GNSS radio occultation lecture 2
impact/some applications

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NWP SAF lecture 2, March 25, 2026

EUMETSAT ROM SAF
RADIO OCCULTATION METEOROLOGY

https://rom-saf.eumetsat.int

Acknowledge

- Hans Gleisner, DMI and ROM SAF
- Mark Ringer, Hadley Centre, Met Office
- Estel Cardellach, IEEC and ROM SAF
- Niels Bormann, ECMWF
- Daisuke Hotta, JMA
- Katrin Lonitz, ECMWF and ROM SAF

Presentations on GNSS-RO applications from ROM SAF/IROWG (2019), IROWG-8 (2021), OPAC/IROWG (2022), ROM SAF workshop (2024), IROWG (2024)

- See presentations at:
  - https://rom-saf.eumetsat.int/romsaf-irowg-2019/en/content/21/program-agenda-by-day
  - https://cpaess.ucar.edu/events/8409/agenda
  - https://opacirowg2022.uni-graz.at/en/scientific-programme/
  - https://ecmwfevents.com/i/8th-eumetsat-rom-saf-user-workshop-on-gnss-radio-occultation-measurements/public/agenda
  - https://www.cosmic.ucar.edu/events/cosmic-jcsda-workshop-irowg-10

Outline

Aim: provide an overview of **some** GNSS-RO applications

Recap from lecture 1

- *GNSS-RO information content, key characteristics - '**core region**', etc.*

As you might expect, many applications are related to these characteristics in the core region

- **GNSS-RO impact in NWP systems from recent OSEs**
- **Key observation climate reanalyses**
- Climate monitoring
- Airborne RO
- Polarimetric radio occultation: retrieving hydrometeor content along path
- Summary

EMAIL me *for ionospheric/space weather/surface pressure information/PBL/radiosonde bias correction.*

Recap

- **All satellite measurements have strengths and weaknesses**. The aim is to construct a robust *global observing system* with a good balance of the different types, **given their distinct characteristics and information content**.

- **GNSS-RO measurements are useful because they complement satellite radiances**

  – Assimilation without **bias correction** (an '*anchor measurement')*

  – Good vertical resolution

- The information content is largest in the "**core region**", between 7-35 km, ***and we will show that*** we see a large NWP impact on upper-tropospheric and lower/middle stratospheric temperatures.

Recap

- **All satellite measurements have strengths and weaknesses**. The aim is to construct a robust *global observing system* with a good balance of the different types, **given their distinct characteristics and information content**.

- **GNSS-RO measurements are useful because they complement satellite radiances**

  – Assimilation without **bias correction** (an '*anchor measurement'*)
  – Good vertical resolution

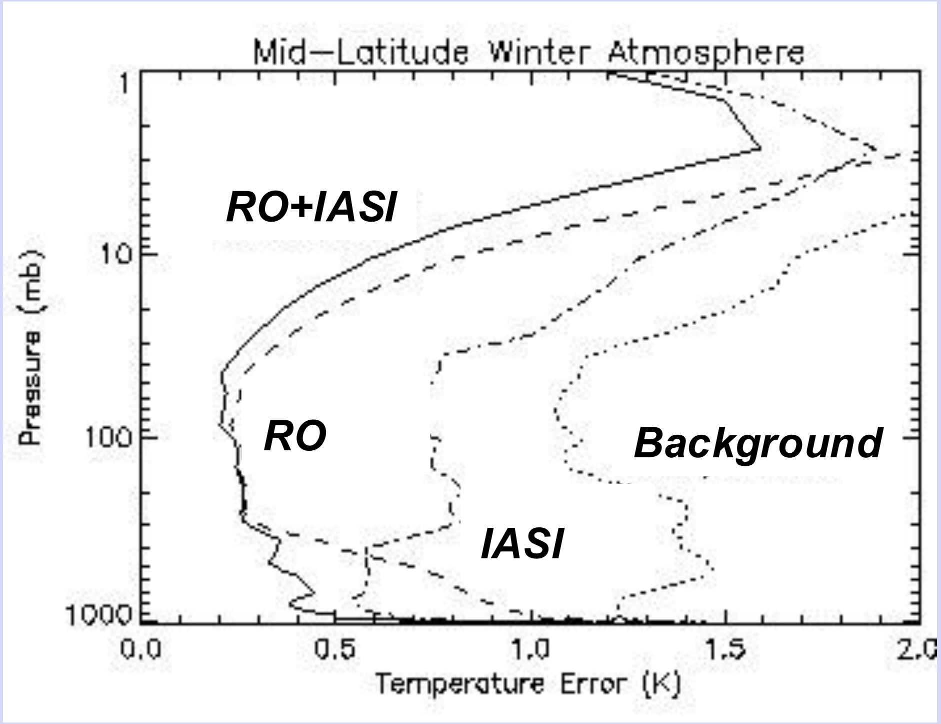
We will come back to this!

- The information content is largest in the "**core region**", between 7-35 km, ***and we will show that*** we see a large NWP impact on upper-tropospheric and lower/middle stratospheric temperatures.

GNSS-RO and IASI: 1D-Var study

Collard and Healy 2003, QJRMS:

Expected/Theoretical *retrieval uncertainty:*



*We expect the biggest impact in upper troposphere, lower/mid stratosphere - the GNSS-RO '**core region**'*

Recent experiments with GNSS-RO removed

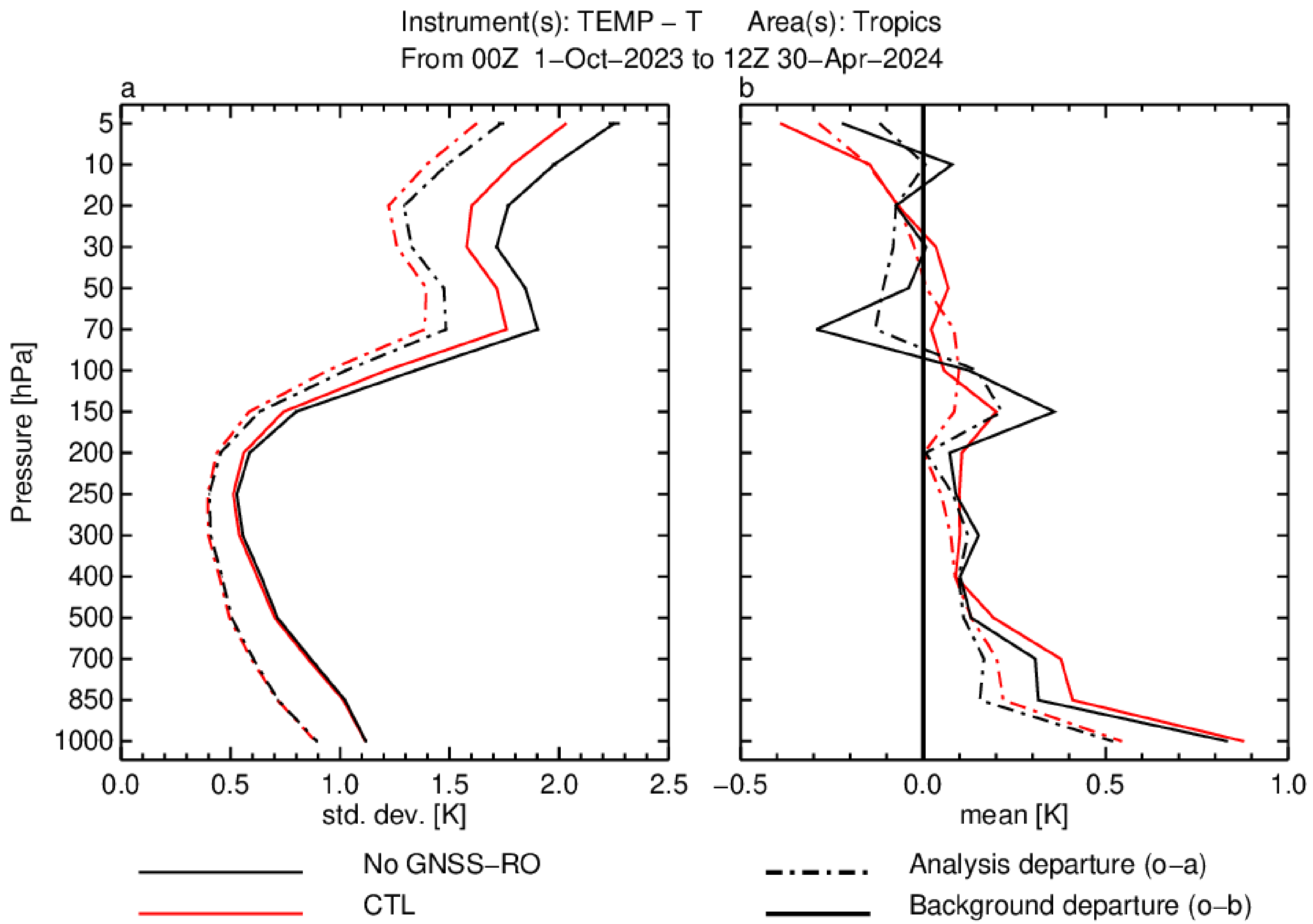
- We assimilate GNSS-RO in operations

- **Ideally**, if we remove GNSS-RO the forecast errors should increase

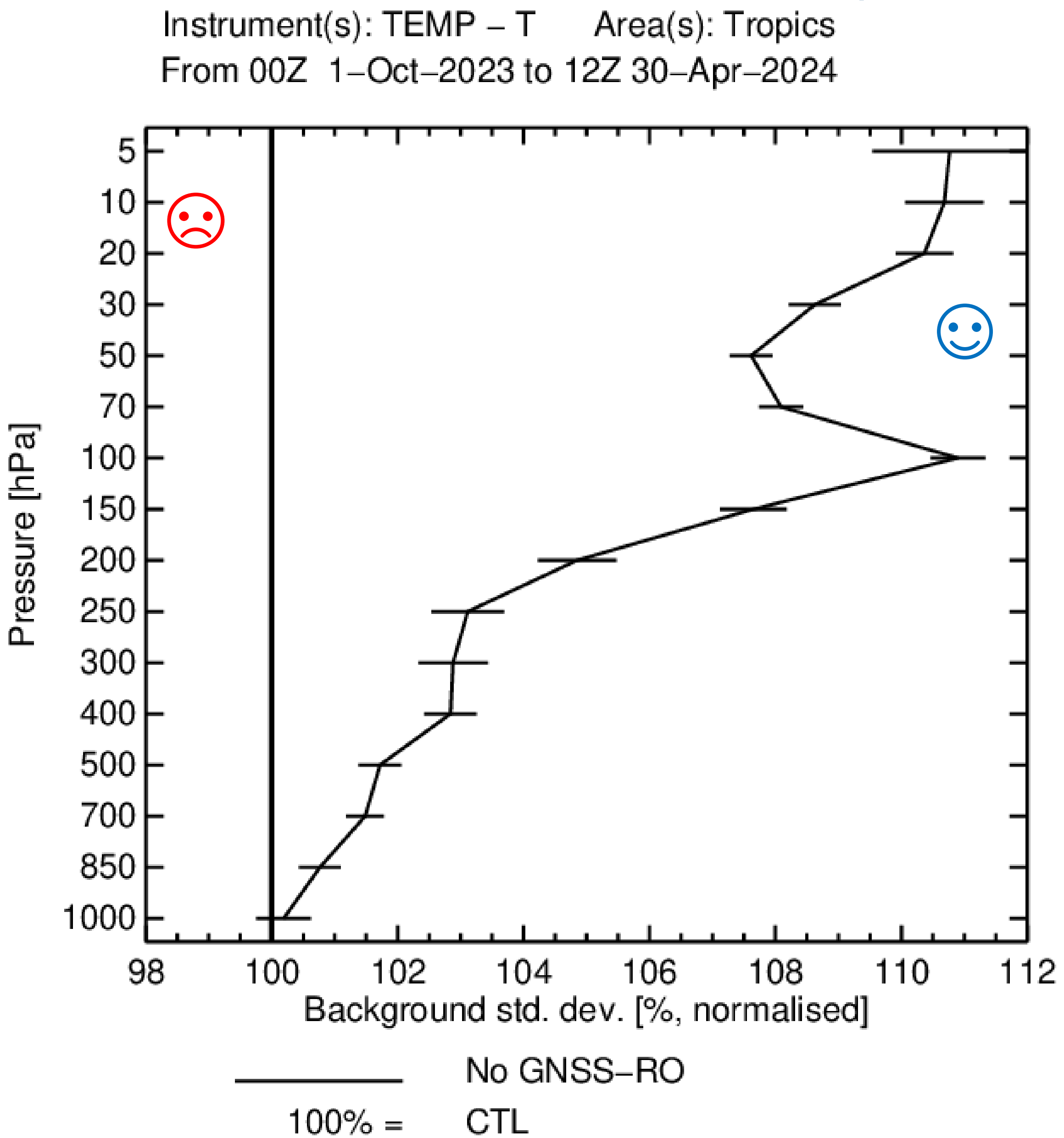
- Recent experiment from October 1, 2023 to April 30, 2024

- For short-range forecasts we can look at how well the forecasts fit other observations – e.g., radiosondes and satellite radiances

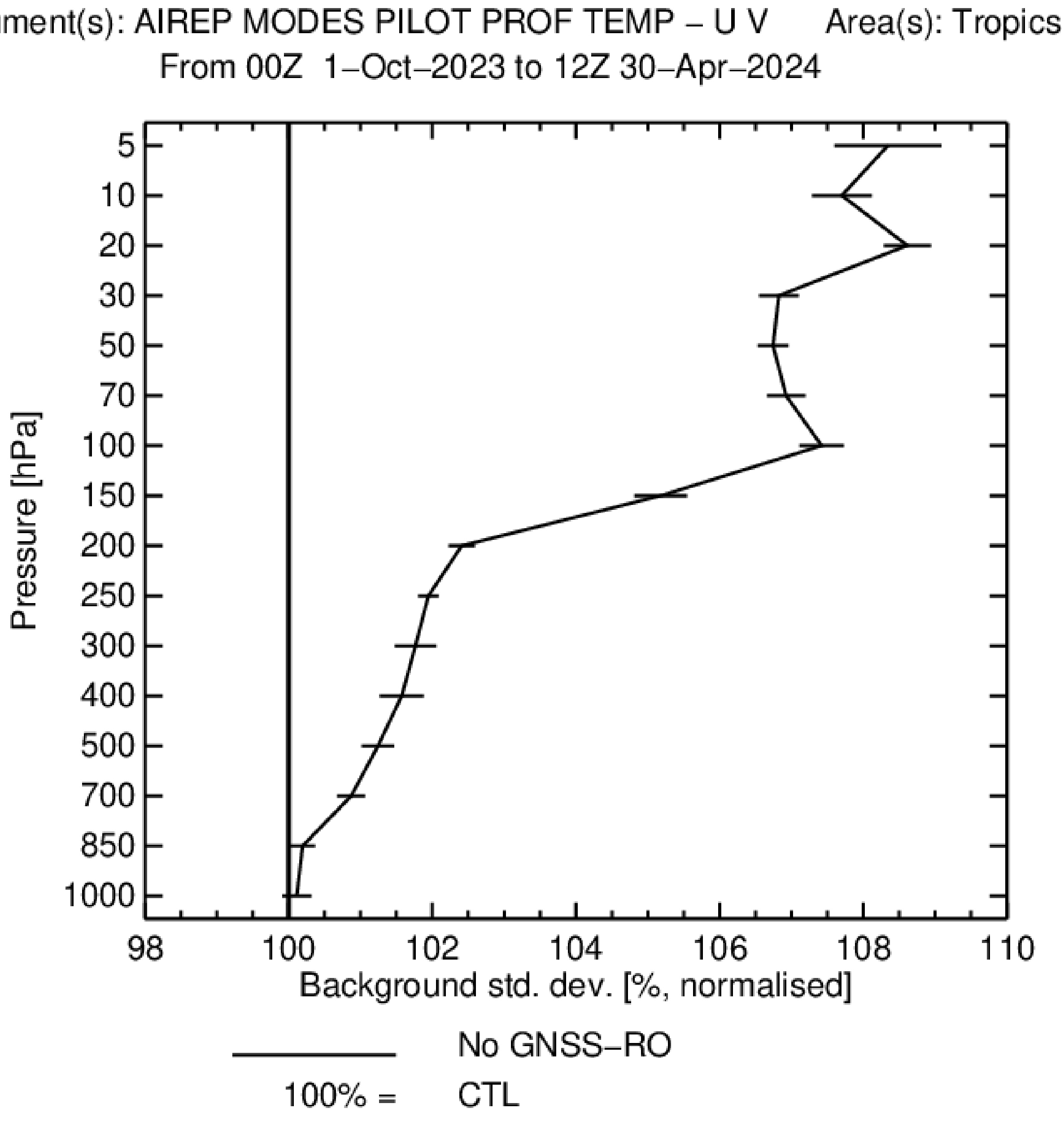
Fit to radiosonde temperatures in **tropics**



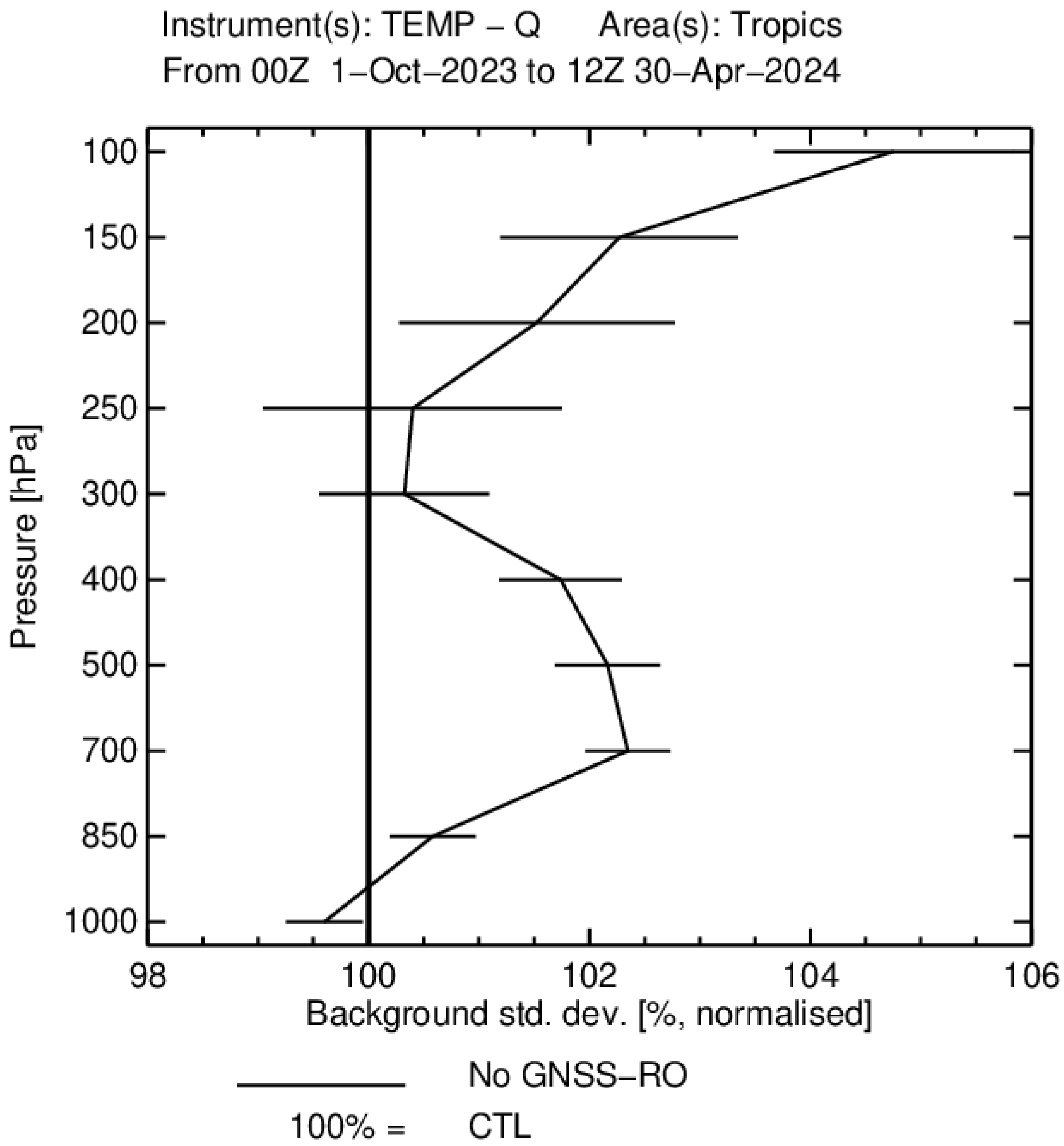
Radiosonde temperatures in tropics (% improvement)



