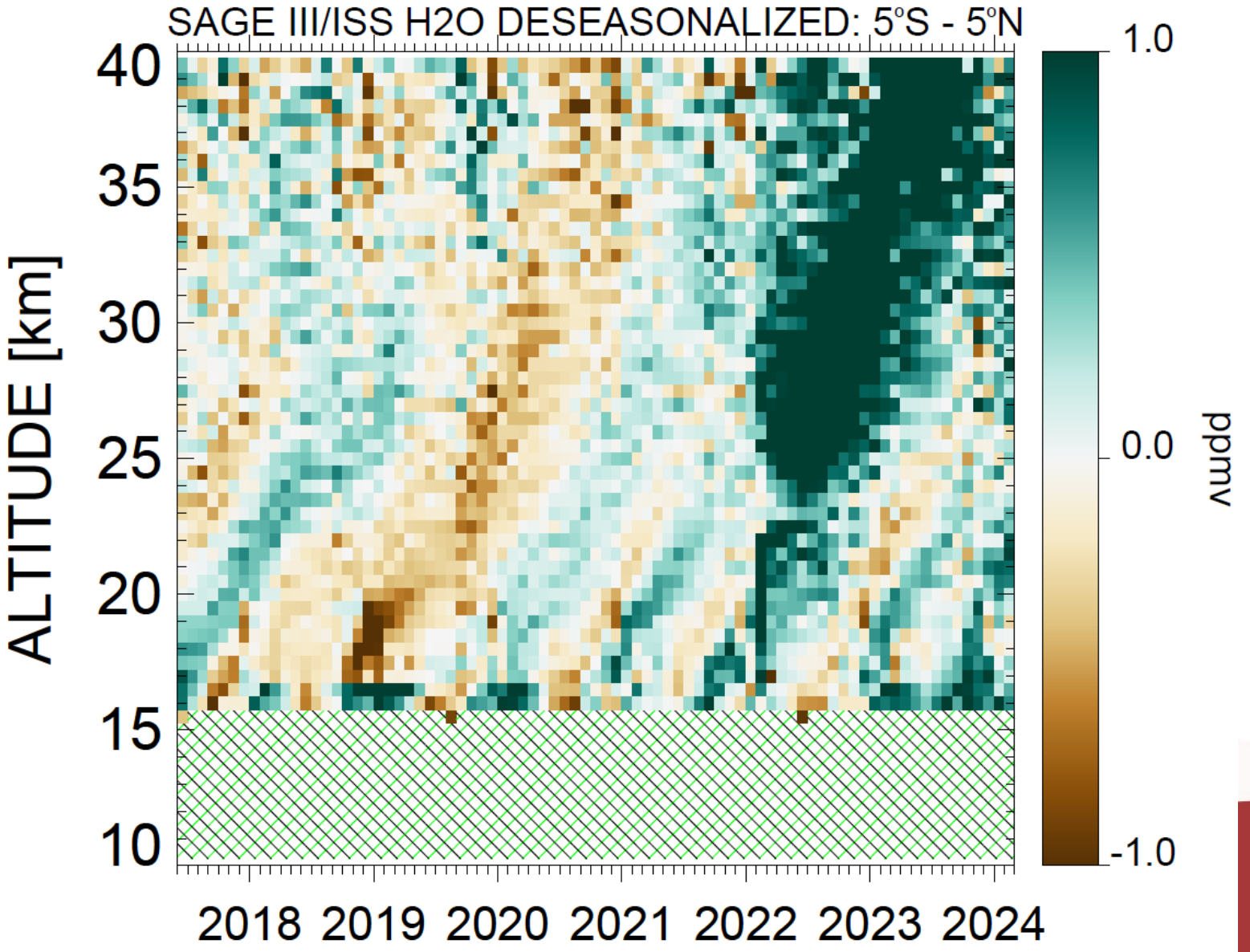
# Spatial Variations Emanate from Tropics

- **Deseasonalized SAGE III/ISS w**
  **modulation of lower stratospl**
  **mid-latitudes associated with**



