COSMIC/JCSDA Workshop and IROWG-10
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Advances in using GNSS radio occultation for climate

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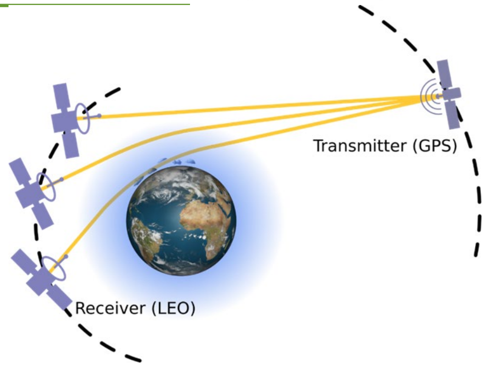
Atmospheric Variability, Extremes, and Climate Change

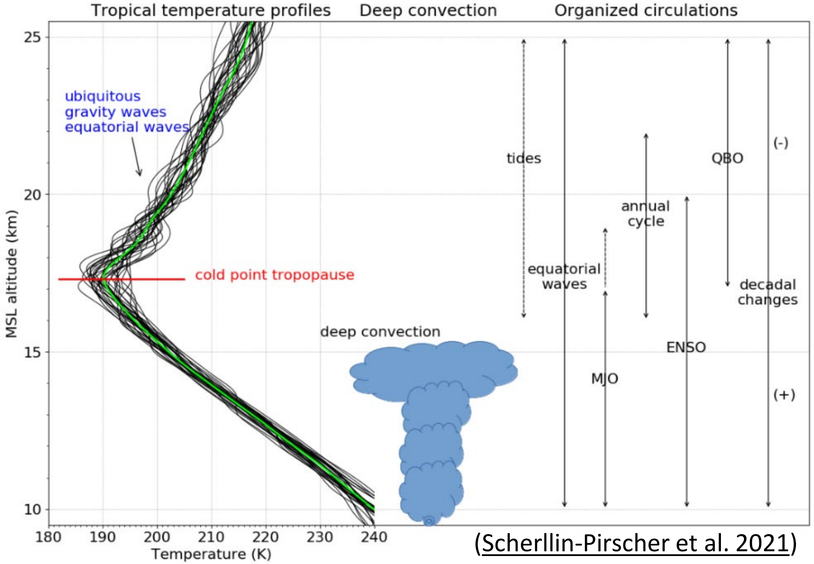


Troposphere – lower stratosphere region and tropopause region

- **Large variability in space and time**
- Relatively small vertical scales
- Small- to large-scale waves
- Diurnal to interannual time scales
- Decadal changes

GNSS RO provide atmospheric observations

- High vertical resolution
- Global coverage
- Long-term stability
- Low structural uncertainty

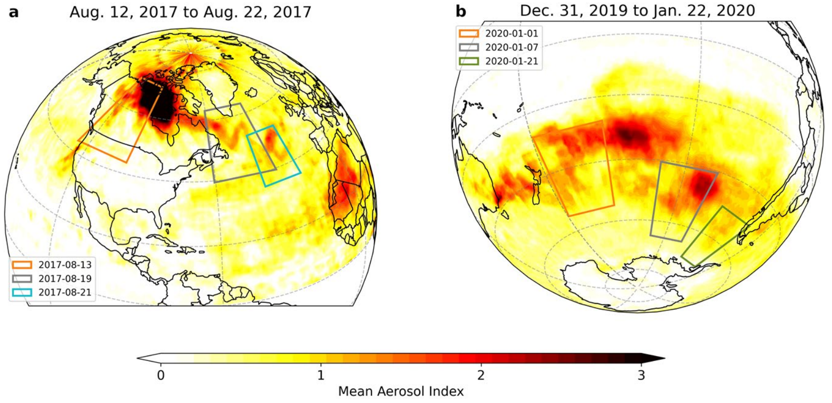


(Scherllin-Pirscher et al. 2021)

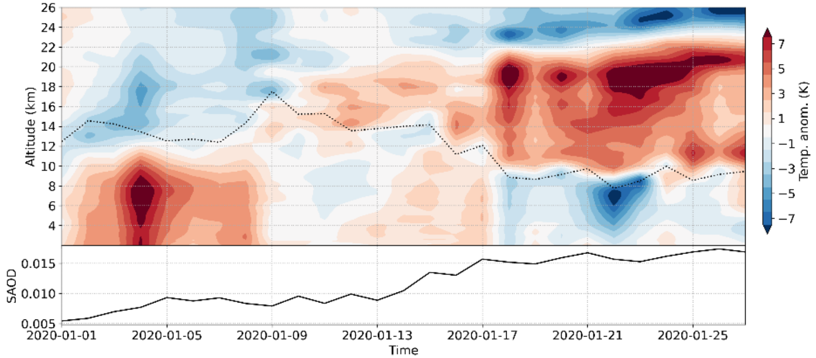
Climate Variability & Extremes – Large Wildfires

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

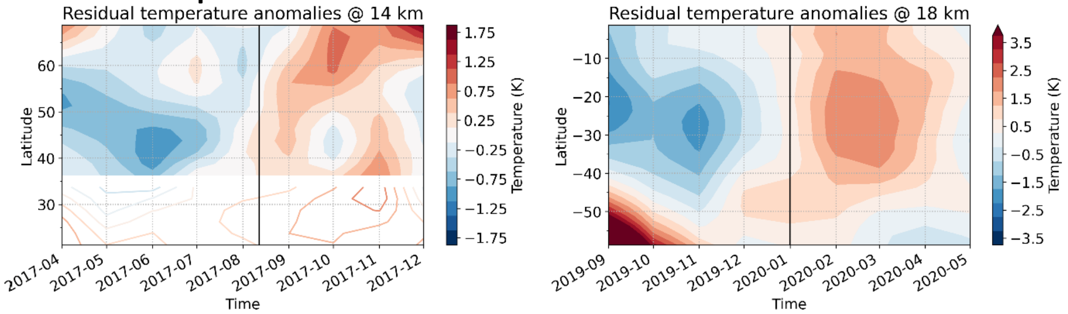
North America 2017 **Australia 2019/2020**



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**

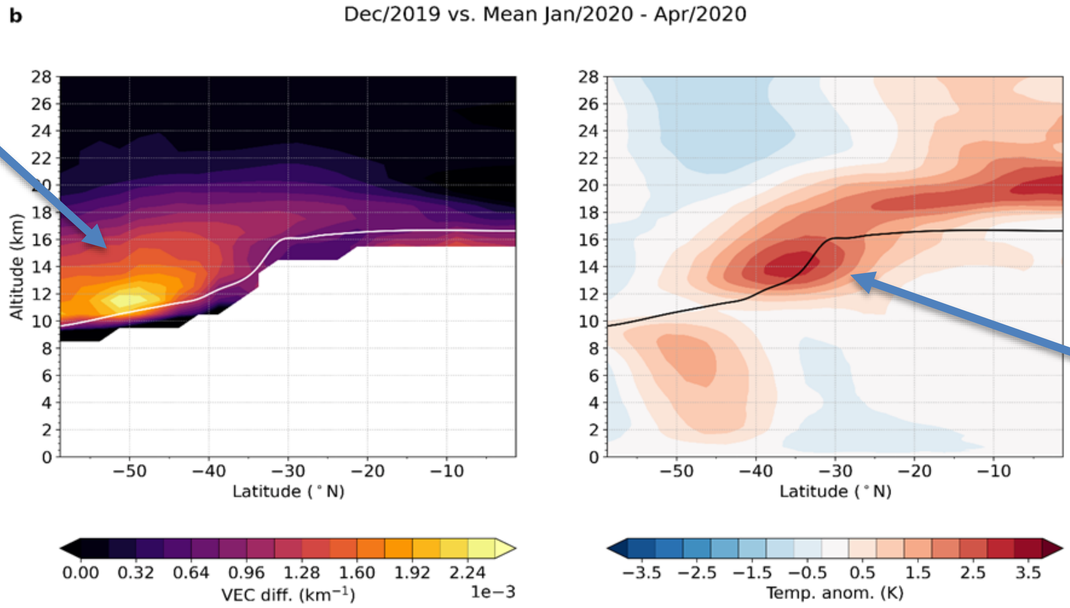
(Stocker et al. Sci Rep 2021)

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

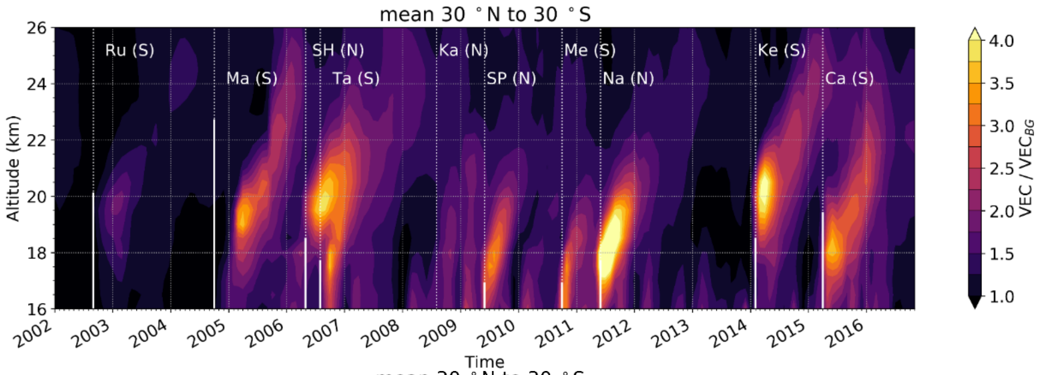


- **Maximum warming of more than 3 K**
- **Short-term climate signal lasting several months**

