Tropospheric and Stratospheric Temperature Trends from Observations

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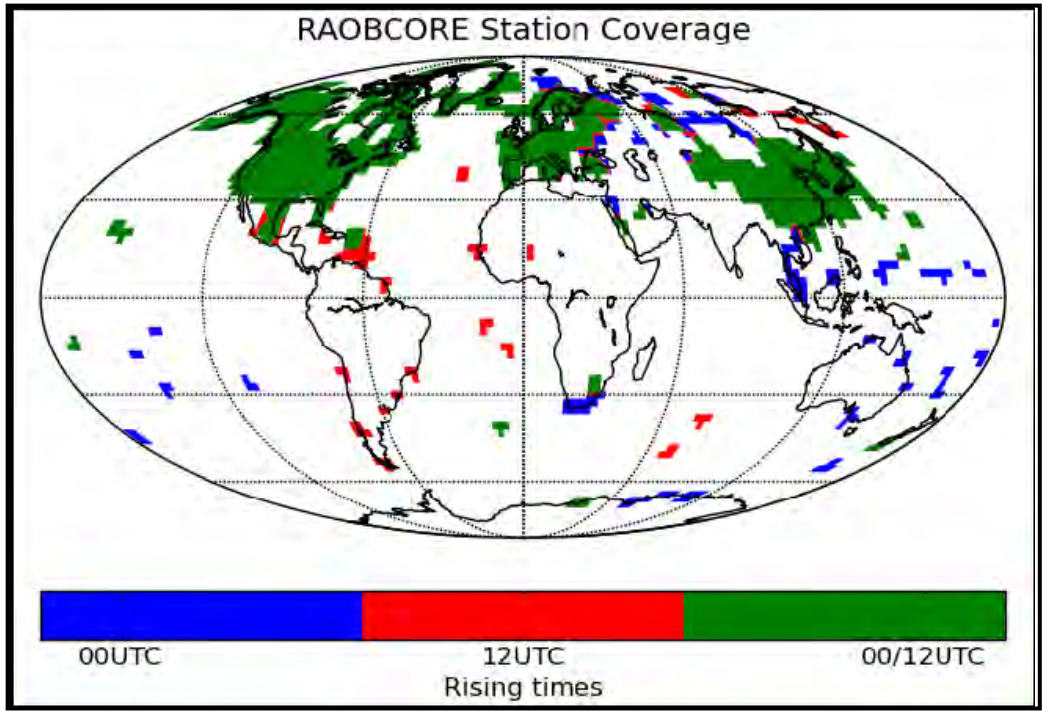
WCRP EPESC – LEADER Science Meeting, Busan, Republic of Korea, 14 – 18 July 2025

Atmospheric Temperature Observations

Radiosondes on weather balloons

- Long time series since 1950s
- High vertical resolution
- Limited spatial coverage, observations mostly over land
- Instrument changes, homogenization

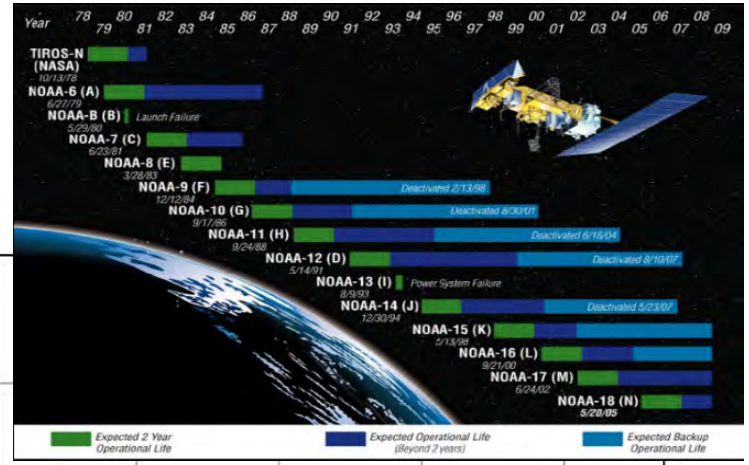


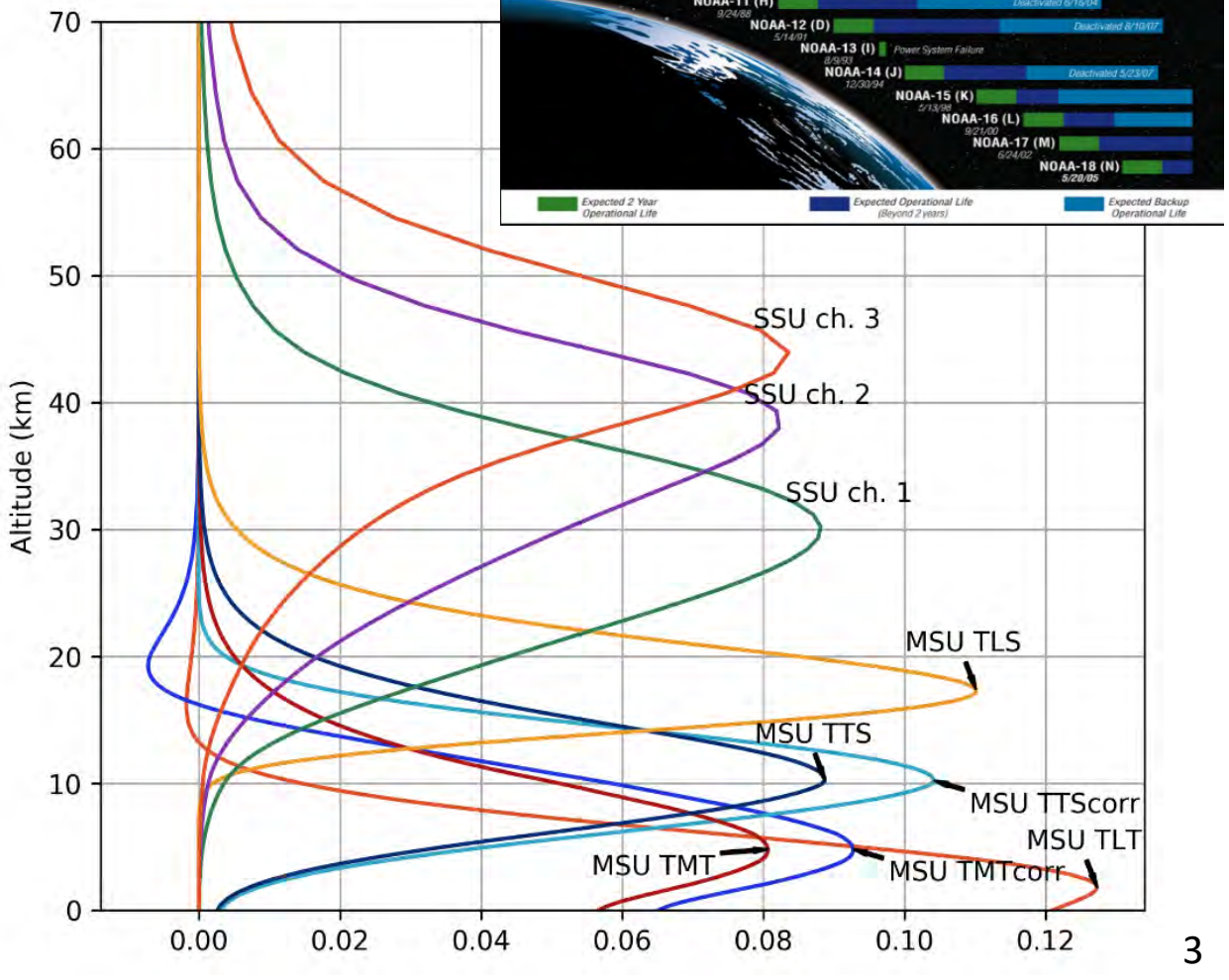
Atmospheric Temperature Observations

Nadir sounders

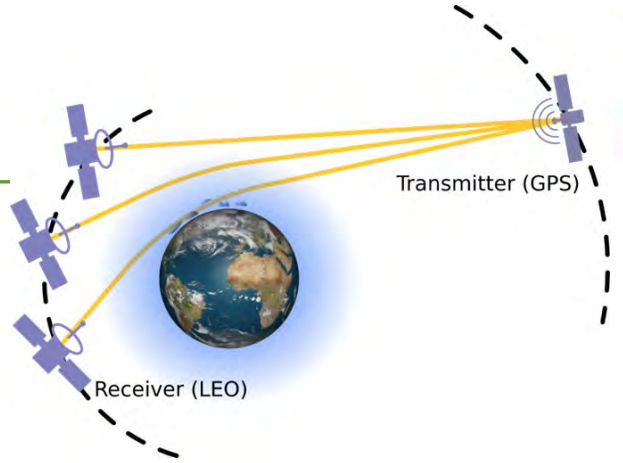
Earth's radiance at microwave or infrared frequencies

- Long time series since 1979
- Need calibration, corrections
- Good horizontal coverage globally
- Low vertical resolution due to **Layer average temperatures**
- **Merged timeseries**
- Stratospheric Sounding Unit (**SSU**): SSU-MLS, SSU-AMSU
- Microwave Sounding Unit (**MSU**) and Advanced MSU merged timeseries





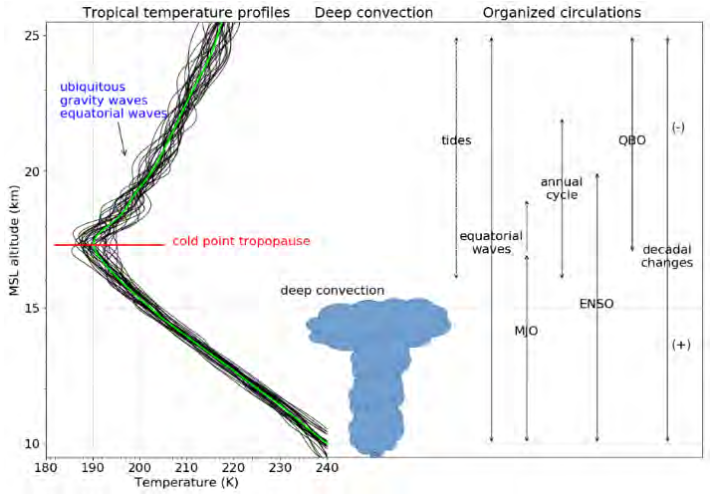
Atmospheric Temperature Observations



Limb sounding

GNSS Radio Occultation (GNSS RO)

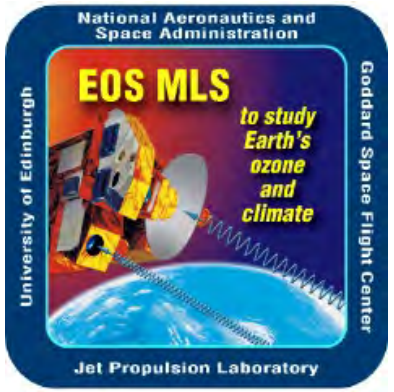
- **Long-term stability,** no inter-mission calibration
- Global coverage
- **High vertical resolution**
- Low structural uncertainty in the UTLS
- Since 2002, now > 20 years of measurements available



(Scherllin-Pirscher et al. JCLI 2021)
(Steiner et al., AMT 2020)

