GNSS radio occultation lecture 2
Impact/ some applications

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NWP SAF lecture 2, March 13, 2024

EUMETSAT ROM SAF

RADIO OCCULTATION METEOROLOGY

http://www.romsaf.org/

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) and OPAC/IROWG (2022)

- See presentations at:
  - https://www.romsaf.org/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/

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
- Retrieving hydrometeor water content
- Summary

***EMAIL me** for 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**

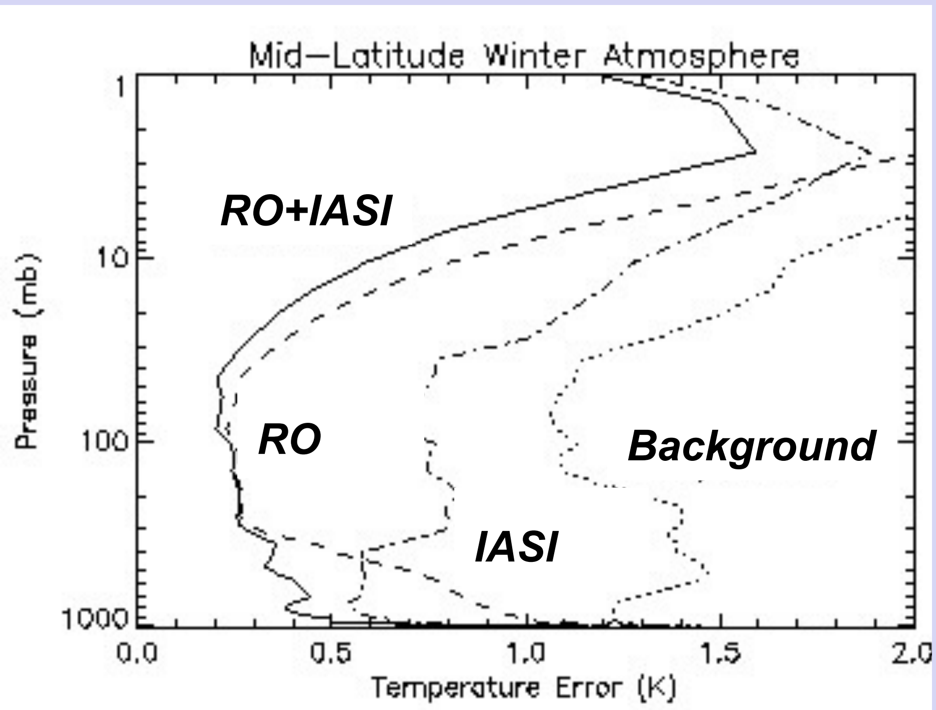
  – Assimilation without bias correction (an "*anchor" measurement)*
  – Good vertical resolution

- 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.

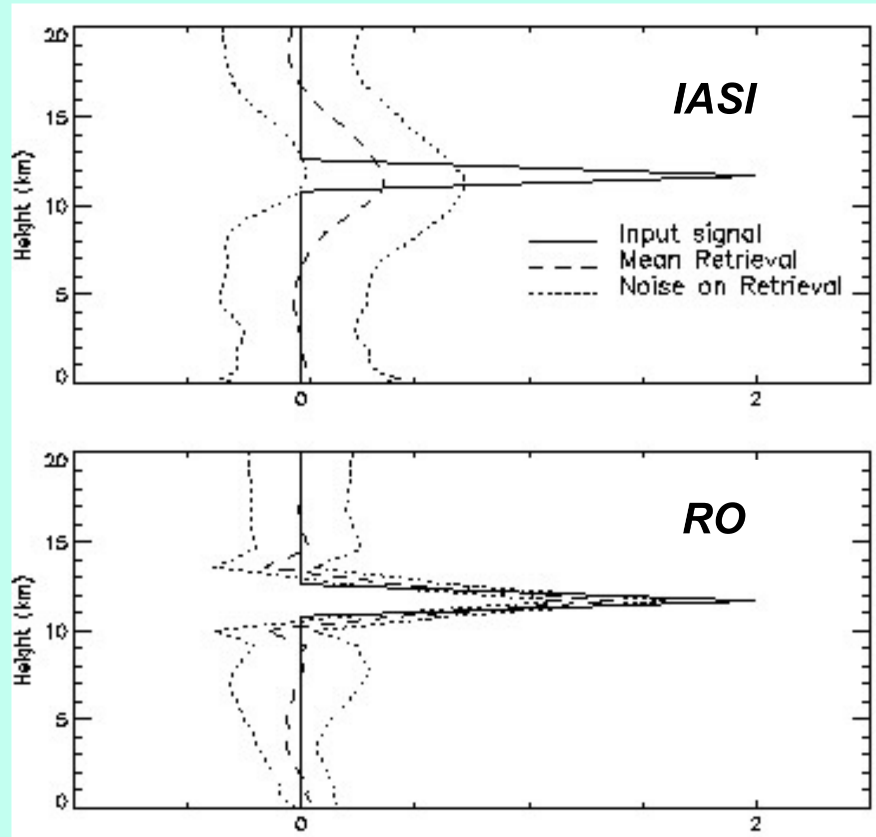
GNSS-RO and IASI: 1DVAR simulations

Collard and Healy 2003, QJRMS:

***Expected** retrieval uncertainty:*



Power to resolve a peak-shaped error in background: Averaging Kernel.



Impact of various observing systems at ECMWF

Provided by Niels Bormann – 2021 annual seminar

https://events.ecmwf.int/event/217/contributions/2049/attachments/1397/2509/AS2021_Bormann.pdf

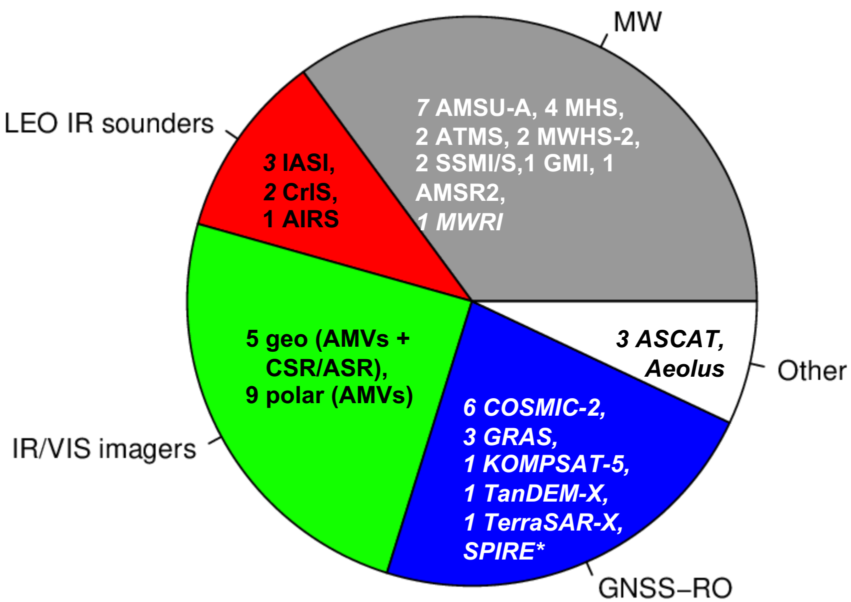
Observing system experiments

- *Periods, 6 months in total:*
  5 Sept – 2 Nov 2020
  1 Jan – 28 Feb 2021
  1 May – 30 June 2021
  (each + 4 days spin-up prior)

- Denial experiments compared to a full system for:
  - *Conventional in-situ observations*
  - MW radiances
  - *IR sounders from LEO*
  - IR/VIS imagers (AMVs + IR radiances)
  - *GNSS-RO*

- *Resolution: T_{CO} 399 (~25 km)*
- *Background error from operational system*

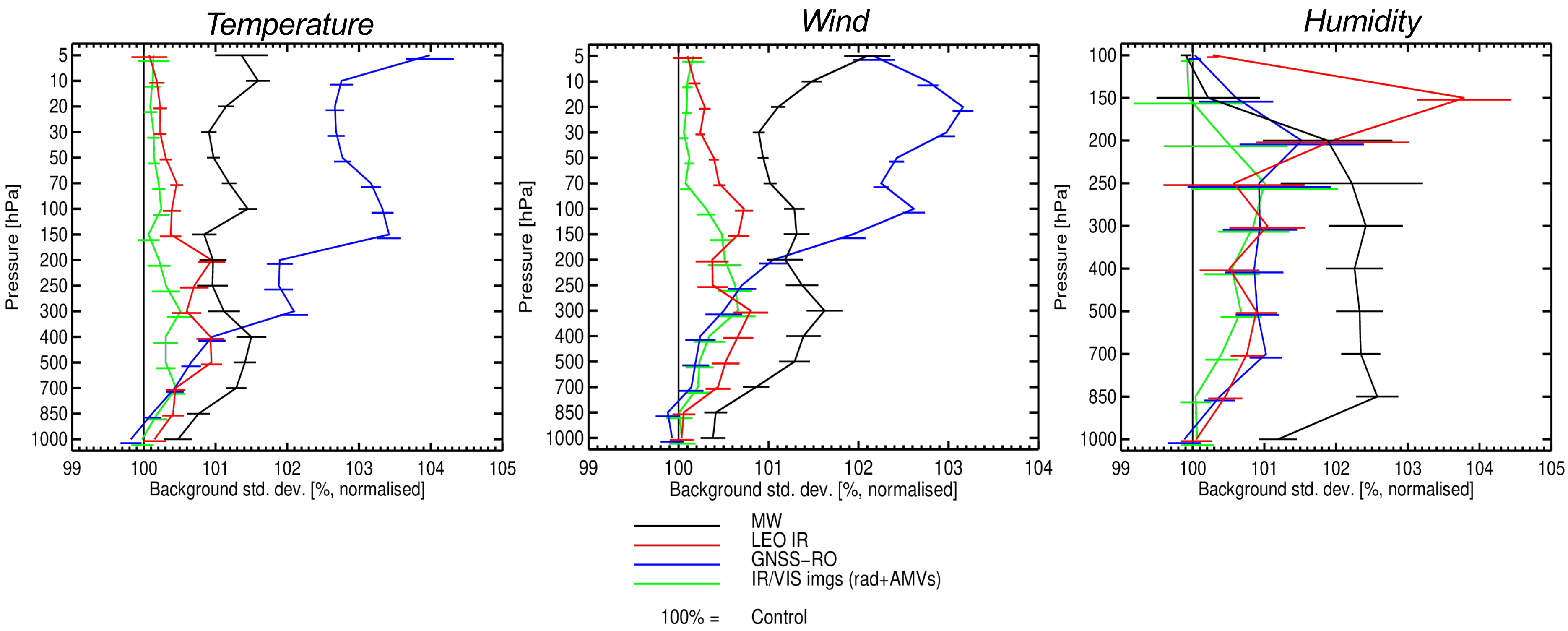
Number of assimilated satellite instruments