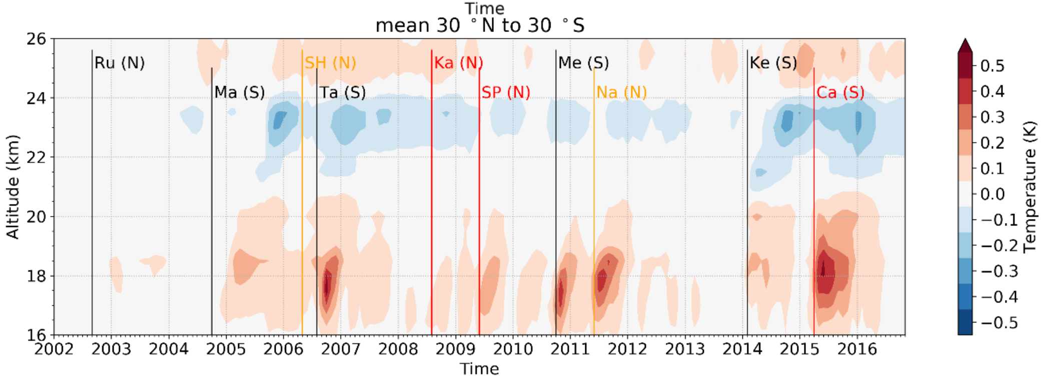
(Stocker et al., 2021)

Volcanic Eruptions – Short-term Climate Impact

- **Temperature variability due to volcanic aerosols in the lower stratosphere**
- **Signals from moderate volcanic eruptions can be detected with RO**



Calbuco Eruption in 2015 (Time.com, 2015)

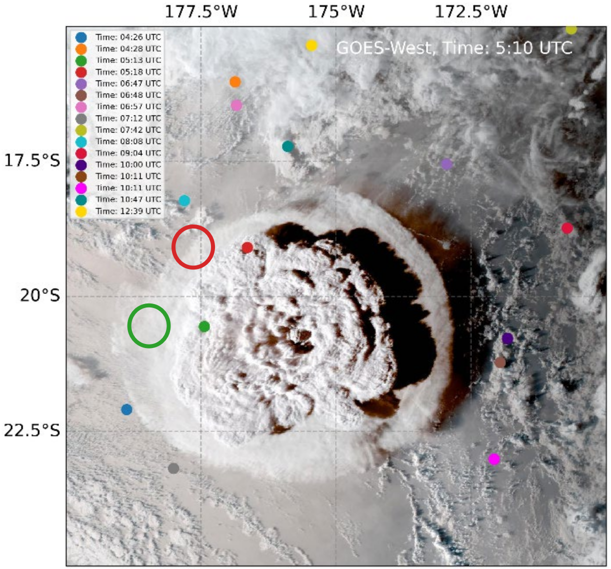


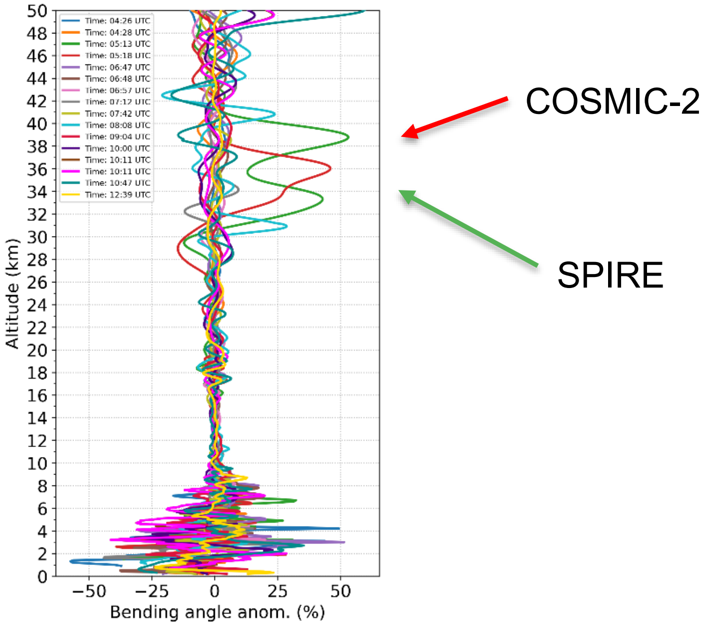
- Cooling at 20-24 km > increased upwelling of ozone-poor air after the eruptions
- **Warming signals in the lowermost stratosphere**
- Up to 0.5 K in the tropical mean

(Stocker et al. GRL 2019)

Climate Variability & Extremes – Hunga Volcano Eruption

- **Observed impacts of the Hunga eruption on stratospheric temperature**
- RO profiles co-located with the early volcanic plume: bending angle anomalies





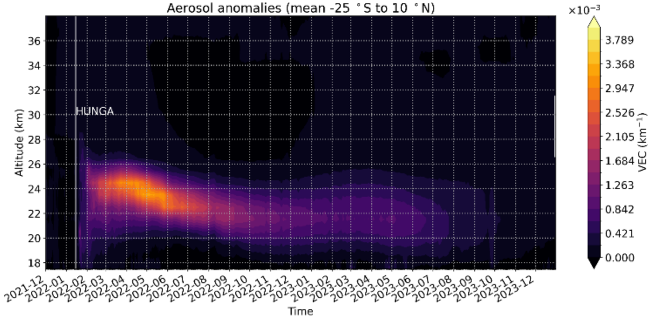
When: Jan. 15, 2022
VEI: 6 (approx.)
SO2 Mass: ~1.5 Mt (initial estim. 0.4–0.5 Mt)
Water Vapor: 50 Mt (hydration of the stratosphere ~50 km)

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

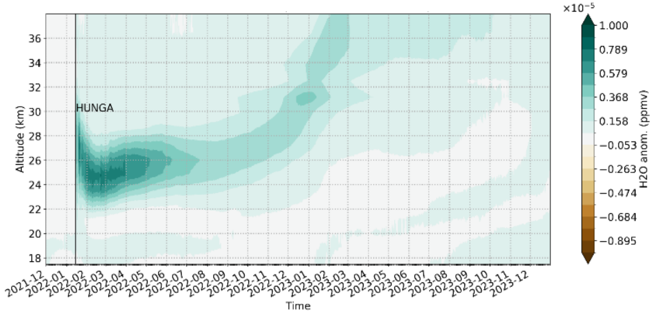
Hunga Volcanic Eruption – Short-term Climate Impact

- **Strong persistent 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

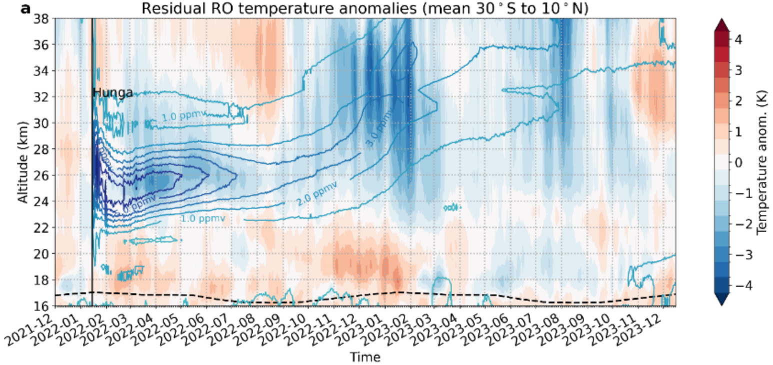


WATER VAPOR ANOMALIES



Minor impact due to aerosols

TEMPERATURE RESIDUAL ANOMALIES



Detection:

Strong cooling over 1.5 years due to water vapor injection

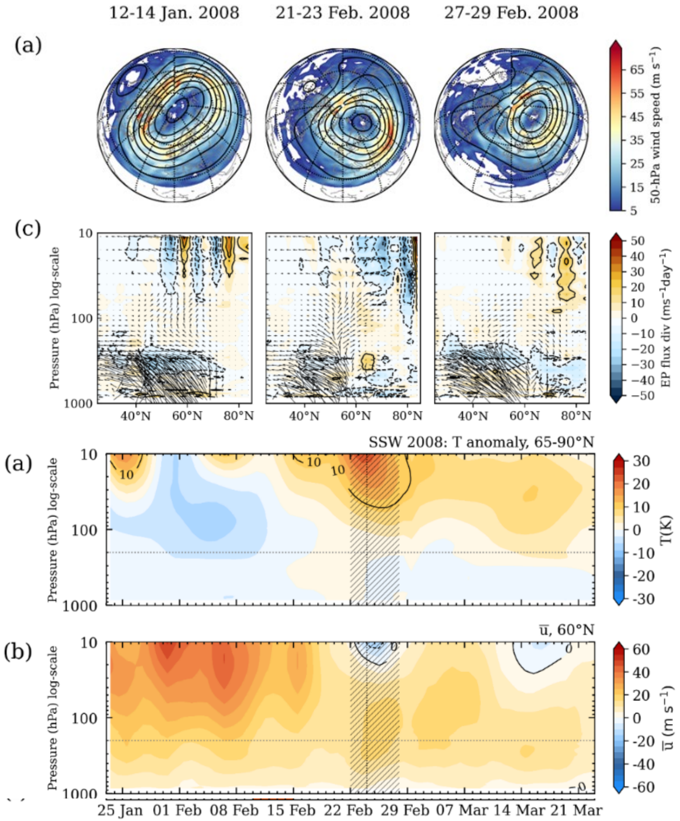
of Hunga into the stratosphere!