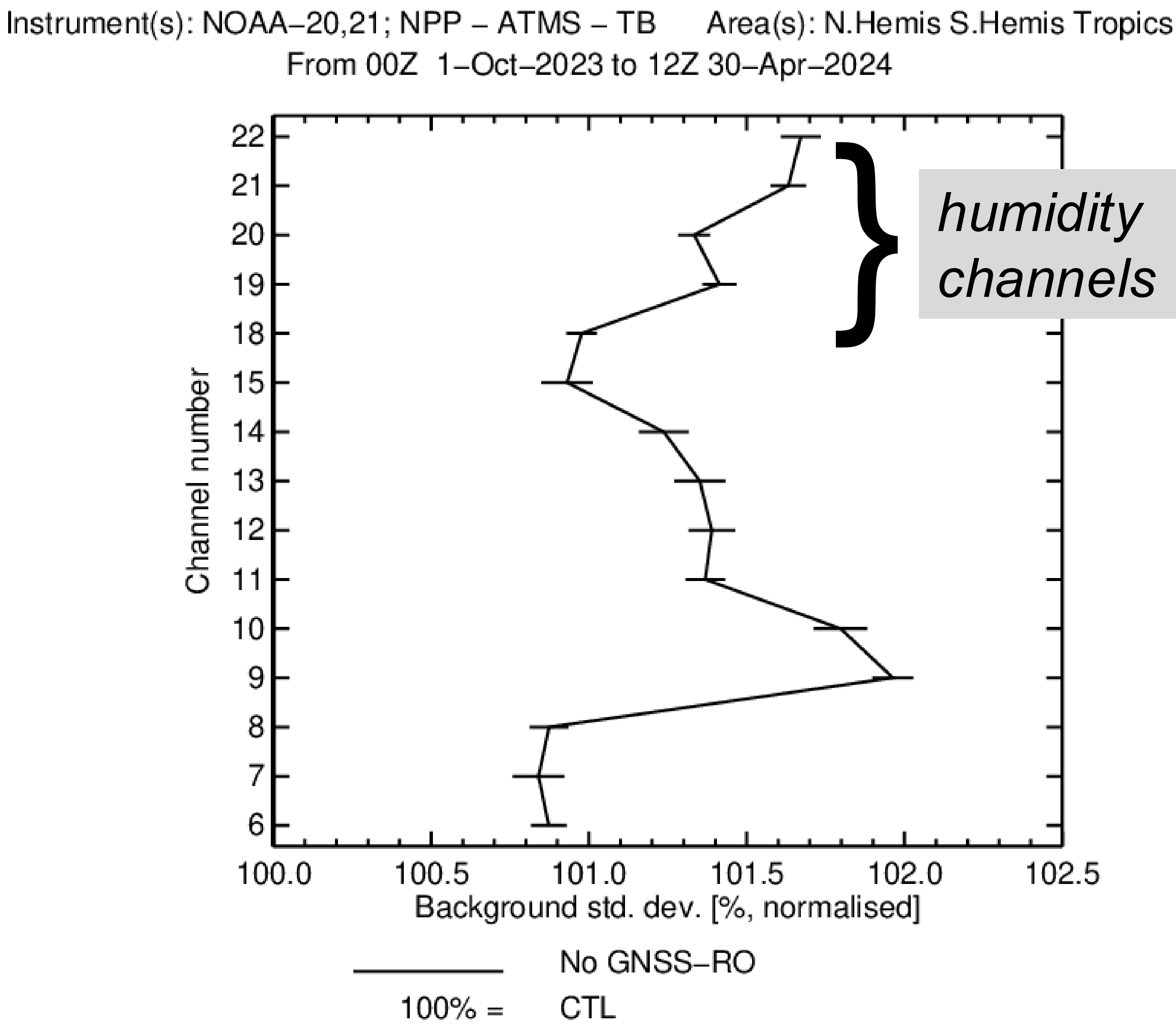
Radiosonde winds in tropics (% improvement)



Radiosonde s.hum in tropics (% improvement)

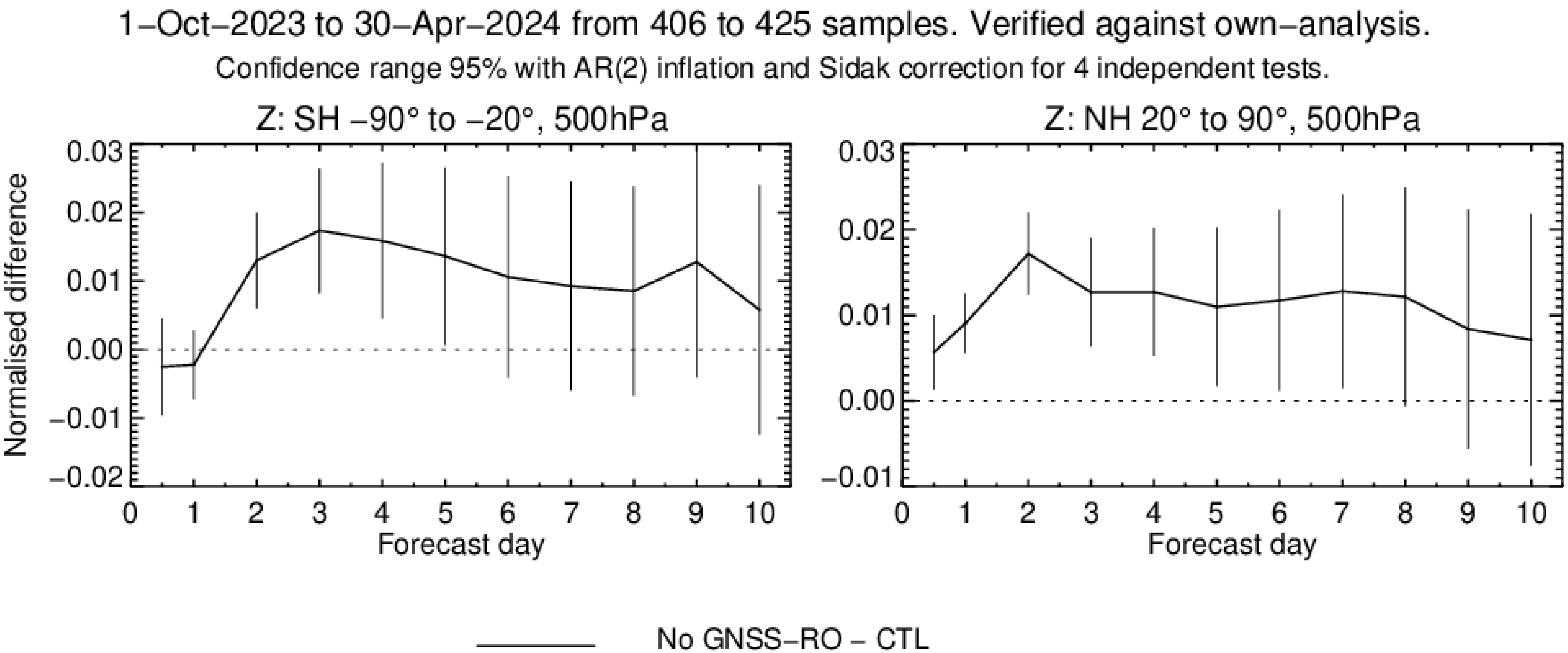


ATMS radiances global (% improvement)



Z500 scores

- Above 0 is good! Z500 RMS scores get worse when GNSS-RO removed



GNSS-RO now having a good impact on tropospheric scores that extends into the medium-range

ECMWF

Great, it's all sorted …

- **… Well, actually** the community has been investigating an issue that becomes more apparent when GNSS-RO numbers are increased to 37000 occultations per day in the **Radio Occultation Meteorology experiment (ROMEX)**

- A number of NWP centers are testing the ROMEX data

- No apply bias correction to the GNSS-RO

- The GNSS-RO observations introduce a ***small*** cold bias in the troposphere when we use 37 K observations per day

- This impacts the Z500 **RMS** scores – but the random errors look good!

- Source of this small bias not understood
  - Forward model or observation processing bias or …
  - But we can adjust (**cheat!**) by changing a refractivity **coefficient** used in the NWP system

$$N = 10^6(n-1)$$
$$= \frac{c_1 P}{T} + \frac{c_2 P_w}{T^2}$$

ECMWF

https://doi.org/10.5194/egusphere-2025-5986

10 Dec 2025

An update to the expression of atmospheric refractivity for GNSS signals

Josep M. Aparicio

Abstract. This study revisits previous formulations of atmospheric refractivity at L-band frequencies, focusing on signals from Global Navigation Satellite Systems (GNSS). A refined model expression is proposed as a function of air density, temperature, and composition, evaluated using a comprehensive set of existing laboratory and atmospheric measurements. The key measurements that most affect the final accuracy are identified, establishing traceable error bounds and indicating where further experimental work could confirm or improve the model.

Recent studies on the use of large volumes of GNSS radio occultation (GNSSRO) observations in Numerical Weather Prediction (NWP) show that the precise formulation of refractivity becomes increasingly critical as data volumes grow. Although the revision is modest, its impact lies within the range where NWP sensitivity becomes non-negligible.

Compared to earlier work, this study (1) incorporates updated fundamental measurements, (2) accounts for the small but measurable variability in atmospheric composition, mainly increasing CO_2 and decreasing O_2, emphasizing that refractivity traceability is composition-dependent, and (3) extends the model to include hydrometeors. A simplified formulation based on hydrometeor oblateness is proposed, suitable for NWP applications where only limited hydrometeor information is available. Nonspherical hydrometeors tend to align during fall, introducing weak birefringence that can be detected during GNSS occultations with dual-polarization receivers.

The resulting refractivity expression is presented as a function of air density, temperature, moisture, and composition, and (using a simplified model of atmospheric evolution) also as a function of density, temperature, moisture, and time.

How to cite. Aparicio, J. M.: An update to the expression of atmospheric refractivity for GNSS signals, EGUsphere [preprint], https://doi.org/10.5194/egusphere-2025-5986, 2025.

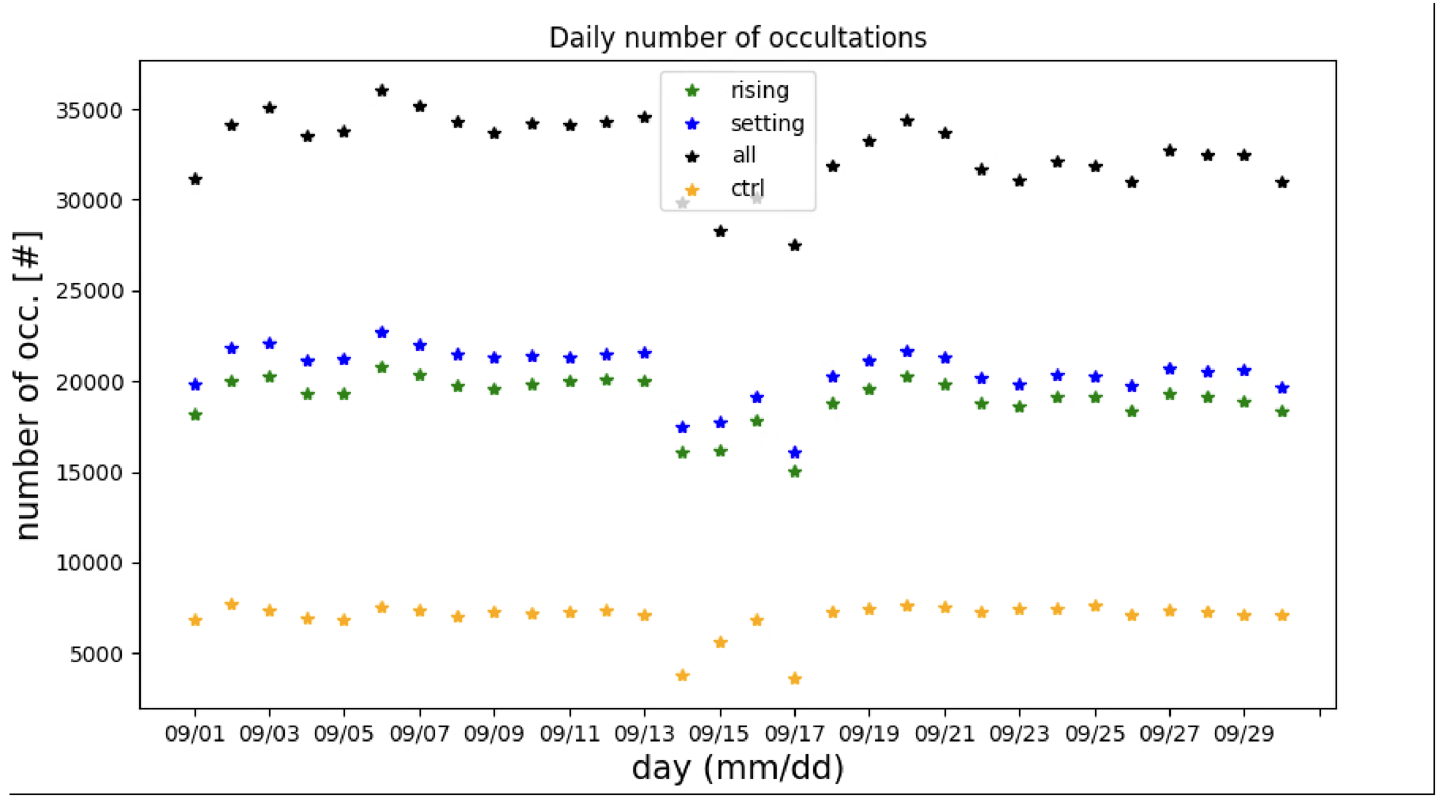
Updates on running ROMEX experiments at ECMWF