** SPIRE: Sept 2020 only*

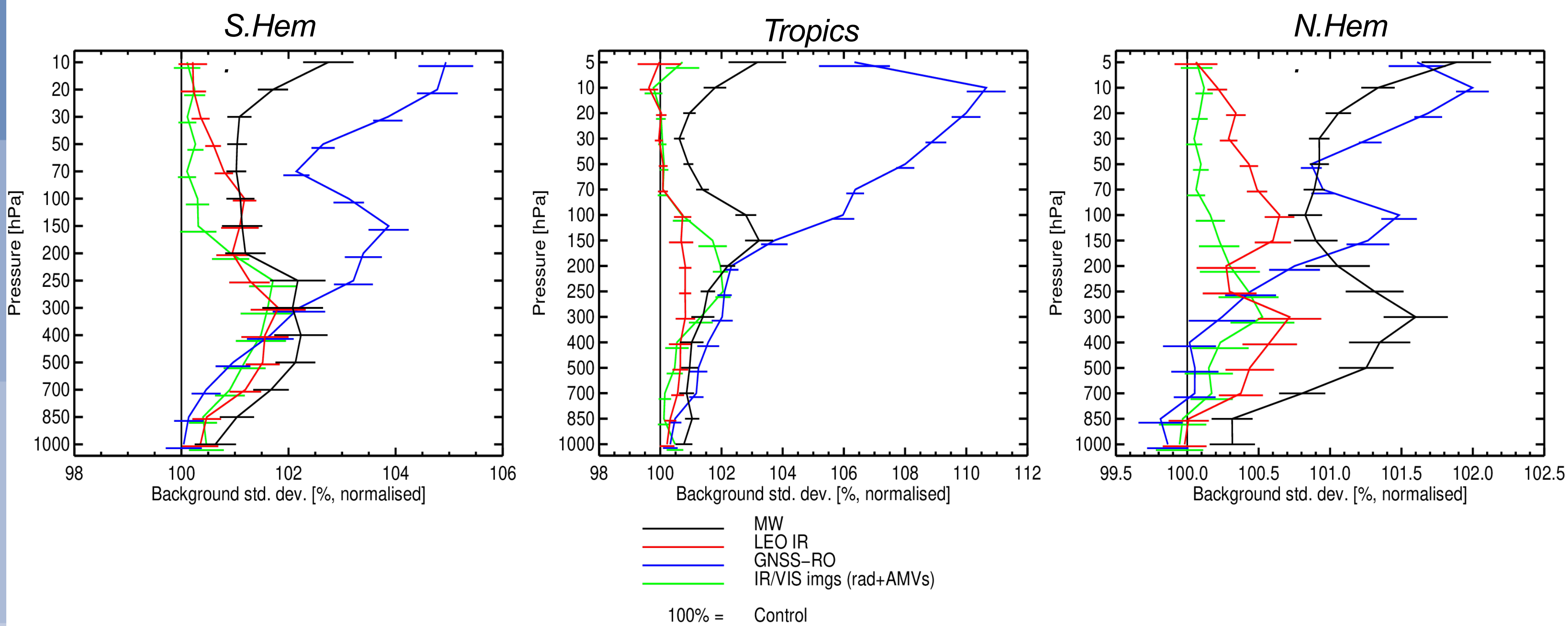
Short-range impact evaluated against in-situ observations: Stdev(o-b)

***Global**, 3 periods combined*



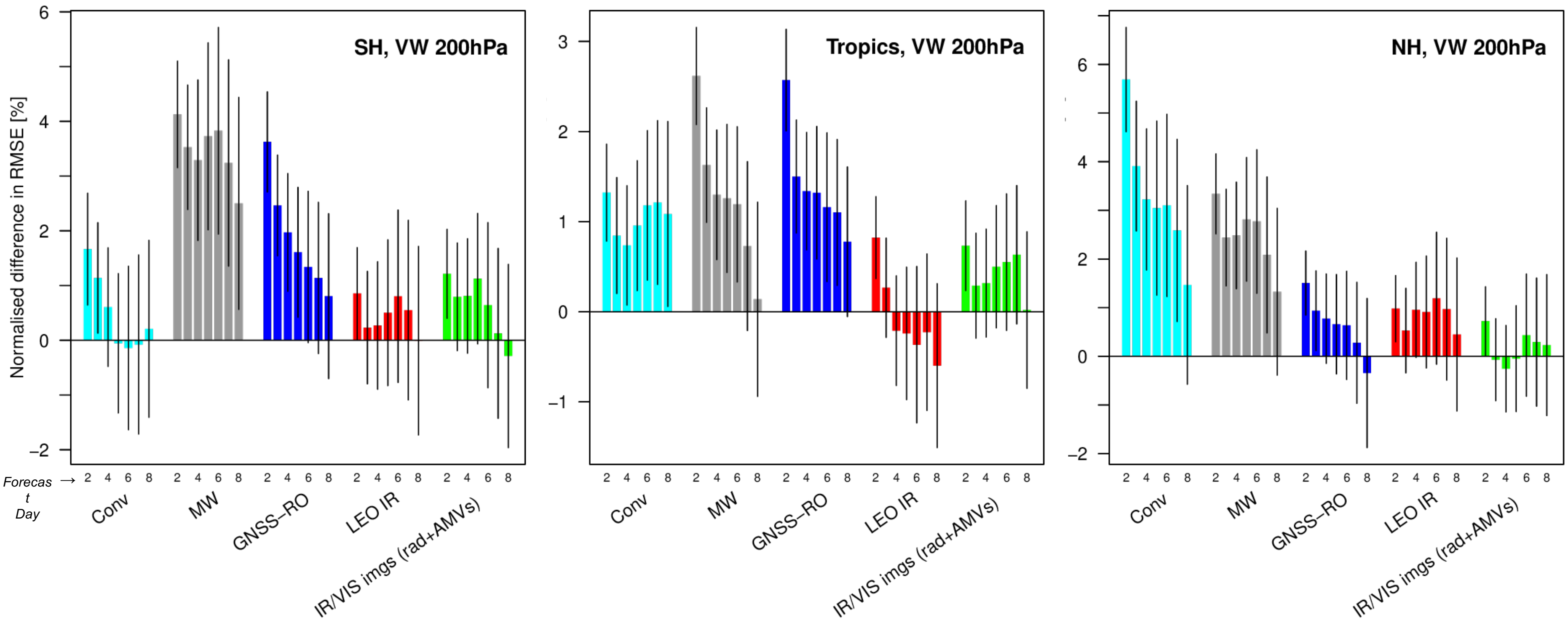
Short-range impact evaluated against in-situ observations: **vector wind**

3 periods combined



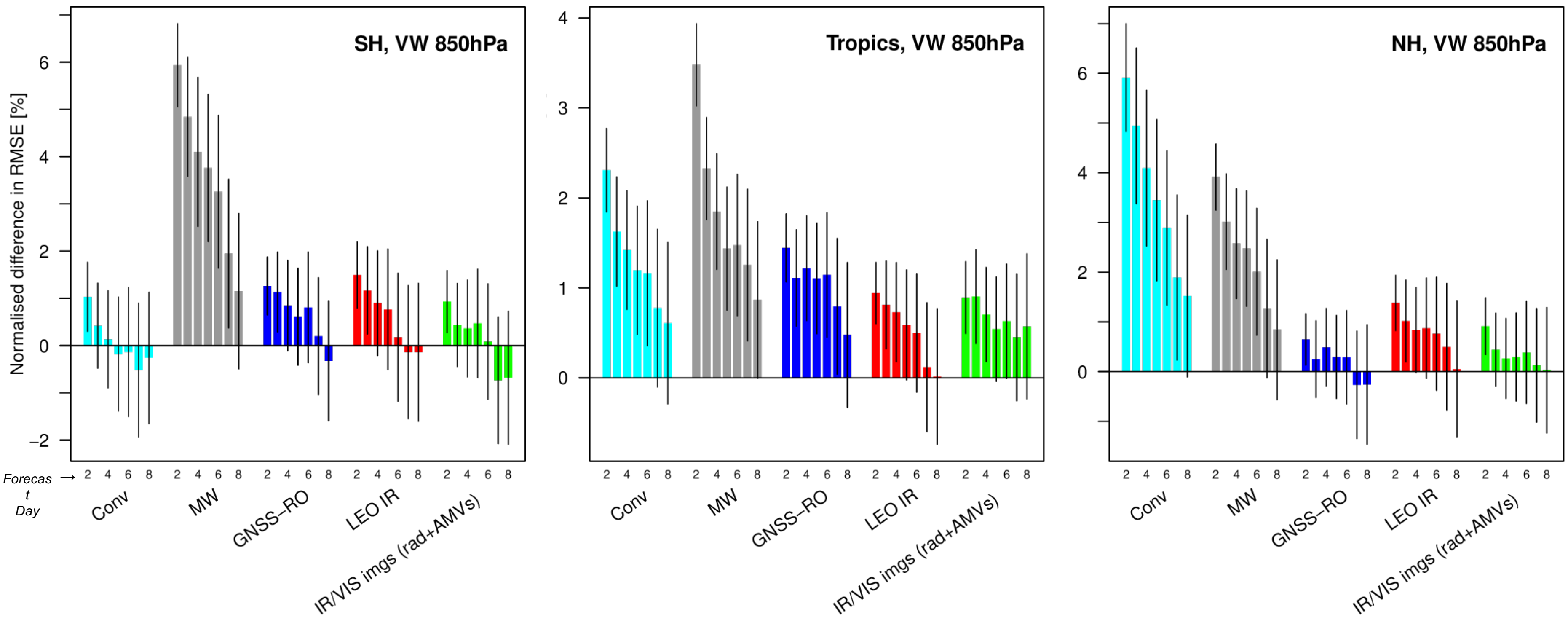
Forecast impact, day 2-8: Wind at 200 hPa

Verified against operational analyses, 3 periods combined



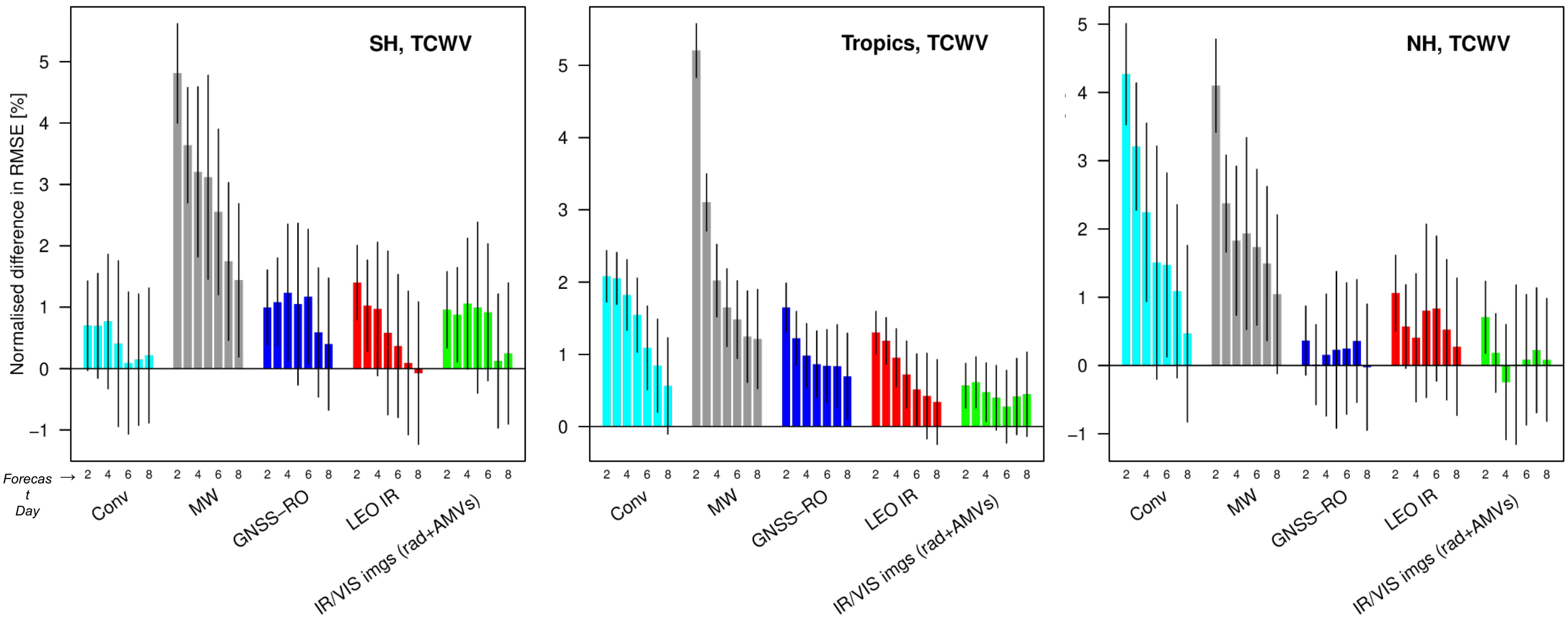
Forecast impact, day 2-8: Wind at 850 hPa

