EUMETSAT – ROM SAF – C3S Satellite ECVs
Online Workshop 2020
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GNSS RO for monitoring atmospheric climate change

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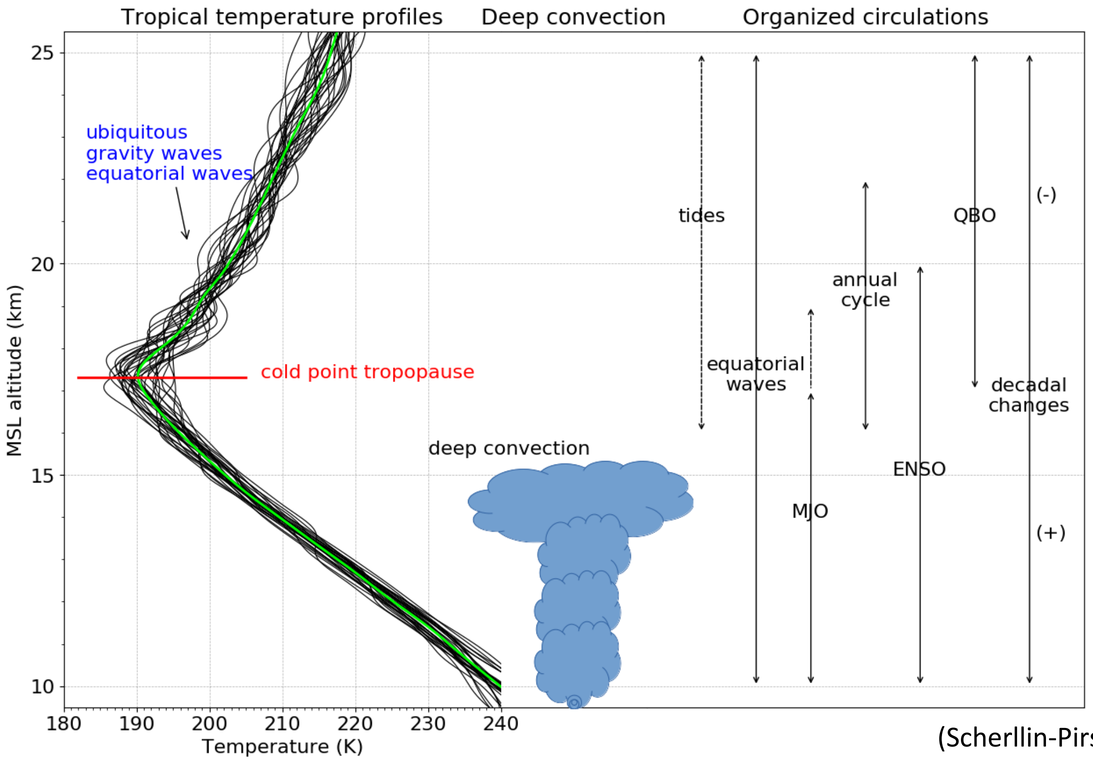
Monitoring Climate Variability

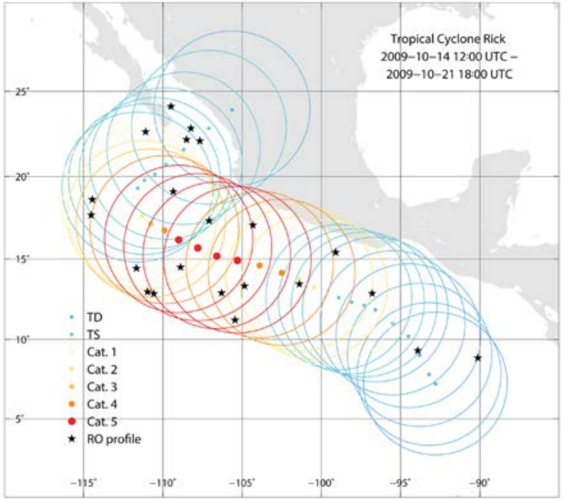
- **Tropical UTLS – large variability in space and time** with relatively small vertical scales, ranges from diurnal to interannual time scales, large-to small-scale waves

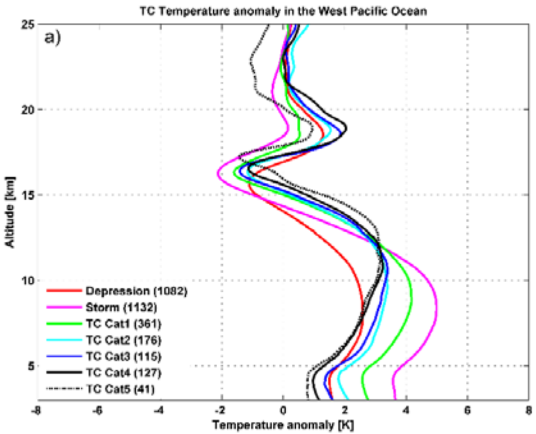


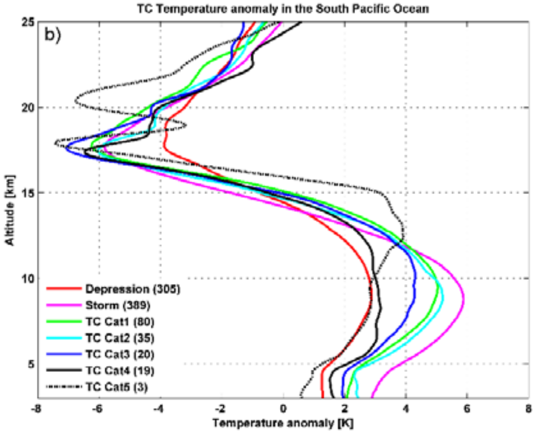
(Scherllin-Pirscher et al. JCLI 2020 in press)

Monitoring Climate Variability – Example Cyclones

- **Convective clouds & tropical cyclones –** vertical thermal structure & cloud tops



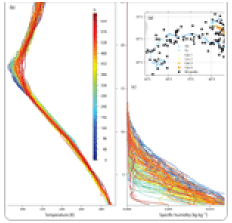




(Biondi et al. ACP 2015)

Tropical cyclones vertical structure from GNSS radio occultation: an archive covering the period 2001–2018

Elżbieta Lasota[1,2], Andrea K. Steiner[3,4], Gottfried Kirchengast[3,4], and Riccardo Biondi[2]

