Vertical separation and meridional transport of the Hunga water vapor and aerosol plumes

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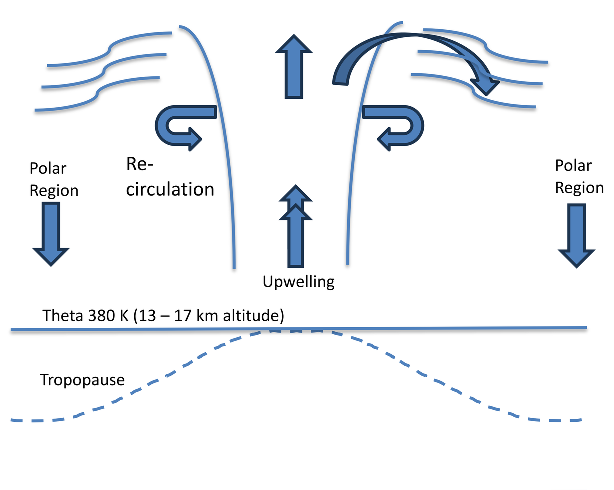
Overview

Following the Hunga eruption in 2022, volcanic water vapor and aerosol plumes were observed moving poleward in the stratosphere, generally in accordance with large scale circulation patterns. Free-flying balloons from a range of latitudinally distributed sites and space-based sensors may be used to track the water vapor and aerosol plumes' progress from the tropics to the poles in both hemispheres. Payloads consisting of a NOAA Global Monitoring Laboratory frost point hygrometer (FPH), a NOAA Chemical Sciences Laboratory portable optical particle spectrometer (POPS), an ECC ozonesonde, and a radiosonde are routinely flown from Boulder, CO, Hilo, Hawaii, La Réunion, France, and Lauder, New Zealand, and payloads consisting of a cryogenic frost point hygrometer (CFH), an ECC ozonesonde and a radiosonde are routinely flown from San Jose, Costa Rica. Additionally, ECC/FPH/POPS launches also took place from Scott Base, Antarctica in austral spring 2022 and 2023 and from Utqiagvik, AK and in boreal spring 2023. The balloon-based vertical profiles, spanning from the surface to ~ 28 km a.s.l. can also resolve the vertical separation of water vapor and aerosol plumes. The buoyancy of air masses, radiative heating, and in the case of particles, gravitational settling, as well as large scale circulation patterns, can influence the altitude of volcanic water vapor and aerosol plumes. In addition, in situ measurements also provide information on the removal of stratospheric water vapor through dehydration in the polar vortex and stratospheric aerosol through gravitational settling, following the Hunga eruption. The observed meridional transport and removal pathways may be directly compared to those in global climate models.

Tropical Leaky Pipe



Science Questions

1) What was the vertical separation of Hunga H_2O and aerosol plumes?
1) Do differences exist in the meridional transport of H_2O and aerosol plumes?
2) What do we know about the different forces acting on these plumes?

Figure 1. Schematic of the global stratosphere and large scale circulation patterns controlling transport.