Verified against operational analyses, 3 periods combined



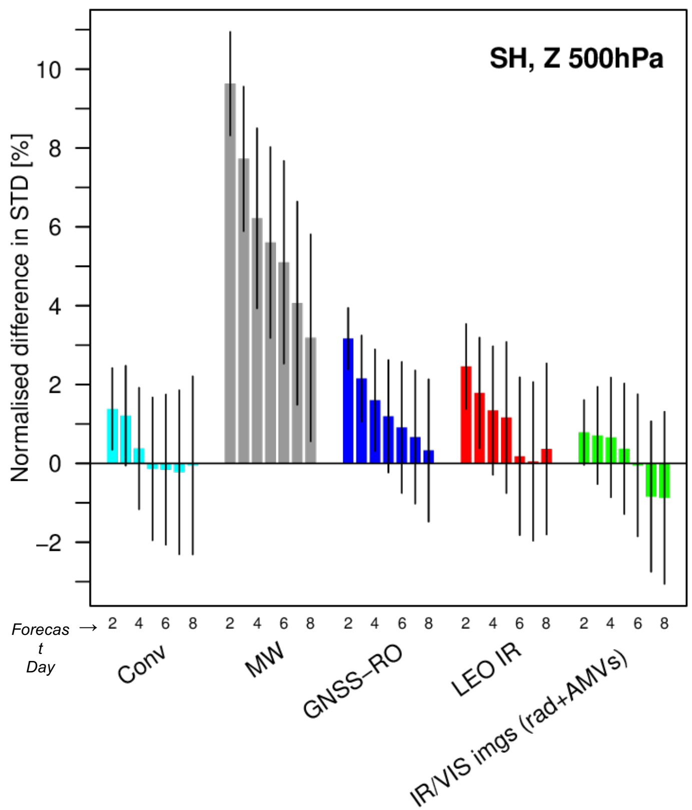
Forecast impact, day 2-8: Total column water vapour

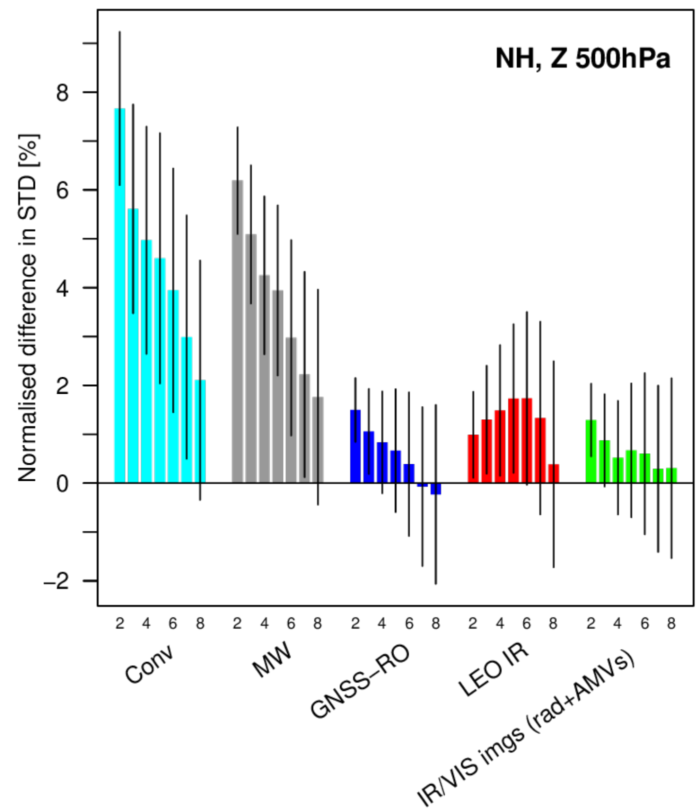
Verified against operational analyses, 3 periods combined



Forecast impact, day 2-8: 500 hPa geopotential

Verified against operational analyses, 3 periods combined





Climate reanalysis applications

Climate reanalysis applications

- **We have only had significant quantities of GNSS-RO since 2006 with the introduction of COSMIC**

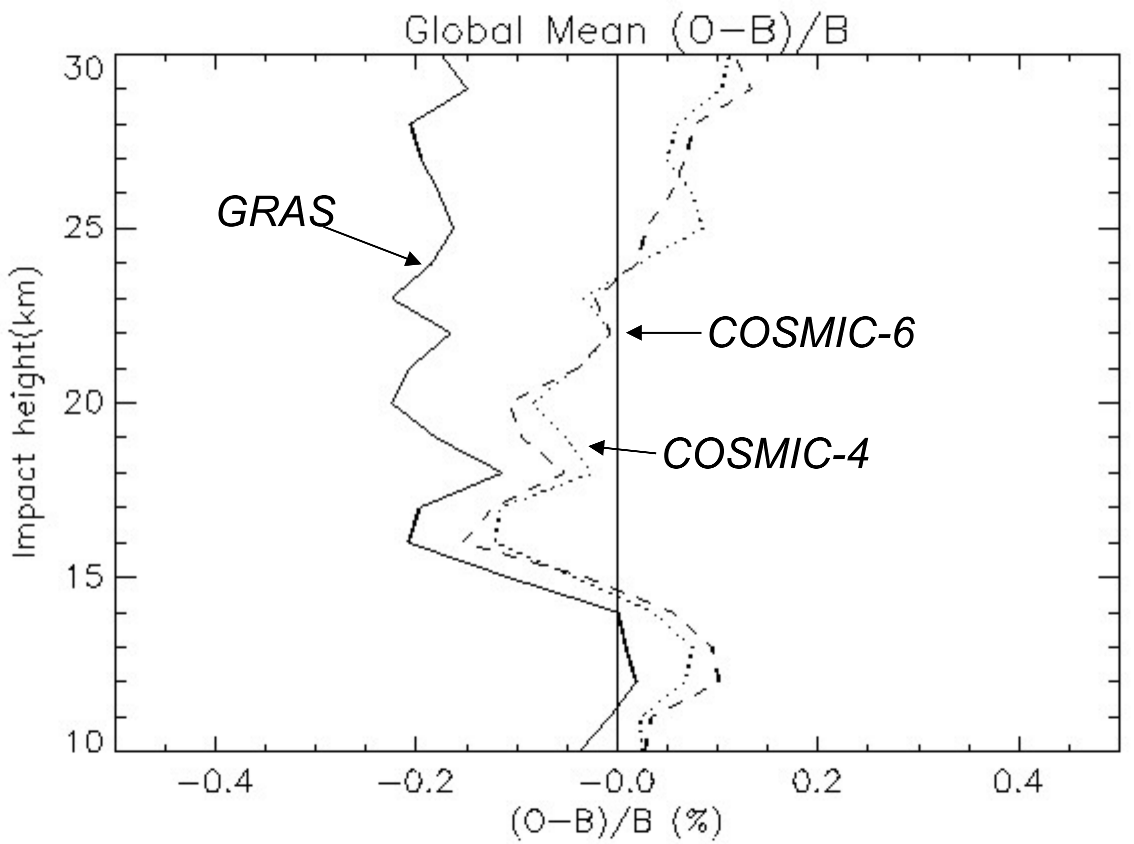
- **Claim**: GNSS-RO measurements should not be biased.

  – It should be possible to introduce data from new instruments without long overlap periods needed for calibration.

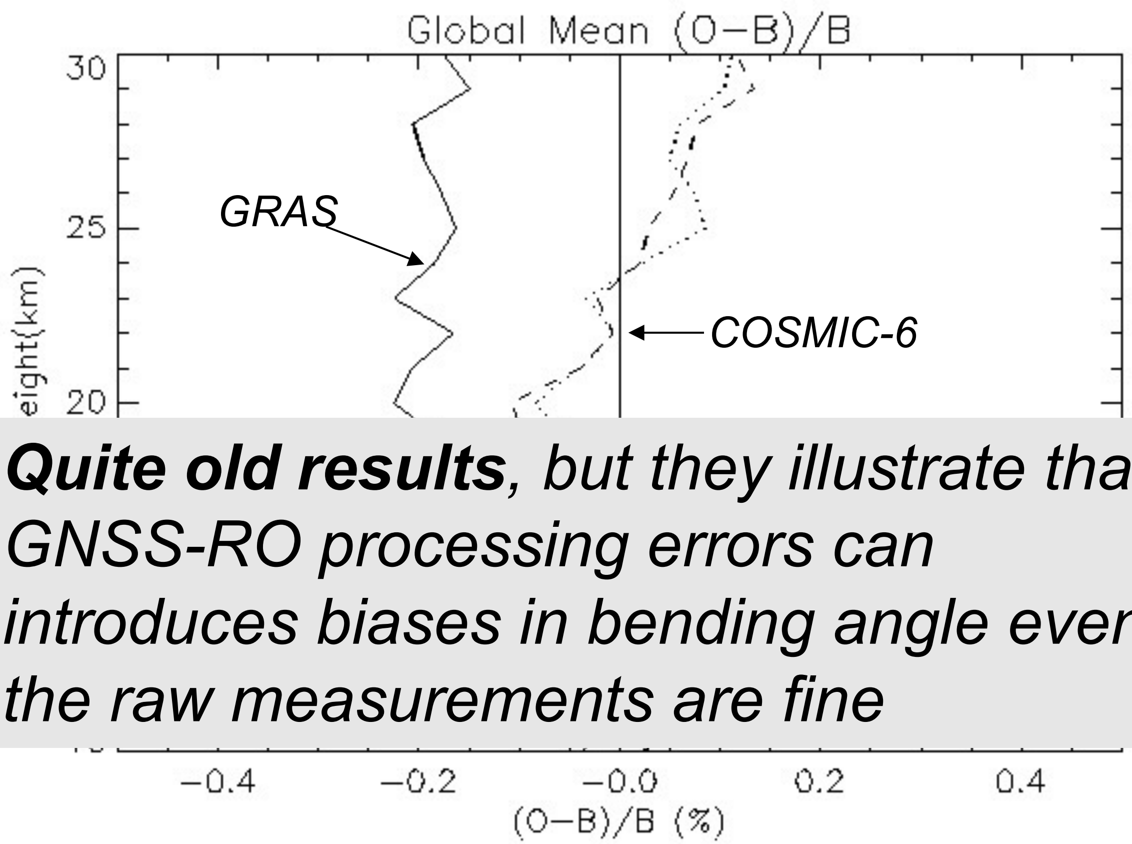
  – No discontinuities in time-series as a result of interchange of GNSS-RO instruments.