# Tropical $H_2O$ Anomalies

- **Year to year variability stratosphere**
- After mid-2022 and below ~23k

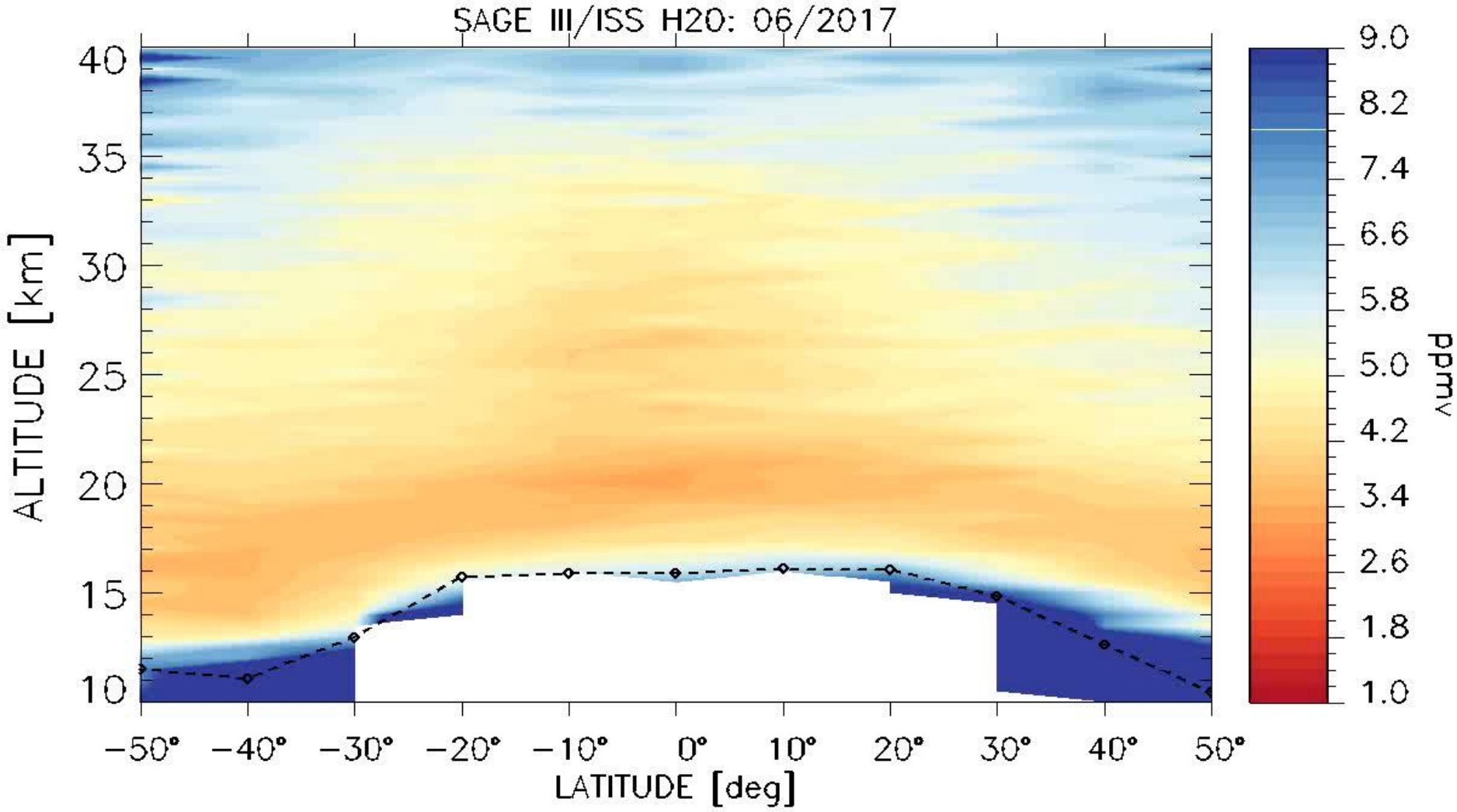


# SAGE III/ISS $H_2O$ Movie

**Items to note:**
**-Seasonal injection of dry tropical air in Feb/Mar**

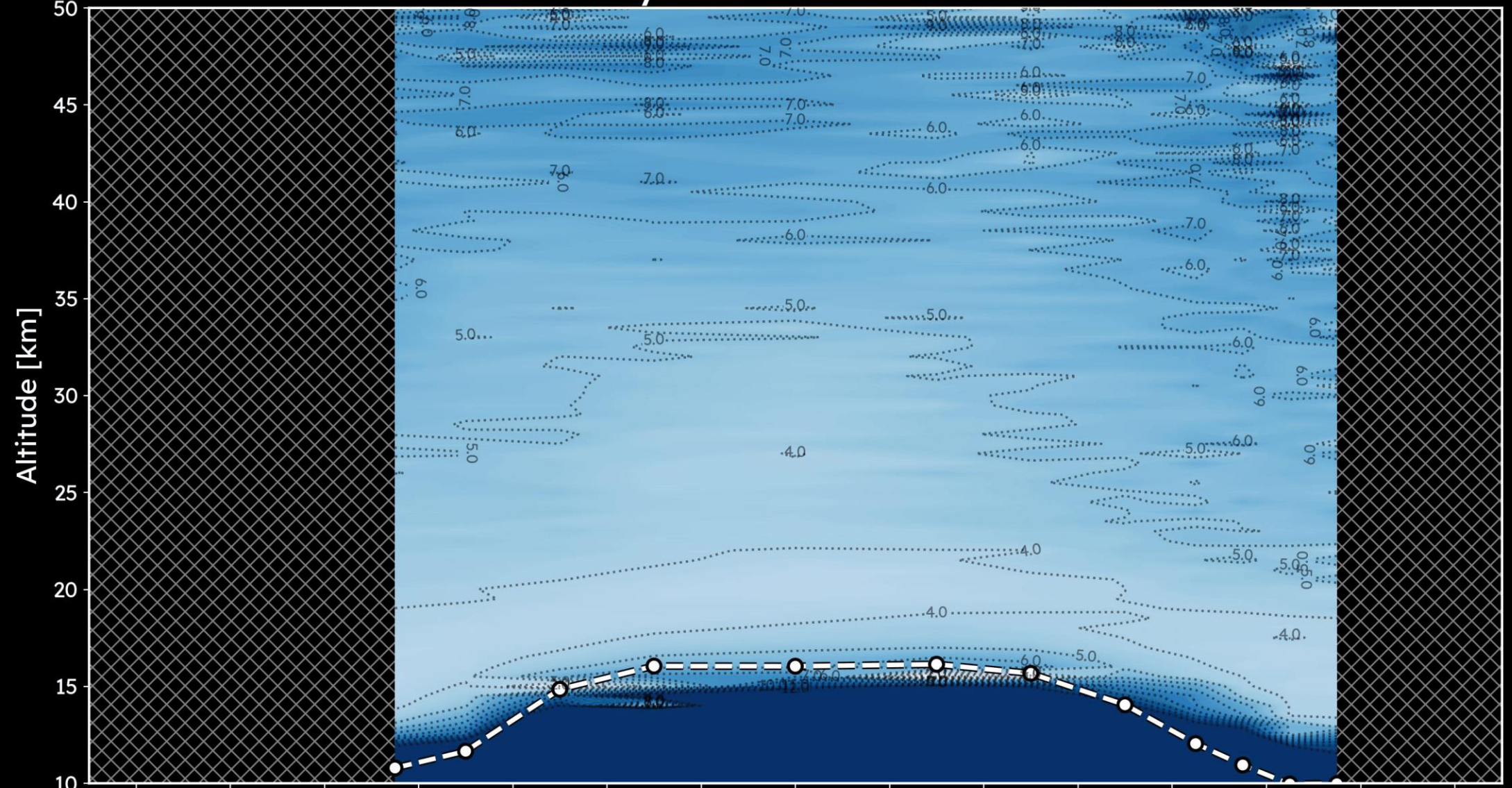
**-Moist air injection near 30N each Aug/Sep**

