Stratospheric particle size growth and cooling by water vapor after the 2022 Hunga Tonga eruption

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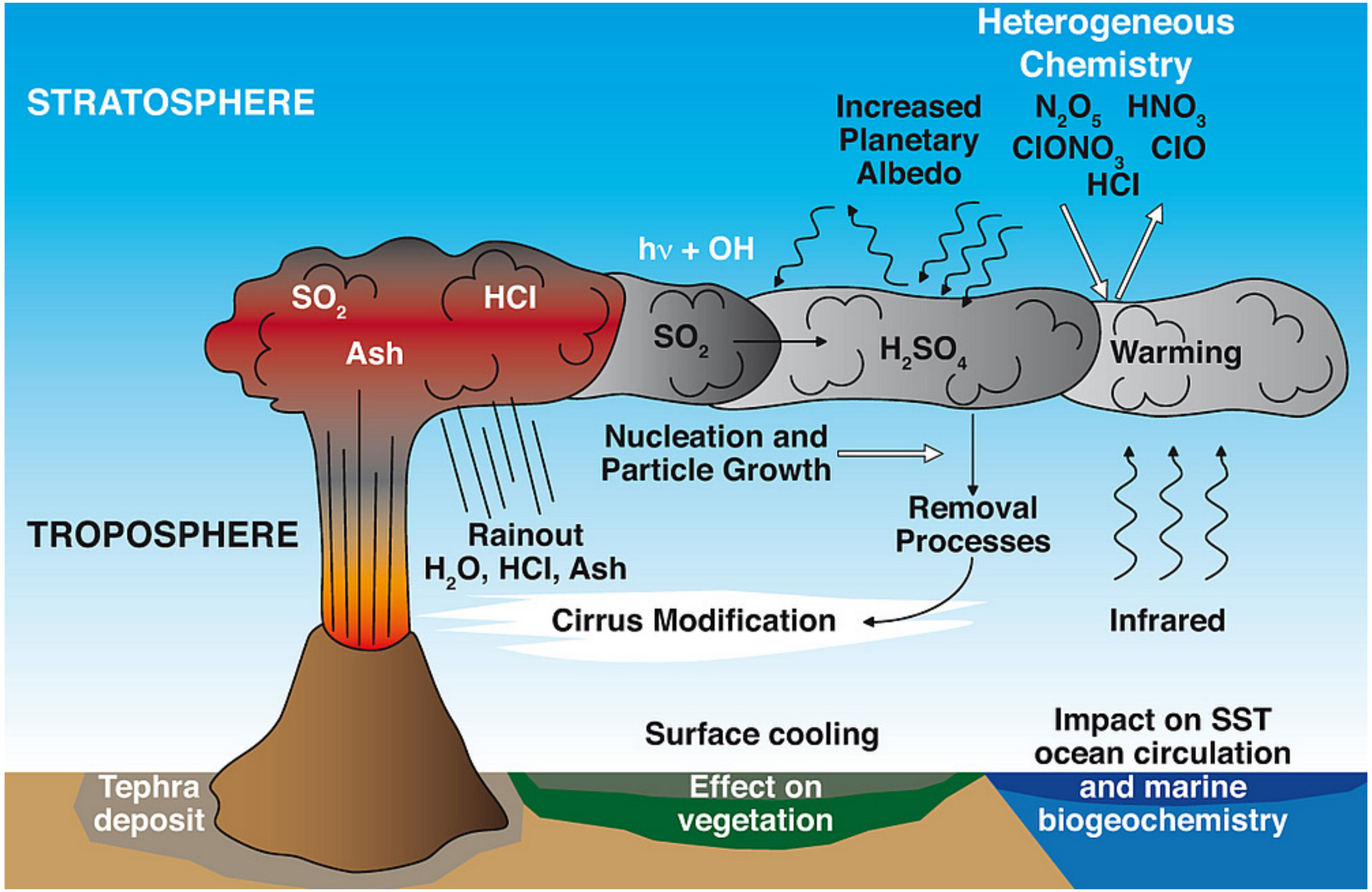
The University of Iowa

Volcanic eruptions impact on the atmosphere

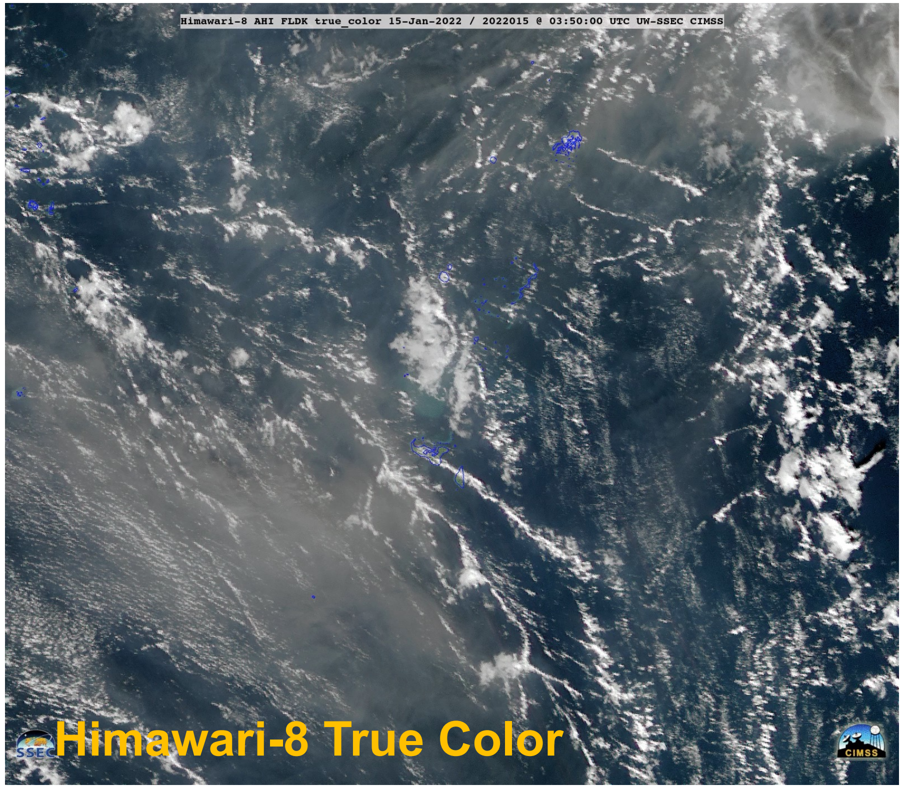


- Emissions: SO_2, volcanic ash, HCl, water vapor
- Reactions: SO_2 + OH → sulfuric acid, nucleation, coagulation, growth
- Chemistry impact: heterogeneous chemistry catalyzed by sulfate particles influence ozone concentration
- Climate impact: aerosols cause surface cooling and stratospheric warming

Hunga Tonga 2022 eruption

- Hunga Tonga volcano at South Pacific (175.38W, 20.57S) has sporadically erupted since 2009 with the most recent activity beginning in late December 2021.
- On Jan.13, 2022 (15:20 UTC), a powerful eruption is captured with a radius of 161.5 miles and sending ash, steam, and gas 12.4 miles into the air.
- However, an even more intense series of explosions began on January 15 (04:14 UTC). The eruptions generated atmospheric shock waves, sonic booms, and tsunami waves that traveled the world and were heard as far away as Alaska.

Unique features	**Phenomenon**
Unexpected explosive energy	unusual height of injection
Submarine volcano	more water vapor injection



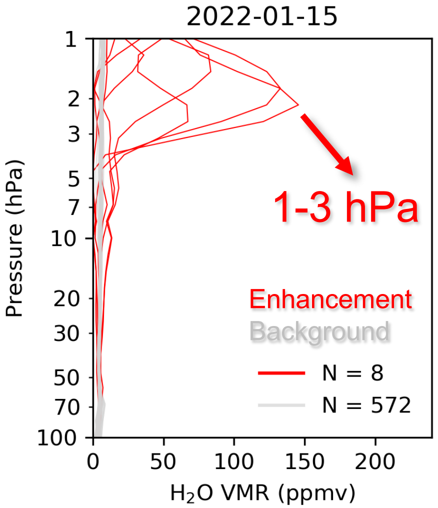
This research:

- ➢ Analyze the evolution of stratospheric composition after Hunga Tonga 2022 eruption, especially water vapor and aerosol properties, from satellite observations.
- ➢ Study the impact of water vapor on aerosols formation and growth, and their combined influence on stratospheric thermal structure due to their opposite radiative forcing.