Repeated in situ balloon-borne measurements

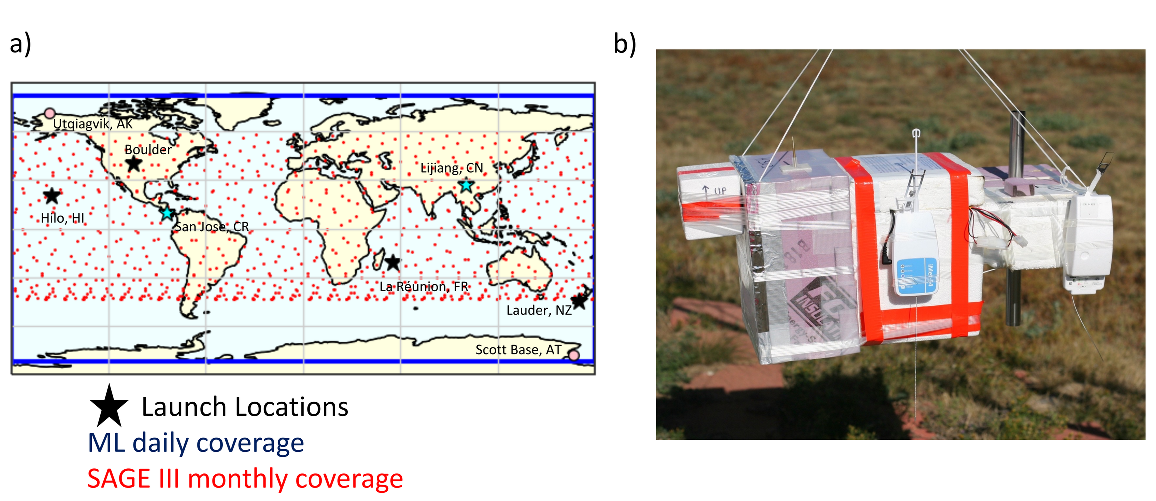


Figure 2. Map regular B^2SAP (black stars) and CFH/ECC ozonesonde (blue stars) launch locations, as well as intensive operation period (IOP) locations (pink circles) with daily near-global MLS (blue) and monthly SAGE III (red) coverage ?(a). Photo of the B^2SAP payload with a NOAA FPH (Hall et al., 2016), Portable Optical Particle Spectrometer (POPS; Gao et al. 2016) , and ECC ozonesonde. Not pictured is the En-SCI CFH, an instrument. similar to the NOAA FPH.