**-Hunga eruption 2022 layer distinct for ~1yr then dispersed globally**



# SAGE III/ISS Water Vapor Mixing Ratio

## Monthly Zonal Means - June 2017



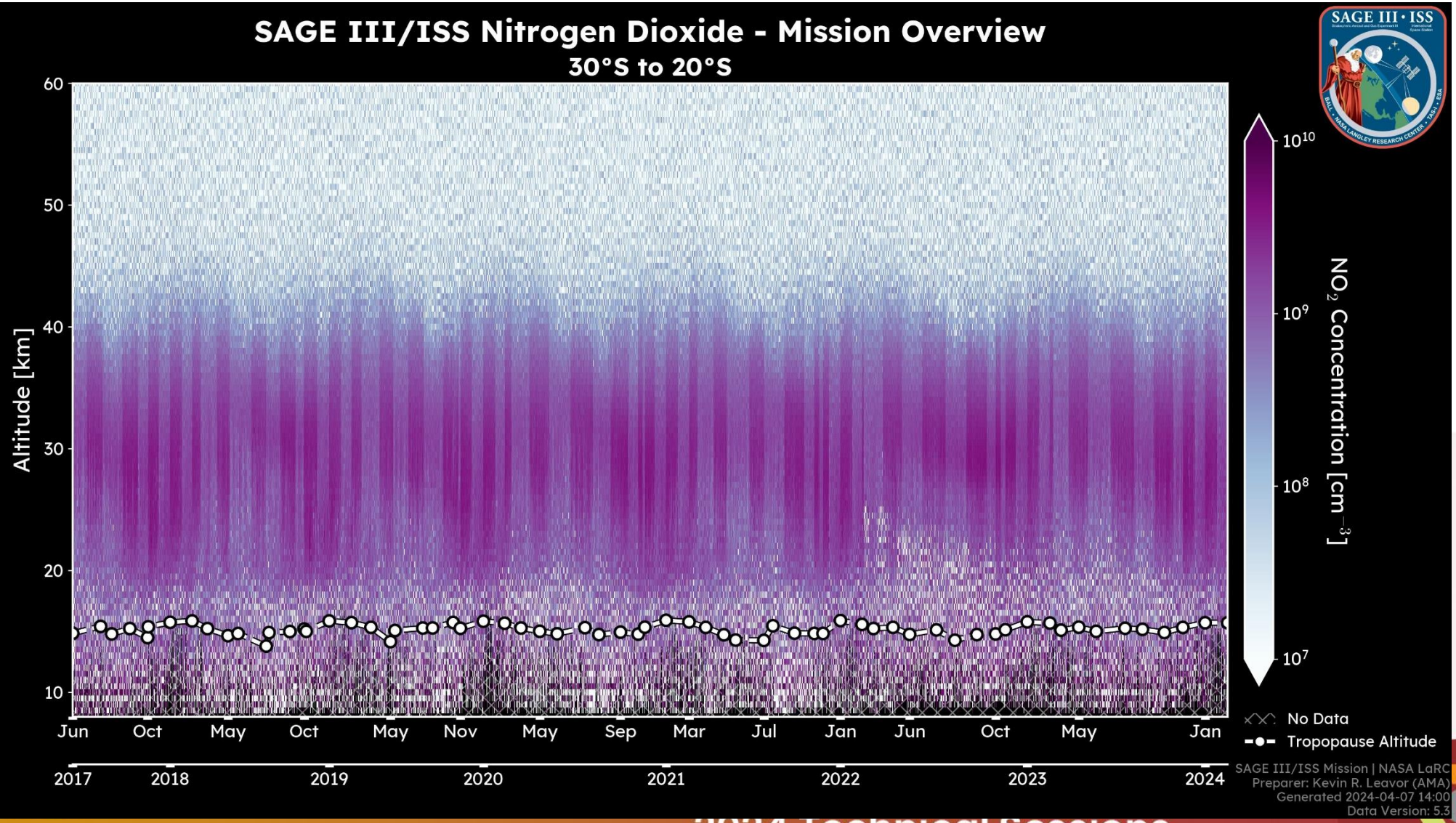


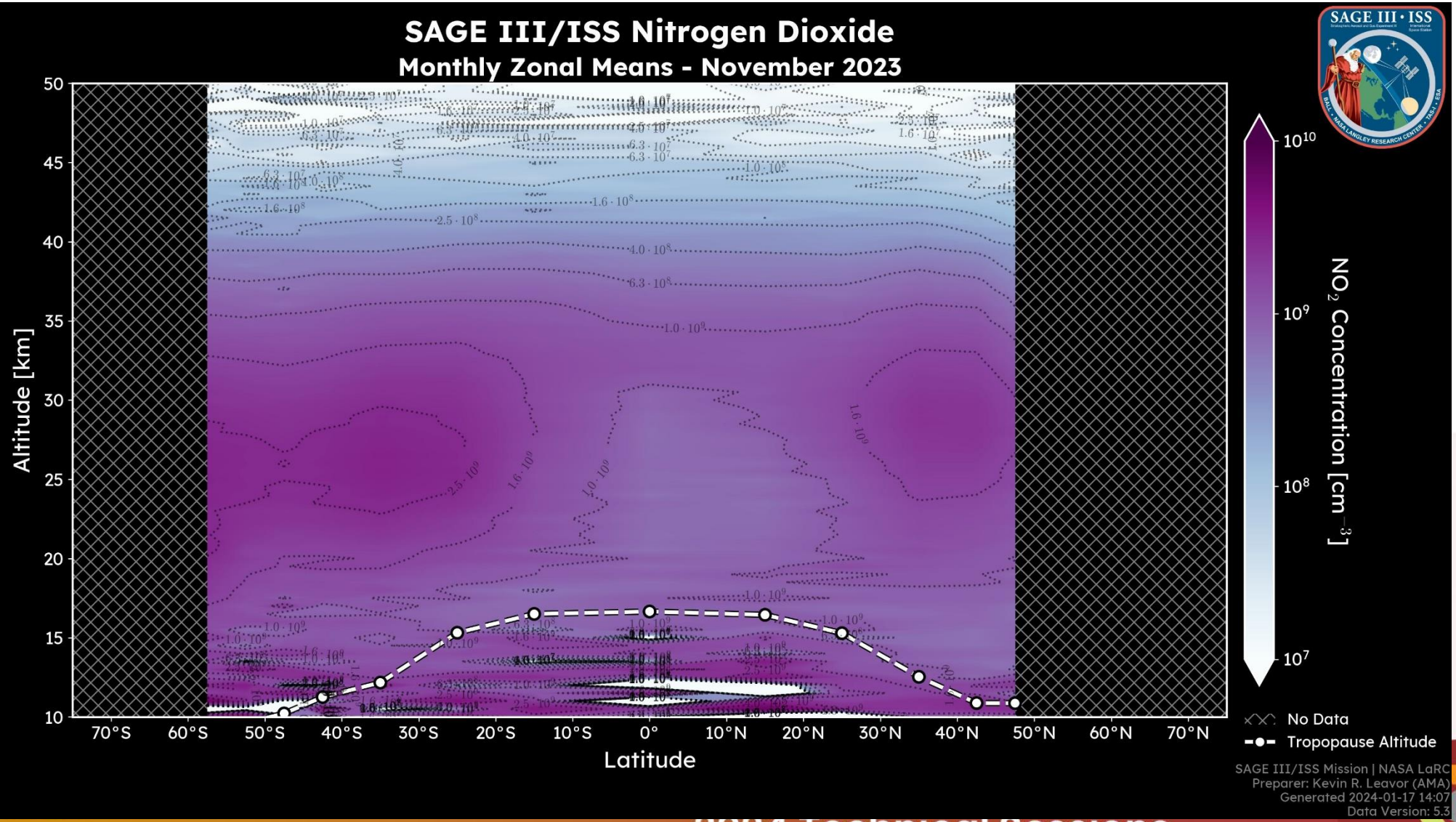
No Data

Tropopause Altitude

SAGE III/ISS Mission | NASA LaRC
Preparer: Kevin R. Leavor (AMA)
Generated 2023-07-13 16:58
Data Version: 5.3

# Nitrogen Dioxide ($NO_2$)




SAGE III/ISS Nitrogen Dioxide