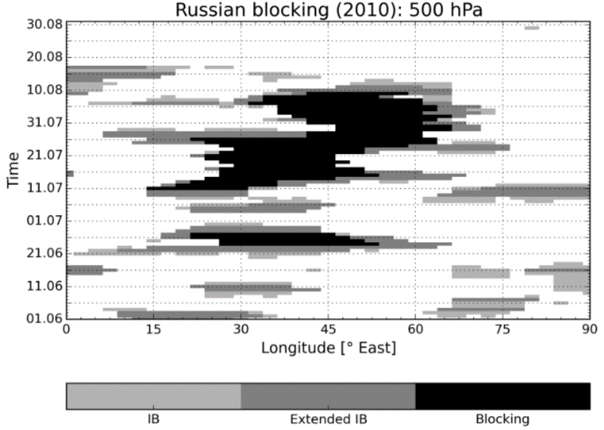


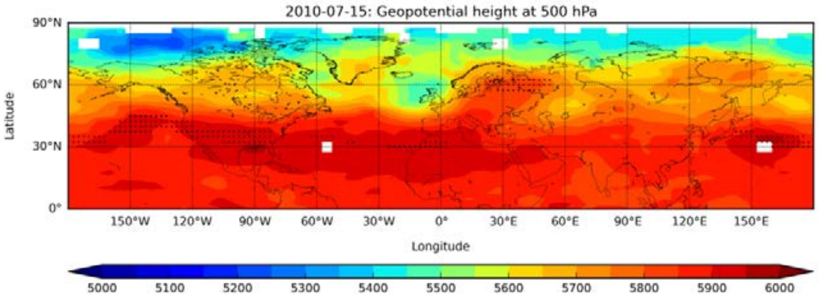
(Lasota et al. 2020; https://doi.org/10.5194/essd-12-2679-2020)

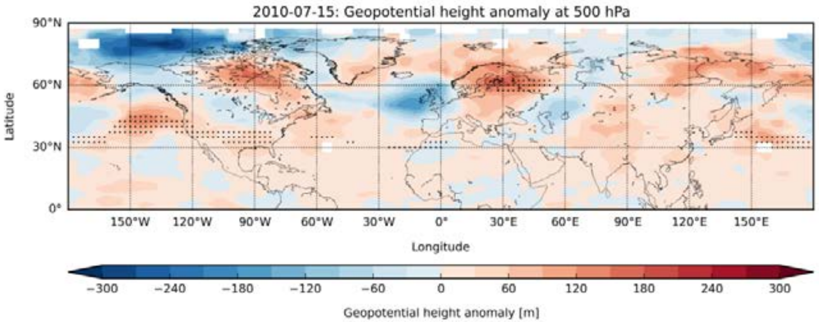
Monitoring Climate Variability – Atmospheric Blocking

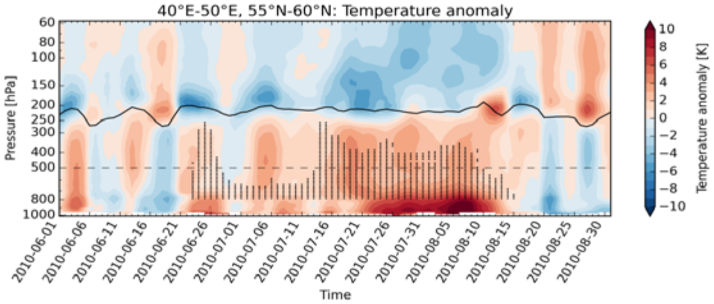
- **Blocking detection** at 500 hPa geopot. height
- Detection possible using full COSMIC coverage

“Russian Blocking” of Jul-Aug 2010 led to an extreme heat wave







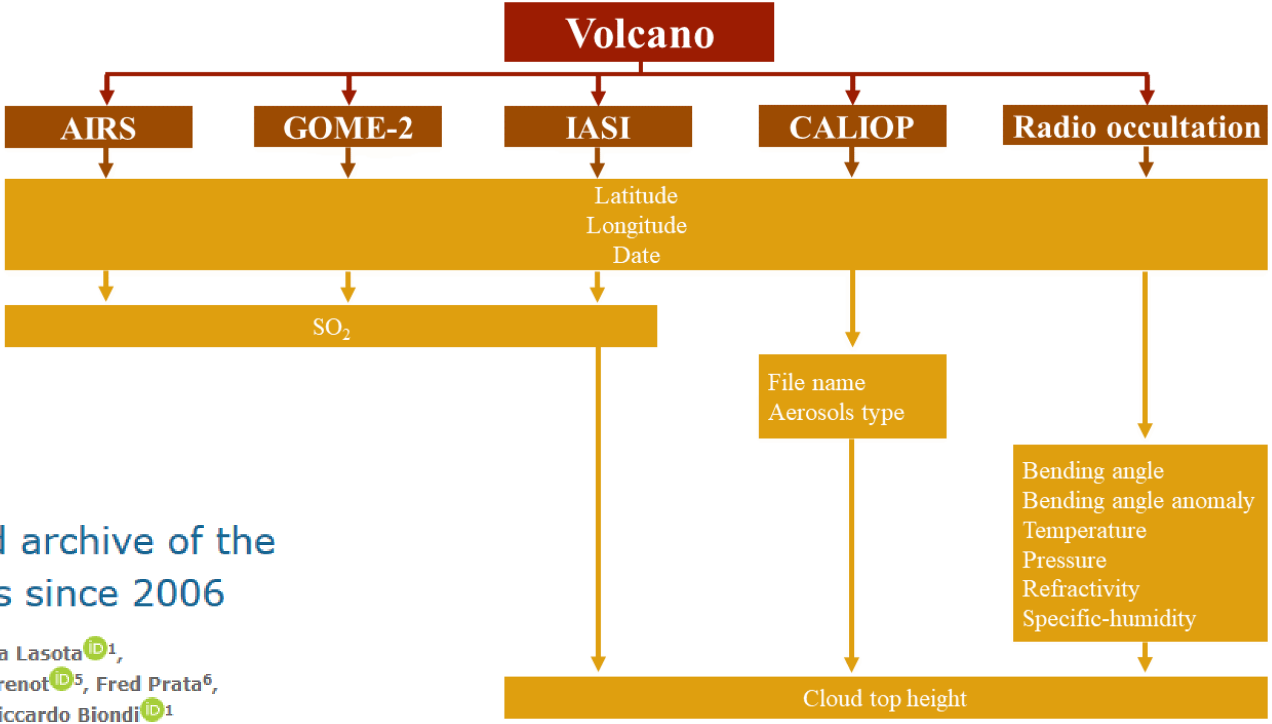


(Brunner et al. ACP 2016; Brunner and Steiner AMT 2018)