See Poster 24A

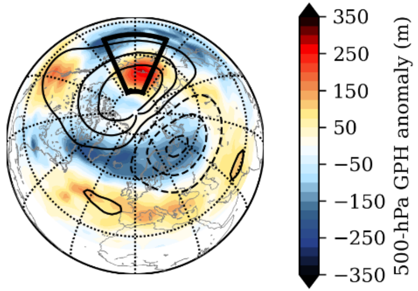
(Stocker et al., Commun. Earth Environ 2024)

Variability & Extremes – SSWs & Blocking from EP flux

- **SSWs & 2 types of downward dynamic interactions with emergence of blocking**



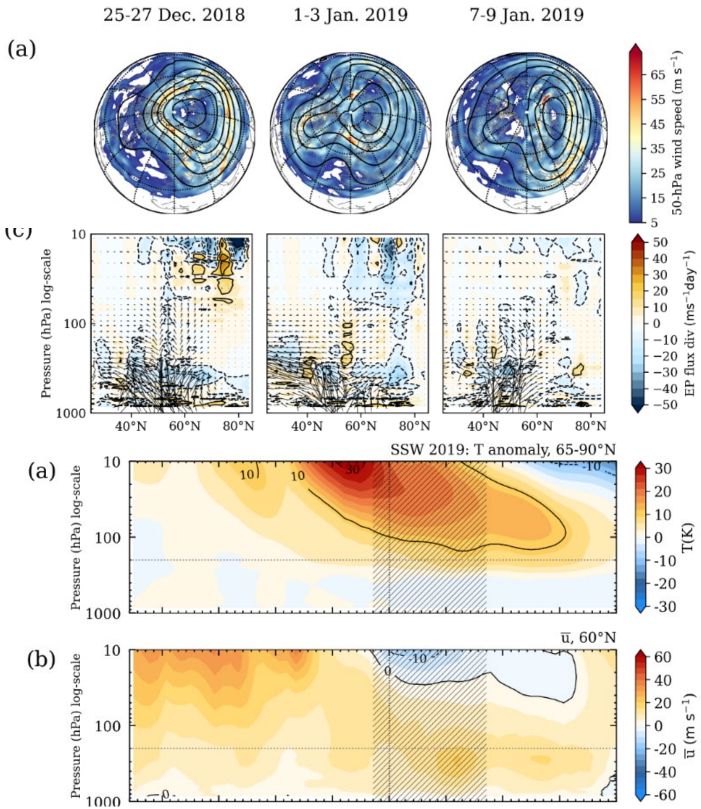
- **Winter 2008**
- **SSW type: displacement, reflecting event**
- **Displacement of the polar vortex** 22 Feb 2008
- Temperature anomaly maximum – short SSW
- Zonal wind reversal (at 60°N) for 6 days
- **Downward propagation of wave activity** (27-29 Feb 2008) from stratosphere to troposphere during vortex recovery
- **Blocking formation in the North Pacific region**



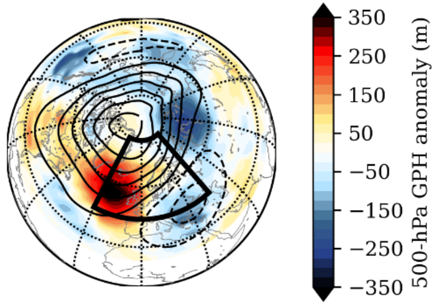
(Yessimbet et al., ACPD 2024 in press)

Variability & Extremes – SSWs & Blocking from EP flux

- **SSWs & 2 types of downward dynamic interactions with emergence of blocking**



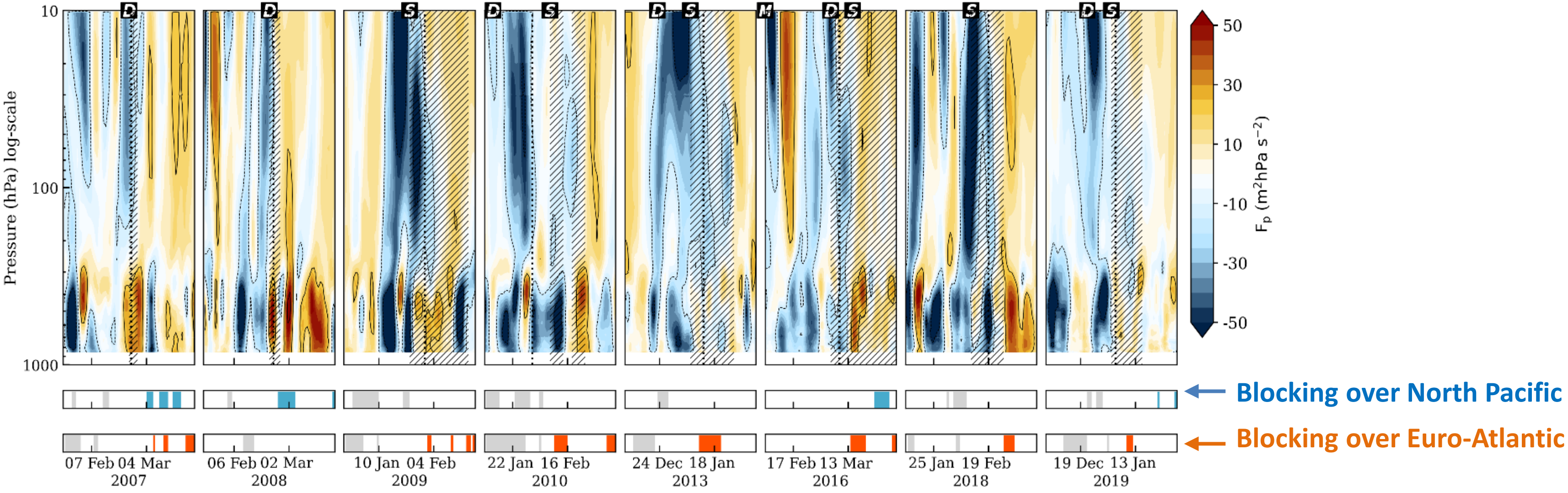
- **Winter 2019**
- **SSW type: vortex split, absorbing event**
- **Split of the polar vortex** 2 Jan 2019
- Long-lasting SSW
- Prolonged zonal wind reversal lasting weeks and upward propagation of the EP flux
- Wave absorption and the subsequent formation of **blocking in the Euro-Atlantic region**



(Yessimbet et al., ACPD 2024 in press)

Variability & Extremes – SSWs & Blocking

- **Vortex displacement (D), reflecting events: subsequent blocking in North Pacific region**
- **Vortex split (S), absorbing events: subsequent blocking in Euro-Atlantic region**

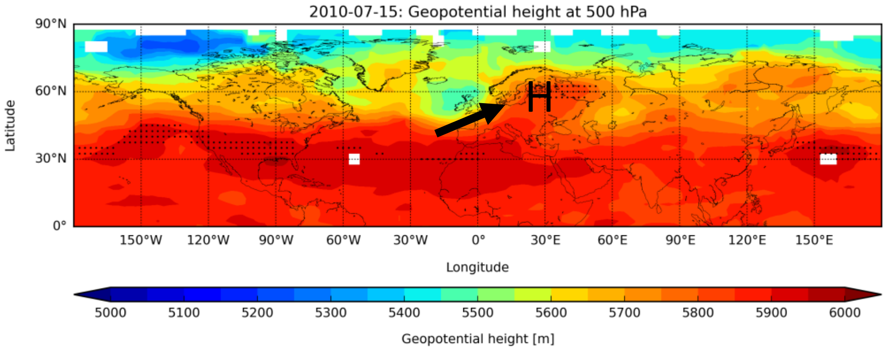


Time-height evolution of the anomaly of the **vertical component of the E-P flux** (45-75° N) for SSW events from 2007 to 2019.
Hatched regions: reversal of the zonal-mean zonal wind at 60° N and 10 hPa; dotted lines: start of SSW recovery phase.
D: vortex displacement, S: vortex split
Lower panels: blocking over North Pacific (blue) and Euro-Atlantic region (orange)

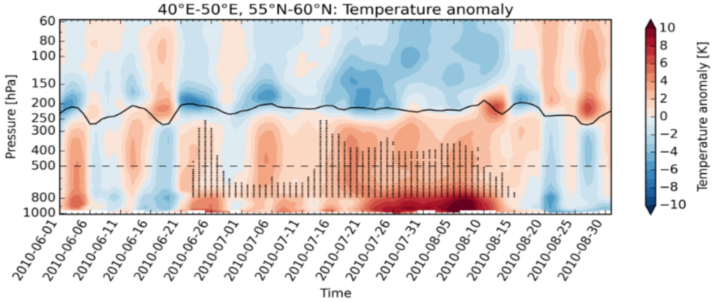
(Yessimbet et al., ACPD 2024 in press)

Climate Variability & Extremes – Atmospheric Blocking

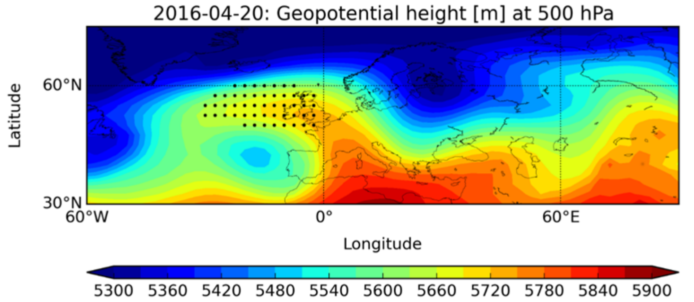
- Blocking over Europe in Summer > **Hot extremes**

