Stratospheric Aerosol Observations and Modeling

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Acknowledgements

- Sampa Das, Parker Case, Ghassan Taha, Luke Oman, Qing Liang, Nick Krotkov, Won-Ei Choi, Paul Newman, Mike Manyin, Steve Steenrod, Valentina Aquila, Kostas Tsigaridis, Robert Field, Nick Gorkavyi, Matt DeLand, Matt Kowalewski and ARGOS team
- Ex-Officio: Arlindo da Silva, Mian Chin, Anne Douglass, Rich Stolarski

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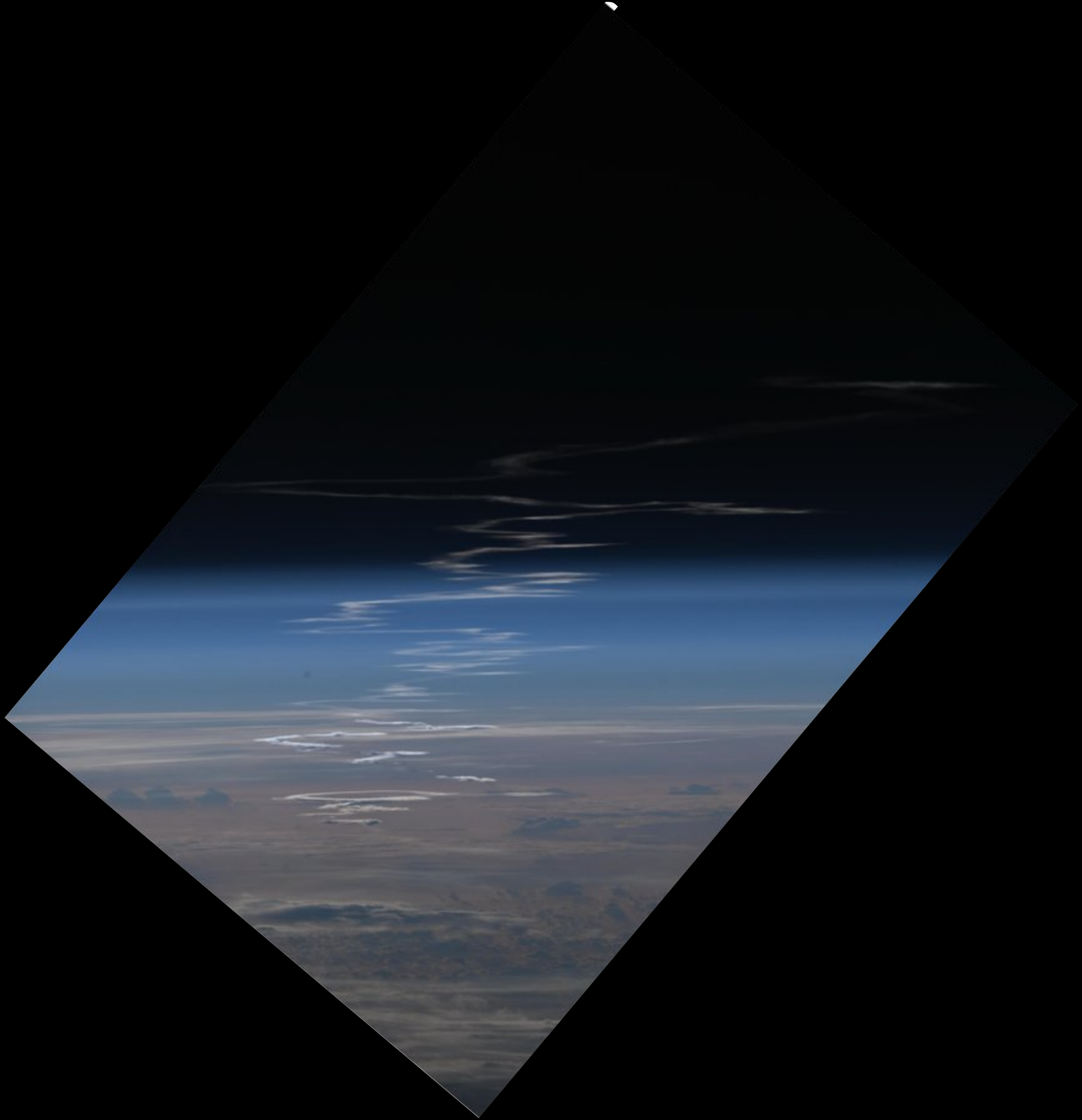


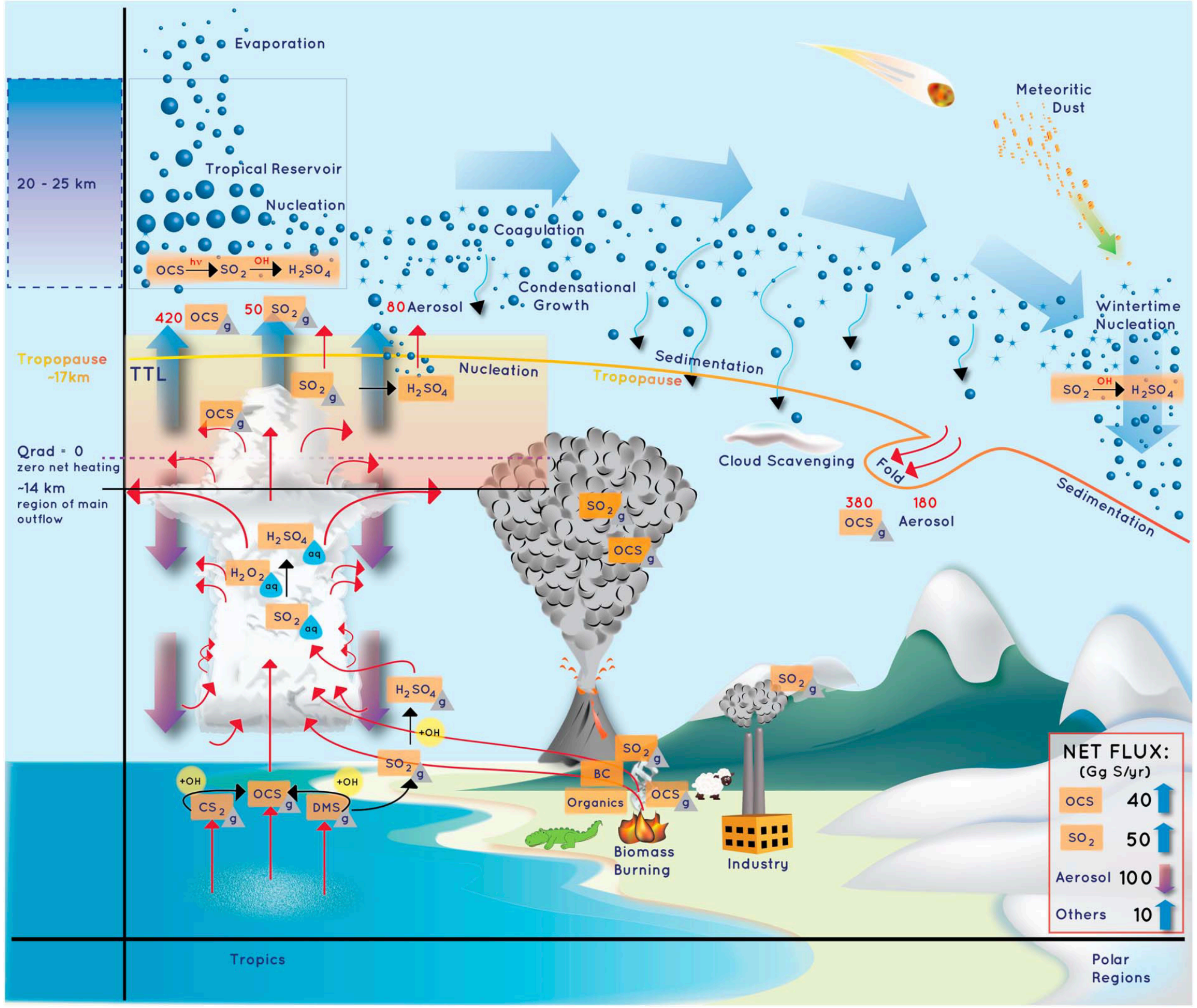
ARTEMIS 2 Launch

ISS image of the plume from the ARTEMIS 2 launch, April 1 2026

Outline

- What stratospheric aerosol is and why it is important
- How we observe and model it
- How it impacts temperature, circulation, chemistry, and retrieval products
- Upcoming field and satellite missions
- Where we go from here

The Stratospheric Aerosol



- Layer of aerosol between roughly the tropopause and 25 km altitude
- Naturally occurring component due to oxidation of biogenic precursors at high altitudes (the “Junge” layer discovered in 1950s)
- Frequently perturbed by volcanic eruptions, pyroCb smoke plumes, surface anthropogenic sources, and increasingly by debris for rocket launches and reentry events
- NB: this is the layer of aerosol that would be directly and intentionally perturbed in stratospheric aerosol injection geoegineering strategies

Kremser, S., Thomason, L. W., Hobe, M. von, Hermann, M., Deshler, T., Timmreck, C., Toohey, M., Stenke, A., Schwarz, J. P., Weigel, R., Fueglistaler, S., Prata, F. J., Vernier, J., Schlager, H., Barnes, J. E., Antuña-Marrero, J., Fairlie, D., Palm, M., Mahieu, E., Notholt, J., Rex, M., Bingen, C., Vanhellemont, F., Bourassa, A., Plane, J. M. C., Klocke, D., Carn, S. A., Clarisse, L., Trickl, T., Neely, R., James, A. D., Rieger, L., Wilson, J. C., and Meland, B.: Stratospheric aerosol—Observations, processes, and impact on climate, Rev Geophys, 54, 278–335, https://doi.org/10.1002/2015rg000511, 2016.

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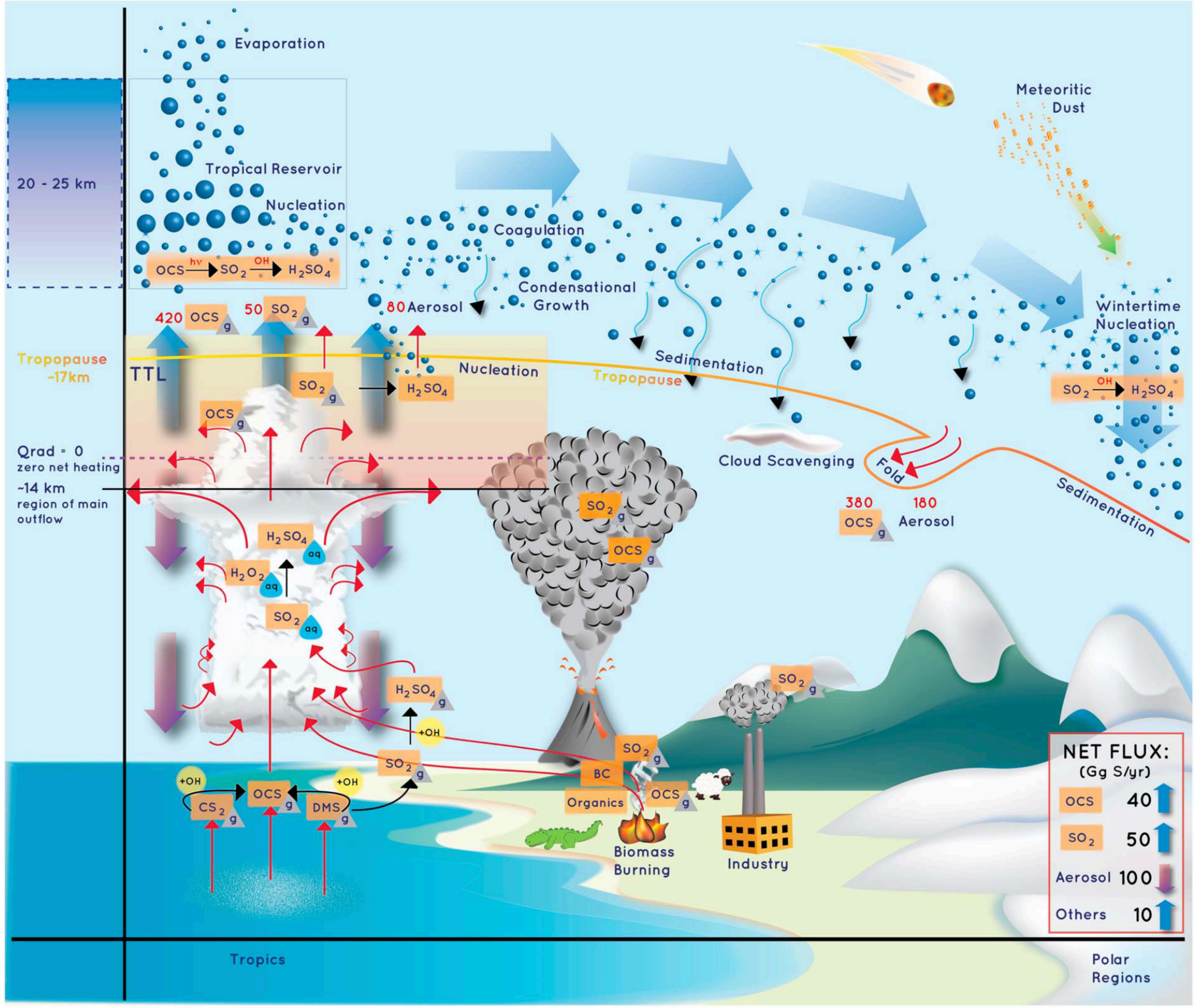
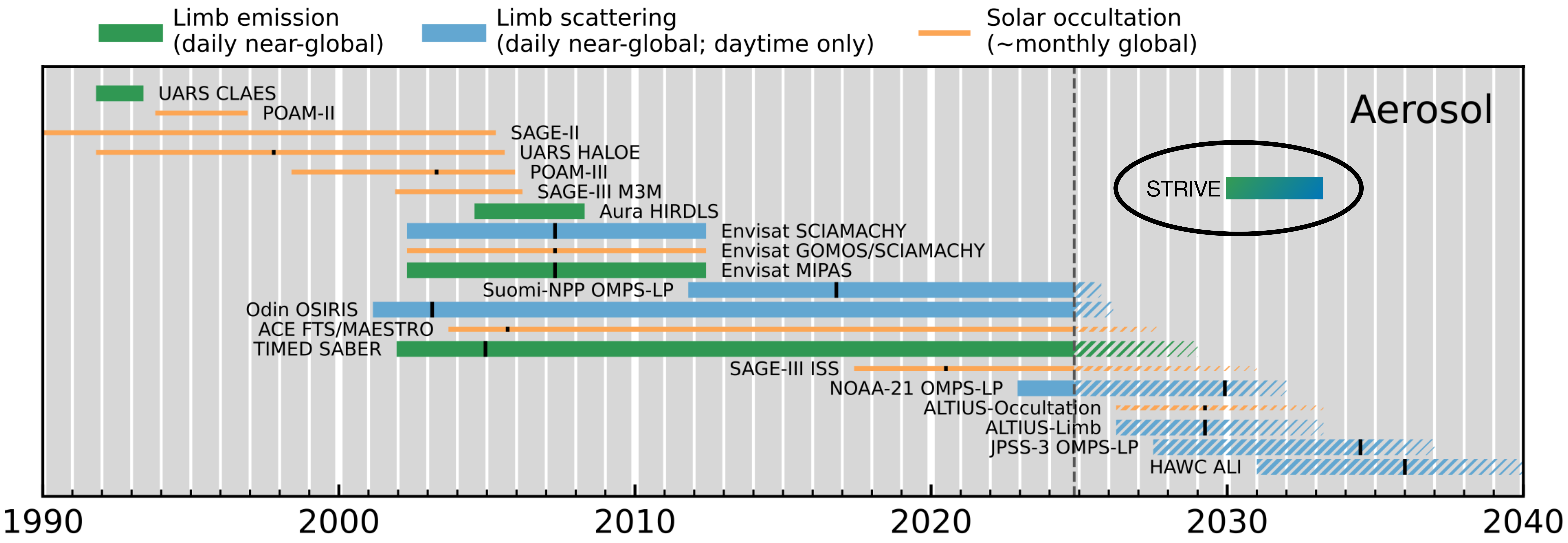
The Stratospheric Aerosol



- **Radiative Forcing:** Increases in the stratospheric aerosol loading lead to warming in the stratosphere and cooling at the surface (e.g., peak 2K stratospheric warming and ~0.4K surface cooling after Pinatubo)
- **Heterogeneous Chemistry:** Increased particle surface area following volcanic eruptions and pyroCb injections is associated with depletion of ozone at stratospheric altitudes

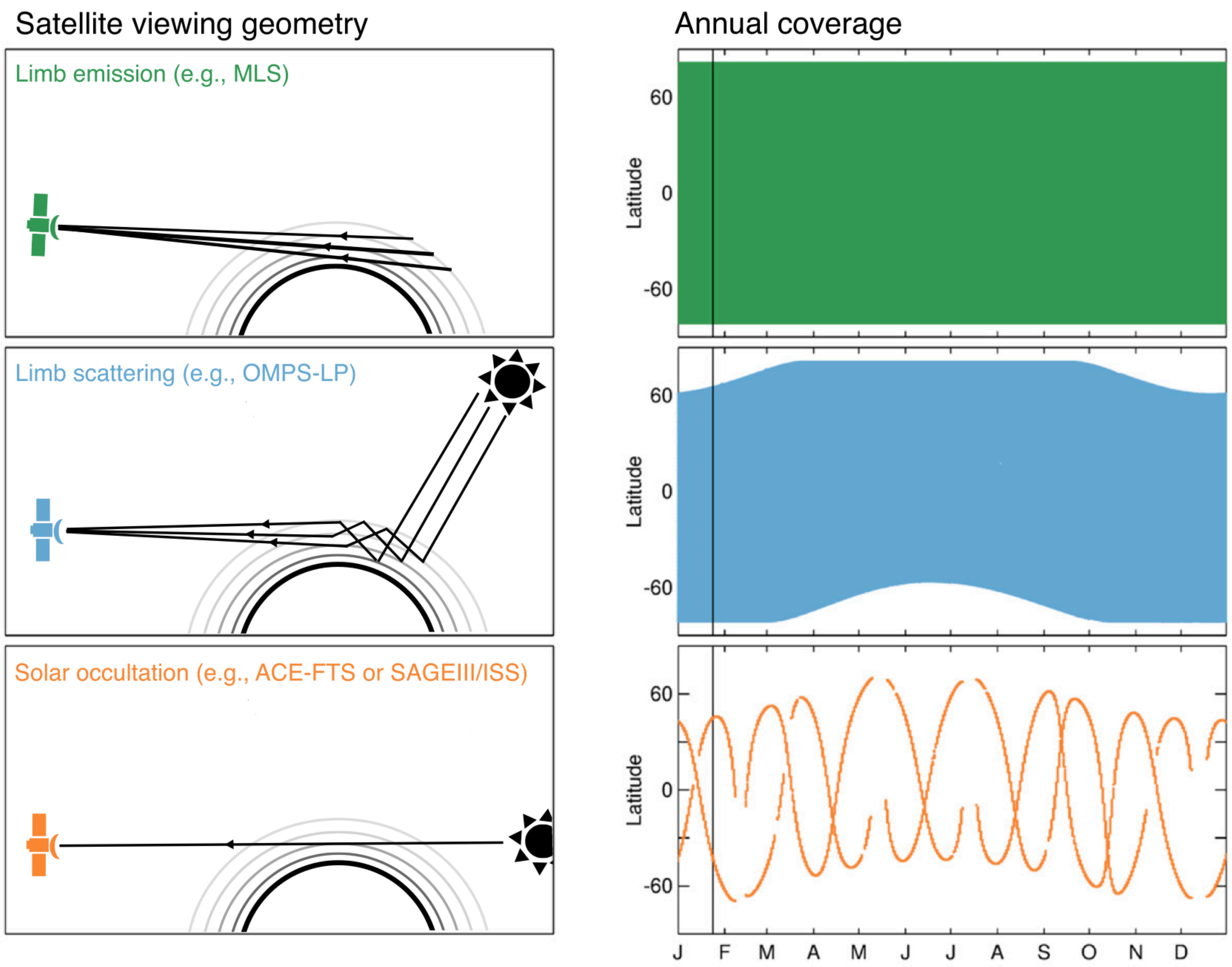
Kremser, S., Thomason, L. W., Hobe, M. von, Hermann, M., Deshler, T., Timmreck, C., Toohey, M., Stenke, A., Schwarz, J. P., Weigel, R., Fueglistaler, S., Prata, F. J., Vernier, J., Schlager, H., Barnes, J. E., Antuña-Marrero, J., Fairlie, D., Palm, M., Mahieu, E., Notholt, J., Rex, M., Bingen, C., Vanhellemont, F., Bourassa, A., Plane, J. M. C., Klocke, D., Carn, S. A., Clarisse, L., Trickl, T., Neely, R., James, A. D., Rieger, L., Wilson, J. C., and Meland, B.: Stratospheric aerosol—Observations, processes, and impact on climate, Rev Geophys, 54, 278–335, https://doi.org/10.1002/2015rg000511, 2016.

Satellite Limb Observations



Salawitch, R. J., Smith, J. B., Selkirk, H., Wargan, K., Chipperfield, M. P., Hossaini, R., Levelt, P. F., Livesey, N. J., McBride, L. A., Millán, L. F., Moyer, E., Santee, M. L., Schoeberl, M. R., Solomon, S., Stone, K., and Worden, H. M.: The Imminent Data Desert: The Future of Stratospheric Monitoring in a Rapidly Changing World, Bull. Am. Meteorol. Soc., 106, E540–E563, https://doi.org/10.1175/bams-d-23-0281.1, 2025.

Limb Viewing Geometry



- The long path length of limb observations gives exceptional sensitivity and allows you to vertically resolve features
- Occultation is as close to a direct measurement as possible, but at the expense of spatial coverage
- Scattering requires retrieval assumptions (PSD) but has better coverage

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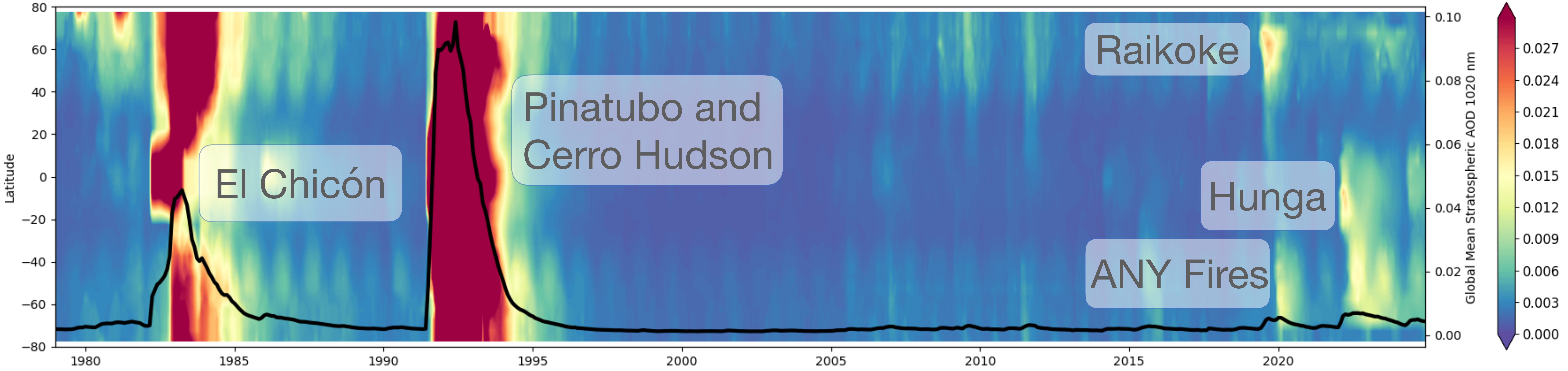
GloSSAC Record of Stratospheric AOD

- Global Space-based Stratospheric Aerosol Climatology
- Leans on SAGE occultation observations prior to 2005 and since 2017, complemented with CALIPSO lidar, OSIRIS and other datasets in gaps



https://asdc.larc.nasa.gov/project/GloSSAC/GloSSAC_2.23

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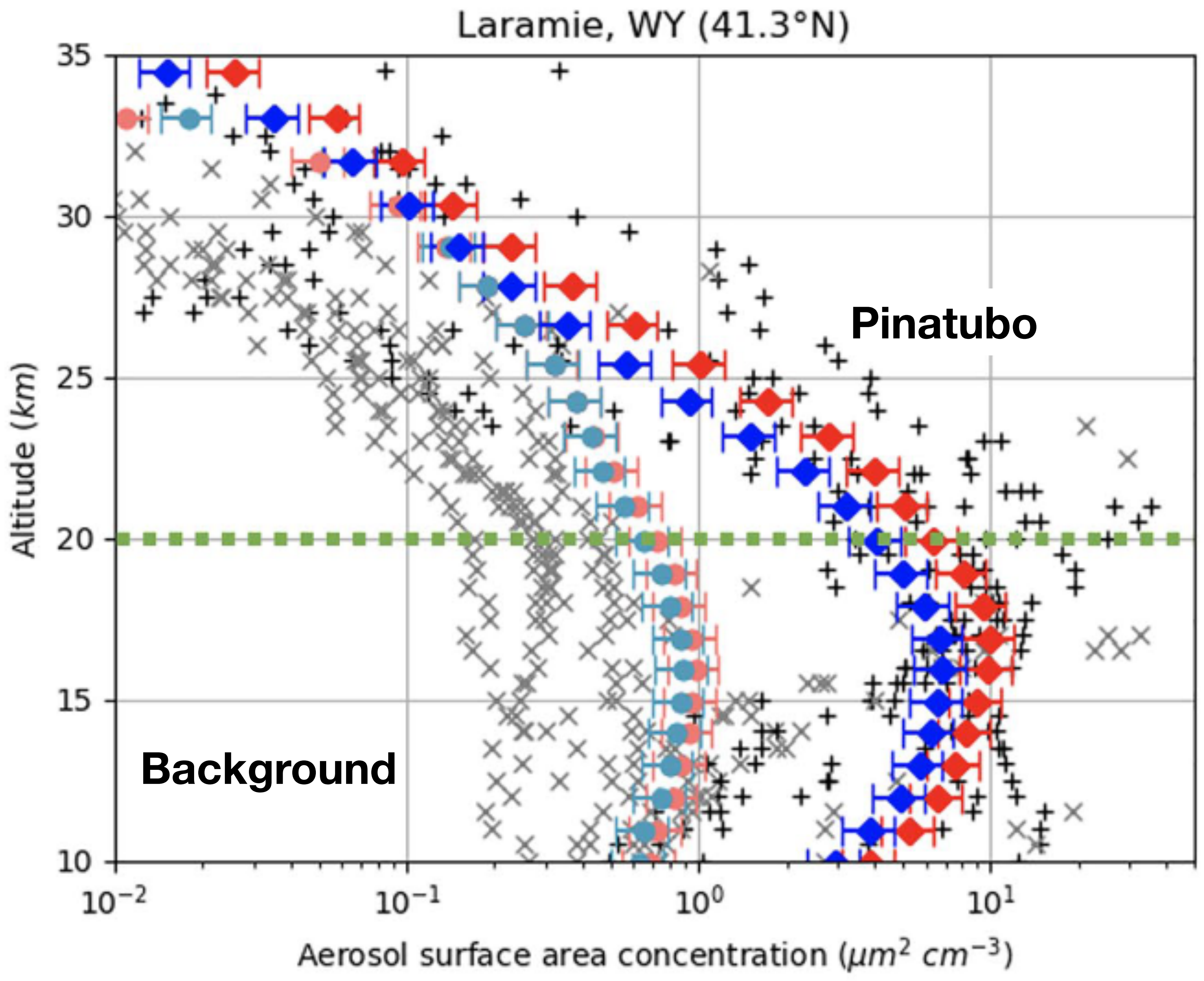
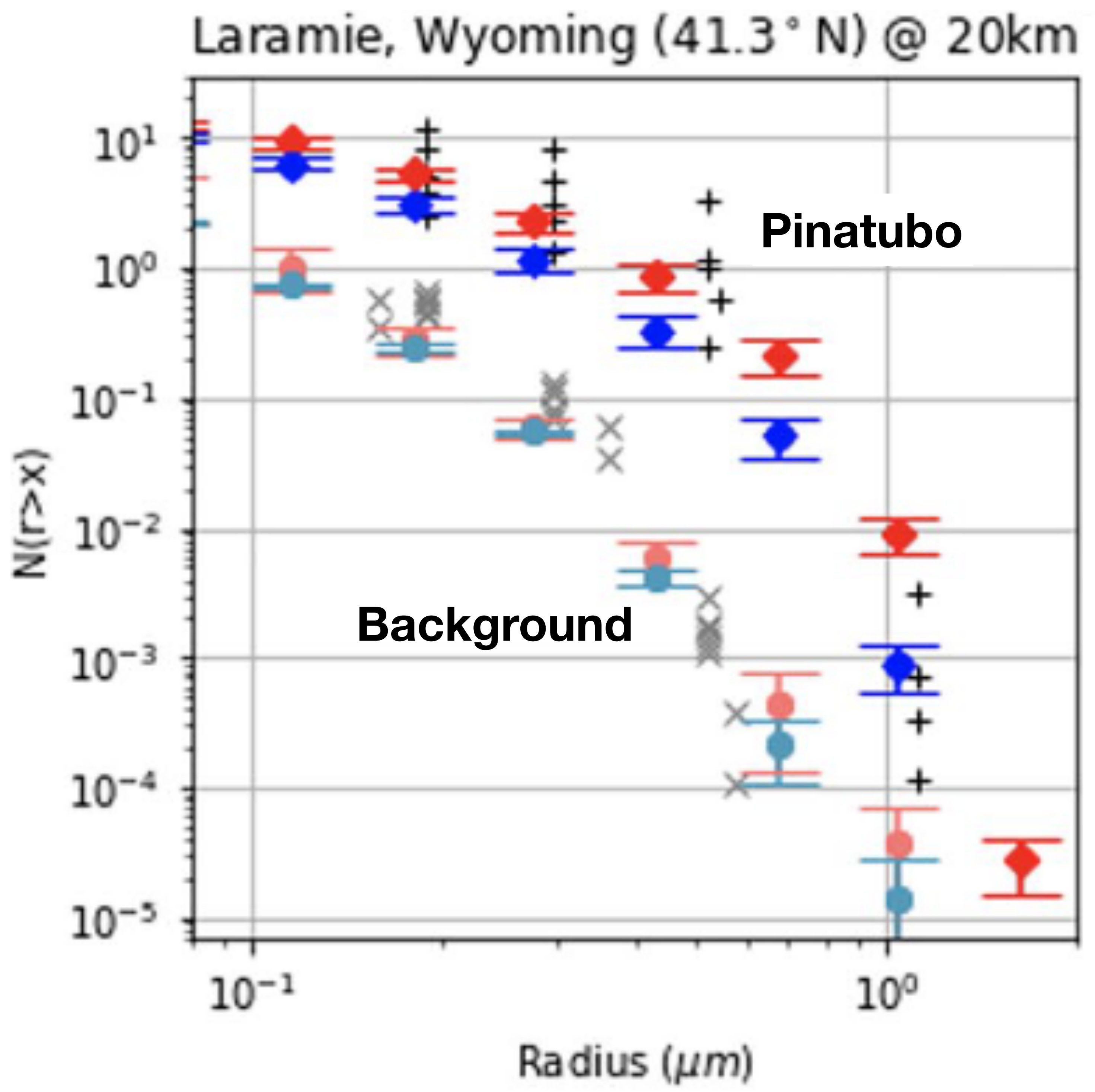
Pinatubo Changes Particle Size and Loading

- Chemical and radiative coupling: GEOS simulations with GEOS-Chem and CARMA microphysics coupled
- Now have size-resolved particle properties

Aerosol Surface Area



Particle Size Distribution



x/+ Balloon Observations at Laramie, Wyoming

●●◆◆ GEOS model simulations sampled at Laramie

Case, P., Colarco, P. R., Toon, B., Aquila, V., and Keller, C. A.: Interactive Stratospheric Aerosol Microphysics-Chemistry Simulations of the 1991 Pinatubo Volcanic Aerosols With Newly Coupled Sectional Aerosol and Stratosphere-Troposphere Chemistry Modules in the NASA GEOS Chemistry-Climate Model (CCM), J. Adv. Model. Earth Syst., 15, https://doi.org/10.1029/2022ms003147, 2023.