Monthly Zonal Means - November 2023
Altitude [km]
Latitude
70°S 60°S 50°S 40°S 30°S 20°S 10°S 0° 10°N 20°N 30°N 40°N 50°N 60°N 70°N
10 15 20 25 30 35 40 45 50
$NO_2$ Concentration [$cm^{-3}$]
$10^{10}$
$10^{9}$
$10^{8}$
$10^{7}$
No Data
Tropopause Altitude
SAGE III/ISS Mission | NASA LaRC
Preparer: Kevin R. Leavor (AMA)
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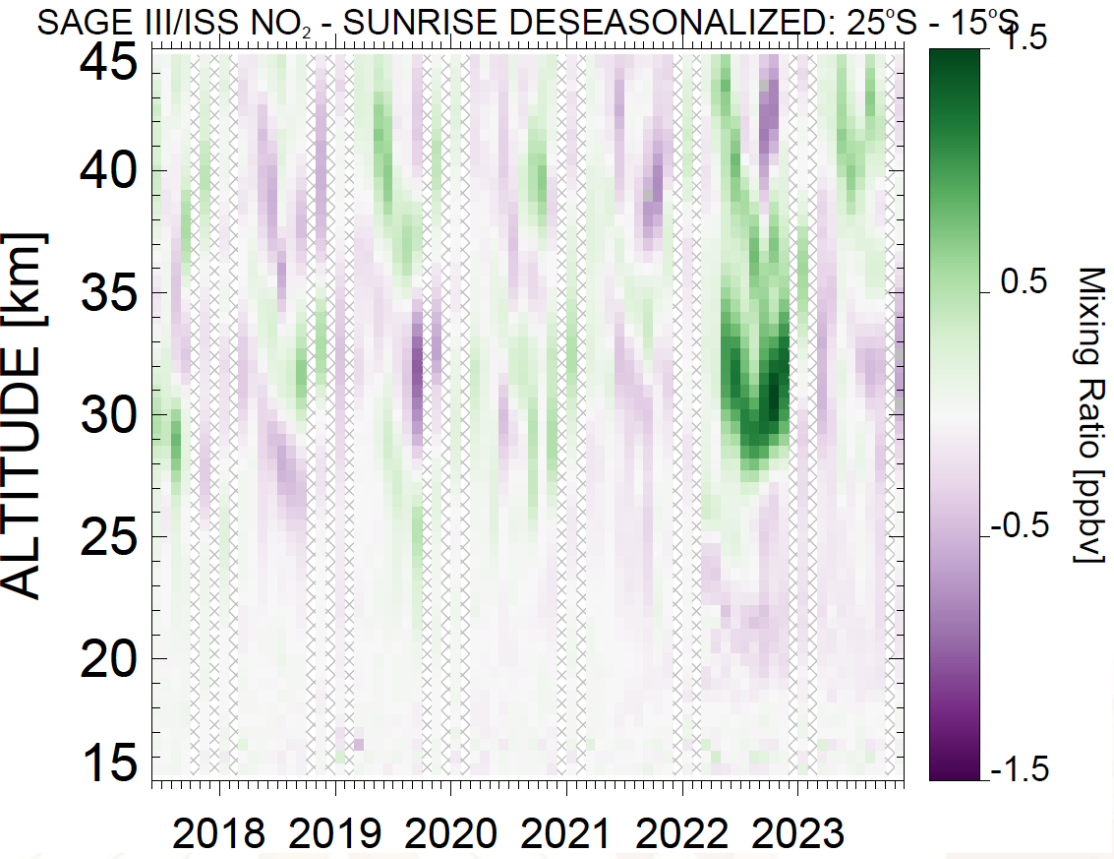
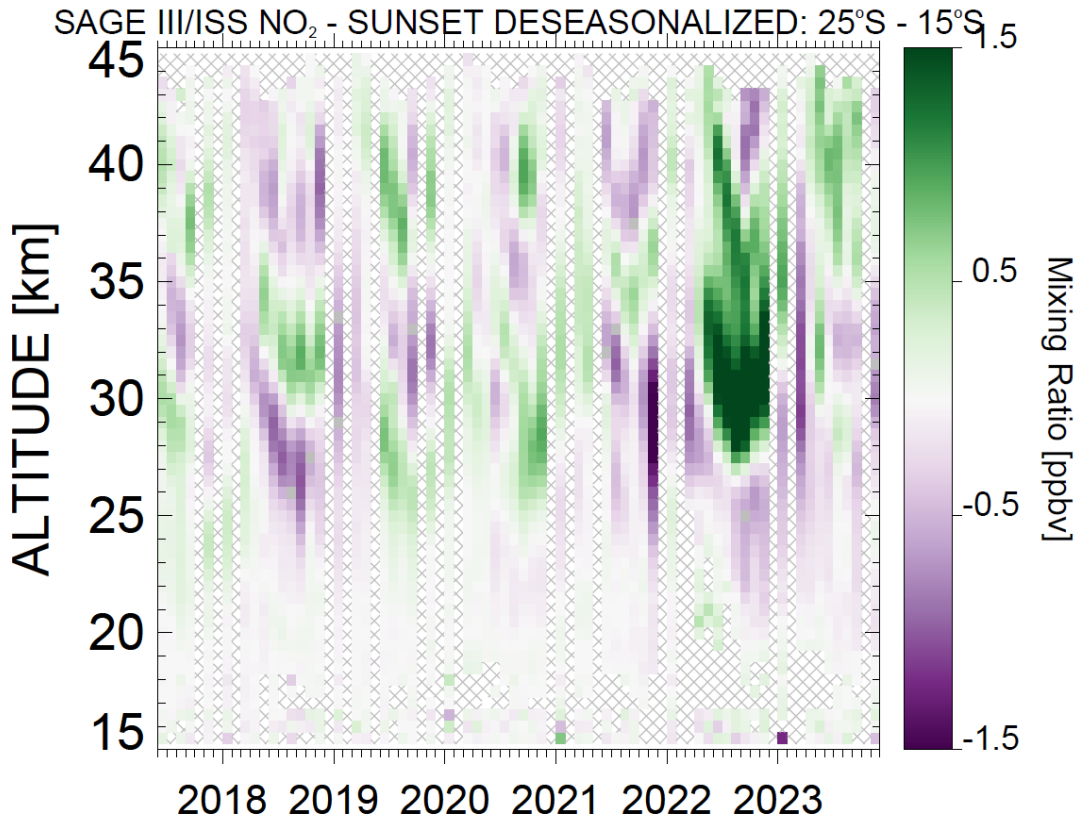
Data Version: 5.3