Monitoring Climate Variability – Example Volcanic Clouds

- **Volcanic clouds –** vertical thermal structure & climate impact

Calbuco Eruption in 2015 (Time.com, 2015



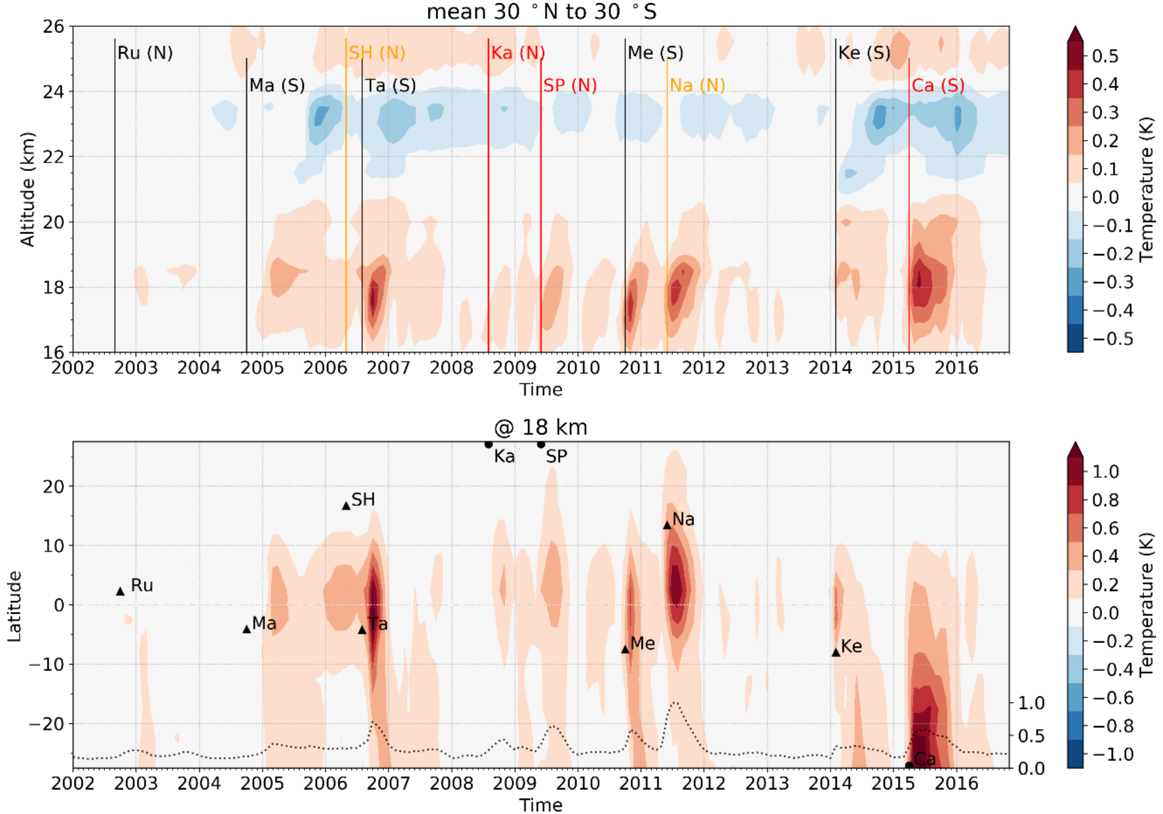
A multi-sensor satellite-based archive of the largest SO_2 volcanic eruptions since 2006

Pierre-Yves Tournigand[1], Valeria Cigala[2], Elzbieta Lasota[1], Mohammed Hammouti[3], Lieven Clarisse[4], Hugues Brenot[5], Fred Prata[6], Gottfried Kirchengast[7], Andrea K. Steiner[7], and Riccardo Biondi[1]

(Tournigand et al. 2020, https://doi.org/10.5194/essd-12-3139-2020)

Monitoring Climate Variability – Volcanic Signals post2000

- **Temperature variability due to volcanic aerosols in lower stratosphere**



▶ Cooling at 20-24 km > increased upwelling of ozone-poor air after the eruptions

▶ **Warming signals in the lowermost stratosphere**

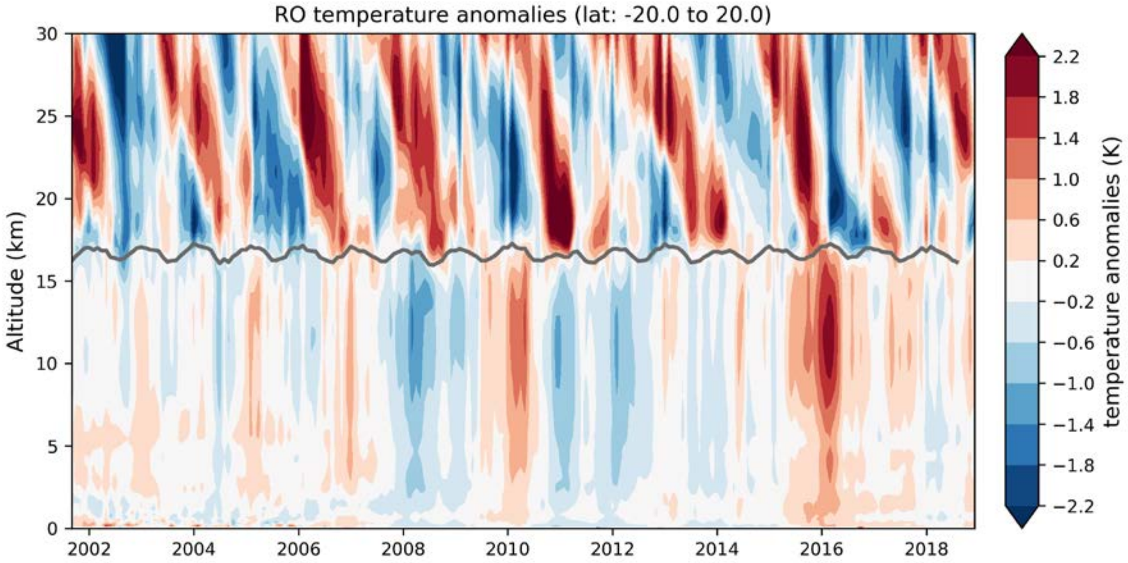
▶ Up to 0.5 K in the tropical mean

▶ Calbuco signal in extratropics

(Stocker et al. GRL 2019)

Monitoring Climate Variability – QBO and ENSO

- **Quasi-Biennial Oscillation (QBO) in tropical lower stratosphere** ~28 months period
  Seasonal-interannual changes in radiative heating & wave momentum fluxes
- **El Niño Southern Oscillation (ENSO) in troposphere** every 3 to 7 years
  Interannual changes in sea surface temperature of the tropical Pacific