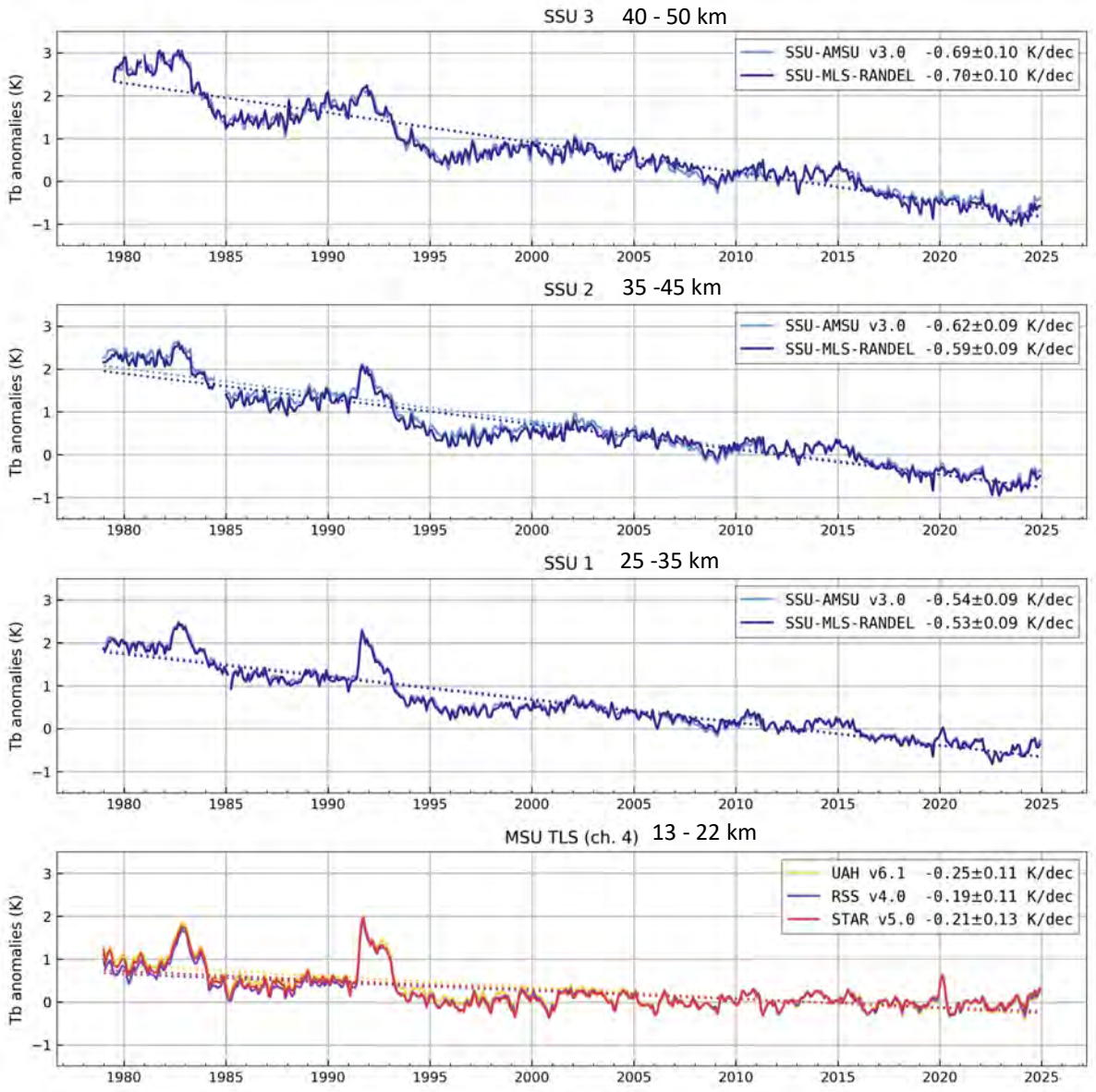
Microwave Limb Sounder (MLS)

- Global coverage
- **Vertical resolution about 3–8 km**
- Since 2004/08 to present (soon reaching eol)



Stratospheric Temperature Trends 1979–2024

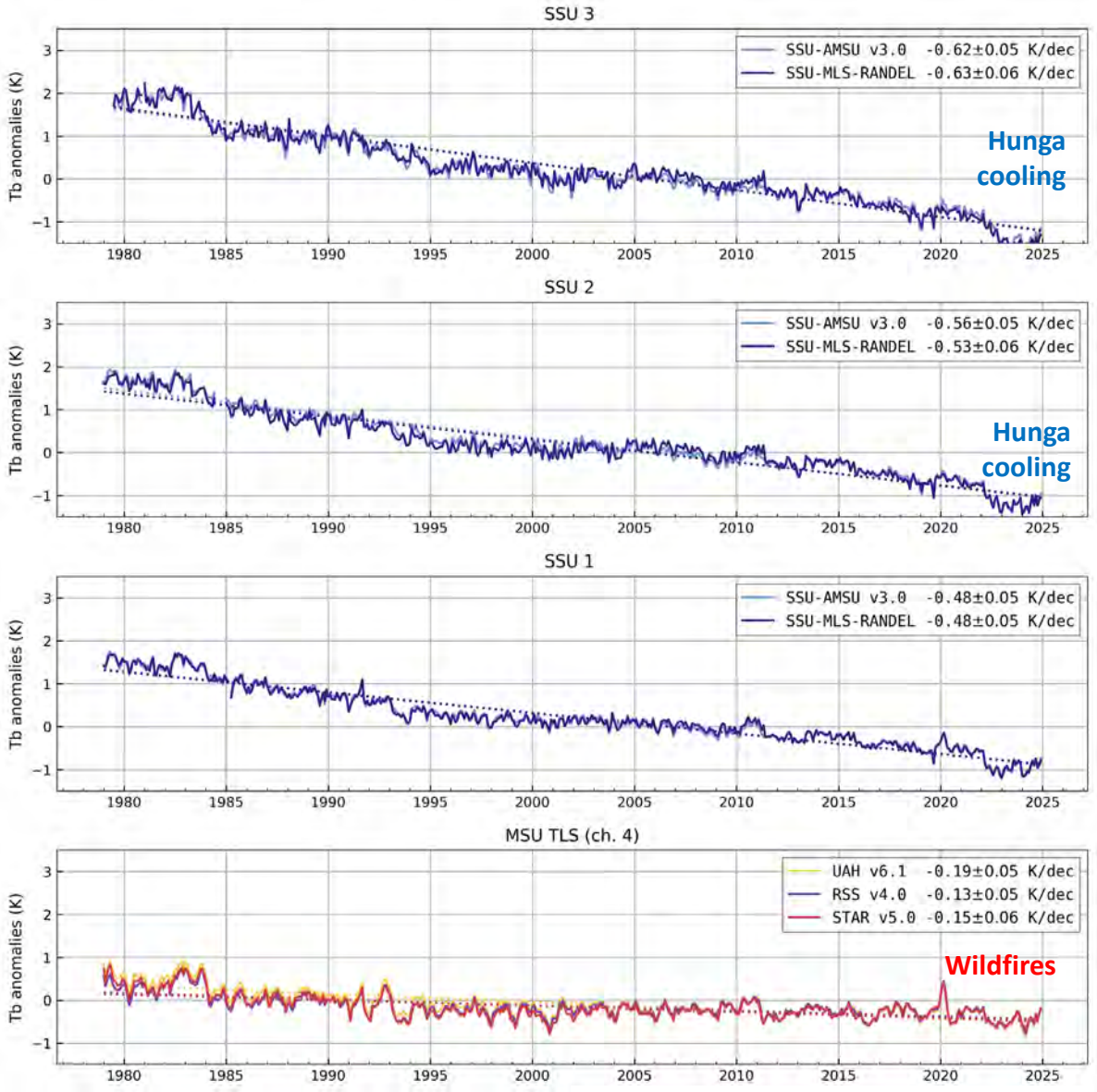
- Merged SSU-MLS, SSU-AMSU
- Merged MSU4-AMSU9 (TLS)
- Standard linear trend
- **Stratospheric cooling 1979-2024**
  -0.7 K/dec at 40-50 km
  -0.6 K/dec at 35-45 km
  -0.5 K/dec at 25-35 km
  -0.2 K/dec at 13-22 km
- **Magnitude increases with height**



(Steiner et al., JCLI 2020, updated datasets)

Stratospheric Temperature Trends 1979–2024

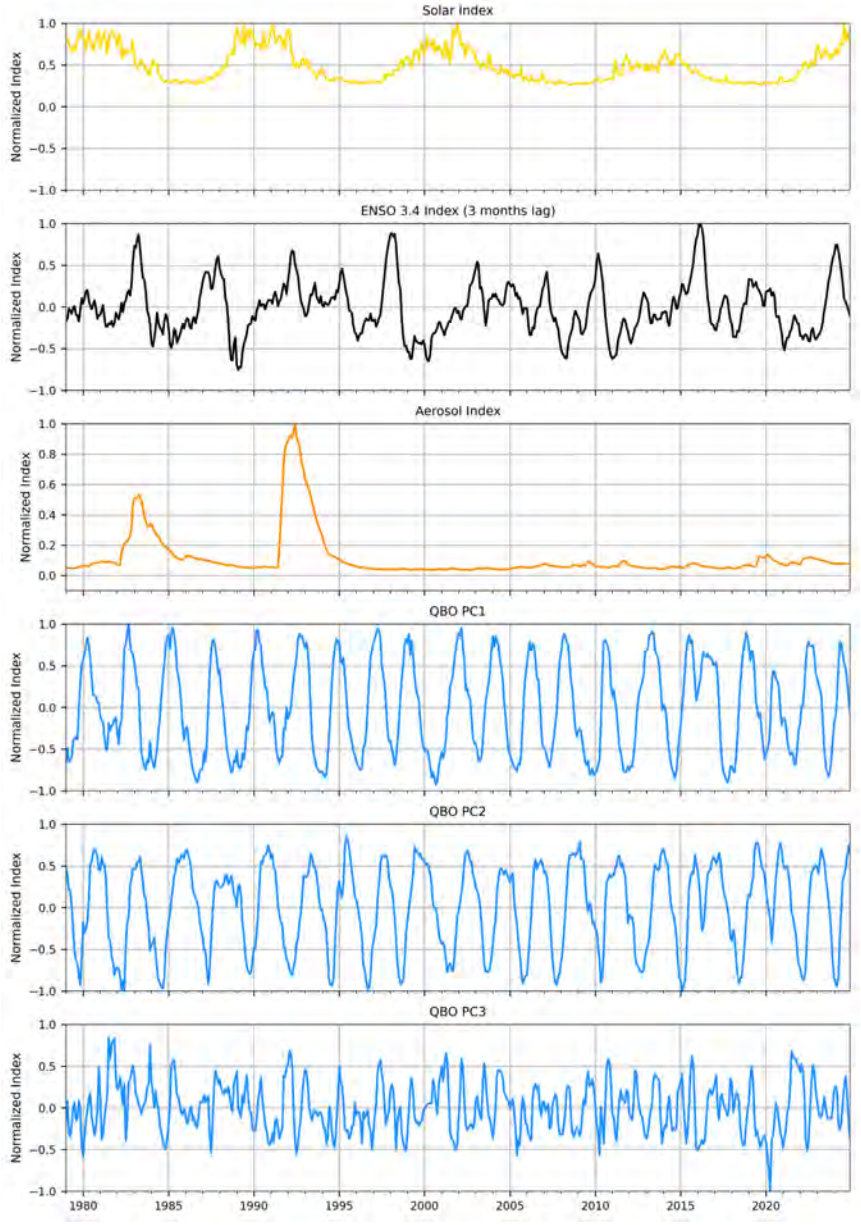
- Multiple linear regression
  trend uncertainty reduced by factor 2
- **Stratospheric cooling 1979-2024**
  -0.62 K/dec at 40-50 km
  -0.55 K/dec at 35-45 km
  -0.5 K/dec at 25-35 km
  -0.15 K/dec at 13-22 km
- **Volcanic signals removed**
- **Wildfire signal**: AOD does not fully reflect warming potential of black carbon
- **Hunga cooling 2022-2023 due to stratospheric water vapor**



(Steiner et al., JCLI 2020, updated datasets)

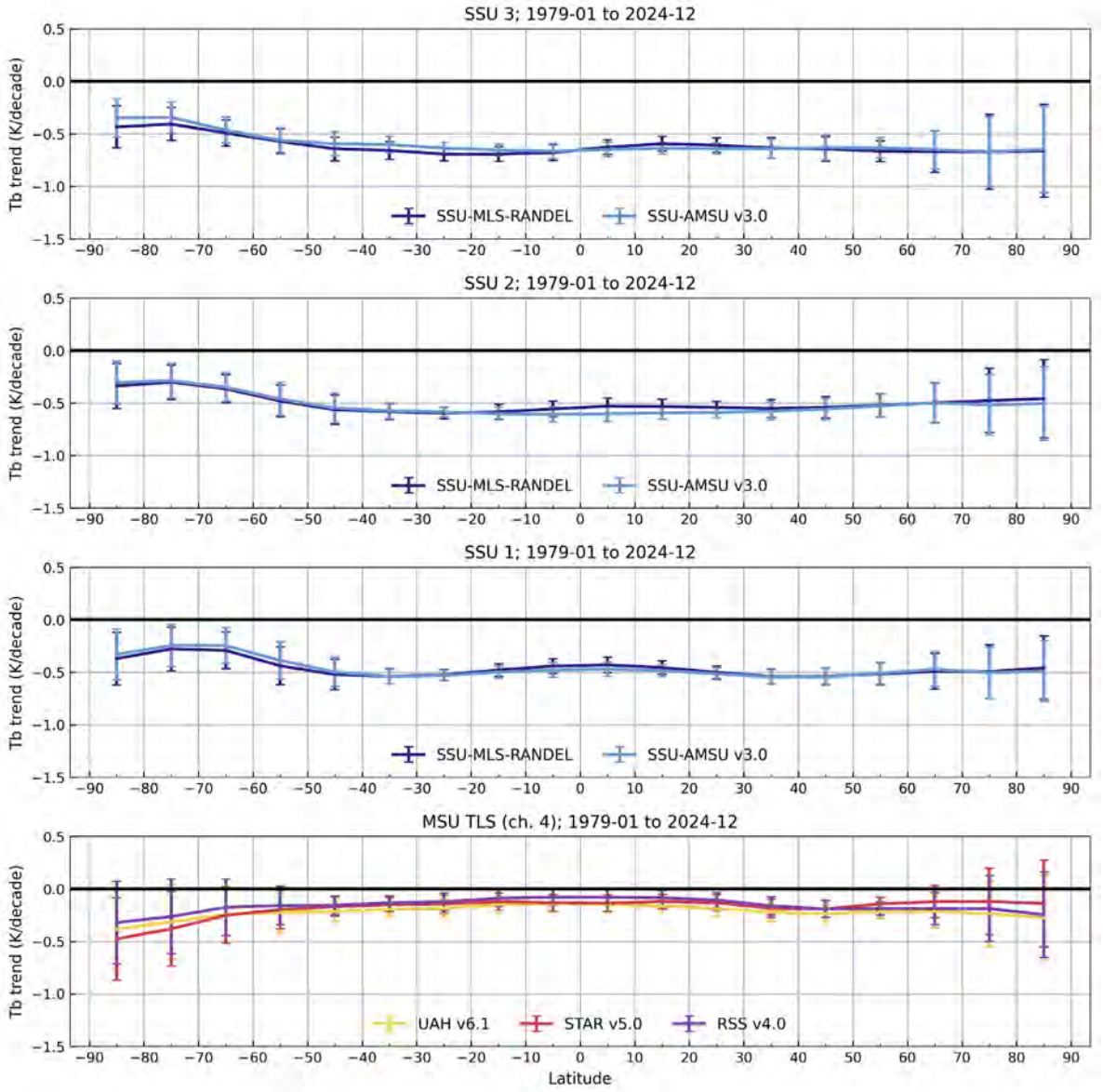
Stratospheric Temperature Trends 1979–2024