Katrin Lonitz

EUMETSAT ROM SAF
RADIO OCCULTATION METEOROLOGY

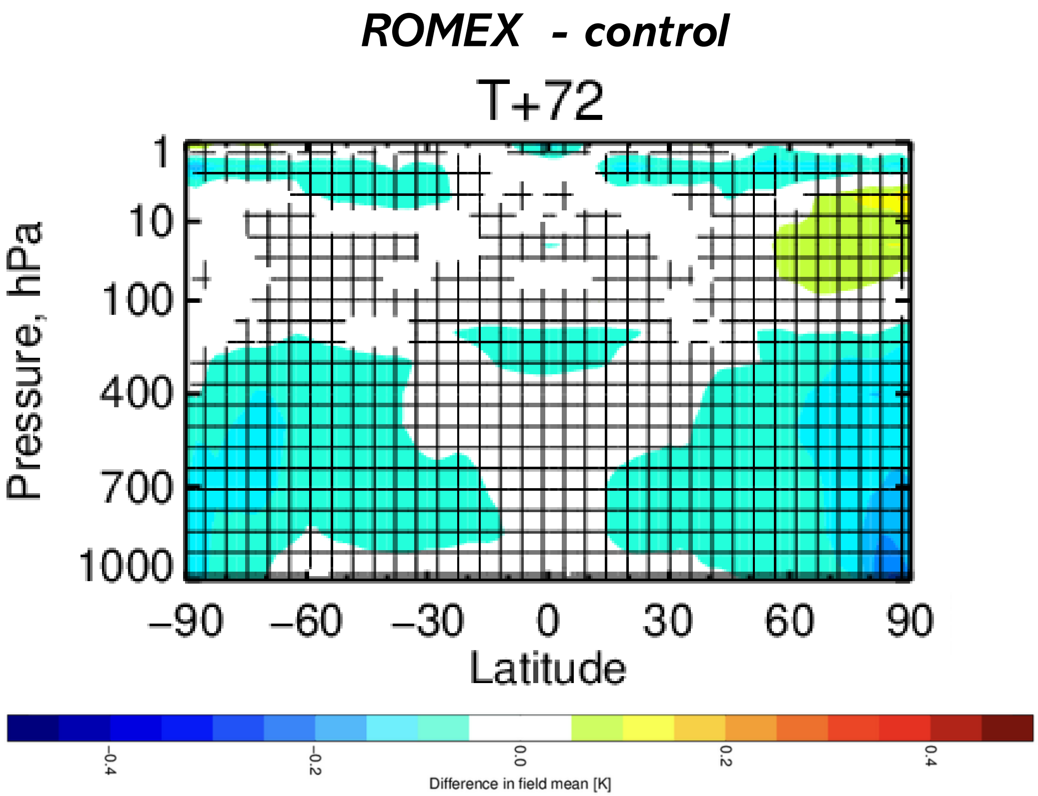
ECMWF

Number of occultations



Mean change in temperature

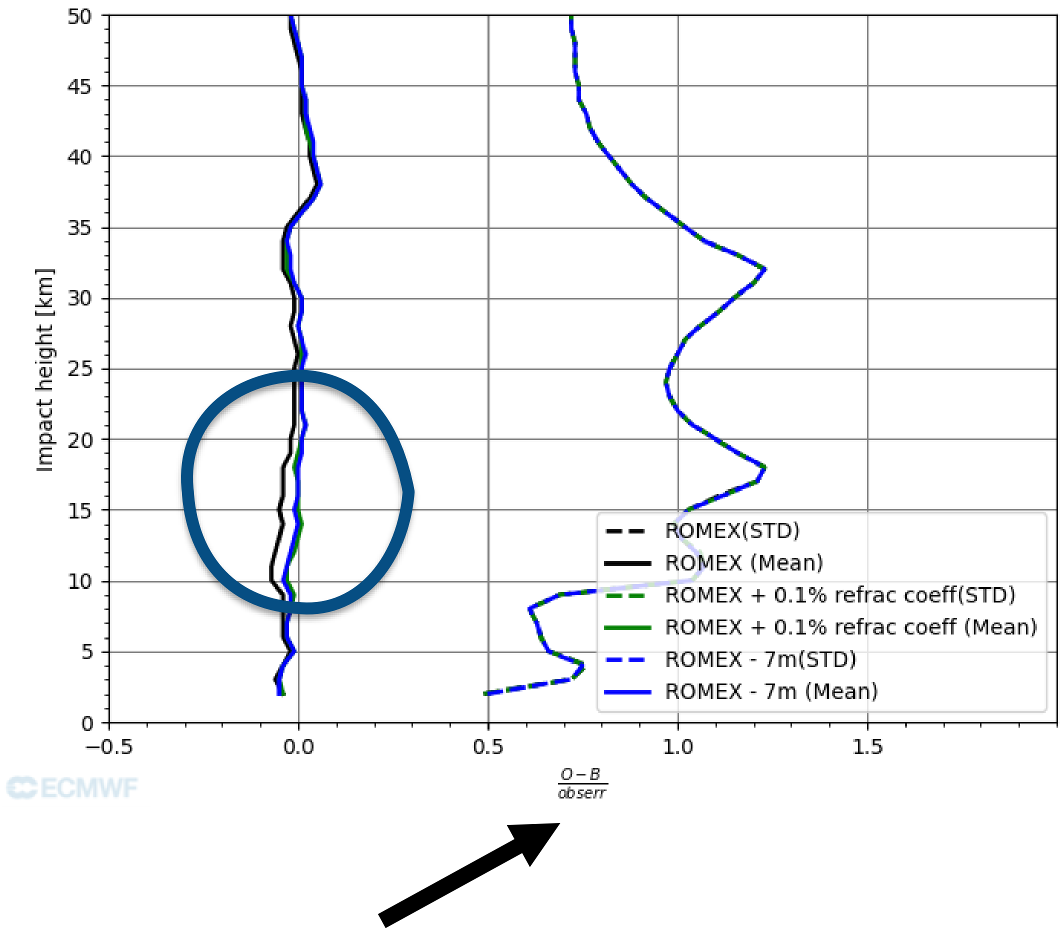
10 Sep – 30 Nov 2022



Testing 0.1 % refrac coefficient in FO

Testing substracting 7m in calculating geometric height in FO

10 – 20 Sept 2022

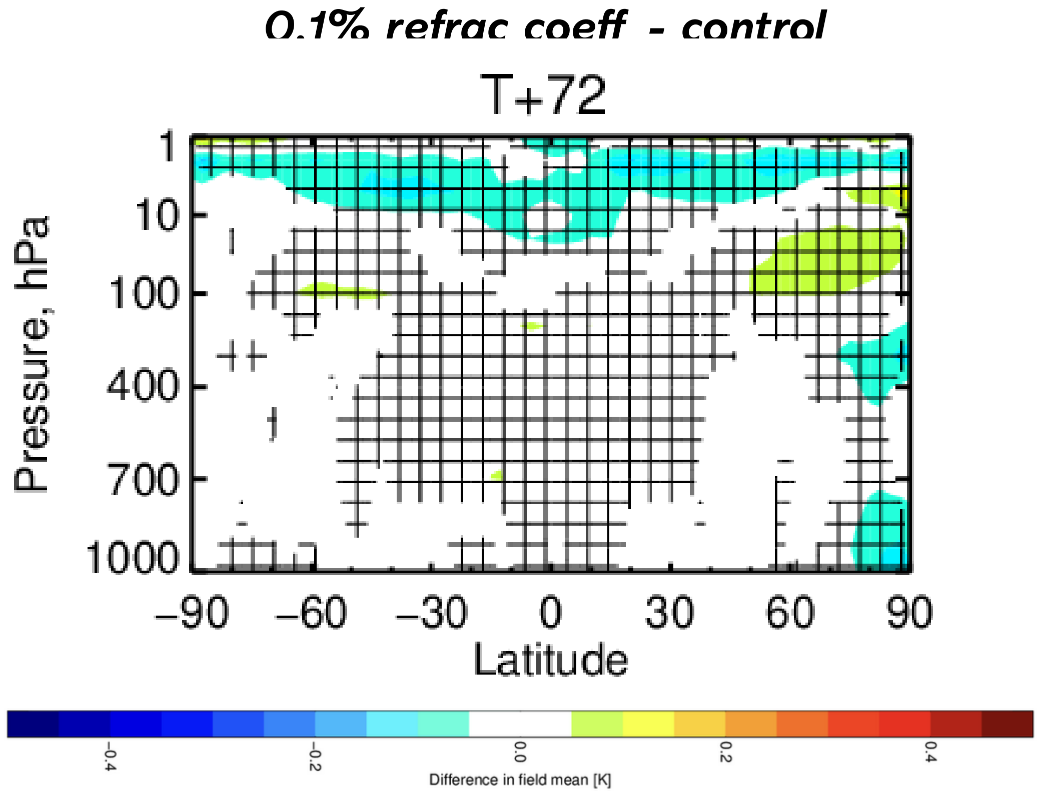


Units of assumed observation error.

ECMWF

mean change in temperature

10 Sep – 30 Nov 2022



mean change in temperature

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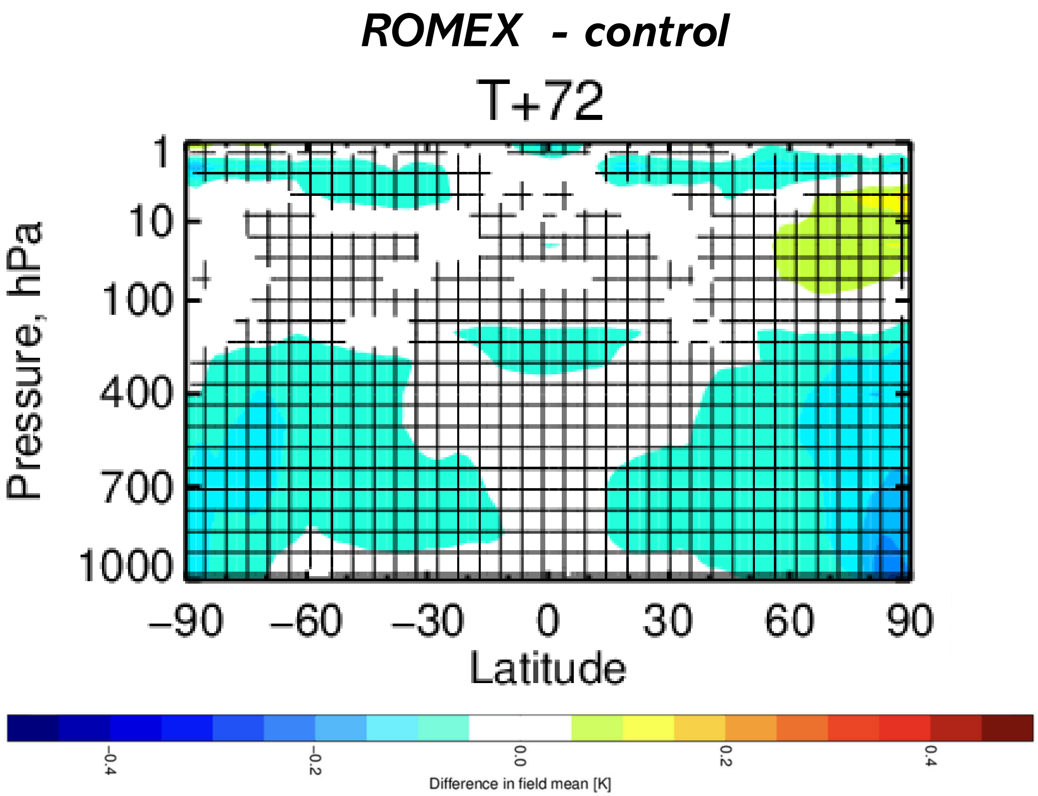


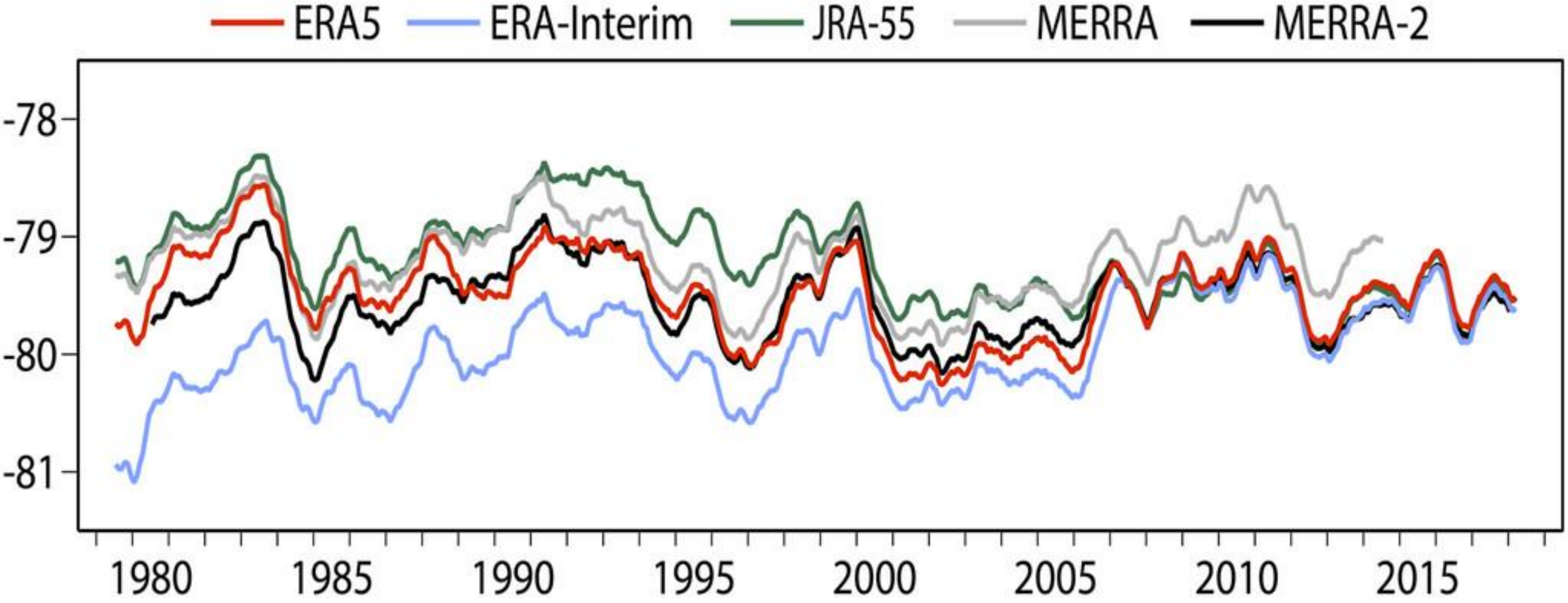
Cooling of atmosph

Climate reanalysis applications

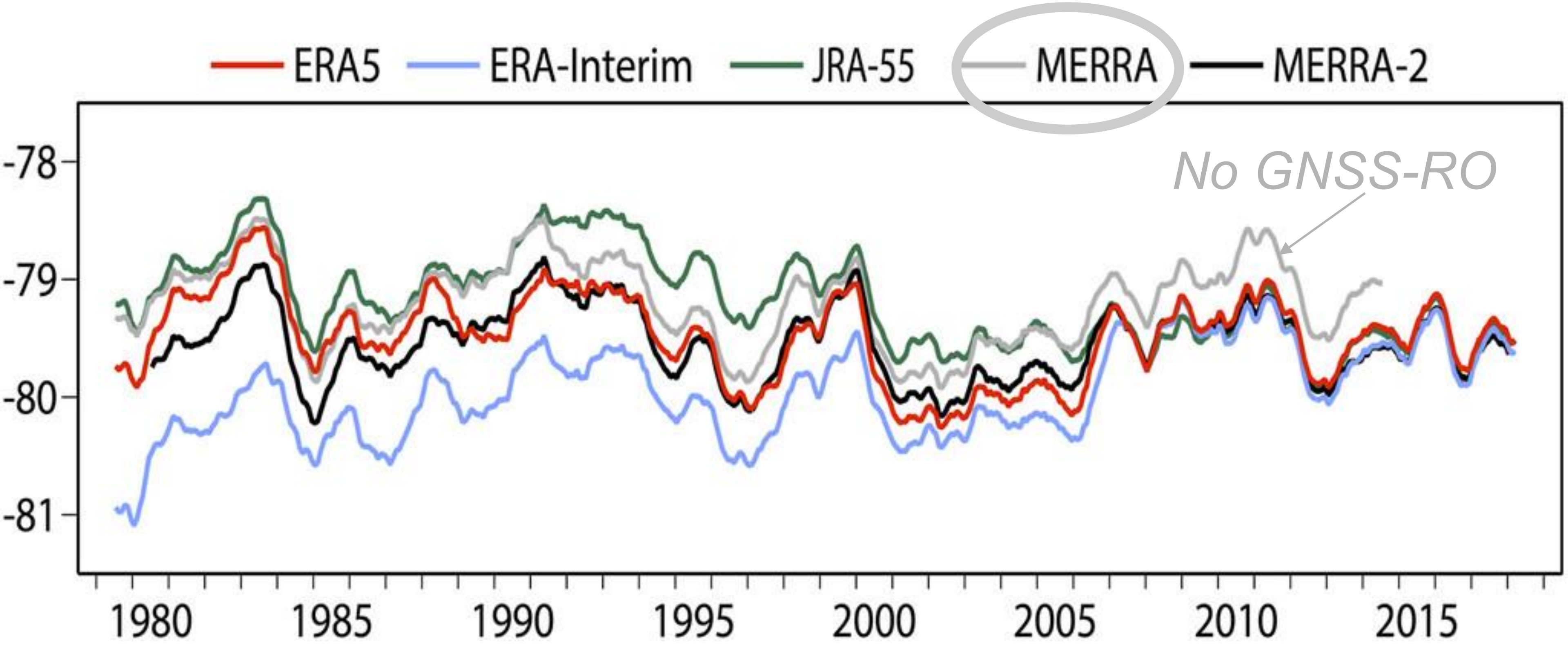
GNSS-RO have improved the consistency between climate reanalyses in the upper-troposphere and lower/middle stratosphere since 2006 with the introduction of COSMIC

Compare ERA-Interim, JRA-55, MERRA, MERRA2, ERA5 reanalysis

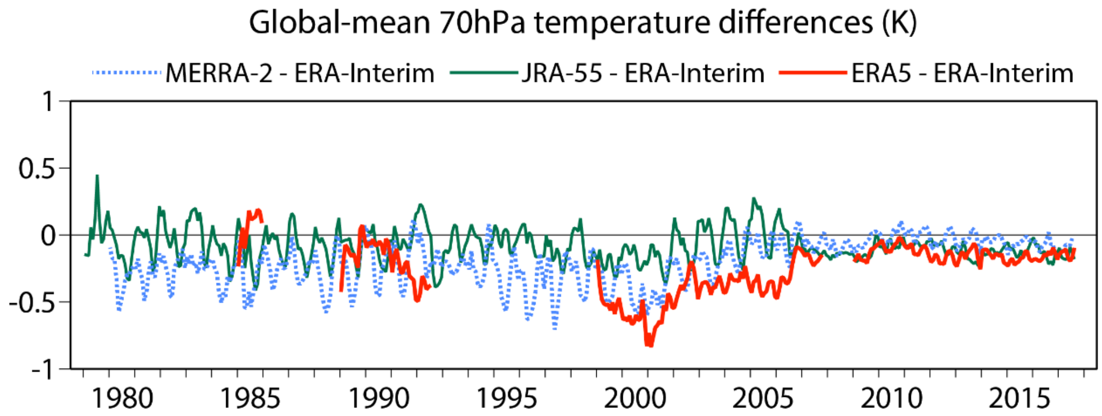
Twelve-month running mean temperature (°C) at 100 hPa averaged over the tropics (20°S to 20°N) from five global reanalyses.



Twelve-month running mean temperature (°C) at 100 hPa averaged over the tropics (20°S to 20°N) from five global reanalyses.



Lower stratospheric global temperature bias in ERA5 (corrected in ERA5.1)



The version of the assimilating model used for ERA5 has a larger cold bias in the lower stratosphere than the version used for ERA-Interim.

The cold bias is controlled by assimilating GNSS-RO data.

Radiosonde data exert a less-effective control on bias in ERA5 than they do in ERA-Interim.

See ERA 5.1 Tech Memo 859

https://www.ecmwf.int/en/publications/technical-memoranda

Climate monitoring applications

*GNSS-RO **<u>is becoming</u>** more important for climate monitoring, as the observation time-series lengthens*

But *which variables should we monitor?*

Bending angles or more geophysical quantities? Recall,

`Satellites do not measure temperature, …'

Recall basic GNSS-RO processing chain:

- Excess phase delays
- Doppler shift
- Bending angle
- Refractivity
- Pressure/Temp. Geopotential height

The RoTrends Project

ROtrends collaboration

RO community started comparison of different processing centres in 2007 (*ROtrends*).

Main aim is to *validate* RO as a climate benchmark, identifying the impact of processing assumptions (*structural uncertainty*).