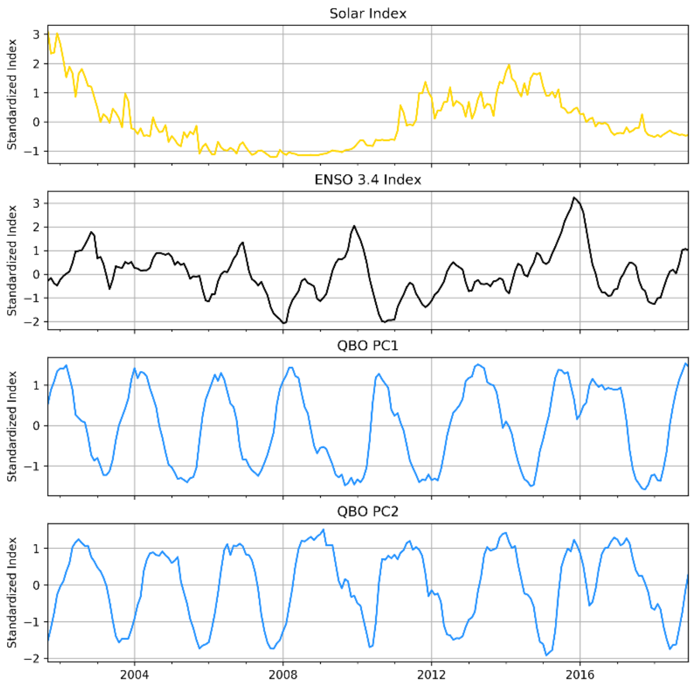
WEGC OPSv5.6 <https://www.eodc.eu/data-services/wegc-gnss-ro/>

(Wilhelmsen et al. AMT 2018)

Trend Detection – Multiple Linear Regression

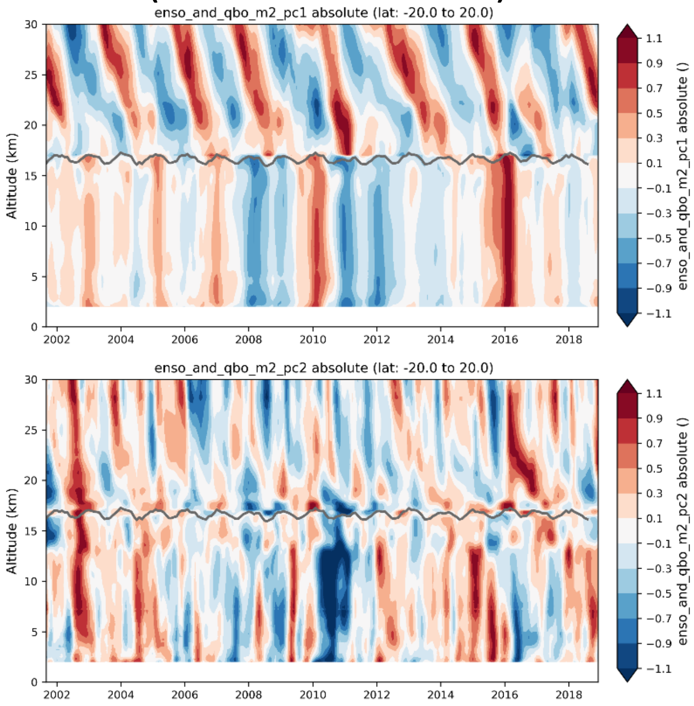
„Conventional“ indices

solar flux, ENSO SST, QBO winds



Height-resolved indices

PCA over gridded RO temperature field (also lat-resolved!)



PC1

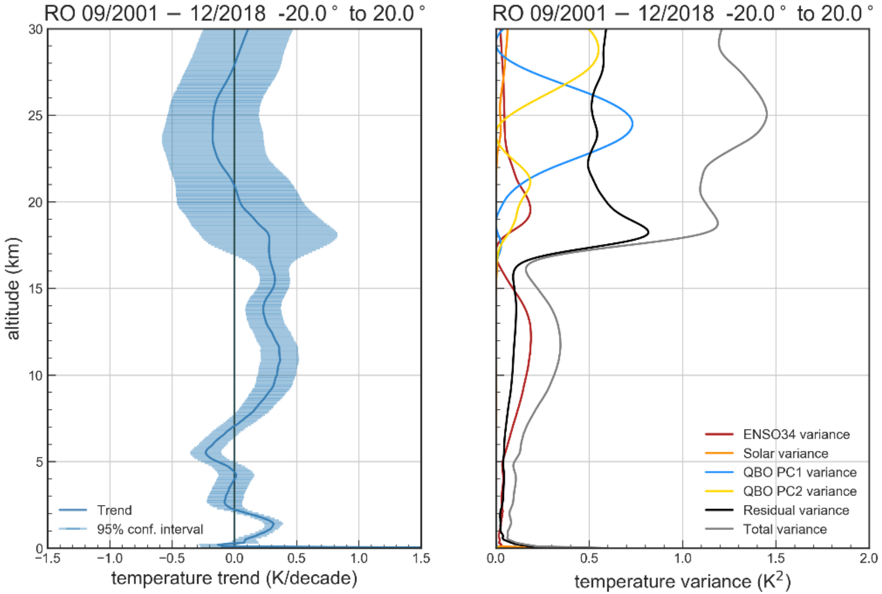
PC2

(Wilhelmsen et al. AMT 2018, Ladstädter et al. ROMSAF-IROWG 2019)

Trend Detection – Multiple Linear Regression

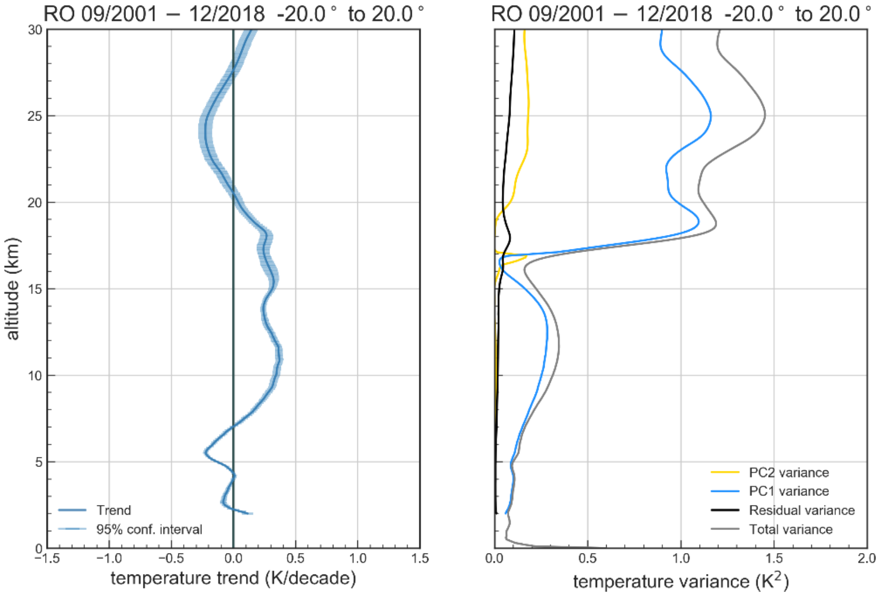
- Vertically resolved trends in tropics and explained variance
- **Height-resolved indices: smaller residual variance and higher SNR**