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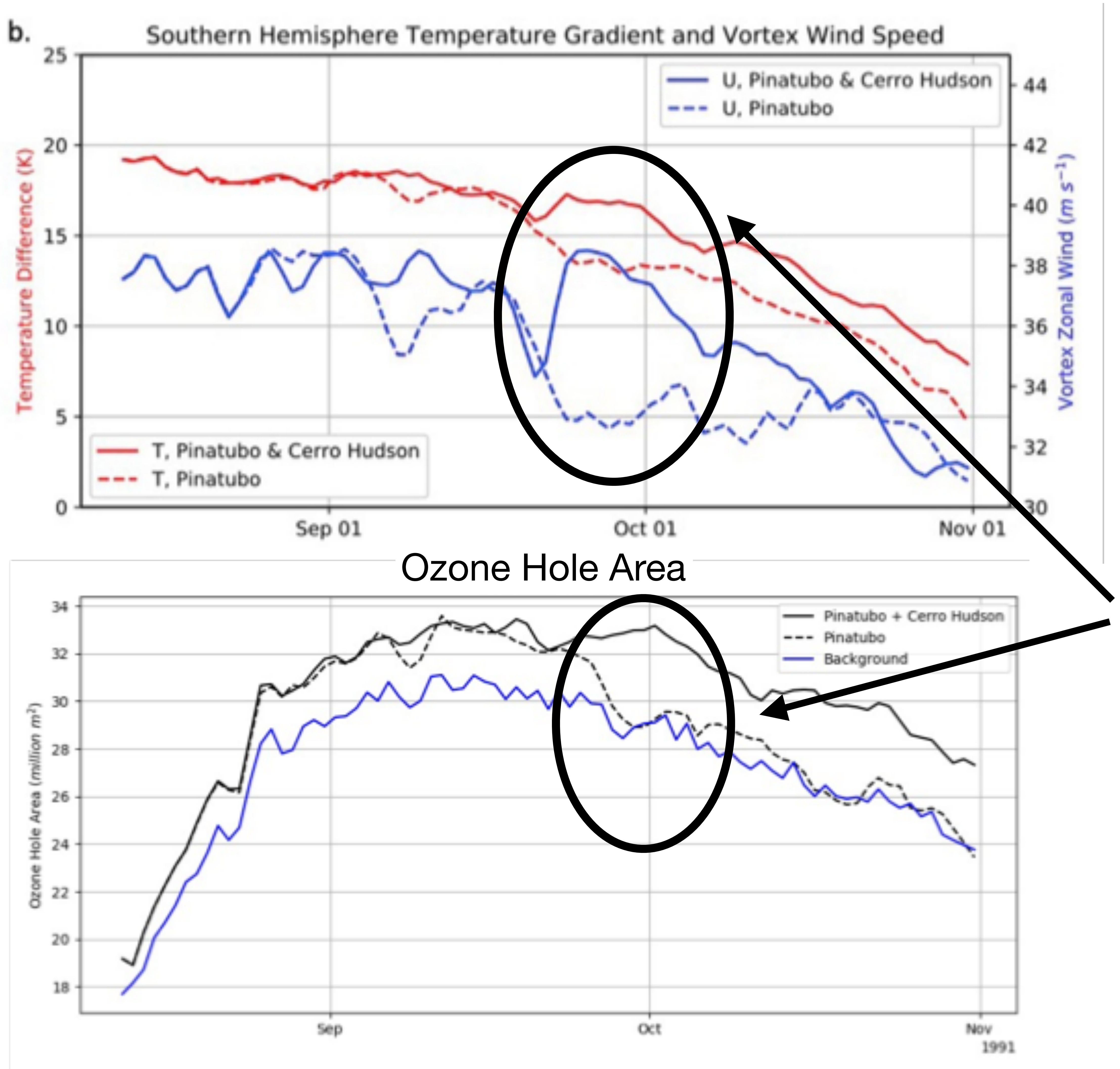
Cerro Hudson Helps Isolate Vortex

- Chemical and radiative coupling: GEOS simulations with GEOS-Chem and CARMA microphysics coupled
- Now have size-resolved particle properties
- Chemical and radiative coupling reveal the role of later Cerro Hudson eruption in isolating polar vortex



Case, P. A., Colarco, P. R., Toon, O. B., and Newman, P. A.: Simulating the Volcanic Sulfate Aerosols From the 1991 Eruption of Cerro Hudson and Their Impact on the 1991 Ozone Hole, Geophys. Res. Lett., 51, https://doi.org/10.1029/2023gl106619, 2024.

Vortex more isolated in simulations with Cerro Hudson

- zonal wind speed enhanced
- ozone hole area is greater

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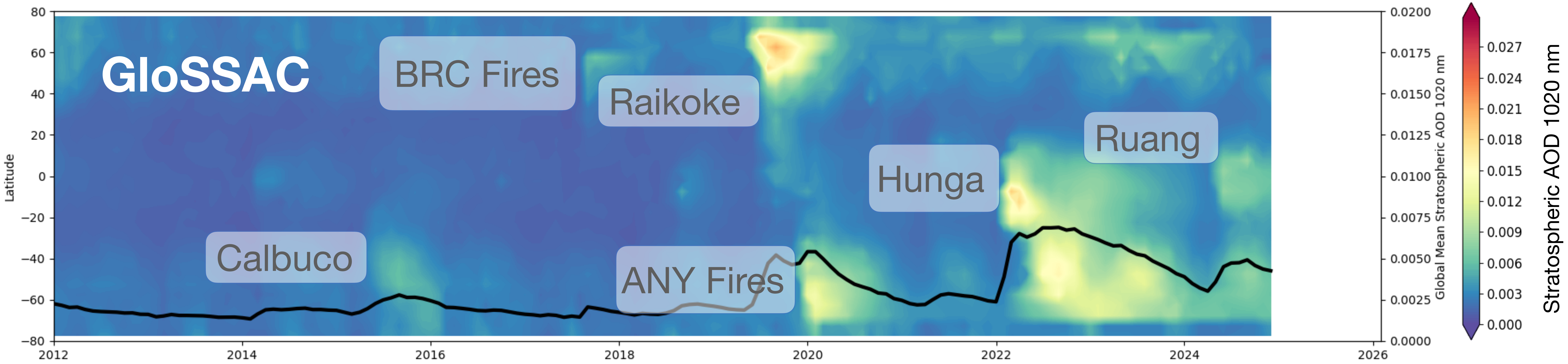
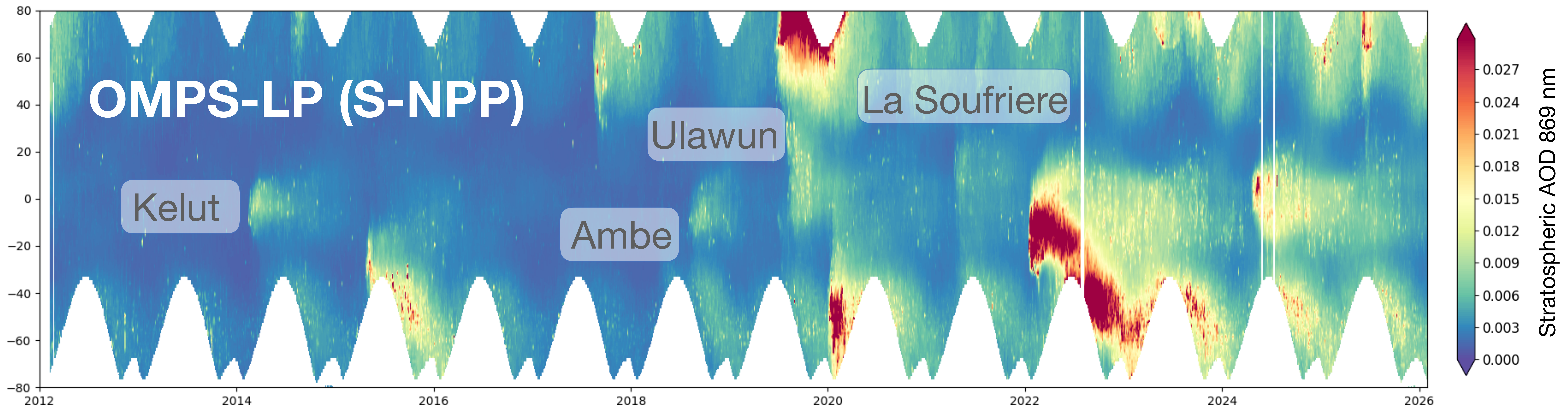
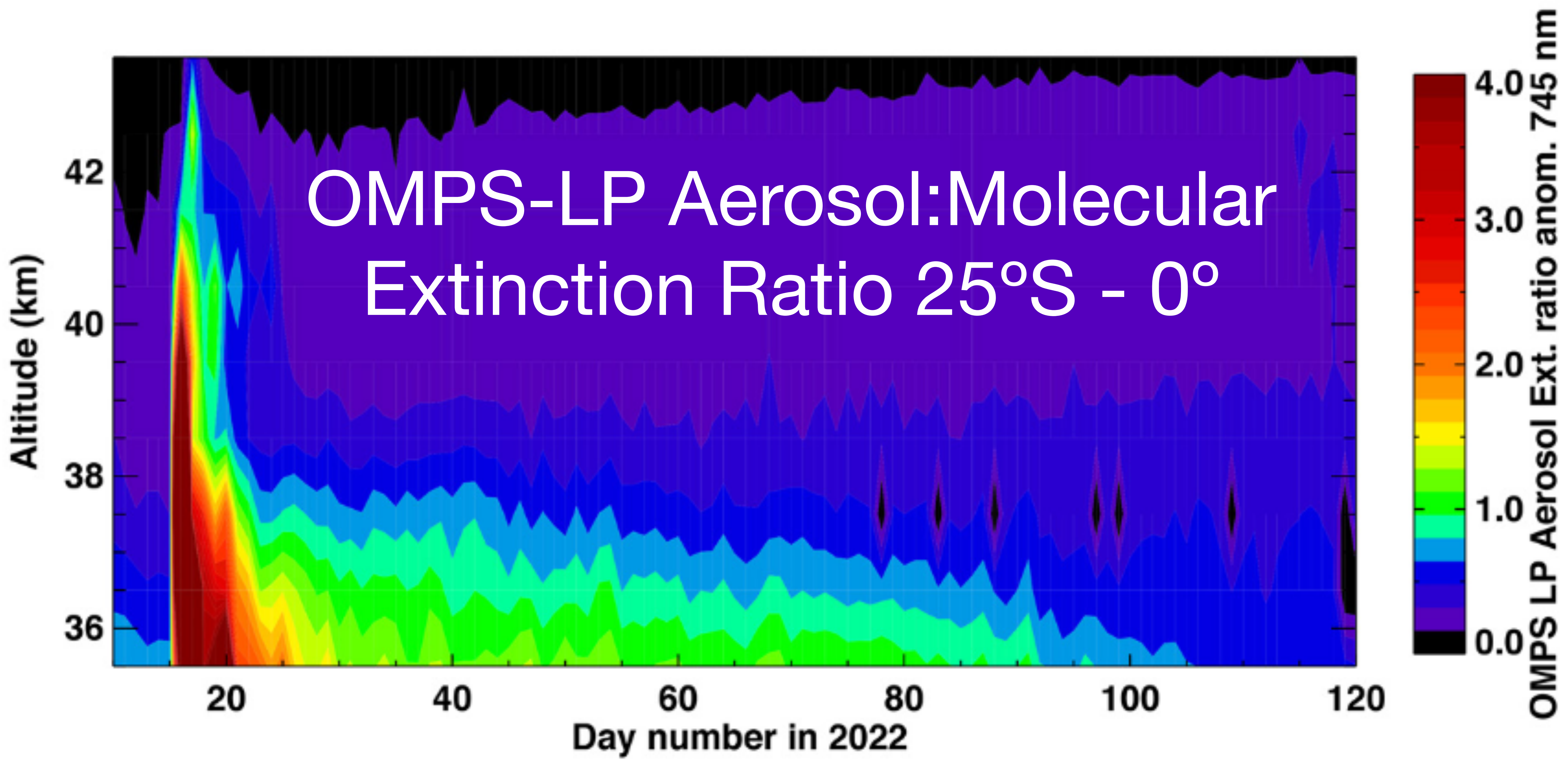
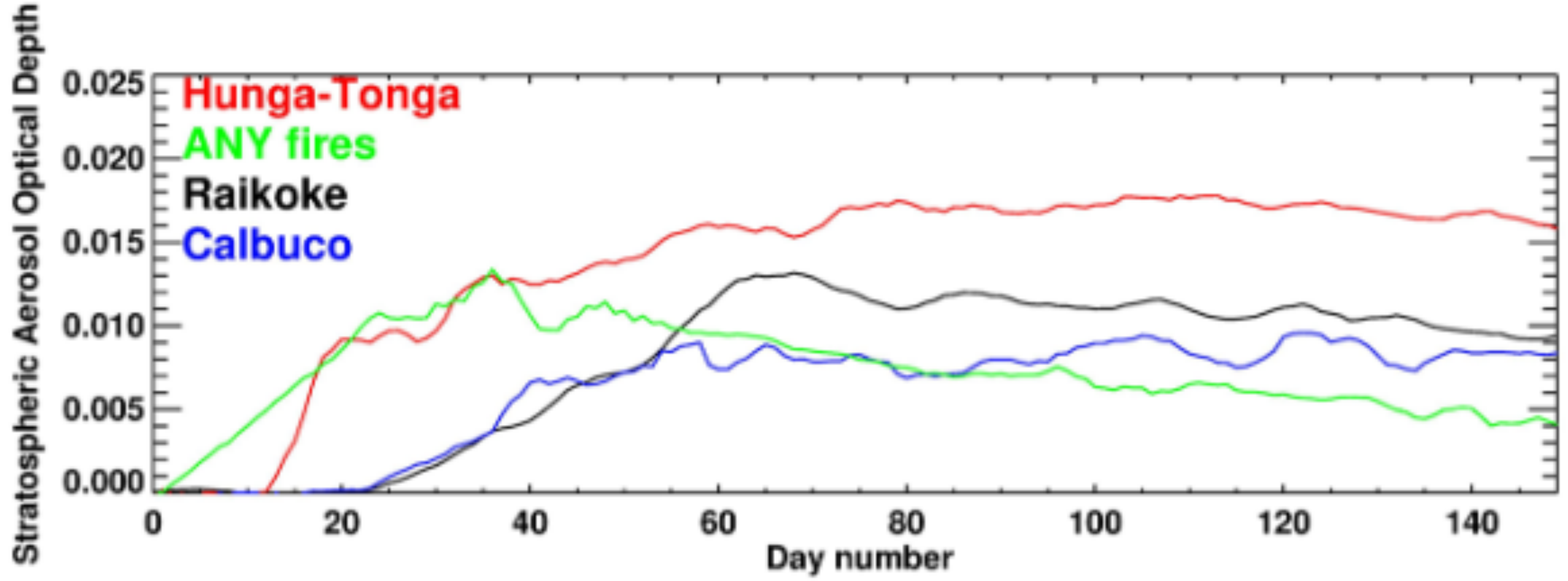
More Recent Period

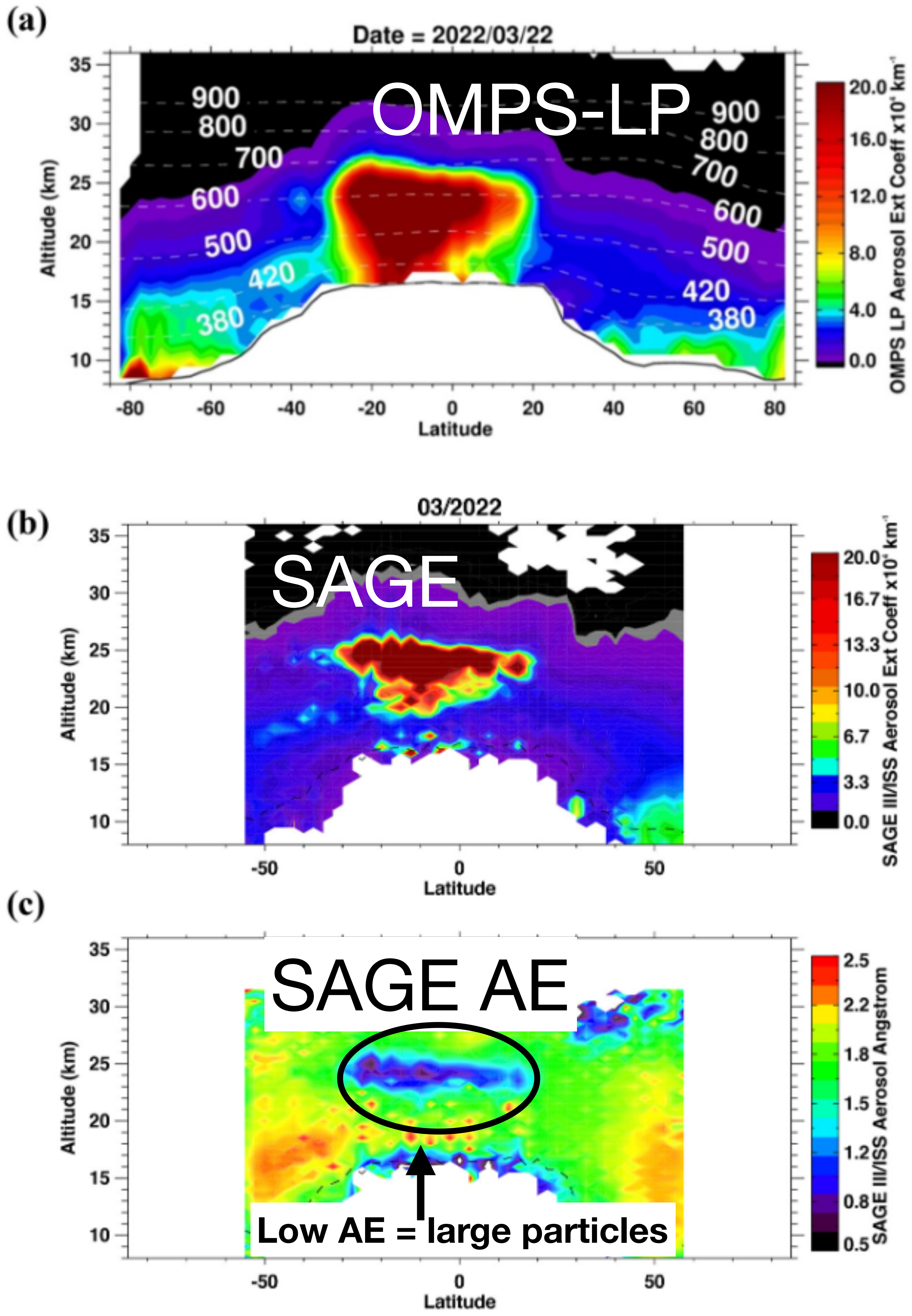




Hunga Observations







Taha, G., Loughman, R., Colarco, P. R., Zhu, T., Thomason, L. W., and Jaross, G.: Tracking the 2022 Hunga Tonga-Hunga Ha'apai Aerosol Cloud in the Upper and Middle Stratosphere Using Space-Based Observations, Geophys Res Lett, 49, https://doi.org/10.1029/2022gl100091, 2022.

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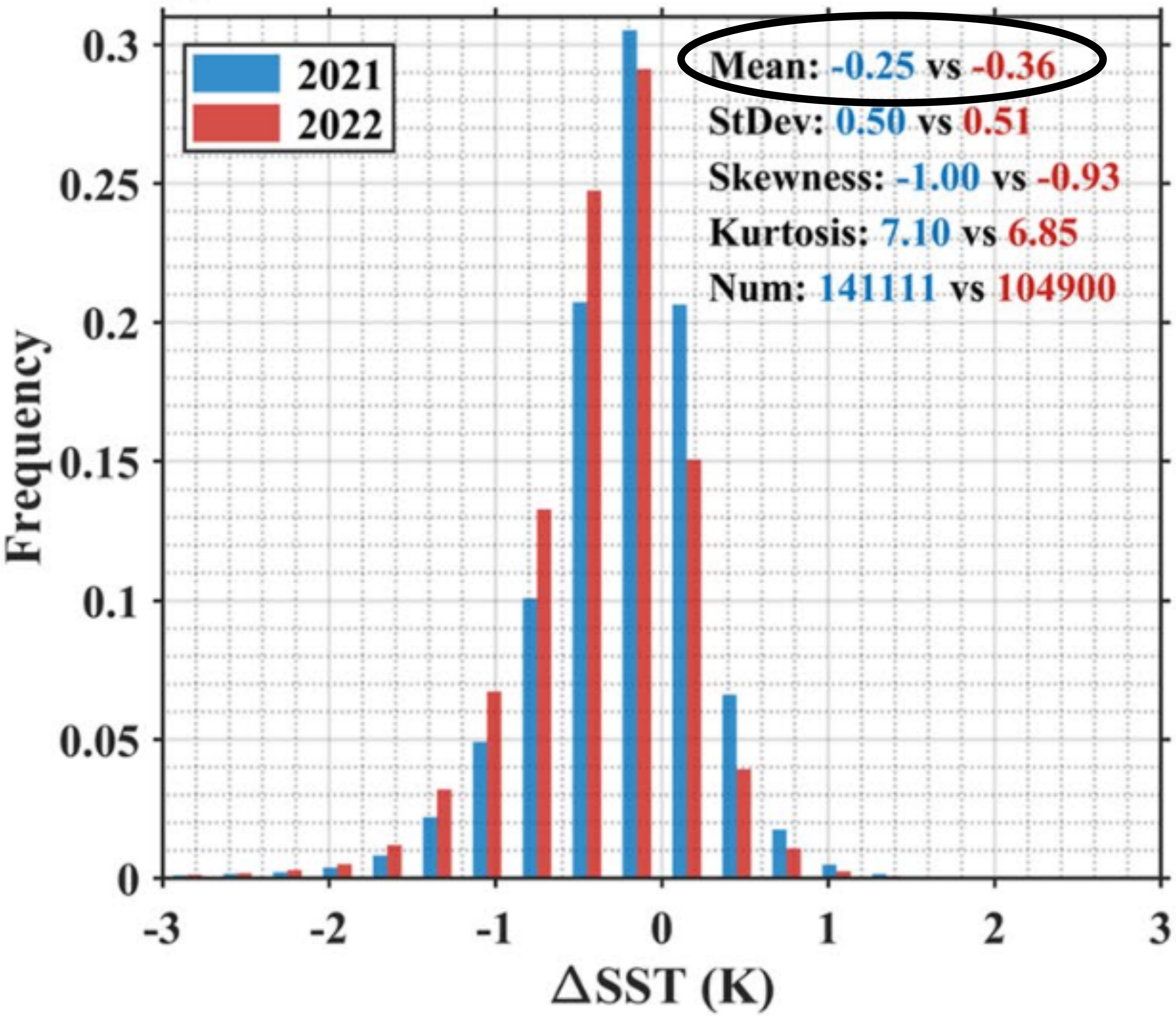
Impacts of Hunga on Retrievals

- MODIS shows apparent SST decrease following Hunga eruption
- This turns out to be a retrieval artifact because IR retrievals are impacted by the high altitude aerosol and water in the plume



Jia, C. and Minnett, P. J.: Effects of the Hunga Tonga-Hunga Ha'apai Eruption on MODIS-Retrieved Sea Surface Temperatures, Geophys. Res. Lett., 50, https://doi.org/10.1029/2023gl104297, 2023.