- **Bending angle time series derived from the ERA-Interim reanalysis were used to investigate this claim**

Global bending angle (o-b)/b departure statistics from **ECMWF operations** for Aug.20 to Sept. 20, **2009**

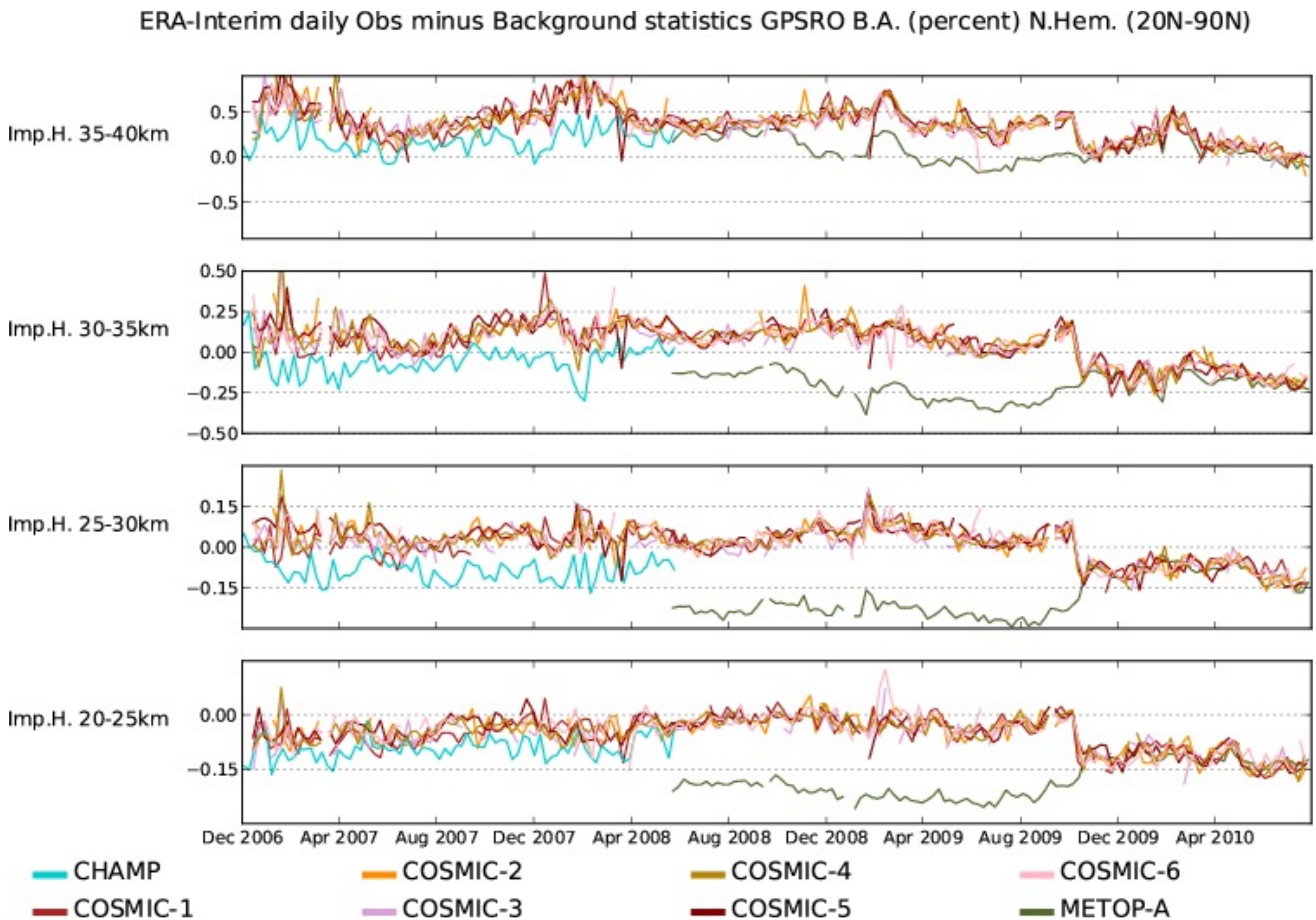


Global bending angle (o-b)/b departure statistics from **ECMWF operations** for Aug.20 to Sept. 20, **2009**

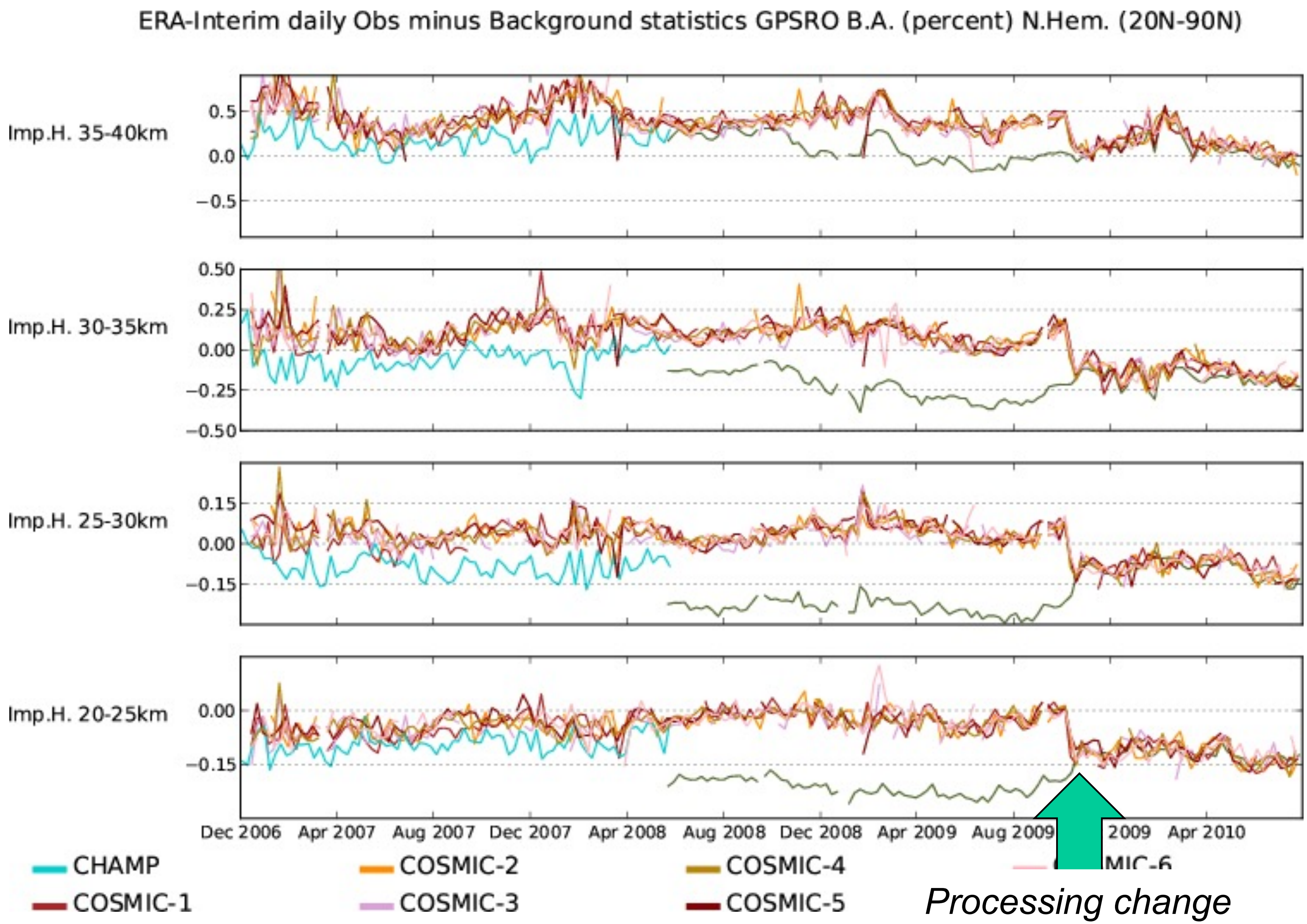


***Quite old results**, but they illustrate that GNSS-RO processing errors can introduces biases in bending angle even if the raw measurements are fine*

Consistency of GNSS-RO bending angles (ERA-Interim Reanalysis, Paul Poli)



Consistency of GNSS-RO bending angles (ERA-Interim Reanalysis, Paul Poli)



Processing change at UCAR

GNSS-RO and the bias correction of radiances

- **“Bias correction schemes for satellite radiances need to be grounded by a reference.”** The reference measurements are often called “***anchor measurements***”

- The assimilation of GNSS-RO anchors the bias corrections we apply to radiances

- We can illustrate this by plotting how the bias corrections applied to radiances change with/without GNSS-RO

VarBC is used at ECMWF
Dee, QJRMS (2007), **131**, pp 3323-3343

- Bias corrected radiances are assimilated.

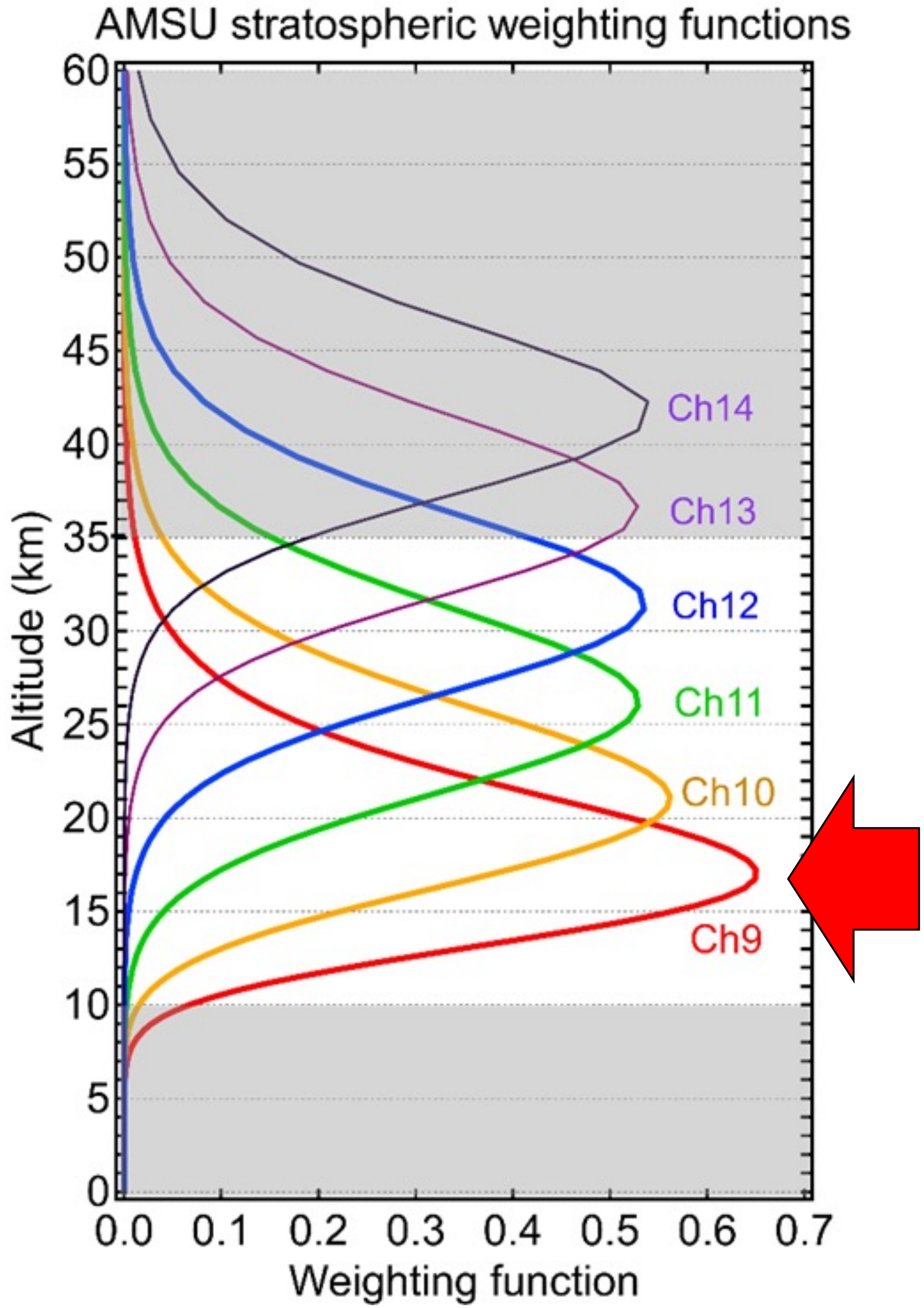
$$\tilde{\mathbf{y}} = \mathbf{y} - \mathbf{b}(\boldsymbol{\beta}, \mathbf{x})$$

$$\mathbf{b}(\boldsymbol{\beta}, \mathbf{x}) = \sum_i \beta_i \mathbf{p}(\mathbf{x})$$

$$J(\mathbf{x}, \boldsymbol{\beta}) = (\mathbf{x}_\mathrm{b} - \mathbf{x})^\mathrm{T} \mathbf{B}_\mathbf{x}^{-1} (\mathbf{x}_\mathrm{b} - \mathbf{x}) + (\boldsymbol{\beta}_\mathrm{b} - \boldsymbol{\beta})^\mathrm{T} \mathbf{B}_{\boldsymbol{\beta}}^{-1} (\boldsymbol{\beta}_\mathrm{b} - \boldsymbol{\beta}) + (\mathbf{y} - \mathbf{b}(\boldsymbol{\beta}, \mathbf{x}) - H(\mathbf{x}))^\mathrm{T} \mathbf{R}^{-1} (\mathbf{y} - \mathbf{b}(\boldsymbol{\beta}, \mathbf{x}) - H(\mathbf{x}))$$