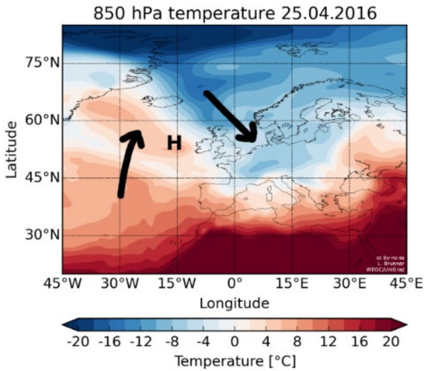


Heat Wave in Russia 2010



- Blocking over Atlantic in Winter/Spring > **Cold Extremes**





Spring frost in Austria & SE-Europe 2016

(Brunner et al. ACP 2016; Brunner and Steiner AMT 2017; Unterberger et al. PLoS ONE 2018)

Observing Extremes to Long-term Climate Changes

World Climate Research Programme

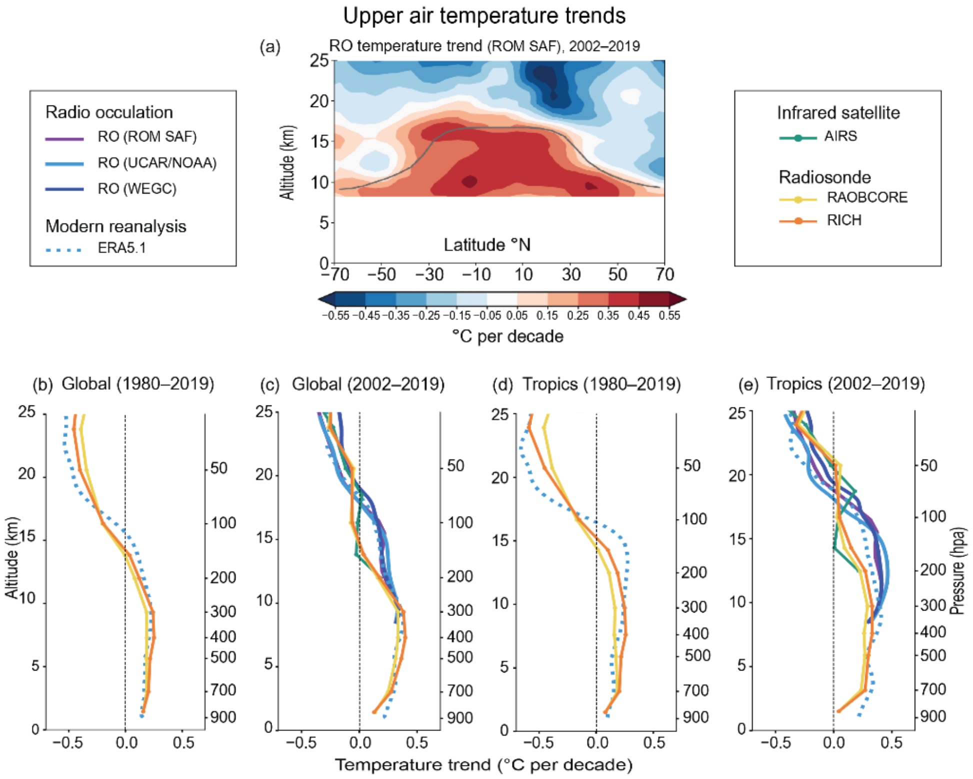
- Core Projects and Lighthouse Activities
- Analysis and prediction of Earth system variability and change
- Climate knowledge that contributes to societal well-being
- UNFCC–IPCC, 2030 Agenda for SD, Disaster risk reduction

APARC Activity on Atmospheric Temperature Changes & their Drivers (ATC)

- Improving atmospheric observational records
- Assessment of atmospheric temperature variability & trends
- Attribution of atmospheric changes to radiative & dynamical drivers

RO Climate Records in the IPCC Report 2021

- **IPCC AR6 WG I Chapter 2**



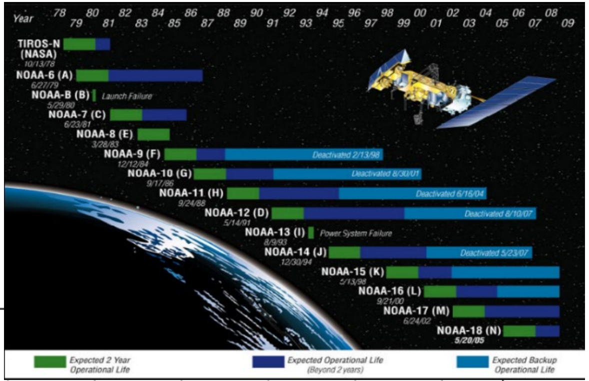
- *"The **troposphere has warmed since at least the 1950s, and it is virtually certain that the stratosphere has cooled.***
- *In the **tropics**, the **upper troposphere has warmed faster than the near-surface since at least 2001**, the period over which **new observation techniques permit more robust quantification** (medium confidence).*
- *It is **virtually certain that the tropopause height has risen globally over 1980–2018**, but there is **low confidence in the magnitude**."* (IPCC WG1 AR6,2021).

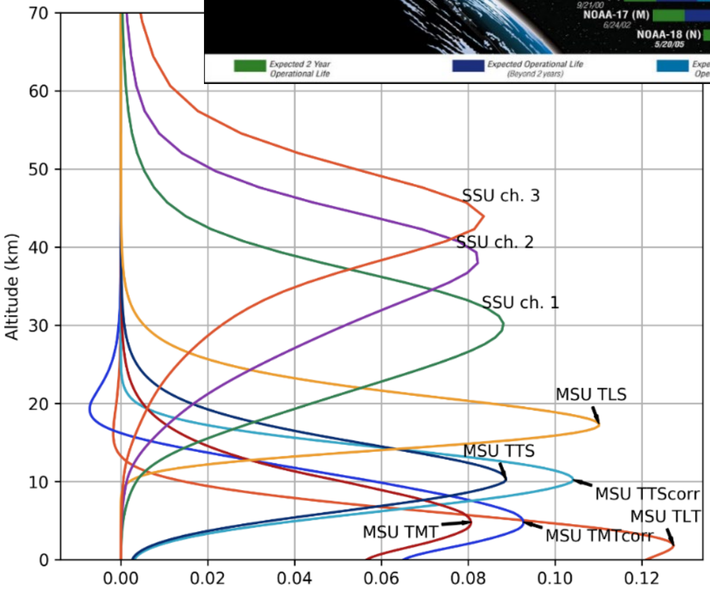
(IPCC, 2021; Fig. 2.12)

Atmospheric Temperature Observations

Layer average temperature records

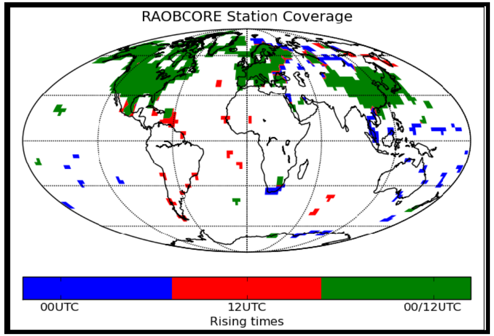
- **Nadir sounders**
- Stratospheric Sounding Unit (SSU)
  Microwave Sounding Unit (MSU), AMSU, ATMS
- Need calibration, corrections
- **Merged series** since 1979





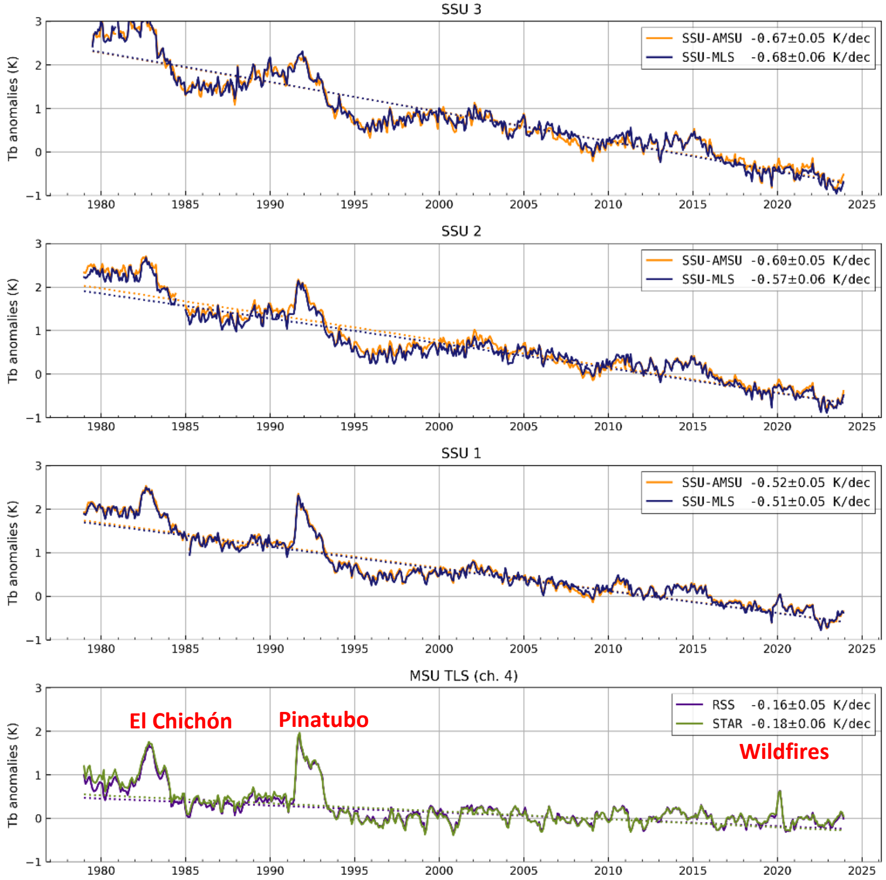
Vertical-resolved temperature records

- Radiosondes since 1958
  Long time series
  Limited spatial coverage
- GNSS RO since 2002
- MLS since 2005