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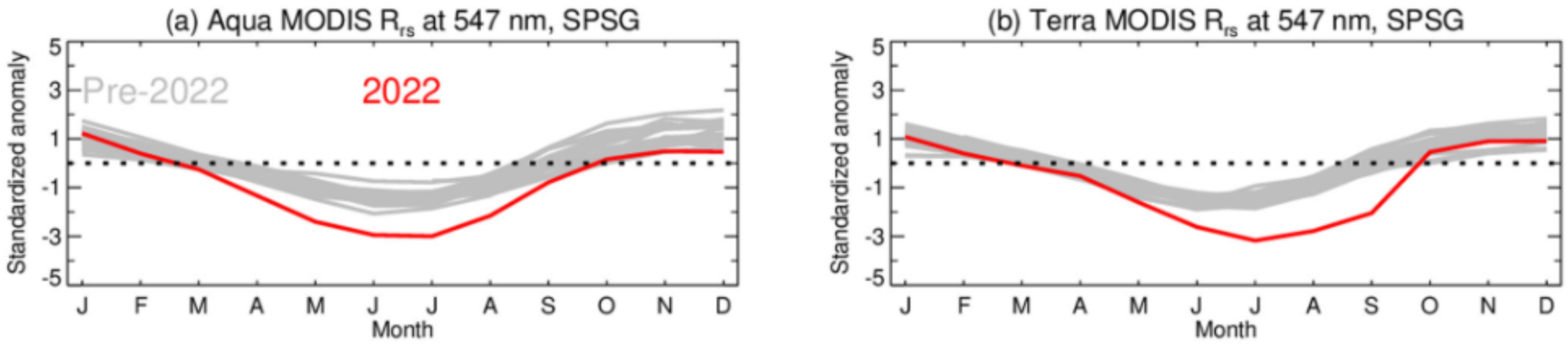
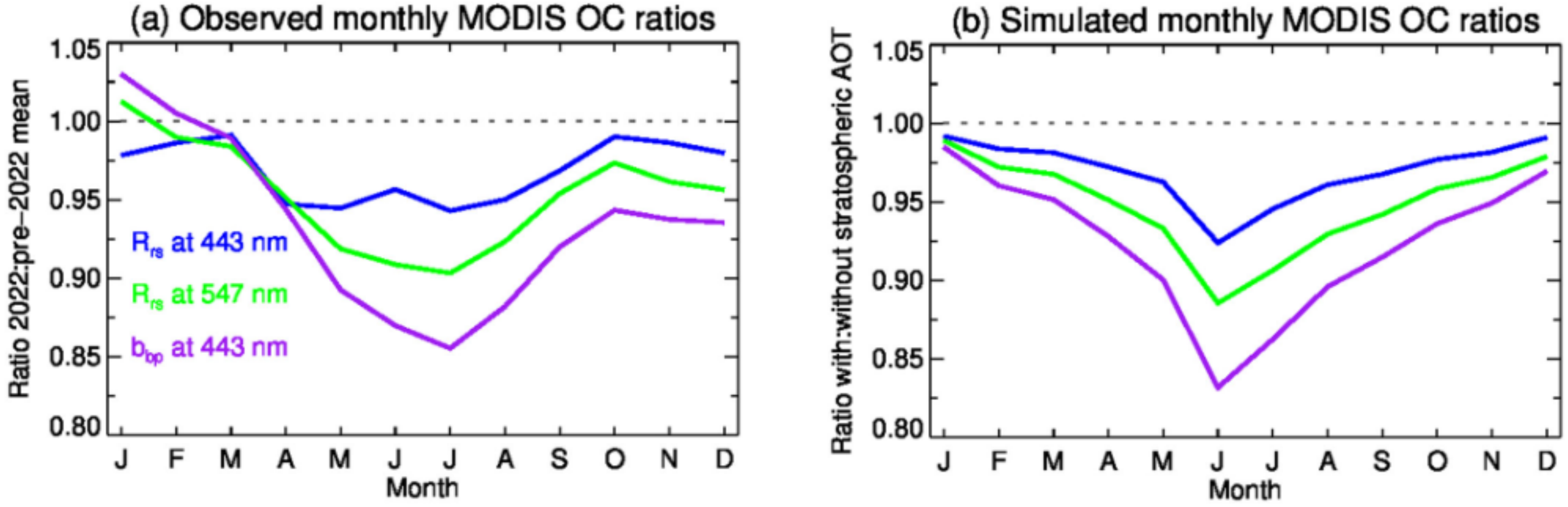
Impacts of Hunga on Retrievals

- **Top:** The Hunga eruption was evident in MODIS ocean color products
- **Bottom:** Hunga aerosol were at similar altitude to stratospheric ozone layer, which interferes with standard retrieval algorithms and leads to erroneously low retrieval of ocean color products

MODIS remotely sensed ocean color (Rsr)



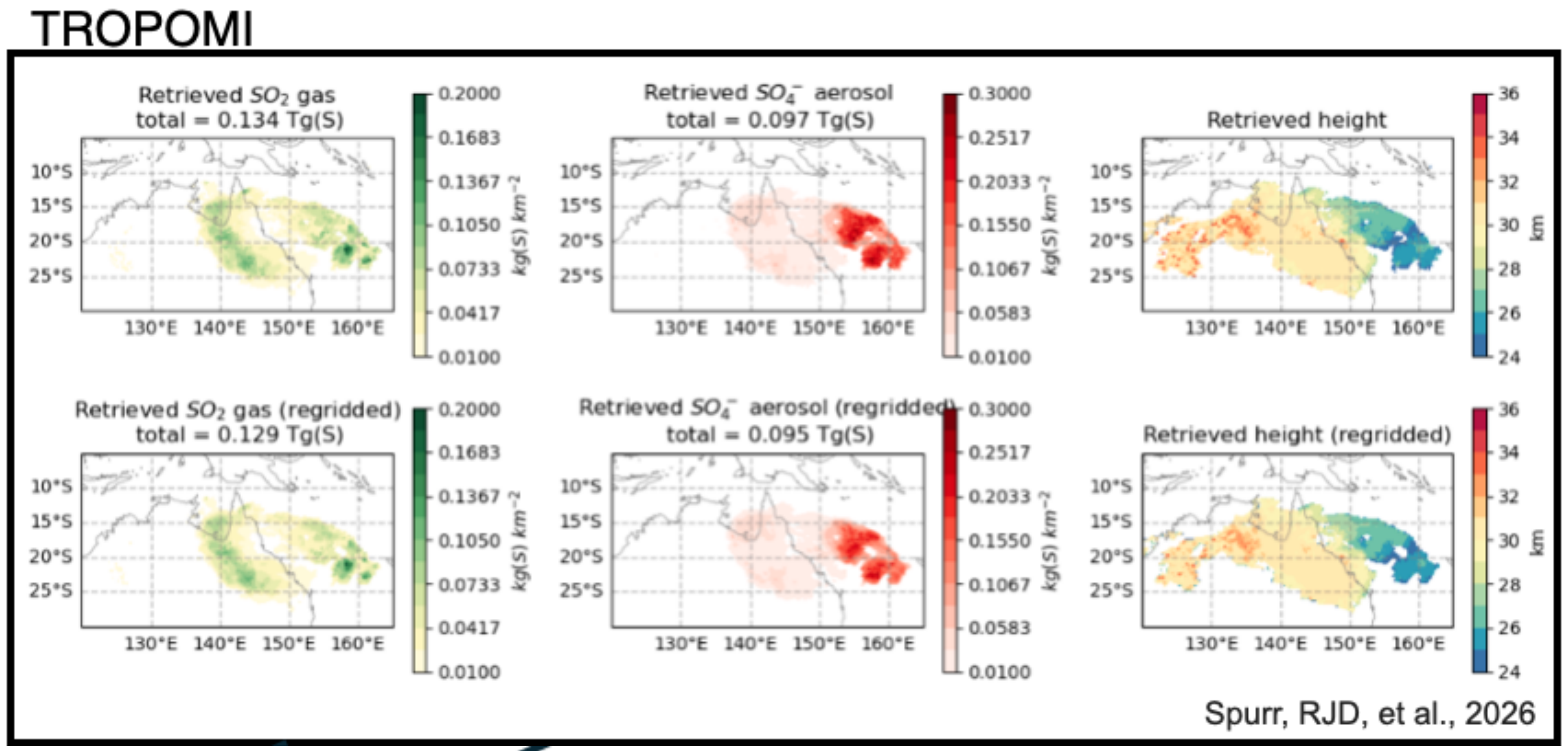
Low anomaly in retrieved products is explained adjusting algorithms to account for aerosol presence at ozone altitude

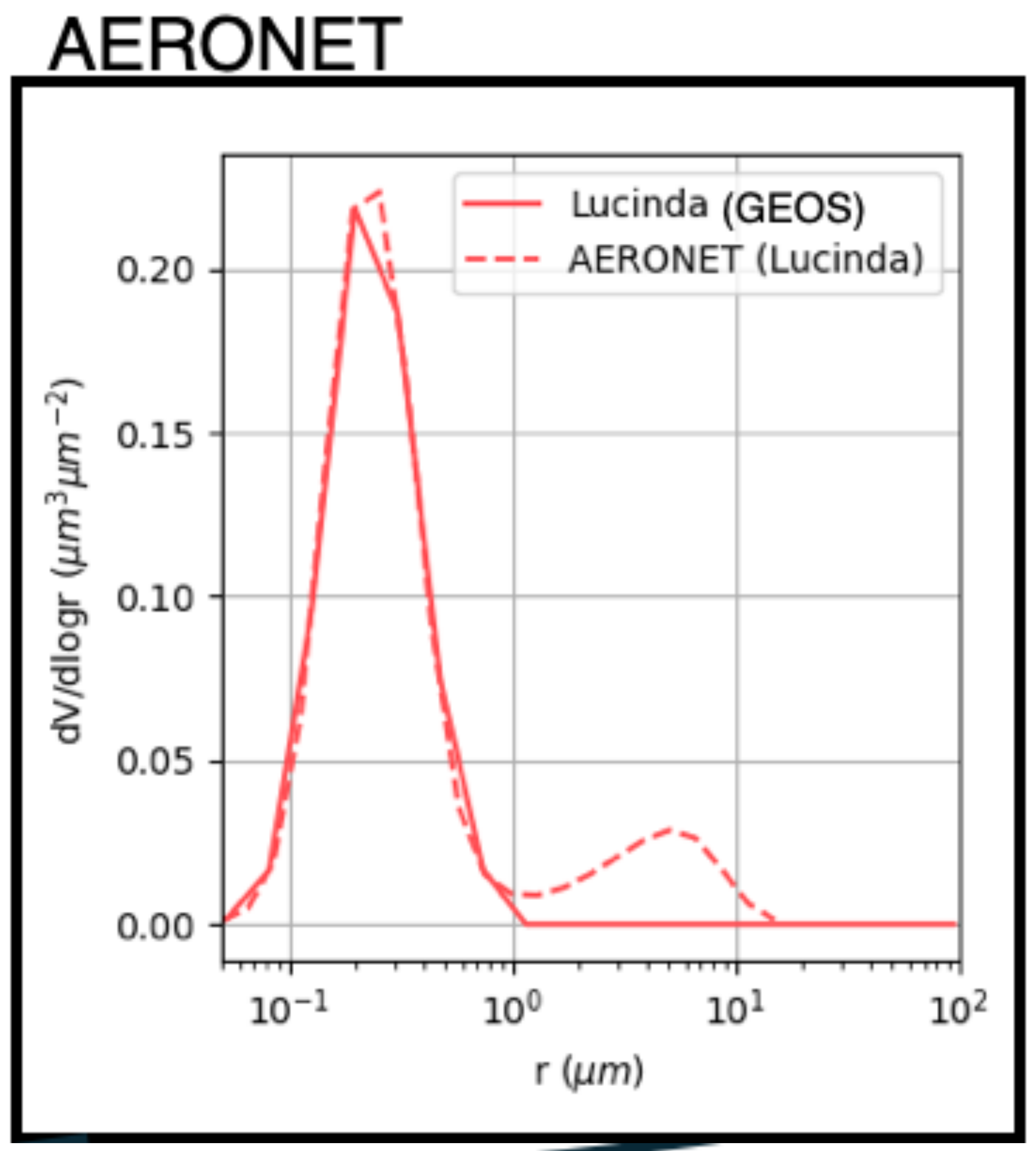


Franz, B. A., Cetinić, I., Ibrahim, A., and Sayer, A. M.: Anomalous trends in global ocean carbon concentrations following the 2022 eruptions of Hunga Tonga-Hunga Ha'apai, Commun. Earth Environ., 5, 247, https://doi.org/10.1038/s43247-024-01421-8, 2024.

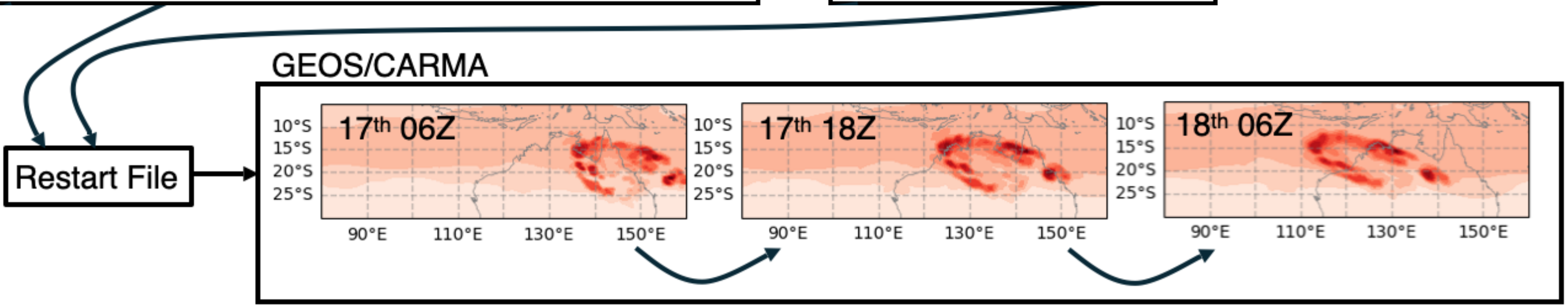
Modeling Hunga

- Prototype for aerosol data assimilation: use TROPOMI observations of Hunga SO_2, aerosol, and height to initialize GEOS coupled chemistry model





Parker Case,
Won-Ei Choi,
Nick Krotkov



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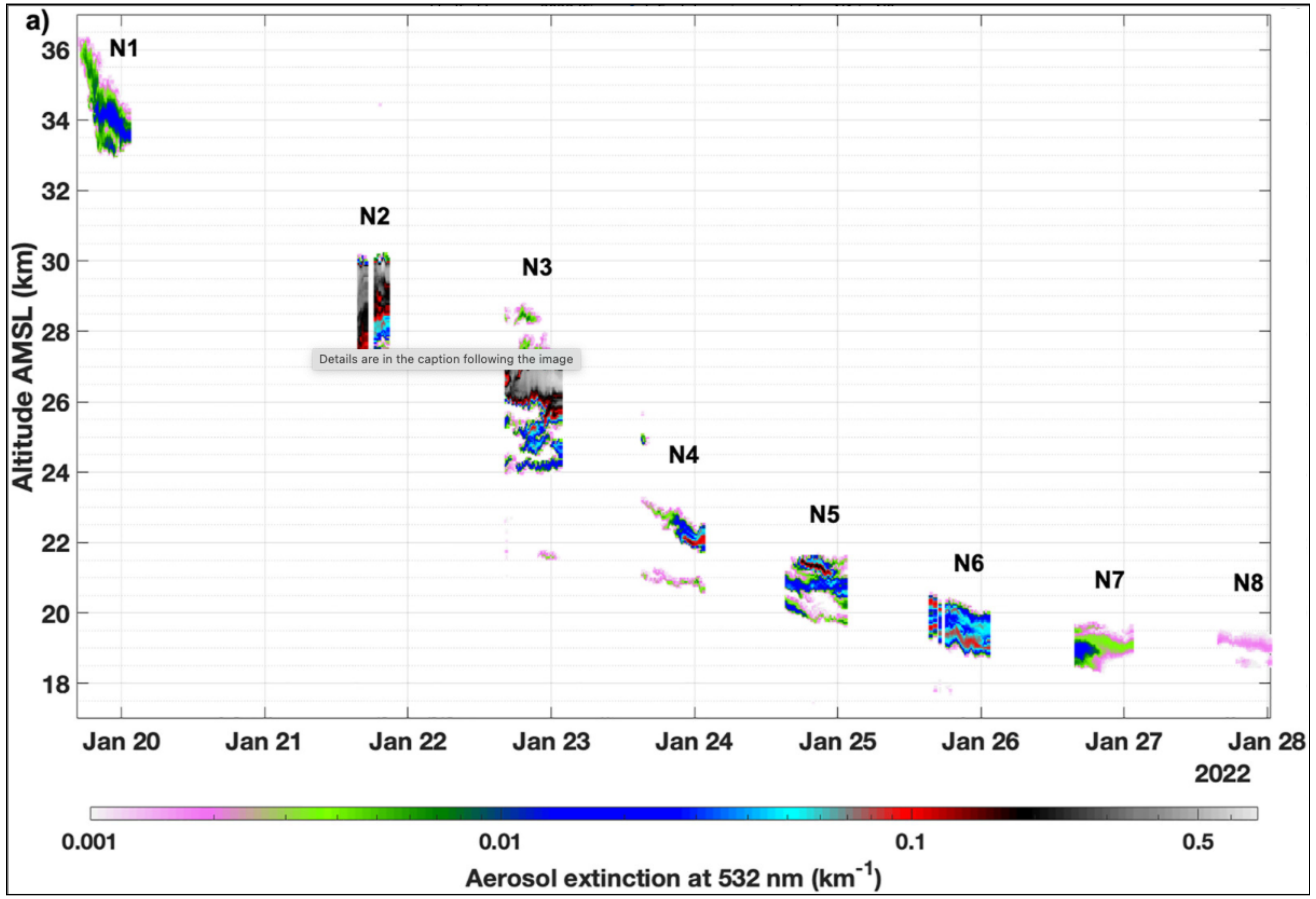
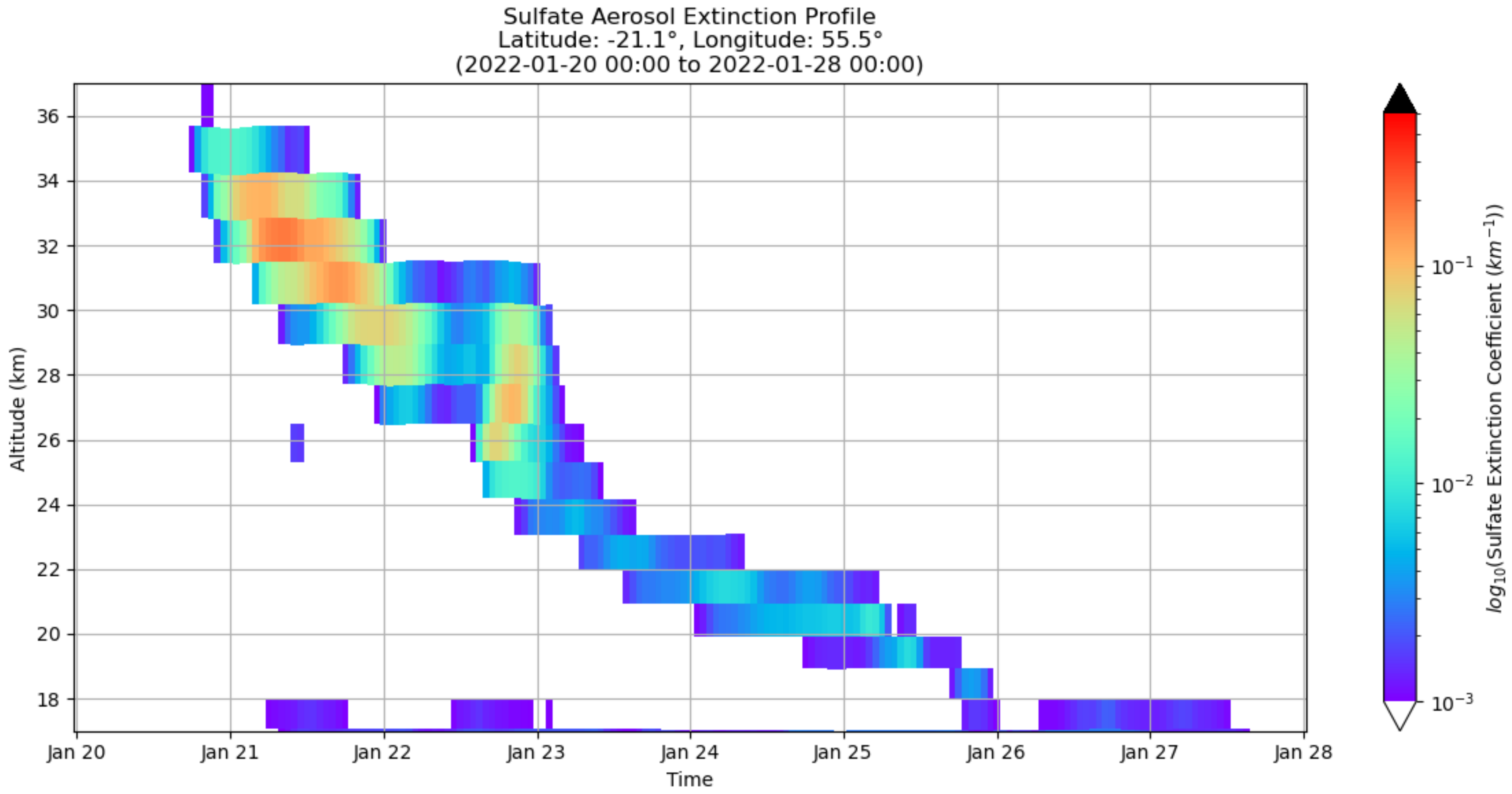
Modeling Hunga

- GEOS simulates well the timing, altitude, and even magnitude of the plume arrival at Le Réunion





Baron, A., Chazette, P., Khaykin, S., Payen, G., Marquestaut, N., Bègue, N., and Duflot, V.: Early Evolution of the Stratospheric Aerosol Plume Following the 2022 Hunga Tonga-Hunga Ha'apai Eruption: Lidar Observations From Reunion (21°S, 55°E), Geophys. Res. Lett., 50, https://doi.org/10.1029/2022gl101751, 2023.

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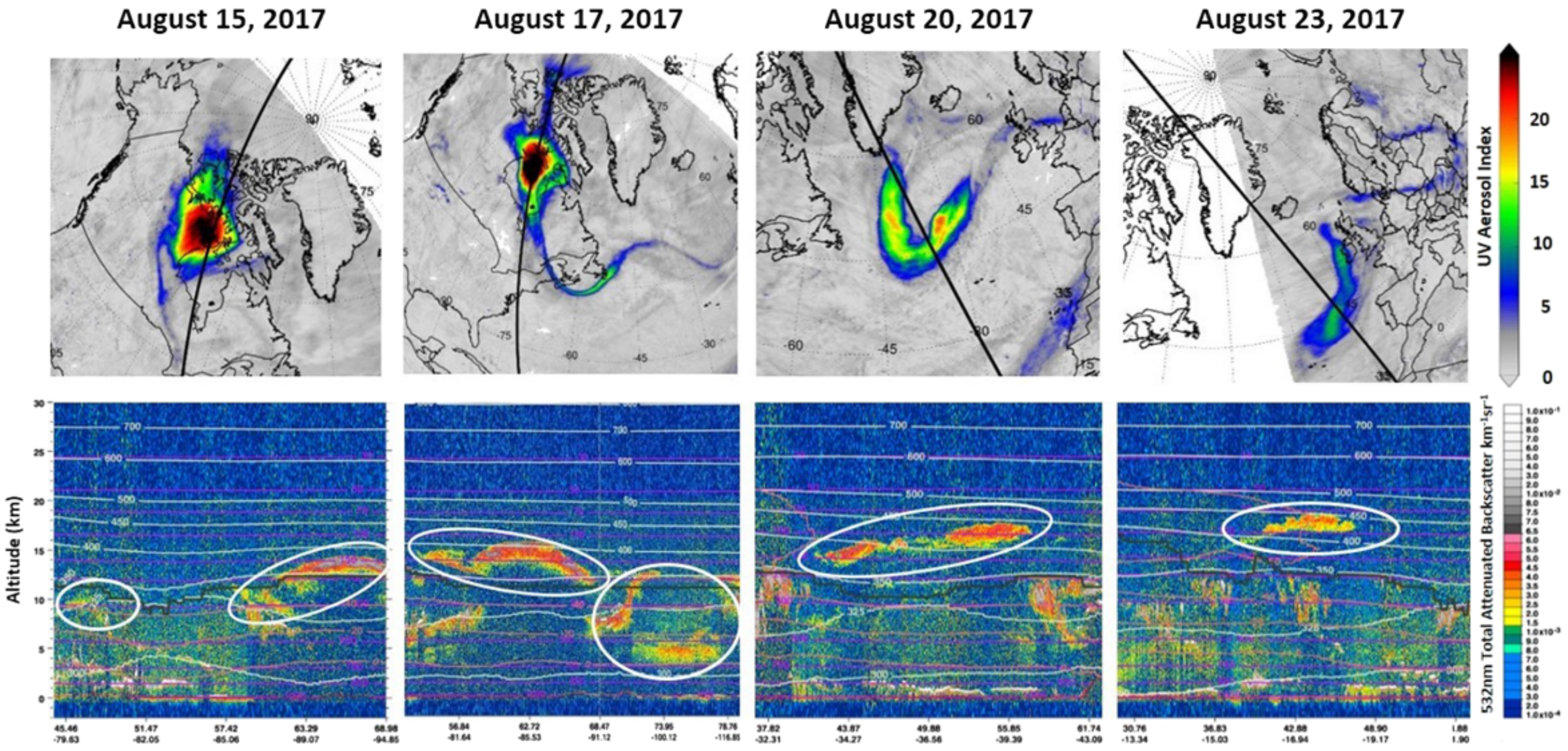
British Columbia PyroCb

- High altitude smoke injection in British Columbia in August 2017 seen by EPIC and CALIOP



Torres, O., Bhartia, P. K., Taha, G., Jethva, H., Das, S., Colarco, P., Krotkov, N., Omar, A., and Ahn, C.: Stratospheric Injection of Massive Smoke Plume From Canadian Boreal Fires in 2017 as Seen by DSCOVR-EPIC, CALIOP, and OMPS-LP Observations, J Geophys Res Atmospheres, 125, https://doi.org/10.1029/2020jd032579, 2020.

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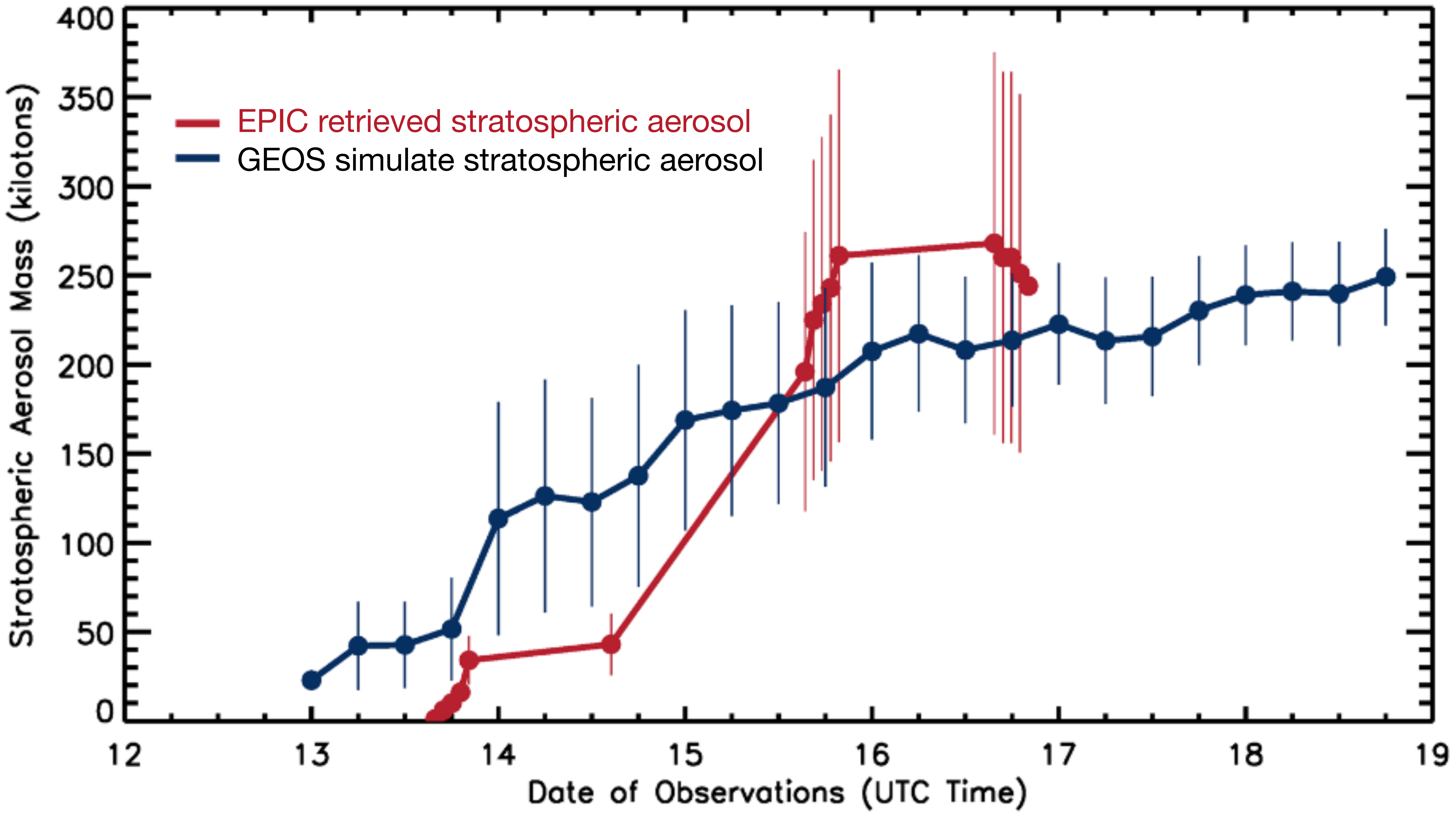
Vertical Ascent of PyroCb

- Shortwave heating in the smoke layer leads to vertical lofting, increasing stratospheric loading over time