- **Multiple linear regression**
- Solar F10.7 index
- ENSO 3.4 index
- Aerosol index
- QBO index: Singapore winds
  PC1
  PC2
  PC3



Latitude-resolved Stratospheric Trends 1979–2024

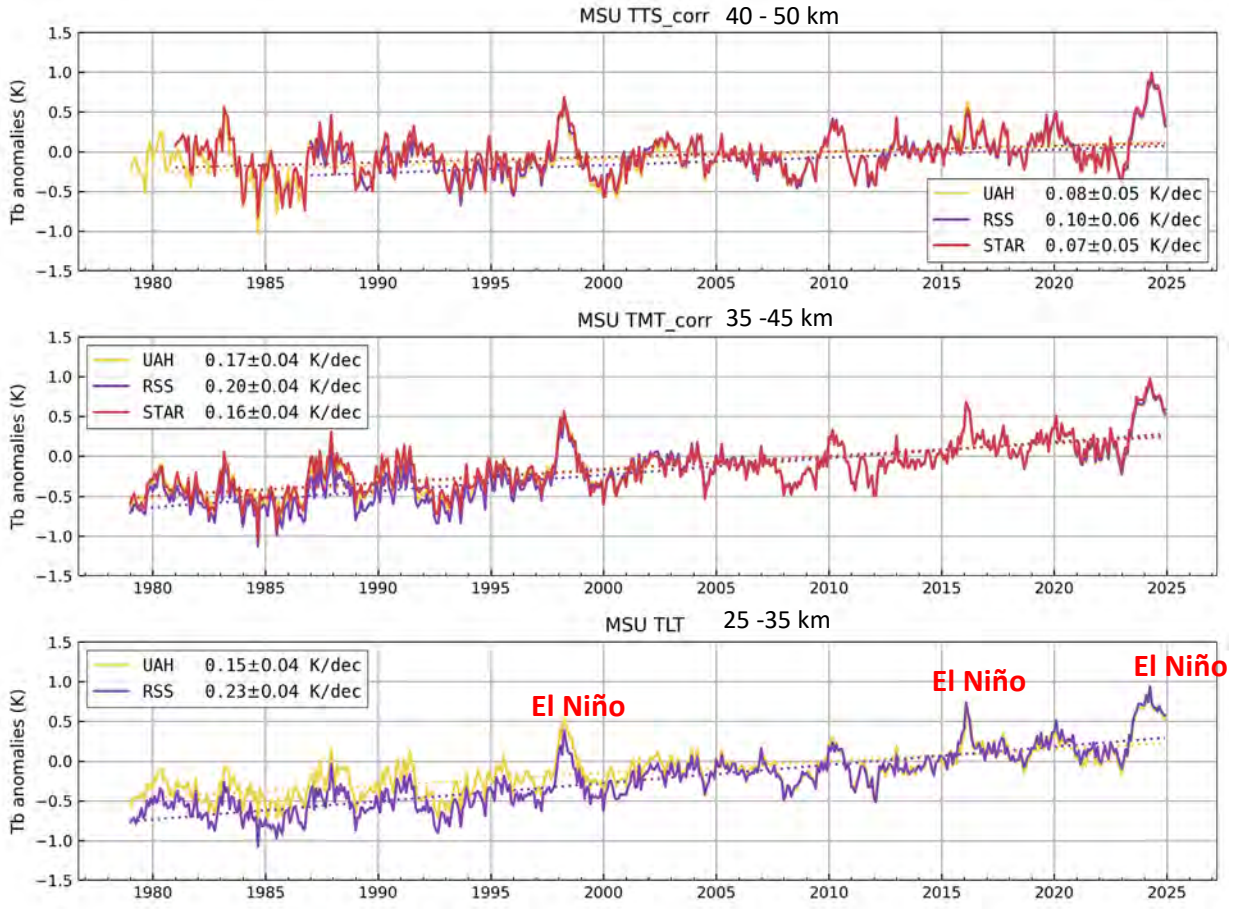
- Multiple linear regression
- **Trends are significant over all latitudes in the stratosphere 1979-2024**
- Except in the lower stratosphere at high latitudes



(Steiner et al., JCLI 2020, updated datasets)

Tropospheric Temperature Trends 1979–2024

- Merged MSU-AMSU channels
- TTS: MSU3+AMSU7
  TMT: MSU2+AMSU5 (+ATMS for STAR)
  corrected for stratospheric contrib.
- Standard linear trend
- **Tropospheric warming 1979-2024**
  +0.07 to 0.10 K/dec for TTScorr
  +0.16 to 0.20 K/dec for TMTcorr
  +0.15 to 0.23 K/dec for TLT



(Steiner et al., JCLI 2020, updated datasets)

Tropospheric Temperature Trends 1979–2024

- Merged MSU-AMSU channels
- TTS: MSU3+AMSU7
  TMT: MSU2+AMSU5 (+ATMS for STAR)
  corrected for stratospheric contrib.
- Multiple linear regression
  Trend uncertainties reduced by factor 2
- **Tropospheric warming 1979-2024**
  +0.07 to 0.11 K/dec for TTScorr
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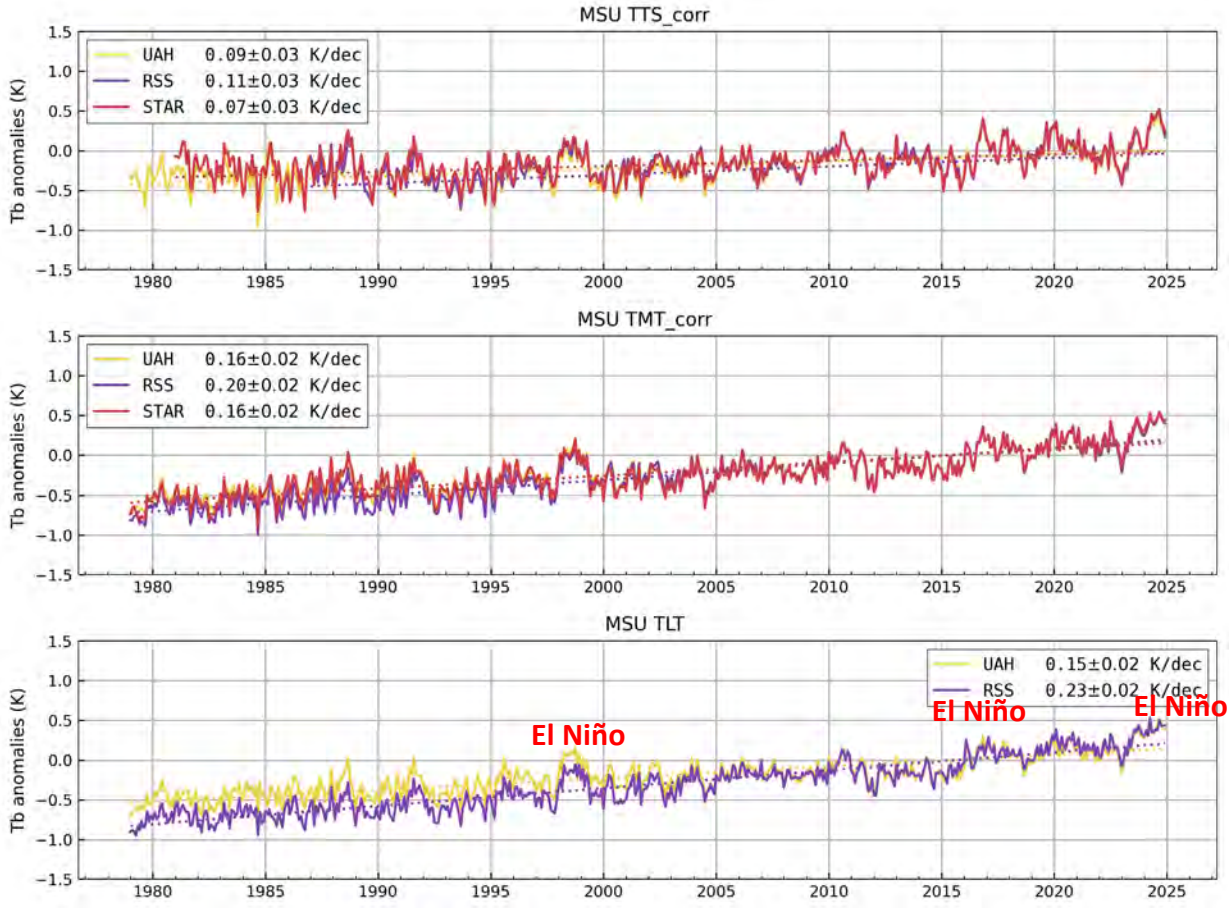
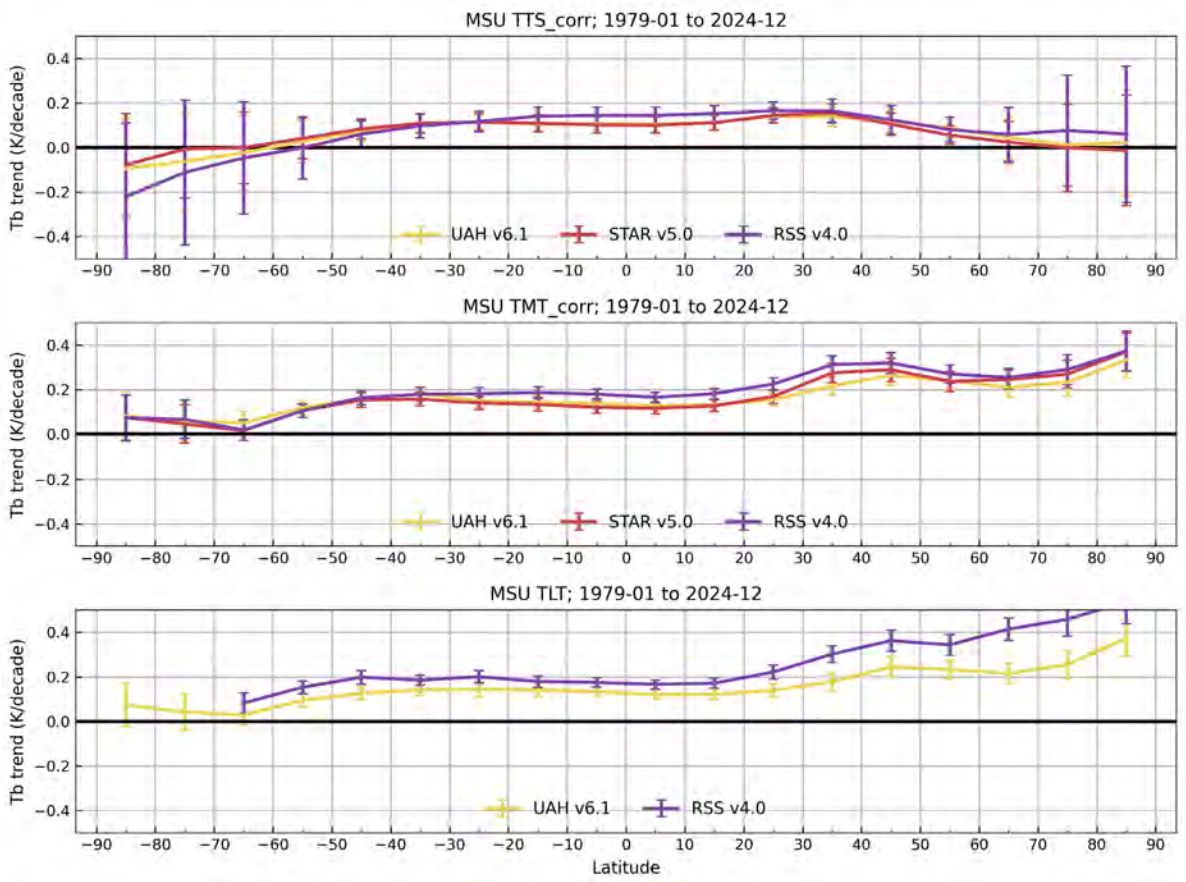