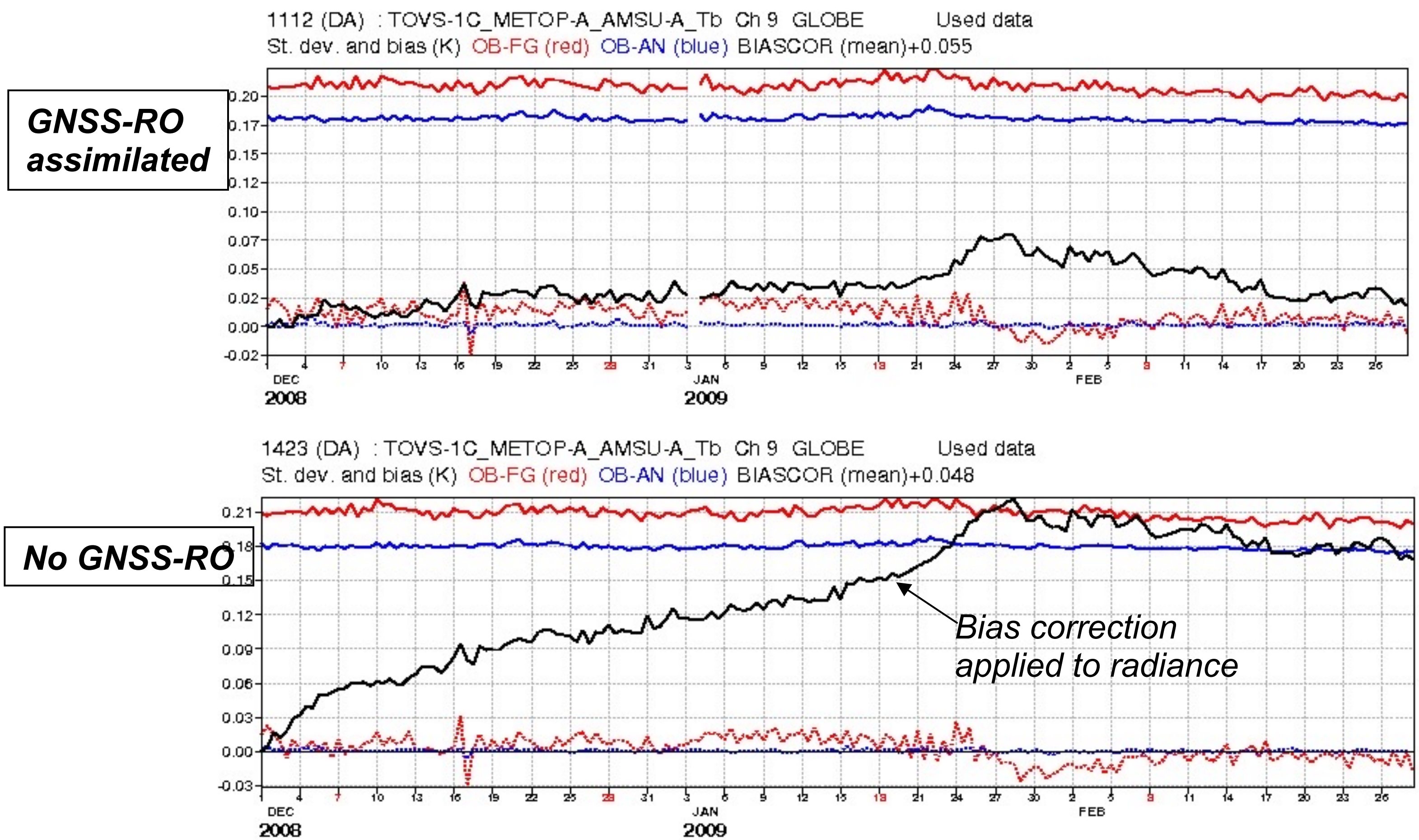
In the 4D-Var, we minimize an augmented cost function, where the bias coefficients are estimated.

- **VarBC assumes an unbiased model.**


AMSU stratospheric weighting functions
Altitude (km)
Weighting function
0
5
10
15
20
25
30
35
40
45
50
55
60
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
Ch14
Ch13
Ch12
Ch11
Ch10
Ch9

Experiment removing GNSS-RO from ERA-Interim (Dec. 08, Jan-Feb 09)

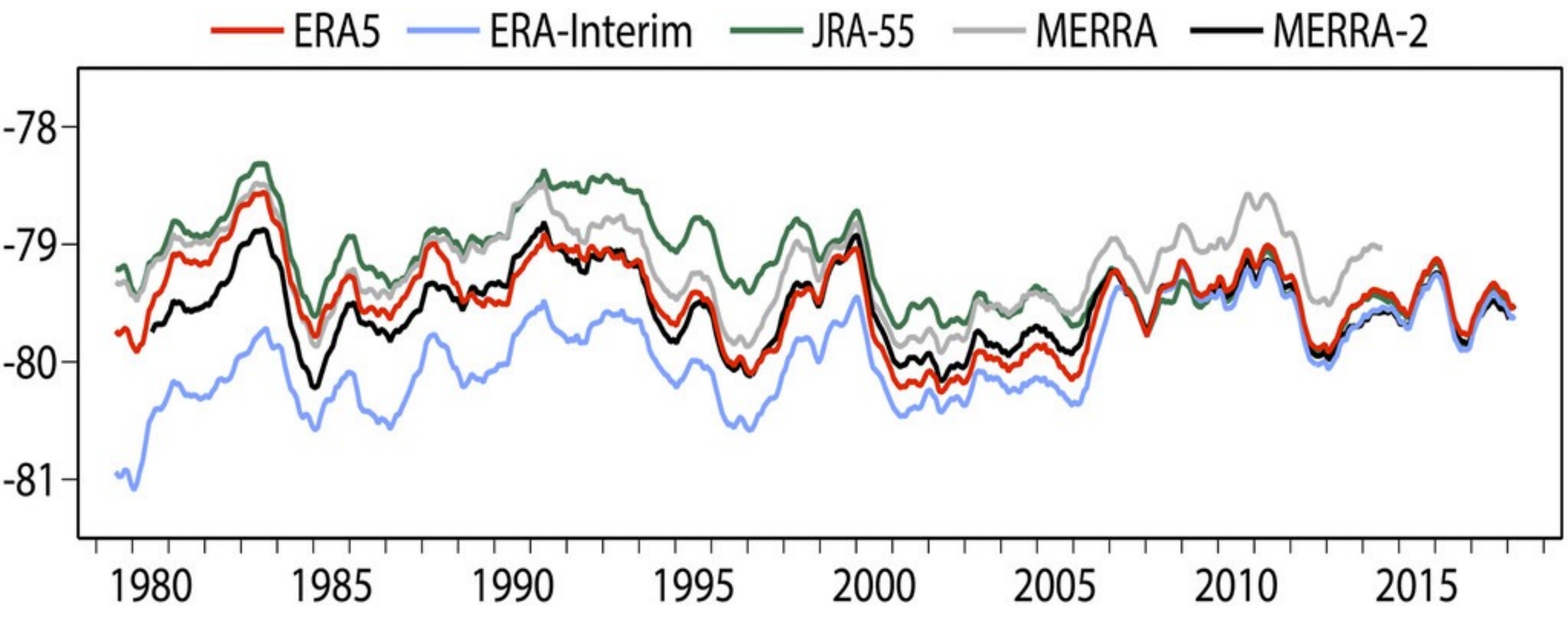
- Impact on bias correction. E.g., globally averaged **Metop-A**, **AMSU-A channel 9 bias correction**.



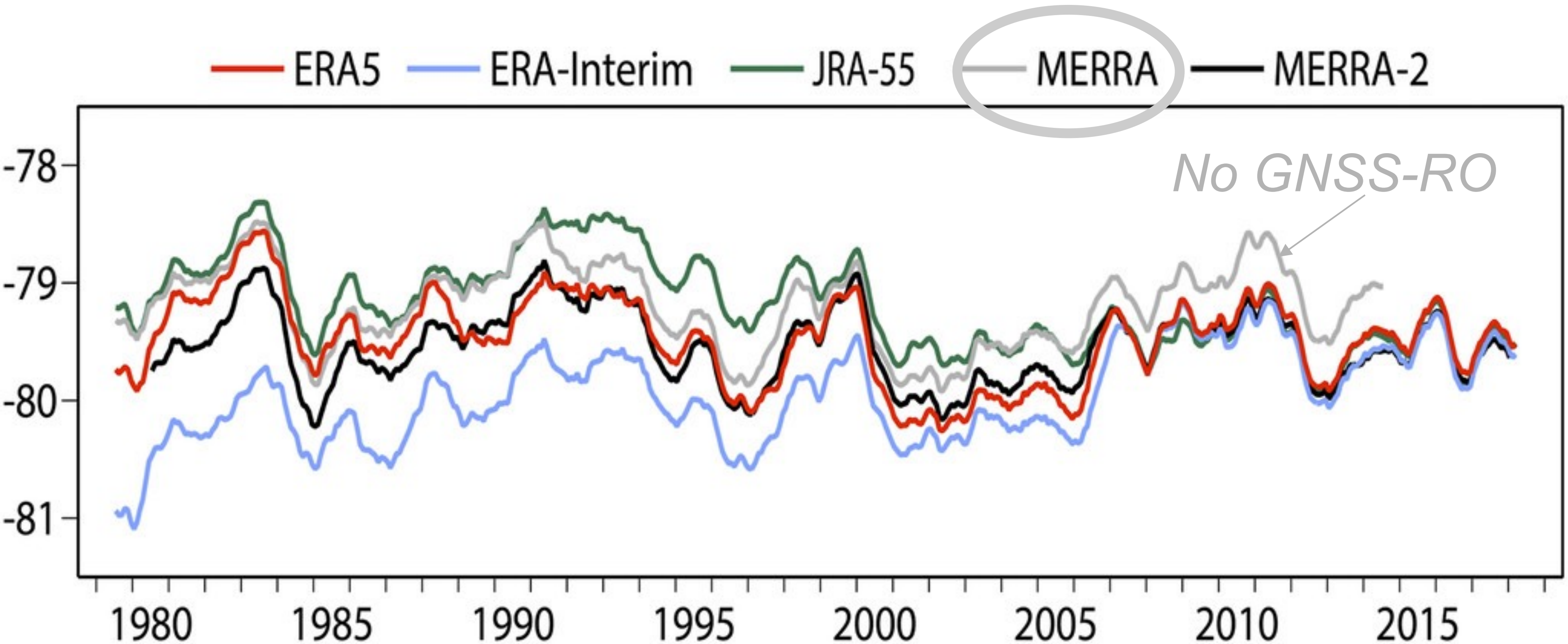
GPS-RO have improved the consistency between climate reanalyses in the upper-troposphere and lower/middle stratosphere since 2006 with the introduction of COSMIC

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

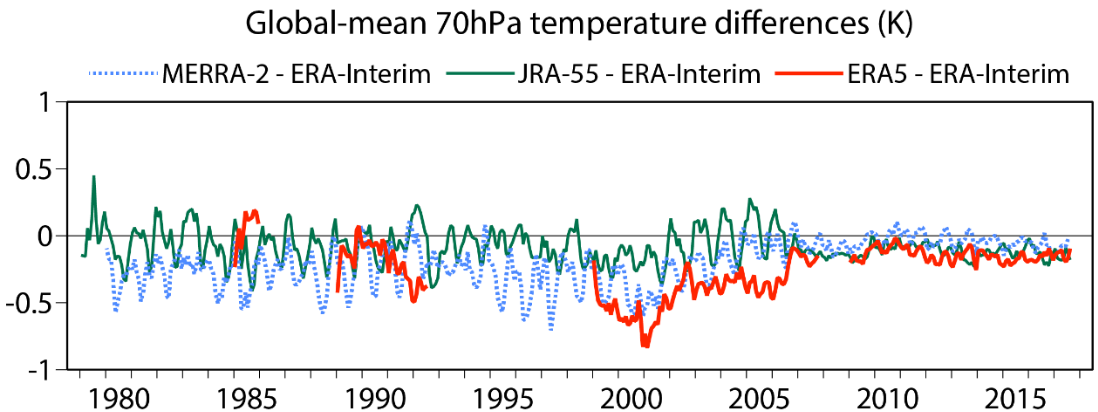
Twelve-month running mean temperature (°C) at 100 hPa averaged over the tropics (20°S to 20°N) from five global reanalyses.