Stratospheric Temperature Trends 1979–2023

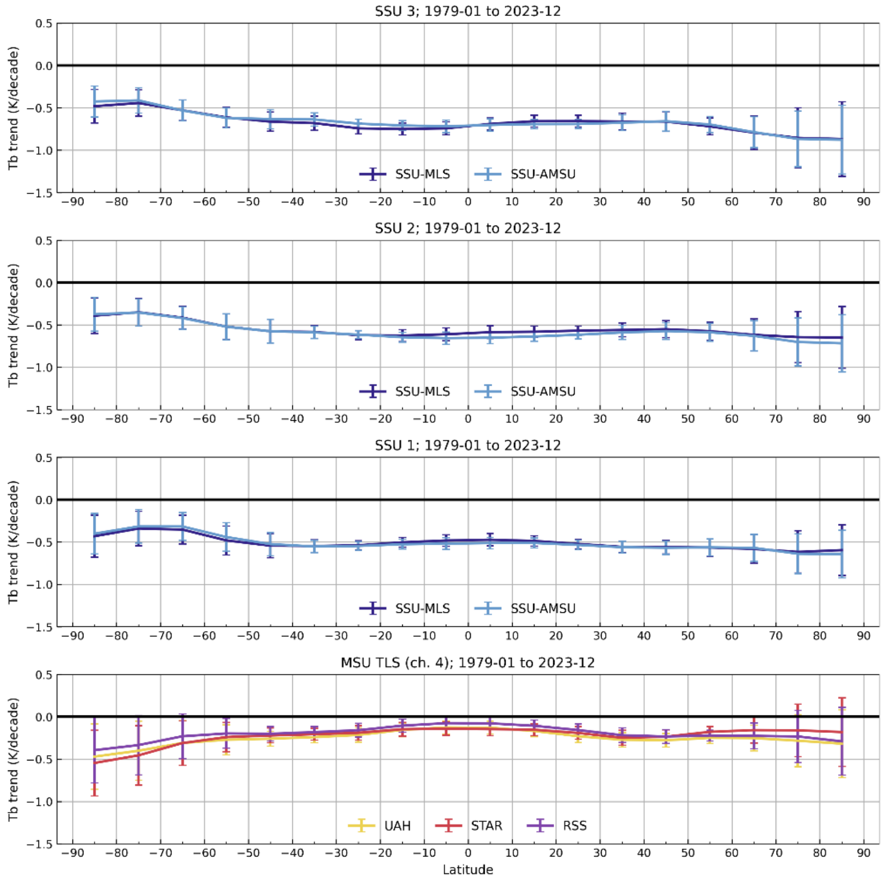
- Merged SSU-MLS, SSU-AMSU
- Merged MSU4-AMSU9 (TLS)
- Multiple linear regression
- **Stratospheric cooling**
- **Magnitude increases with height**
- **Stratospheric trends 1979-2023**
  -0.7 K/dec at 40-50 km
  -0.6 K/dec at 35-45 km
  -0.5 K/dec at 25-35 km
  -0.17 K/dec at 13-22 km



(Steiner et al., JCLI 2020, updated)

Latitude-resolved Stratospheric Trends 1979–2023

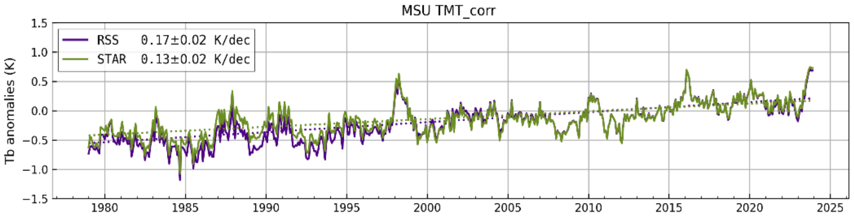
- Merged SSU-MLS, SSU-AMSU, TLS
- **Latitude-resolved trends 1979-2023**
- Multiple linear regression
- Largest trends at northern high lats
- Smaller trends at southern high lats
- Larger uncertainty at high latitudes due to larger variability

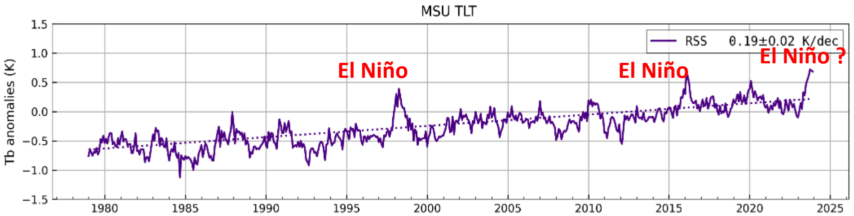


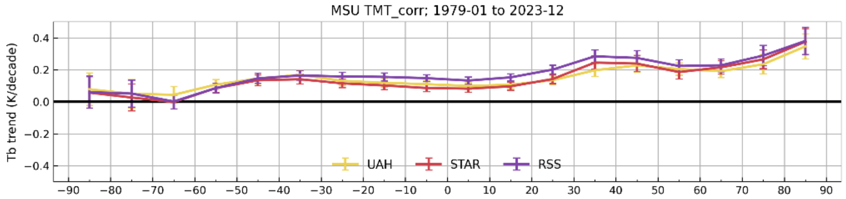
(Steiner et al., JCLI 2020, updated)

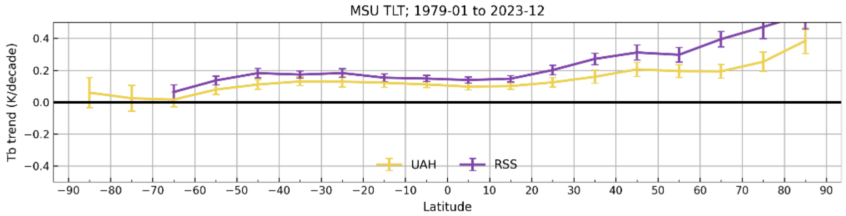
Tropospheric Temperature Trends 1979–2023

- Merged MSU-AMSU channels
- TTS: MSU3+AMSU7
  TMT: MSU2+AMSU5
  corrected for stratospheric contrib.
- Multiple linear regression
- **Tropospheric warming trends 1979-2023**
  +0.1 K/dec for TTScorr
  +0.15 K/dec for TMTcorr
  +0.2 K/dec for TLT
- Warming over all latitudes
  Largest warming at northern high lats



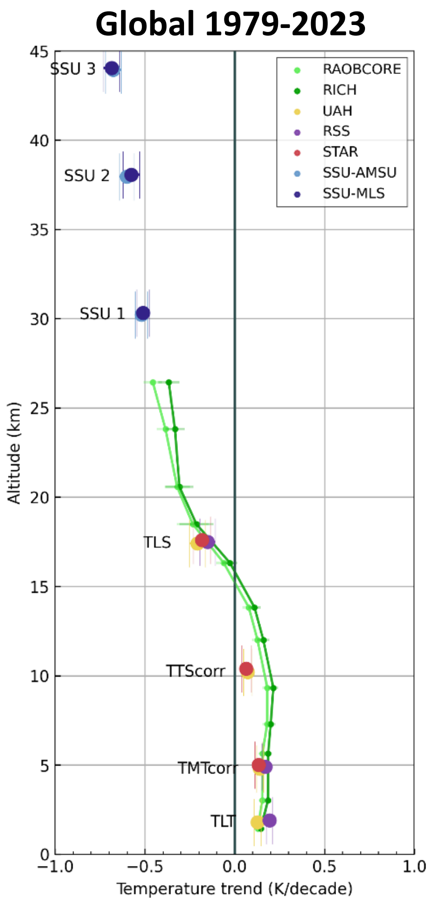


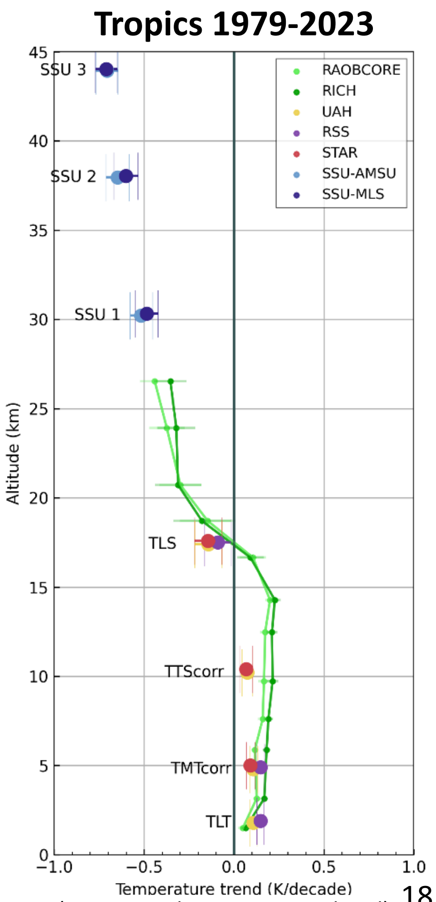




Vertical-resolved Trends 1979–2023

- Merged SSU and AMSU/MLS
- Merged MSU/AMSU
- **Radiosondes RICHv1.9, RAOBCOREv1.9**
- **Significant stratospheric cooling**
  1979-2023 of –0.2 to –0.7 K/dec
- **Significant tropospheric warming**
  1979-2023 of ~0.2 K/dec