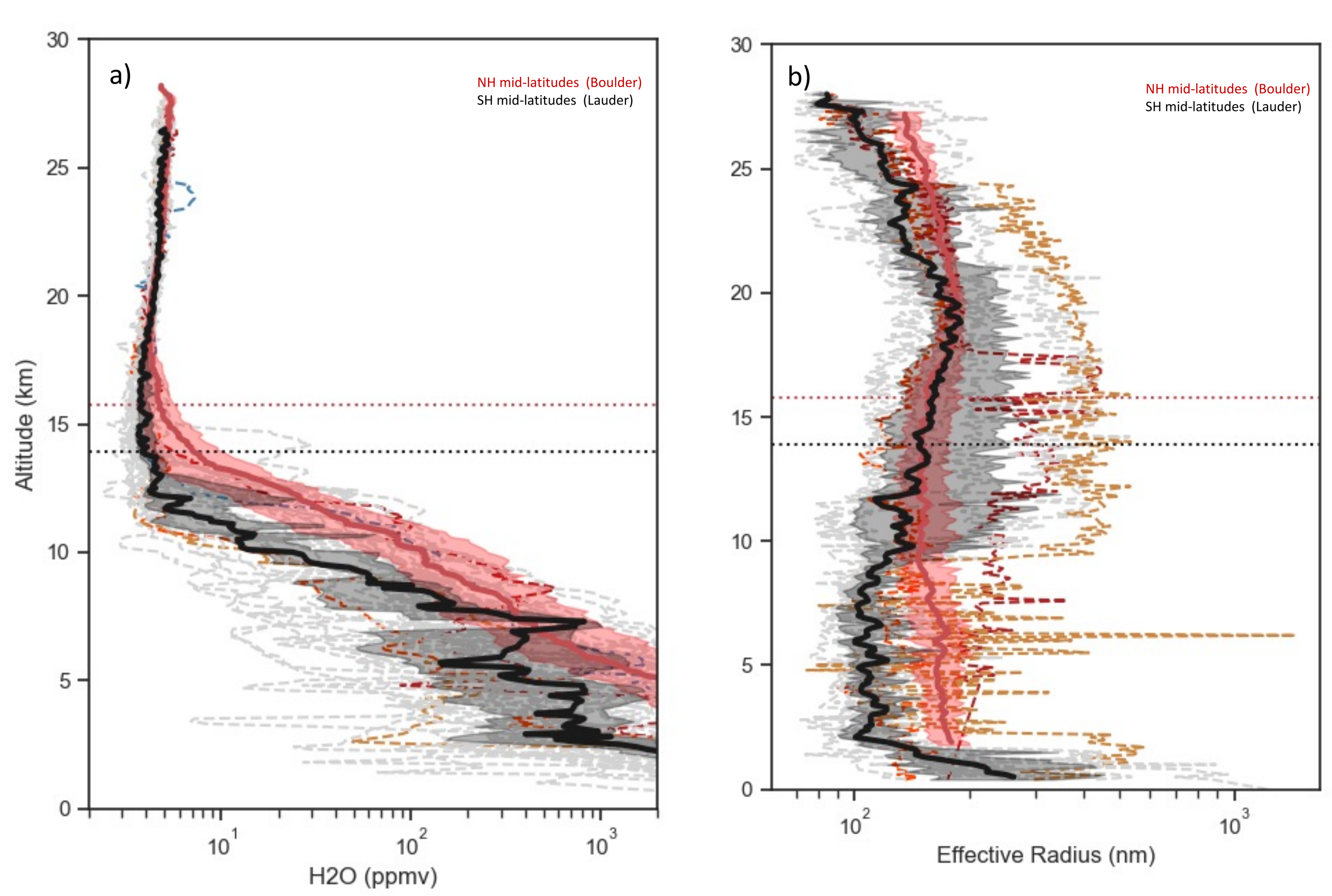


Figure 3. Median pre-Hunga baseline stratospheric H_2O (a) and aerosol effective radius (b) with altitude over Southern Hemisphere (SH) and Northern Hemisphere (NH) midlatitudes between 2019 and 2022 shown in bold red (NH) and black (SH) lines. IQR is shown in corresponding shaded regions. Pre-Hunga stratospheric H_2O ranges from ~ 4 – 5 ppmv between the tropopause and 28 km, and pre-Hunga aerosol effective radius peaks at 185 nm at 19 km in both hemispheres during this period.

Transport and diffusion of the H_2O and aerosol plumes

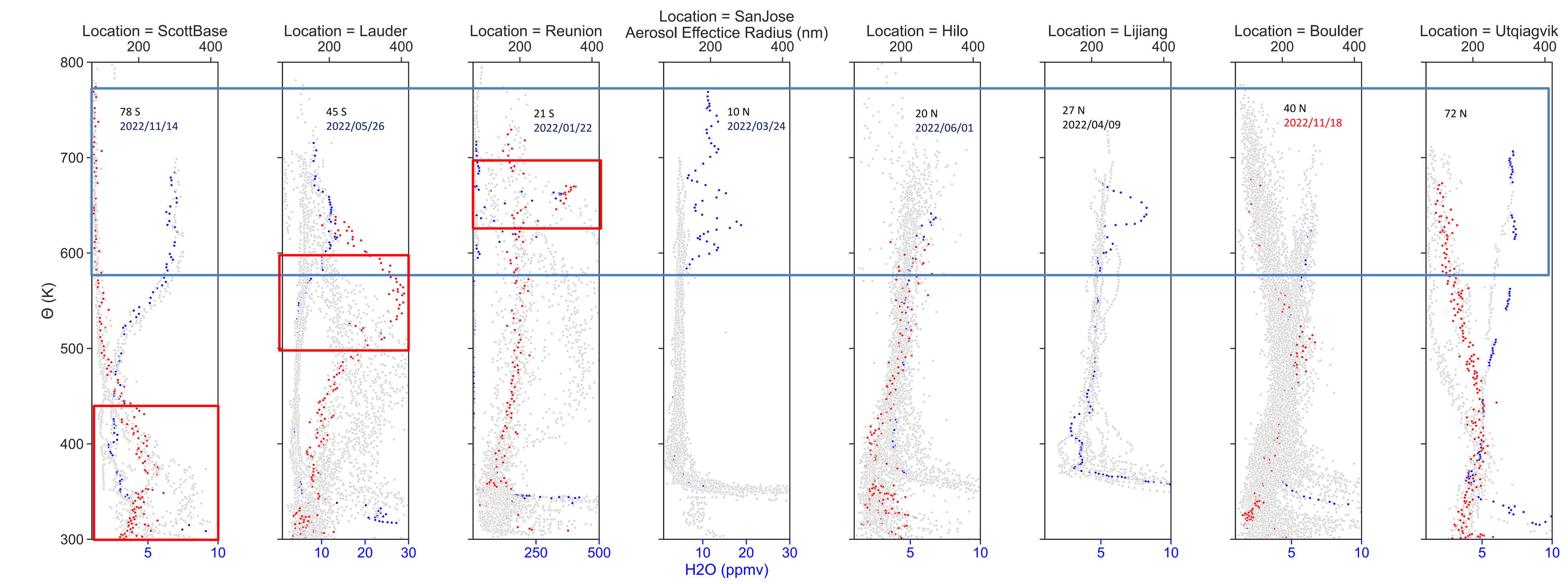


Figure 4. Vertical profiles of H_2O and aerosol effective radius (m^3/m^2) with potential temperature. H_2O is transported along isentropes within a few months. Dilution in the NH results in smaller H_2O enhancements and lower aerosol effective radii in the NH. Measurements binned to 0.1 km altitude.