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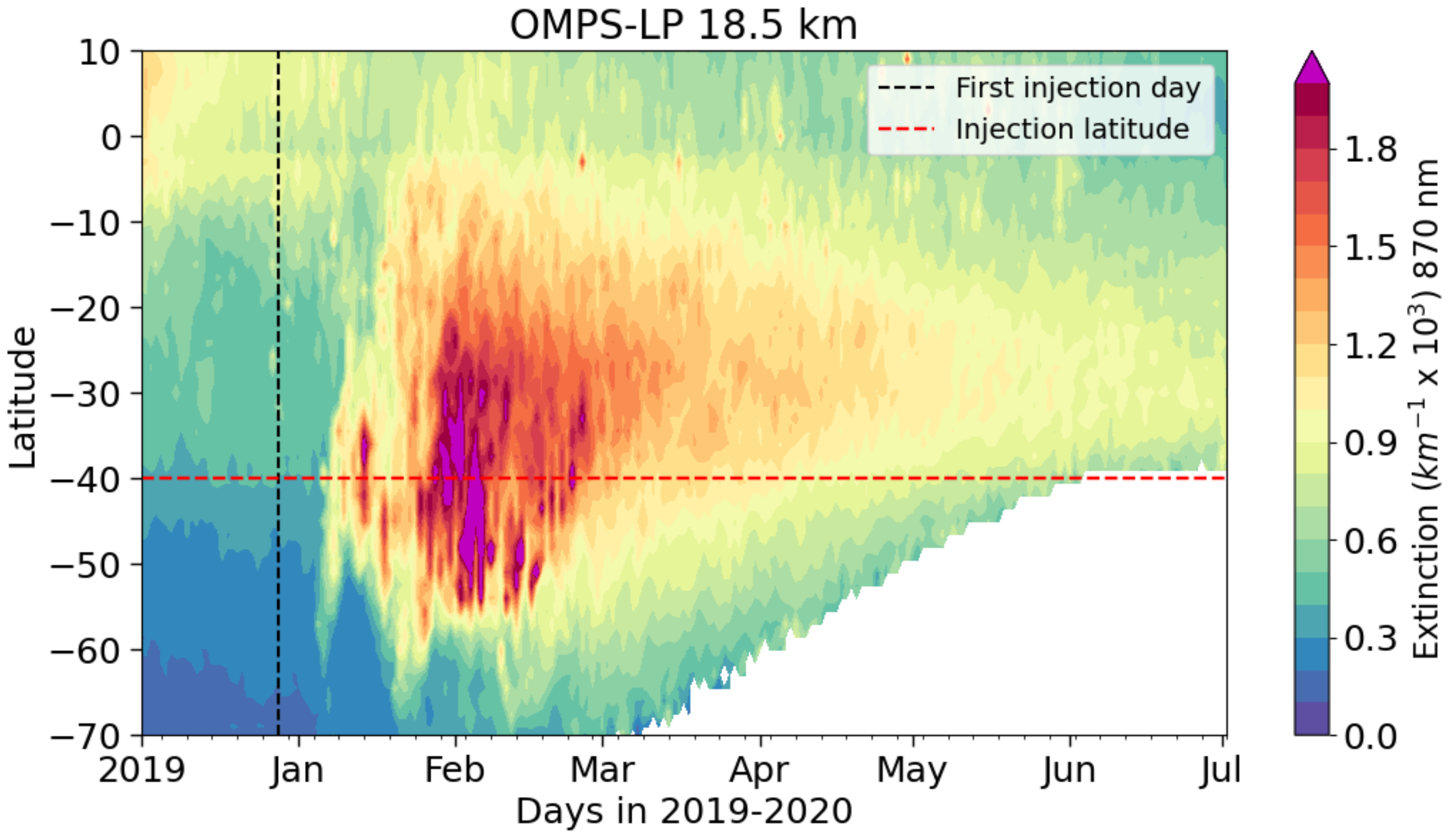
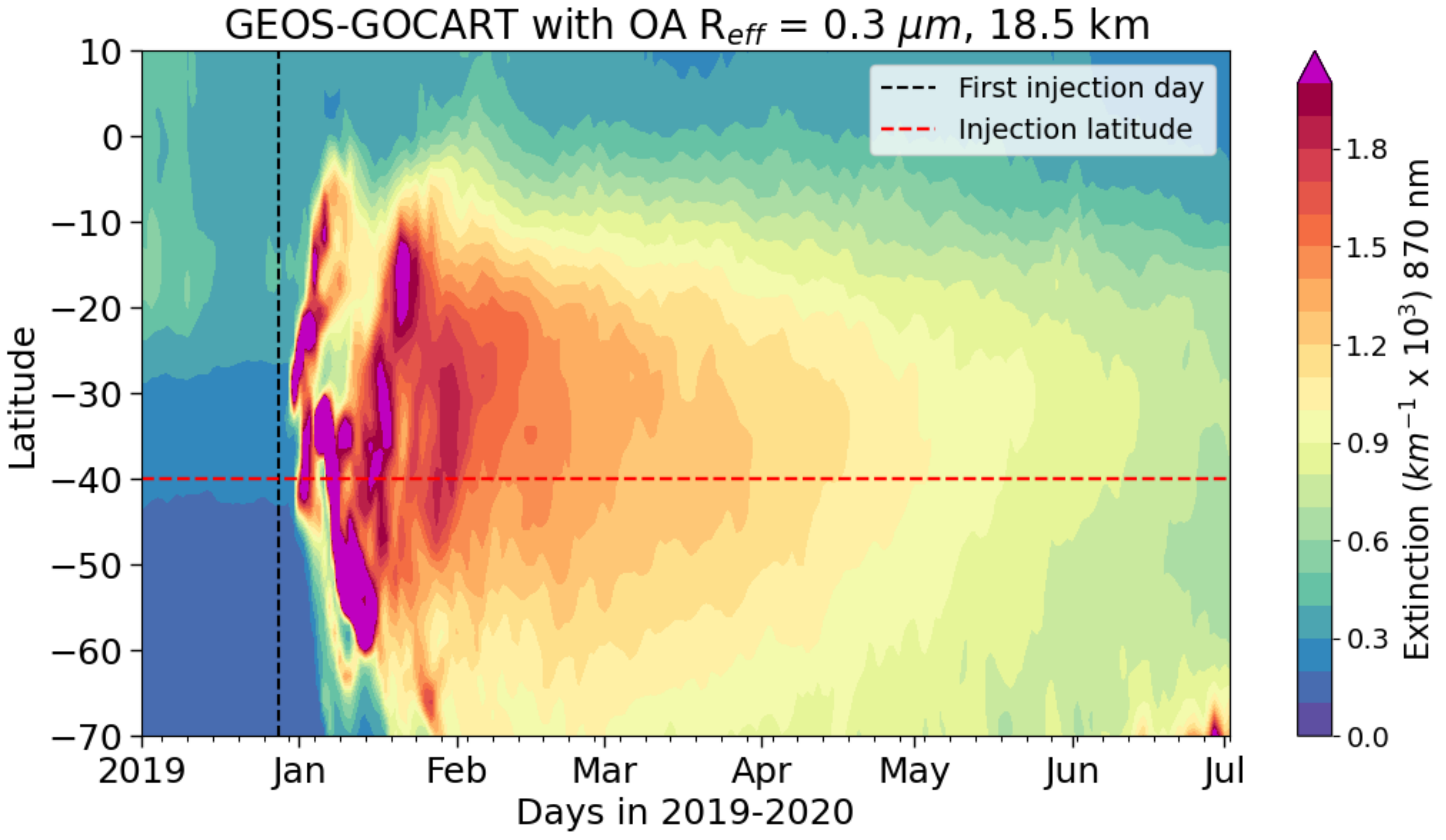
2019/2020 Australian PyroCb

- Particle properties are key: with appropriate assumptions of pyroCb smoke size we can reasonably simulate the radiative impact and aerosol loading compared to OMPS-LP





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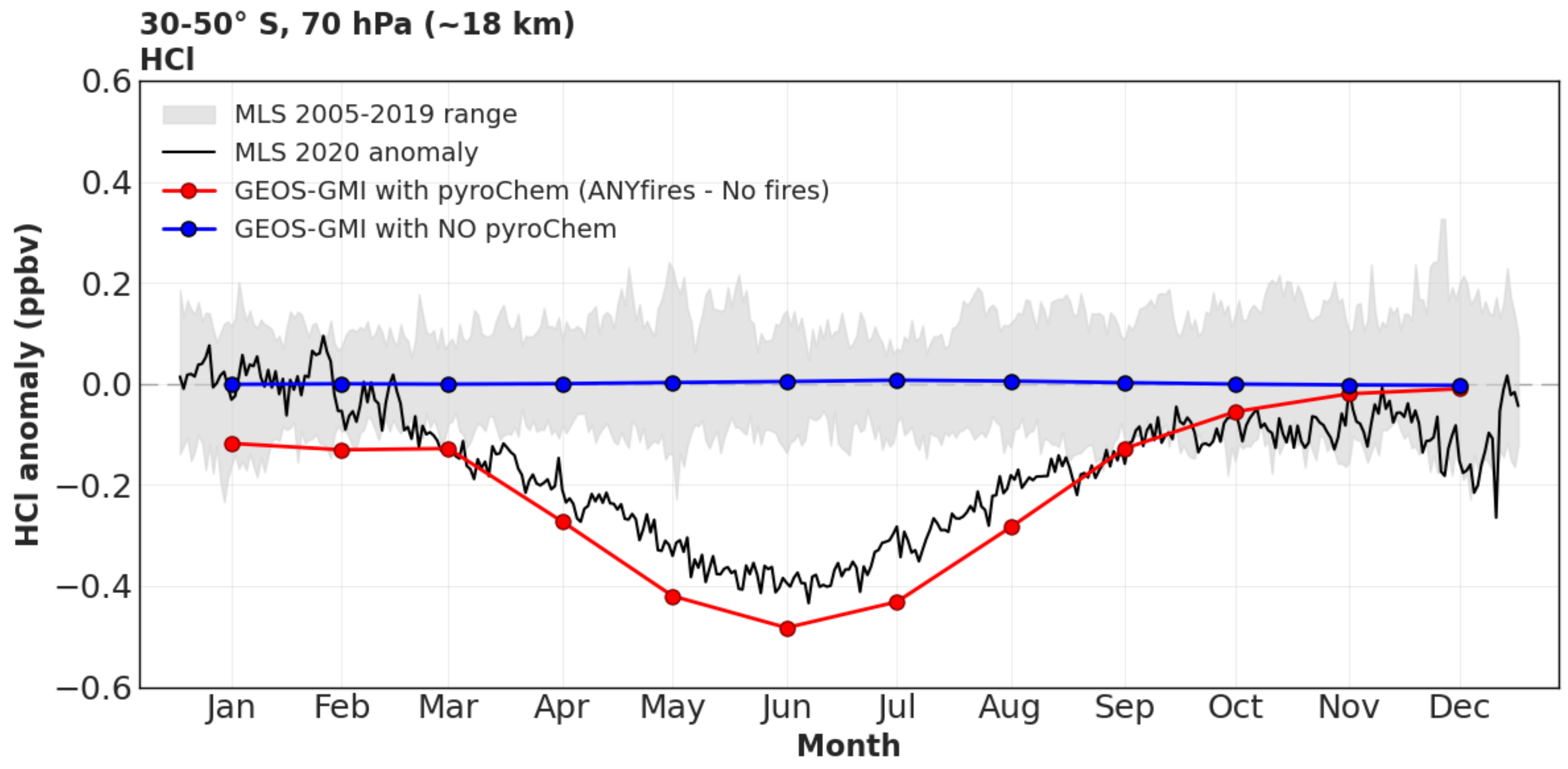
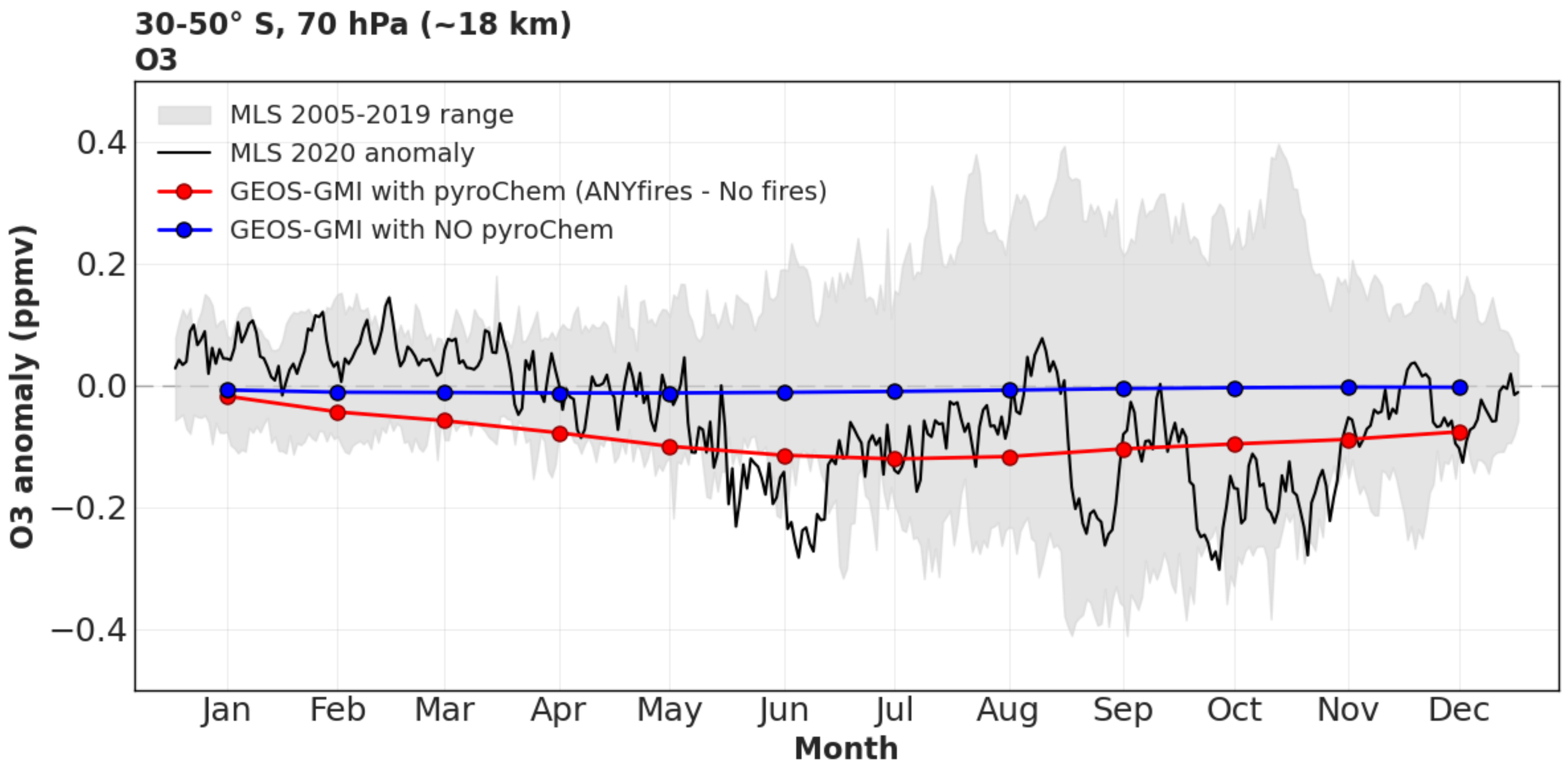
Smoke Impacts Ozone

- Smoke from the Australian fires was observed by MLS to cause a repartitioning of stratospheric chlorine compounds and so impact the stratospheric ozone layer
- The observed chemical impacts are well reproduced when smoke-specific heterogeneous reaction rates and temperature dependencies are applied in the GMI chemistry mechanism, distinct from those used for sulfates





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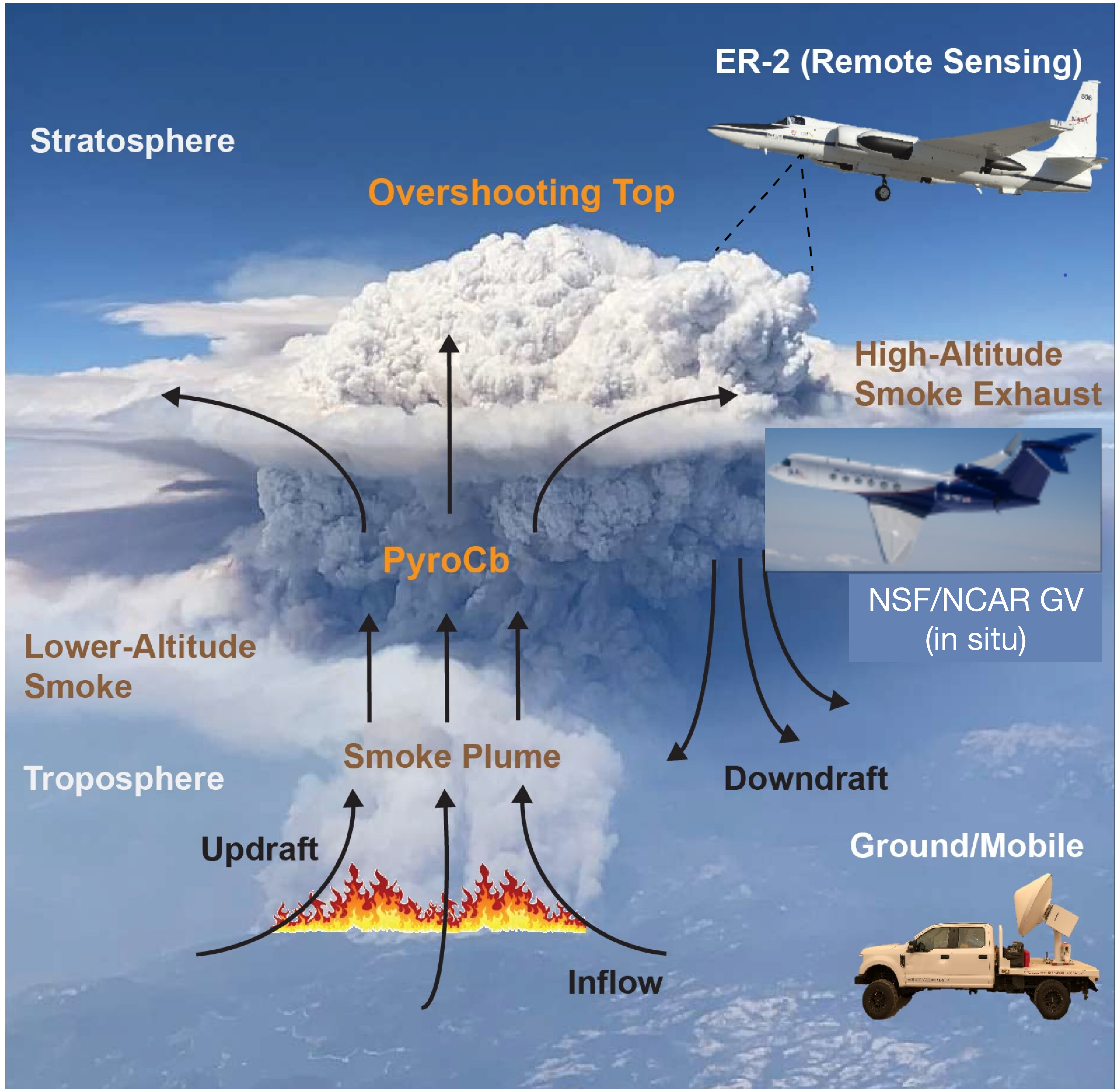
INSPYRE EVS Campaign



Goals

- Characterize physical links between pyroCb development and extreme wildfire behavior.
- Constrain the role of pyroCb activity in the Earth system.

Objectives

- Determine the fire and atmospheric conditions that produce pyroCbs.
- Identify the mechanisms that control stratospheric smoke injection.
- Assess how pyroCb-injected smoke plumes alter the upper troposphere and lower stratosphere (UTLS).

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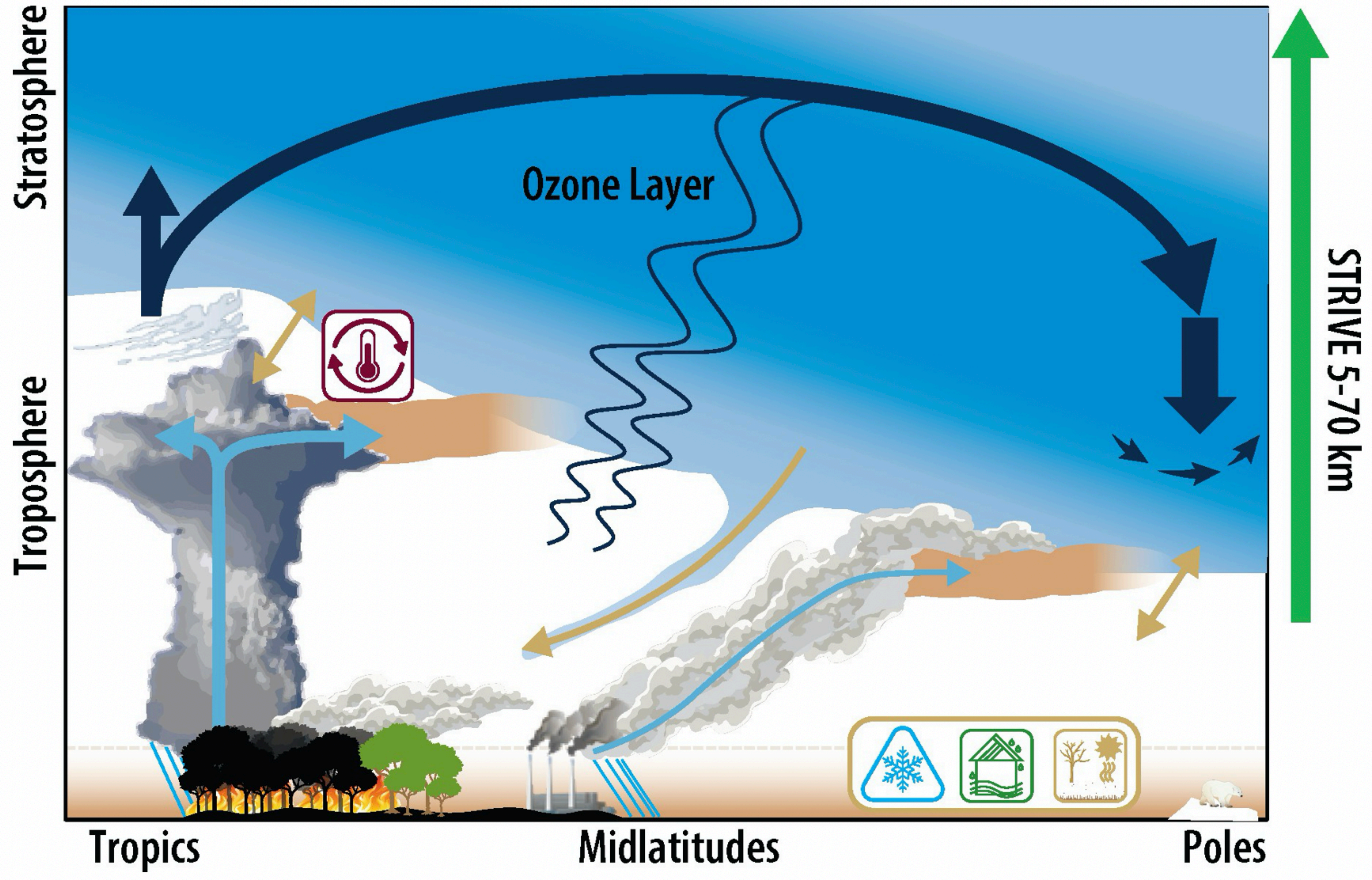
STRIVE ESE Mission

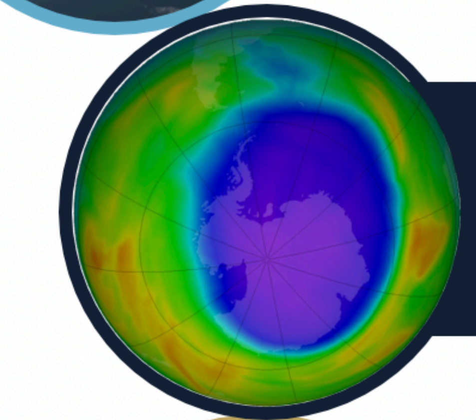
Composition: O_3, H_2O, CH_4, N_2O, CO, NO_2, HNO_3, $ClONO_2$, CFCs, aerosols, etc...



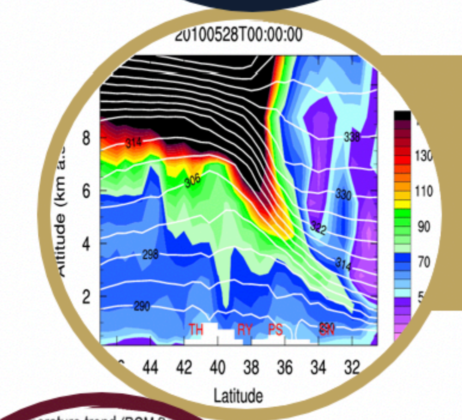
Complex interactions driven by processes on small spatial (10s km horiz., 1 km vertical) and short temporal scales (days)

Objectives:

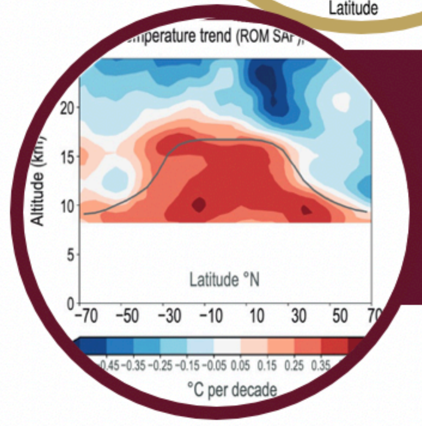
Convective and Large-Scale Transport



Ozone Layer Recovery



Stratosphere-Troposphere Coupling



Atmospheric Feedbacks

STRIVE has the novel ability to resolve small-scale vertical structures of atmospheric composition and temperature, enabling new insights into processes of troposphere-stratosphere interactions

…convective outflow, gravity waves, STE, cirrus clouds, volcanic eruptions, wildfire plumes, monsoon pollution…

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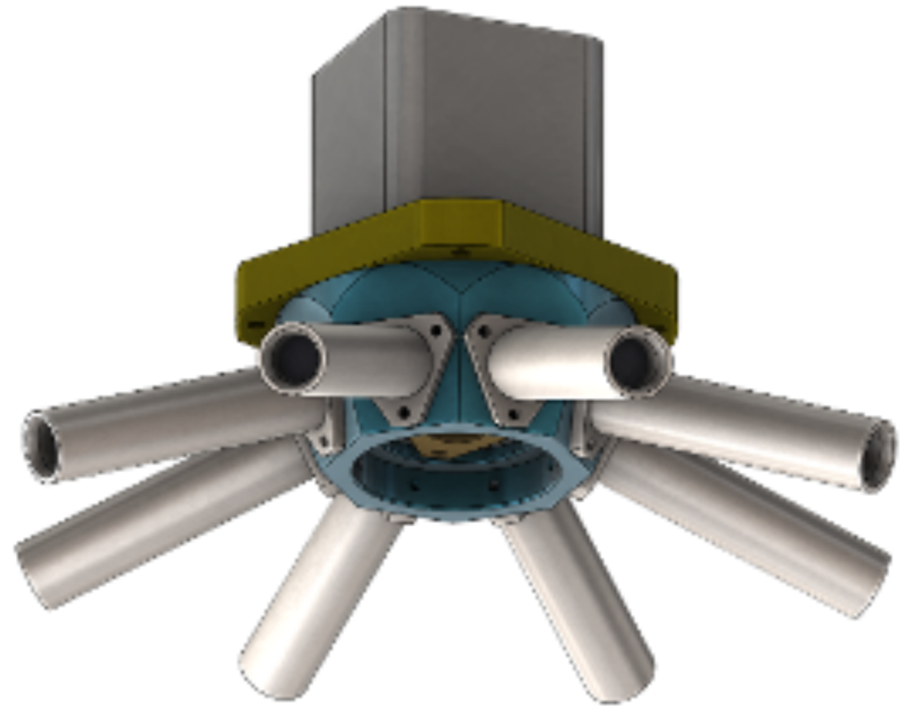
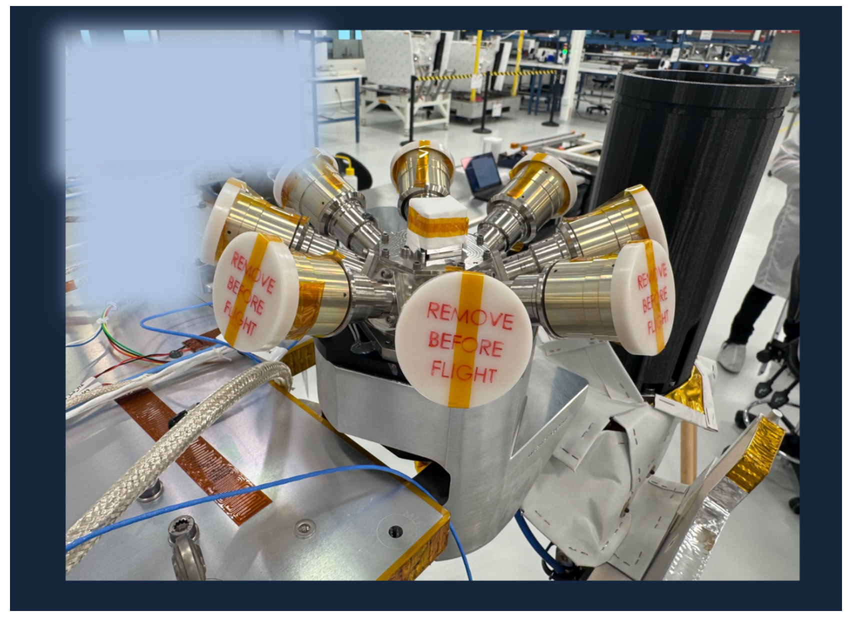
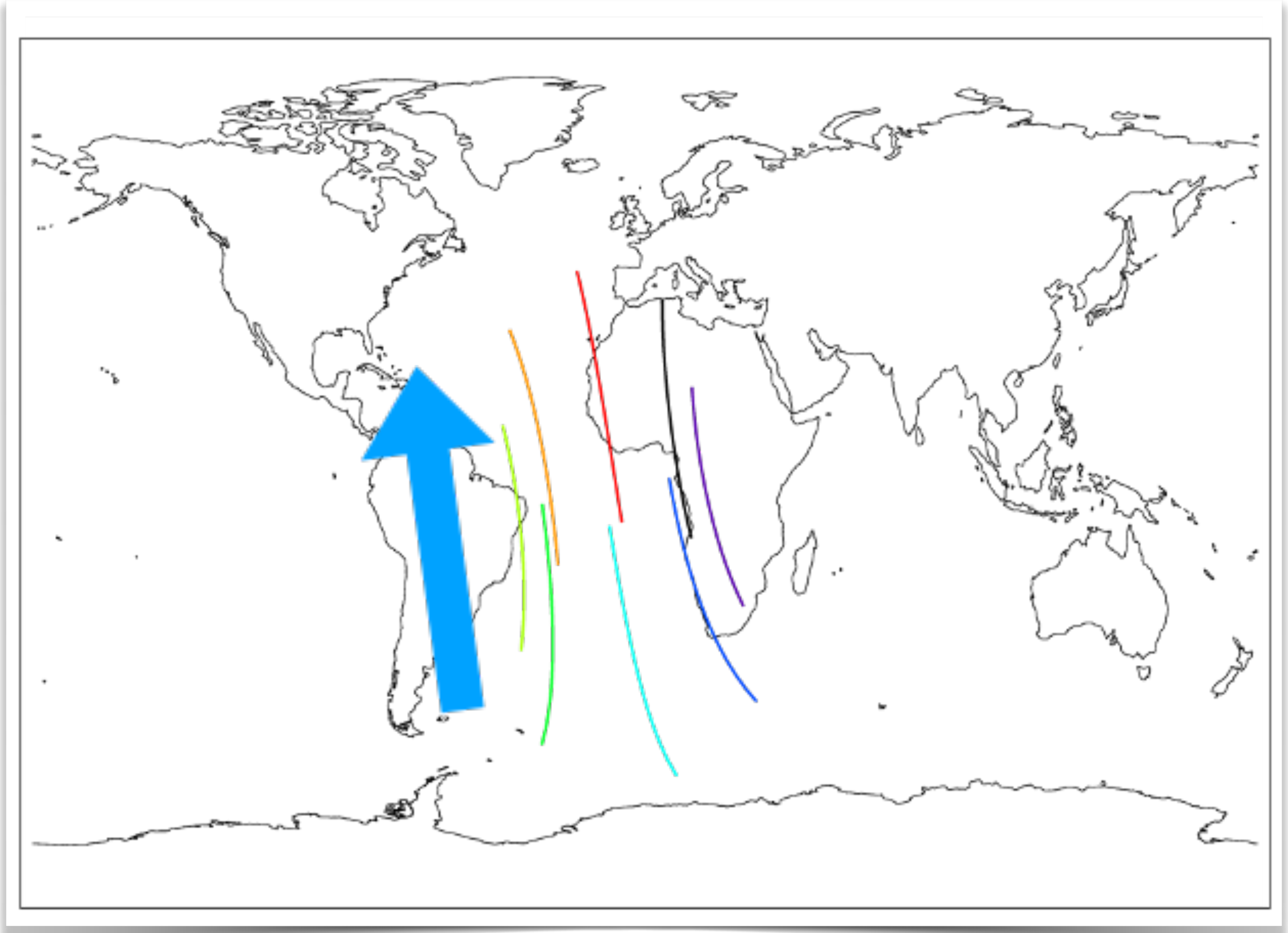
ARGOS