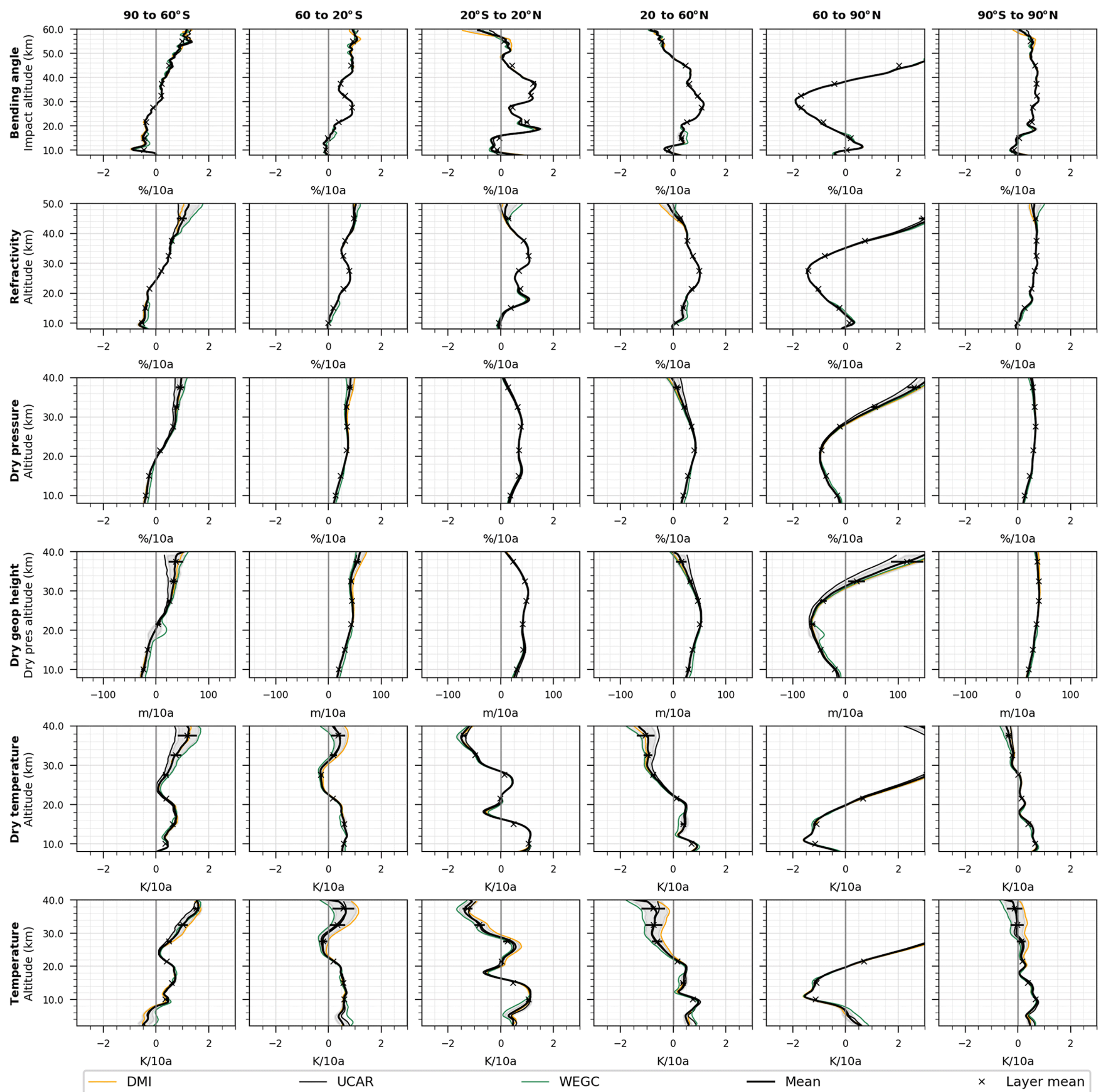
- *ROtrends* partners: ROM SAF, JPL, GFZ, UCAR, WEGC, and EUMETSAT

- Common focus on CHAMP data, Aug 2001 to Sep 2008

- Aiming at improved understanding of ***structural uncertainty,*** whilst still keeping the algorithm/software development independent

- Some recent results described in *Steiner et al.* [2020]
  - https://amt.copernicus.org/articles/13/2547/2020/

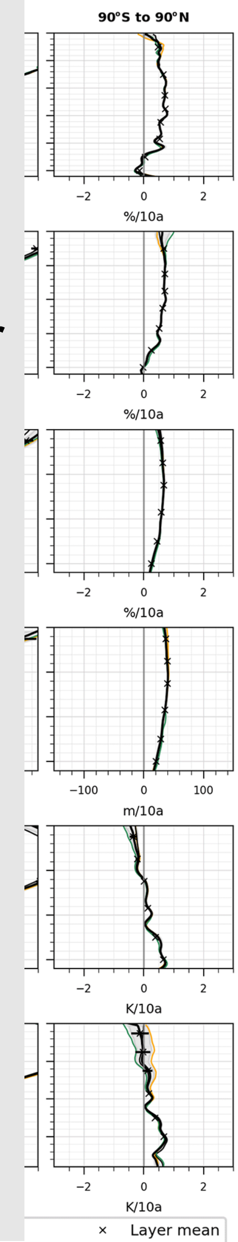
Steiner et al, Figure 10 (Metop GRAS)



Solid black = multi-centre mean

Gray = standard deviation about mean

Steiner et al, Figure 10 (Metop GRAS)



Solid black = mean

Gray = standa
mean

`<u>Structural uncertainty</u>'

The trends from the centers diverge slightly as we move to more geophysical parameters because of different assumptions made in their processing

*Illustrates the reliance on a-priori! Plus, the temperature **retrieval** is very sensitive to noise. Be wary above 35 km!*

***Early lecture on this course**:*

'Satellites do not measure temperature, …'

Bending angle for climate monitoring
Simulation study using the Hadley Centre climate model

Simulation studies to assess:

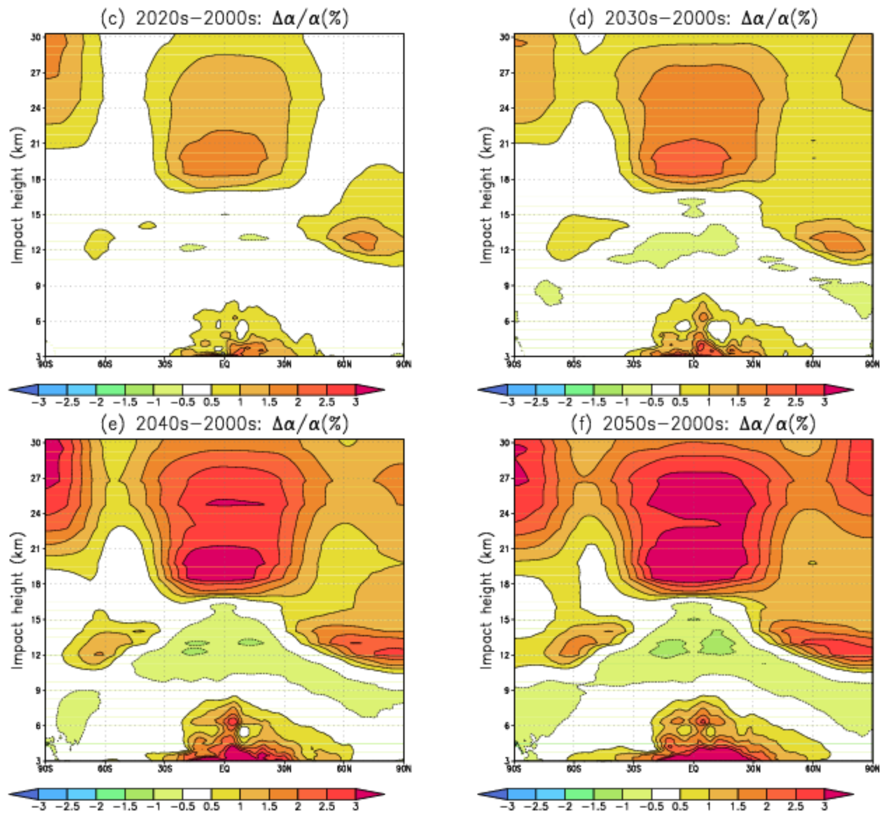
- potential of GNSS-RO for detecting climate trends
- what variable should we monitor?
- information content of GNSS-RO in relation to other sensors

Simulations (conducted in mid 2002's!) use:

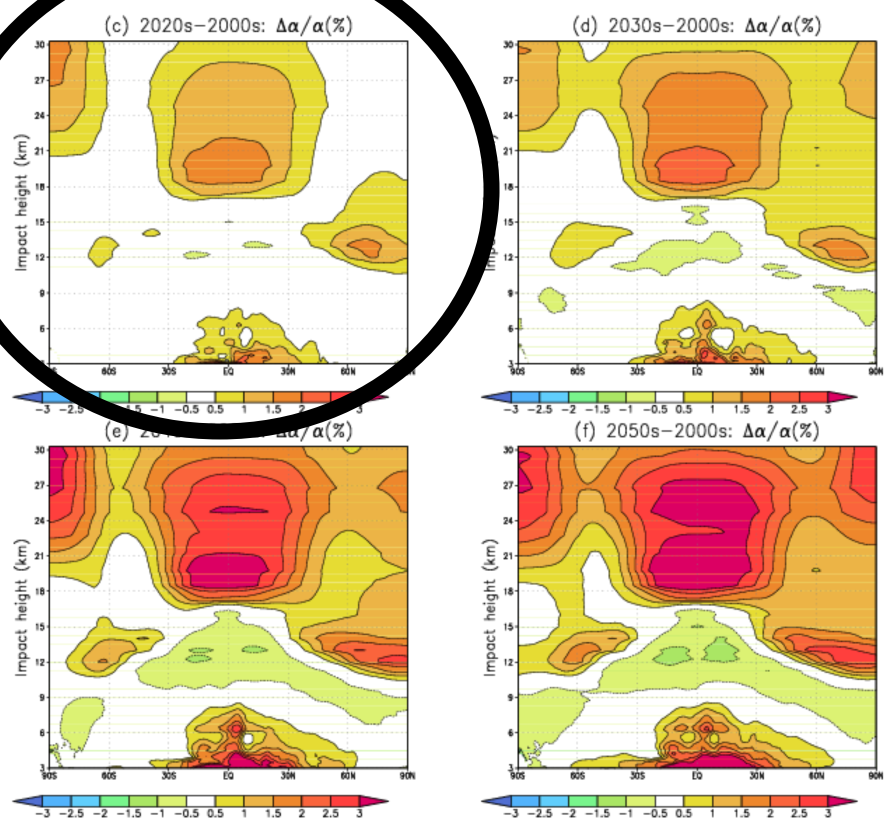
- Met Office Hadley Centre coupled climate model (HadGEM1)
- Climate change scenario (A1B) for 2000 – 2100
- Forward modelling of the GNSS-RO bending angles – **what does this climate scenario look like in bending angle space?**

Provided by Mark Ringer (Hadley Centre)

Change in zonally averaged bending angles vs 2000



Change in zonally averaged bending angles vs 2000

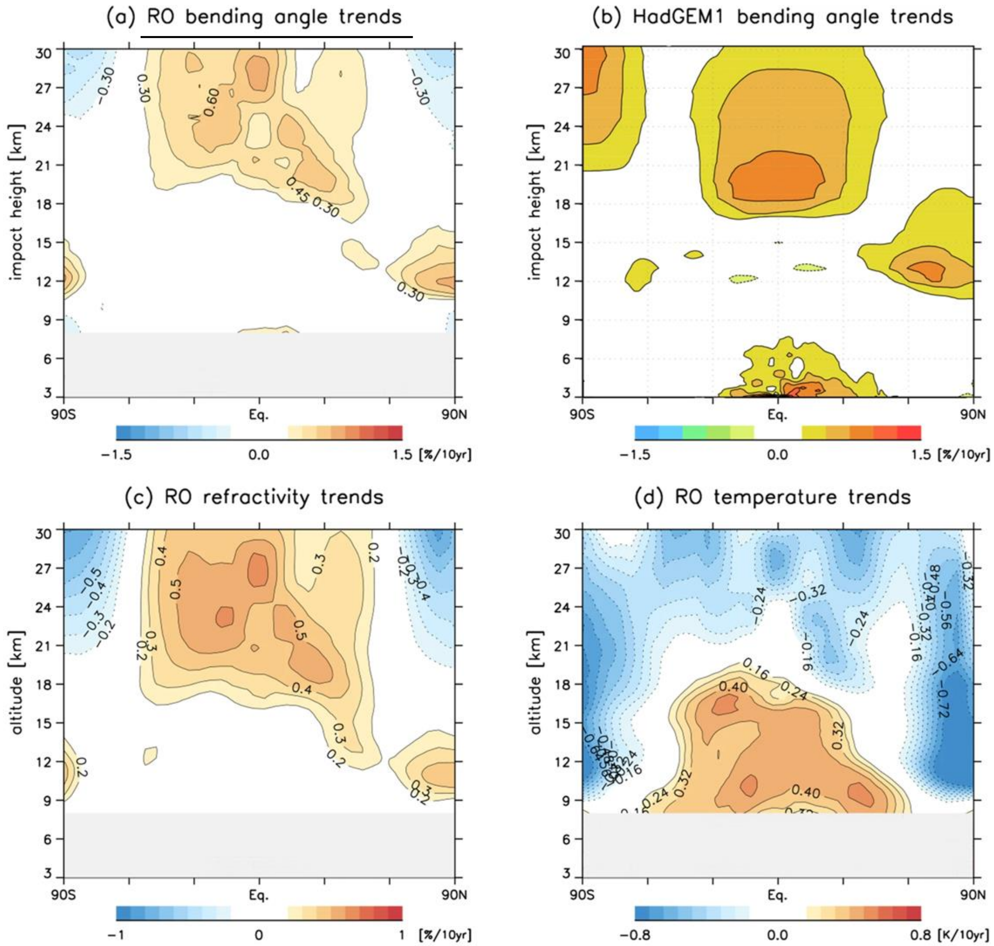


ROM SAF

(published 2022)

Simulated in 2006

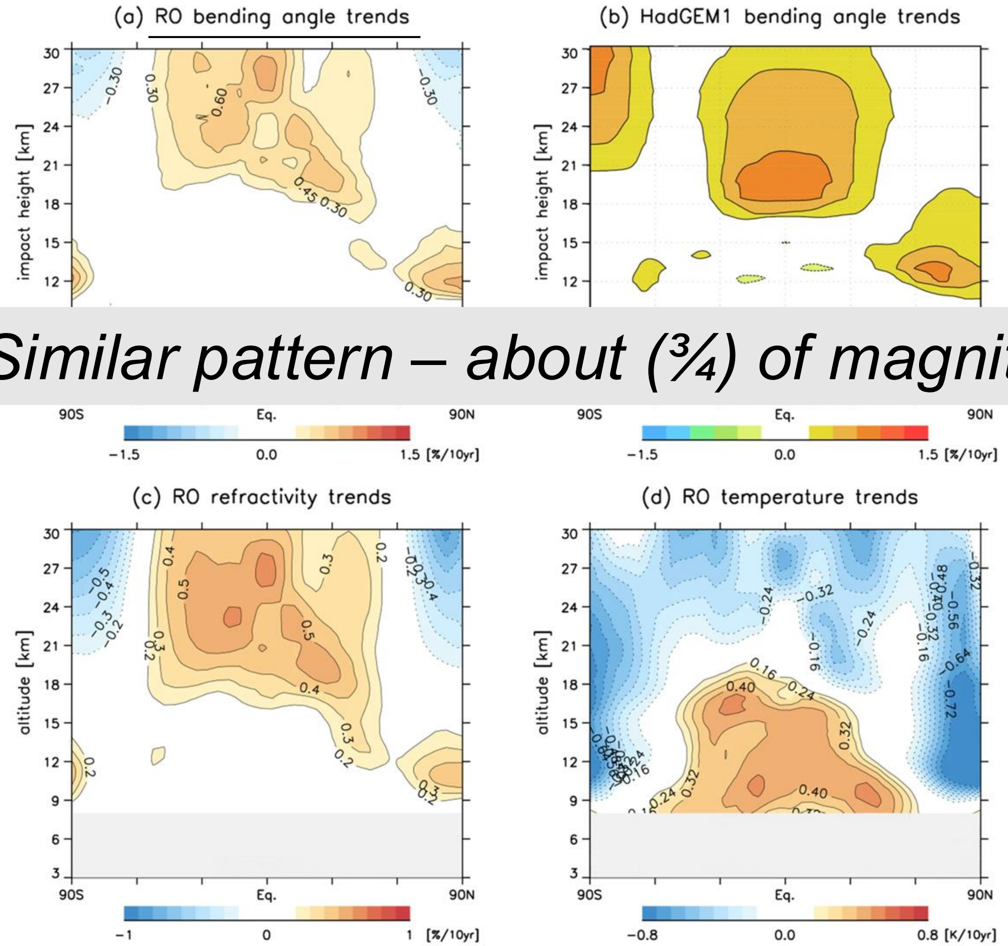
(published 2007)



https://www.nature.com/articles/s41612-022-00229-7

ROM SAF | Simulated in 2006

(published 2022) | (published 2007)



Similar pattern – about (¾) of magnitude

https://www.nature.com/articles/s41612-022-00229-7

Problem with monitoring bending angles

- More difficult to interpret than geophysical quantities
  - not intuitive

- Most climate related work looks at temperature/geopotential heights.

Contribution to IPCC AR6*

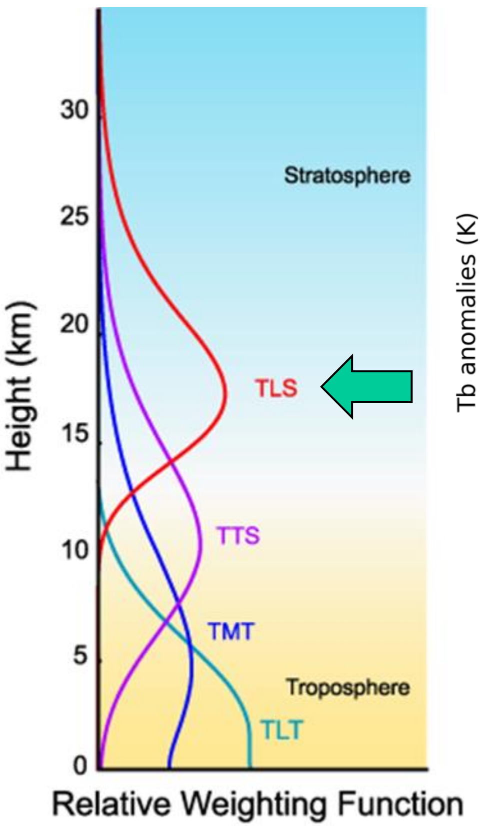
https://www.ipcc.ch/assessment-report/ar6/

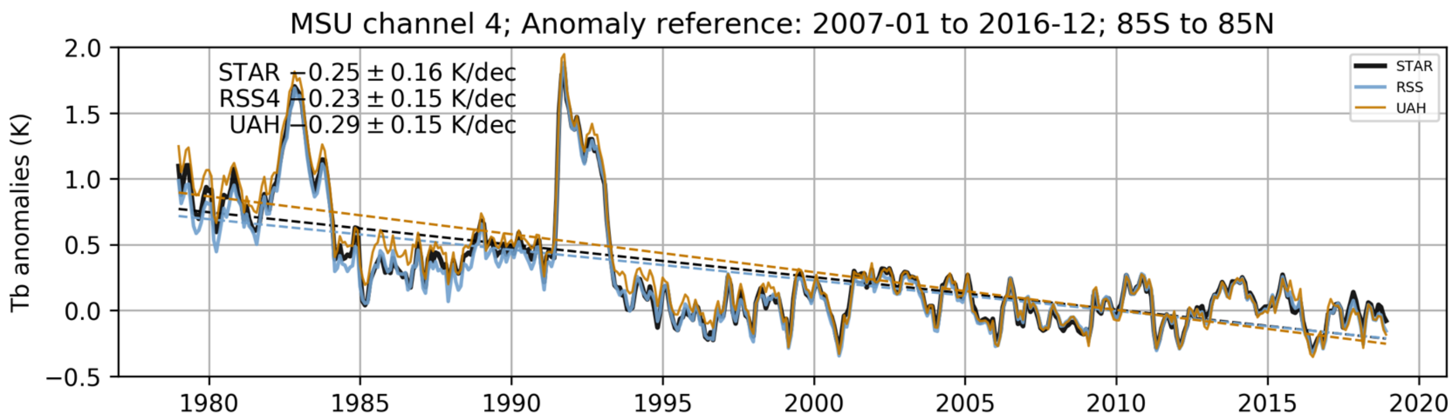
Compare trends retrieved from GNSS-RO in the "core region" with other observations

How do temperature trends in the tropics vary with height? Do the climate models look reasonable?