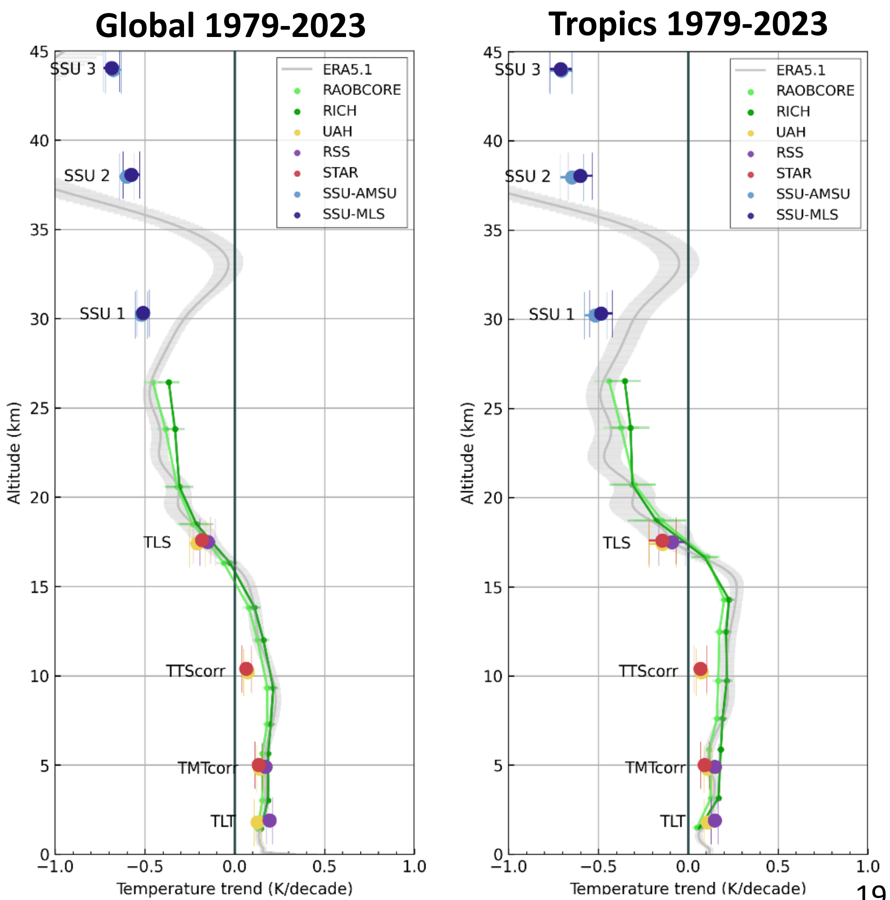




(Steiner et al., JCLI 2020, updated)

Vertical-resolved Trends 1979–2023

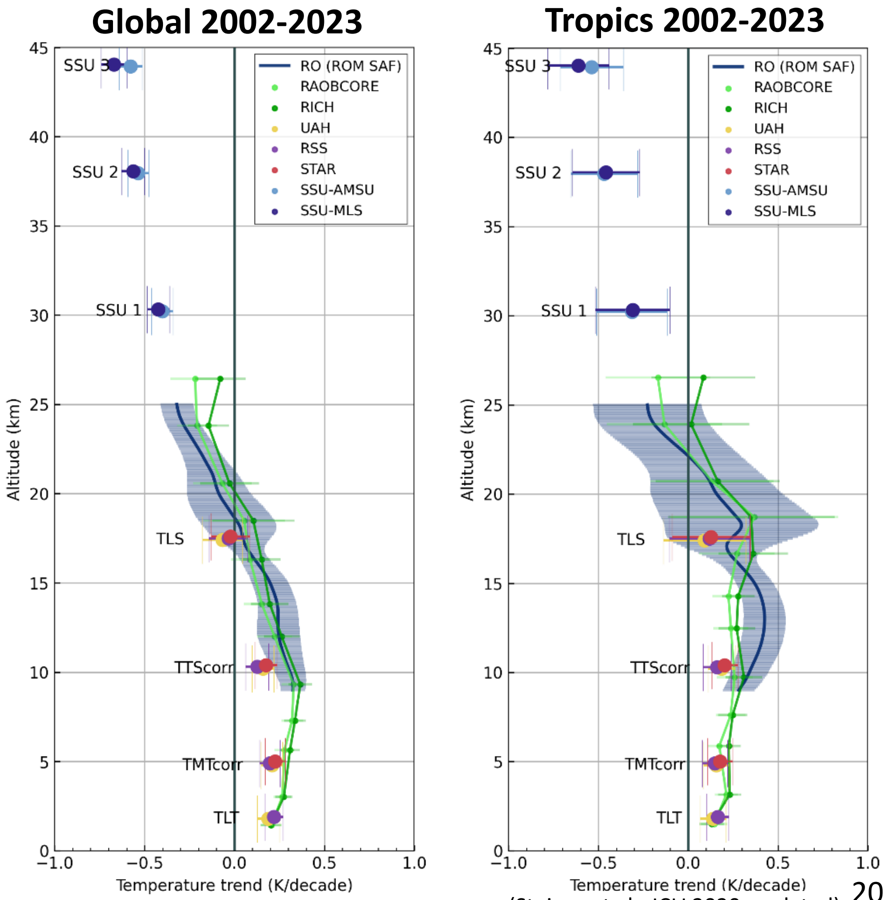
- Merged SSU and AMSU/MLS
- Merged MSU/AMSU
- Radiosondes RICHv1.9, RAOBCOREv1.9
- **ERA5**



(Steiner et al., JCLI 2020, updated)

Vertical-resolved Trends 2002–2023

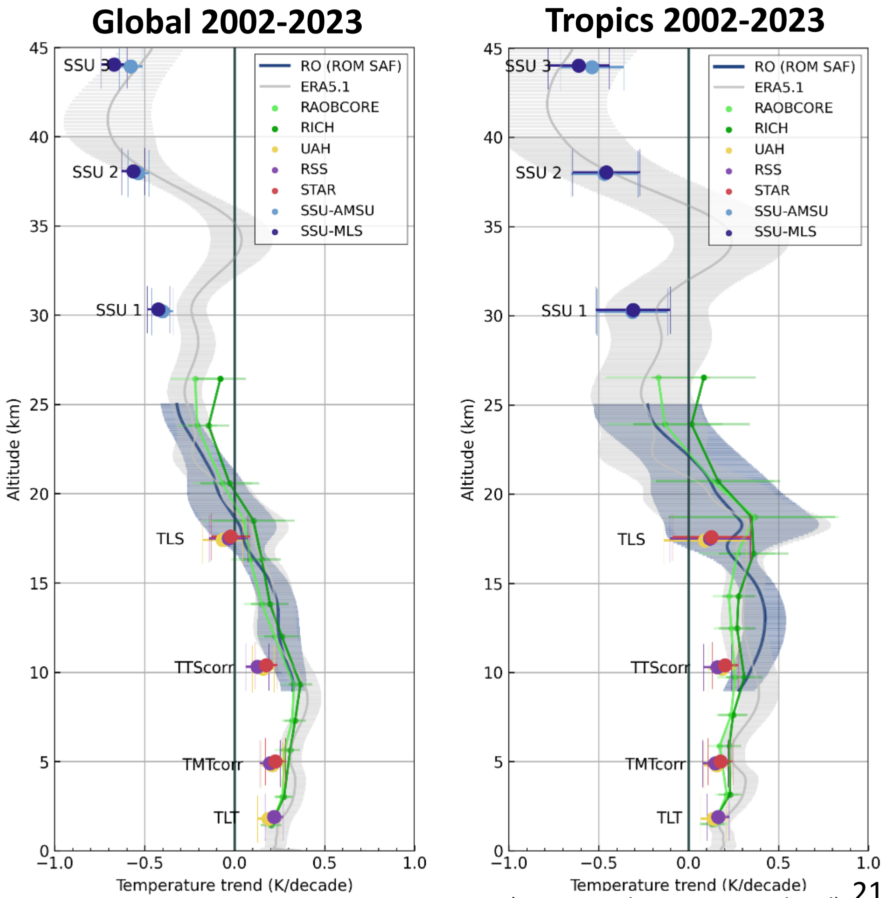
- Merged SSU-AMSU/MLS, MSU/AMSU
- Radiosondes RICHv1.9, RAOBCOREv1.9
- **Radio Occultation consistent with RS**
- **MSU/AMSU smaller trends in MT to UT**
- Significant stratospheric cooling 2002-2023 of up to –0.7 K/dec
- **Significant tropospheric warming 2002-2023 of 0.2 to 0.4 K/dec**
- **Tropical upper tropospheric warming**
- **Tropical lowermost stratosphere warms**
- **Transition warming to cooling shifted up**