Water vapor emission and evolution

Extremely large WV w.r.t. SO_2 emission (160Tg vs. 0.22Tg)

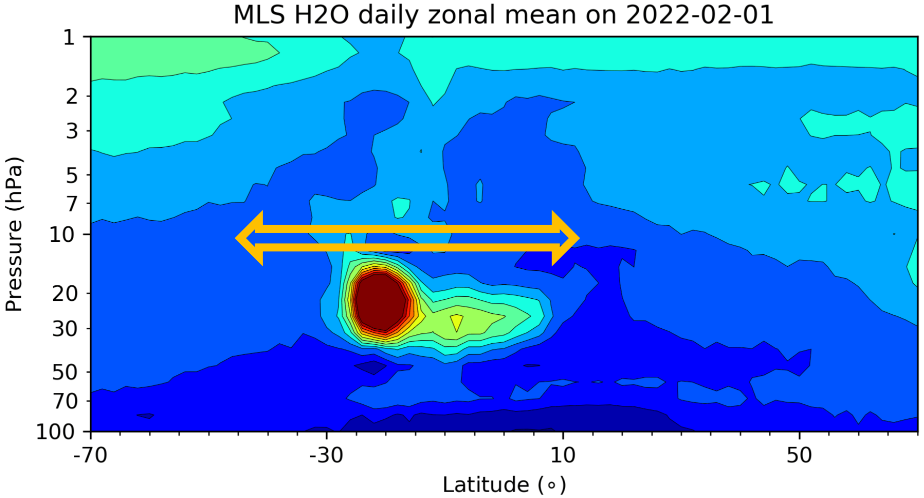
- ❖ MLS daily profile (v4.23):


2022-01-15

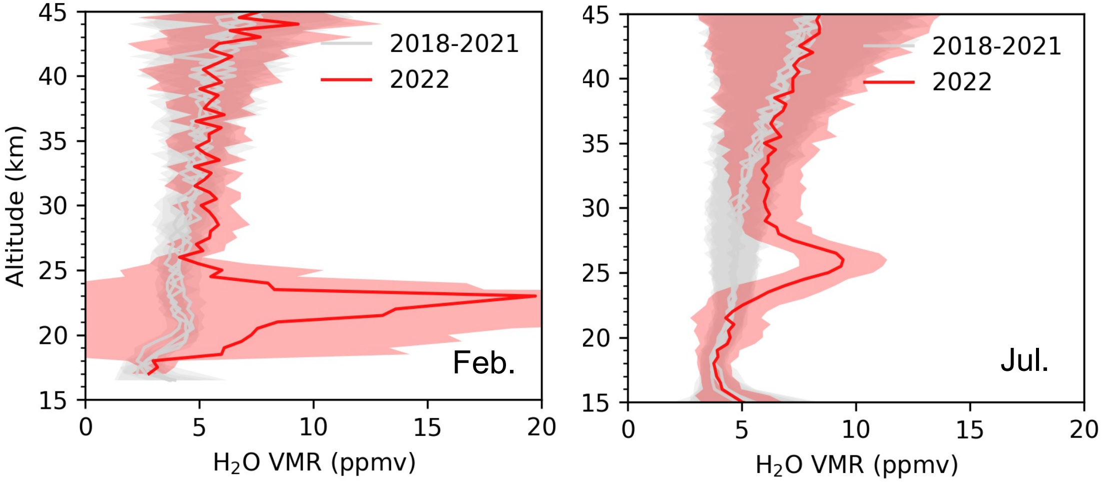
1-3 hPa

Enhancement

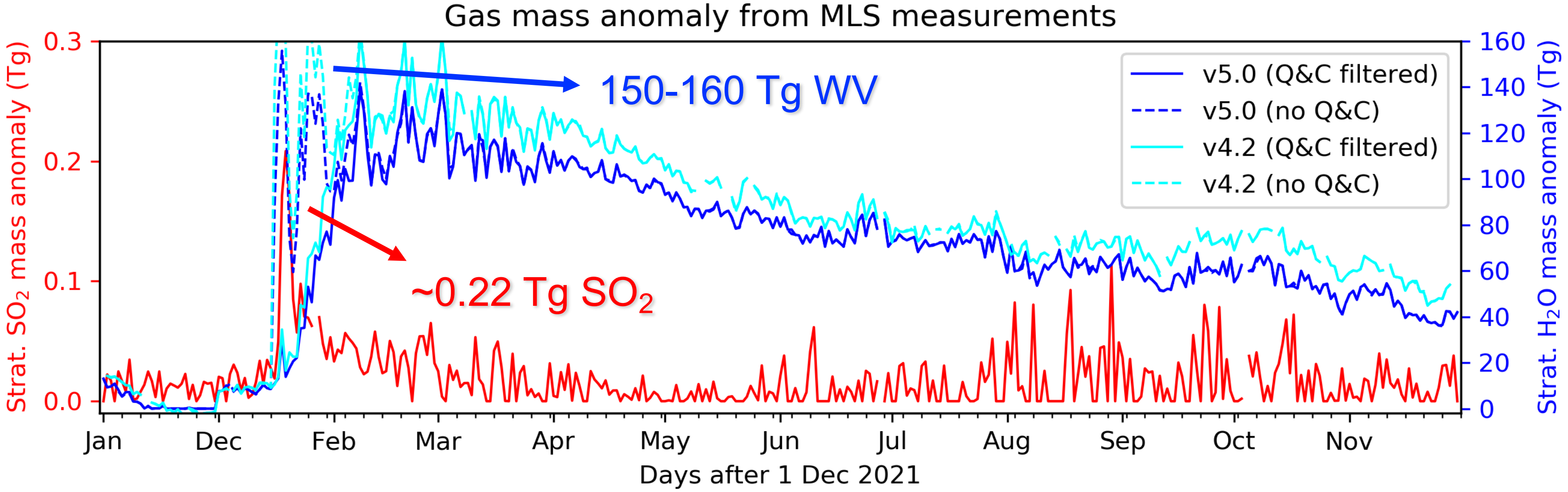
Background


MLS H2O daily zonal mean on 2022-02-01

- ❖ SAGEIII/ISS monthly average in [0˚, 40˚S]



- ❖ Estimate emitted stratospheric gas mass from MLS:


Gas mass anomaly from MLS measurements

150-160 Tg WV

~0.22 Tg SO_2

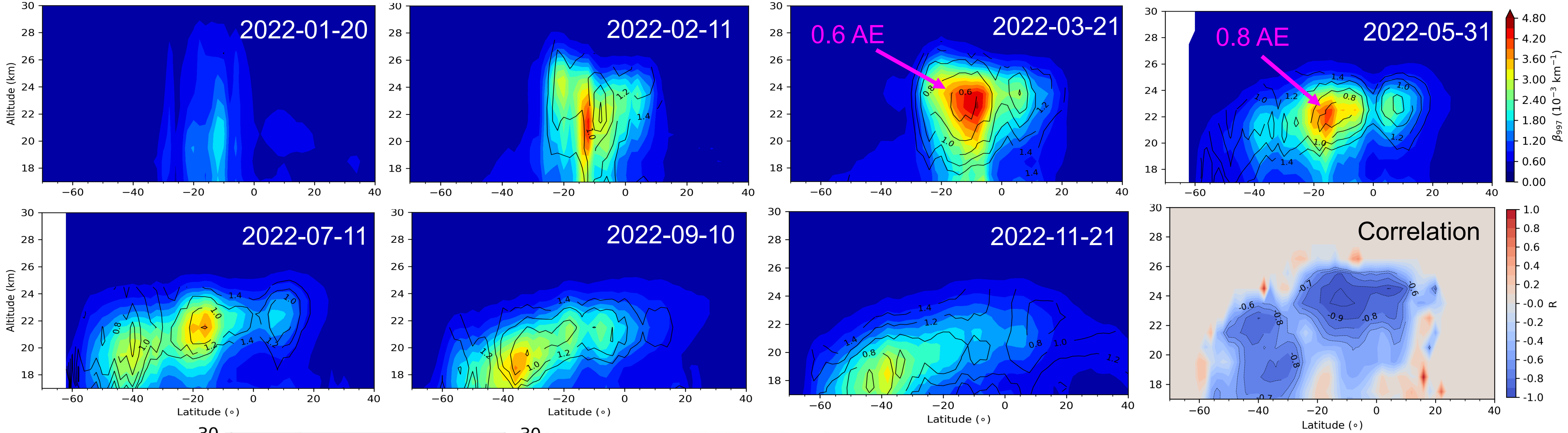
- Long-lived (~1y) WV enhancement was found at 20-30 hPa (23-27 km).

- ➢ 1991 Mt. Pinatubo eruption: ~18 Tg SO2; 100-150 Tg WV
- ➢ 2015 Calbuco eruption: 0.3 Tg SO2; 2 Tg WV

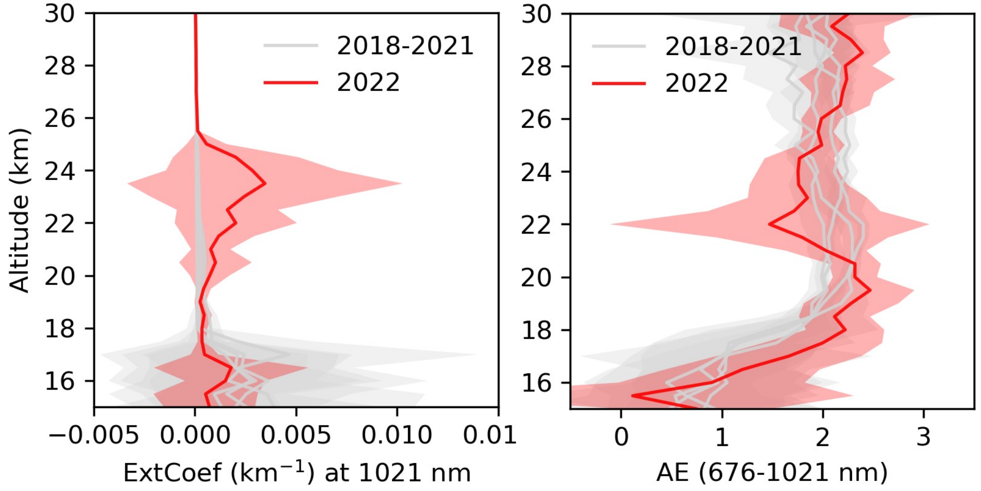
Aerosol plume evolution

Extremely large particles at high altitude (22-24 km) within 2 months after eruption

- ❖ OMPS-LP daily zonal mean aerosol extinction (β_{997}) and AE (675-997nm) profiles:

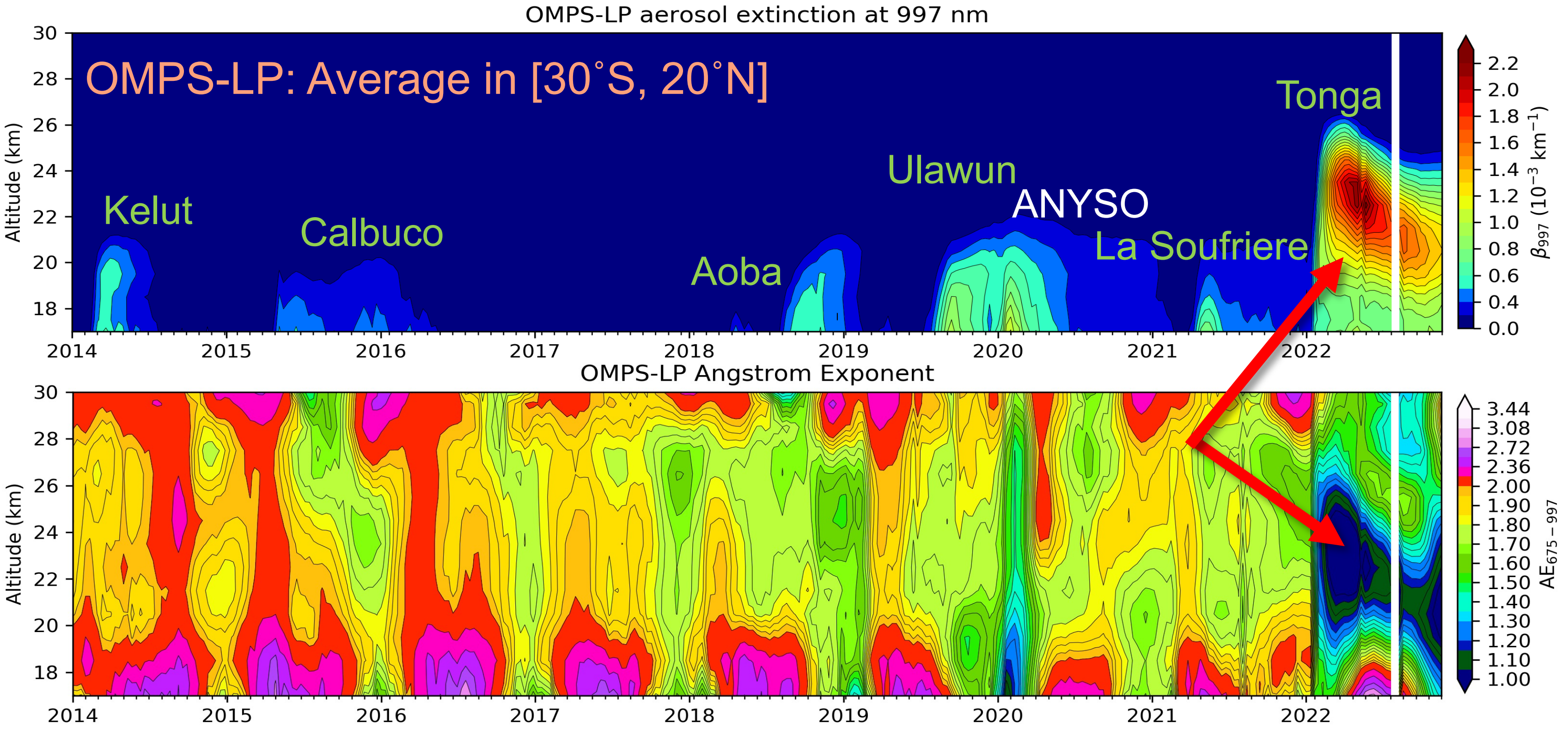


- ❖ SAGE III/ISS monthly mean: (Feb. 2022)



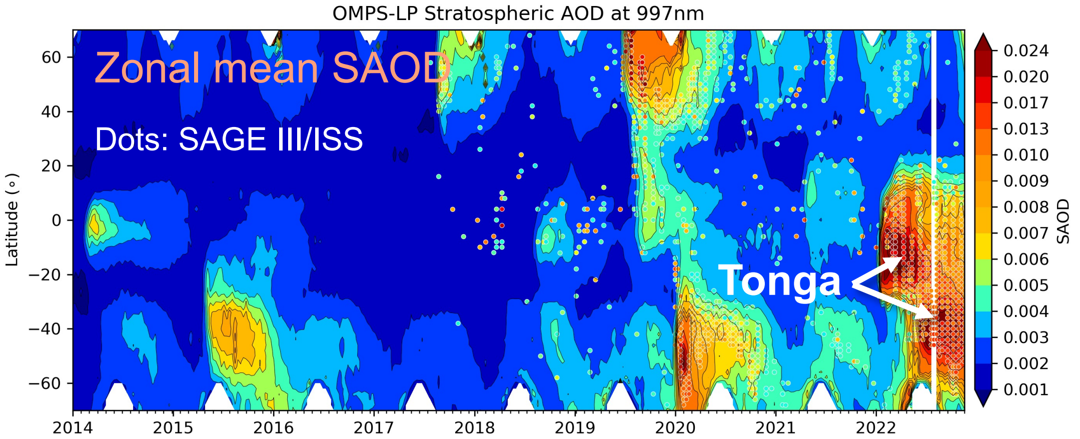
- The unusual stronger aerosol extinction and lower AE were found at 22-24 km after Tonga eruption.
- The evolution of vertical and zonal distribution of this low AE negatively correlated with strong β_{997} (correlation coefficient R < -0.8) in both subtropics and mid-latitude.

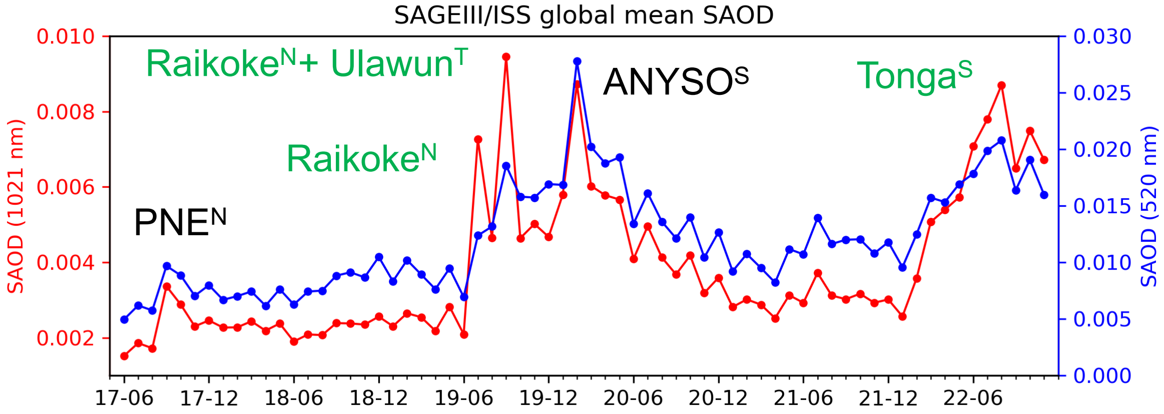
The strongest perturbation in the past 10 yrs



- Tonga eruption increased β_{997} from lower to middle stratosphere (22-24 km) to the largest value since 2014, while the other events mainly influenced UTLS with weaker β_{997}.

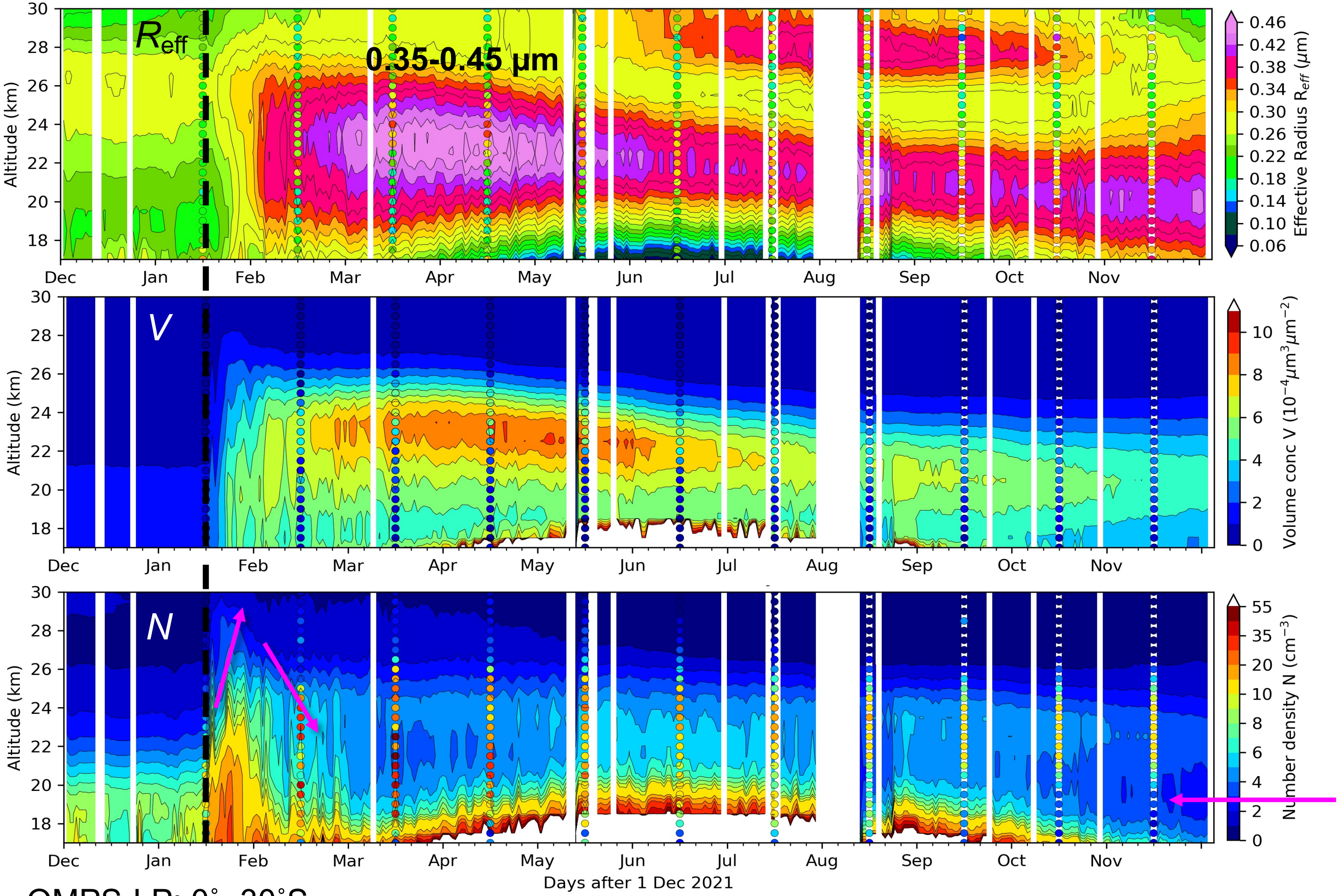
- Stratospheric AE (675-997nm) reached the lowest value due to Tonga eruption in low latitude.