- Aerosol Radiometer for Global Observations of the Stratosphere (ARGOS)
- ARGOS builds off OMPS-LP heritage and will observe stratospheric aerosol profiles from 0 - 60 km with 0.5 km sampling at 870 and 1550 nm with 8 apertures for improved spatial and angular sampling of aerosol







ARGOS timeline

PI: Matt DeLand (SSAI)

- 2015: NASA IRAD
- 2016: NASA IIP
- 2021: NASA InVEST
- 2025: ARGOS launched on Loft Orbital Longbow bus as tech demo on SpaceX Transport 13 (March 2025)
- 2026: ARGOS selected as part of STRIVE Earth System Explorer

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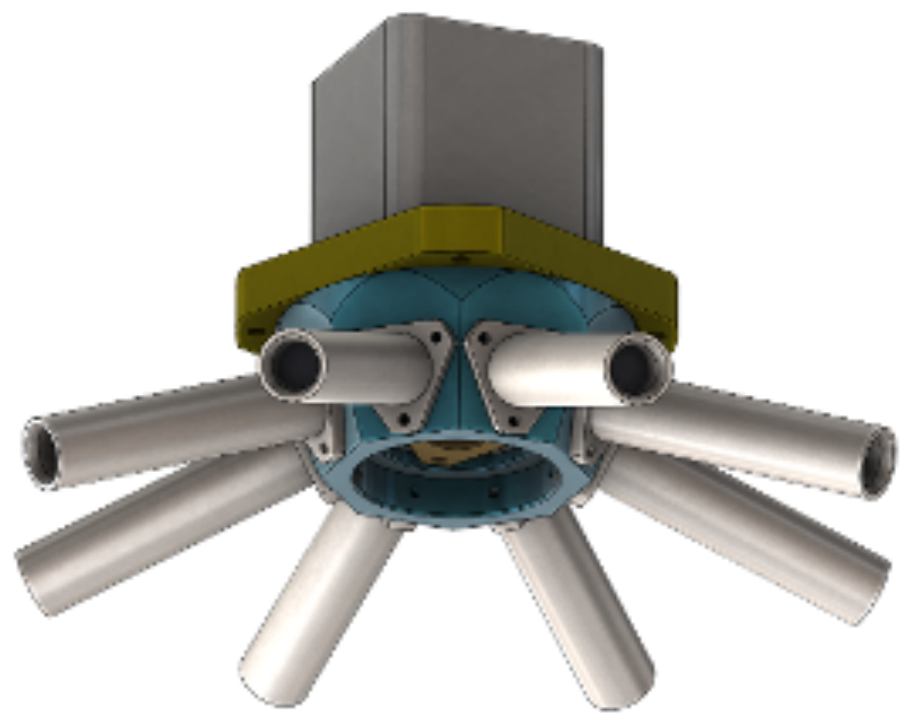

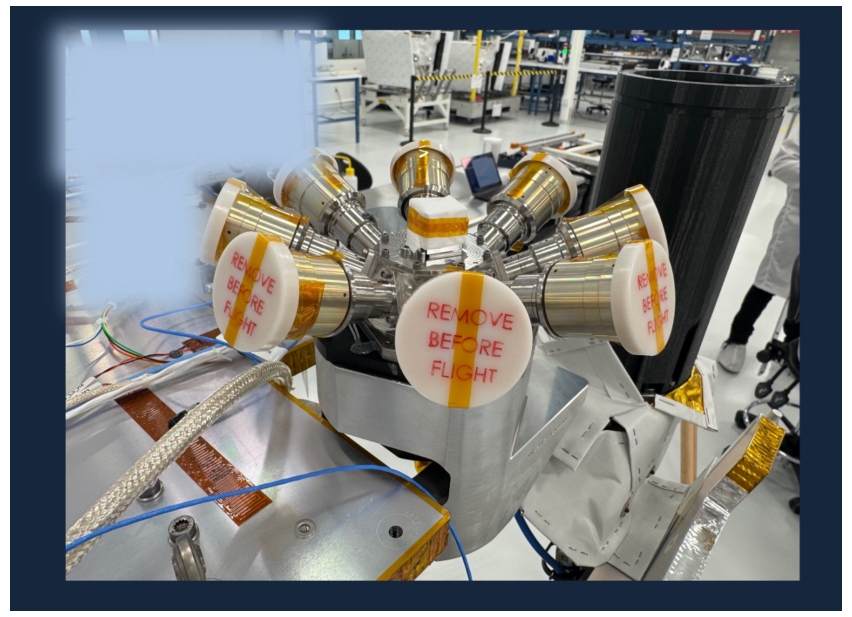

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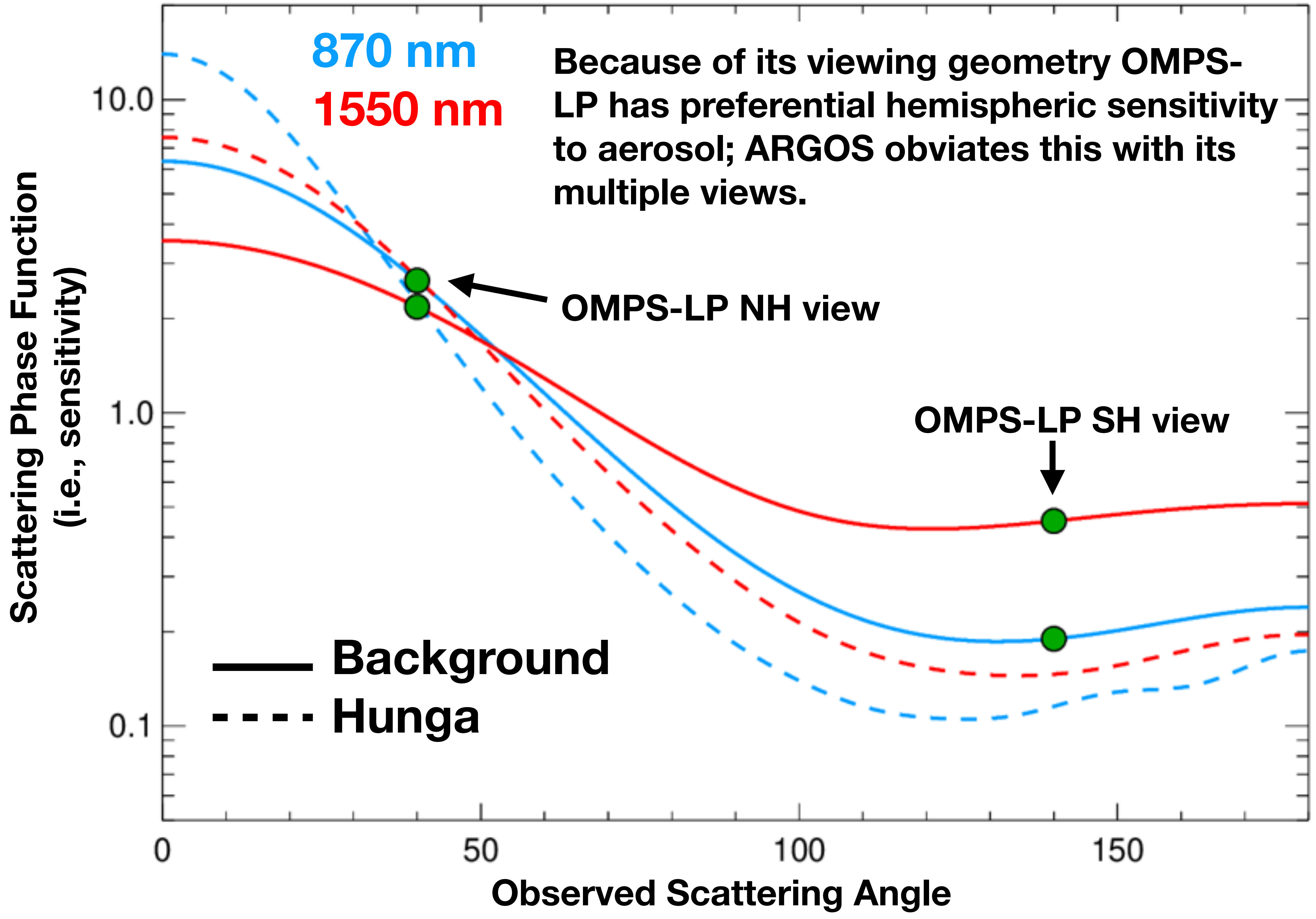

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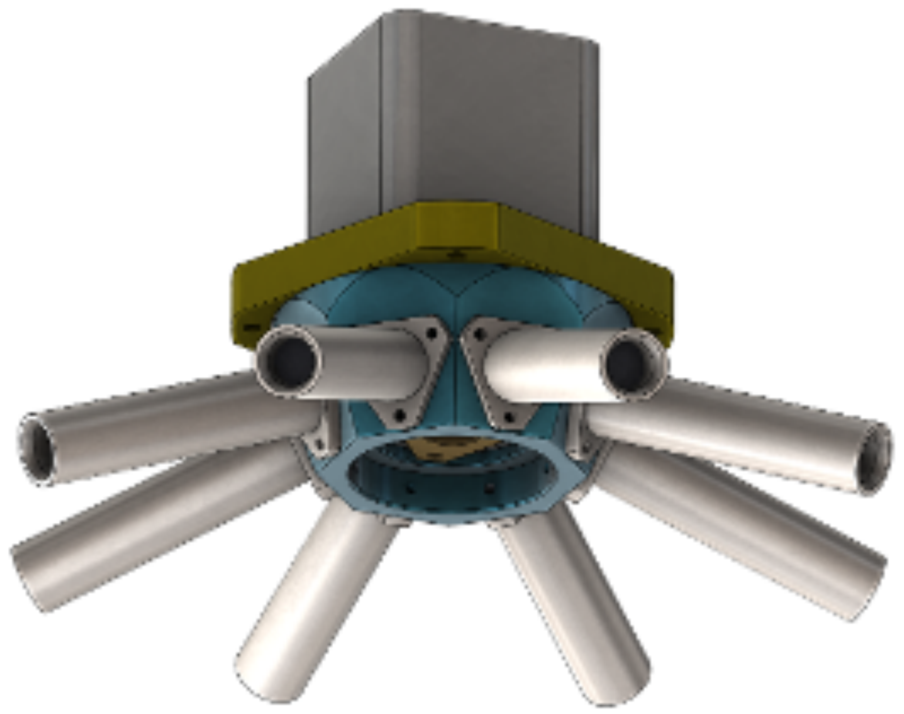

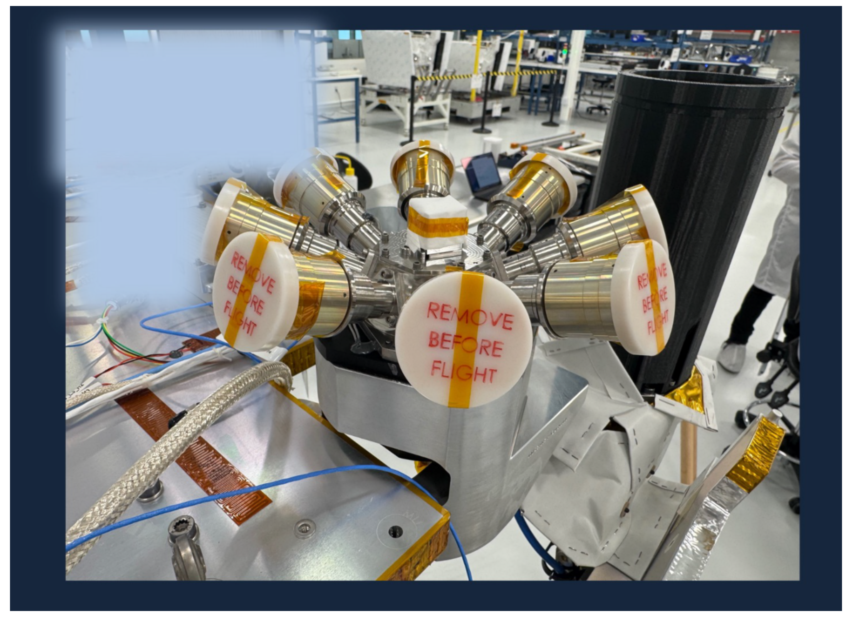

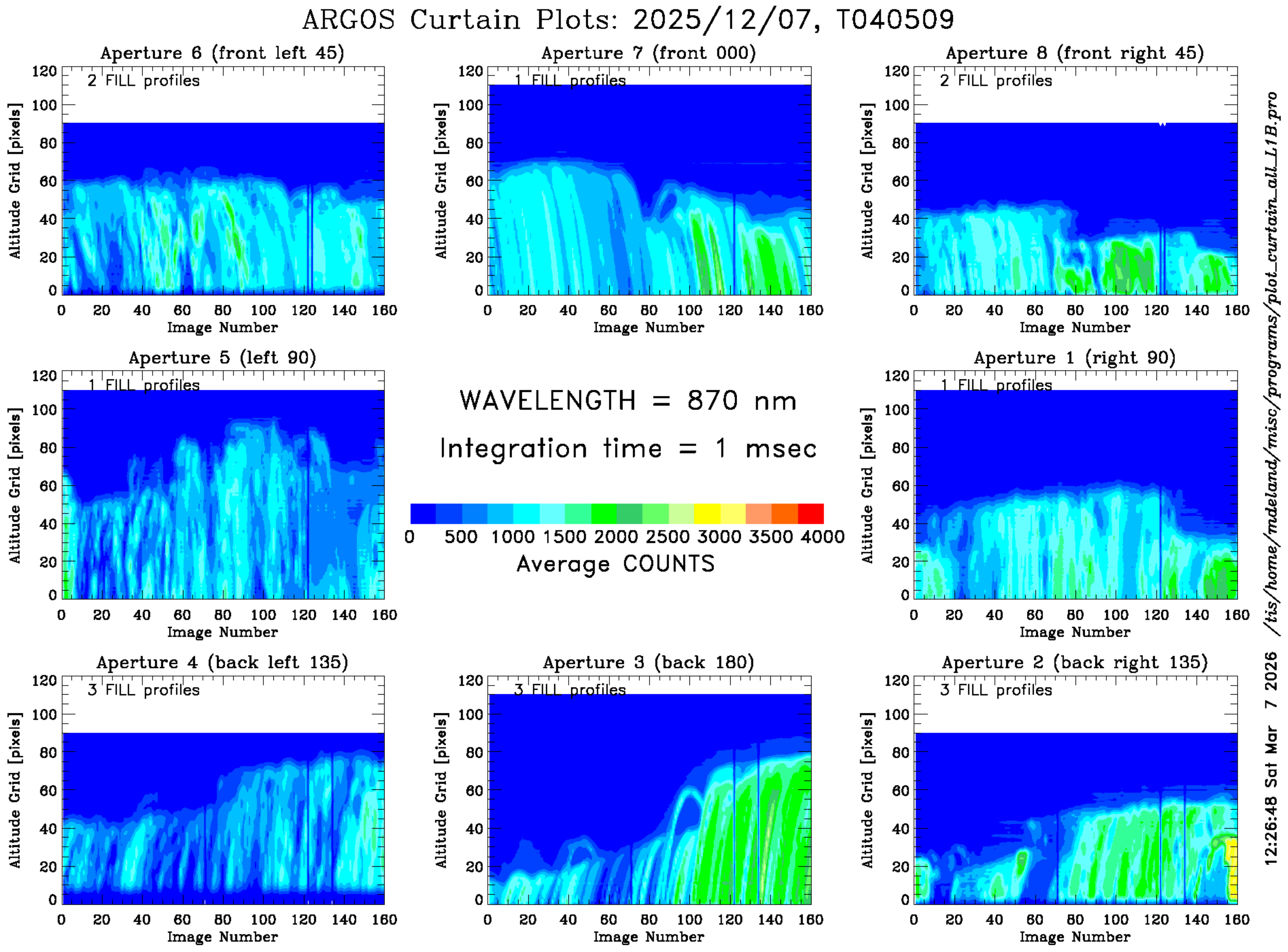

ARGOS timeline

PI: Matt DeLand (SSAI)

- 2015: NASA IRAD
- 2016: NASA IIP
- 2021: NASA InVEST
- 2025: ARGOS launched on Loft Orbital Longbow bus as tech demo on SpaceX Transport 13 (March 2025)
- 2026: ARGOS selected as part of STRIVE Earth System Explorer

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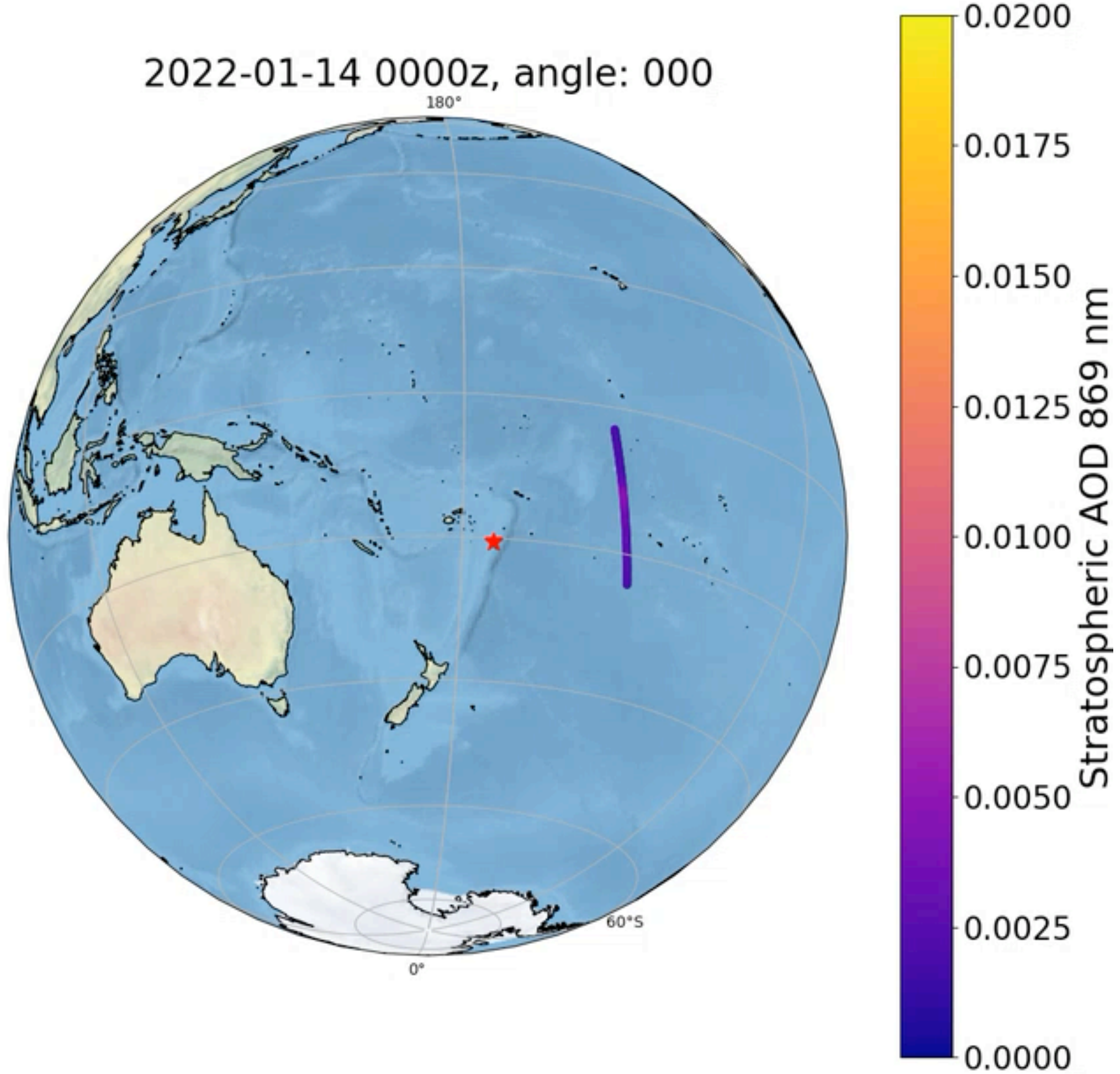
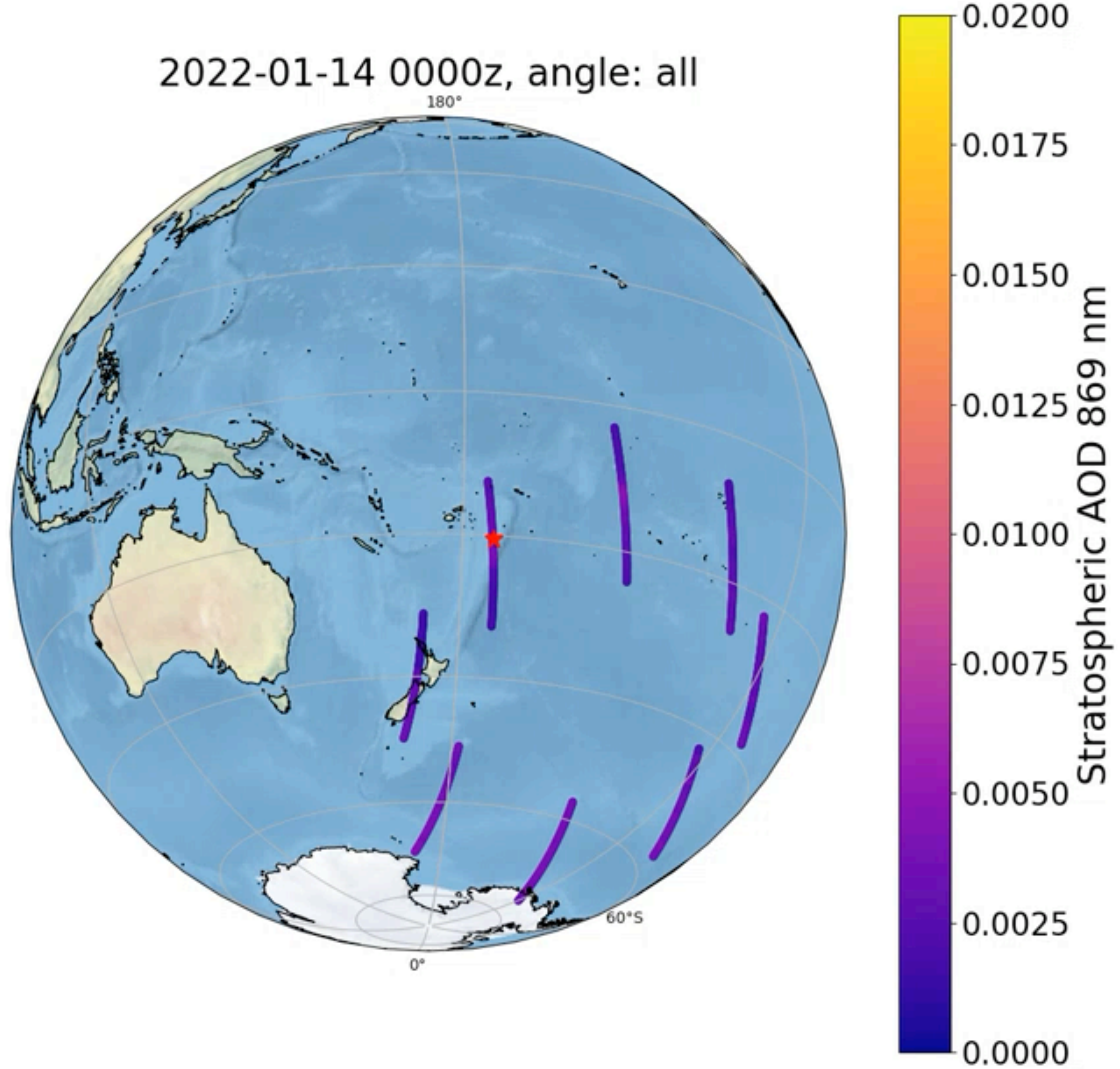
ARGOS Sampling

Single View Coverage
(like OMPS-LP)

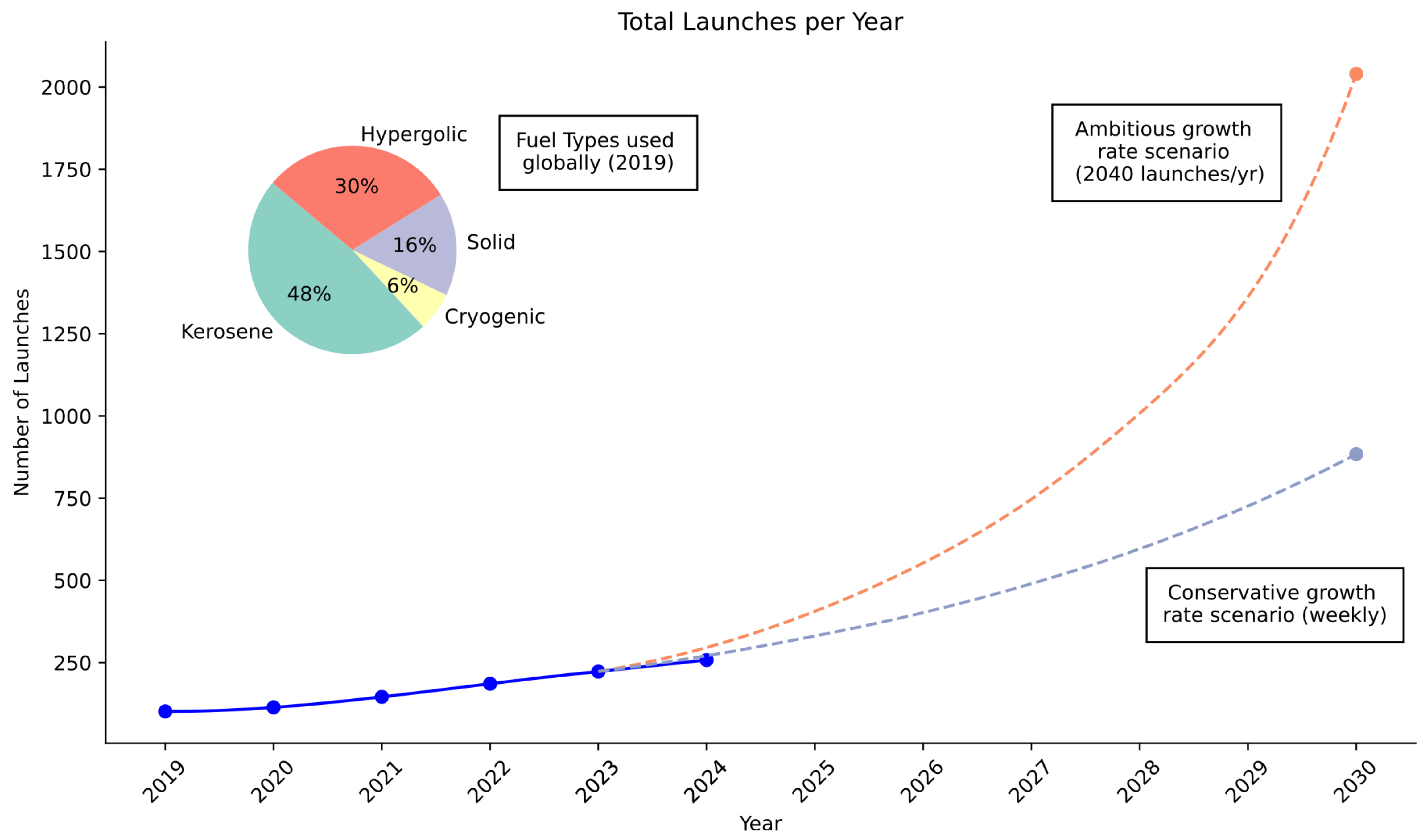
All ARGOS Views

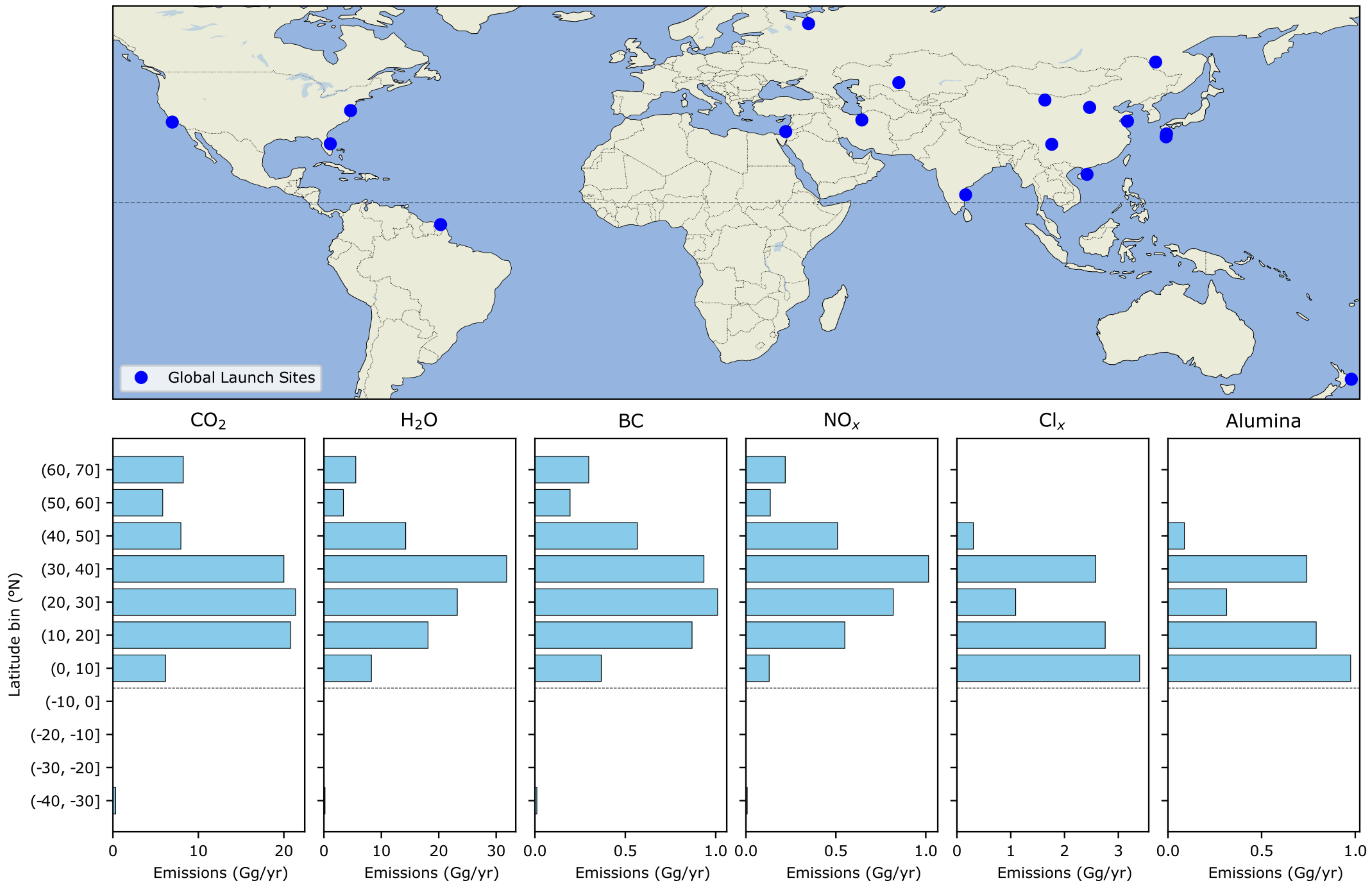




Rocket Launches and Orbital Debris

- Pollutants from rocket launches are radiatively active and, along with orbital debris, contribute to ozone loss in the stratosphere
- How much of an impact depends on the pace of rocket launches/re-entries and fuels used





Revell, L. E., Bannister, M. T., Brown, T. F. M., Sukhodolov, T., Vattioni, S., Dykema, J., Frame, D. J., Cater, J., Chiodo, G., and Rozanov, E.: Near-future rocket launches could slow ozone recovery, npj Clim. Atmos. Sci., 8, 212, https://doi.org/10.1038/s41612-025-01098-6, 2025.