(Steiner et al., JCLI 2020, updated datasets)

Latitude-resolved Tropospheric Trends 1979–2024

- Multiple linear regression
- **Warming over all latitudes**
  Largest warming at northern high lats
- Larger uncertainty at high latitudes due to larger variability

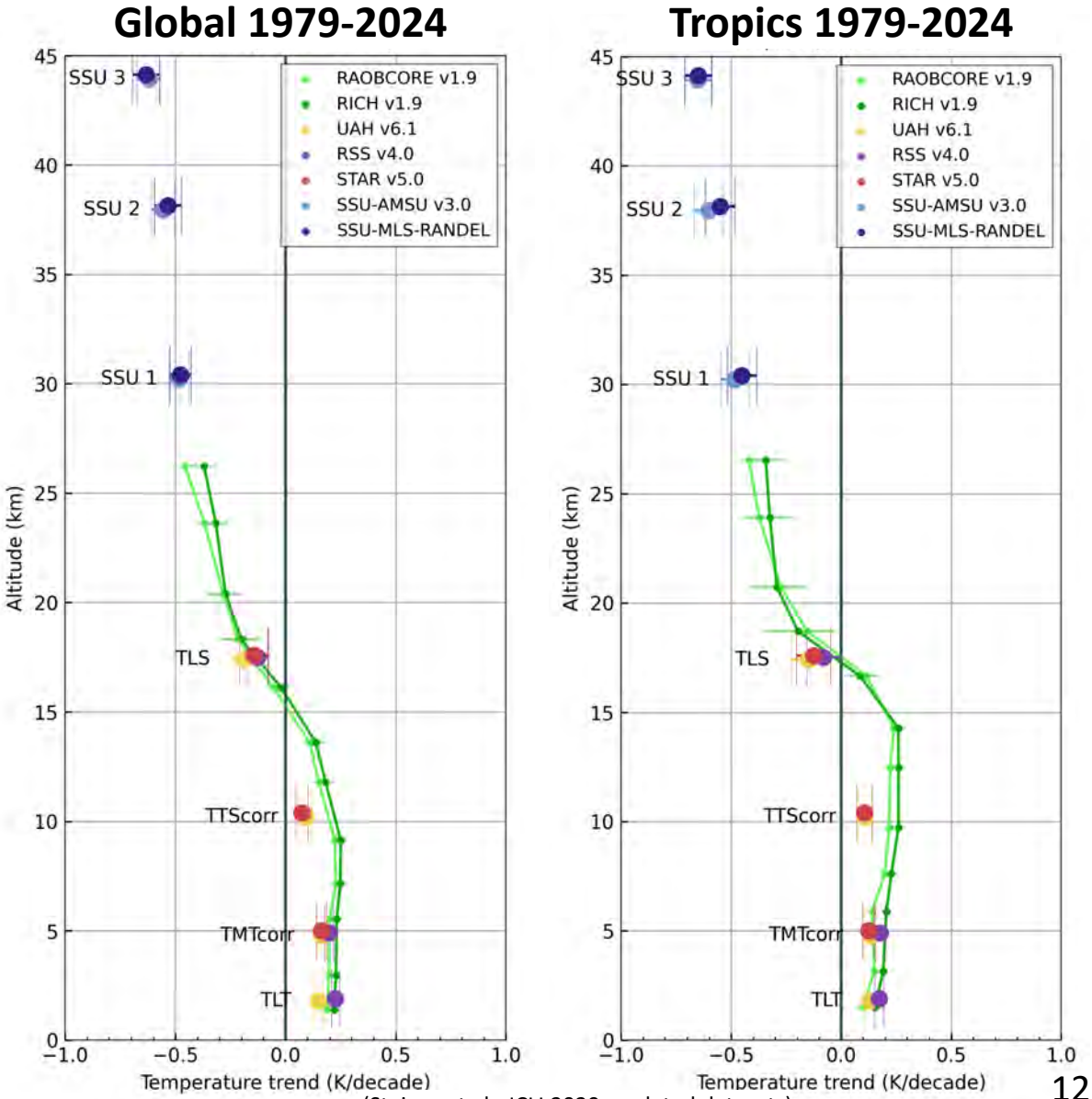


(Steiner et al., JCLI 2020, updated datasets)

Vertical-resolved Trends 1979–2024

- Merged SSU and AMSU/MLS
- Merged MSU/AMSU
- Radiosondes RICHv1.9, RAOBCOREv1.9

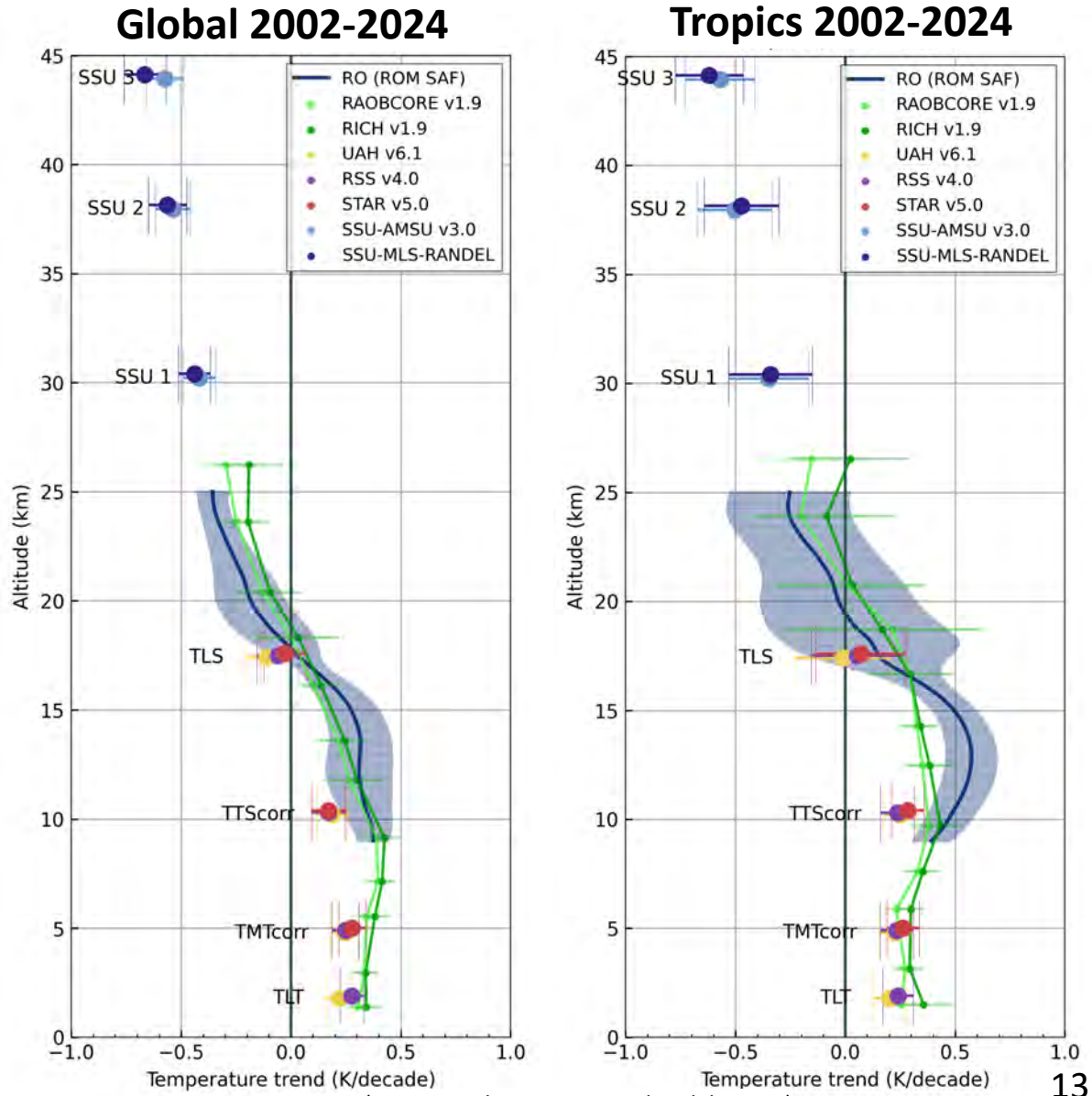
- **Significant stratospheric cooling**
  1979-2024 of about –0.2 to –0.7 K/dec
- **Significant tropospheric warming**
  1979-2024 of about 0.2 K/dec
- **Radiosondes: larger trend in tropical UT**
- AMSU TTScorr: smaller trends



(Steiner et al., JCLI 2020, updated datasets)

Vertical-resolved Trends 2002–2024

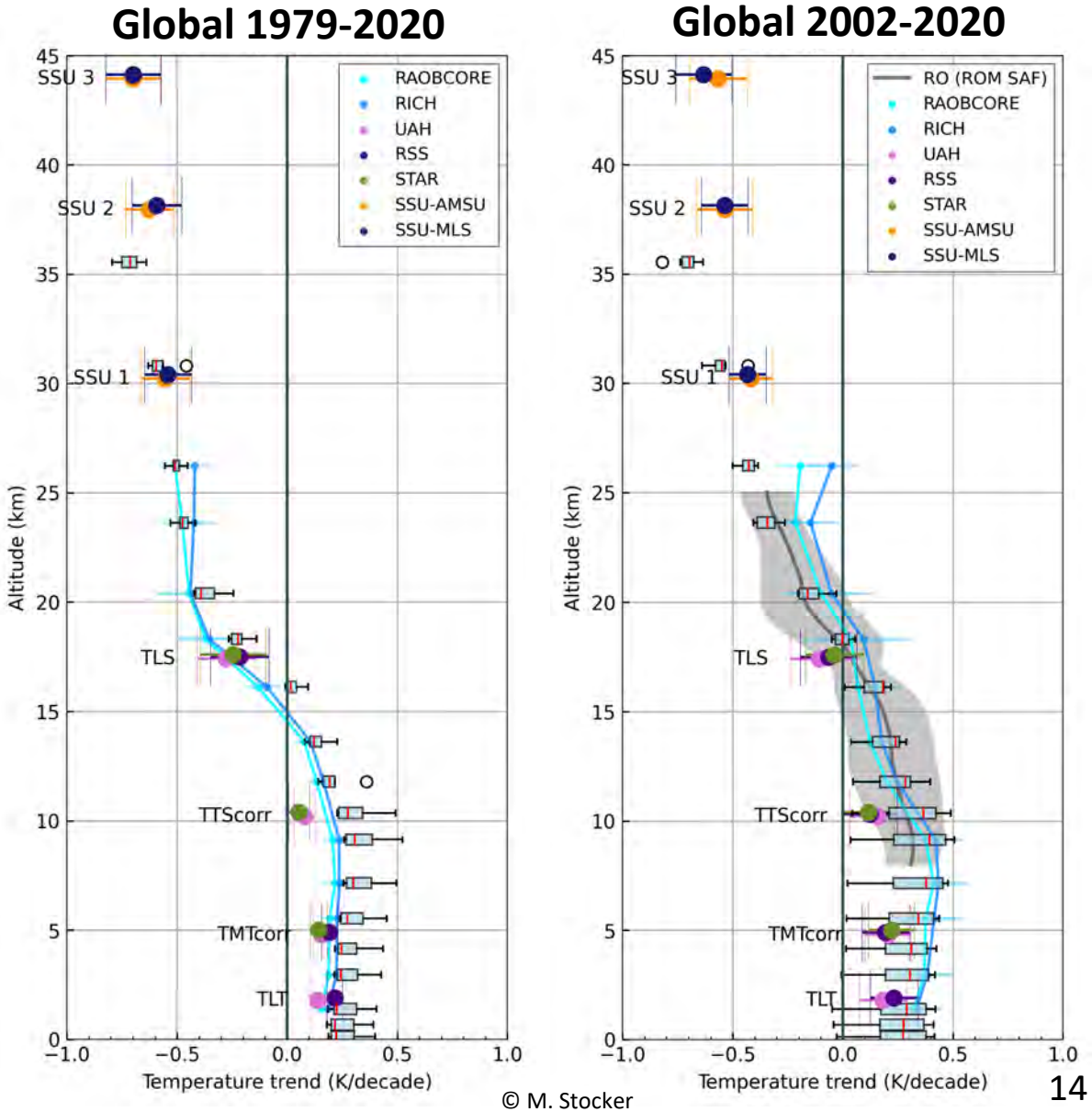
- Significant stratospheric cooling 2002-2024 of up to –0.7 K/dec
- **Significant tropospheric warming 2002-2024 of 0.2 to 0.4 K/dec**
- AMSU shows smaller trends
- **Consistency between RO and RS**
- **Tropical upper tropospheric warming**
- **Tropical lowermost stratosphere warms**