# $NO_2$ anomalies in latitude band of HTHH eruption

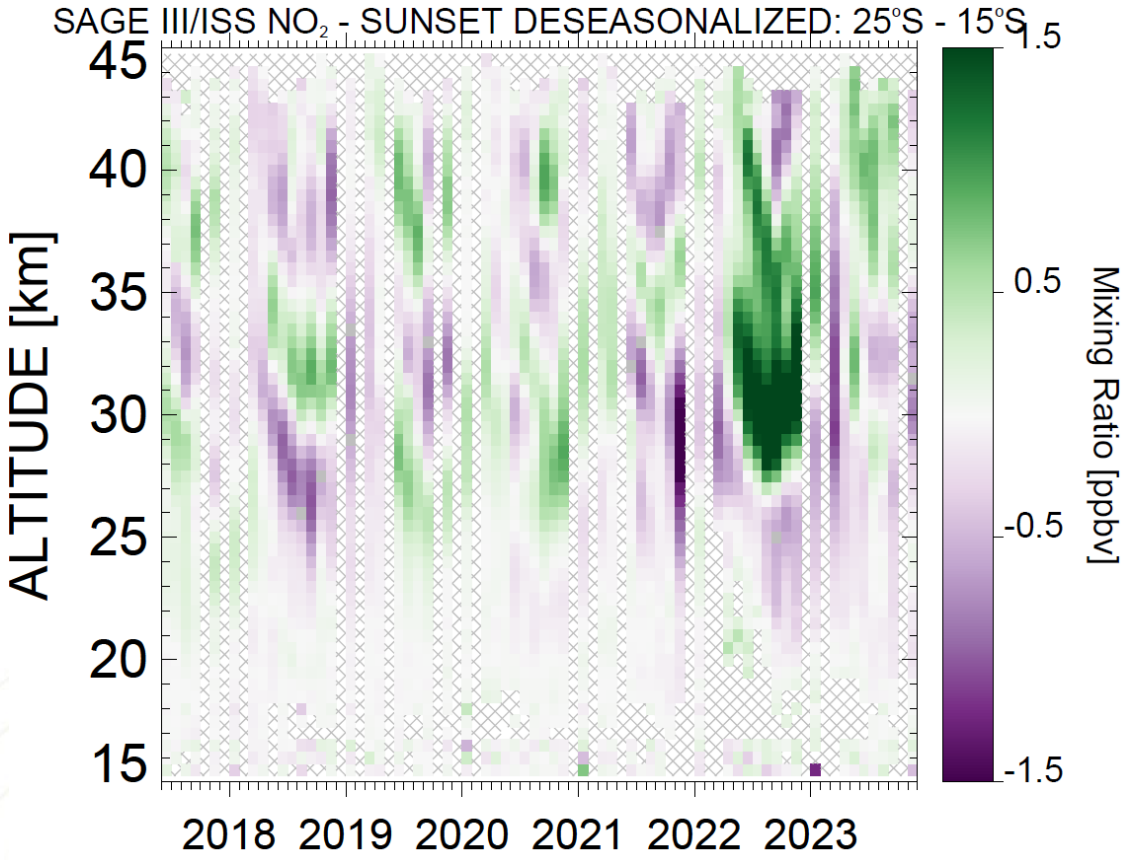


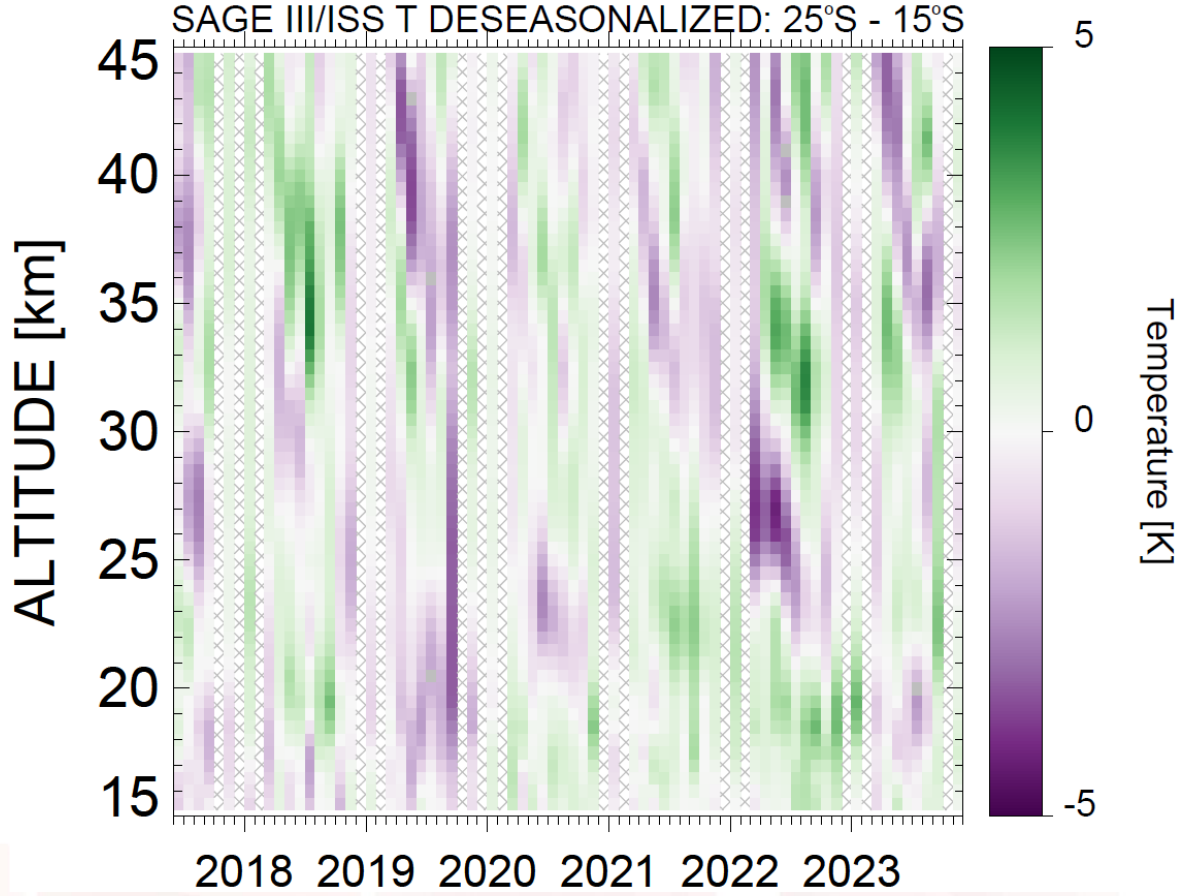




- Deseasonalized $NO_2$ has similar patterns in SR and SS, but different absolute magnitude

- Anomalies after HTHH largest in 6 yr record