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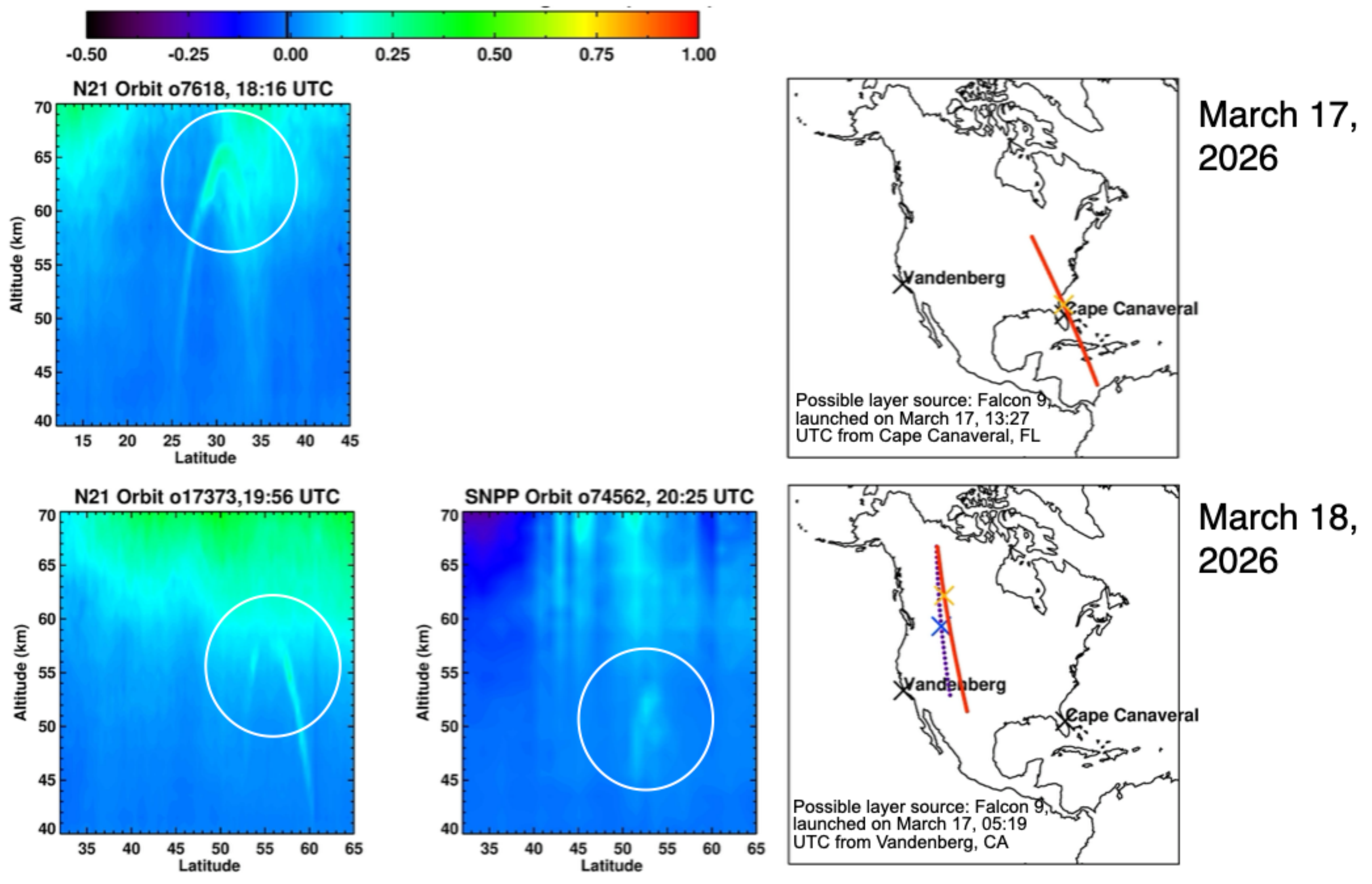
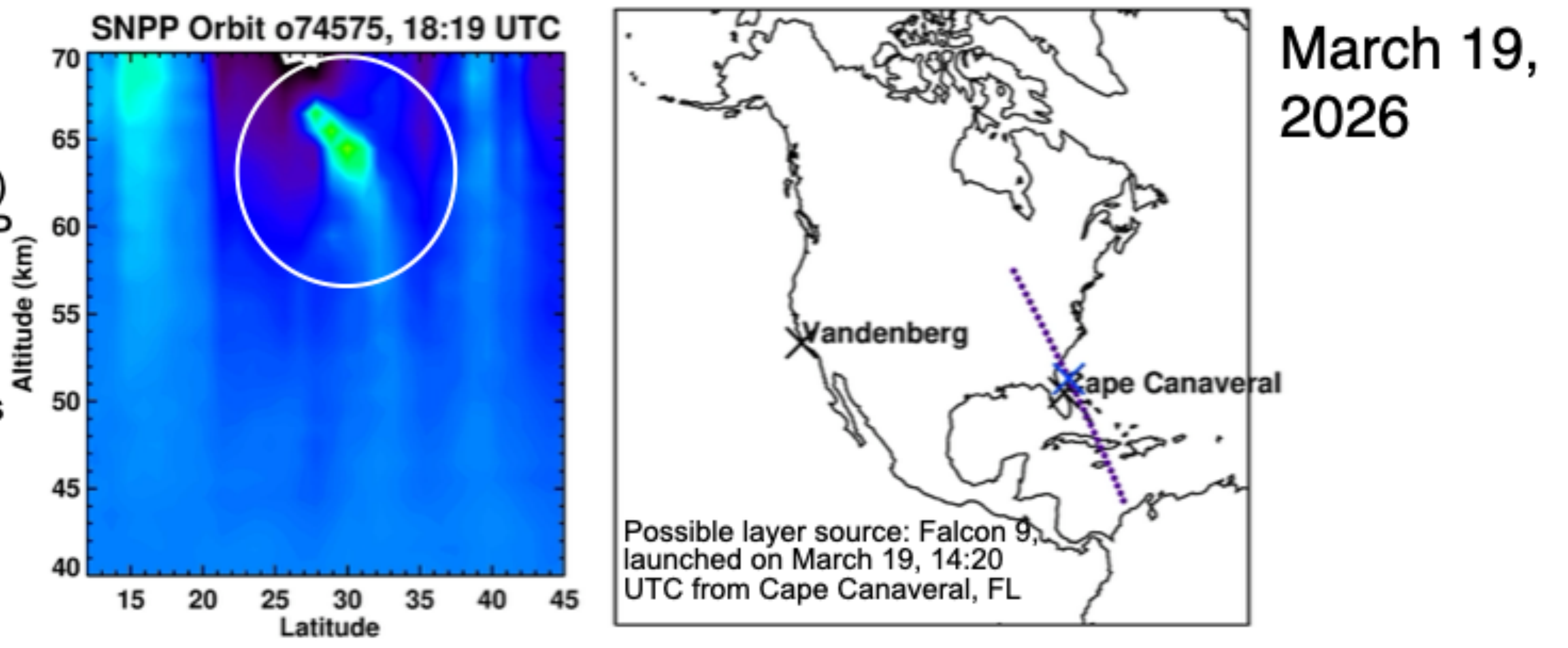
Rocket Launches and Orbital Debris



Latitudinal profiles of stratospheric aerosol scattering index (ASI) at 675 nm from the Ozone Monitoring and Profiler Suite Limb Profiler (OMPS-LP) instrument on the NOAA-21 and SNPP (left) and the location of these profiles (right) measured on 17, 18, and 19 March 2026. Black crosses are for the launch sites. Orange and blue crosses are for the layers' location. White circles indicate the detected aerosol layer.



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Ghassan Taha

Conclusions

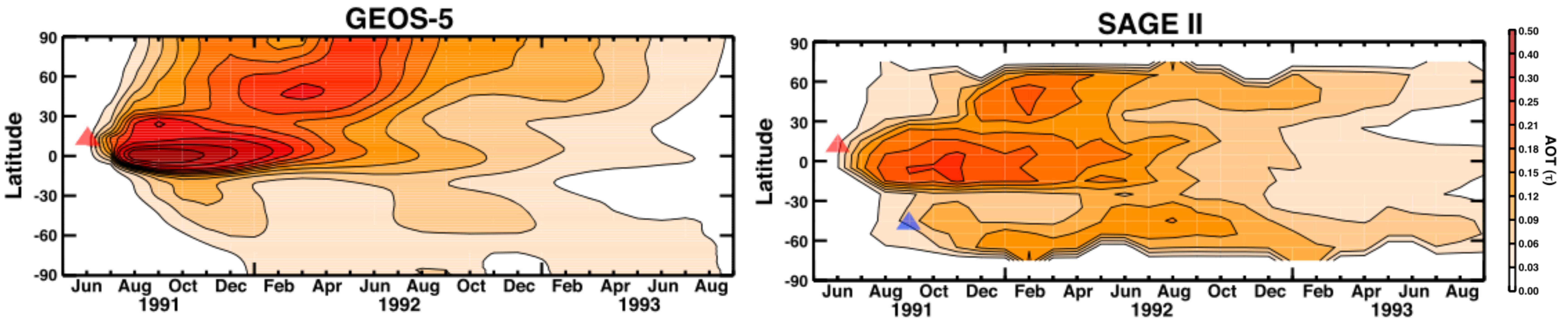
- Stratospheric aerosols are dynamic, with volcanic eruptions, pyroCb, and increasingly impacts of launch and reentry events affecting their distributions.
- Stratospheric aerosols affect the chemistry, radiative forcing, and dynamics of the stratosphere, directly impact the surface temperature and satellite retrievals.
- Stratospheric aerosol are not explicitly simulated in GEOS-FP or S2S. Tools to do so have been developed and are integrated in the GEOS model, though some simplification is needed for near-real time applications.
- Adding stratospheric aerosol perturbations to GEOS will improve dynamical and chemical forecasts. This remedies our ability to respond to and understand future events (e.g., volcanoes, pyroCbs, geoengineering).
- We need further development of satellite aerosol assimilation (OMPS-LP, STRIVE/ARGOS), improvement of particle property and chemistry assumptions (INSPYRE), and to extend capacity (e.g., launch and orbital debris).
- ICAP-centric: being able to say something about stratospheric aerosol distributions has applications to hazard avoidance, event detection and attribution, and communication (i.e., light transmission) in the upper atmosphere

Backups

Pinatubo Impacts Circulation

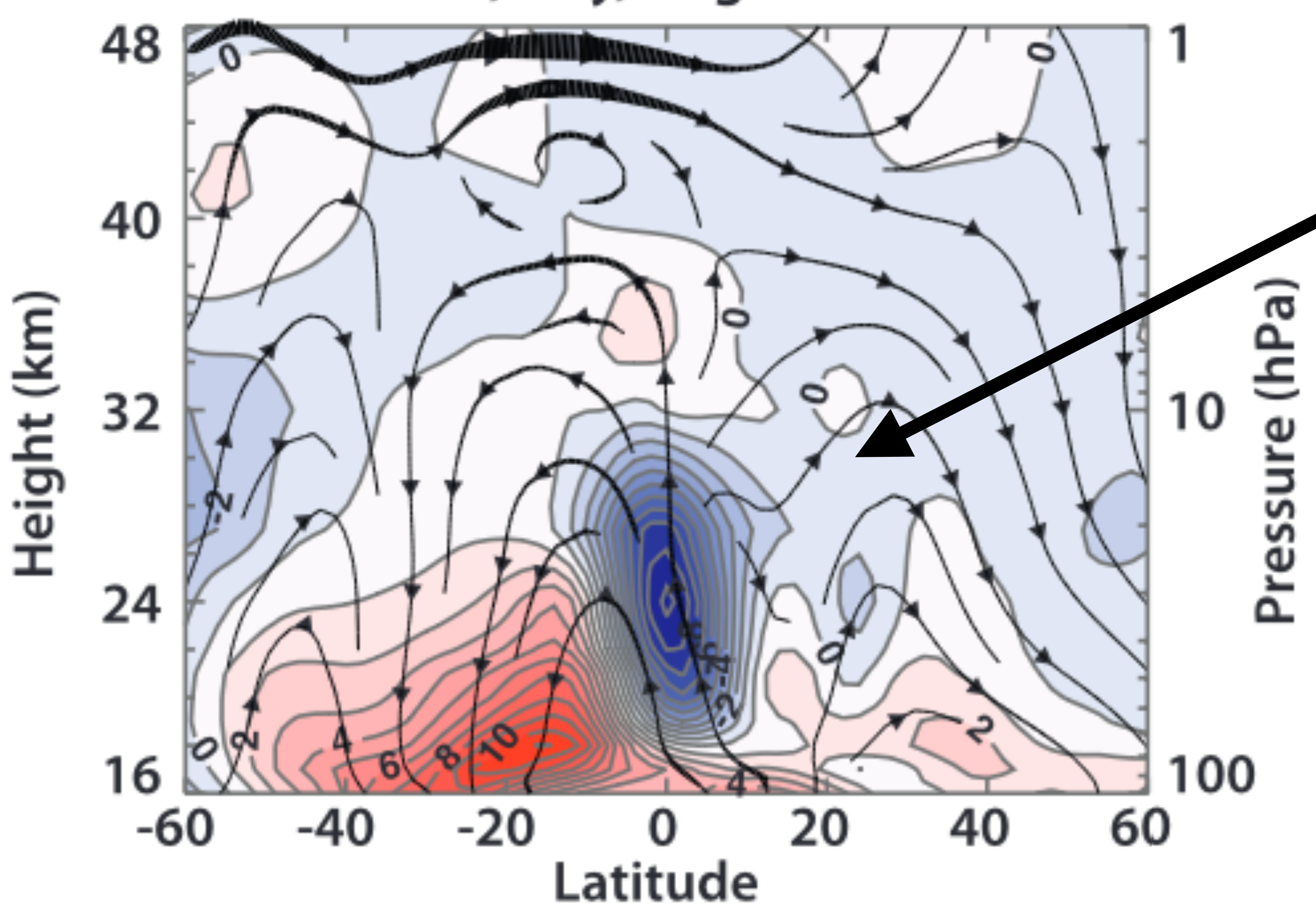
- Pinatubo aerosols simulated and radiatively coupled in GEOS with GOCART
- Radiative impacts change circulation which impact ozone distribution

Aerosol Optical Thickness



Aquila, V., et al. https://doi.org/10.1029/2011jd016968, 2012.

Ozone Anomaly



Upward motion caused by aerosol heating brings low ozone air from lower stratosphere to higher altitudes

Aquila, V., et al. https://doi.org/10.1175/jas-d-12-0143.1, 2013.

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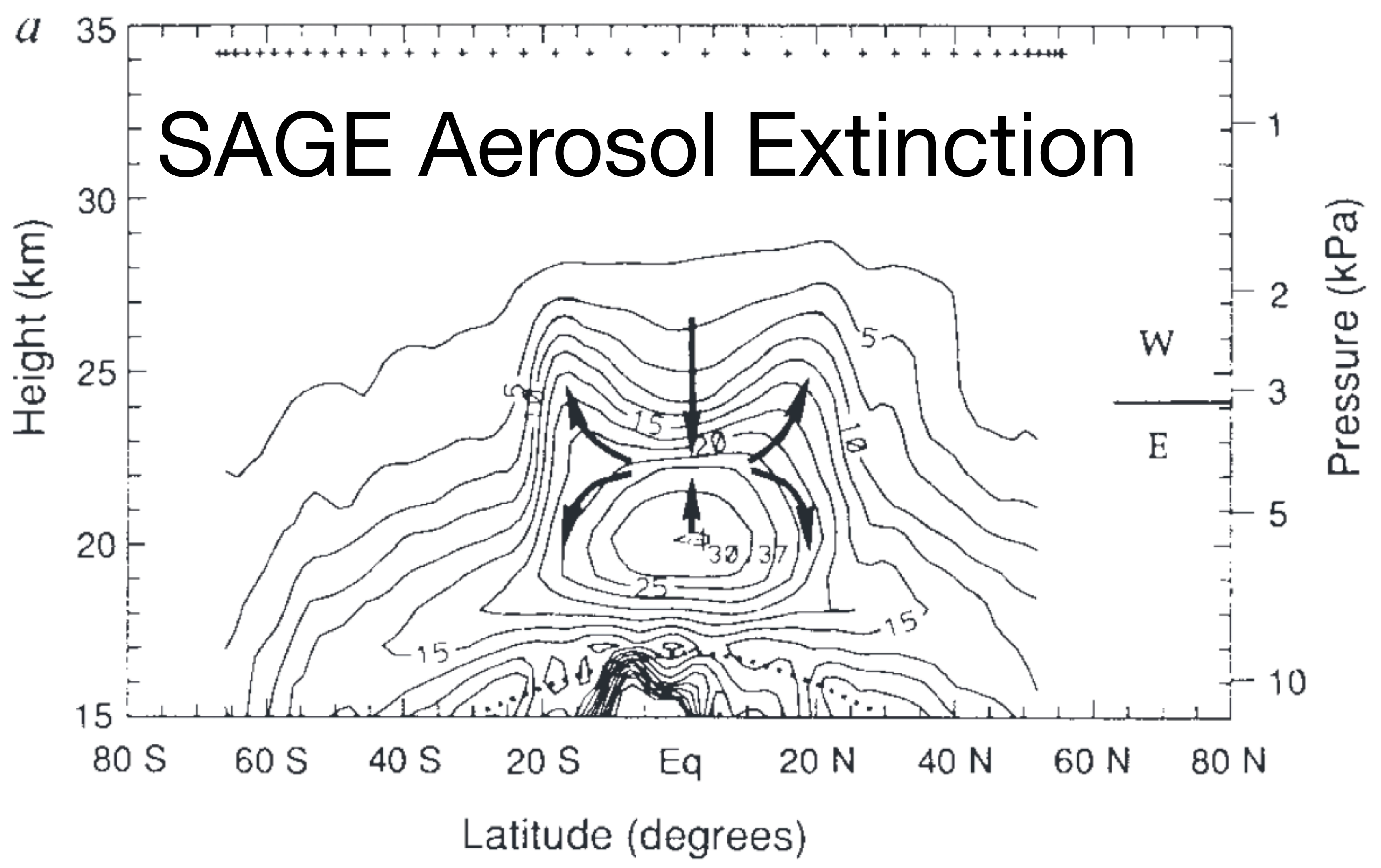
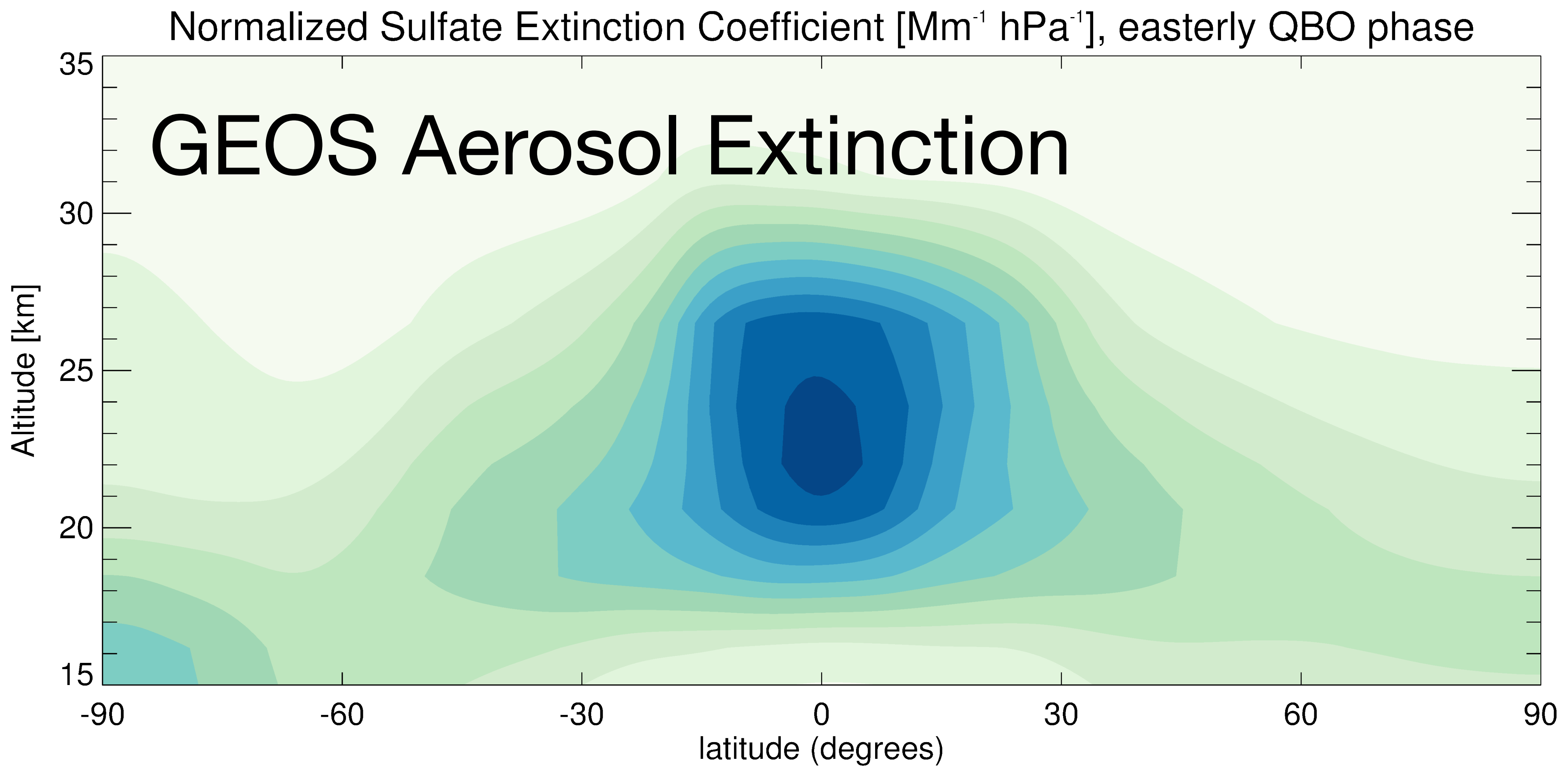
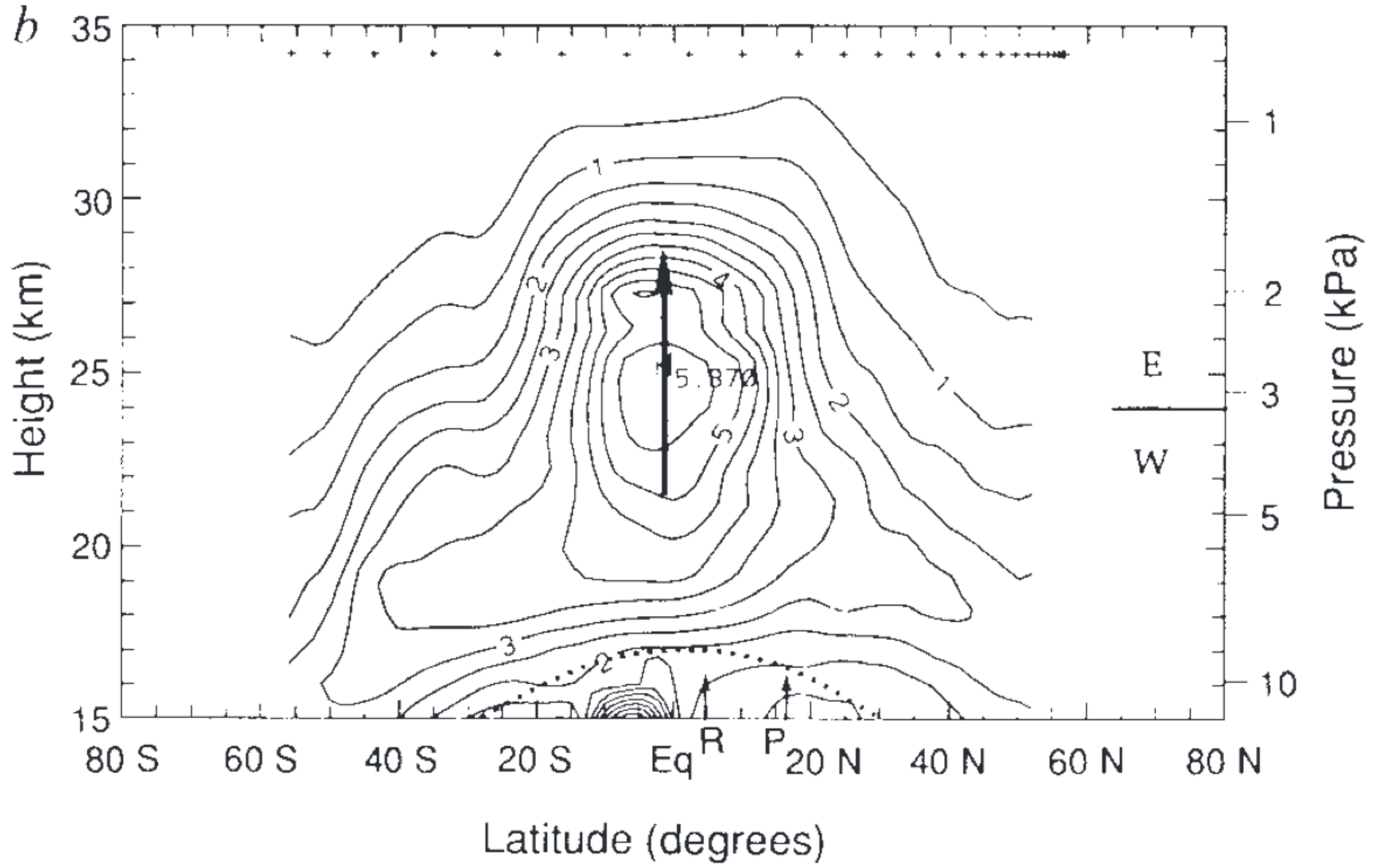
The Junge Layer Responds to QBO Forcing

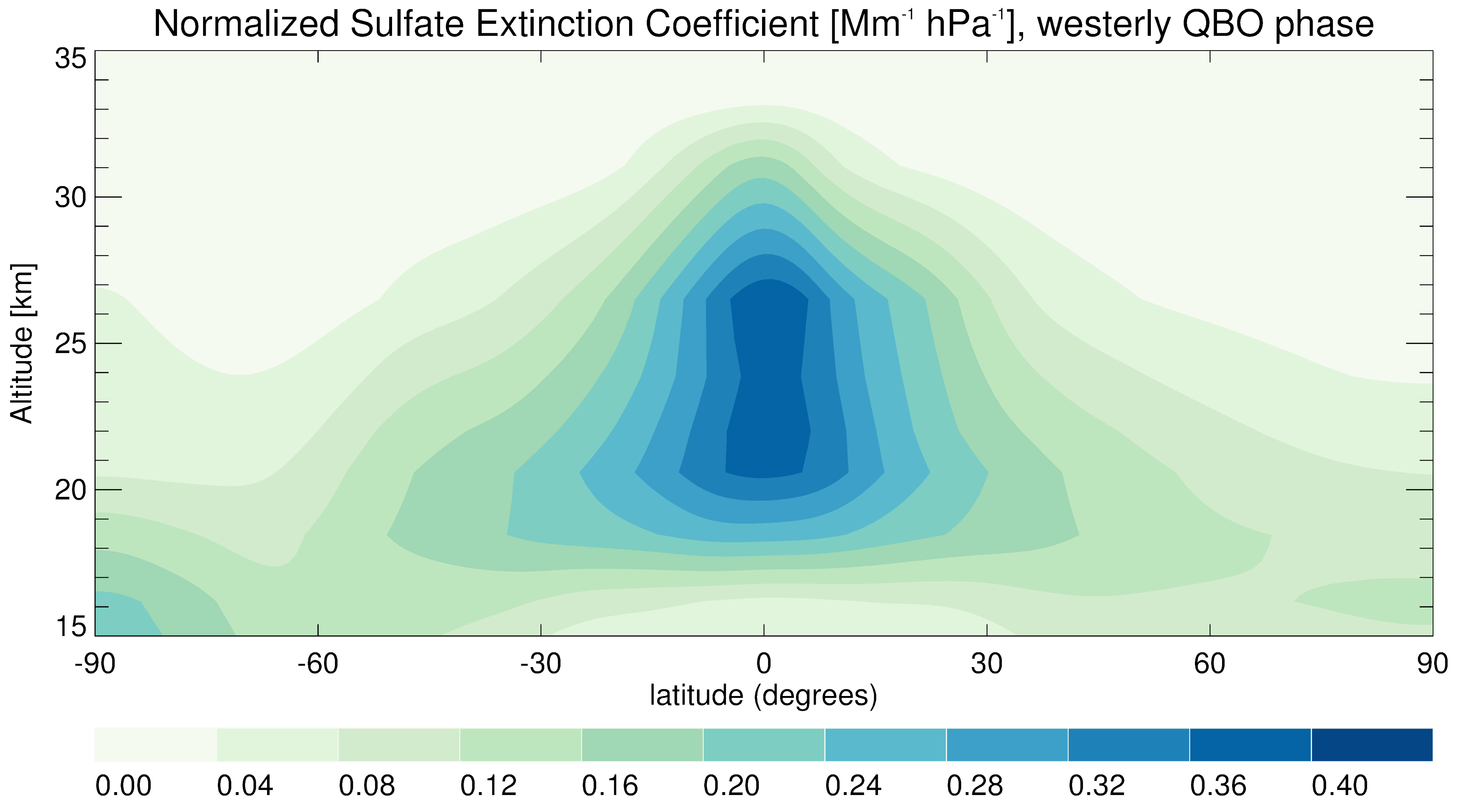
QBO Easterly Phase





QBO Westerly Phase





Trepte, C. R. and Hitchman, M. H.: Tropical Stratospheric Circulation Deduced From Satellite Aerosol Data, Nature, 355, 626 628, https://doi.org/10.1038/355626a0, 1992.