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 ***is becoming*** *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 GPS-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*).

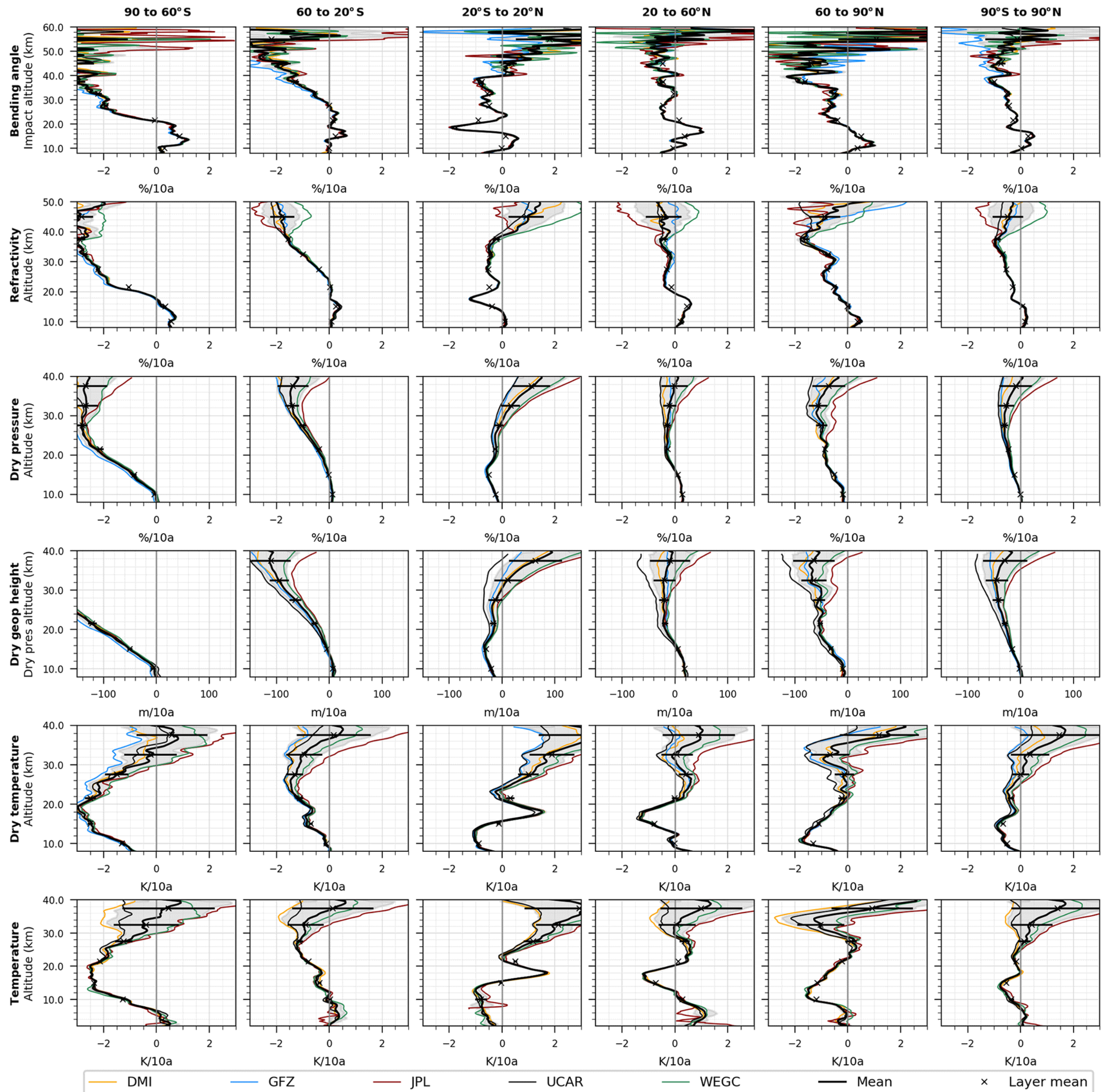
Main aim is to *validate* RO as a climate benchmark, identifying the impact of processing assumptions (*structural uncertainty*).

- *ROtrends* partners: DMI, 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/

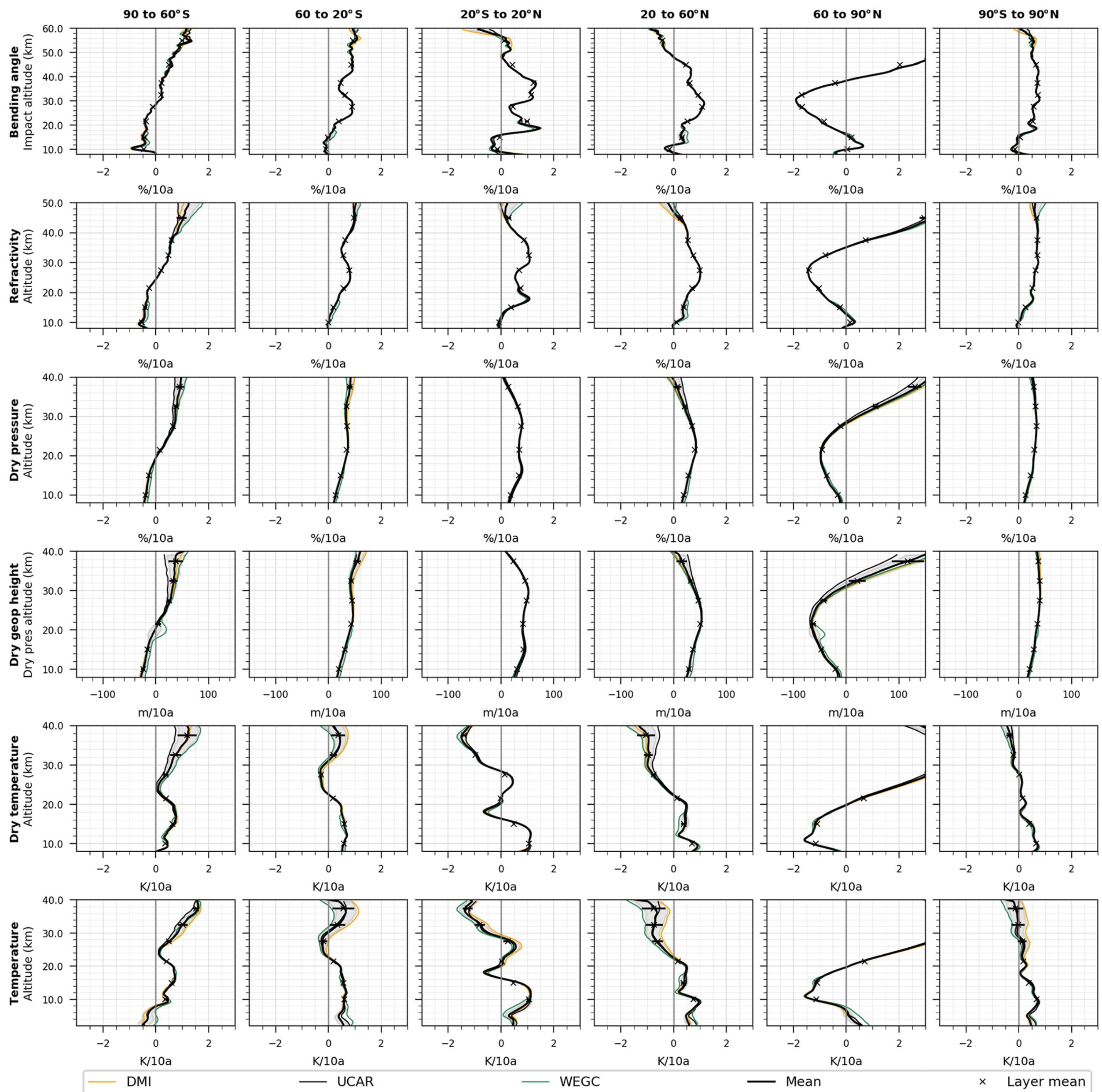
Steiner et al, Figure 8 (Champ)

Solid black = multi-centre mean

Gray = standard deviation about mean



Steiner et al, Figure 10 (Metop GRAS)



Solid black = multi-centre mean

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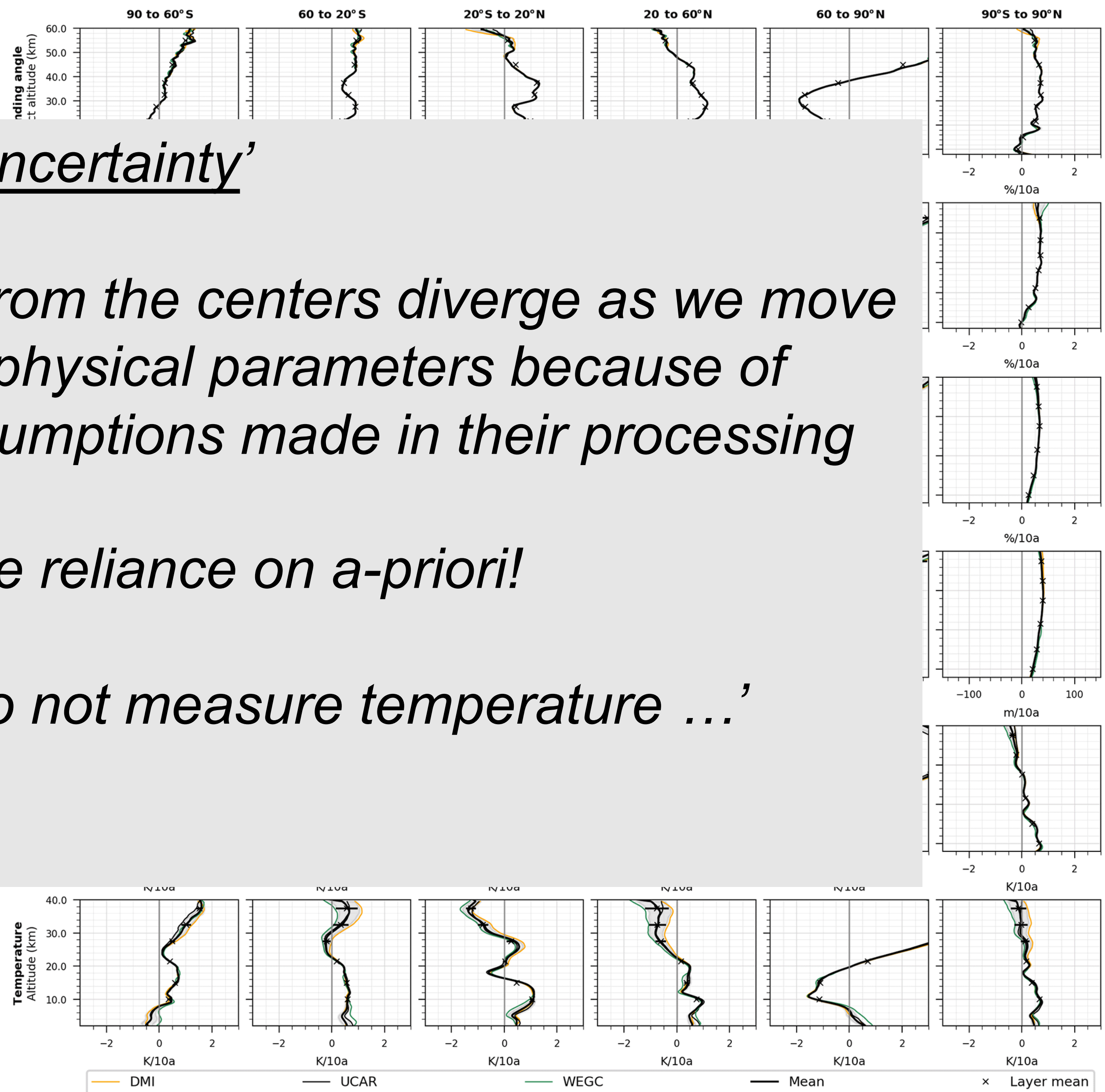
Steiner et al, Figure 10 (Metop GRAS)



`Structural uncertainty'

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

Illustrates the reliance on a-priori!