*The Intergovernmental Panel on Climate Change Assessment Report 6

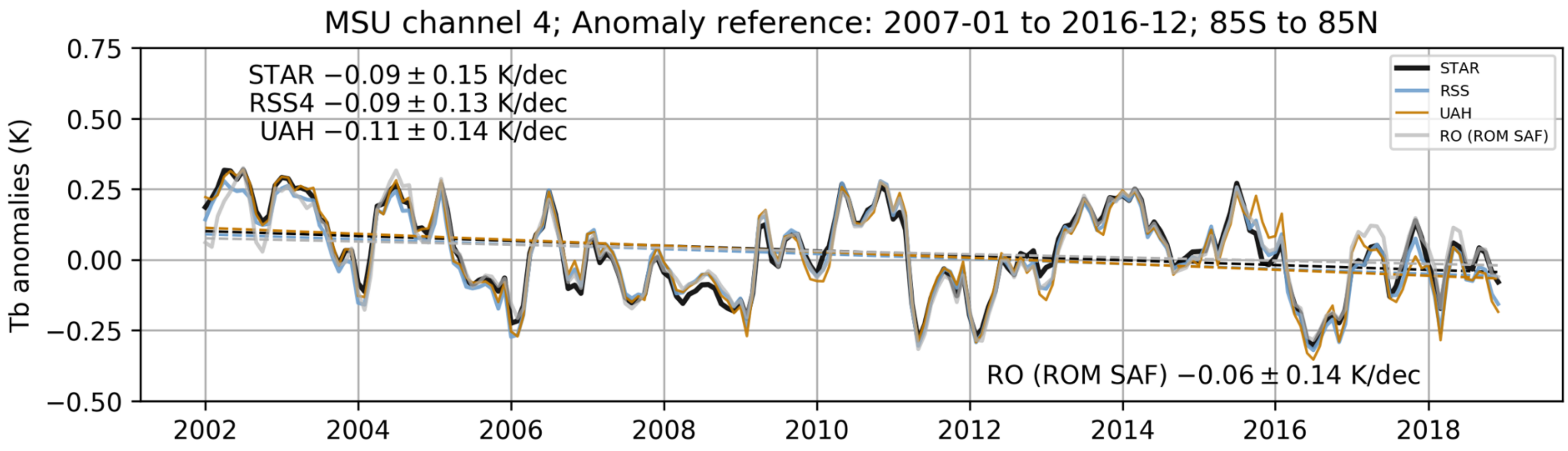
Comparing GNSS-RO with MSU radiances (Global)





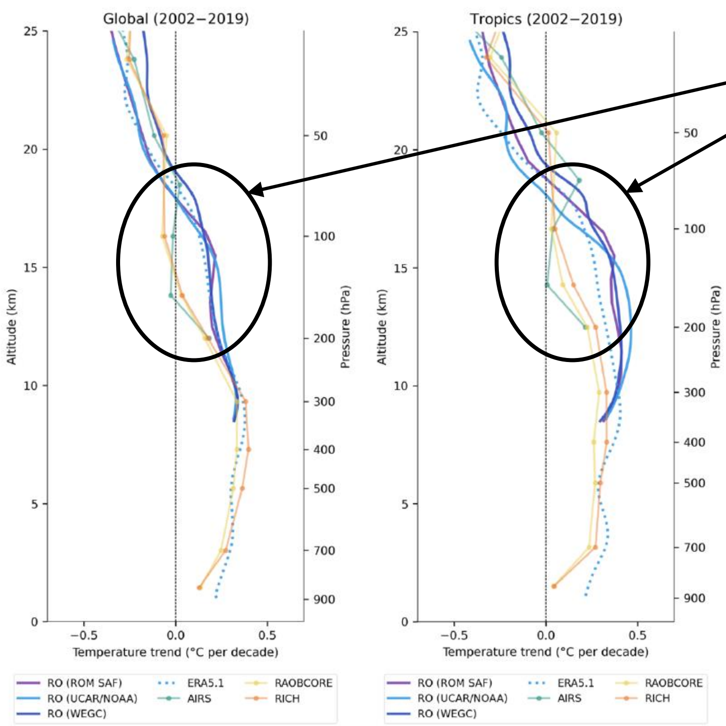
We can forward model GNSS-RO anomalies to MSU ch 4 (AMSU ch 9, TLS) brightness temperatures from 2002 (CHAMP). ***Qu:*** ***Which climate dataset most consistent with GNSS-RO since 2002?***

MSU-4 and GNSS-RO anomalies 2002-2018



Good consistency between MSU-4 and GNSS-RO from 2002.

Obs temperature trends in IPCC AR6



In the AR6 report, the trends in radiosonde and AIRS data are different from RO and ERA5 in the UTLS region.

It has been shown that radiosonde quality can explain the RO-RS differences, and that a subset of higher quality radiosondes agree better with RO (Steiner et al, 2020).

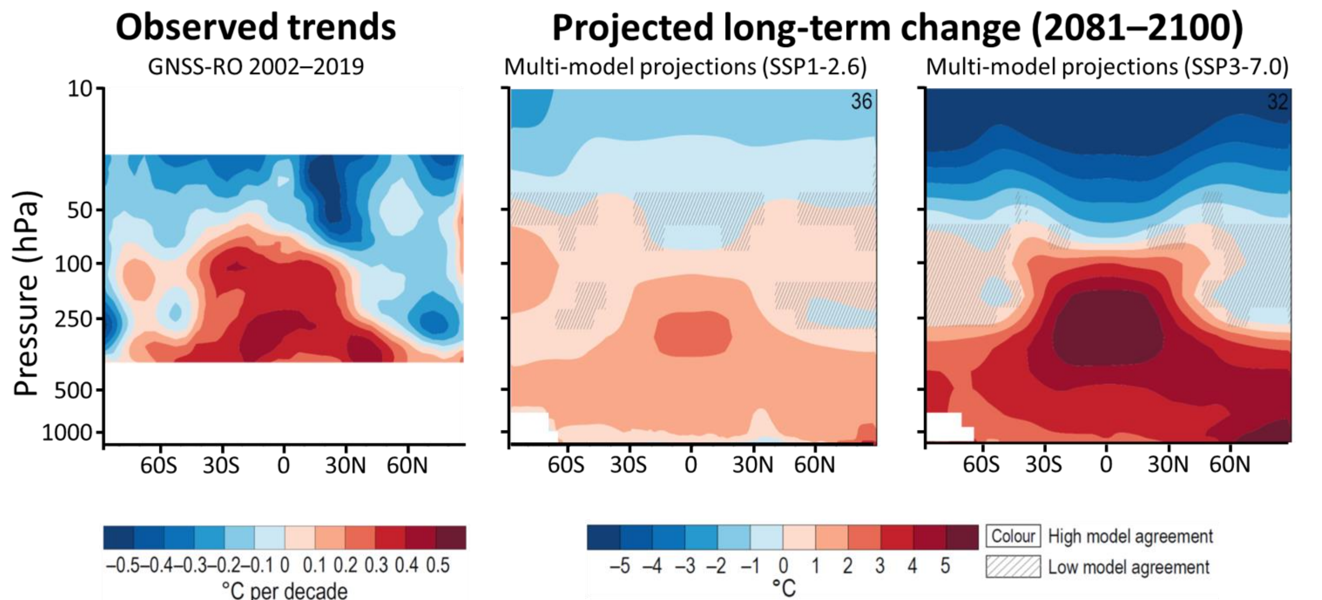
For the RO-AIRS differences, there is currently no generally accepted explanation – it could be cloud contamination, retrieval issues, sampling issues, null space, etc.

From ROM SAF VS40 report (Florian Ladstädter)

https://www.romsaf.eumetsat.int/Publications/reports/romsaf_vs40_rep_v10.pdf

Global upper air temperature trends

contribution to the IPCC AR6 WG1 report

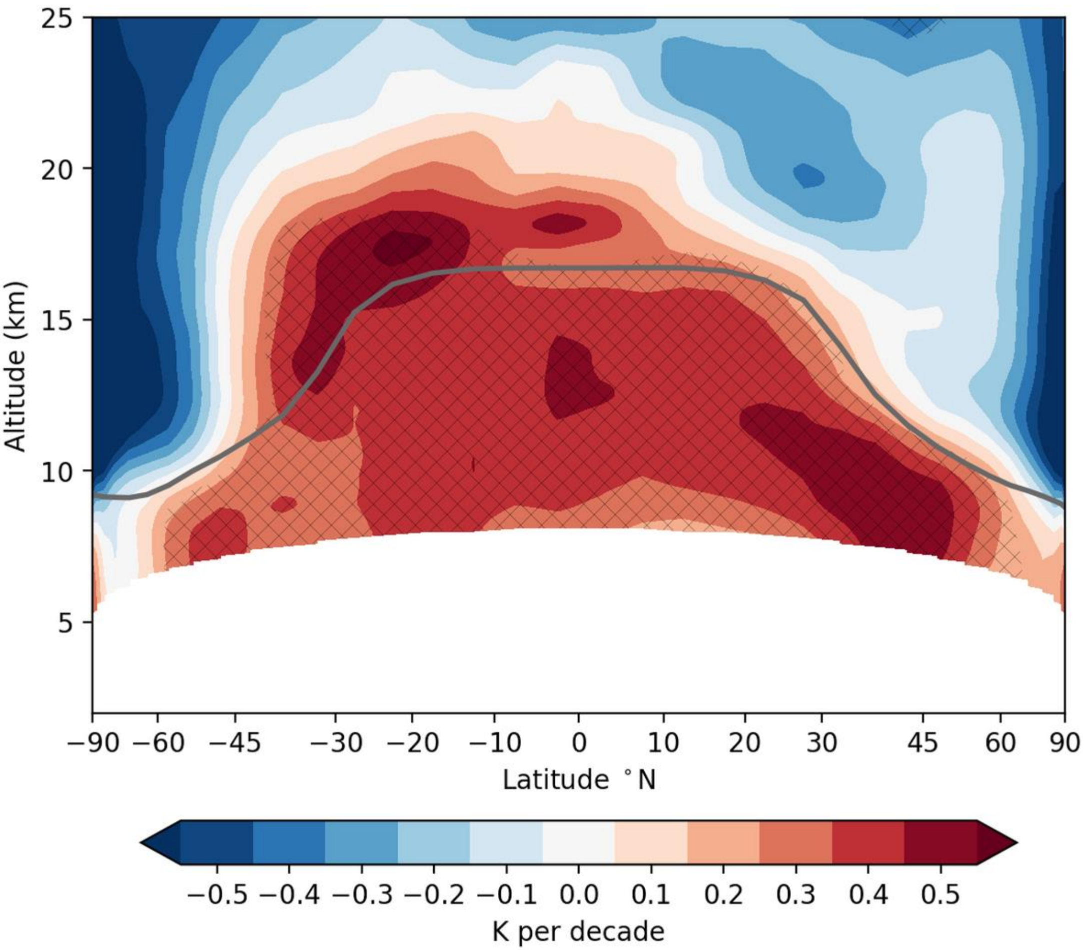


From IPCC AR6 WG 1, Technical Summary

Observed trends in ROM SAF RO data (left) in K/decade compared to projected temperature changes in CMIP6 models under a middle/low scenario (SSP1-2.6) and a middle-high scenario (SSP3-7.0).

Latest results, extending out to December 2021

Ladstädter, F., Steiner, A.K. & Gleisner, H. Resolving the 21st century temperature trends of the upper troposphere–lower stratosphere with satellite observations. *Sci Rep* **13**, 1306 (2023).
https://doi.org/10.1038/s41598-023-28222-x



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Article | Open access | Published: 24 January 2023

Resolving the 21st century temperature trends of the upper troposphere–lower stratosphere with satellite observations

Florian Ladstädter, Andrea K. Steiner & Hans Gleisner

AIRBORNE RO

Essentially targeting GNSS-RO observations by putting a GNSS receiver on an aircraft

Atmospheric rivers

https://doi.org/10.1175/BAMS-D-17-0157.1

THE DEFINITION AS IT APPEARS IN THE *GLOSSARY OF METEOROLOGY*

Atmospheric river–

A long, narrow, and transient corridor of strong horizontal water vapor transport that is typically associated with a low-level jet stream ahead of the cold front of an extratropical cyclone. The water vapor in atmospheric rivers is supplied by tropical and/or extratropical moisture sources.

Atmospheric rivers frequently lead to heavy precipitation where they are forced upward— for example, by mountains or by ascent in the warm conveyor belt. Horizontal water vapor transport in the midlatitudes occurs primarily in atmospheric rivers and is focused in the lower troposphere.

Atmospheric rivers are the largest "rivers" of fresh water on Earth, transporting on average more than double the flow of the Amazon River.

AMS American Meteorological Society | Journals

From: Lavers DA, Wilson AM, Ralph FM, et al. Advancing Atmospheric River Science and Inspiring Future Development of the <u>Atmospheric River Reconnaissance</u> Program. Bull. Amer. Meteor. Soc.. 2024;105(1):E75-E83. doi:10.1175/BAMS-D-23-0278.1

DOI: https://doi.org/10.1175/BAMS-D-23-0278.1

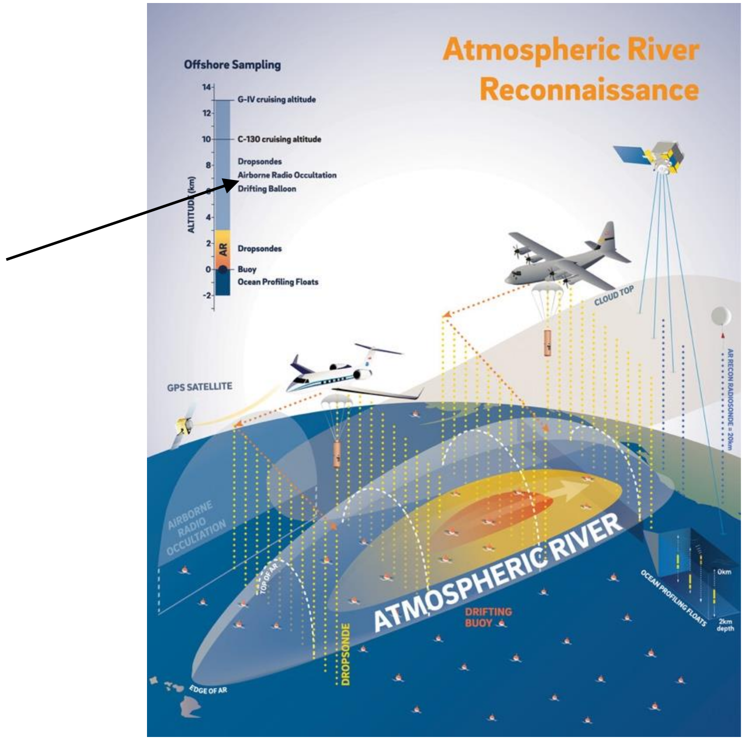


Fig. 2. A schematic showing the observing platforms currently used in the AR Recon program. This is an updated schematic that was first published in Zheng et al. (2021).

From: Lavers DA, Wilson AM, Ralph FM, et al. Advancing Atmospheric River Science and Inspiring Future Development of the Atmospheric River Reconnaissance Program. Bull. Amer. Meteor. Soc.. 2024;105(1):E75-E83. doi:10.1175/BAMS-D-23-0278.1
DOI: https://doi.org/10.1175/BAMS-D-23-0278.1