Conventional indices



trend with 95% conf.int. explained variance

Height-resolved indices

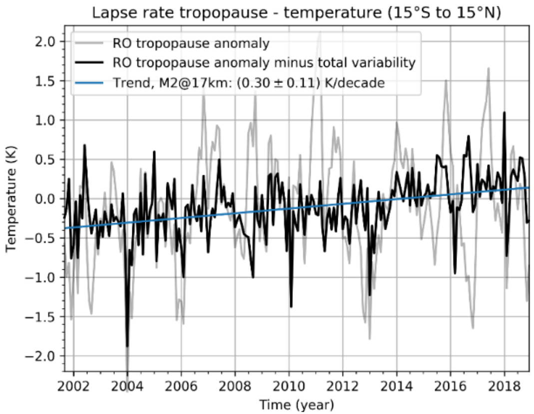


trend with 95% conf.int. explained variance

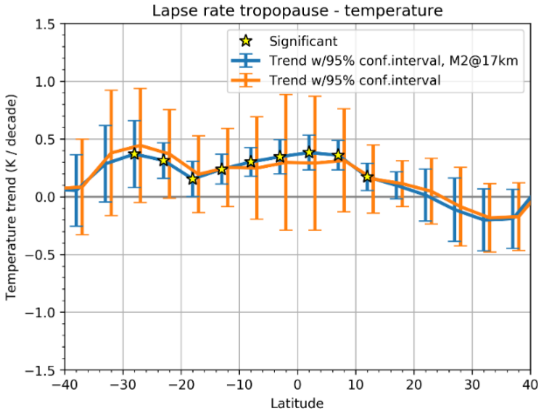
(Ladstädter et al. ROMSAF-IROWG 2019)

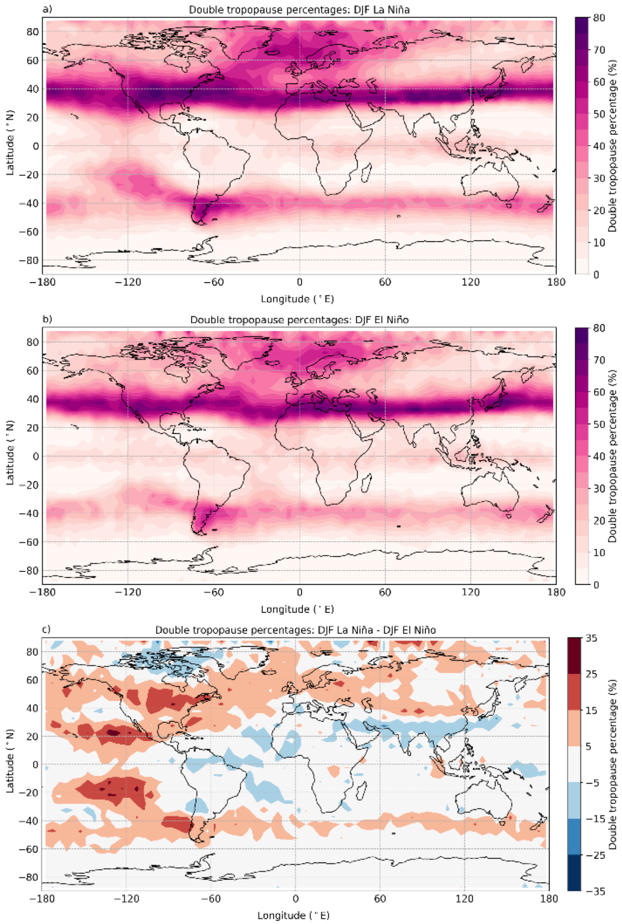
Tropopause Variability and Trends from RO

Tropopause Temperature



Warming of tropical tropopause





Double Tropopause Frequency

La Niña

El Niño

(H. Wilhelmsen WEGC 2019; Wilhelmsen et al. GRL 2020)

Temperature Trends 2002–2018

- Merged SSU and AMSU
- Radiosondes: RAOBCORE, RICH
- **Radio Occultation**
- Surface HadCRUT4
- Significant tropospheric warming 2002-2018 of 0.25 to 0.35 K/dec
- Warming weaker in MSU

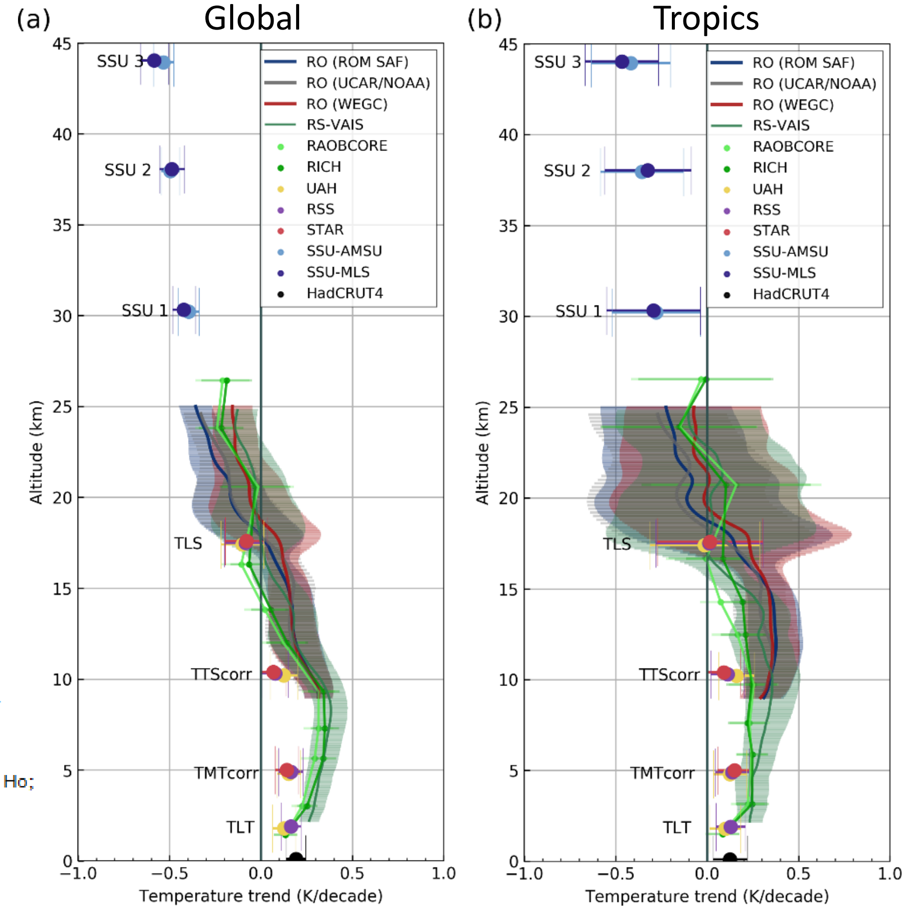
RESEARCH ARTICLE | 21 AUGUST 2020

Observed Temperature Changes in the Troposphere and Stratosphere from 1979 to 2018