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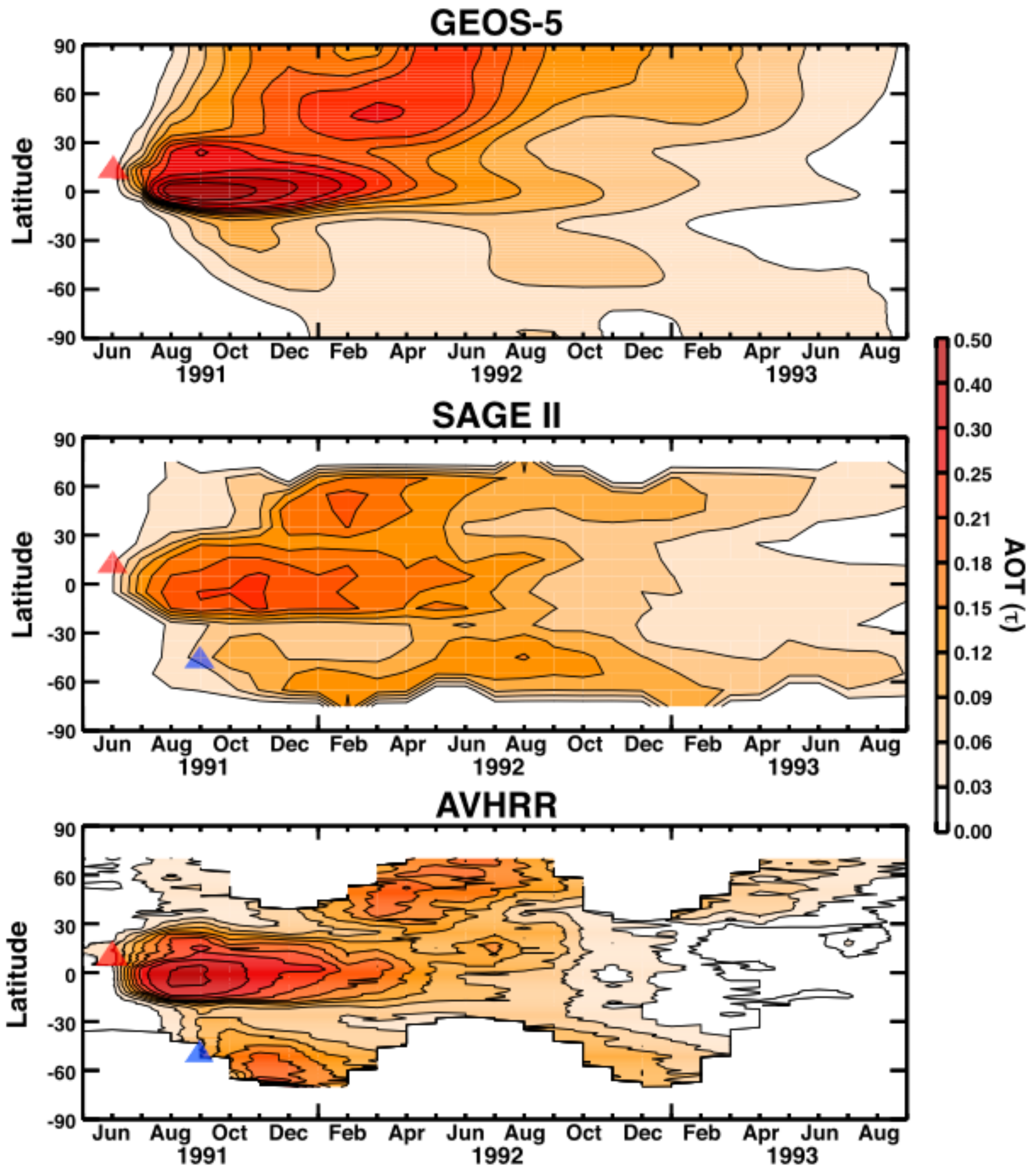
Pinatubo Impacts

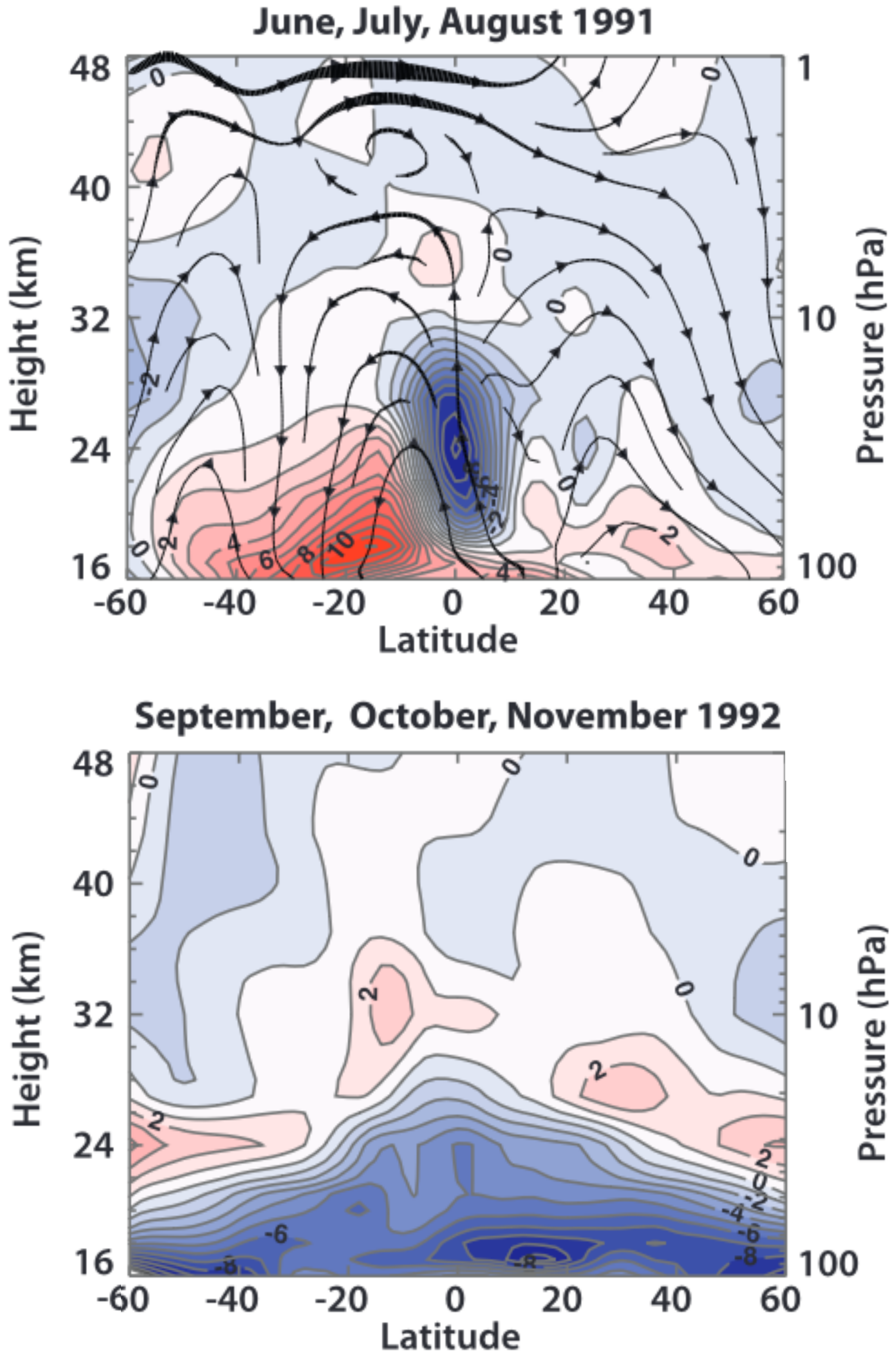
- Pinatubo aerosols simulated and radiatively coupled in GEOS with GOCART
- Radiative impacts change circulation which impact ozone distribution
- Limitation of fixed size assumption in GOCART and no coupling to chemistry

Aerosol Optical Thickness



Aquila, V., et al. https://doi.org/10.1029/2011jd016968, 2012.

Ozone Anomaly

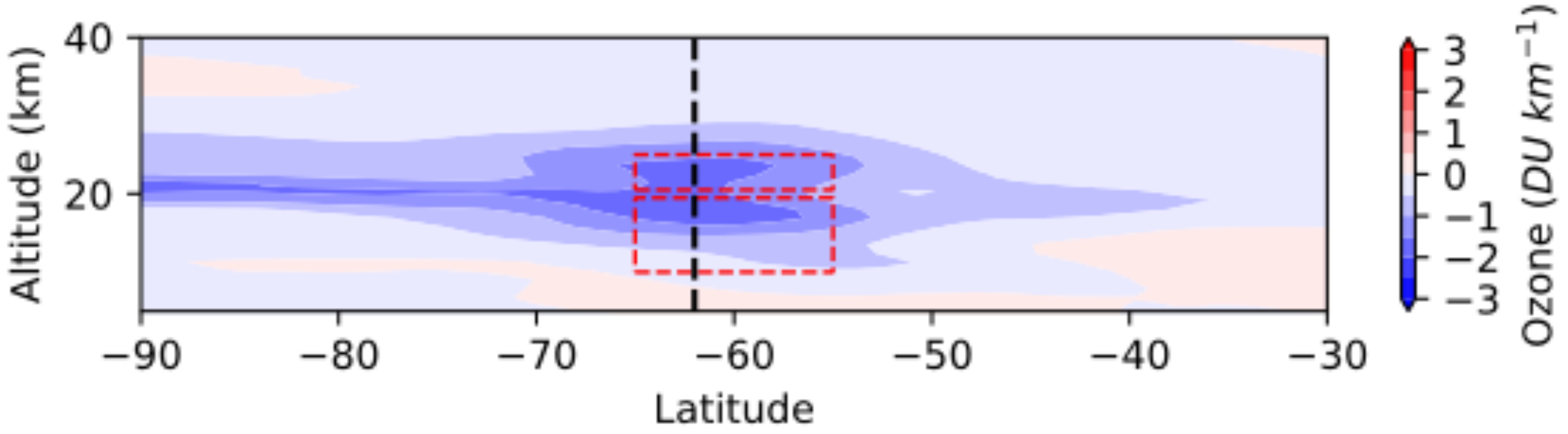


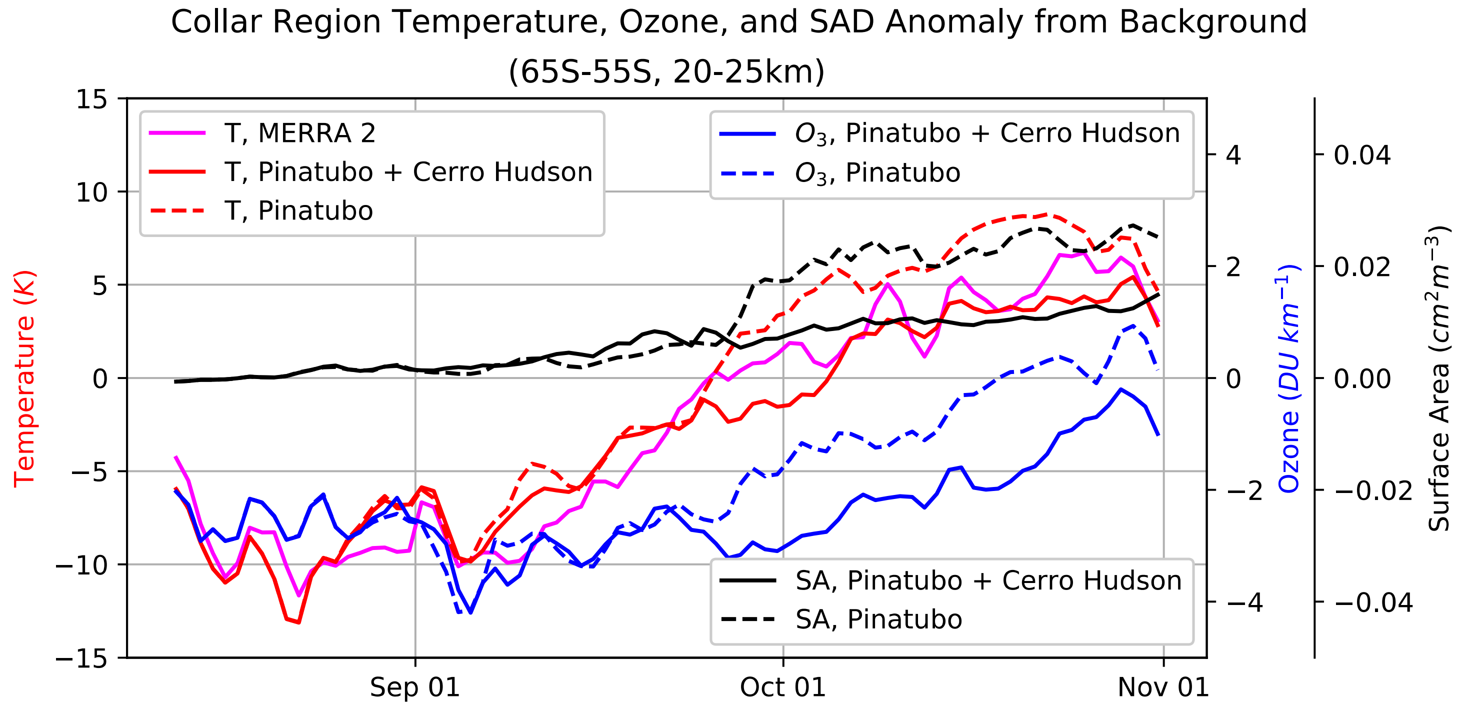
Aquila, V., et al. https://doi.org/10.1175/jas-d-12-0143.1, 2013.

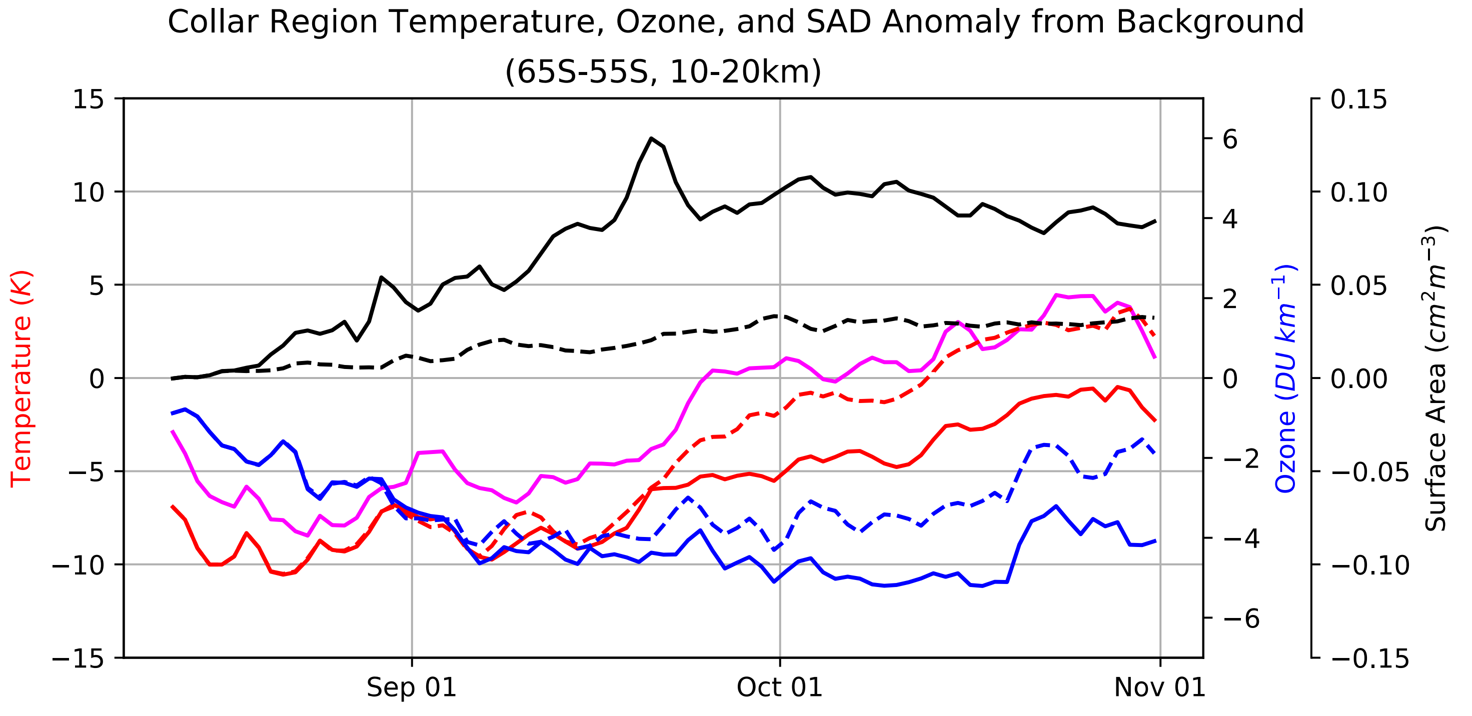
Pinatubo and Hudson

- Now have a tool for aerosol-radiation-chemistry coupled studies:
- In any other year the August 1991 eruption of Cerro Hudson in Chile would have been a major event
- Radiative forcing from Hudson inhibits breakdown of vortex and results in deeper ozone hole than if it hadn't happened

October 1991 Zonal Ozone Concentration Difference (Pinatubo+Cerro Hudson) - (Pinatubo-only) runs







Case, P. A., Colarco, P. R., Toon, O. B., and Newman, P. A.: Simulating the Volcanic Sulfate Aerosols From the 1991 Eruption of Cerro Hudson and Their Impact on the 1991 Ozone Hole, Geophys. Res. Lett., 51, https://doi.org/10.1029/2023gl106619, 2024.

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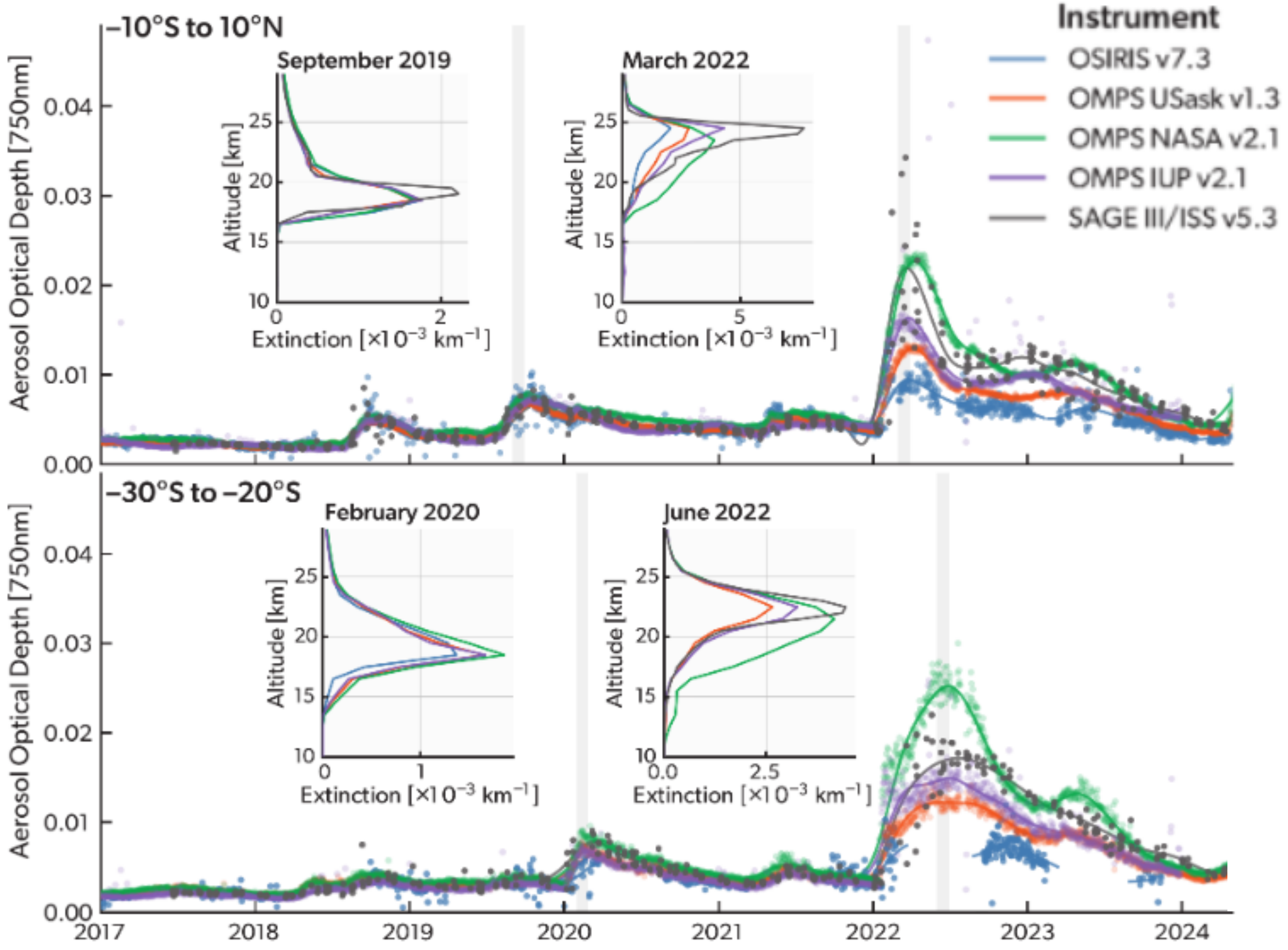
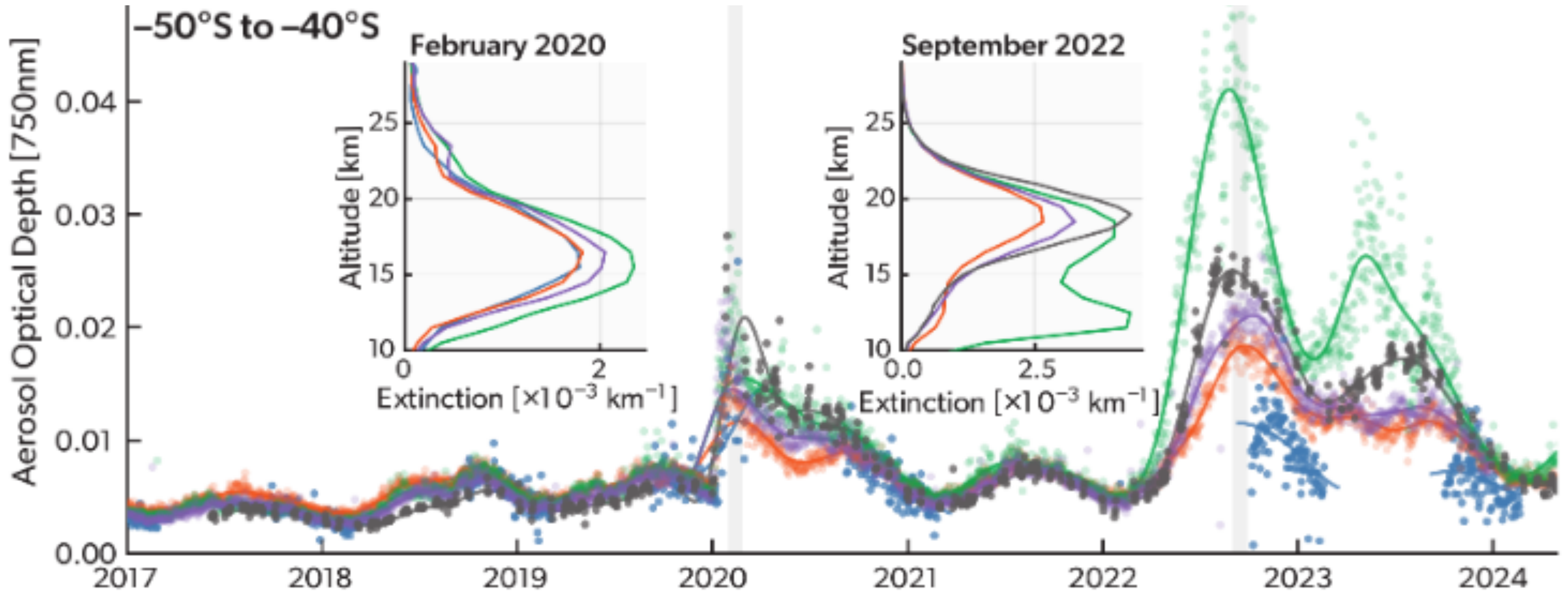
Observational Challenge



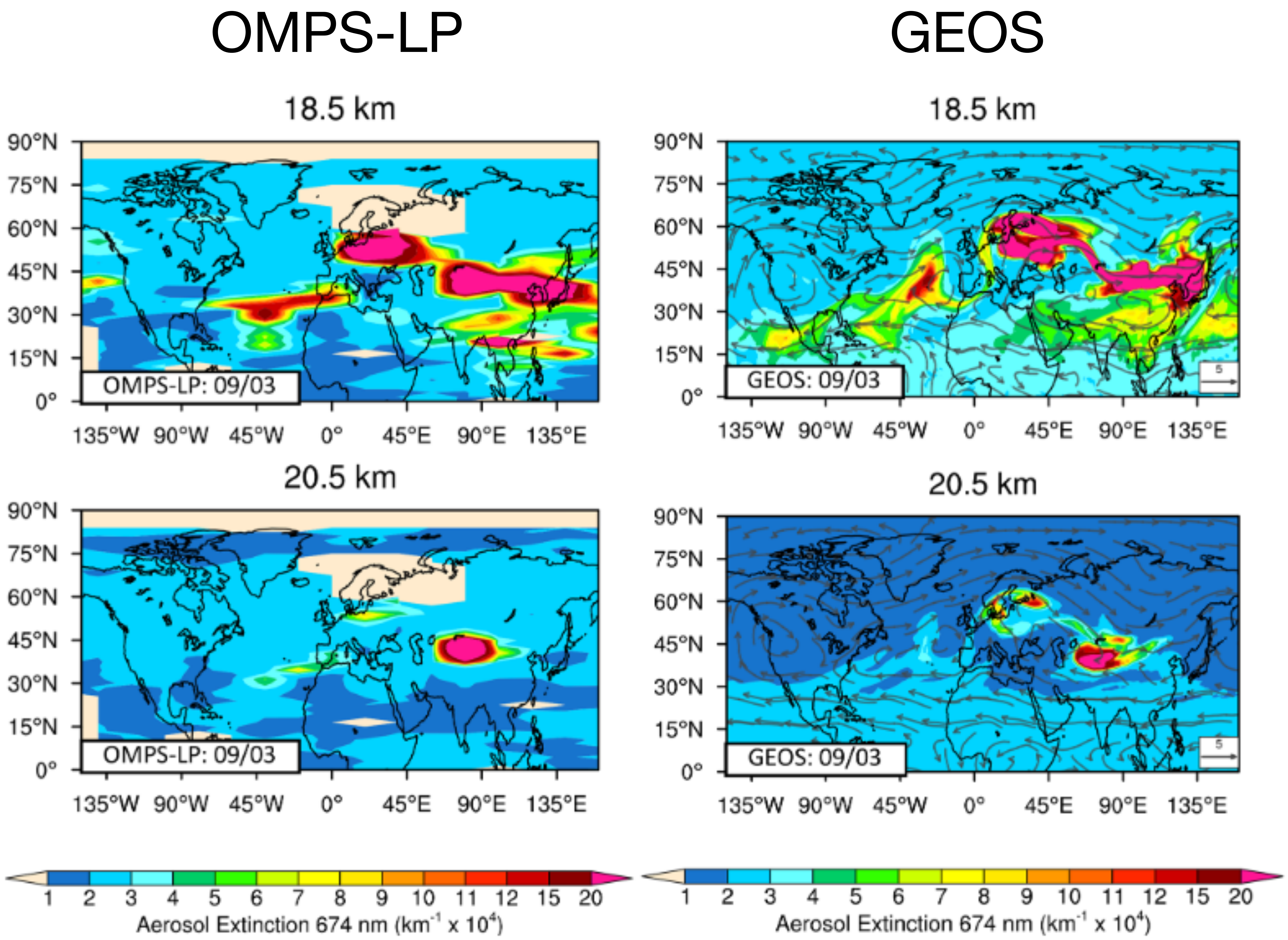


- Satellites largely agree on pre-eruption AOD magnitude
- Post-eruption differences in the assumed particle size distribution in various retrievals lead to large variability in AOD