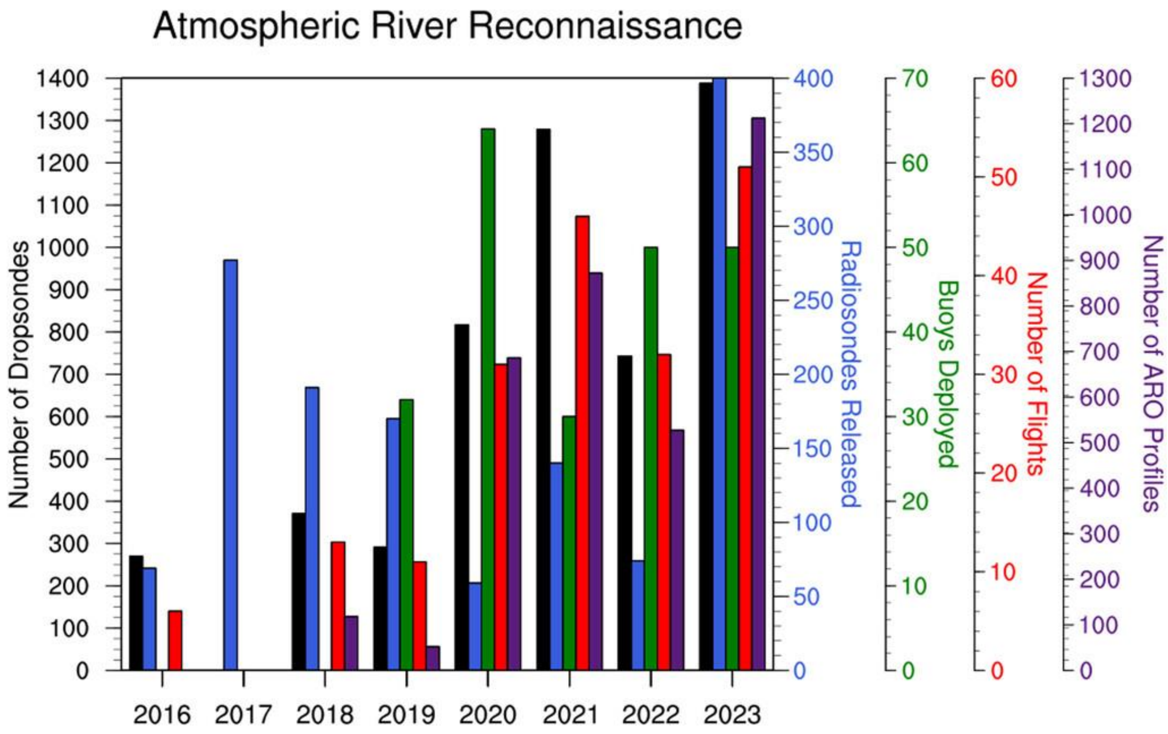
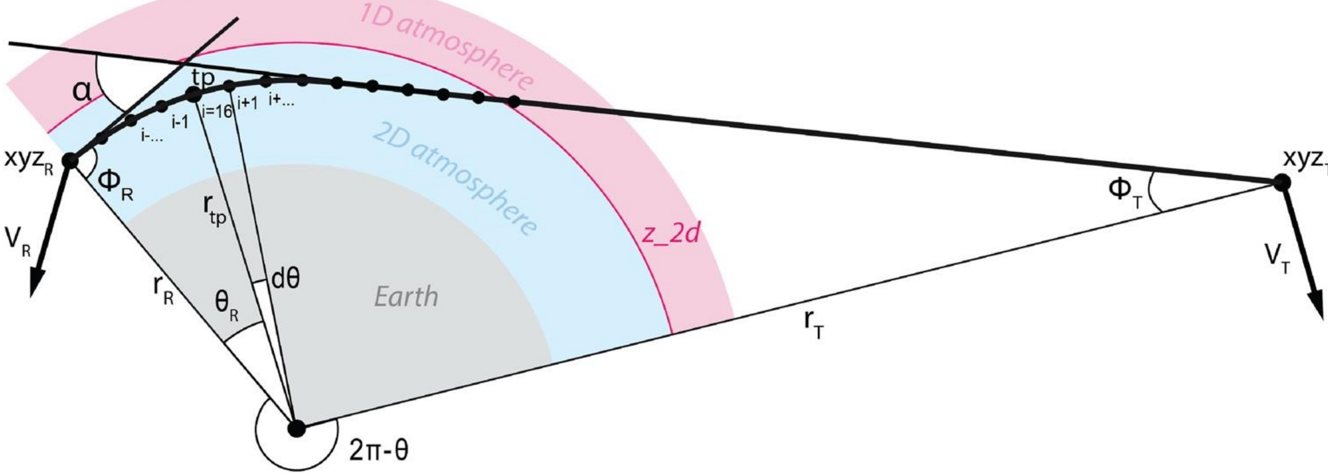
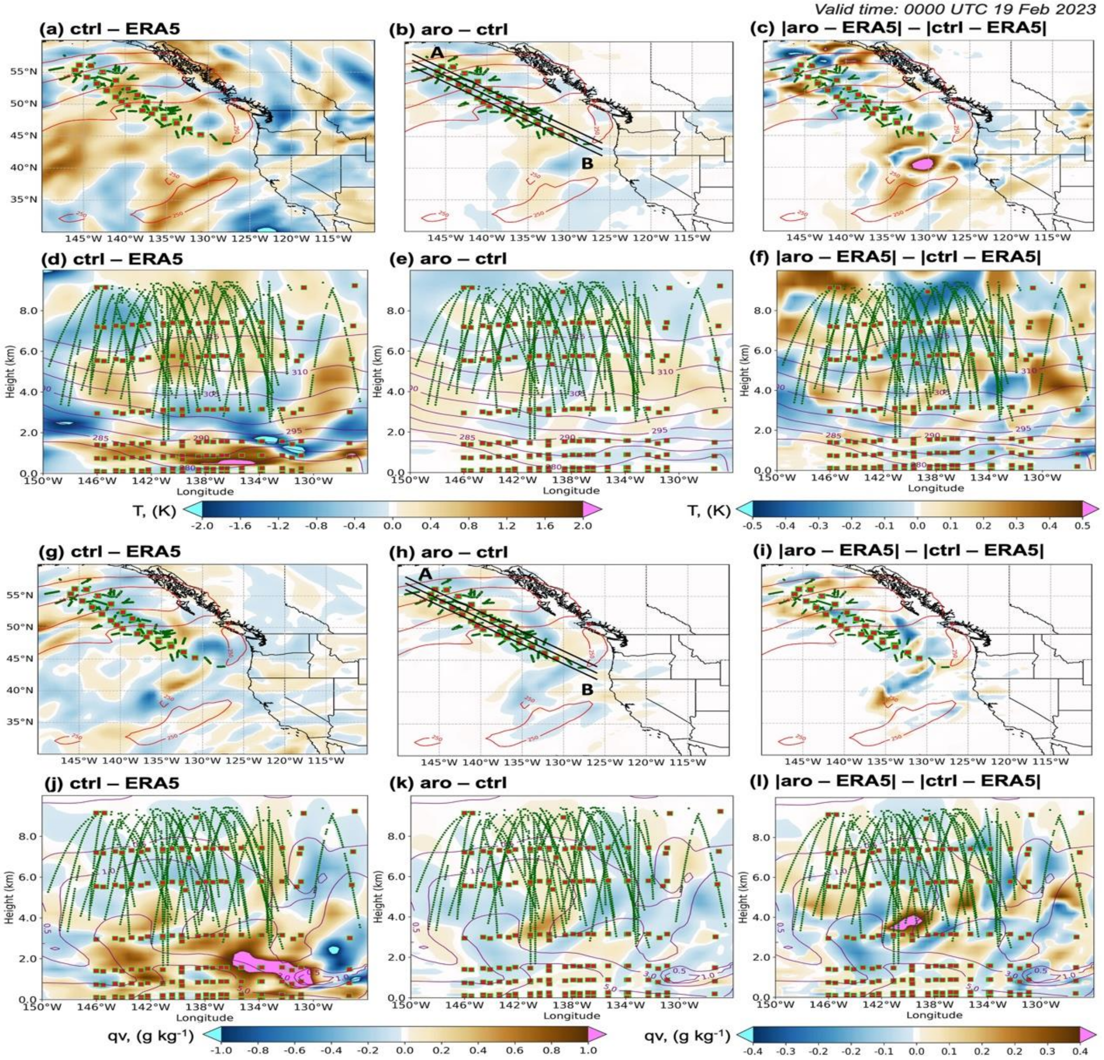


Fig. 1. A bar chart of the number of observations in each AR Recon season since 2016. The figure includes the number of dropsondes (black), radiosondes (blue), drifting buoys (green), flights (red), and ARO profiles (purple).

Forward Modeling of Bending Angles *With a Two-Dimensional Operator for GNSS Airborne Radio Occultations in Atmospheric Rivers*



J Adv Model Earth Syst, Volume: 17, Issue: 4, First published: 12 April 2025, DOI: (10.1029/2024MS004324)



Geophysical Research Letters, Volume: 52, Issue: 13, First published: 03 July 2025, DOI: (10.1029/2025GL115639)

Polarimetric RO: a modification to the standard GNSS-RO concept

(Slides, Estel Cardellach).

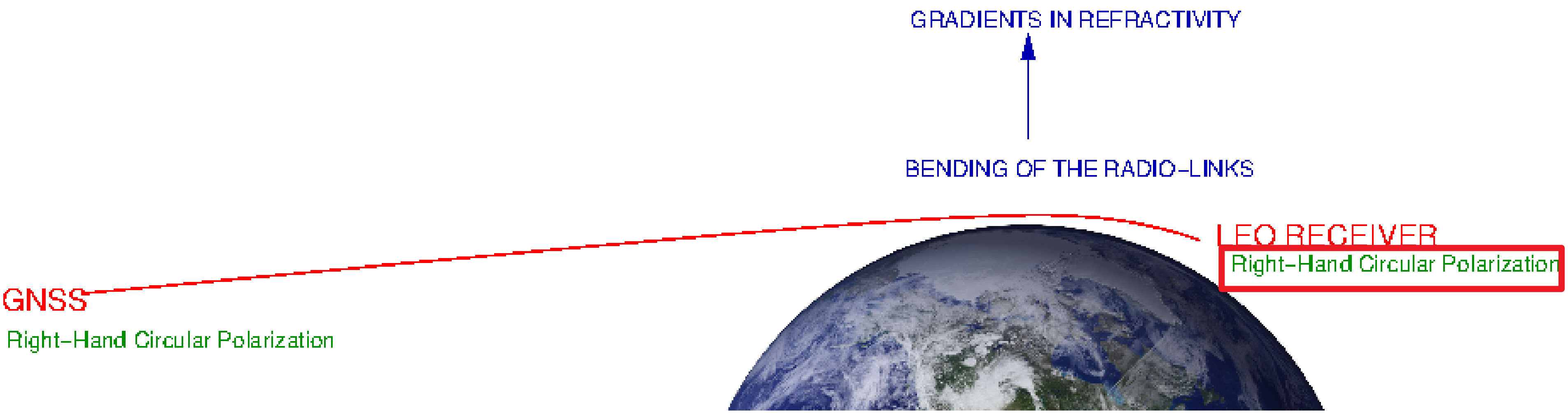
Geophysical Research Letters

Research Letter | Open Access

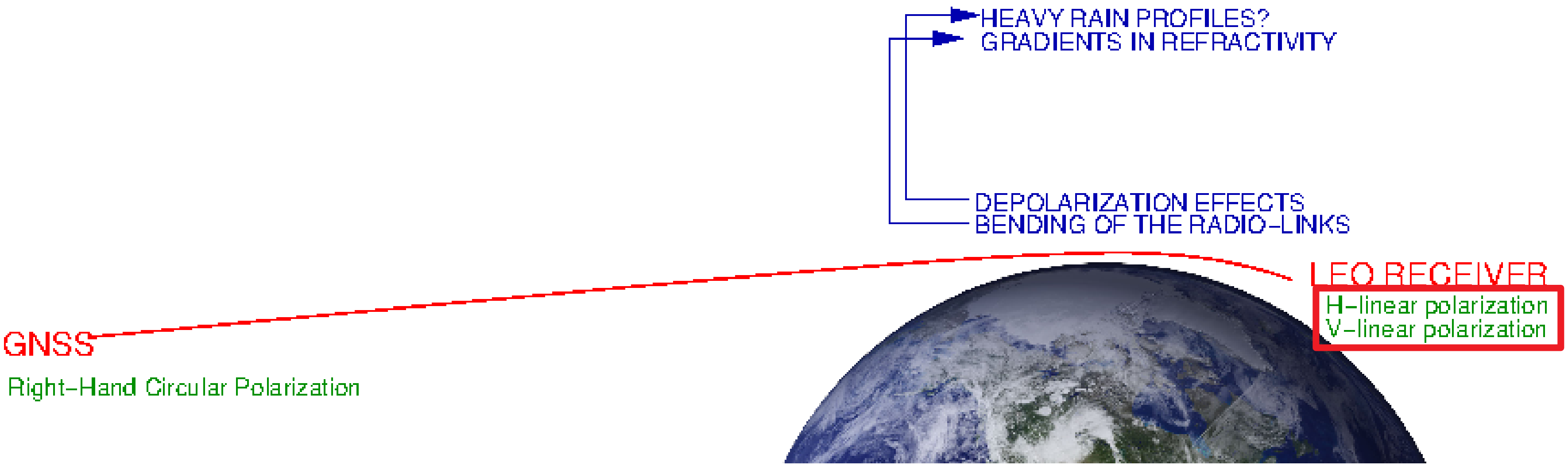
Sensing Heavy Precipitation With GNSS Polarimetric Radio Occultations

E. Cardellach, S. Oliveras, A. Rius, S. Tomás, C. O. Ao, G. W. Franklin, B. A. Iijima, D. Kuang, T. K. Meehan, R. Padullés, M. de la Torre Juárez, F. J. Turk, D. C. Hunt, W. S. Schreiner ... See all authors

First published: 21 December 2018 | https://doi.org/10.1029/2018GL080412



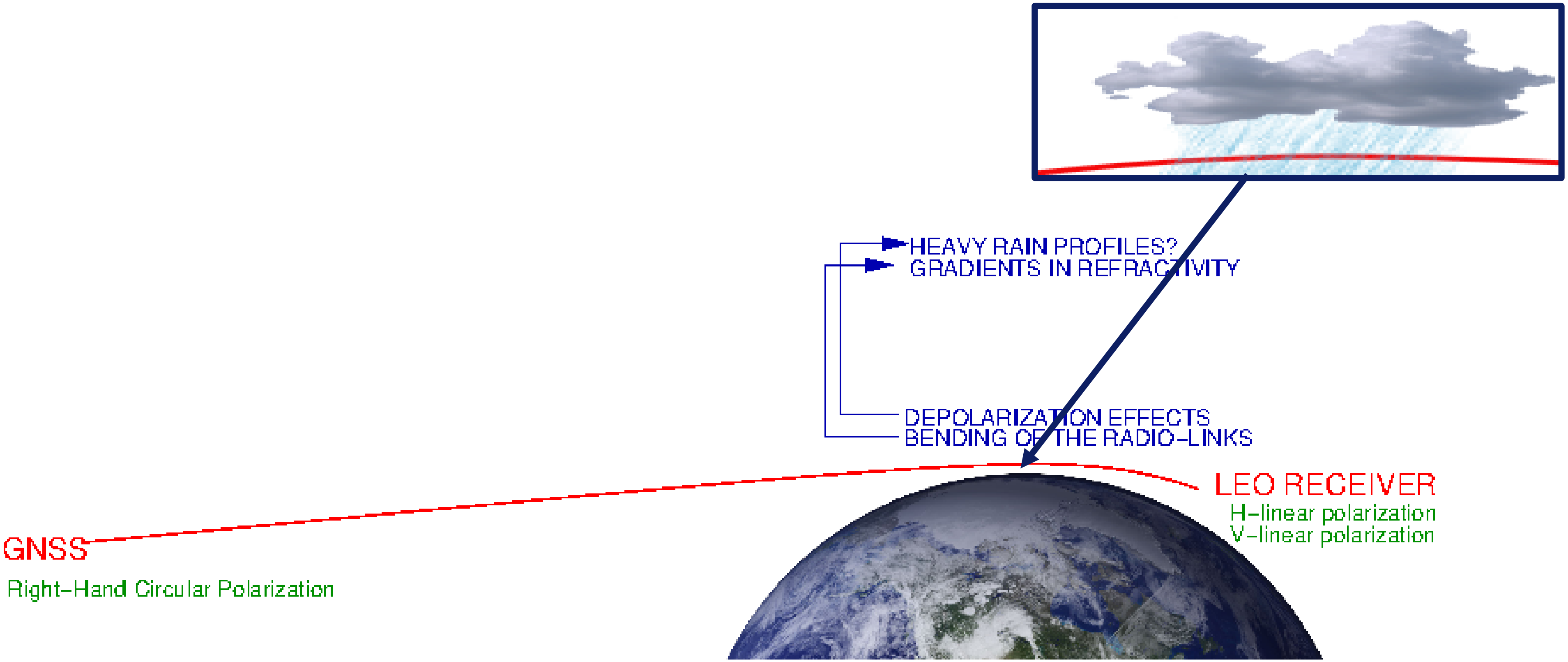
'TYPICAL' GNSS RO PRODUCTS: *VERTICAL PROFILES OF THERMODYNAMIC VARIABLES at the tangent point (typically temperature, pressure, humidity)*



'NEW' GNSS-PRO PRODUCTS:

VERTICAL PROFILES OF THERMODYNAMIC VARIABLES (typically temperature, pressure, water vapor)

+ VERTICAL PROFILES OF INTENSE RAIN



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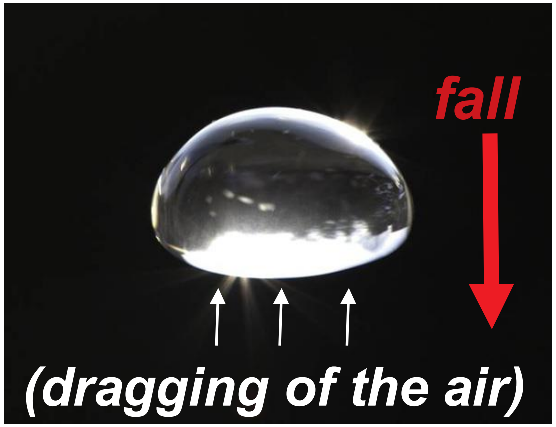
VERTICAL PROFILES OF THERMODYNAMIC VARIABLES (typically temperature, pressure, water vapor)

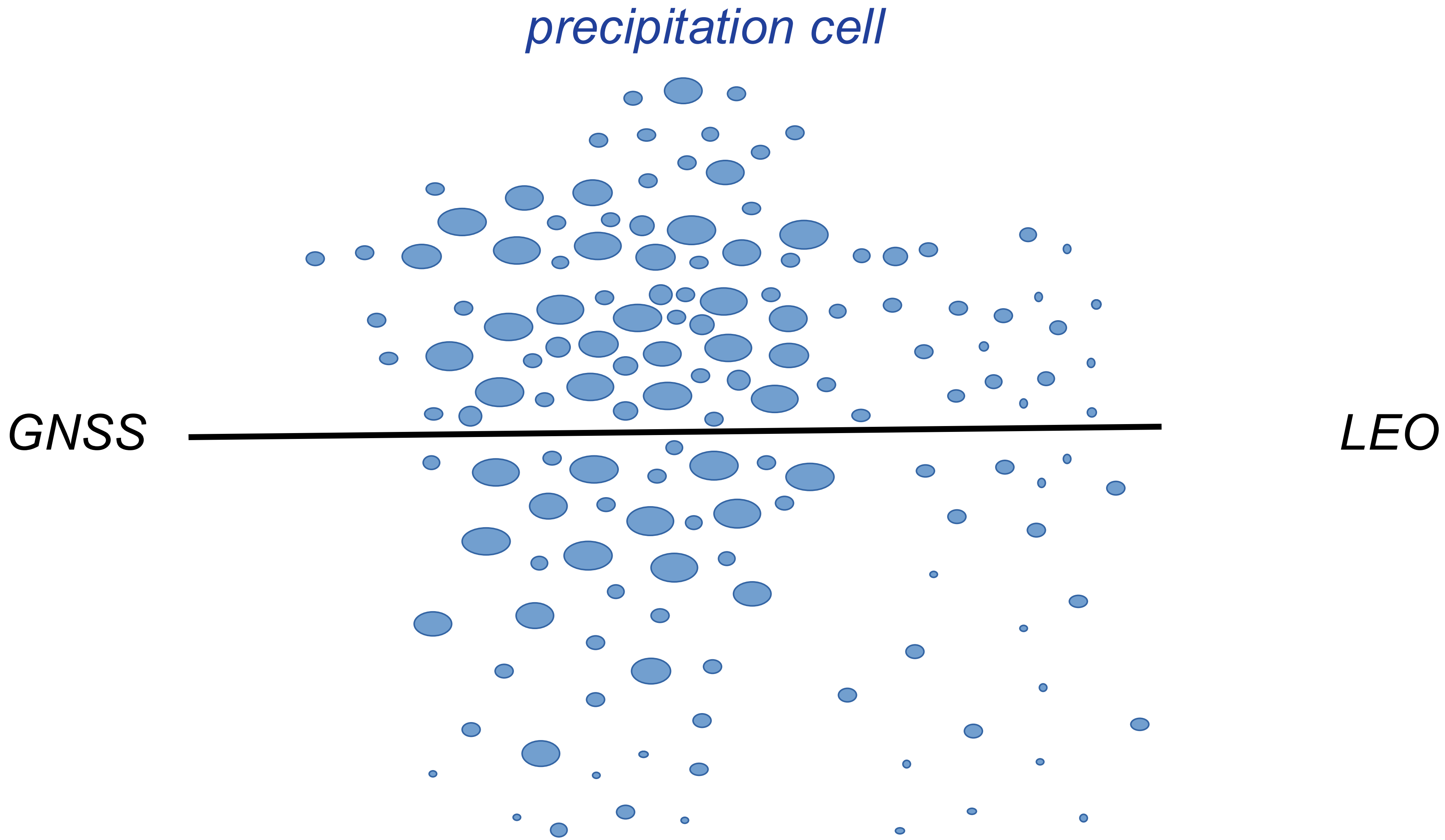
+ VERTICAL PROFILES OF INTENSE RAIN

To understand this concept it is important to keep in mind that the big falling rain drops ARE NOT like this