`Satellites do not measure temperature …'

Solid black
mean

Gray = stan
mean

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

Simulation studies to assess:

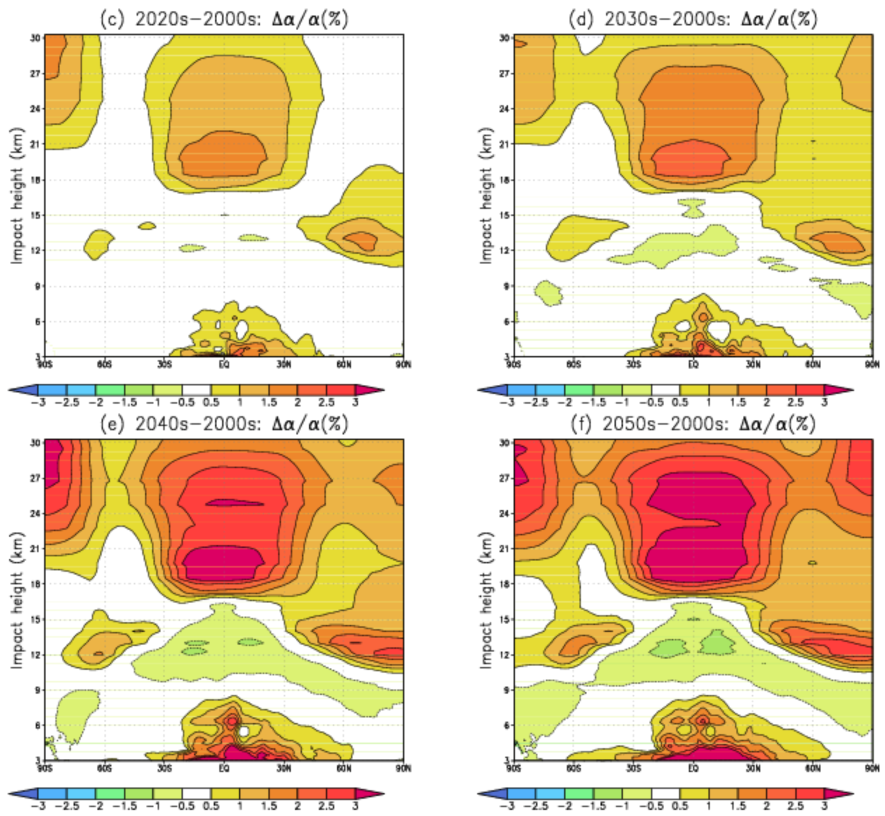
- potential of GNSS-RO for detecting climate trends
- what variable should we monitor?
- information content of GNSS-RO in relation to other sensors

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?**

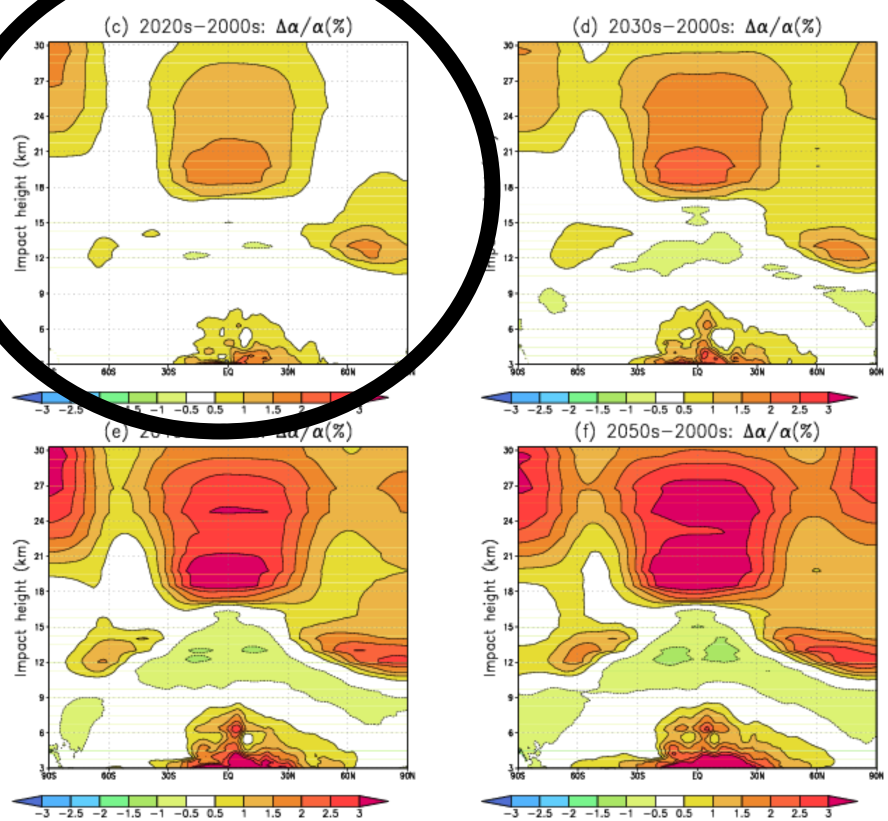
Provided by Mark Ringer (Hadley Centre)

Change in zonally averaged bending angles vs 2000



https://www.romsaf.org/Publications/articles/2007_ringer-healy_GL032462.pdf

Change in zonally averaged bending angles vs 2000



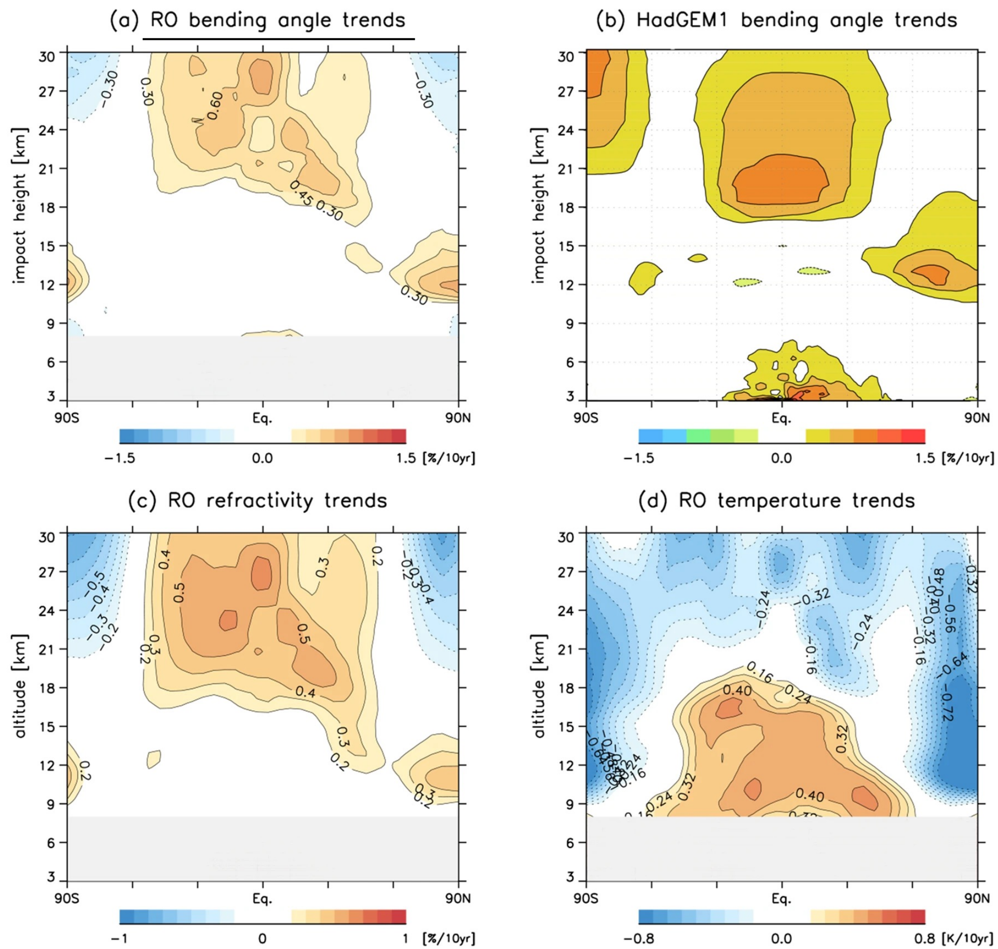
https://www.romsaf.org/Publications/articles/2007_ringer-healy_GL032462.pdf

ROM SAF

Simulated in 2006

(published 2022)

(published 2007)



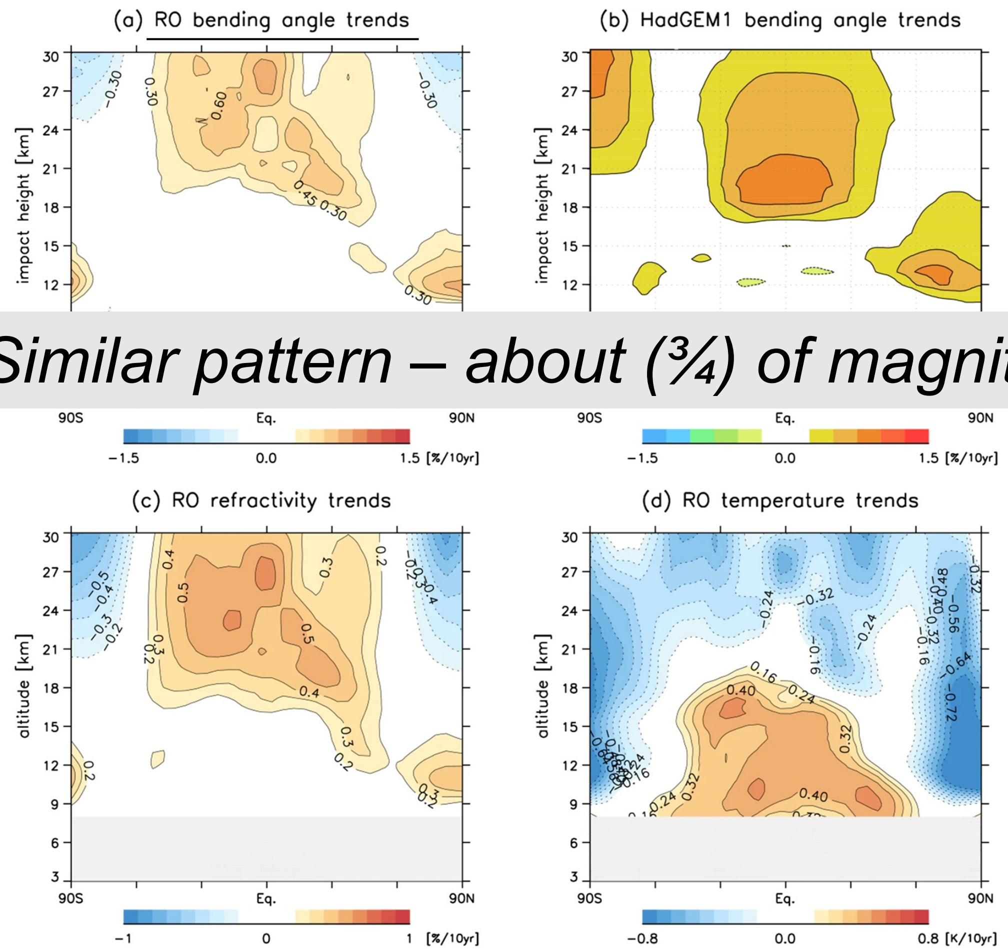
https://www.nature.com/articles/s41612-022-00229-7

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.