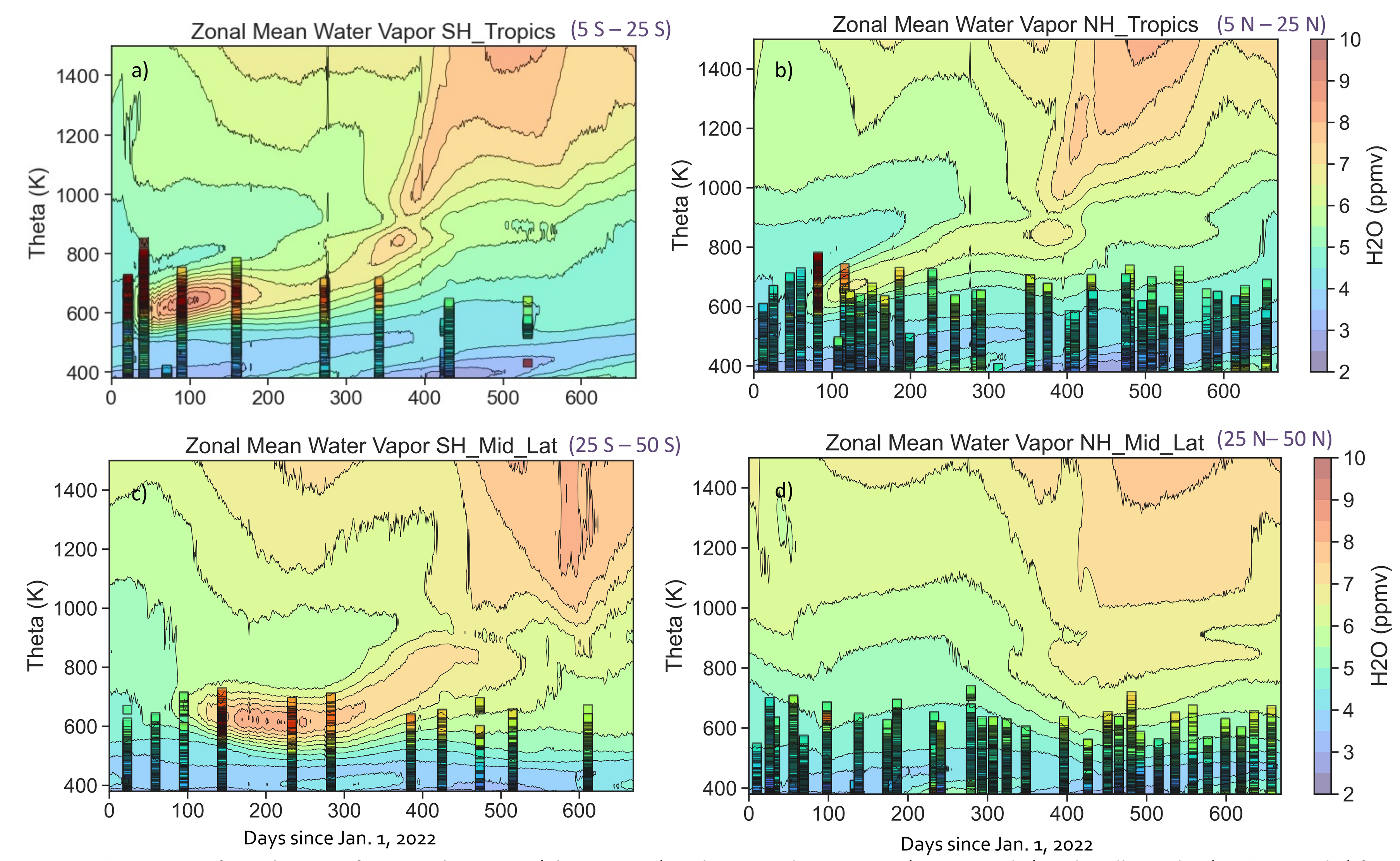


Figure 5. Timeseries of zonal mean of stratospheric H_2O (above 380 K) in the SH and NH tropics (5-25 N and S) and midlatitudes (25-50 N and S) from MLS V5. Sonde FPH and CFH measurements from each region shown as squares. Shows transport initially to SH midlatitudes and NH tropics along isentropes. Thereafter, upward vertical transport of H_2O is visible, resulting in transport to NH midlatitudes.