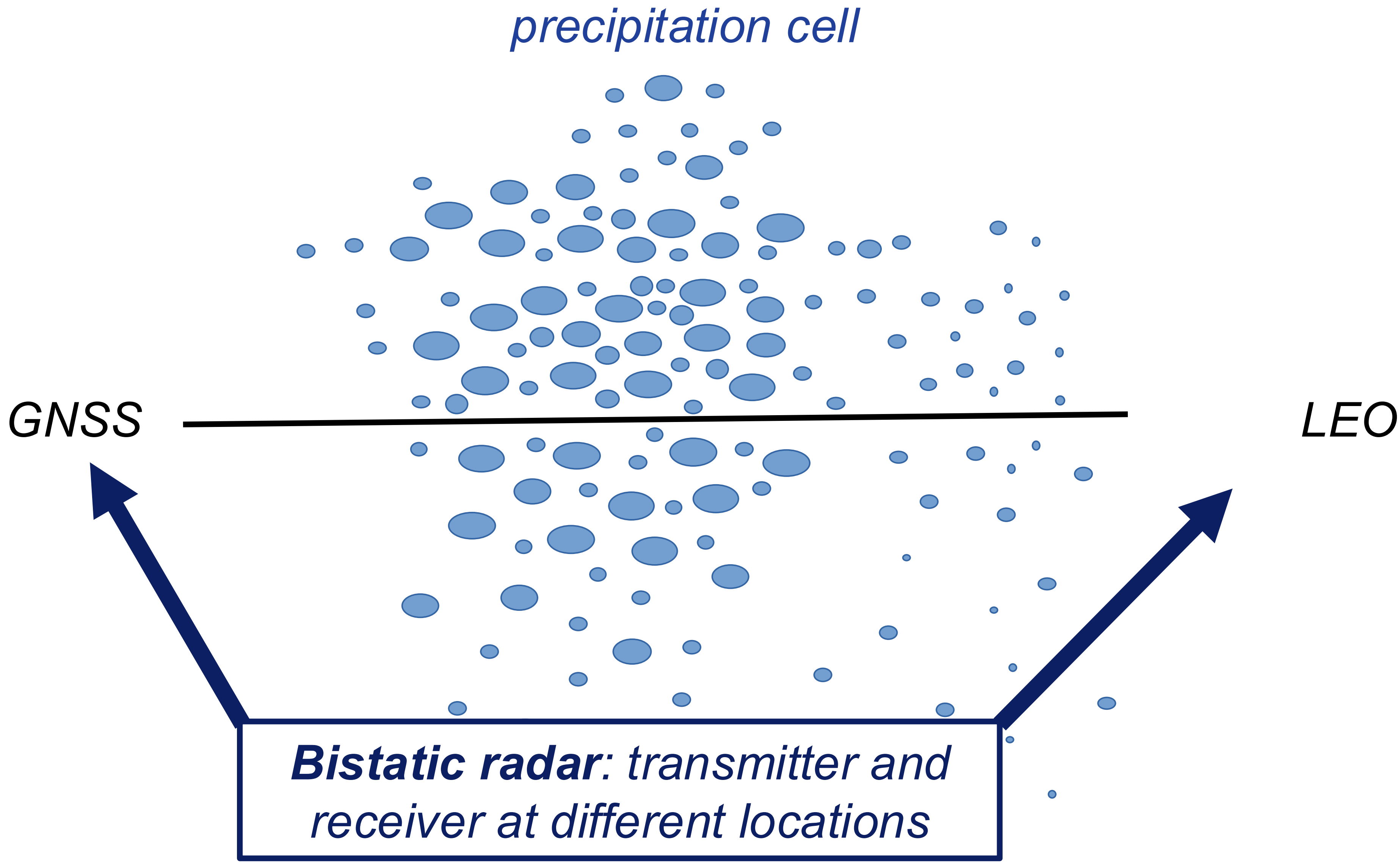
but rather LIKE

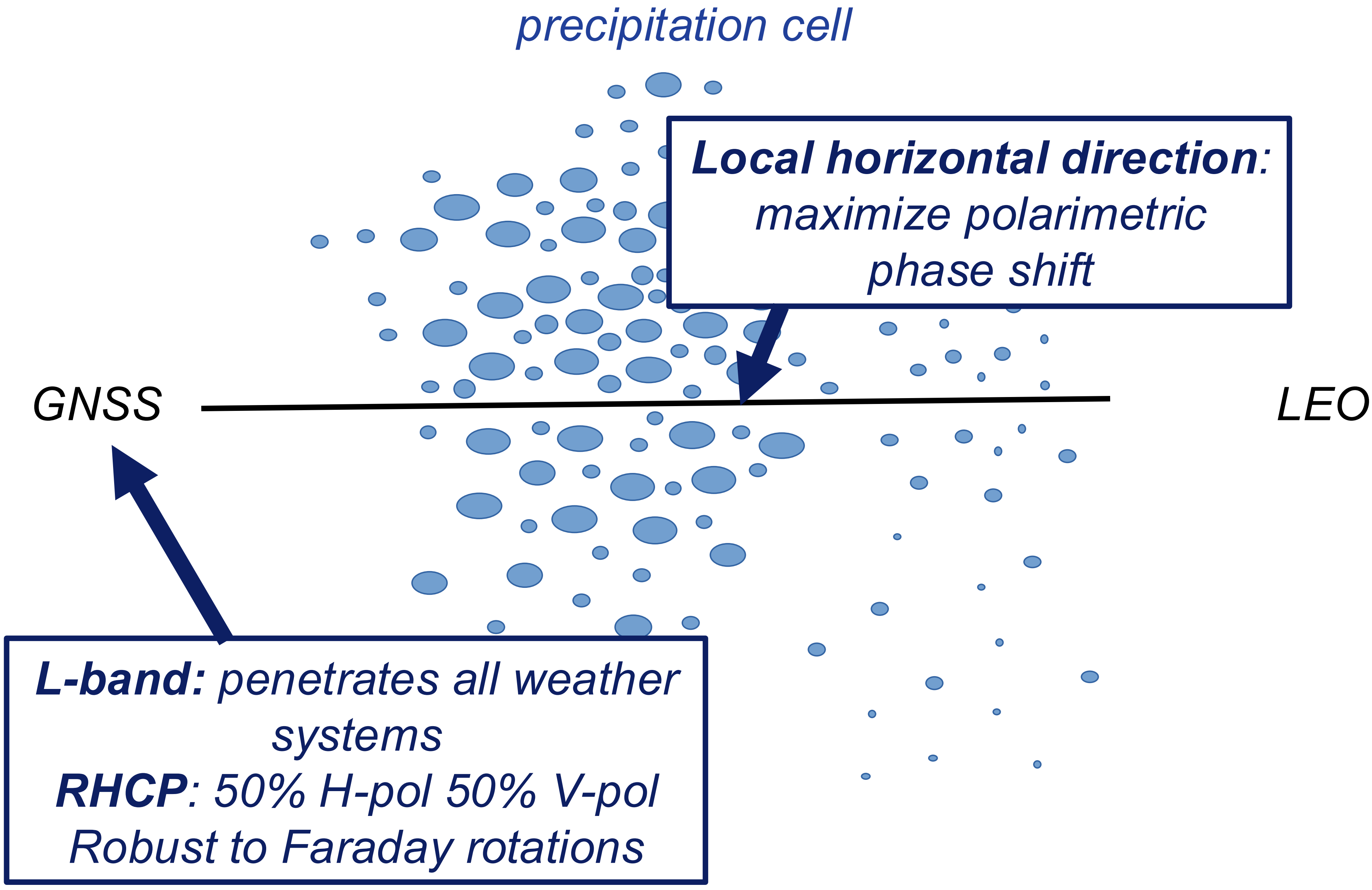


Vertical dimension shorter than Horizontal dimension → different propagation delays

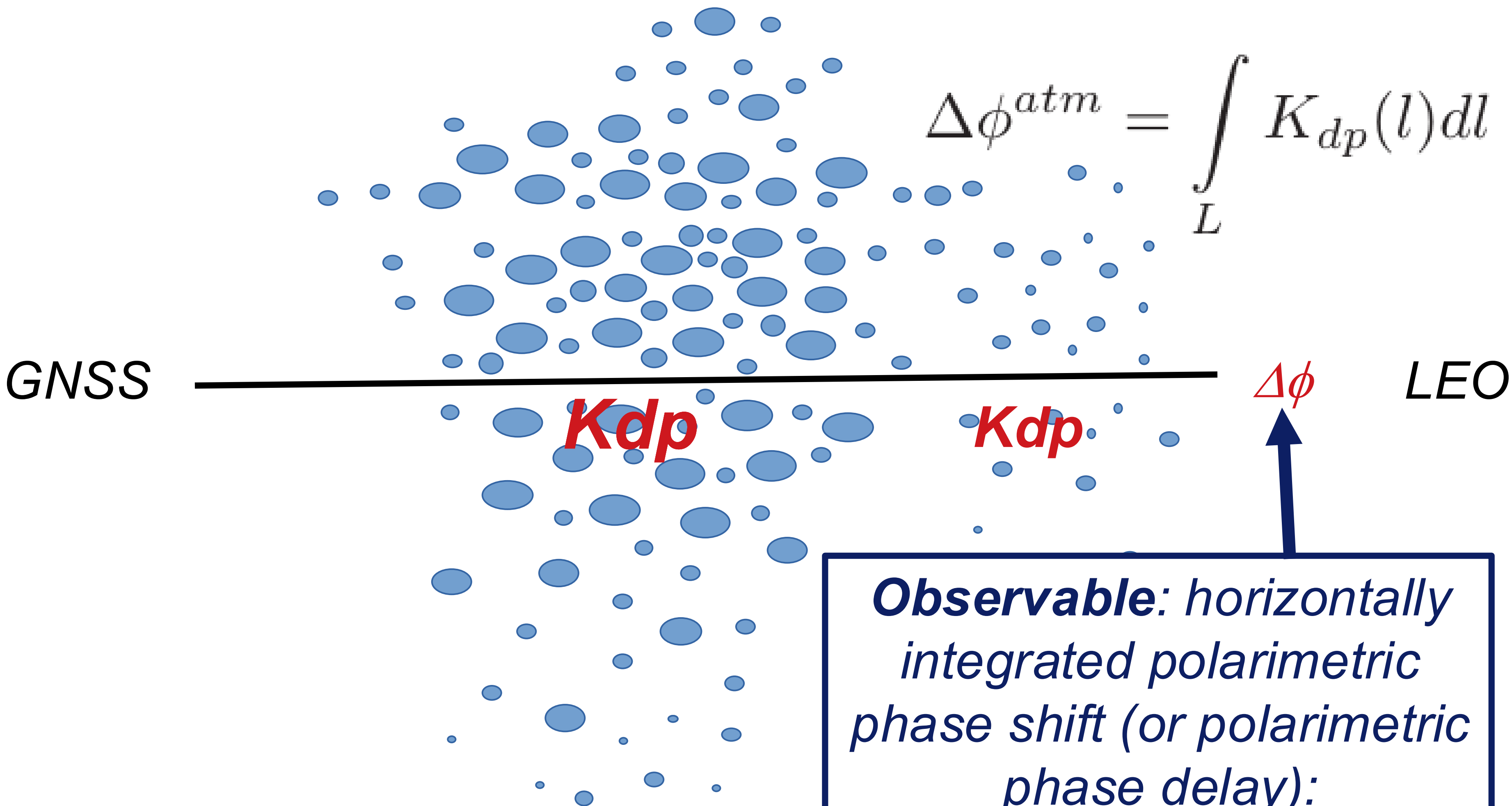


precipitation cell
GNSS
LEO


precipitation cell
GNSS
LEO
Bistatic radar: transmitter and receiver at different locations


precipitation cell
Local horizontal direction: maximize polarimetric phase shift
GNSS
LEO
L-band: penetrates all weather systems
RHCP: 50% H-pol 50% V-pol
Robust to Faraday rotations

precipitation cell

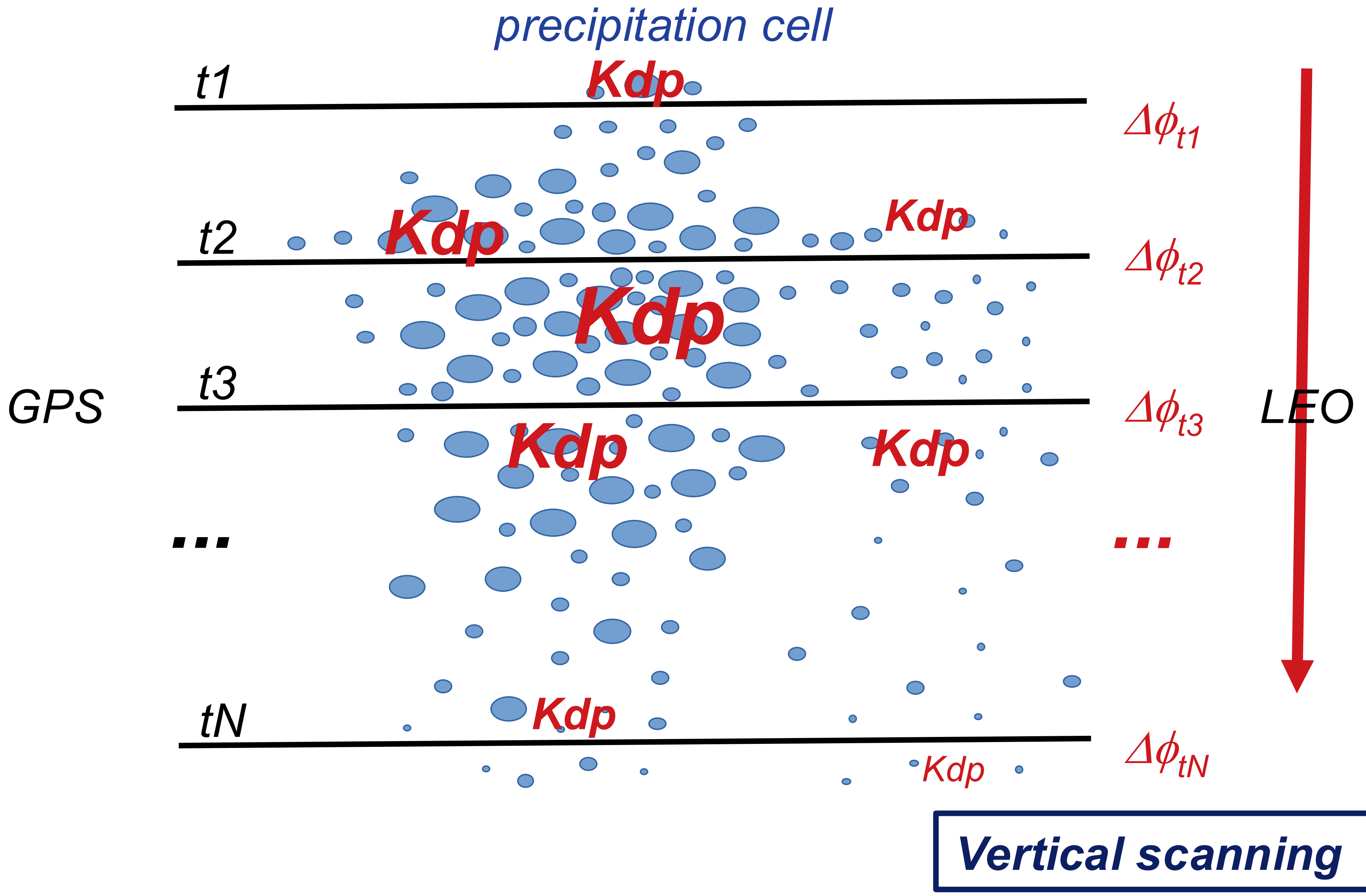


$$\Delta\phi^{atm} = \int_L K_{dp}(l)dl$$

***Observable**: horizontally integrated polarimetric phase shift (or polarimetric phase delay):*

$\Delta\phi = \phi_H - \phi_V$

Delay of H-pol longer than V-pol!