A. K. Steiner; F. Ladstädter; W. J. Randel; A. C. Maycock; Q. Fu; C. Claud; H. Gleisner; L. Haimberger; S.-P. Ho; P. Keckhut T. Leblanc; C. Mears; L. M. Polvani; B. D. Santer; T. Schmidt; V. Sofieva; R. Wing; C.-Z. Zou

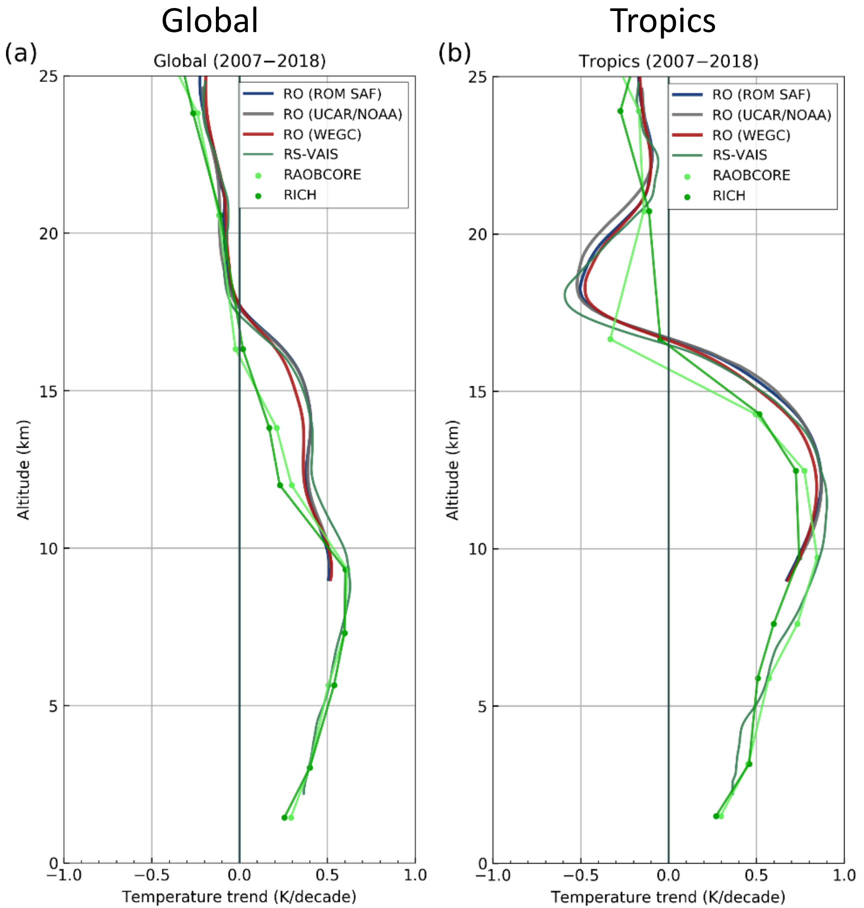
J. Climate (2020) 33 (19): 8165–8194.

(Steiner et al. 2020 https://doi.org/10.1175/JCLI-d-19-0998.1)



Temperature Trends 2007–2018

- **Radio Occultation past CHAMP**
- Excellent agreement in RO records from 3 different centers



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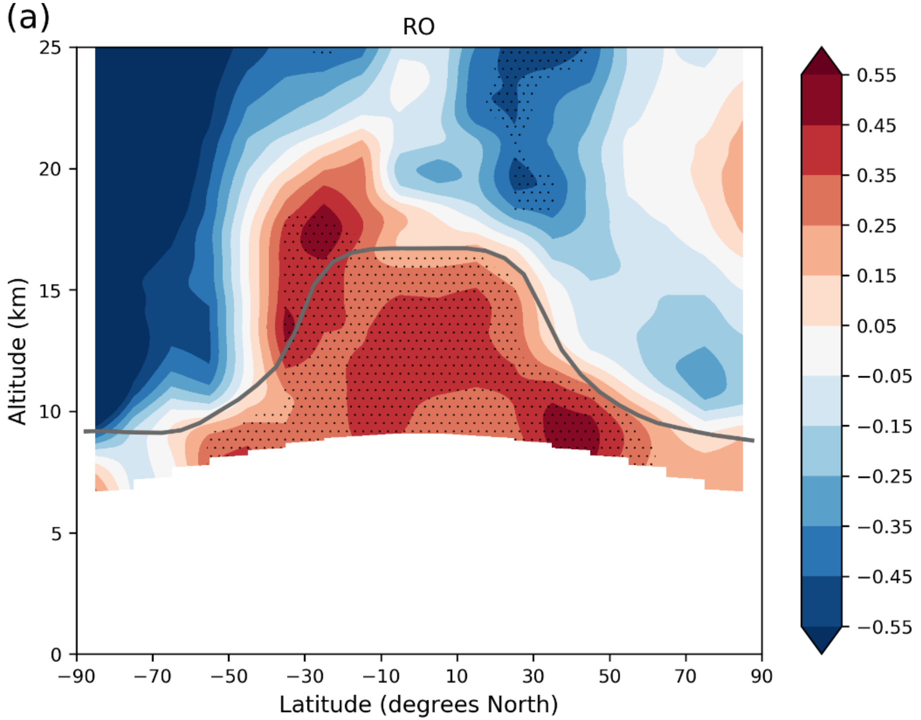
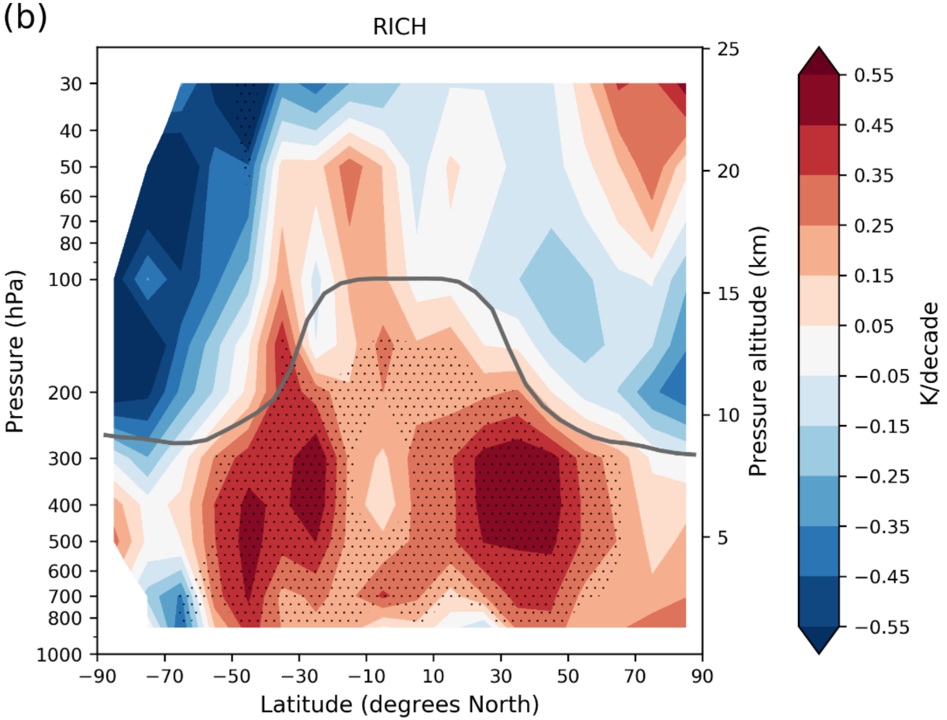
Latitude-height Resolved Trends 2002–2018