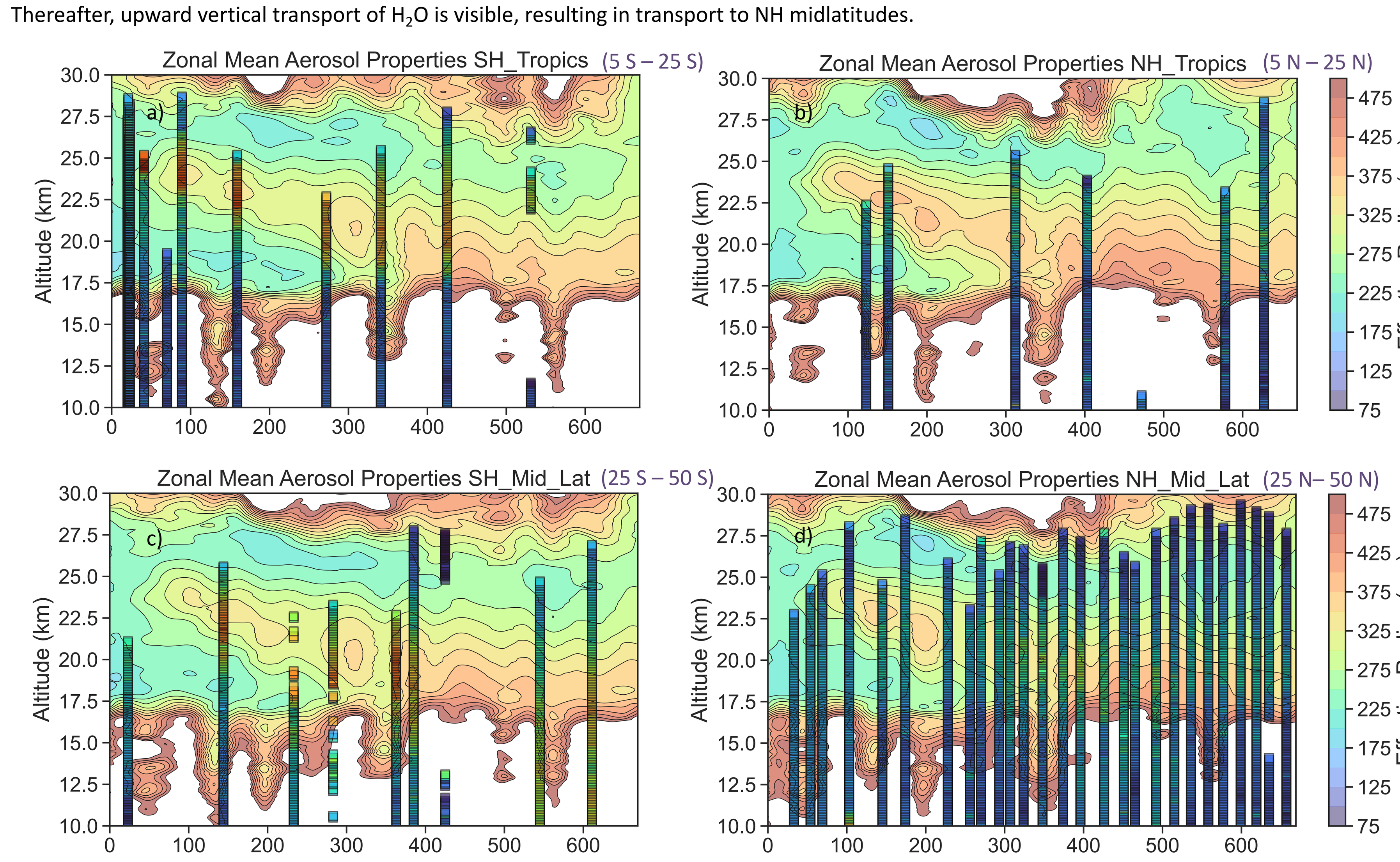


Figure 6. Timeseries of zonal mean stratospheric aerosol effective radius from SAGE III with altitude to 30 km. POPS aerosol effective radius from each region shown as squares. Downward vertical transport of the aerosol plume due to gravitational settling is visible in all regions. Sonde observations agree better in the SH than NH, due to location of launches and variability across the region.