(Steiner et al., JCLI 2020, updated)

Vertical-resolved Trends 2002–2023

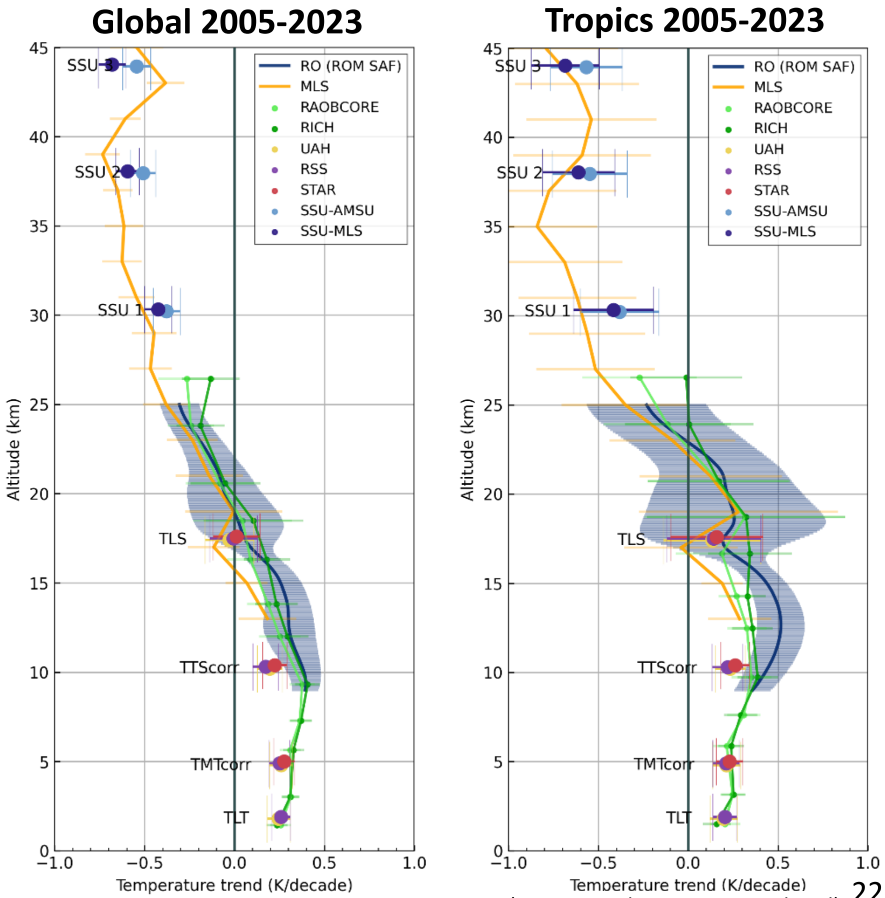
- Merged SSU and AMSU/MLS
- Merged MSU/AMSU
- Radiosondes RICHv1.9, RAOBCOREv1.9
- **Radio Occultation**
- **ERA5 consistent in the troposphere and near SSU levels in the stratosphere**



(Steiner et al., JCLI 2020, updated)

Vertical-resolved Trends 2005–2023

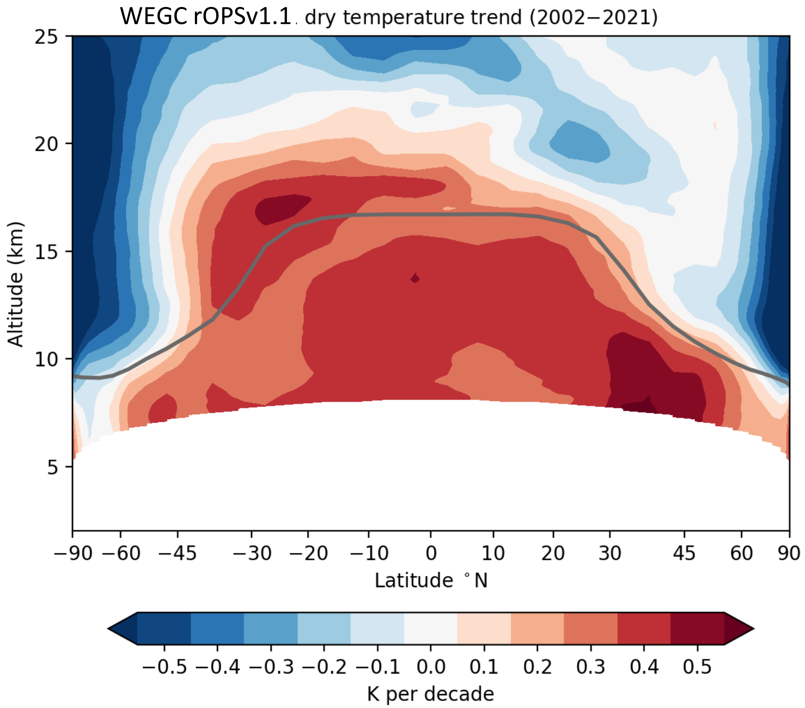
- Merged SSU and AMSU
- Merged MSU/AMSU
- Radiosondes RICHv1.9, RAOBCOREv1.9
- **Radio Occultation**
- **MLS v5 consistent within uncertainties**

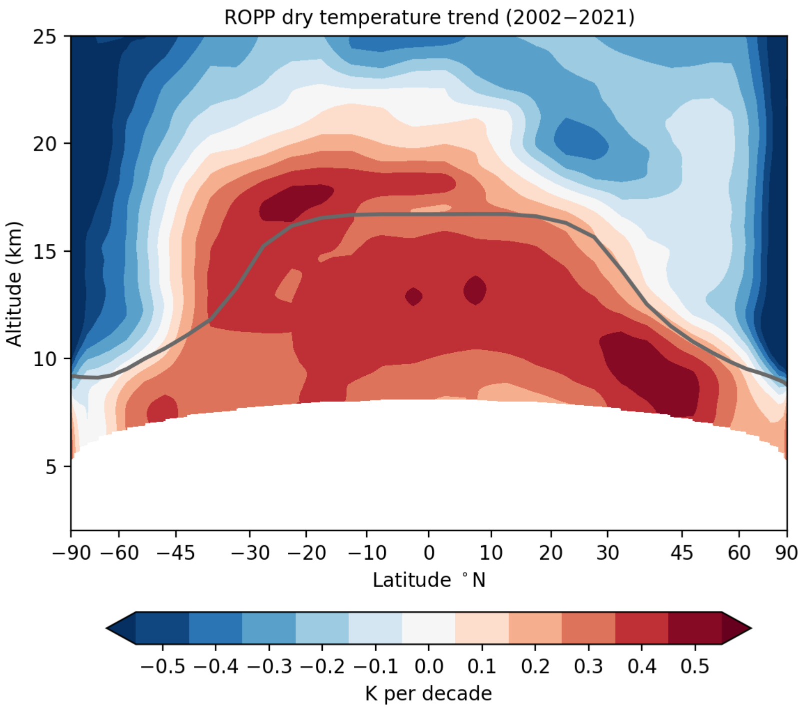


(Steiner et al., JCLI 2020, updated)

Height-latitude-resolved Temperature Trends 2002–2021

- **RO observations: Strong warming in tropical UTLS and SH subtropics**
- **WEGC rOPSv1.1 climate record** consistent with ROPP climate record