  - Increases > 2 ppbv above the aerosol layer
  - Decreases occur below the increases

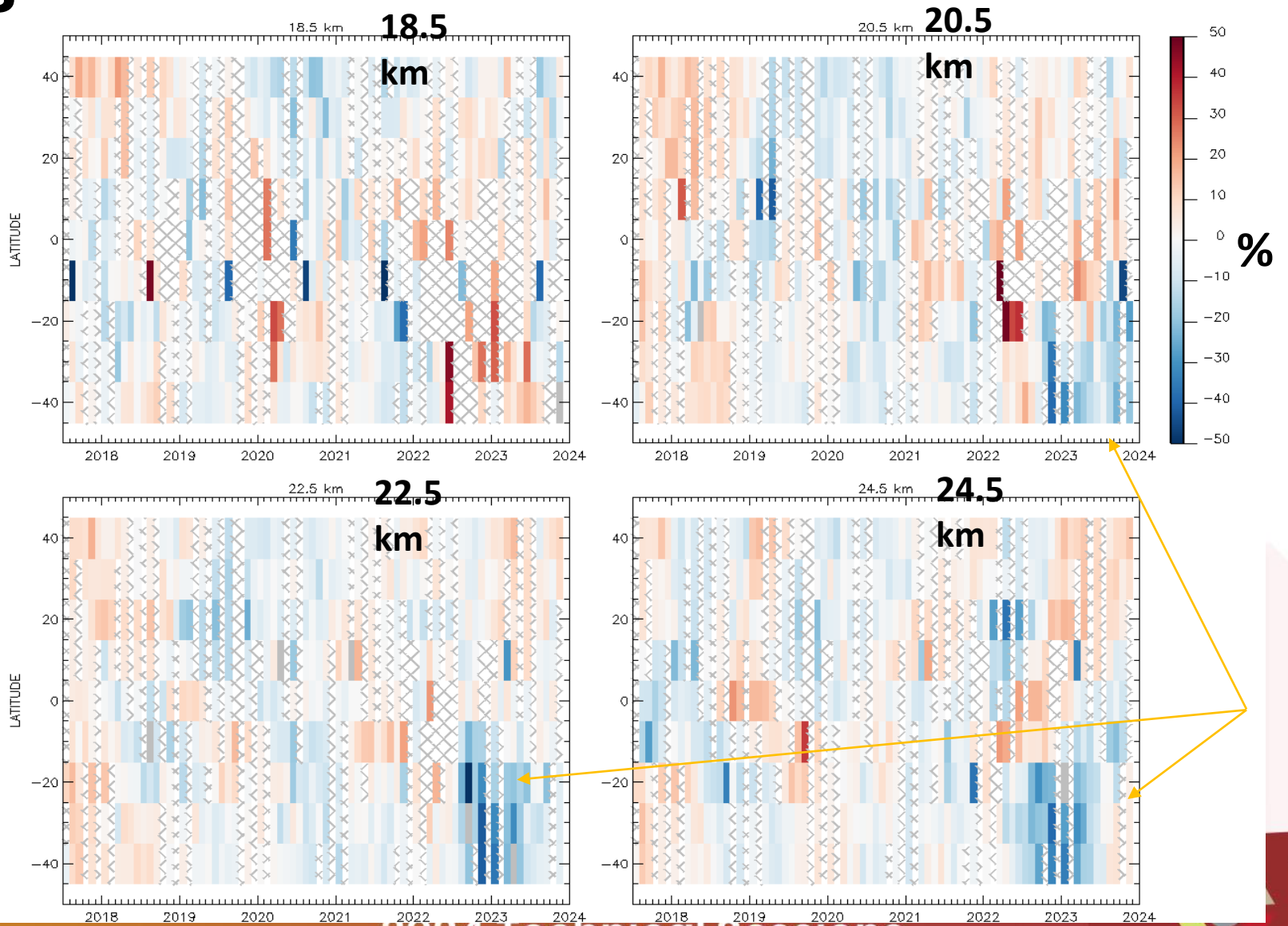
# Correlation with temperature changes is opposite during 2022 vs. rest of record



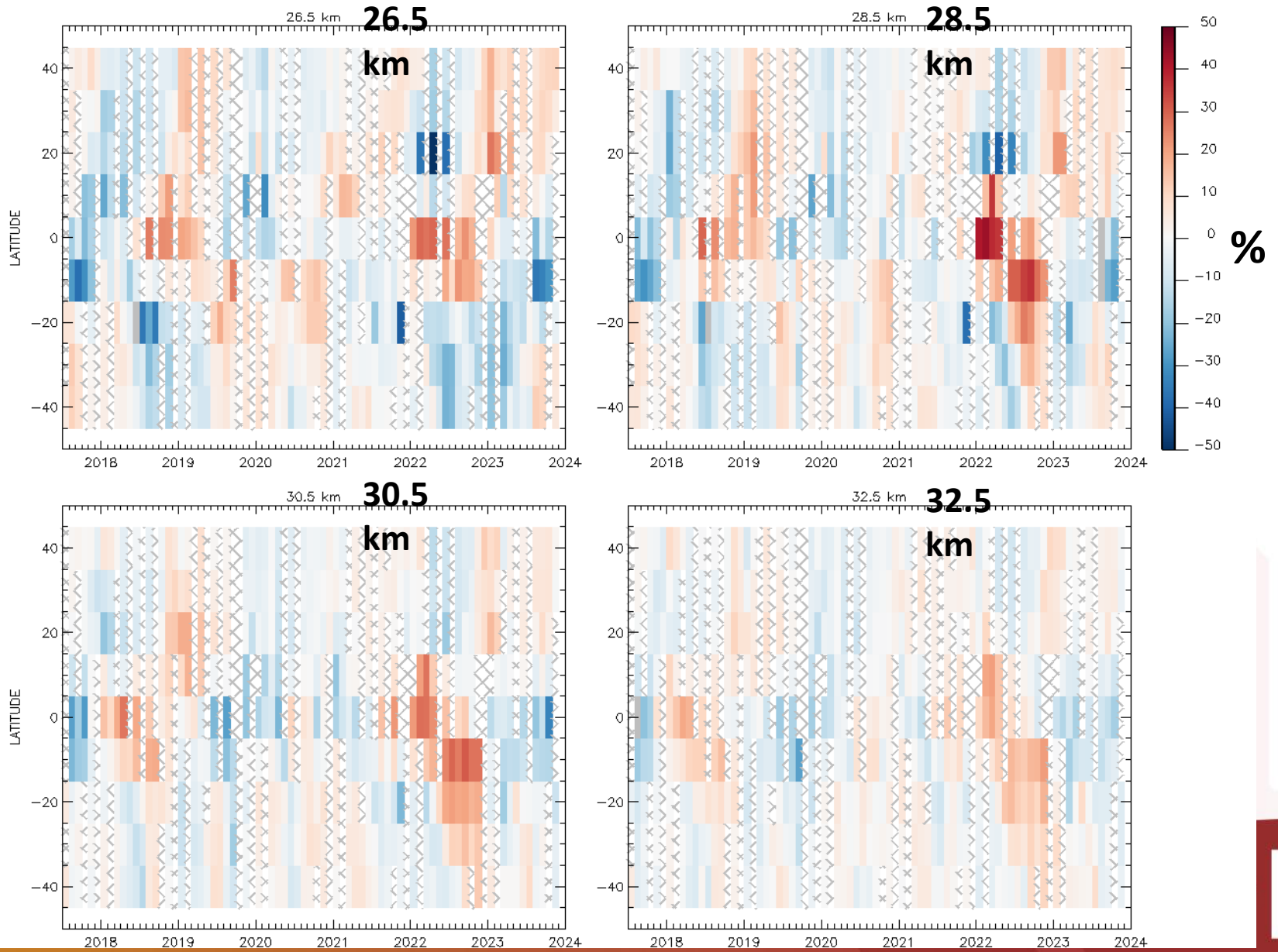
# Deseasonalized sunset $NO_2$ on constant altitude surfaces