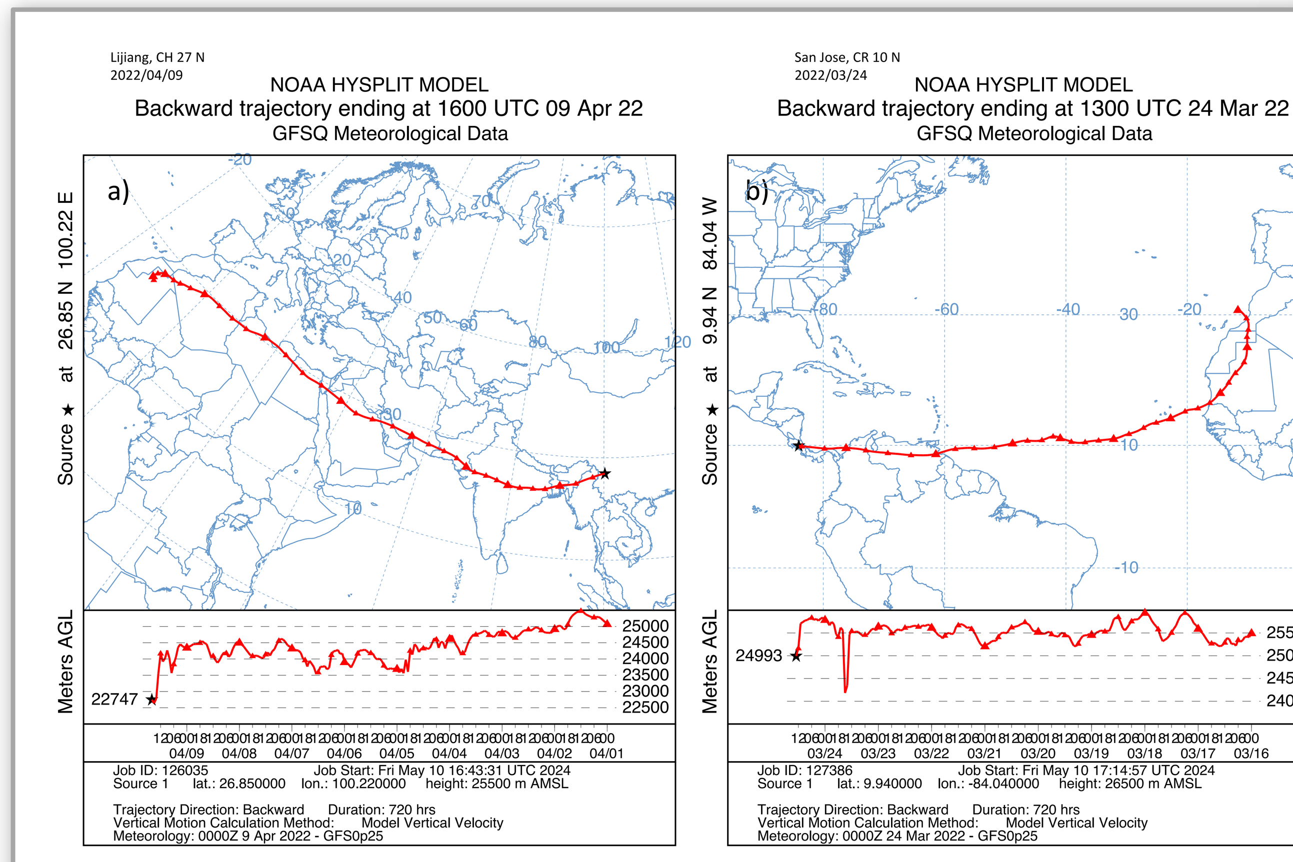


Figure 7. NOAA GFSQ (0.25 degree) Hysplit archive trajectories, dating back from time and location of measurements over Lijian, CN (a) and San Jose, CR (b) on 2022/04/09 and 2022/03/24, respectively. Archive trajectories suggest transport along isentropes, but provide no evidence of transport from lower latitudes.