(Steiner et al., JCLI 2020, updated datasets)

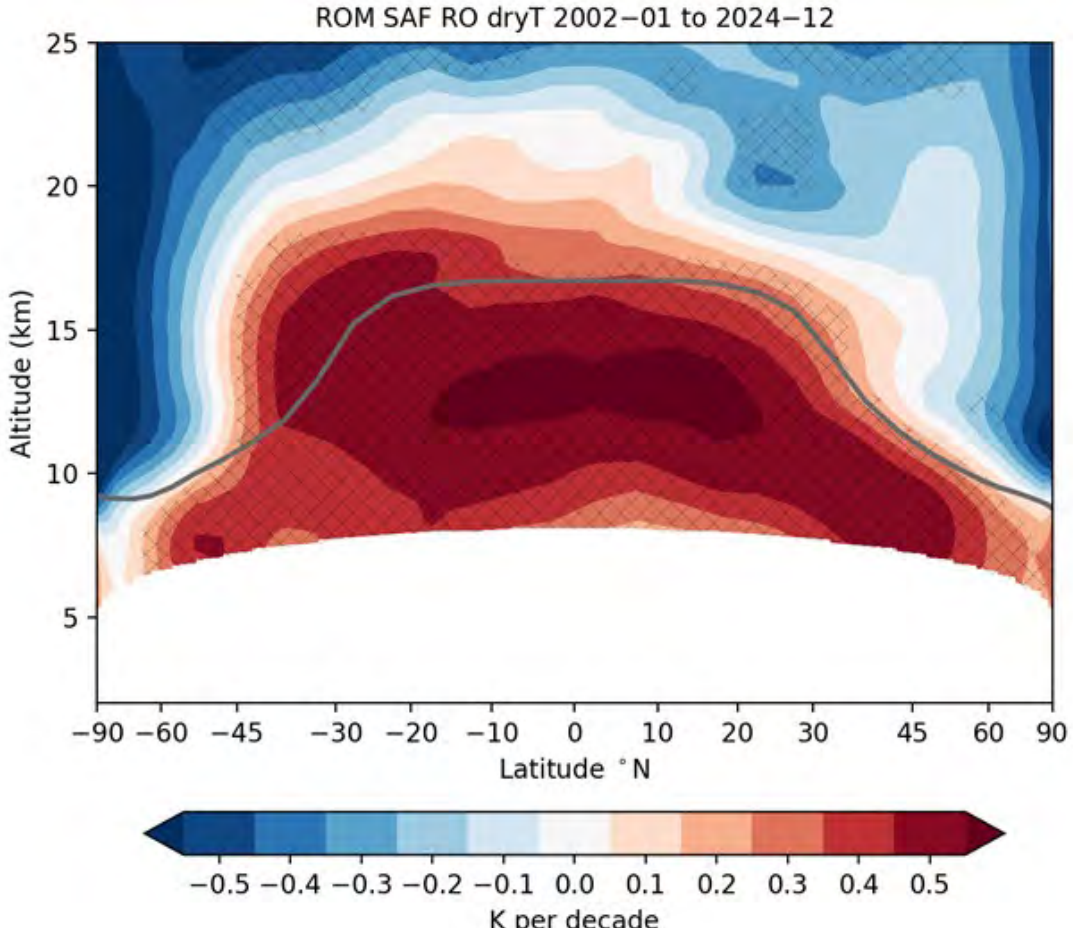
Vertical-resolved Trends – Observations & Models

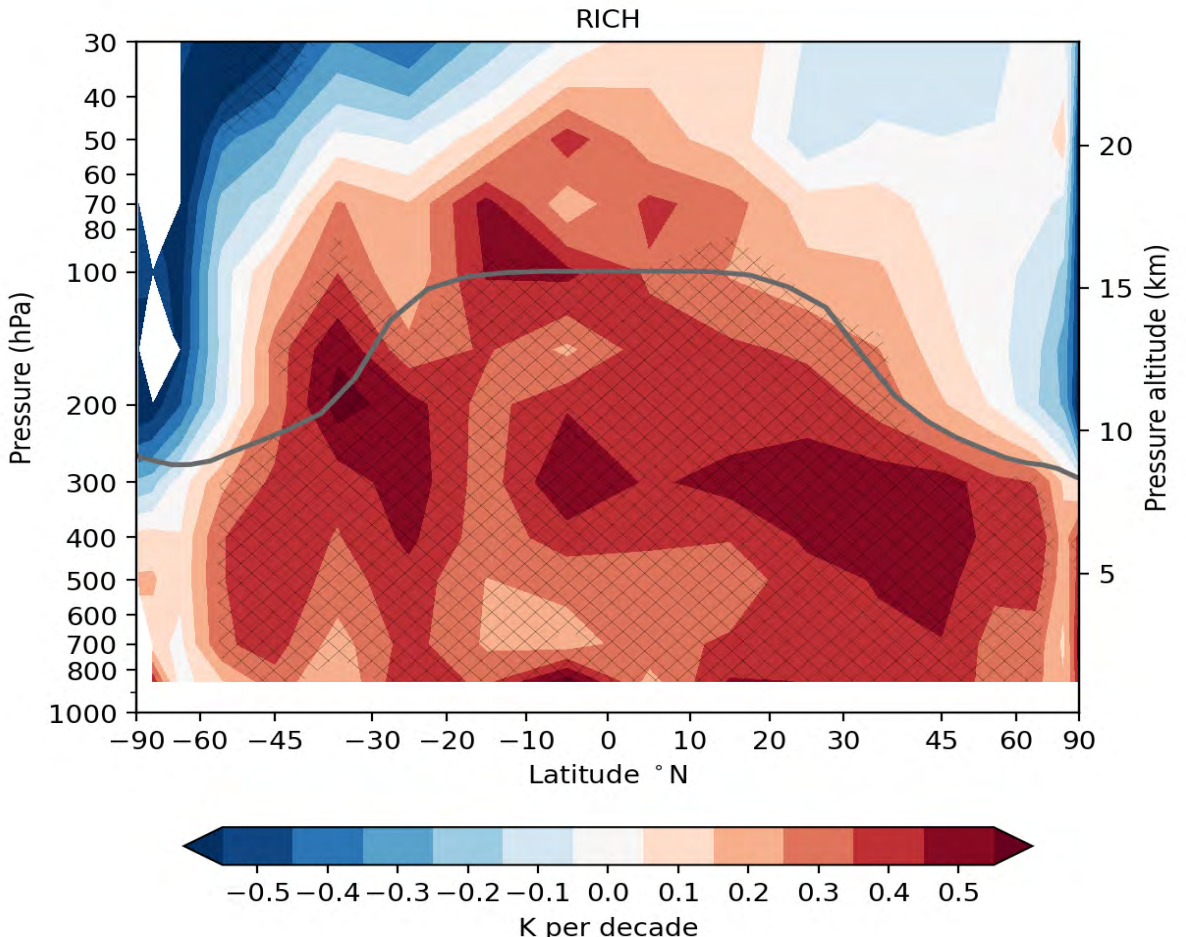
- **Comparison with LESFMIP model trends**
- Ensemble means for all forcing runs (hist-all) IPSL-CM6A-LR, CanESM5, CMCC-CM2-SR5, FGOALS-g3, NorESM2-LM, HadGEM3-GC31-LL, GISS-E2-1-G
- **More by Matthias Stocker**
  Presentation on Fri. 18 July, Session D-1



Height-latitude-resolved Temperature Trends 2002–2024

- **RO observations: Strong warming in tropical UTLS and SH subtropics**
- **RO consistent with radiosondes**, radiosondes sparse in tropics and SH

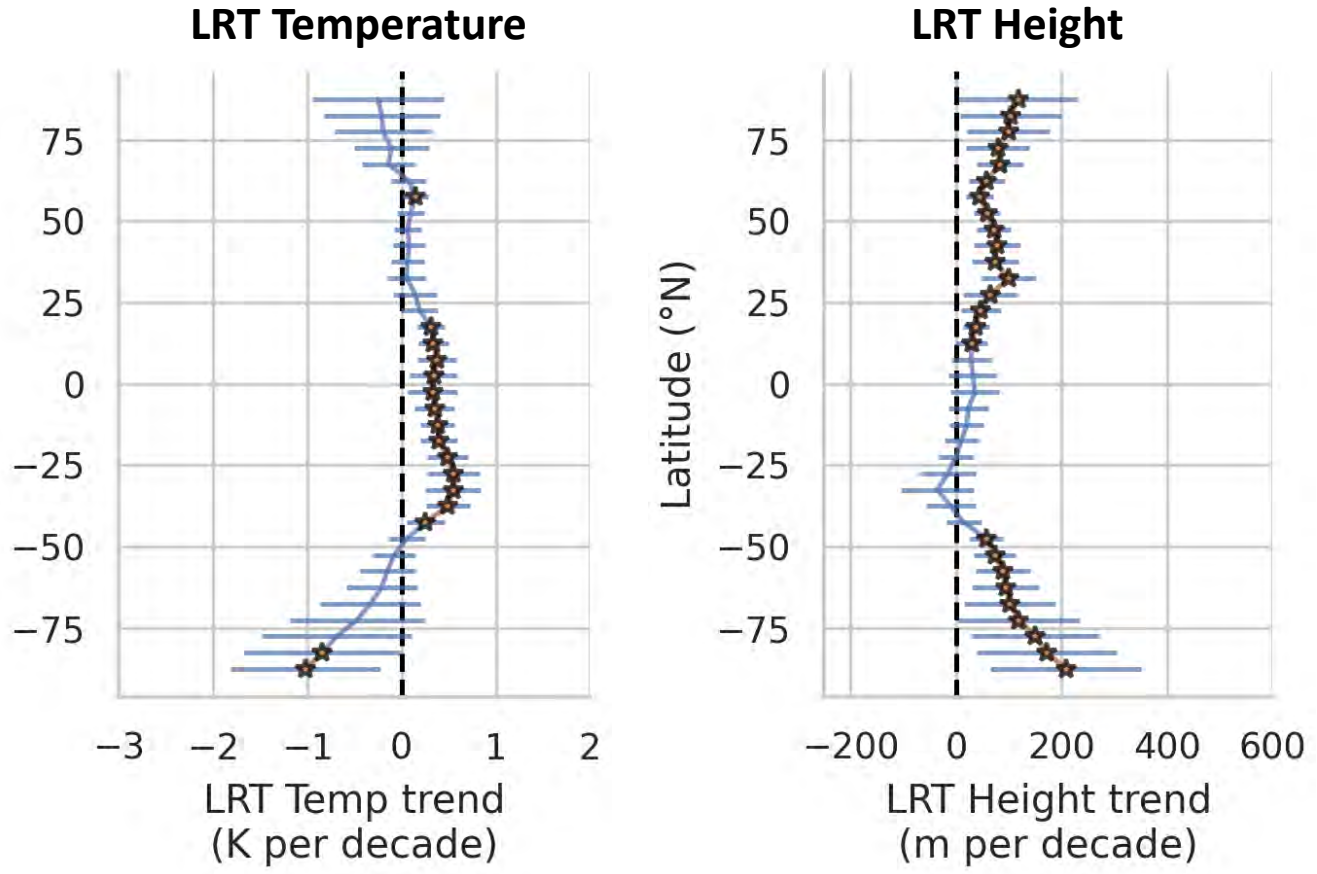




(Ladstädter et al. 2023; updated data and plots)

Tropopause trends 2002–2024

- **Lapse rate tropopause height and temperature** – annual mean trends
- **Increase in tropical tropopause temperature** with NH/SH asymmetry
- **Significant rise of the tropopause** throughout NH, and in mid-to high SH; but not in tropics