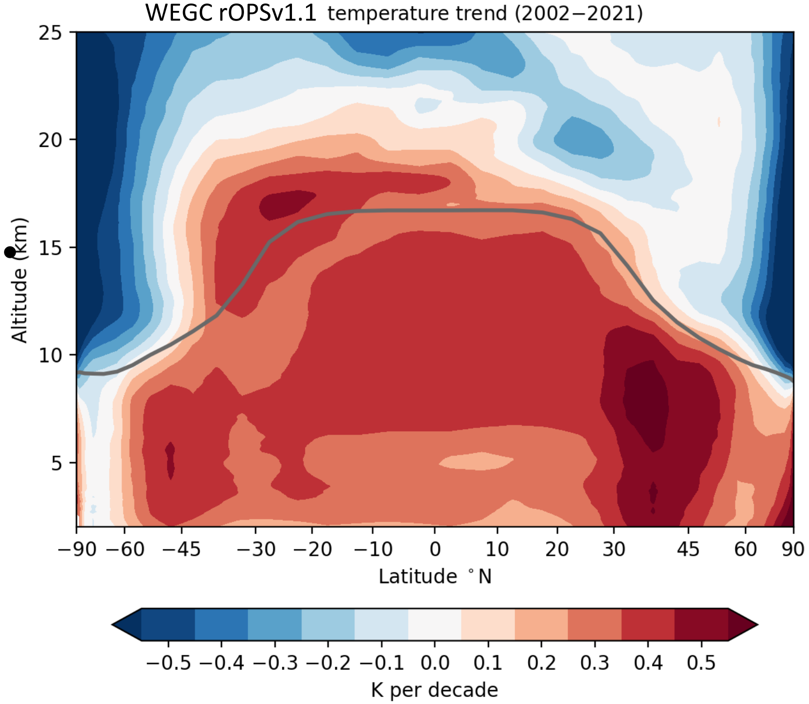


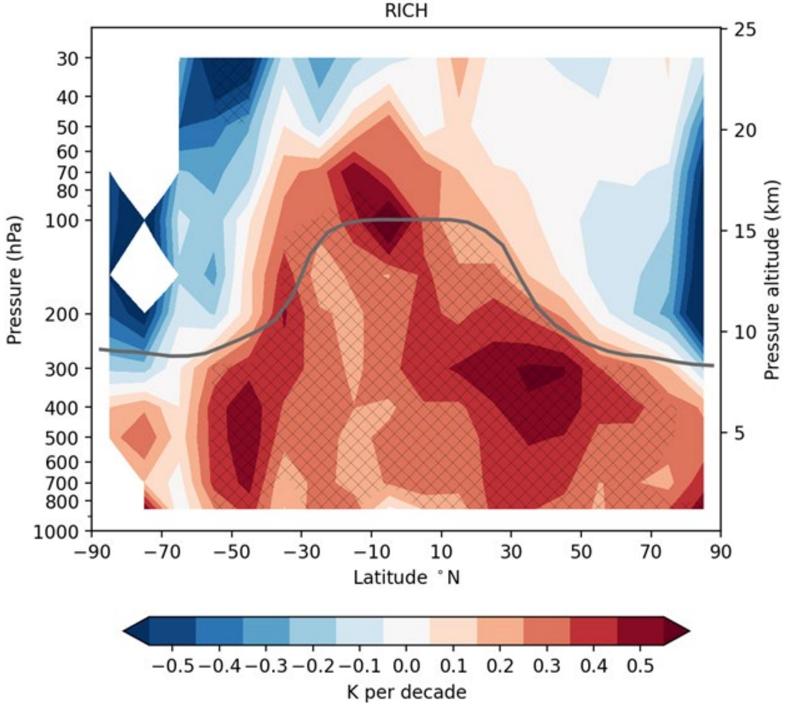


(Ladstädter et al. 2023; update with new WEGC rOPSv1.1 record; see presentation of Marc Schwärz Fri. 13.09.2024 on rOPSv1.1 results)

Height-latitude-resolved Temperature Trends 2002–2021

- **Strong warming in tropical UTLS and SH subtropics**
- **WEGC rOPSv1.1 consistent with radiosondes**, radiosondes sparse in tropics and SH

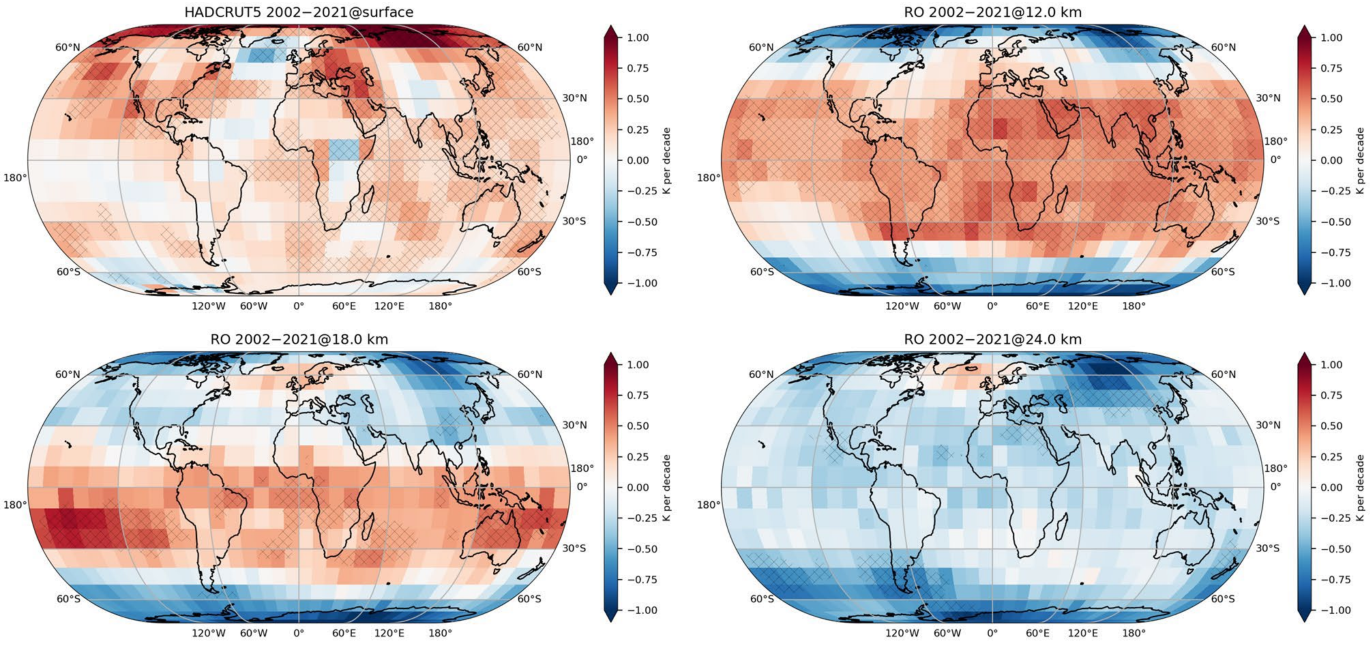




(see presentation of Marc Schwärz Fri. 13.09.2024 on rOPSv1.1 results)

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**

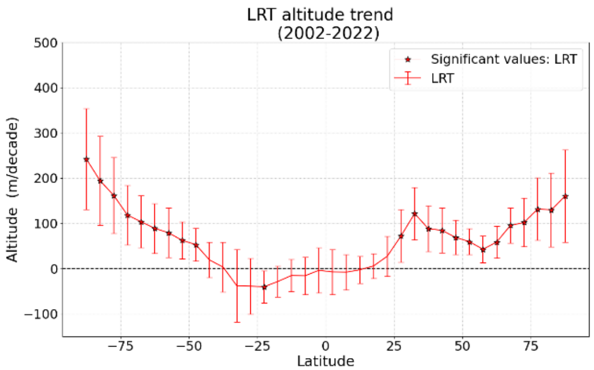


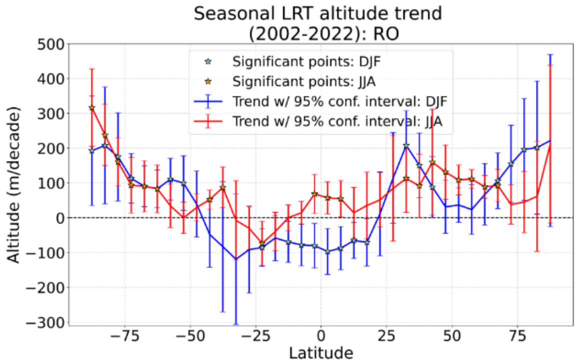
(Ladstädter et al. 2023)

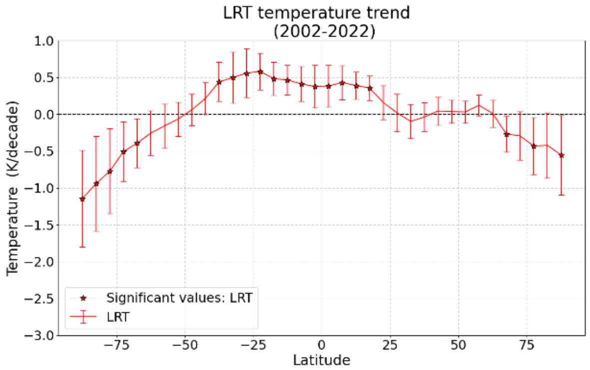
Tropopause Change

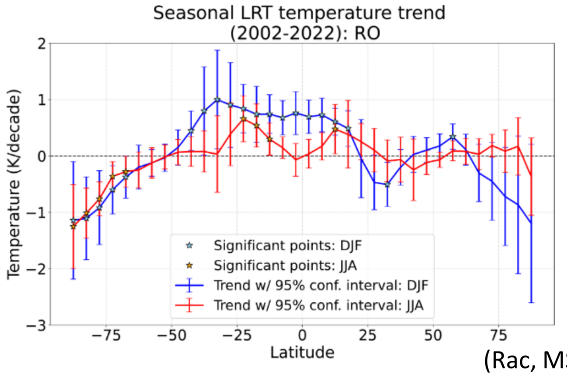
Wegener Center
UNI GRAZ

- **Increase in LRT height & decrease in temperature at mid- to high latitudes**
- **Increase in LRT temperature in tropics,** altitude shows different trends in DJF and JJA







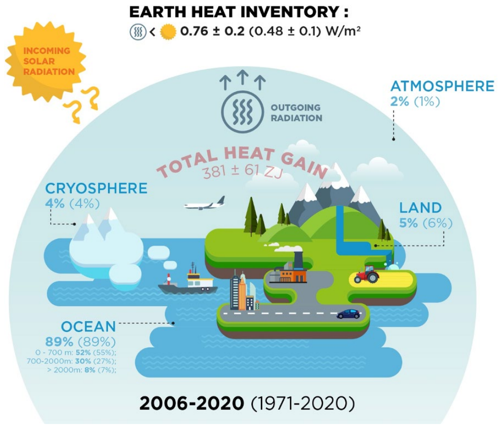


(Rac, MSc thesis 2024, paper in prep.)

GNSS RO – challenges ahead

Preparations for the next IPCC climate report and challenges ahead require a focus on:

- **Production and publication of new/reprocessed RO climate data records** and validation, including the **measurements from recent RO missions**
- **Provision of climate variables and climate indicators**
- Contributing to better **understanding of Earth's changing climate, e.g.,**
  - atmospheric processes and dynamics
  - atmospheric trends and their causes
  - climate feedbacks and Earth's energy imbalance
  - changes and impacts of extremes



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