Findings

- Pre-Hunga median H_2O between the tropopause and 28 km is < 5.5 ppmv over SH midlatitudes
- Pre-Hunga median aerosol effective radius above the tropopause has a maximum of ~185 nm, occurring at 19 km.
- Aura Microwave Limb Souder (MLS) has provided (2004- 04/2024) near global daily coverage, in comparison to Stratospheric Aerosol Gas Experiment (SAGE III) occultation satellite on the International Space Station. (Both MLS and SAGE III provide H_2O measurements). Sonde observations in the tropics and midlatitudes provide a glimpse of large scale transport with measurements up to 800 K potential temperature and/or 30 km altitude.
- After the Hunga eruption, in situ and satellite observations show the isentropic transport of H_2O plumes to 27 N and 45 S within 3-4 months.
- After 3-4 months H_2O is uplifted and transported in accordance with Brewer-Dobson circulation to the NH midlatitudes.
- Dilution results in smaller H_2O and aerosol effective radius enhancements, the latter (aerosol effective radius; m^3/m^2), as aerosol surface area becomes dominated by other (non-Hunga) particles of smaller size.
- Large enhancements in aerosol effective radius (> 400 nm) are observed at SH midlatitudes (45 S).
- Smaller enhancements in aerosol effective radius (> 200 nm) are observed in the NH.
- Vertical transport of aerosol plume downward in altitude (and across isentropes) is driven by gravitational settling of particles.
- Aerosol transport to SH and NH mid-latitudes appears to occur earlier than H_2O transport.
- NOAA GFSQ (0.25 degree) Hysplit archive trajectories indicate transport occurred along isentropes but provide no evidence of transport from lower latitudes.
- **Vertical separation of H_2O and aerosol plumes driven by combination of H_2O uplift and transport through Brewer Dobson circulation and gravitational settling of large particles, resulting in differences in the arrival of these plumes to NH midlatitudes (and possibly also SH midlatitudes).**

References/ Acknowledgements

Asher, E. C., Todt, M. A., Rosenlof, K., Thornberry, T., Gao, Ru-Shan, Taha, Ghassan, et al. (2023). Unexpectedly rapid aerosol formation in the Hunga Tonga plume, *120*(44). https://doi.org/10.1073/pnas.2219547120

Asher, E. C., Baron, A., Yu, P., Todt, M. A., Smale, P., et al., (submitted to Journal of Geophysical Research). Baseline Balloon Stratospheric Aerosol Profiles (B^2SAP) – Perturbations in the Southern Hemisphere, 2019 – 2022.

Gao, R. S., Telg, H., McLaughlin, R. J., Ciciora, S. J., Watts, L. A., Richardson, M. S., et al. (2016). A light-weight, high-sensitivity particle spectrometer for PM2.5 aerosol measurements. *Aerosol Science and Technology*, *50*(1), 88–99. https://doi.org/10.1080/02786826.2015.1131809

Hall, E. G., Jordan, A. F., Hurst, D. F., Oltmans, S. J., Vömel, H., Kühnreich, B., & Ebert, V. (2016). Advancements, measurement uncertainties, and recent comparisons of the NOAAfrost point hygrometer. *Atmospheric Measurement Techniques*, *9*(9), 4295–4310. https://doi.org/10.5194/amt-9-4295-2016

Todt, M. A., Asher, E., Hall, E., Cullis, P., Jordan, A., Xiong, K., et al. (2023). Baseline Balloon Stratospheric Aerosol Profiles (B^2 SAP)- Systematic measurements of aerosol number density and size. *Journal of Geophysical Research: Atmospheres*, e2022JD038041. https://doi.org/10.1029/2022JD038041

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