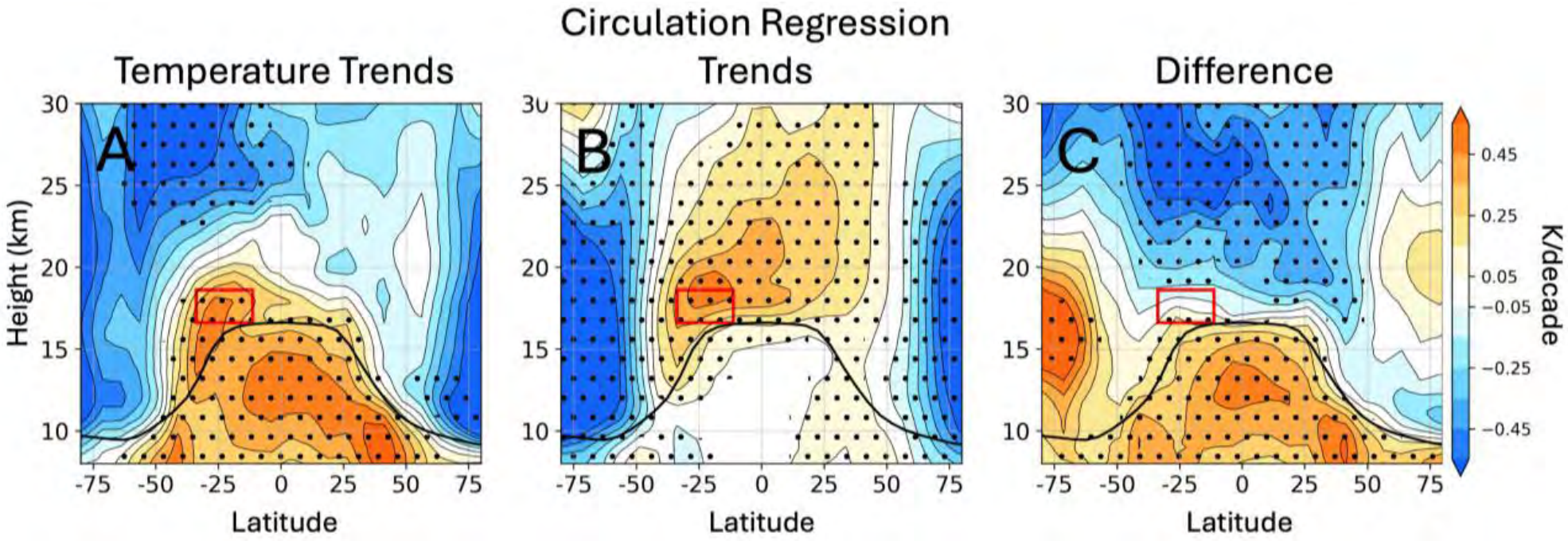


Presentation on tropopause trends
at BACO-25, Session M10
Wed 23 July, 13:30
Convention Hall 1F, C106-107

(Ladstädter et al., in review for ACP, doi:10.5194/egusphere-2025-2100)

Warming of SH Subtropical Lower Stratosphere and Antarctic Ozone Healing

- **SH subtropical lower stratosphere warming linked to BDC slowdown**
- Circulation changes also cool the Antarctic lower stratosphere and mask the Antarctic ozone healing from October to December
- **Removing circulation changes reveals Antarctic warming and ozone healing**



(Sweeney et al., AGU Adv., in press; Fig.4)

Summary

- Significant stratospheric cooling and tropospheric warming 1979-2024
- Strong tropospheric warming observed in last two decades
- Strong warming also in the lower stratosphere in SH (sub)tropics
- Rise of tropopause height in the NH and in mid-to high SH
- Increase in tropical tropopause temperature (asymmetric)
- Warming in the lower stratosphere in SH (sub)tropics linked to BDC slowdown from October to December masking ozone healing

Thanks for your attention!

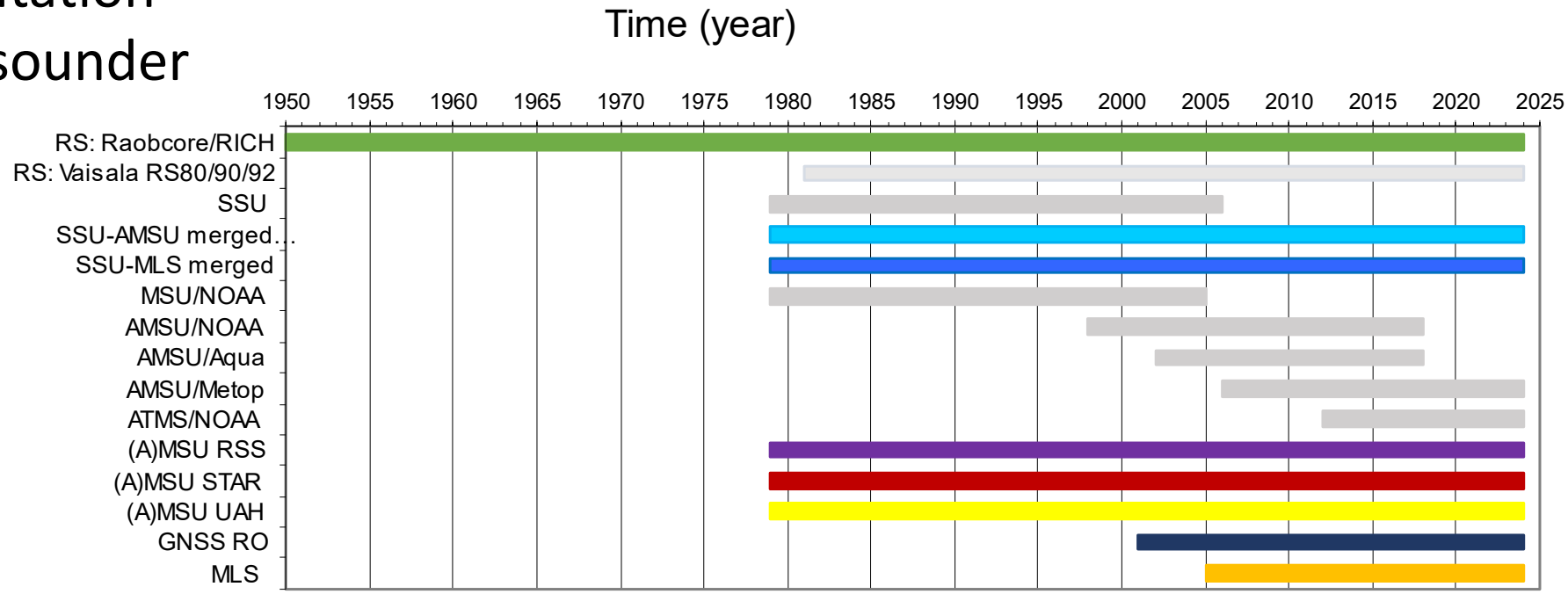
Observational Records

Layer average brightness temperatures: merged timeseries since 1979

- Stratospheric Sounding Unit (SSU): SSU-MLS, SSU-AMSU
- Microwave Sounding Unit (MSU) and Advanced MSU merged timeseries

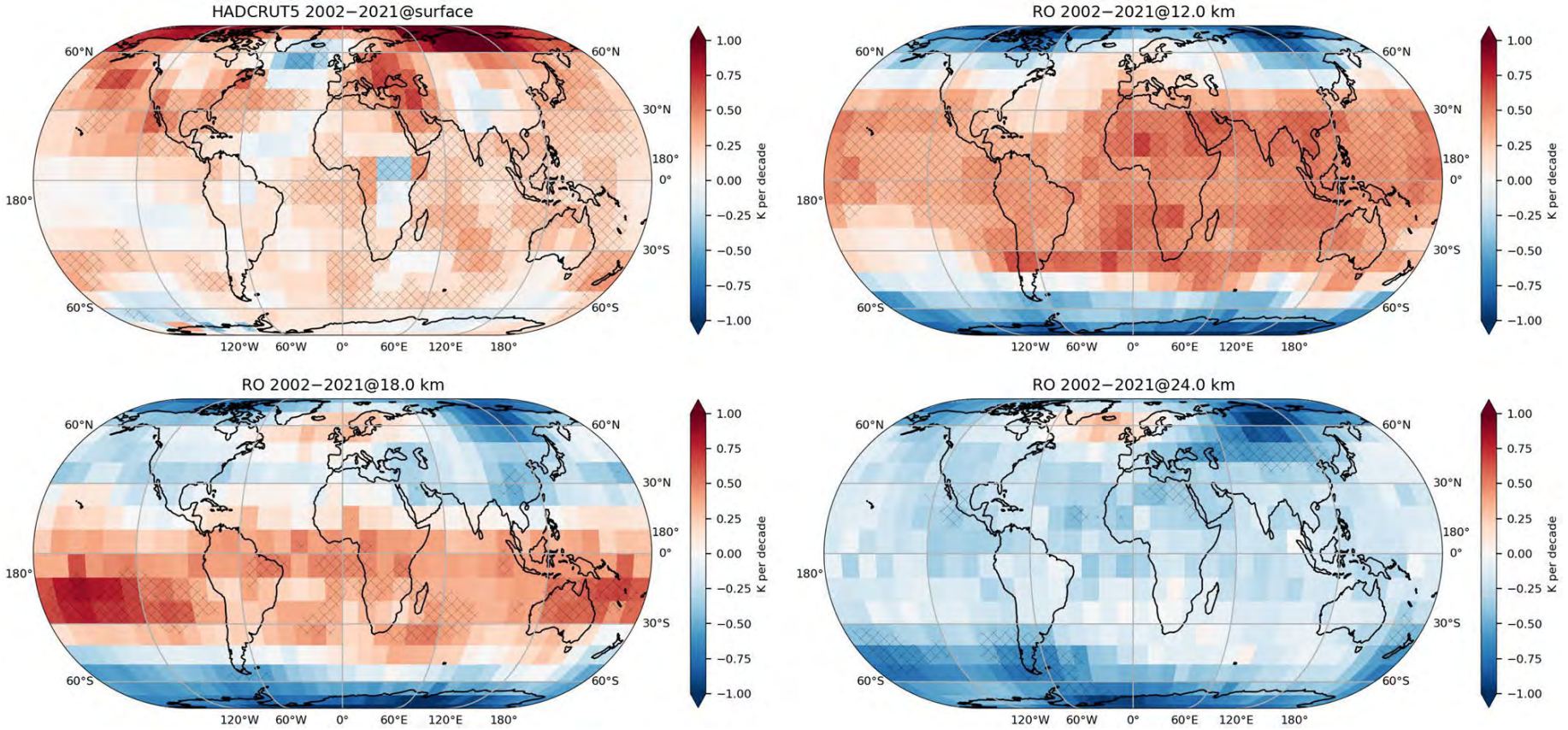
Vertically resolved temperatures:

- Radiosondes (RAOBCORE, RICH)
- GNSS Radio occultation
- Microwave limb sounder



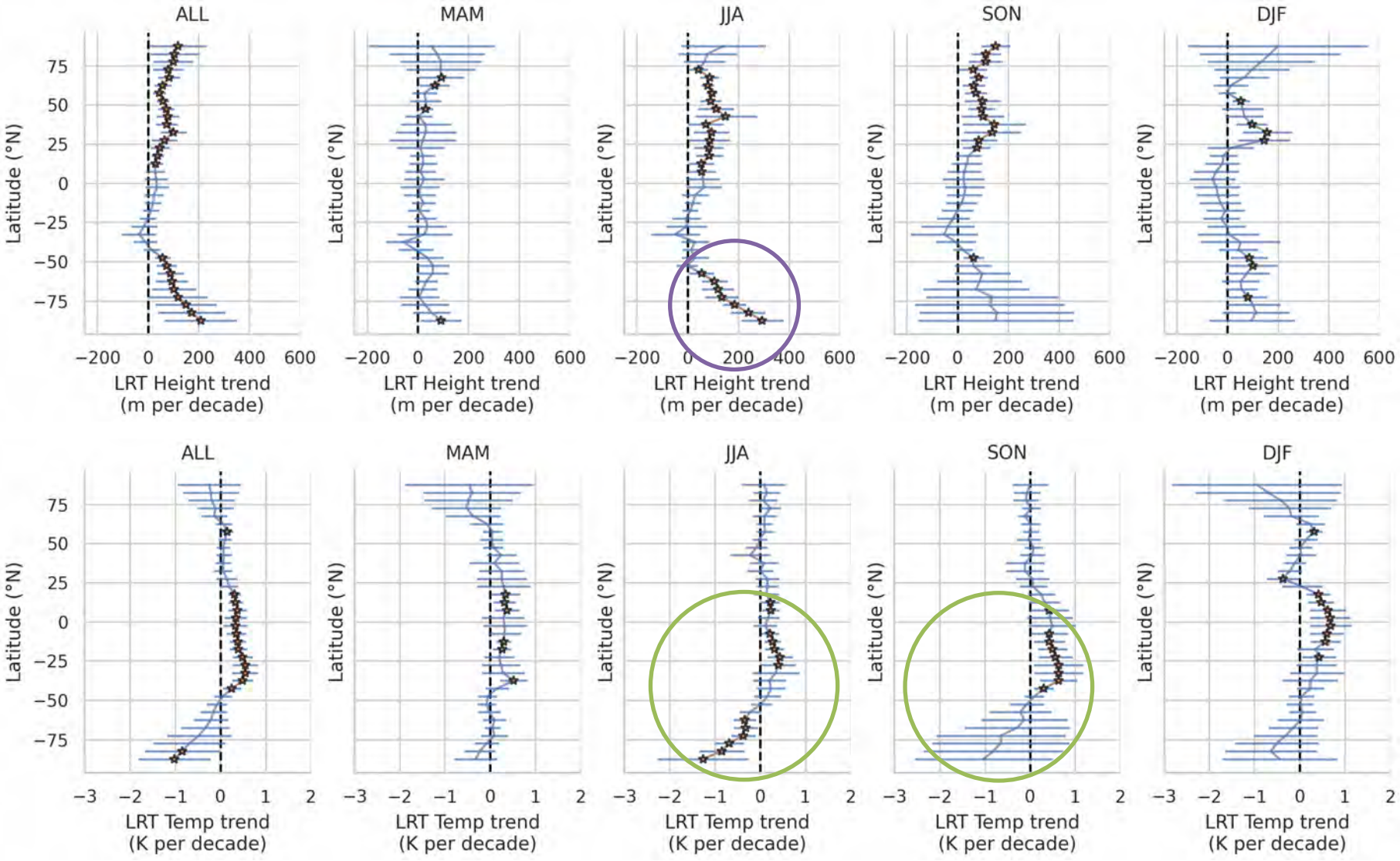
Height-latitude-resolved Temperature Trends 2002–2021

- **Amplified warming in the upper troposphere**
- **Hemispheric asymmetry of LS trends**, possible connection with ozone
- **Cooling in the stratosphere**



(Ladstädter et al. 2023)

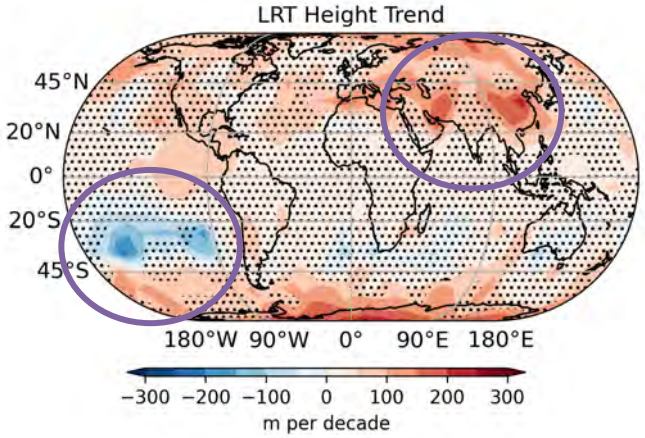
LRT trends, seasonally

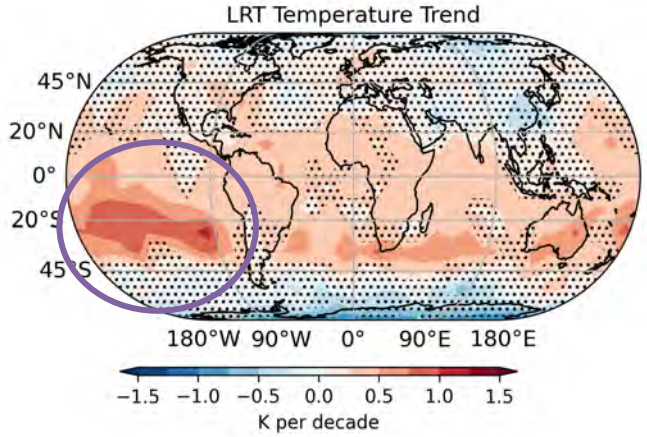


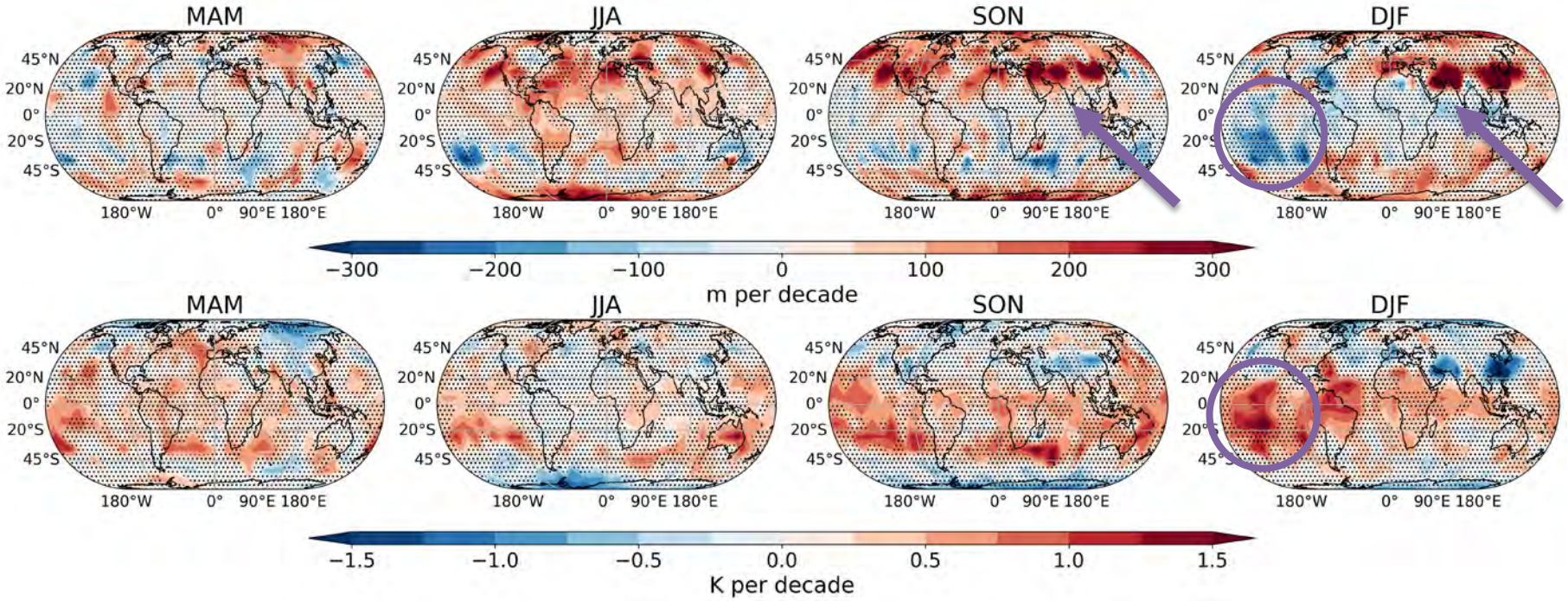
- Trend patterns generally persistent across seasons; SON and JJA similar pattern to overall trend
- Large positive height trends in SH polar winter
- Almost zero trend in NH spring
- Dipole temperature structure in SH spring between tropics and pole – BDC changes?

(Ladstädter et al., in review, doi:10.5194/egusphere-2025-2100)

LRT trends regional/seasonal





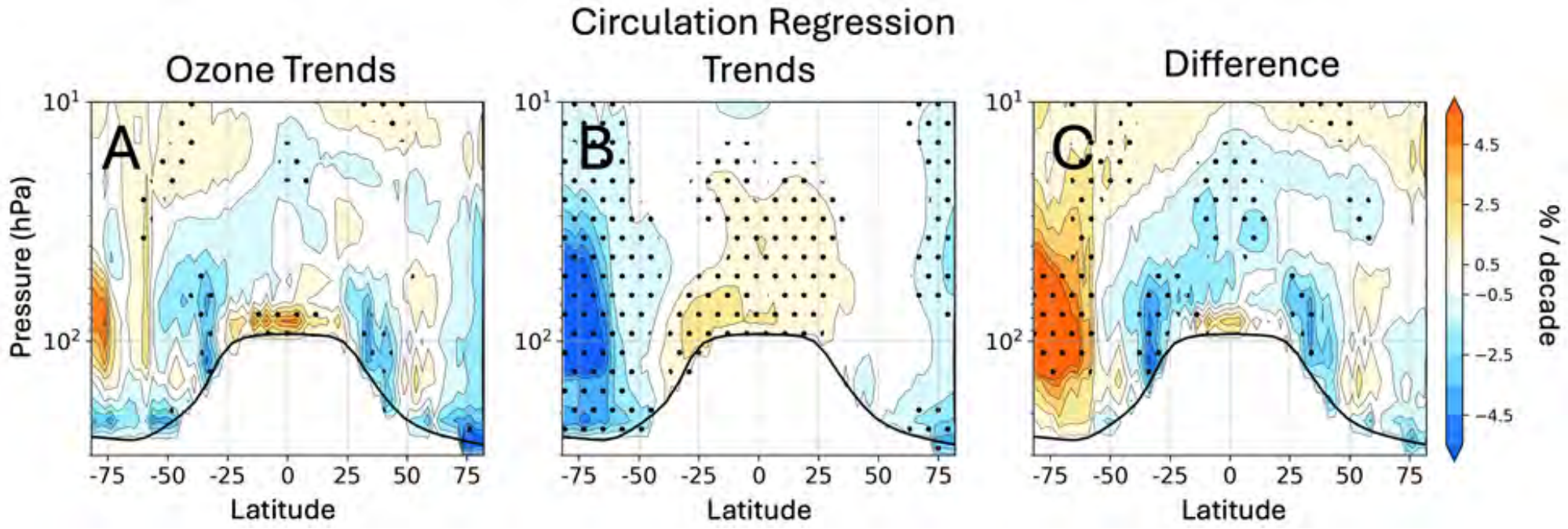


- LRT height trends not homogeneous across longitudes
- Large positive LRT height trends pronounced over Asian SON and DJF, and over SH polar region
- Large positive LRT temperature trend in SH subtropics from South Pacific region, especially DJF and SON. Corresponds to negative height trend there
- Prominent changes in the subtropics could relate to tropical width?

(Ladstädter et al., in review, doi:10.5194/egusphere-2025-2100)

Warming of SH Subtropical Lower Stratosphere and Antarctic Ozone Healing

- Annual-mean ozone shows **insignificant trends in Antarctic ozone** poleward of 75°S (A).
- Ozone trends **associated with AWLS-related circulation variability** (B). Ozone **increase in the tropical lower stratosphere and decrease in the Antarctic**, reflecting **change in SH-BDC**.
- Ozone trends after **removing the circulation variability, revealing an increase in Antarctic ozone** (C).