Radio Occultation



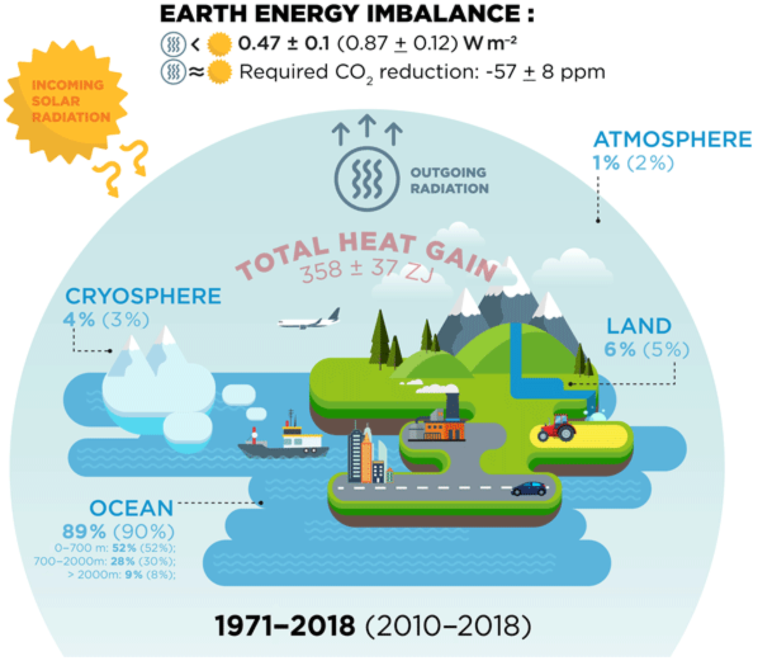
Radiosondes RICH



(Steiner et al. 2020 https://doi.org/10.1175/JCLI-d-19-0998.1)

Heat Gain in the Earth System

- **Most recent study on heat gain in the Earth system since the 1970s from observations** states a total heat gain of 358±37 ZJ, which is equivalent to a global heating rate of 0.47±0.1Wm^{-2}.
- 2010-2018: 90% of heat stored in oceans, 5% land, 3% cryosphere melting, 2% for atmosphere warming (RO data used here).

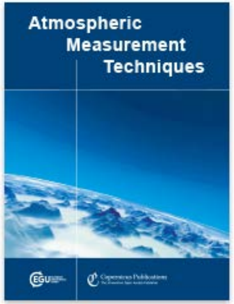


Schuckmann et al., ESSD (2020)

Structural Uncertainty – RO Processing Centers

RO processing centers work on intercomparison of RO records since 2007

- The aim is to improve the maturity of RO data for use as climate data records
- Community publications: Ho et al. 2009; 2012; Steiner et al. 2013
- Recent community publication: Steiner et al., AMT 2020

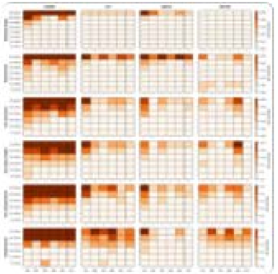


Research article

20 May 2020

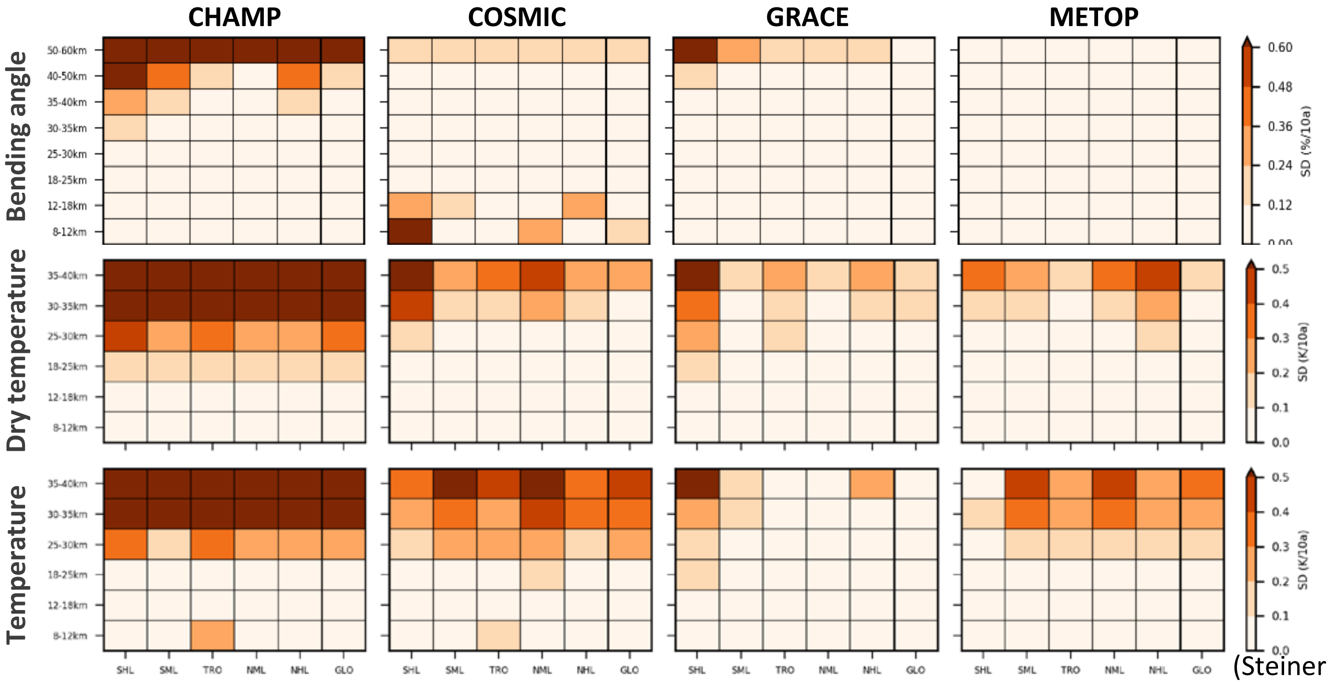
Consistency and structural uncertainty of multi-mission GPS radio occultation records