Aerosol microphysics evolution

Rapid particle size growth comparable to that after Pinatubo eruption within 2 months



OMPS-LP: 0˚ -30˚S

- R_{eff} can reach the largest of 0.35 ~ 0.45 μm at 22-24 km from March 2022, larger than background of ~0.22 μm and smaller than Pinatubo aerosols with the largest size of 0.5-0.6 μm.

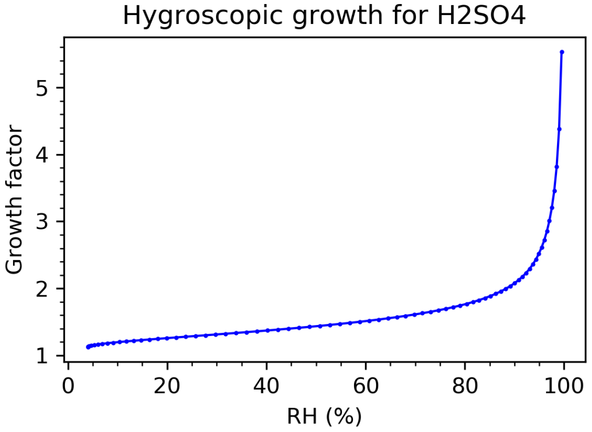
- Although the Tonga aerosols didn't grow to the same largest size of Pinatubo aerosols, the rate of particle size growth was comparable during the first two months after volcanic eruption.

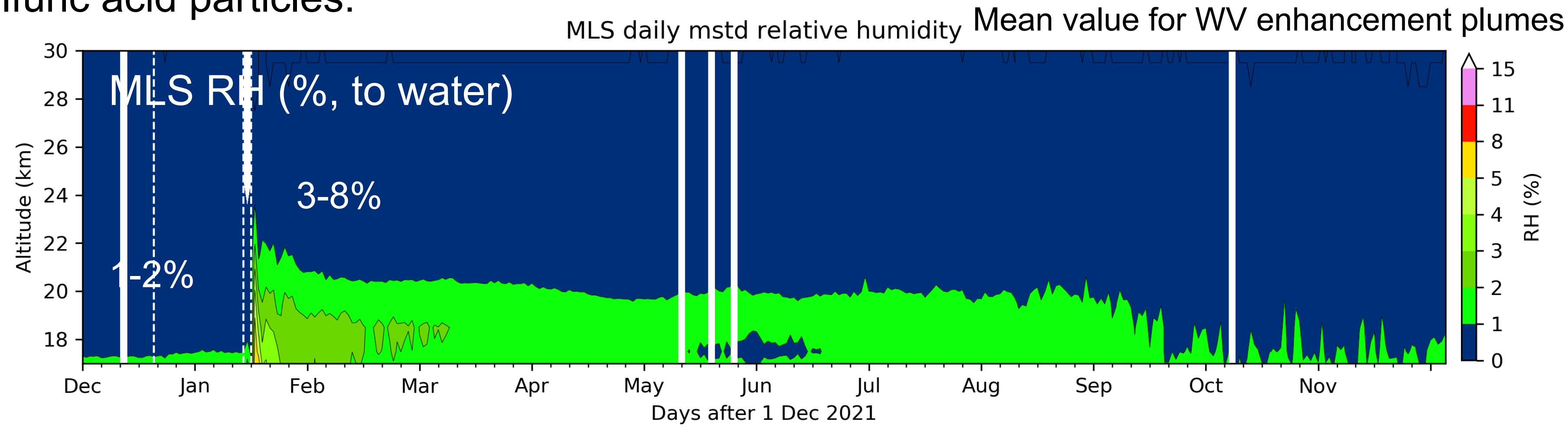
Dots: SAGE III/ISS monthly mean

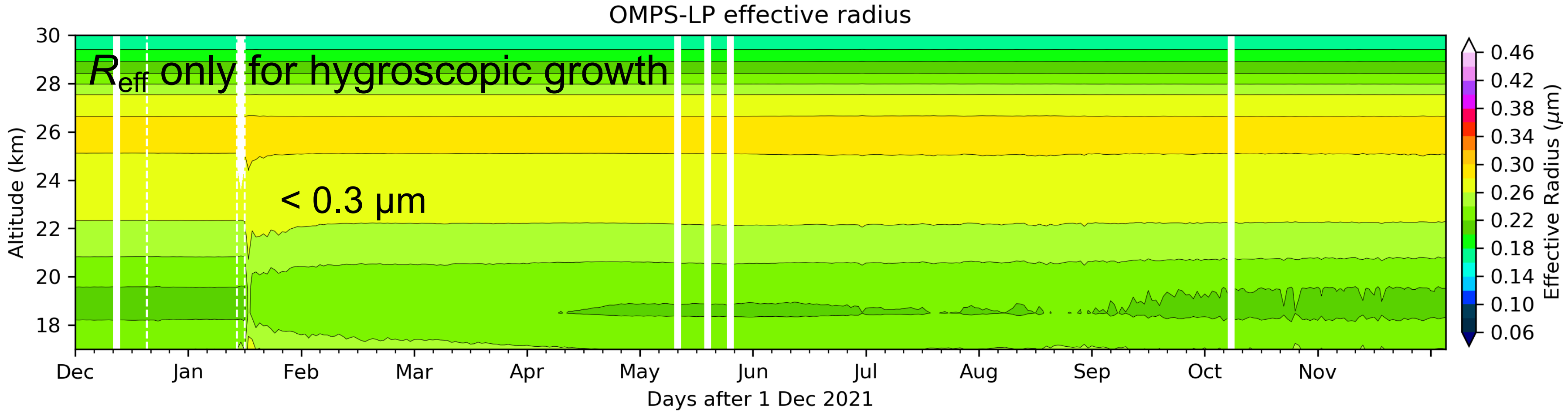
Aerosols hygroscopic growth

Can only lead to growth to R_{eff} < 0.3 μm, smaller than observations

❖ Hygroscopic growth for sulfuric acid particles:




Mean value for WV enhancement plumes



- Even though the WV enhancement lived for ~1 year from MLS, the daily mean relative humidity (RH) only increased 2-6%.

- According to the relationship of hygroscopic growth with RH, the sulfuric acid particles can only grow to < 0.3 μm during the first half month after eruption, smaller than OMPS-LP observations.

Multiple Particle microphysical processes & modeling

Nucleation, condensation, coagulation, hygroscopic growth, sedimentation ….