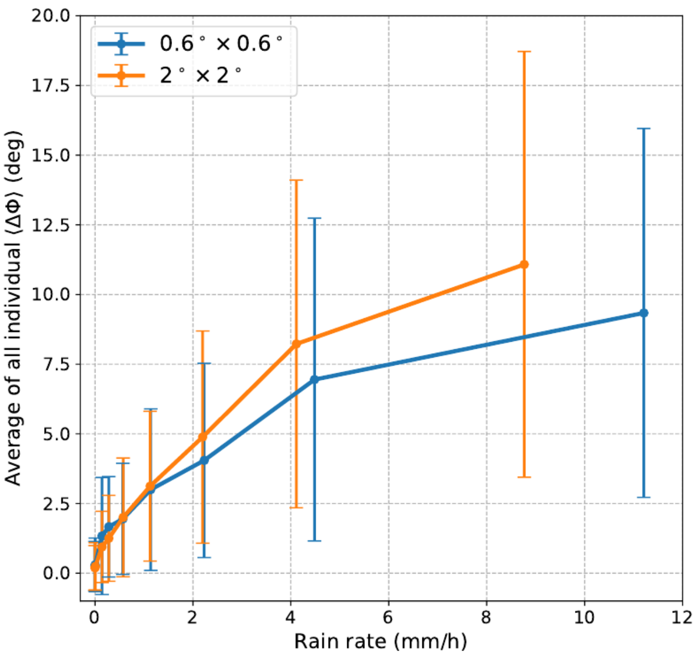
precipitation cell
t1
Kdp
$\Delta\phi_{t1}$
t2
Kdp
Kdp
$\Delta\phi_{t2}$
Kdp
GPS
t3
$\Delta\phi_{t3}$
LEO
Kdp
Kdp
...
...
tN
Kdp
$\Delta\phi_{tN}$
Kdp
Vertical scanning

Measurement concept being tested aboard the PAZ satellite (ROHP-PAZ experiment)

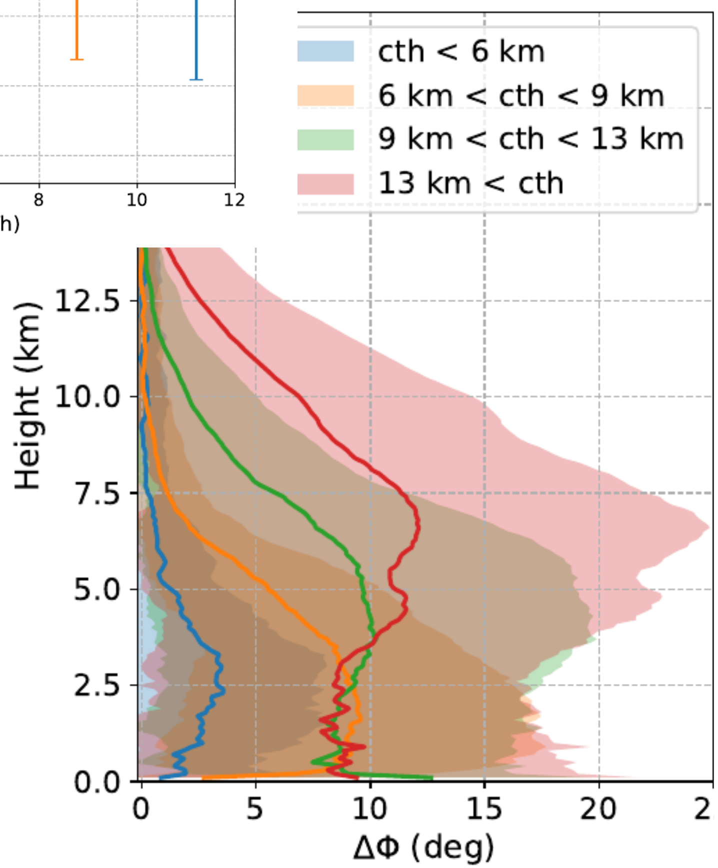
*Sucessful launch on **February 22, 2018**, by SpaceX (Falcon9).*

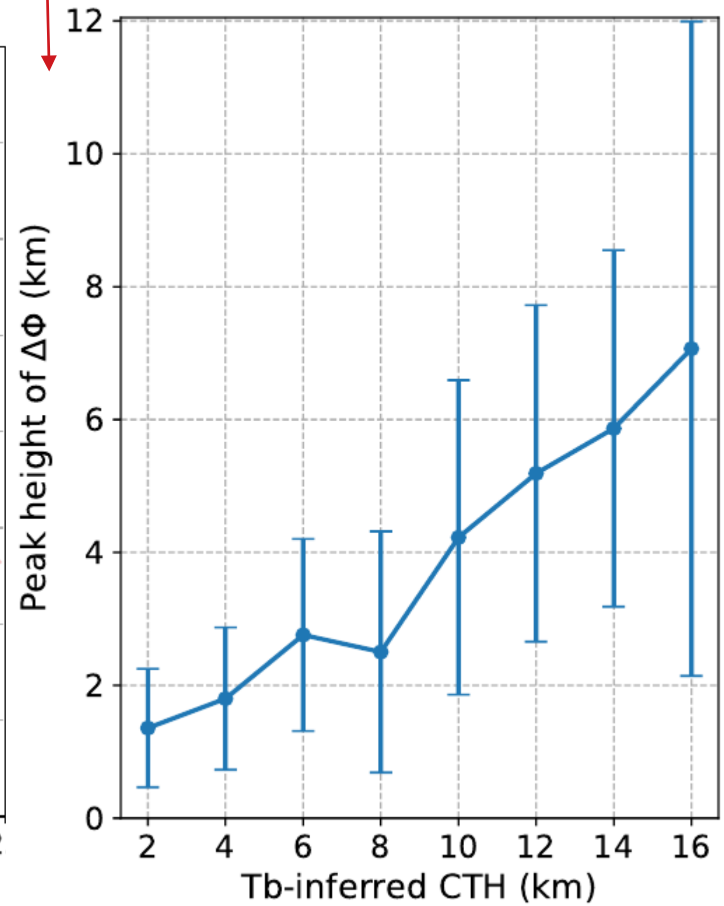
*GNSS RO experiment **activated on May 10**, 2018.*

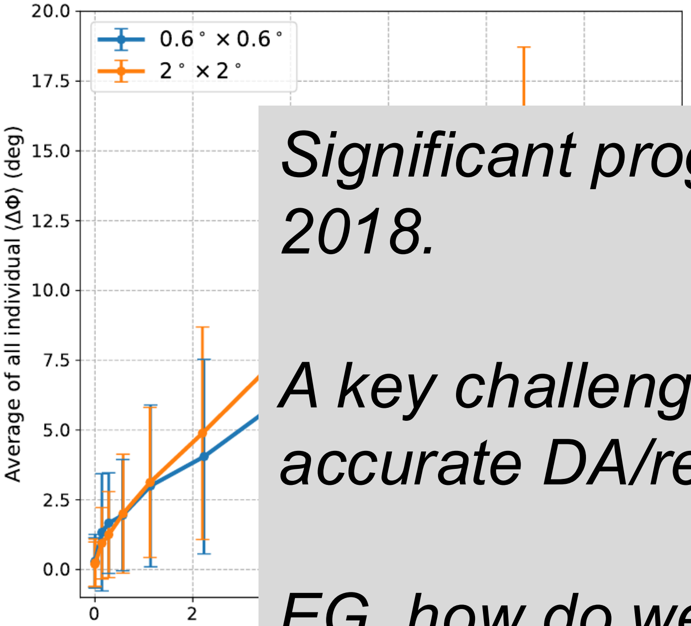
Rain rate vs polarimetric delay



polarimetric delay as function of altitude and Cloud Top Height (cth)







Rain rate vs polarimetric delay

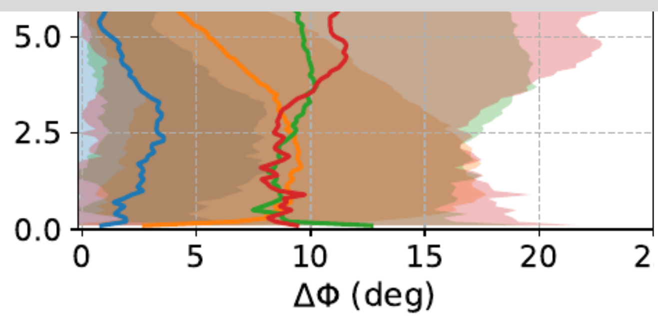
th)

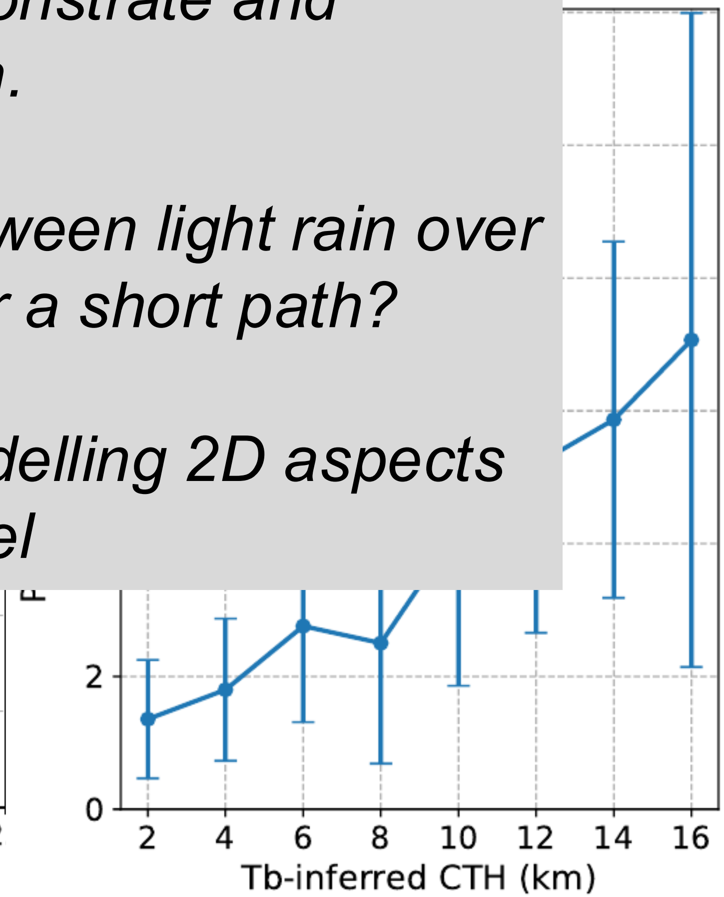
Significant progress since the launch of PAZ in 2018.

A key challenge will be to demonstrate and accurate DA/retrieval approach.

EG, how do we distinguish between light rain over a long path or intense rain over a short path?

If we assimilated this data, modelling 2D aspects will be key –> 2D forward model





PRO observable Φ_{DP} (differential phase shift) and its analogy to GNSS-RO bending angle

- PRO observable
- = integral of K_{DP} along the ray path:

$$\Phi_{\mathrm{DP}} = \int_{\mathrm{GNSS}}^{\mathrm{LEO}} K_{\mathrm{DP}}(s)\,ds$$

- *RO observable*
- *= bending angle*
- *= integral of infinitesimal bending along the ray path:*

$$\alpha = \int_{\mathrm{GNSS}}^{\mathrm{LEO}} \left(\frac{d\alpha}{ds}\right) ds$$

→*Natural analogy between PRO and regular RO observable*

→*can exploit the existing forward operator for RO bending angle*

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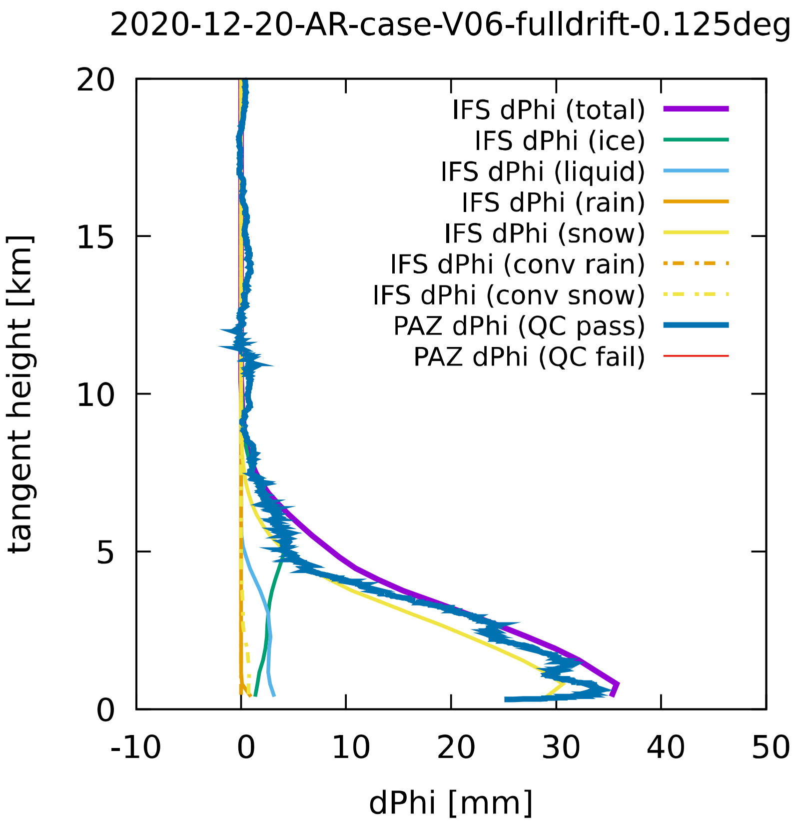
Forward model
https://amt.copernicus.org/articles/17/1075/2024/

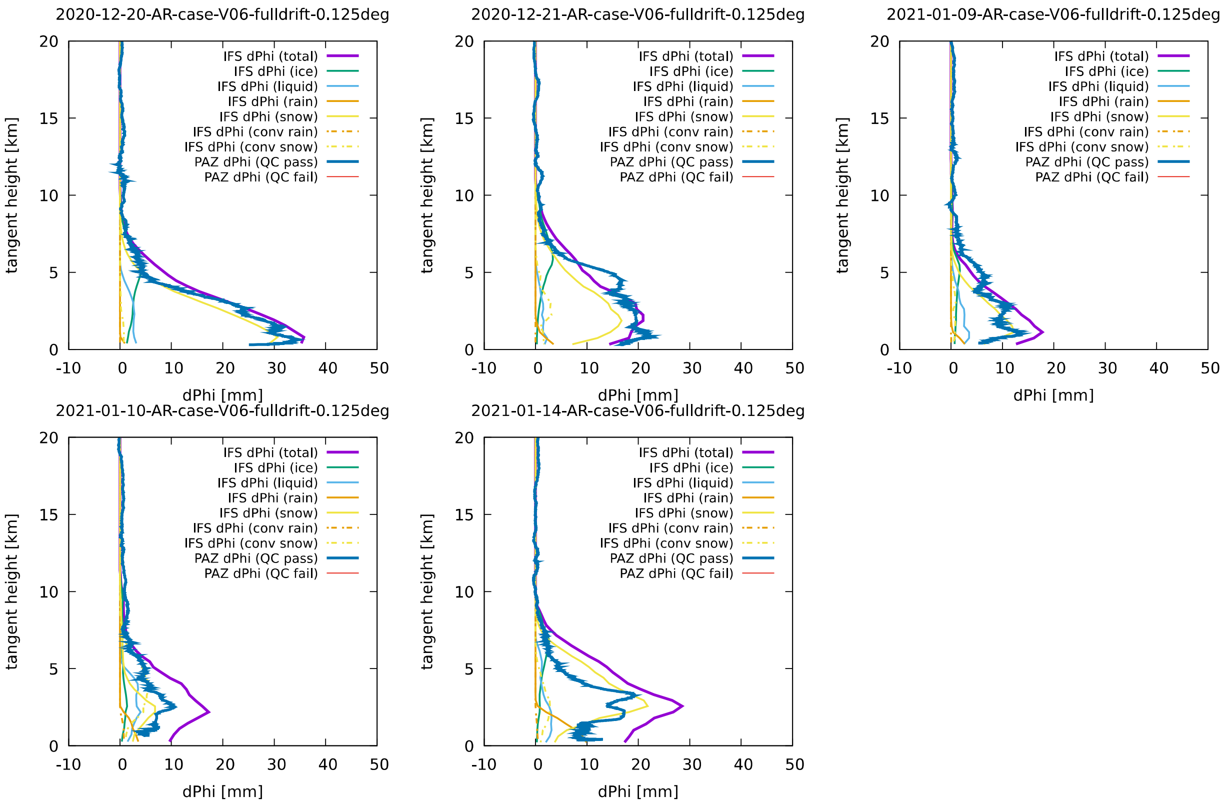
ECMWF

Results: Overall agreement of simulated vs observed Φ_{DP}



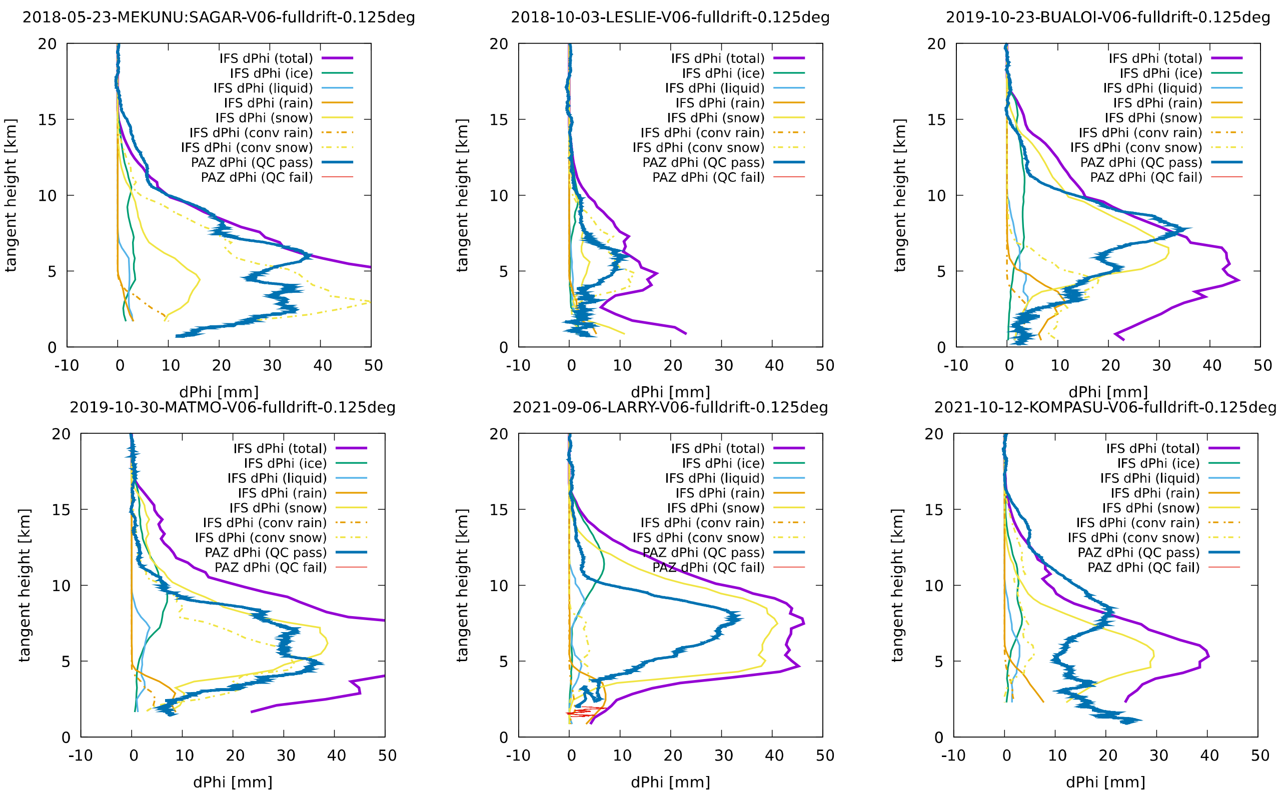
- *Result for an Atmospheric River (AR) case*
- *Very good agreement between simulated total (blue) and observed (purple) profiles.*
  - *despite many simplifying assumptions!*
- *Resolved-scale snow (yellow solid) is the dominant contribution*

Results: Overall agreement of simulated vs observed Φ_{DP}



- *Results for all 5 AR cases*
- *Very good agreement in all the cases,*
- *which is great!*
- *However....*

Results: Overall agreement of simulated vs observed Φ_{DP}



- *Results for all TC cases show poor agreement between simulation and observation*
  - *"Shape" of the profiles do not match*
  - *Amplitude also systematically overestimated*

Summary

- Given an overview of applications and pointed to published sources where possible.

- Recent impact on NWP performance
  - Good, but ROMEX is leading to new questions

- The GNSS-RO are now key observations for climate reanalyses and have led to improved consistency between reanalyses since 2006

- Climate monitoring with GNSS-RO is becoming increasingly important. Inclusion in the IPCC AR6 is an important step forward for the community

- Introduced ARO and the polarimetric RO concept and recent forward modelling work. ESA PRO assimilation project in progress