APARC Hunga Report

Modeling Transport

- Simulated smoke lofting depends on model assumptions of particle properties
- With appropriate assumptions we can simulate the vertical and horizontal transport of the plume over weeks to months



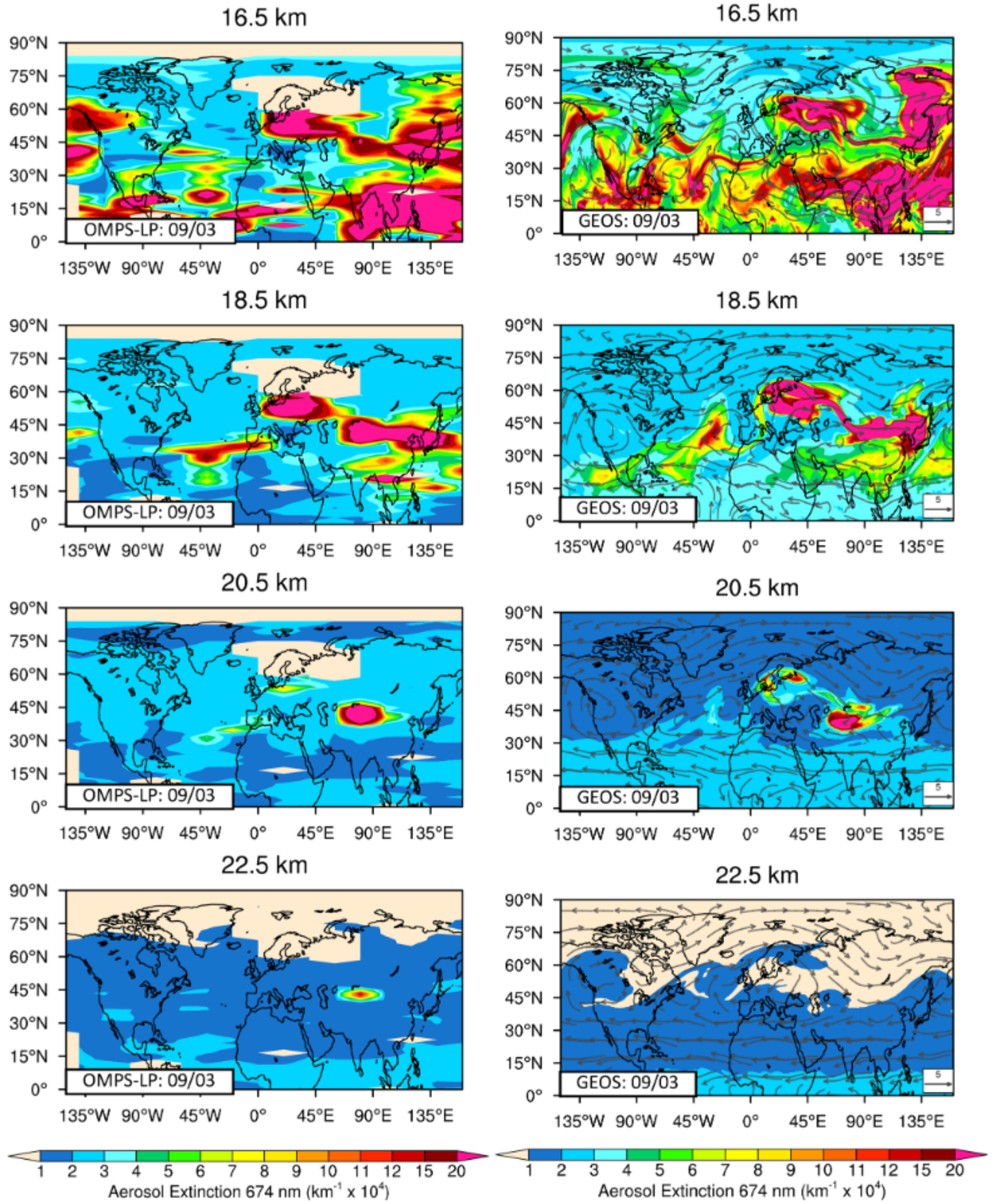
Das, S., Colarco, P. R., Oman, L. D., Taha, G., and Torres, O.: The long-term transport and radiative impacts of the 2017 British Columbia pyrocumulonimbus smoke aerosols in the stratosphere, Atmos Chem Phys, 21, 12069–12090, https://doi.org/10.5194/acp-21-12069-2021, 2021.

GODDARD EARTH SCIENCES

Modeling Transport

- Simulated smoke lofting depends on model assumptions of particle properties
- With appropriate assumptions we can simulate the vertical and horizontal transport of the plume over weeks to months

OMPS-LP

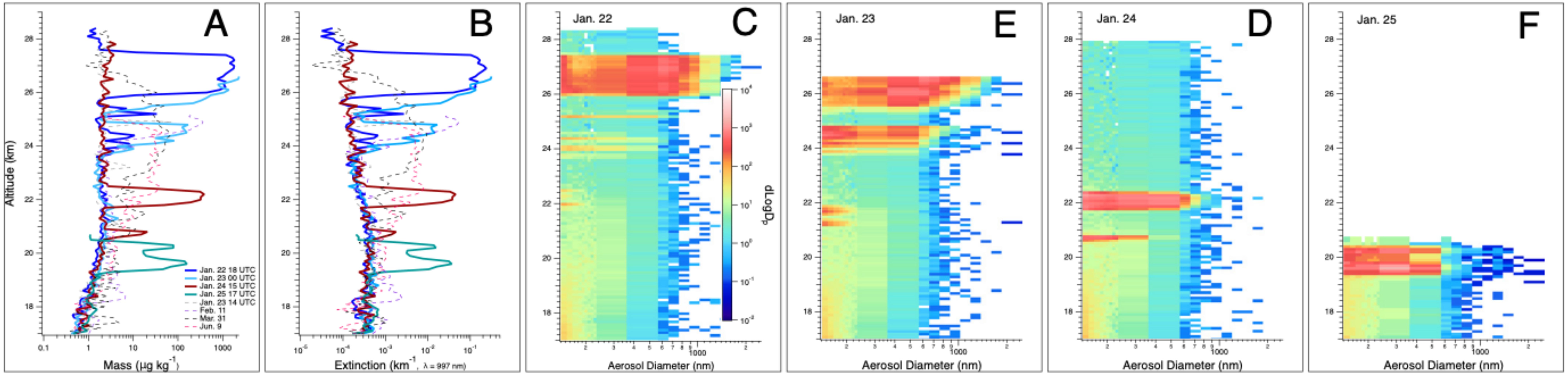


GEOS

Das, S., Colarco, P. R., Oman, L. D., Taha, G., and Torres, O.: The long-term transport and radiative impacts of the 2017 British Columbia pyrocumulonimbus smoke aerosols in the stratosphere, Atmos Chem Phys, 21, 12069–12090, https://doi.org/10.5194/acp-21-12069-2021, 2021.

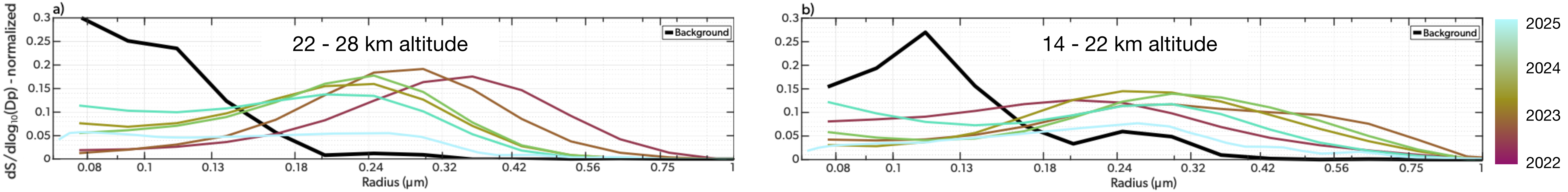
Hunga Observations

NOAA Balloon Observations of Particle Amount and Size at La Réunion



Asher, E., Todt, M., Rosenlof, K., Thornberry, T., Gao, R.-S., Taha, G., Walter, P., Alvarez, S., Flynn, J., Davis, S. M., Evan, S., Brioude, J., Metzger, J.-M., Hurst, D. F., Hall, E., and Xiong, K.: Unexpectedly rapid aerosol formation in the Hunga Tonga plume, Proc. Natl. Acad. Sci., 120, e2219547120, https://doi.org/10.1073/pnas.2219547120, 2023.

Time Evolution of Particle Size Distribution at Lauder, New Zealand

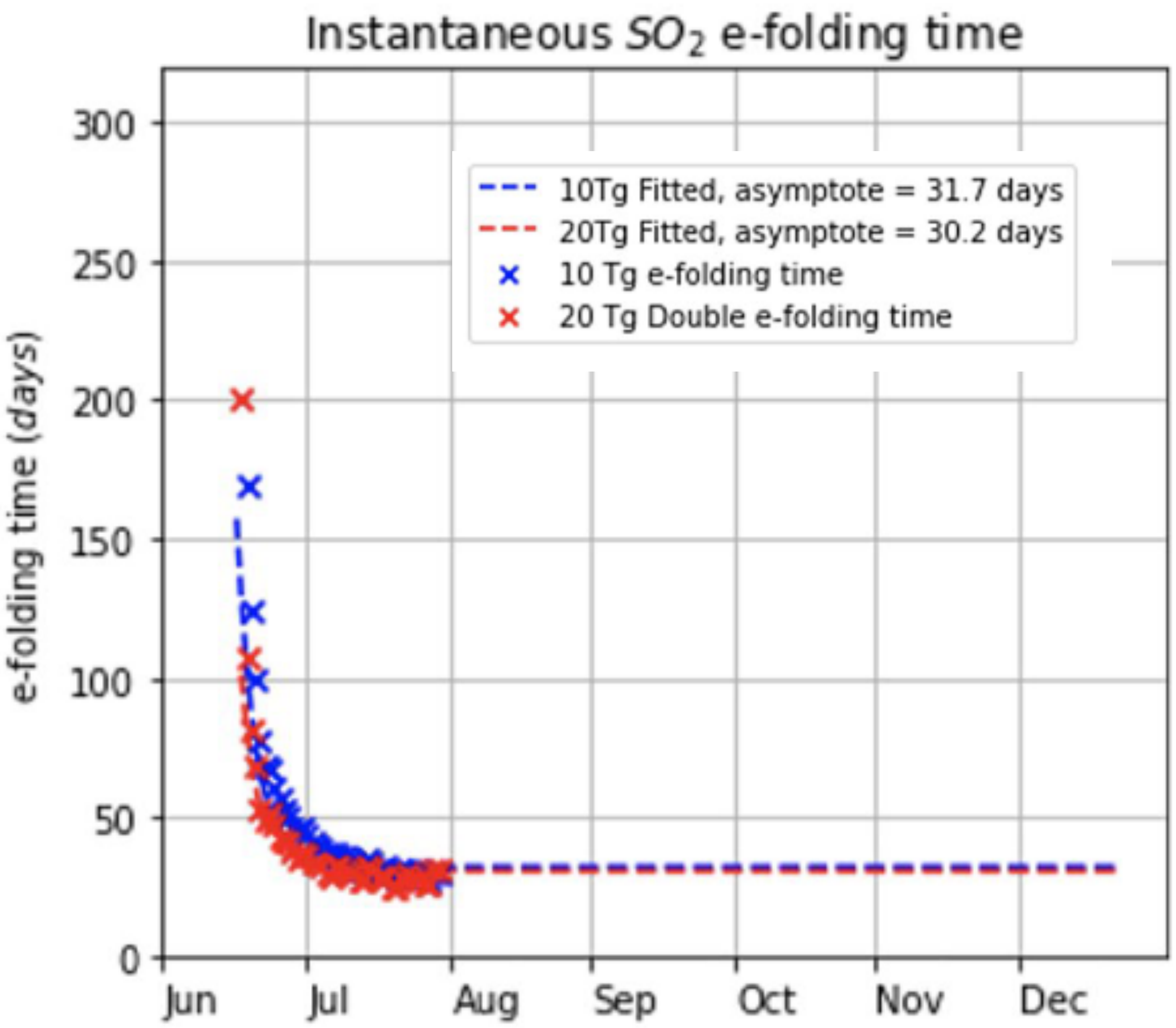


APARC Hunga Report

GODDARD EARTH SCIENCES

Pinatubo Impacts

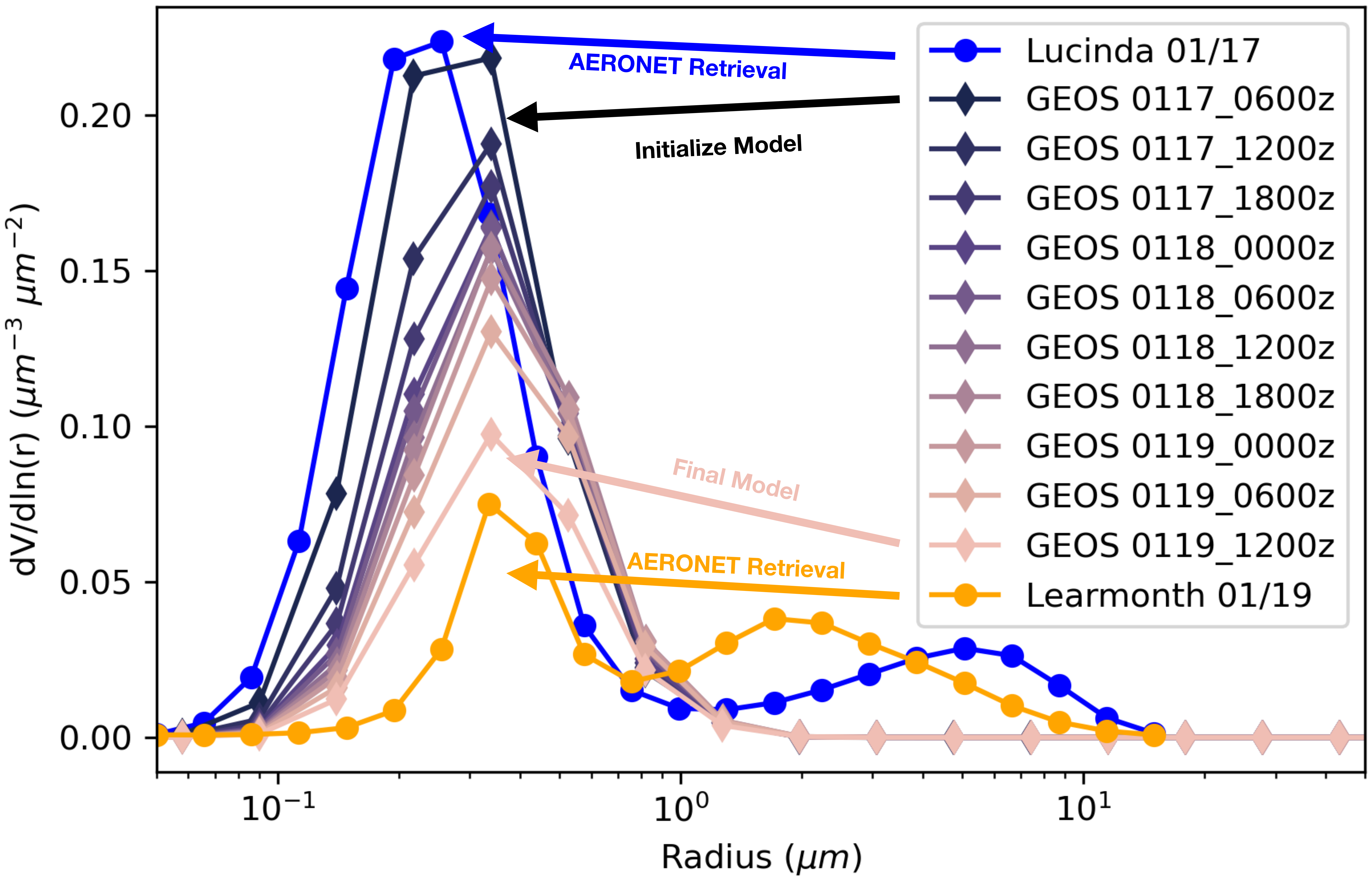
- Chemical and radiative coupling: GEOS simulations with GEOS-Chem and CARMA microphysics coupled
- Now have size-resolved particle properties
- Coupling to chemistry mechanism shows slower SO_2 to aerosol conversion due to saturation



Case, P., Colarco, P. R., Toon, B., Aquila, V., and Keller, C. A.: Interactive Stratospheric Aerosol Microphysics-Chemistry Simulations of the 1991 Pinatubo Volcanic Aerosols With Newly Coupled Sectional Aerosol and Stratosphere-Troposphere Chemistry Modules in the NASA GEOS Chemistry-Climate Model (CCM), J. Adv. Model. Earth Syst., 15, https://doi.org/10.1029/2022ms003147, 2023.

Modeling Hunga

- GEOS CARMA simulates the observed particle growth over a 48 hour period



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Aerosol Composition

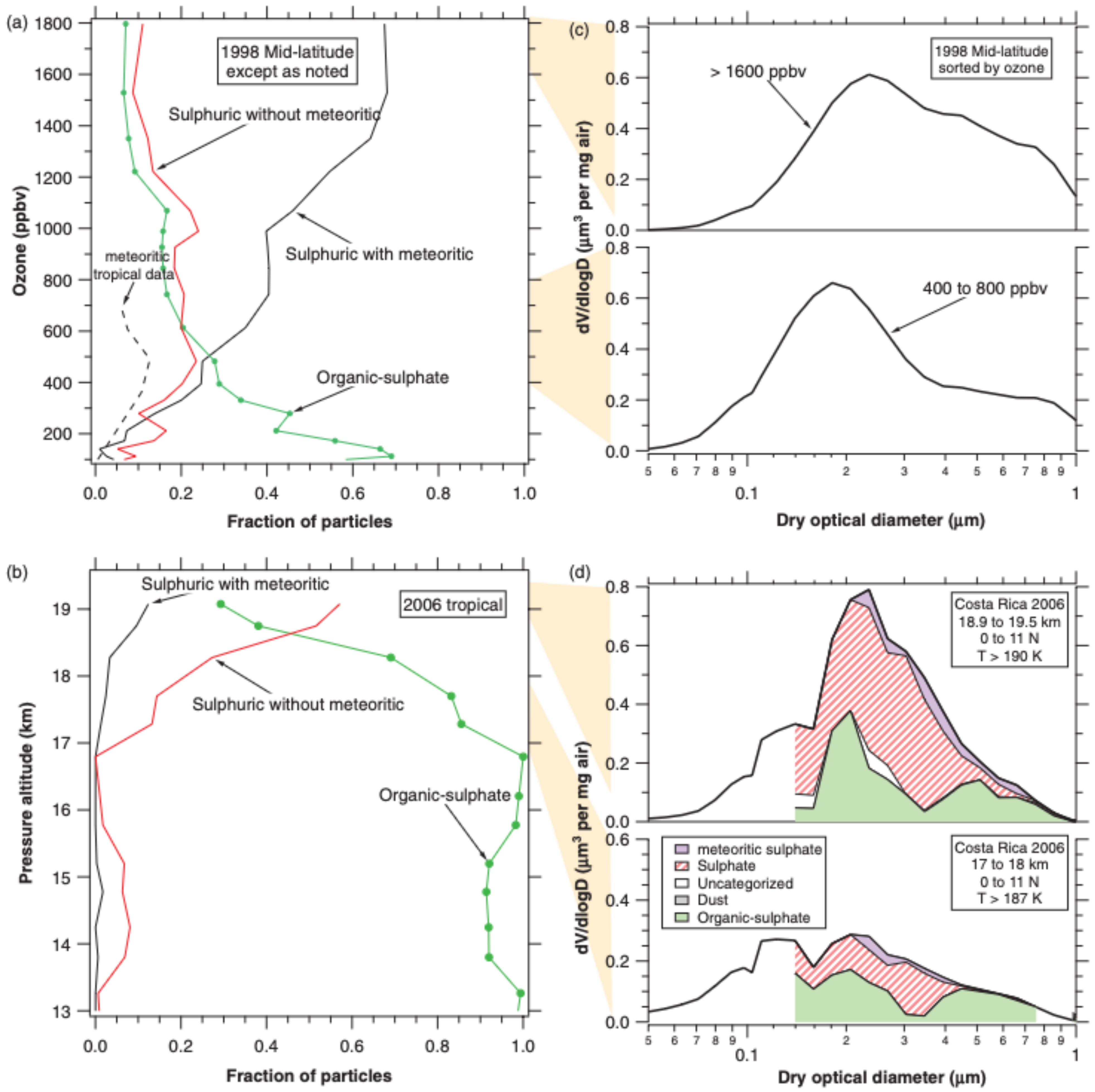

Figure 3. Vertical profiles of the fraction of analyzed particles classified into three major types of stratospheric particles. (a) Uses ozone as a vertical coordinate for seven flights between 26 and 46°N in April and May 1998 from Houston. The tropopause was often near 100 ppbv ozone. (b) Uses altitude for 13 flights between 0 and 11°N in January and February 2006 from Costa Rica. Tropopauses during these tropical flights were mostly between 17 and 18 km. For comparison, data on sulphuric acid particles with meteoritic metals from the 2006 tropical flights are shown in the top panel. Data from other years (not shown) agree well with these flights: these have the best statistics and altitude ranges. Panels (c) and (d) show the size distributions from the University of Denver Focused Cavity Aerosol Spectrometer (FCAS) optical particle counter for subsets of the vertical distributions. In 2006 the PALMS size measurement was accurate enough to apportion the size distribution. The additional volume above 18.9 km was due to added sulphuric acid particles.

Murphy, D. M., Froyd, K. D., Schwarz, J. P., and Wilson, J. C.: Observations of the chemical composition of stratospheric aerosol particles, Q. J. R. Meteorol. Soc., 140, 1269–1278, https://doi.org/10.1002/qj.2213, 2014.

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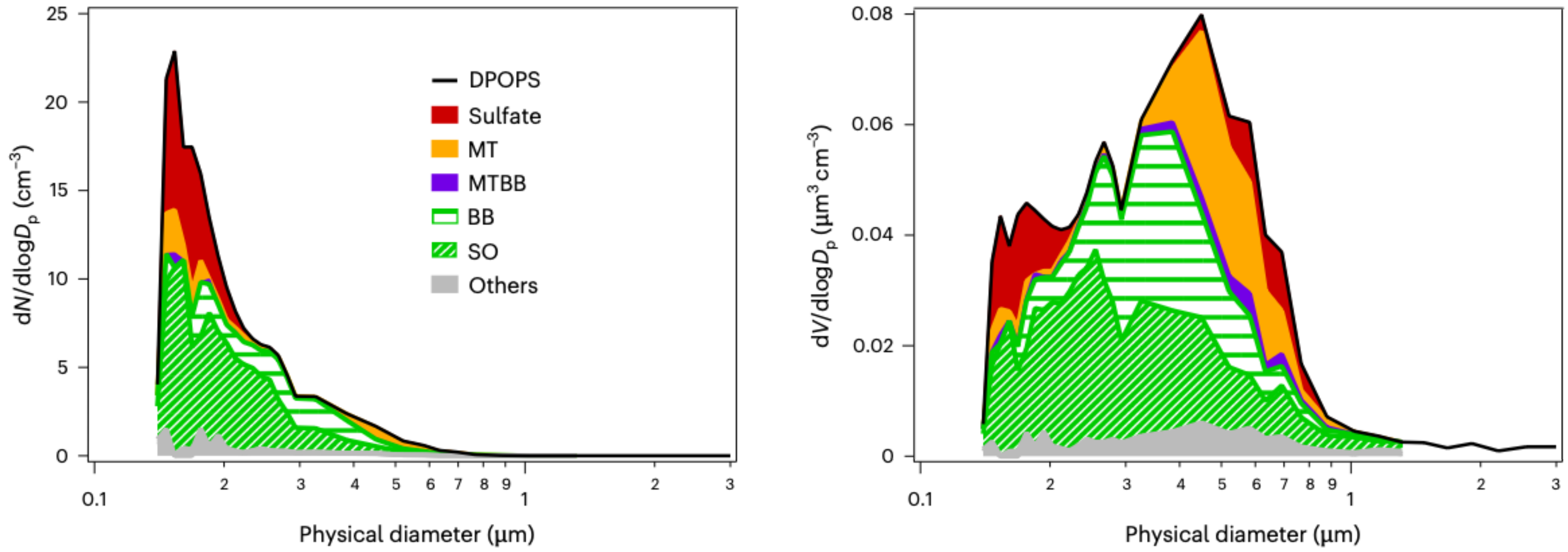
Aerosol Composition

- There is variability in lower stratospheric aerosol composition independent of large impulsive events

Number | Volume

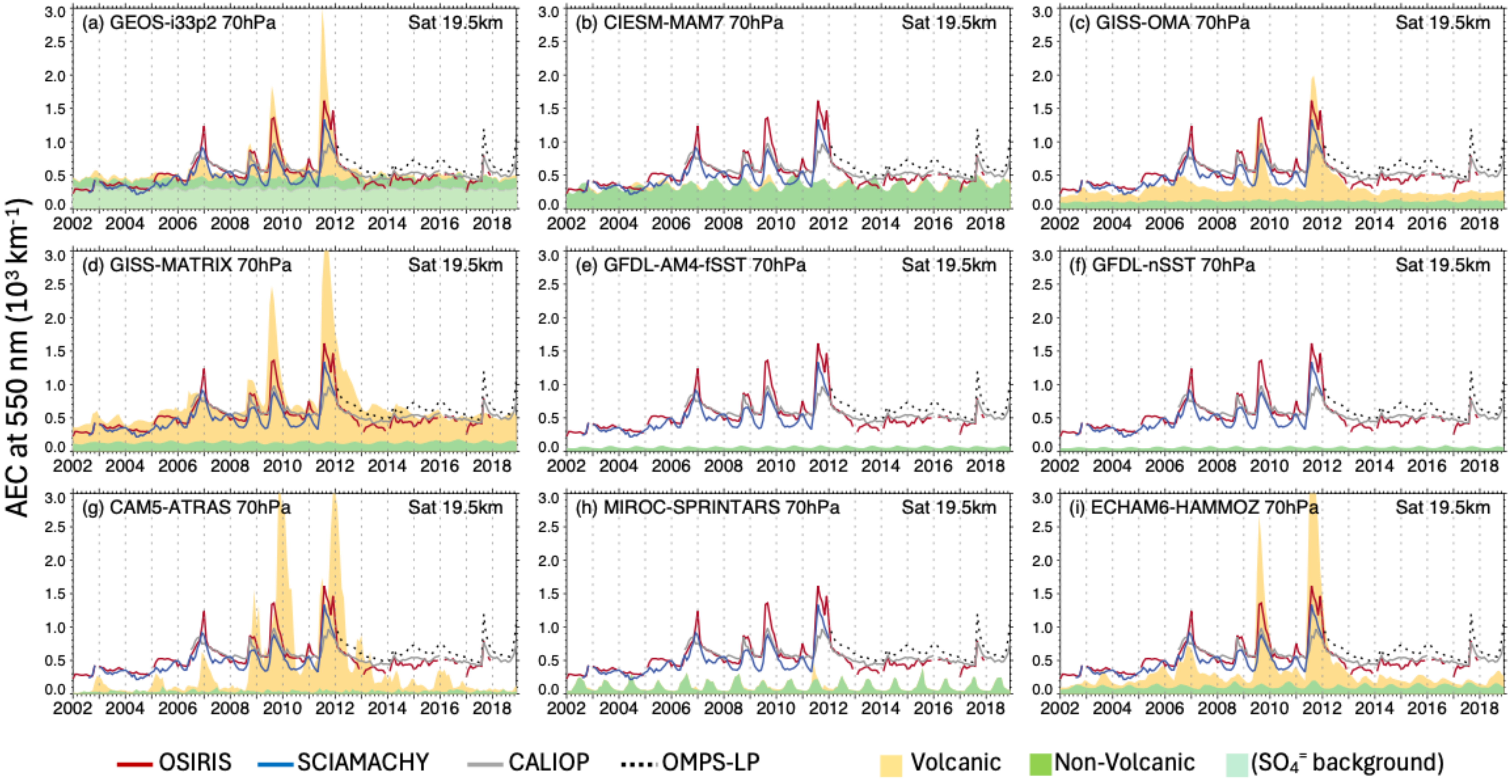


Airborne PALMS-NG Observations from Troposphere to Trop + 5.5 km

Shen, X., Jacquot, J. L., Li, Y., Sharpe, S. A. L., Dykema, J. A., Schill, G. P., Bowman, K. P., Homeyer, C. R., Fraund, M., Moffet, R. C., Olayemi, T. E., Pittman, J. V., Rivera-Adorno, F. A., Murphy, D. M., Smith, J. B., Laskin, A., Keutsch, F. N., and Cziczo, D. J.: Stratospheric aerosol perturbation by tropospheric biomass burning and deep convection, Nat. Geosci., 18, 1109–1116, https://doi.org/10.1038/s41561-025-01821-1, 2025.

Aerosol Composition

- Models exhibit wide compositional variability in the lower stratospheric aerosol due to source, process, and particle property uncertainty (here for aerosol extinction coefficient (AEC) in Asian Summer Monsoon)



Chin, M., Wright, J. S., Bian, H., Tan, Q., Pan, X., Takemura, T., Matsui, H., Tsigaridis, K., Bauer, S., Ginoux, P., Peng, Y., Guo, Z., Fadnavis, S., Laakso, A., Burrows, J. P., Taha, G., Kar, J., Rozanov, A., Arosio, C., Rieger, L., and Bourassa, A.: Variability and trends of upper-tropospheric aerosols over the Asian summer monsoon region: An AeroCom multi-model study, EGUsphere, 2026, 1–24, https://doi.org/10.5194/egusphere-2025-6257, 2026.