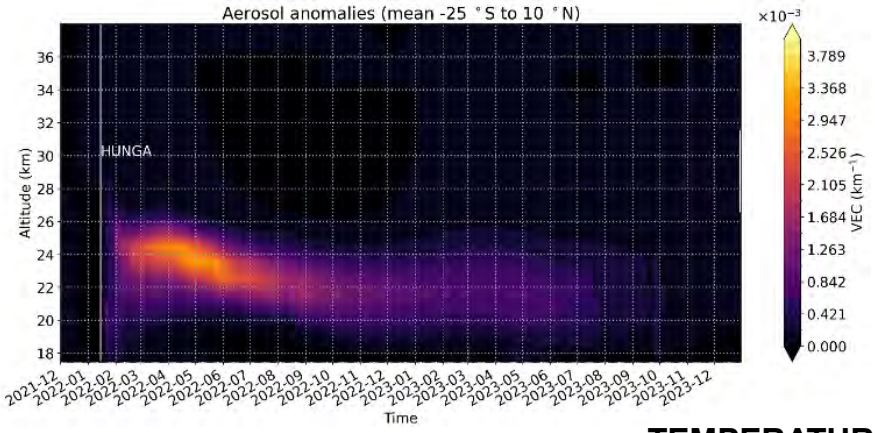


(Sweeney et al., AGU Adv., in press; Fig.8)

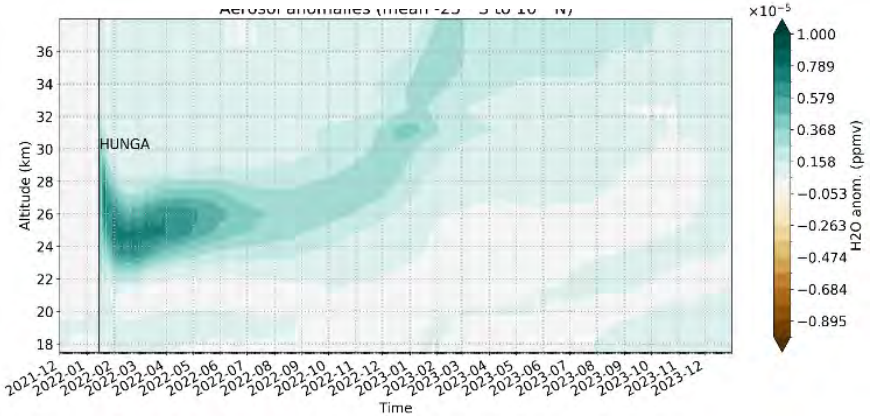
Hunga Volcanic Eruption – Short-term Climate Impact

- **Radiative cooling of up to –4 K in the tropical and subtropical middle stratosphere until mid-2023, clearly corresponding to the water vapor distribution**

AEROSOL ANOMALIES

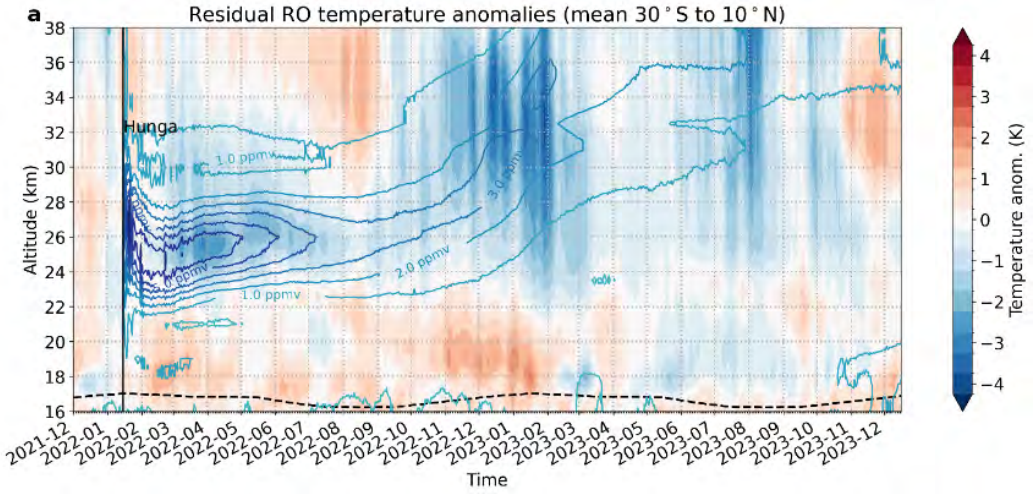


WATER VAPOR ANOMALIES



Minor impact due to aerosols

TEMPERATURE RESIDUAL ANOMALIES



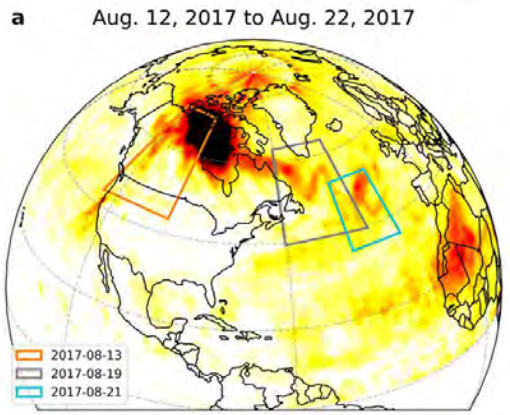
Detection (GNSS RO, MLS): Strong cooling over 1.5 years due to water vapor injection of Hunga into the stratosphere!

(Stocker et al., Commun. Earth Environ 2024)

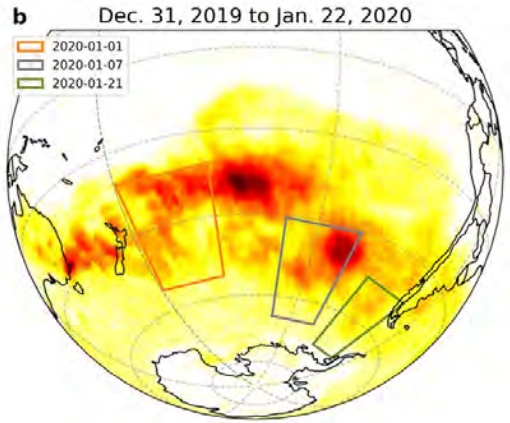
Climate Variability & Extremes – Large Wildfires

- **Large wildfire events with aerosol emissions comparable to moderate volcanic eruptions**

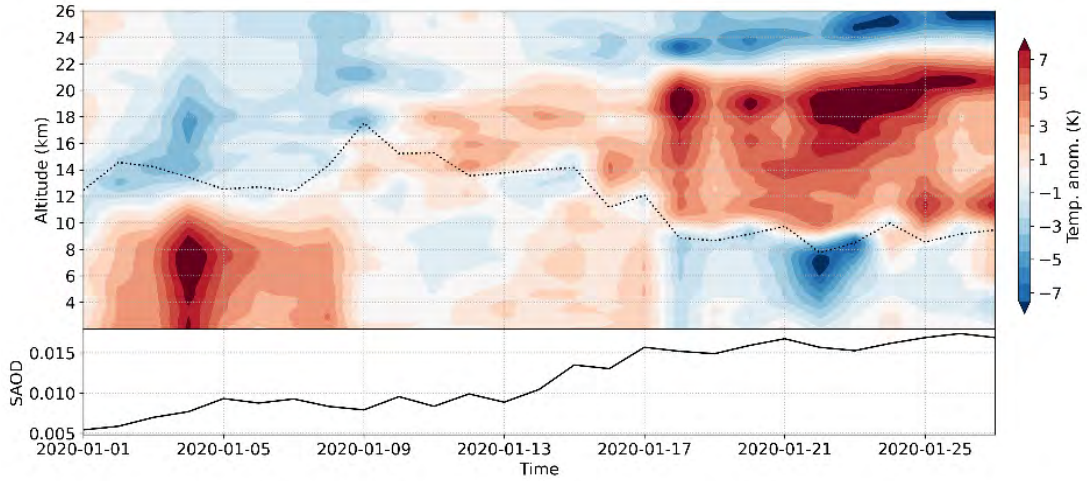
North America 2017



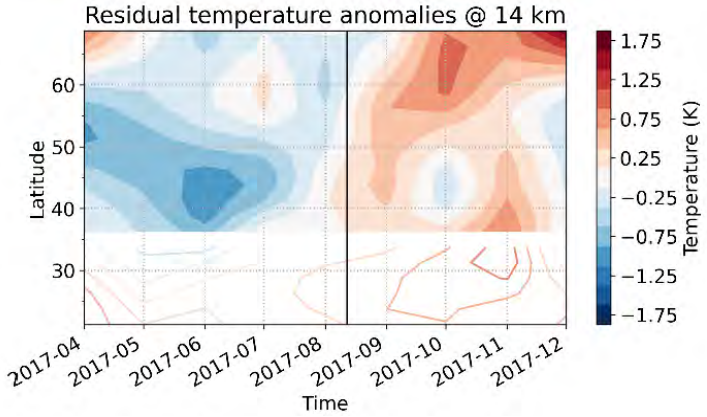
Australia 2019/2020

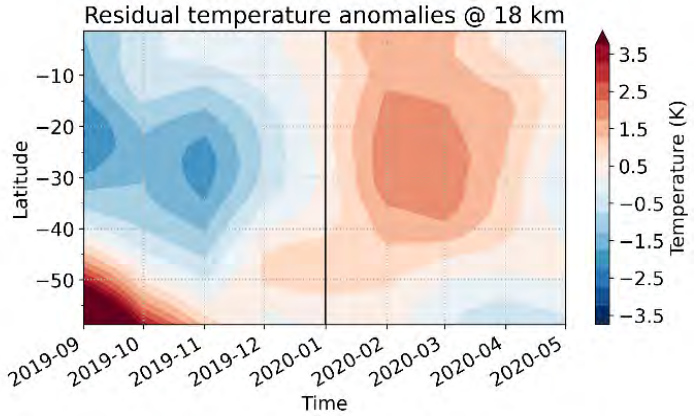


Temperature anomalies in first weeks of the Australian wildfires



Temperature anomalies before & after the wildfire events





- **Daily temperature anomalies during the first weeks collocated with aerosol plume**
- **Zonal temperature anomalies before & after the wildfire events**
- **Warming in the stratosphere**

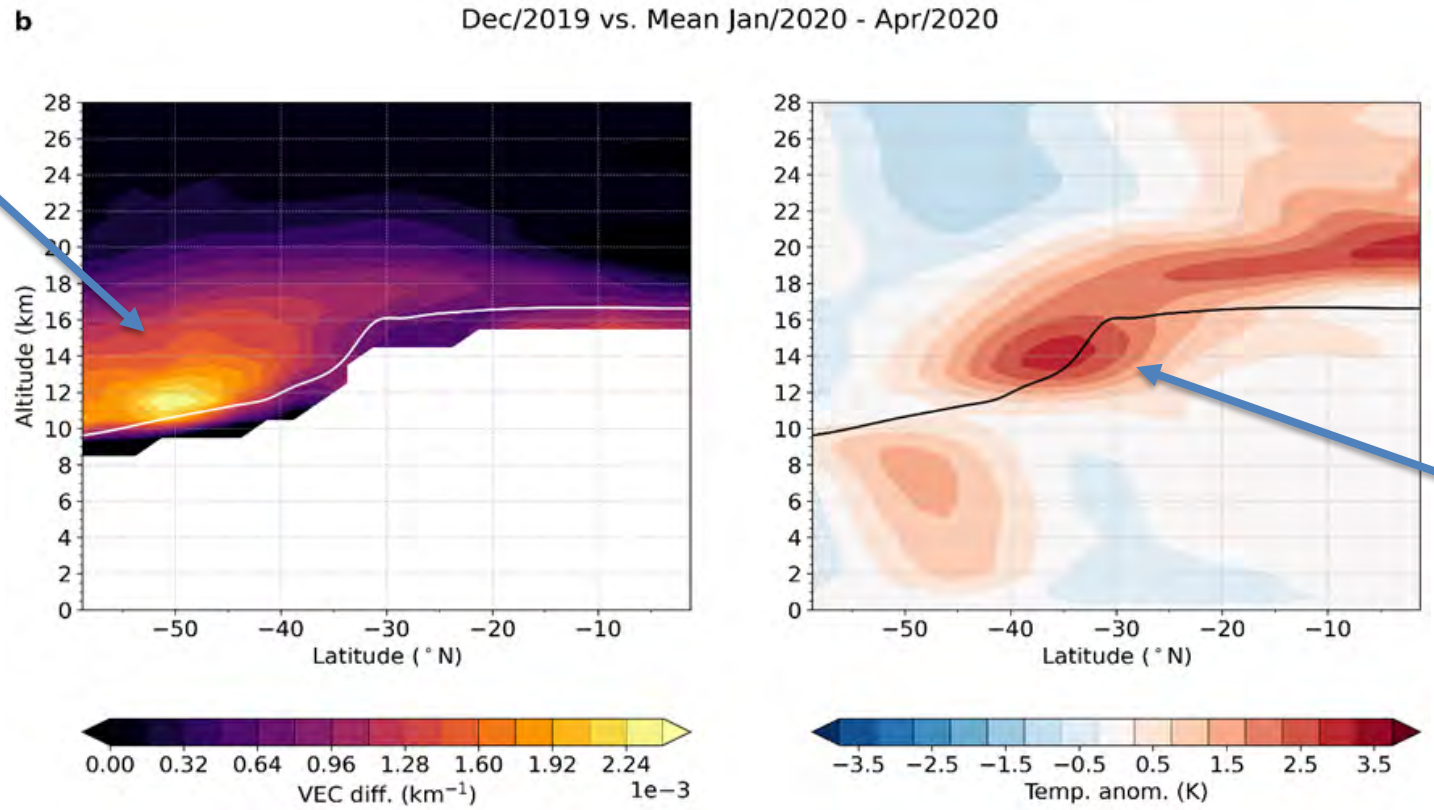
(Stocker et al. Sci Rep 2021)

Large Wildfires – Short-term Climate Impact

- **The Australian wildfires caused a warming of the stratosphere larger than any signal from recent volcanic eruptions**

Aerosol signal **not in line with** the maximum **warming**

Meridional **aerosol transport** / insolation



- **Maximum warming of more than 3 K**
- **Short-term climate signal lasting several months**

(Stocker et al., 2021)