Andrea K. Steiner[1,2], Florian Ladstädter[1,2], Chi O. Ao[3], Hans Gleisner[4], Shu-Peng Ho[5], Doug Hunt[6], Torsten Schmidt[7], Ulrich Foelsche[2,1], Gottfried Kirchengast[1,2], Ying-Hwa Kuo[6], Kent B. Lauritsen[4], Anthony J. Mannucci[3], Johannes K. Nielsen[4], William Schreiner[6], Marc Schwärz[1,2], Sergey Sokolovskiy[6], Stig Syndergaard[4], and Jens Wickert[7,8]



Structural Uncertainty of Multi-mission GNSS RO Records

- Standard deviation of RO trends from 5 data centers: **lowest at 8-25 km for all RO variables**
- **Temperature: 0.05 K/decade globally, ~0.1 K/decade at all latitudes >>> GCOS long-term stability**
- **For trend detection: CHAMP is limiting >25 km**, Newer missions, COSMIC, GRACE, METOP, usable to higher altitudes (due to advanced receivers and lower bending angle noise)



(Steiner et al. AMT 2020)

Sources of Uncertainty

Receiver noise

- CHAMP high; GRACE, COSMIC, Metop low
- Background information introduced

Space-time coverage (sampling error)

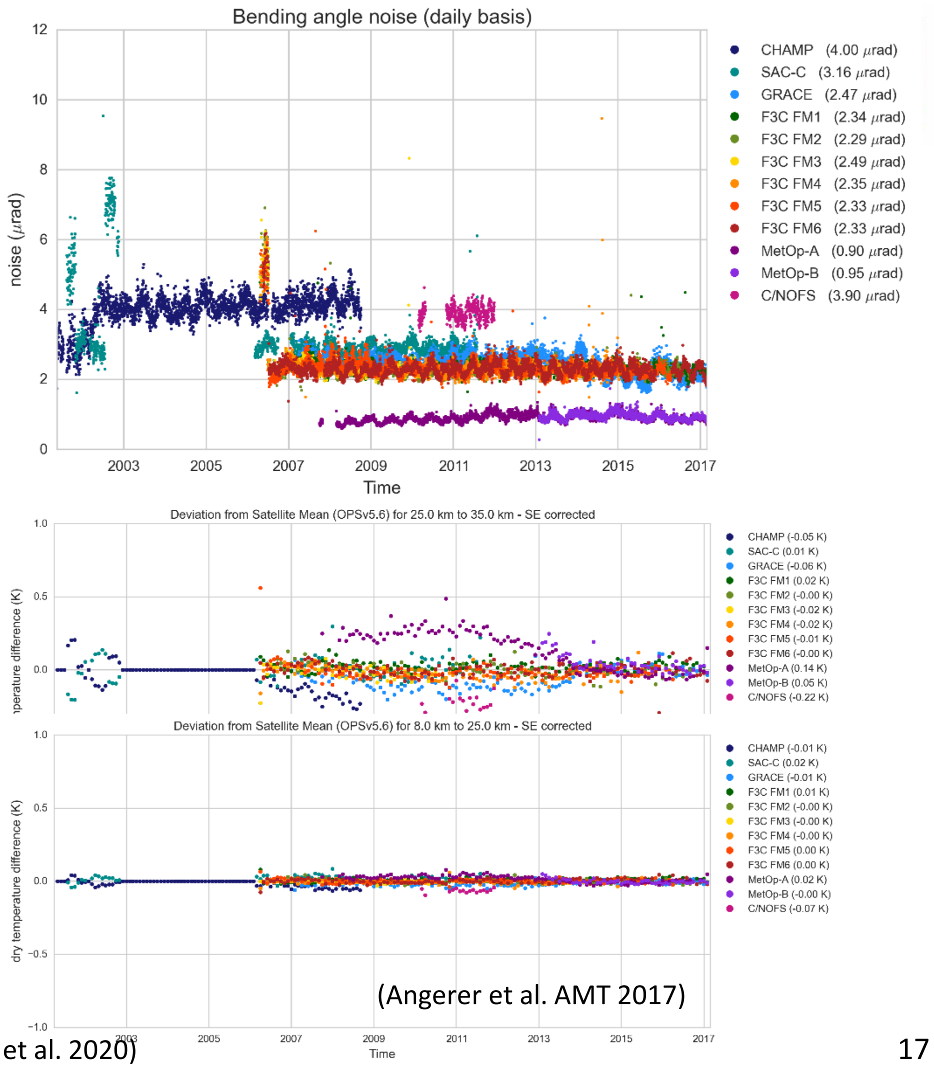
- CHAMP: low data amount
- GRACE,COSMIC: good coverage
- Metop: incomplete local time coverage

Wet-dry ambiguity

- Background information introduced

Described by

- Empirical error models
- Uncertainty propagation
- Structural uncertainty



(Angerer et al. AMT 2017)

(Scherllin-Pirscher et al. 2011a;b; 2017; Schwarz et al. 2017;2018; Innerkofler et al. 2020)

GCOS Requirements for Climate Data Records

GCOS aim is to ensure that the climate system is monitored sufficiently homogeneous, stable and accurate

Climate monitoring principles for Fundamental Climate Data Records (FCDR & CDRs)

- traceability to reliable reference standards
- **long-term stability**
- **homogeneity & reproducibility**
- global and temporal coverage
- accuracy and adequate resolution in space and time

Requirements for Essential Climate Variable (ECV) upper-air temperature

- horizontal resolution: 25 km in UT, 100 km in LS
- vertical resolution: 1 km UT, 2 km LS
- accuracy (root-mean-square) < 0.5 K
- **stability of 0.05 K per decade** (GCOS 2016)

RO Applications – Added Value

- Characterization of spatio-temporal variability of the **tropical tropopause region**
- Detection of sharp vertical gradients associated with **deep convection and tropical cyclones** including cooling at the cloud top and secondary tropopauses
- Atmospheric thermal structure disturbance due to **volcanic clouds**
- Quantification of **GW** vertical and horizontal wavelengths, and momentum fluxes
- Characterization of **equatorially-trapped waves, seasonal and inter-annual variability**
- Sub-seasonal variability associated with the **MJO**
- Three-dimensional thermal structure during **ENSO events and QBO variability**
- **Vertically-resolved short-term trends** of different atmospheric parameters
- **Evaluation** of other observational data, atmospheric analyses, reanalyses, climate models

Thanks for funds to: esa, asap FFG, FWF, WCRP World Climate Research Programme