❖ Ordinary differential equations (ODE):

1. Initial condition: N_0, V_0, $R_{\mathrm{eff},0}$;

The variation rate of X due to condensation between $t_{i\text{-}1}$ and t_i (X: R_{eff}, V, or N)

2. At the ith time step (t_i):

$$\left(\frac{dX}{dt}\right)_i = \left(\frac{dX}{dt}\right)_{\mathrm{nucleation},i} + \left(\frac{dX}{dt}\right)_{\mathrm{condensation},i} + \left(\frac{dX}{dt}\right)_{\mathrm{coagulation},i} + \left(\frac{dX}{dt}\right)_{\mathrm{hygroscopicity},i} + \left(\frac{dX}{dt}\right)_{\mathrm{transport},i}$$

3. Relationship among R_{eff}, V, or N:

$$N_i = N_{i-1} + \left(\frac{dN}{dt}\right)_i$$

$$V_i = V_{i-1} + \left(\frac{dV}{dt}\right)_i$$

$$v_{a,i} = \frac{V_i}{N_i}$$

$$R_{\mathrm{eff},i} = g\left(v_{a,i}\right)$$

(Mie code)

4. Physical characteristics of each process:

Process	Nucleation	Coagulation	Condensation	Hygroscopic growth	Transport*
N	↑	↓	–	–	– (little ↓)
V	– (little↑)	–	↑	↑	↓
R_{eff}	↓	↑	↑	↑	↓

*Note: include sedimentation and evaporation

↓

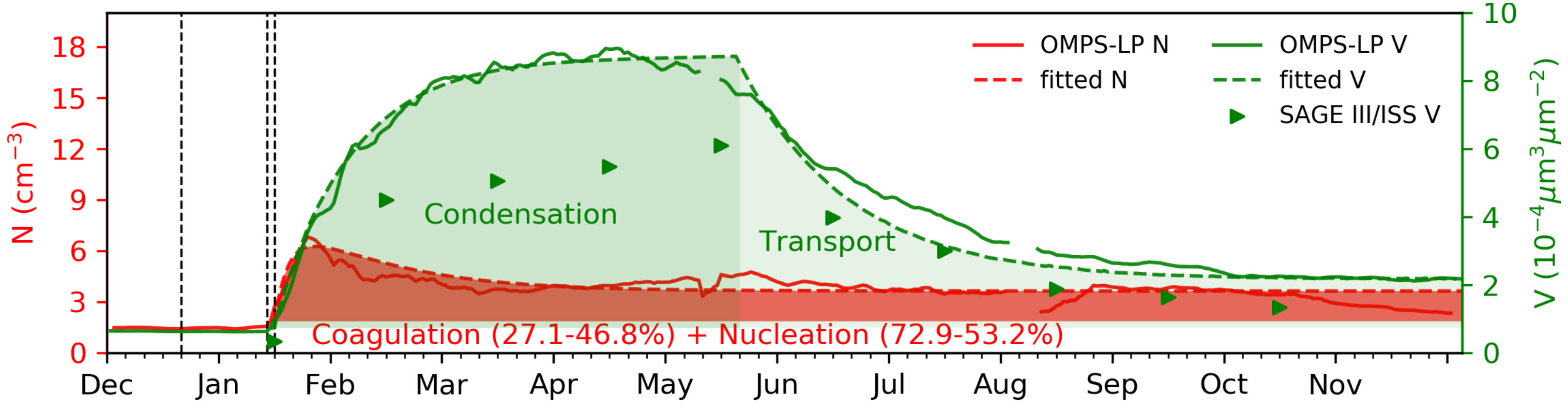
Parameterize: $\left(\frac{dN}{dt}\right)_{\mathrm{nucleation},i}$, coagulation coefficient K_i, $\left(\frac{dV}{dt}\right)_{\mathrm{condensation},i}$, $\left(\frac{dV}{dt}\right)_{\mathrm{transport},i}$

5. Assume exponential function of time: e.g. $K_i = m\,\exp(-nt_i)$, fitting m and n from observations

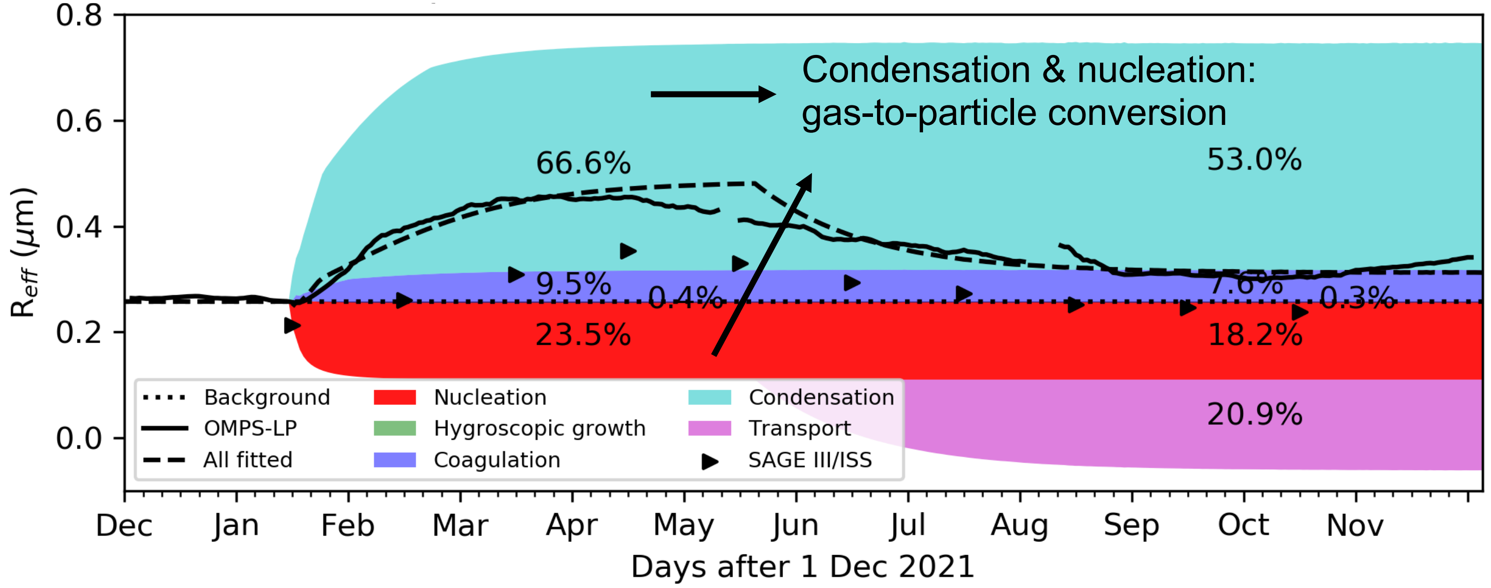
Contribution of each process

Nucleation & condensation (gas-to-particle conversion) dominate rapid particle size growth

❖ Fitting *N* and *V*:



❖ Contribution to R_{eff}:



- Condensation interpreted approximately 100% of *V* increasing and *V* growth rate can be parameterized using exponential decay with ~20 days e-folding time.

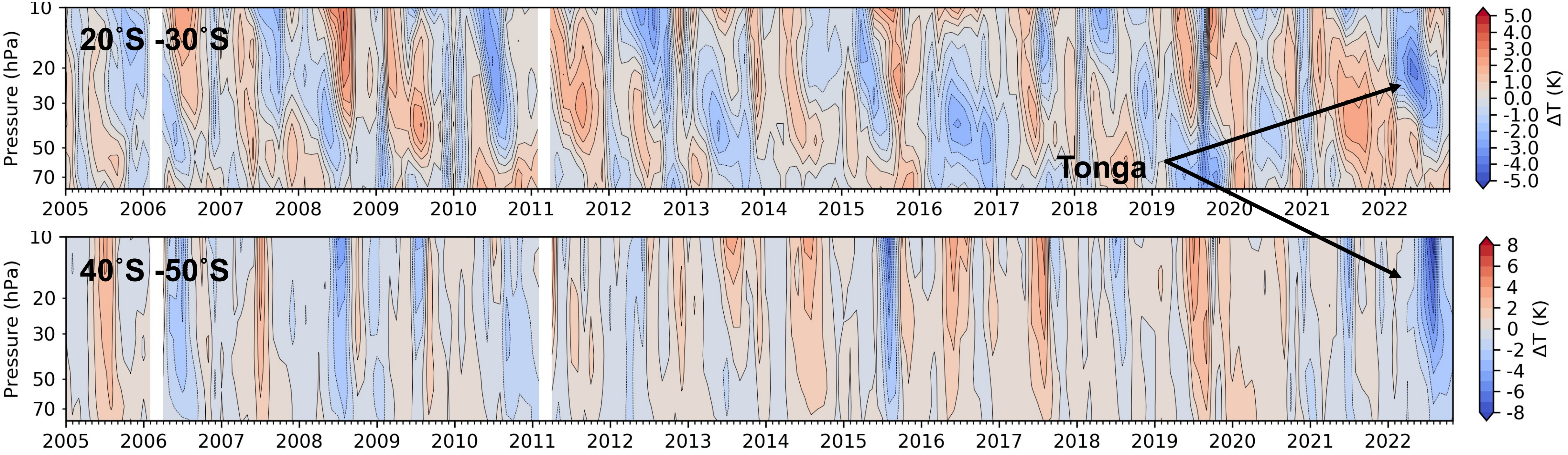
- Due to *V* vs. R_{eff} relationship, the size growth of Tonga aerosols was controlled by the gas-to-particle conversion including condensation (66%) and nucleation (~24%), whose rate relies on the concentration of sulfuric acid vapor produced from SO_2 oxidation by OH enhanced from WV emission.