- Changes a

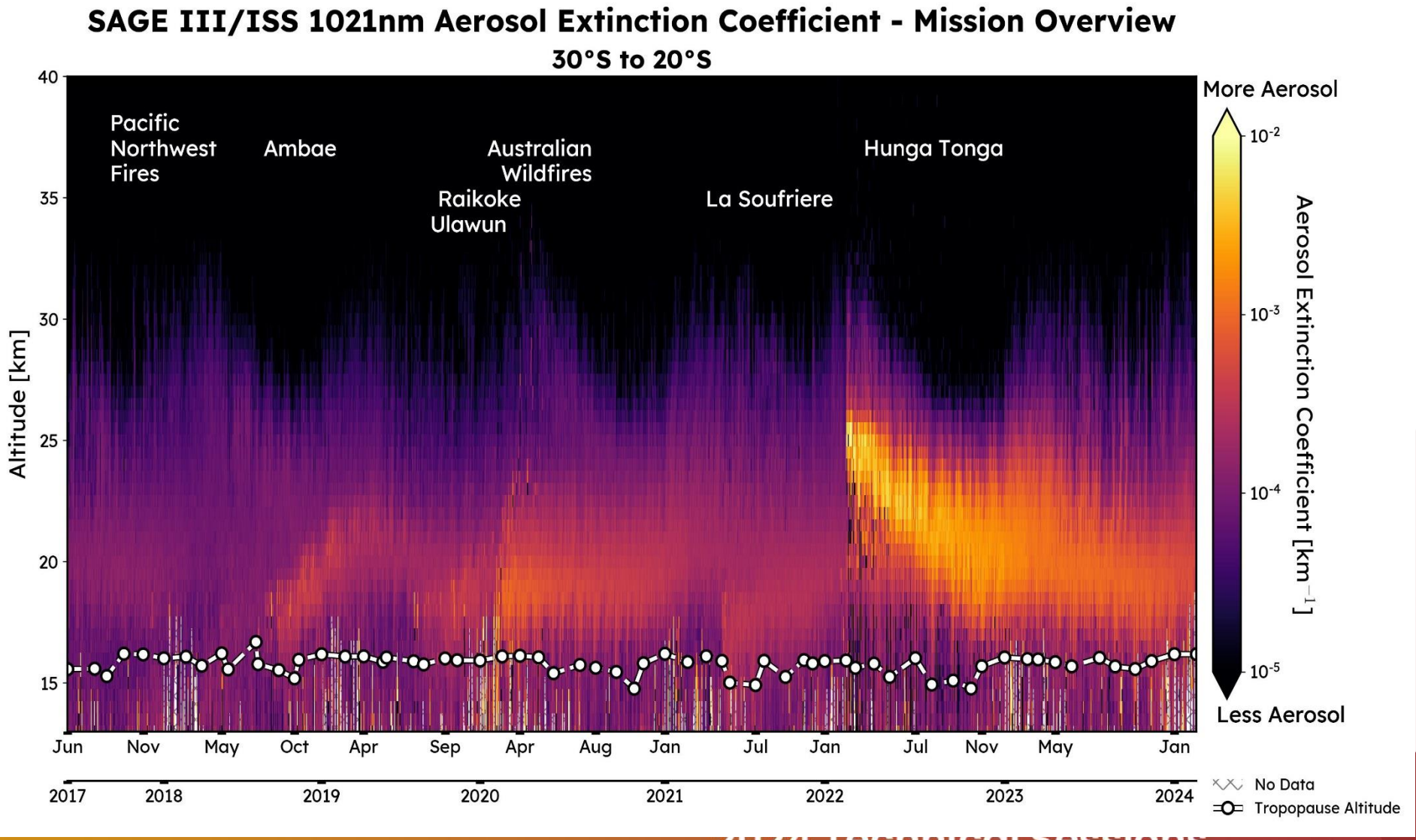


# Deseasonalized sunset $NO_2$ on constant altitude surface

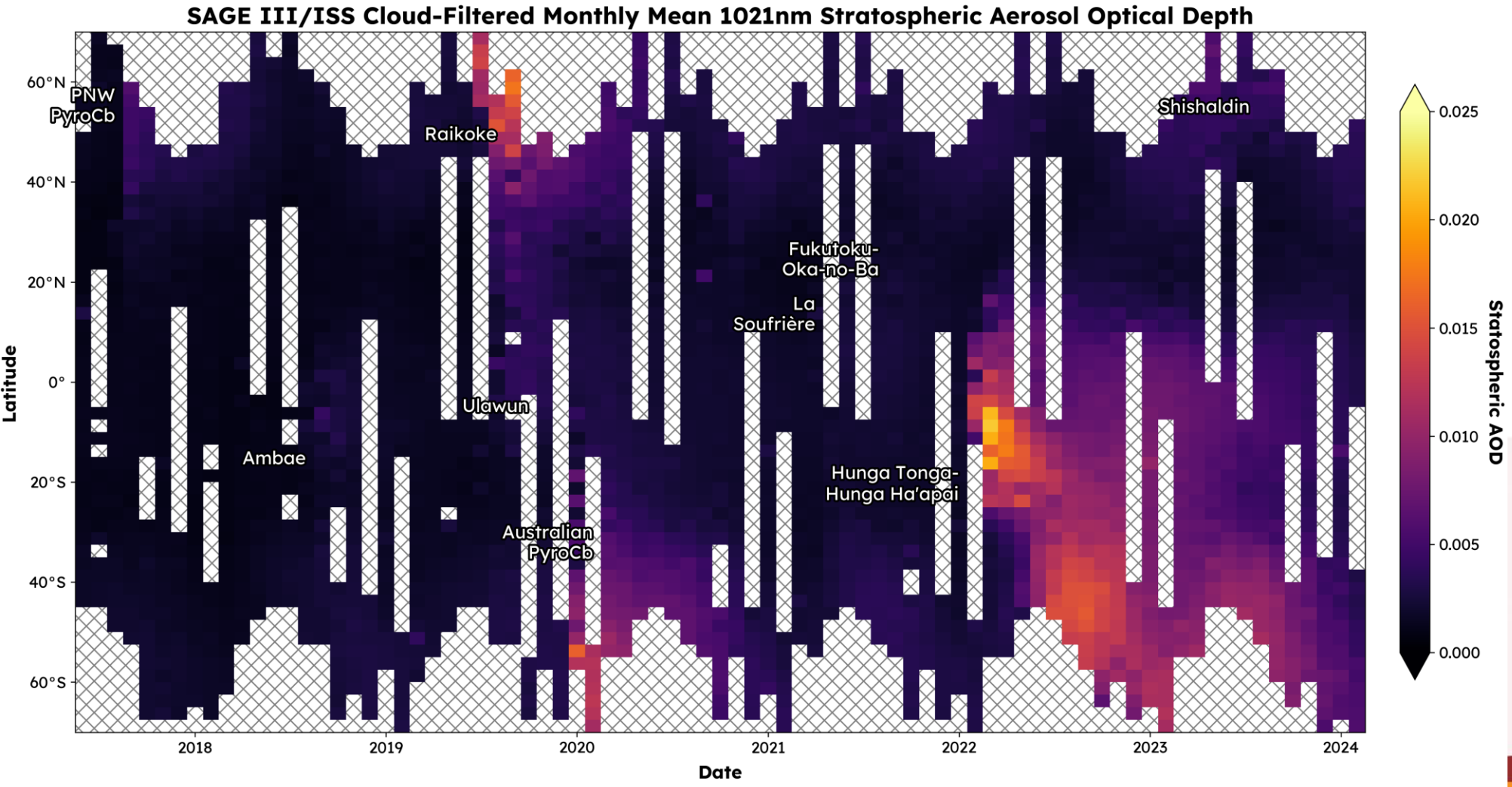
- Changes



# Stratospheric Aerosol

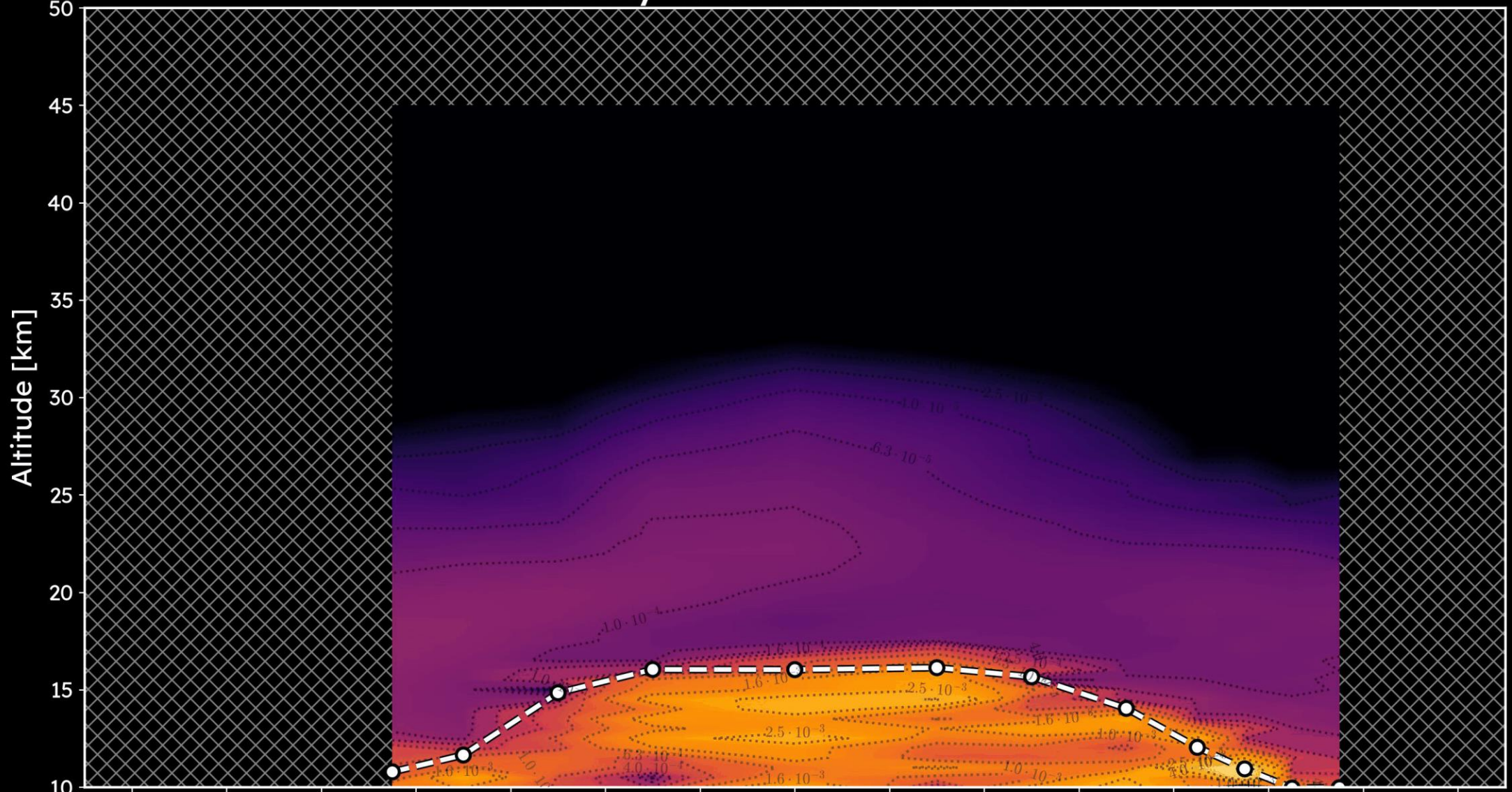


# Stratospheric Aerosol Optical Depth



# SAGE III/ISS 1021nm Aerosol Extinction Coefficient

## Monthly Zonal Means - June 2017





No Data

Tropopause Altitude

SAGE III/ISS Mission | NASA LaRC
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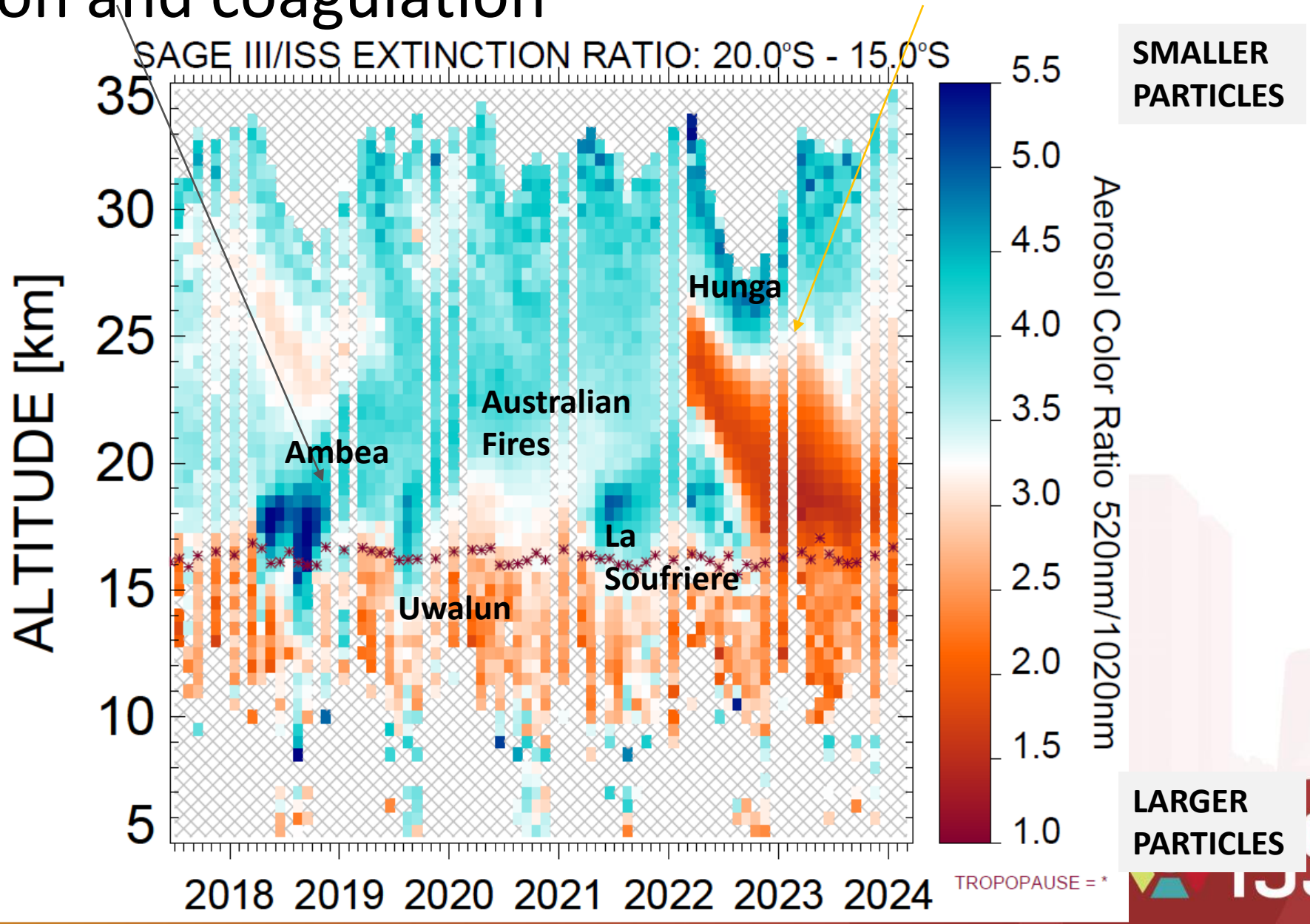
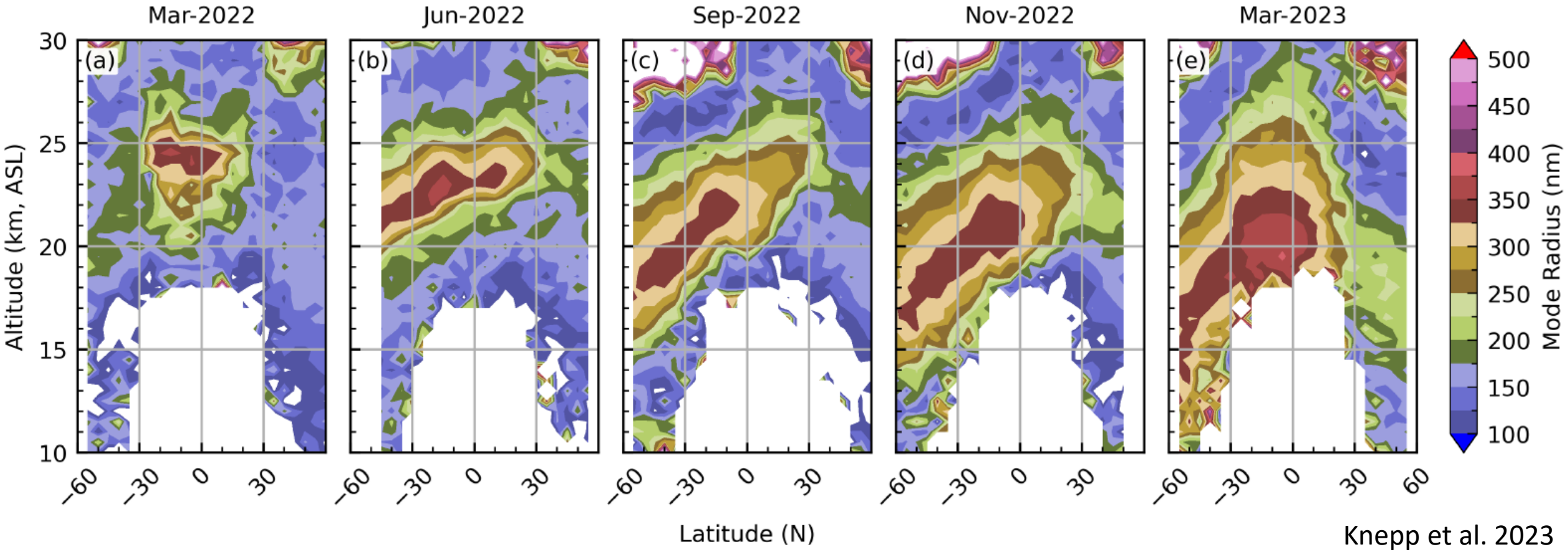
Data Version: 5.3

# Multi-wavelength data shows events with new particle formation and coagulation



# Estimated Mode Particle Radius from Multi-wavelength Data



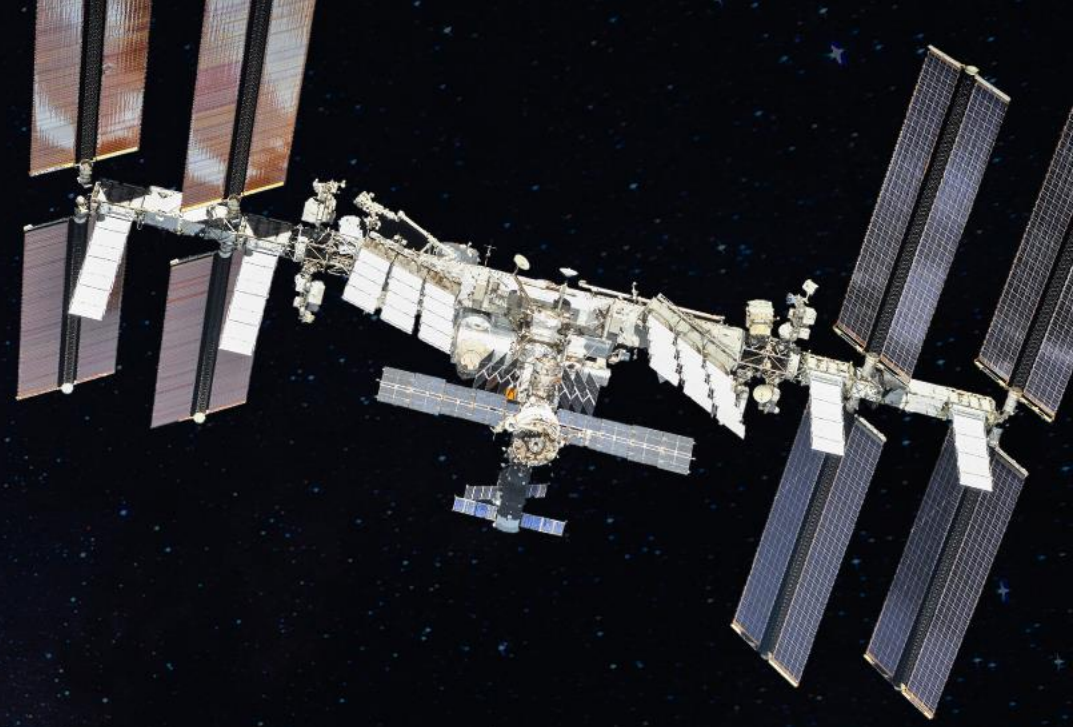

Knepp et al. 2023

**More than 2 yrs later, the global stratospheric aerosols are still under the influence of Hunga eruption in terms of size and amount**

# Summary

- **SAGE III/ISS is a collaborative Earth science mission – key element in climate observing system - to study the recovery of the global ozone layer and the evolving climate.**
- **Since June 2017, SAGE III/ISS has documented many natural variations of stratospheric constituents and the historical perturbation by the Hunga volcanic eruption.**
  - **Largest perturbation of $H_2O$ in SAGE II & III records**
  - **Largest $NO_2$ perturbation in SAGE III record**
  - **Aerosol increase from Pinatubo still largest in SAGE record**
- Mission approved through 2026, manifested on ISS through 2030, bridging to future missions observing the stratosphere


ELC4
ESP3



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-Earth Science Division

NASA Space Operations Mission Directorate

-ISS Program Office

European Space Agency

-Thales Alenia Space

NASA Langley Research Center manages the mission for NASA Earth Science with major contributions from the ISS Program and the European Space Agency.

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