Observed temperature negative anomaly

Negative ΔT lasting 4-7 months in the stratosphere, the strongest cooling in mid-latitude after Pinatubo

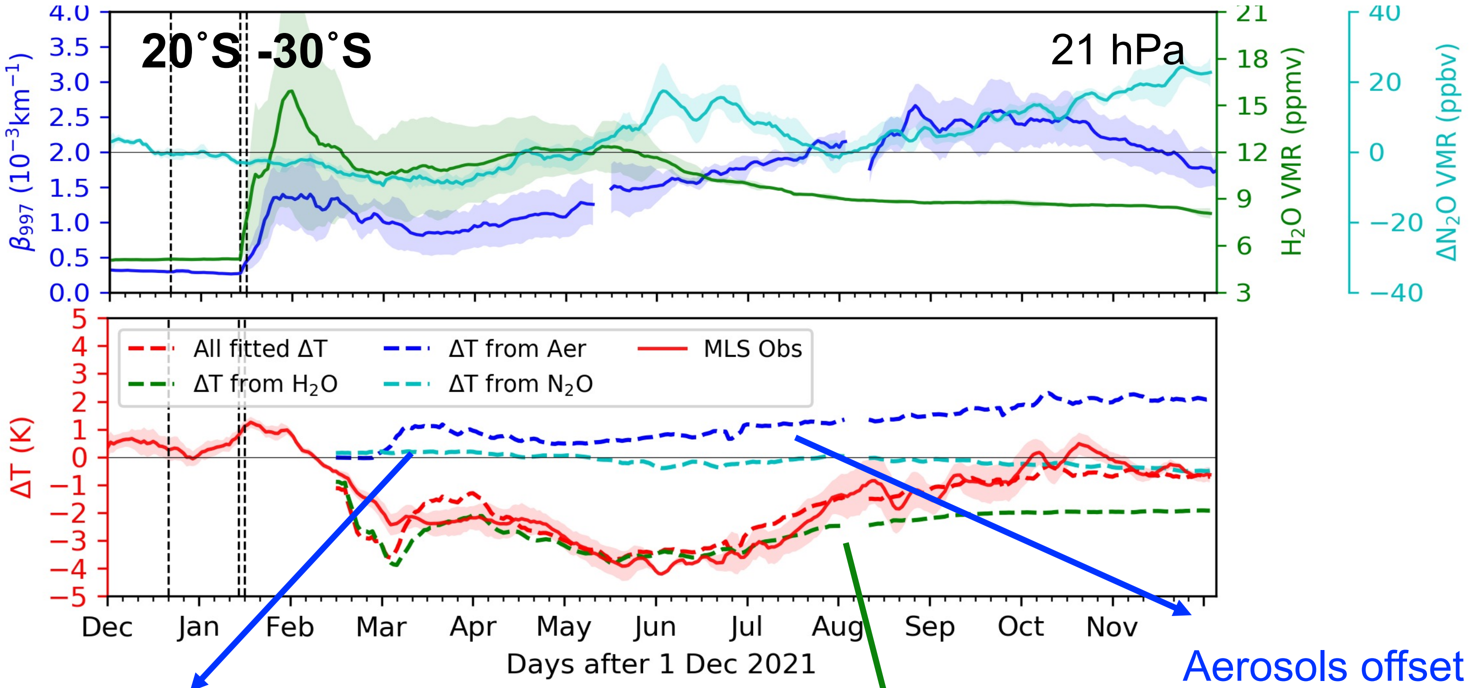
- The temperature showed strong negative anomaly (ΔT) of -4 K for 4-7 months, and even reached -8 K in mid-latitude. The stratospheric cooling after Tonga eruption is indeed the coolest period in mid-latitude since 1994 after Pinatubo eruption (MERRA-2 data).

❖ MLS temperature profile anomaly:



WV cooling vs. aerosols warming

Large particles warming offset 20%-50% WV cooling, net cooling effect

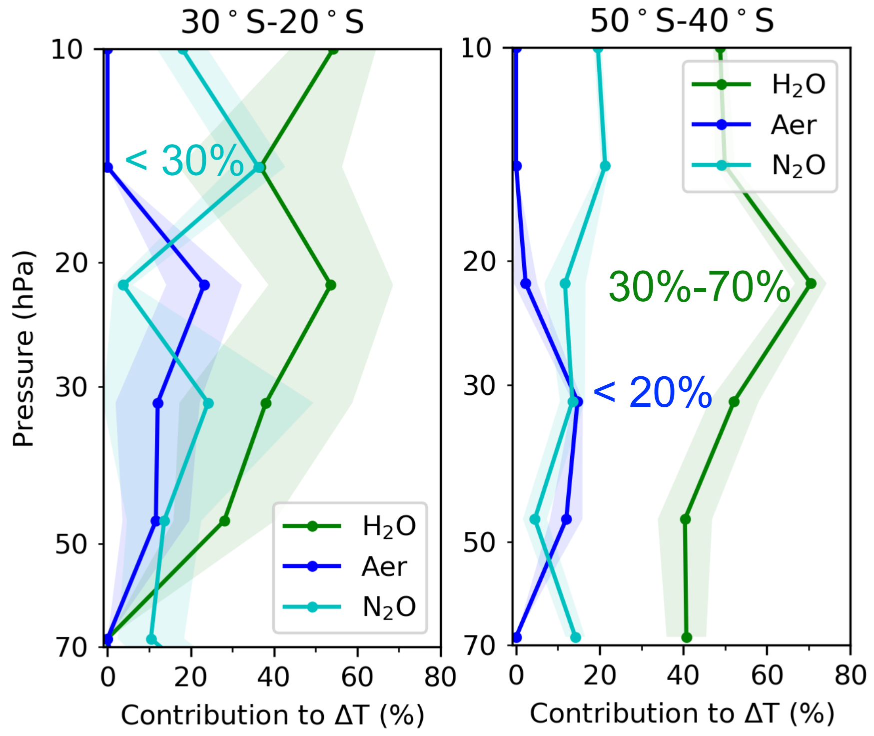


Particle size growth causes ΔT increase

WV explained most of negative ΔT

Aerosols offset 20%-50% WV cooling

❖ Contribution to ΔT :



❖ The multi-variable linear regression of temperature anomaly :

$$\Delta T = a\Delta WV + b\Delta\beta_{997} + c\Delta N_2O + d.$$

WV: cooling, a < 0; Aer: warming, b > 0; dynamics change, c; assume response time for temperature change (~1 month)

Conclusions

- Observed from space, aerosol particle size grew significantly from ~0.22 μm to 0.35-0.45 μm in the stratosphere (22-24 km) within only two months after 2022 HT eruption, comparable to that of 1991 Mt Pinatubo, but with only 1/80 of Pinatubo SO_2 emission.

- From parameterization of particle evolution using an analytical model involving multiple aerosol microphysical processes, we found that due to accelerated sulfuric acid vapor production from the unprecedented HT WV emission (150-160 Tg), fast gas-to-particle conversion including condensation and nucleation contributed ~90% particle size growth.

- Although aerosols warming offsets 20-50% of the cooling associated with WV, their net effect overwhelmingly caused by WV leads to the observed -8~-4K stratospheric cooling (10-50 hPa) lasting 4-7 months after HT eruption.

- This study showed process-level of understanding the unprecedented and disparate roles of WV from HT eruption in perturbing atmospheric composition and thermal structure through satellite observation analysis.

(Chen et al., 2023, submitted)

Acknowledgement

backup

Derive aerosol parameters from AE and β

❖ Estimate effective radius (R_{eff}), volume concentration (V) and number density (N):

1. Estimate H2SO4 weights:

   From MLS daily mean WV and temperature profile, assess H2SO4 weights in sulfuric acid particles *(Steele and Hamill, 1981)*

2. Create LUT and derive R_{eff} from AE measurements:

$$\mathrm{AE} = -\frac{\ln\left(\frac{\beta_{\lambda_1}}{\beta_{\lambda_2}}\right)}{\ln\left(\frac{\lambda_1}{\lambda_2}\right)}, \qquad \frac{\beta_{\lambda_1}}{\beta_{\lambda_2}} = \frac{Q_{\lambda_1}}{Q_{\lambda_2}}$$

Use Mie code to calculate the Q_{997} (extinction efficiency), v_0 (averaged aerosol volume per particle) and AE (675-997 nm) for different aerosol effective radius, variance (R_{eff} and v_{eff}) and H2SO4 weights (related to refractive index) *(Russell et al. 1996),* then interpolate the AE LUT to get the optimal effective radius for $v_{\text{eff}} = 0.2$

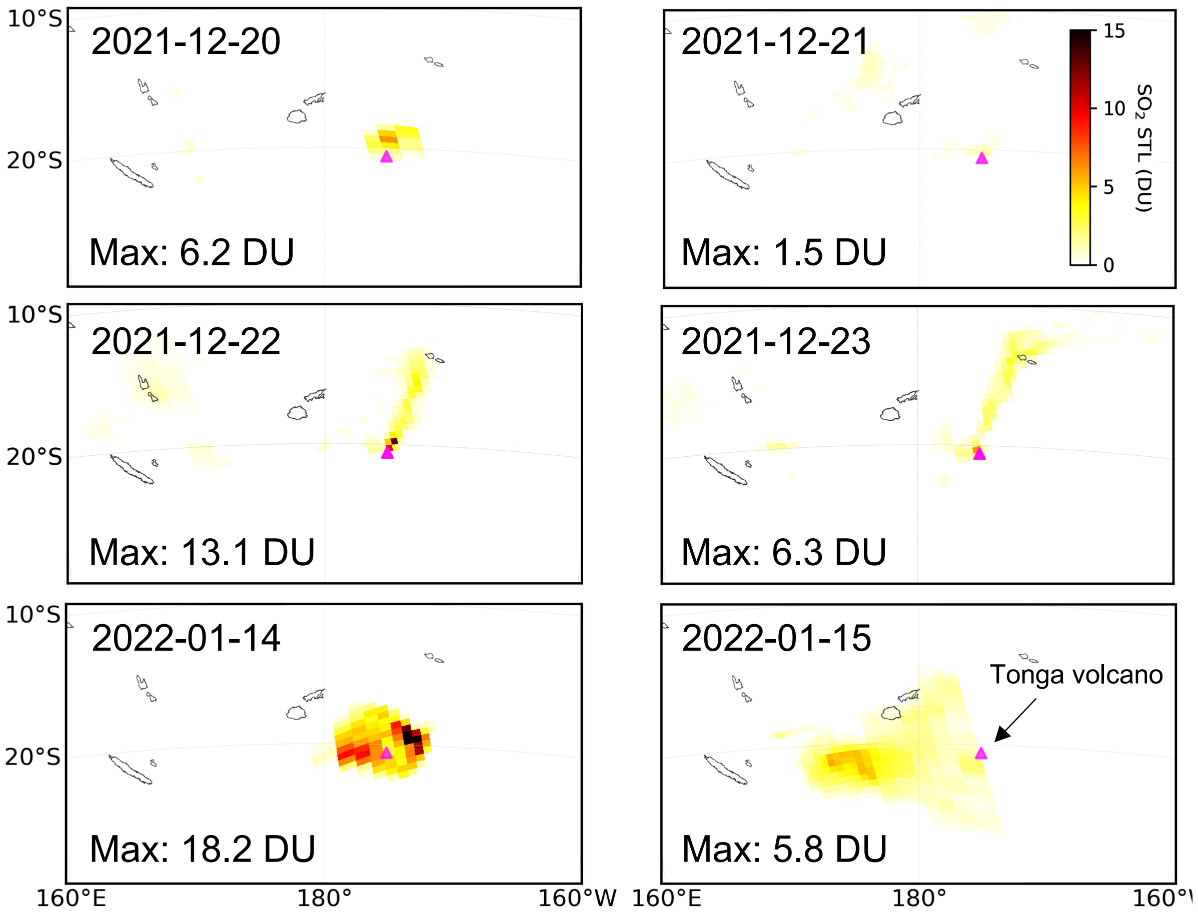
3. Derive V and N from β measurements:

$$R_{\text{eff}} = \frac{\int_{r_1}^{r_2} \pi r^3 n(r)dr}{\int_{r_1}^{r_2} \pi r^2 n(r)dr}, \qquad G = \int_{r_1}^{r_2} \pi r^2 n(r)dr$$

$$V = \frac{4}{3}\int_{r_1}^{r_2} \pi r^3 n(r)dr = \frac{4}{3} R_{\text{eff}} G = \frac{4}{3}\frac{\beta_{\lambda 1} R_{\text{eff}}}{Q_{\lambda 1}}, \qquad N = \int_{r_1}^{r_2} n(r)dr = \frac{V}{v_0}$$

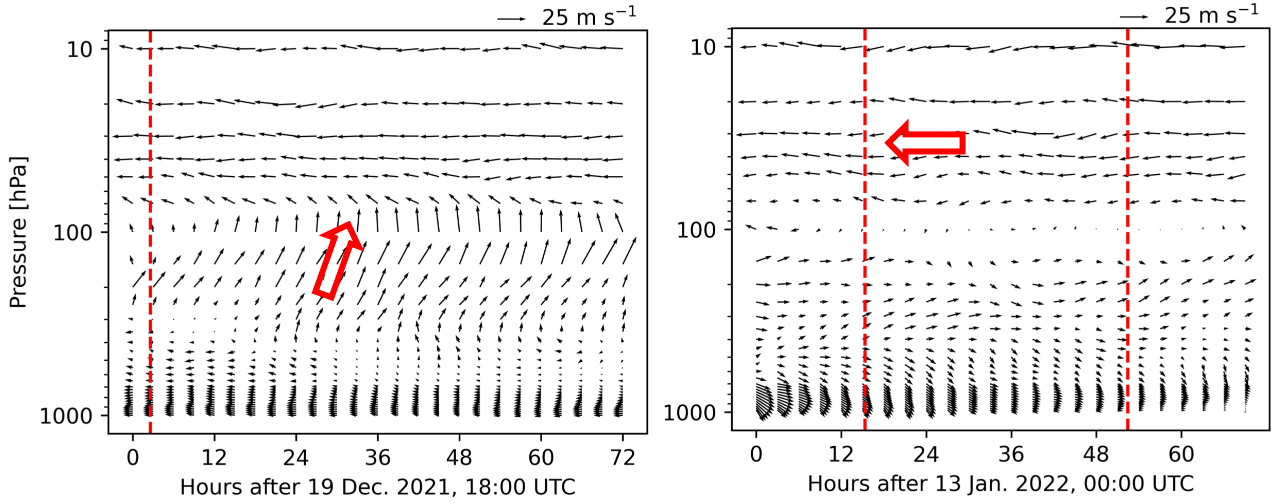
SO_2 injection

- OMPS-NM SO2 STL column density:

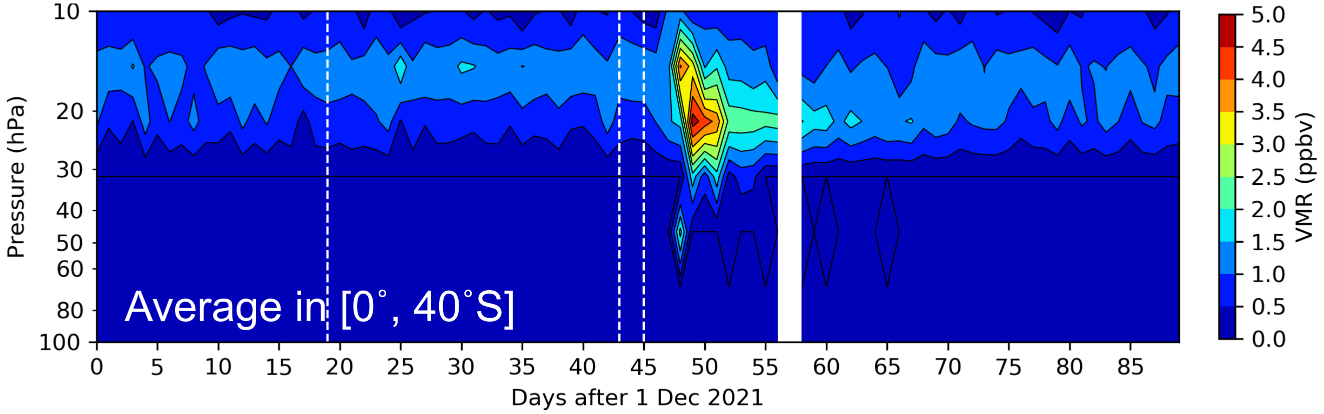


- SO_2 injection reaches 10 hPa.
- SO_2 returned to background value in ~15 days.

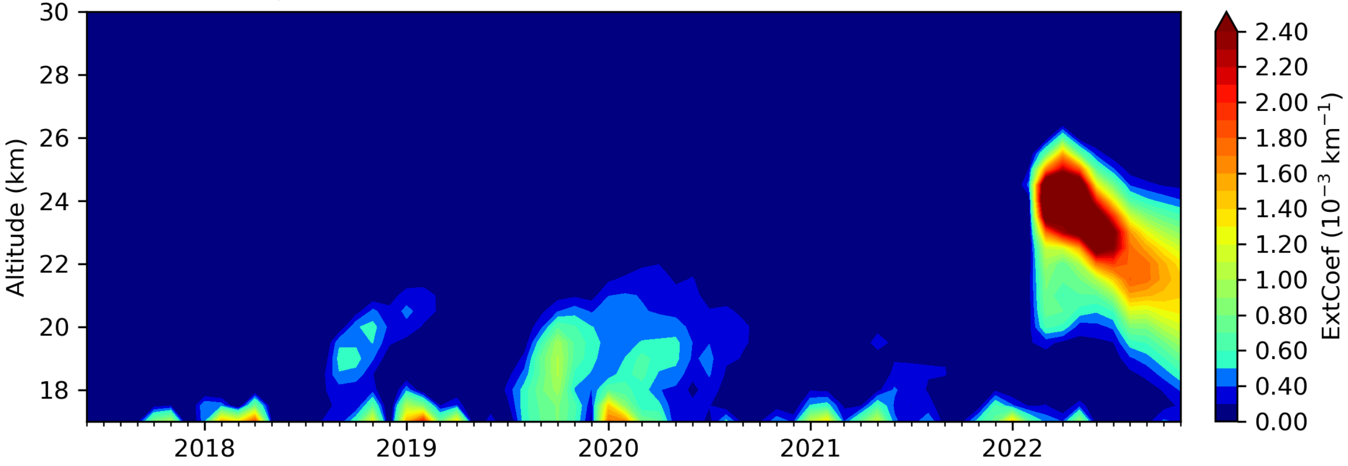
- MERRA-2 wind vector profile:



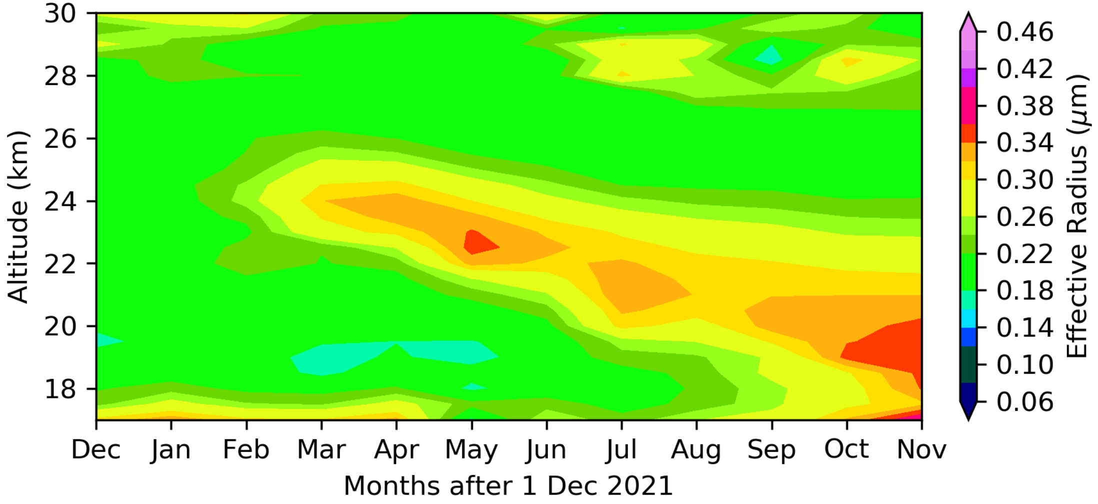
- MLS daily averaged SO2 VMR profile:



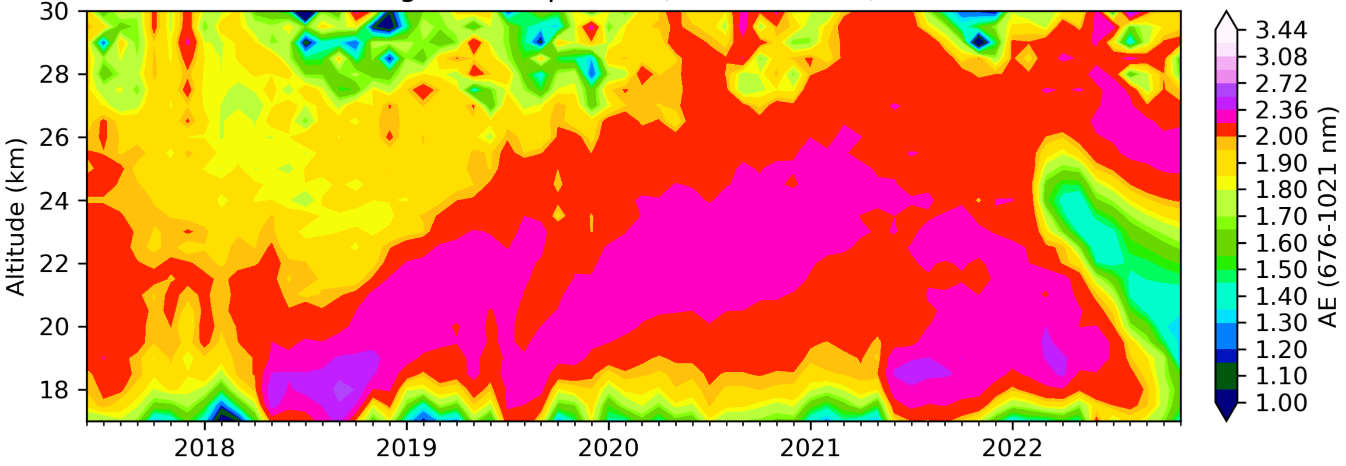
SAGEIII/ISS 1021nm aerosol extinction coefficient at 30°S-20°N



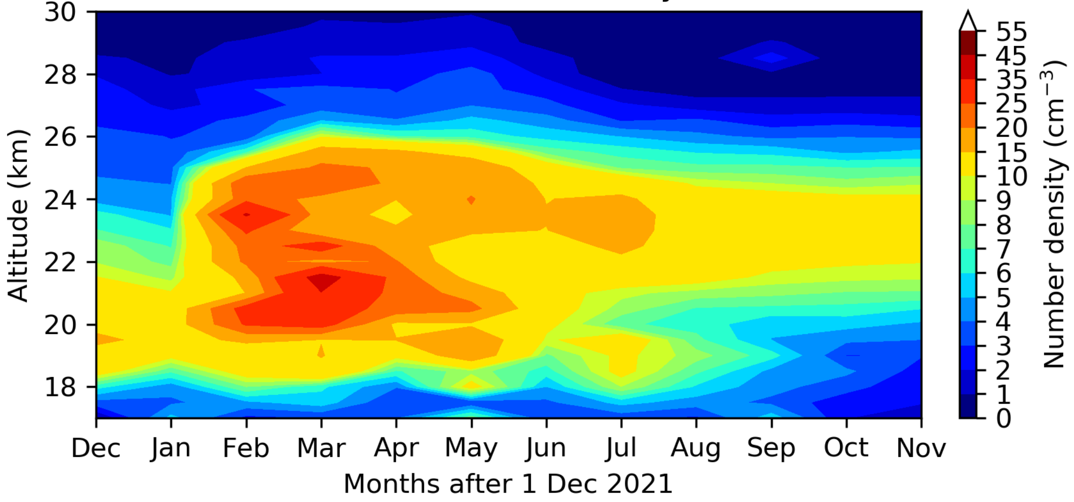
SAGEIII/ISS sulfate effective radius at 30°S-20°N



SAGEIII/ISS Angstrom Exponent (676-1021 nm) at 30°S-20°N

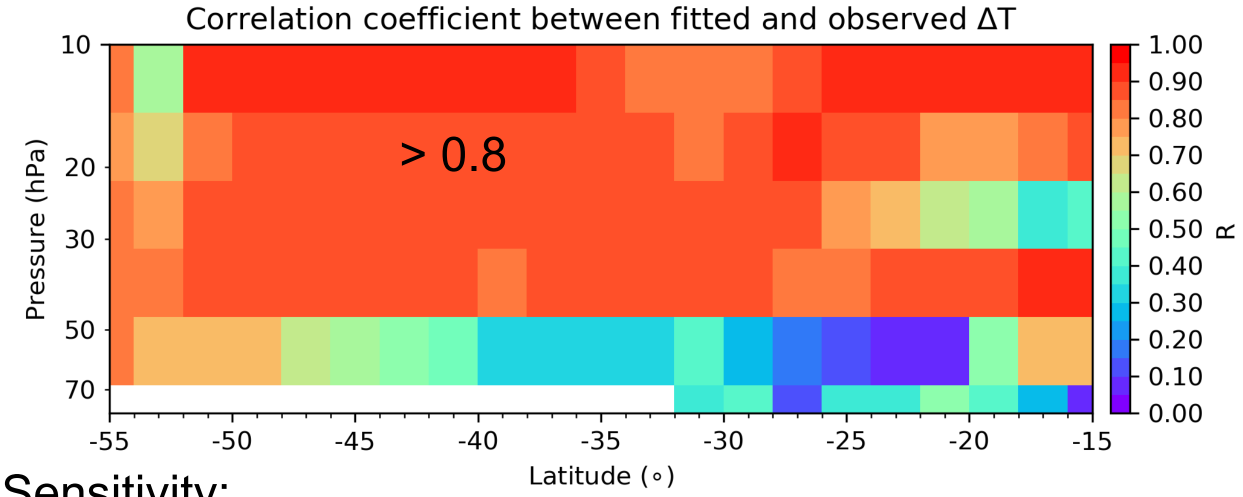


SAGEIII/ISS sulfate number density at 30°S-20°N

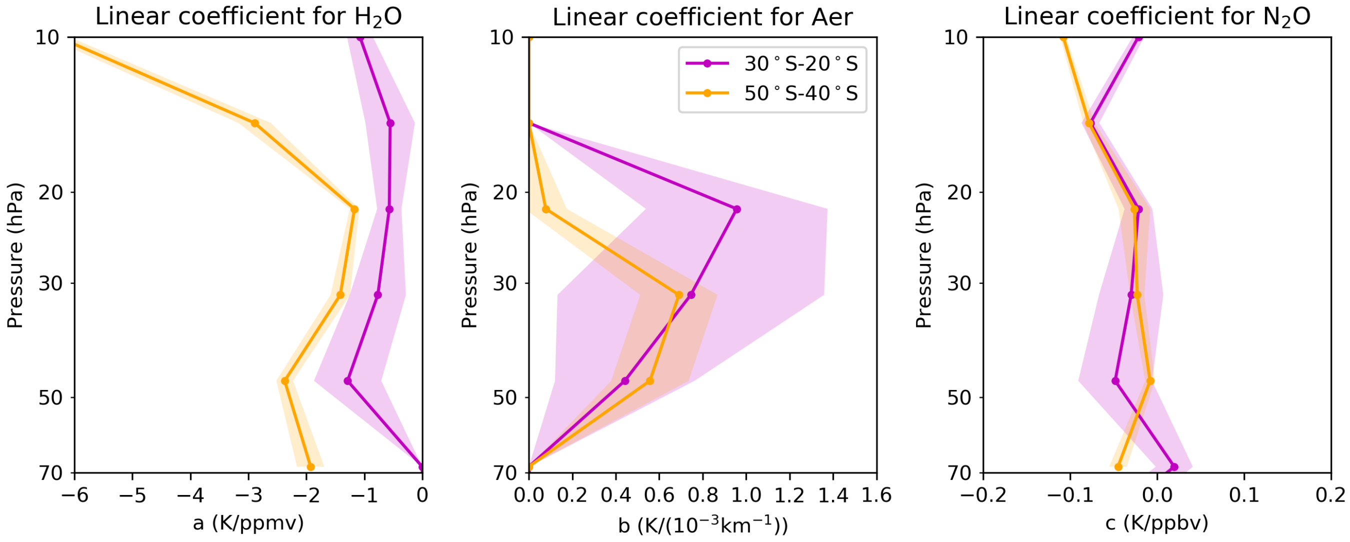


Contribution of WV and aerosols to ΔT

- Fitting vs. observation:


Correlation coefficient between fitted and observed ΔT

- Sensitivity:


Linear coefficient for H_2O

Linear coefficient for Aer

Linear coefficient for N_2O

- Mid-latitude temperature was more sensitive to WV enhancement cooling with 1.5-6 K/ppmv, especially at higher altitude (10 hPa) than subtropics with 0.5-1.5 K/ppmv. The sensitivity of ΔT to aerosol extinction enhancement was similar in different latitudes in the stratosphere (0.4-1.0 K/(10-3km-1)) .