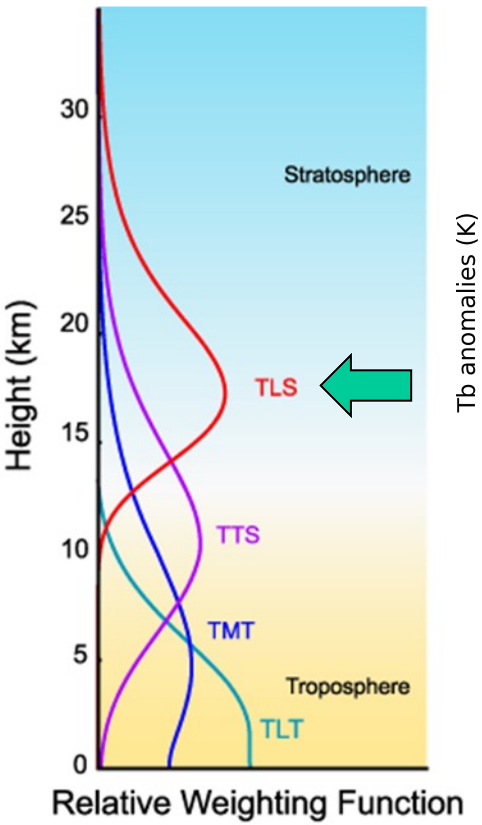
Contribution to IPCC AR6

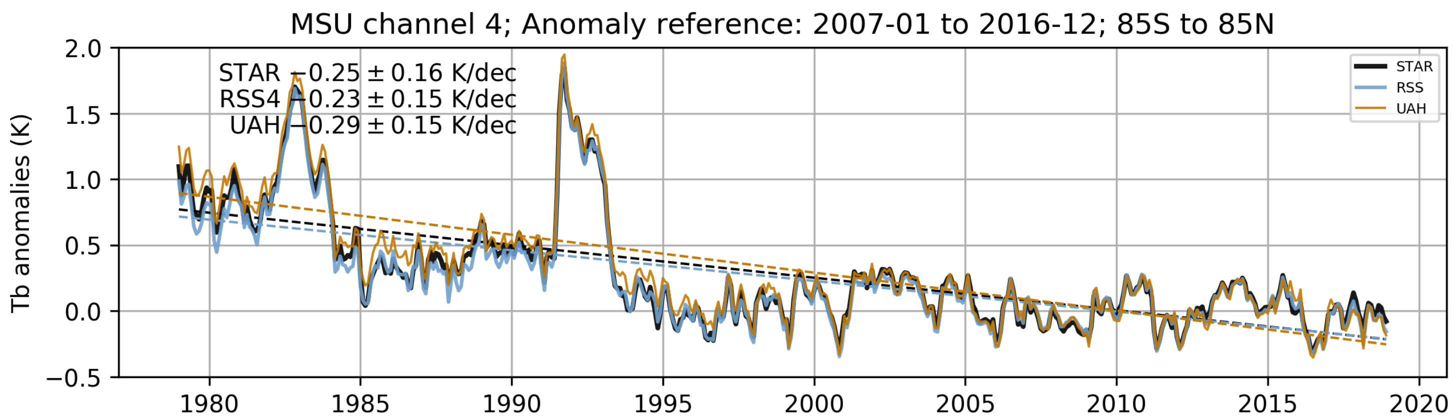
https://www.ipcc.ch/assessment-report/ar6/

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?

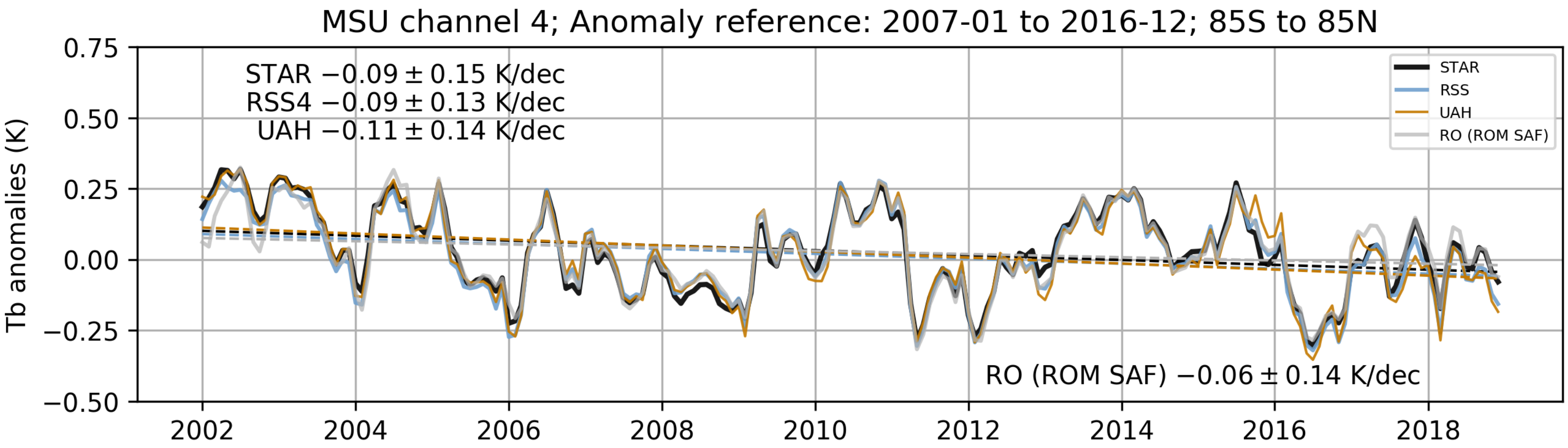
Comparing GNSS-RO with MSU radiances (Global)





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?***

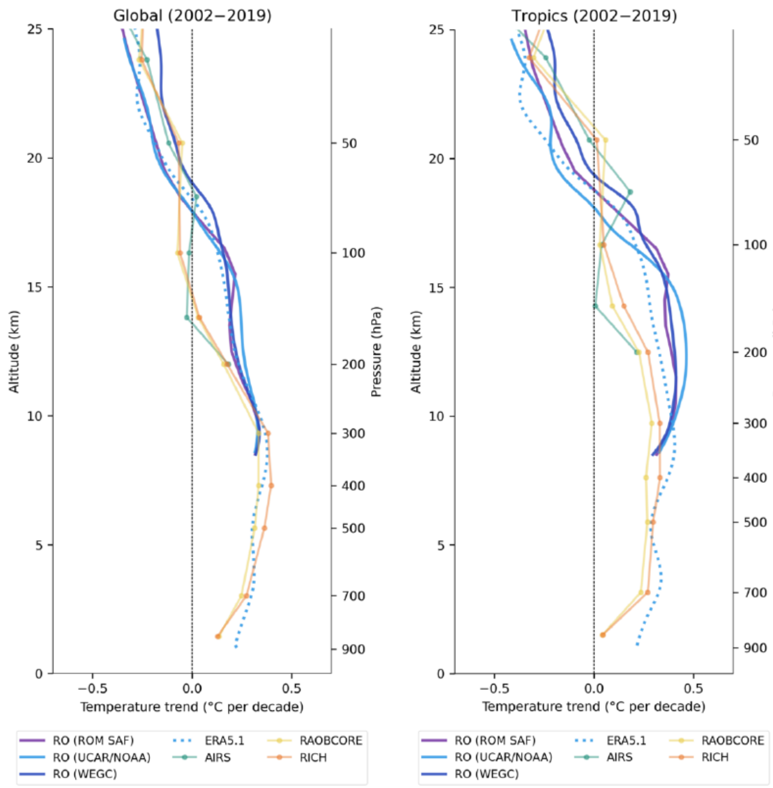
MSU-4 and GNSS-RO anomalies 2002-2018



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

Contribution to the IPCC AR6 report

– observed temperature trends in the tropical upper troposphere –



Decadal temperature trends as function of altitude from:

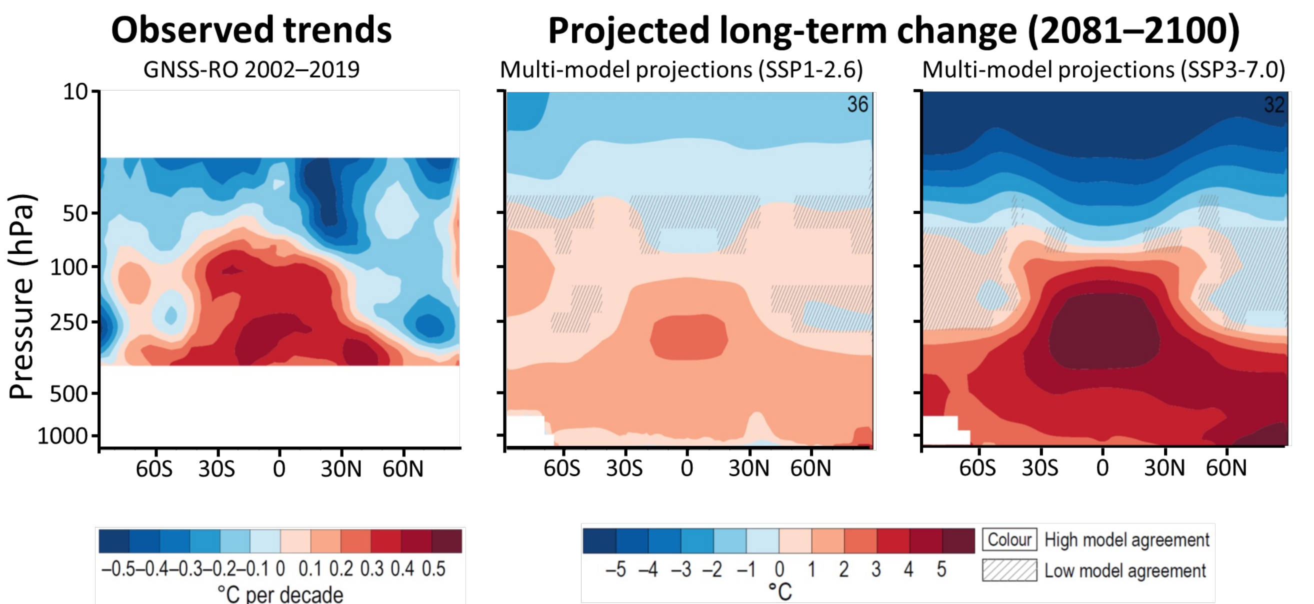
- *RO data from: ROM SAF, UCAR/NOAA, Wegener Center, Graz (WEGC)*
- *Radiosonde datasets: RAOBCORE, RICH*
- *AIRS data*
- *ERA5 data*

From ROM SAF VS40 report (Florian Ladstädter)

https://www.romsaf.org/Publications/reports/romsaf_vs40_rep_v10.pdf

Global upper air temperature trends

contribution to the IPCC AR6 WG1 report

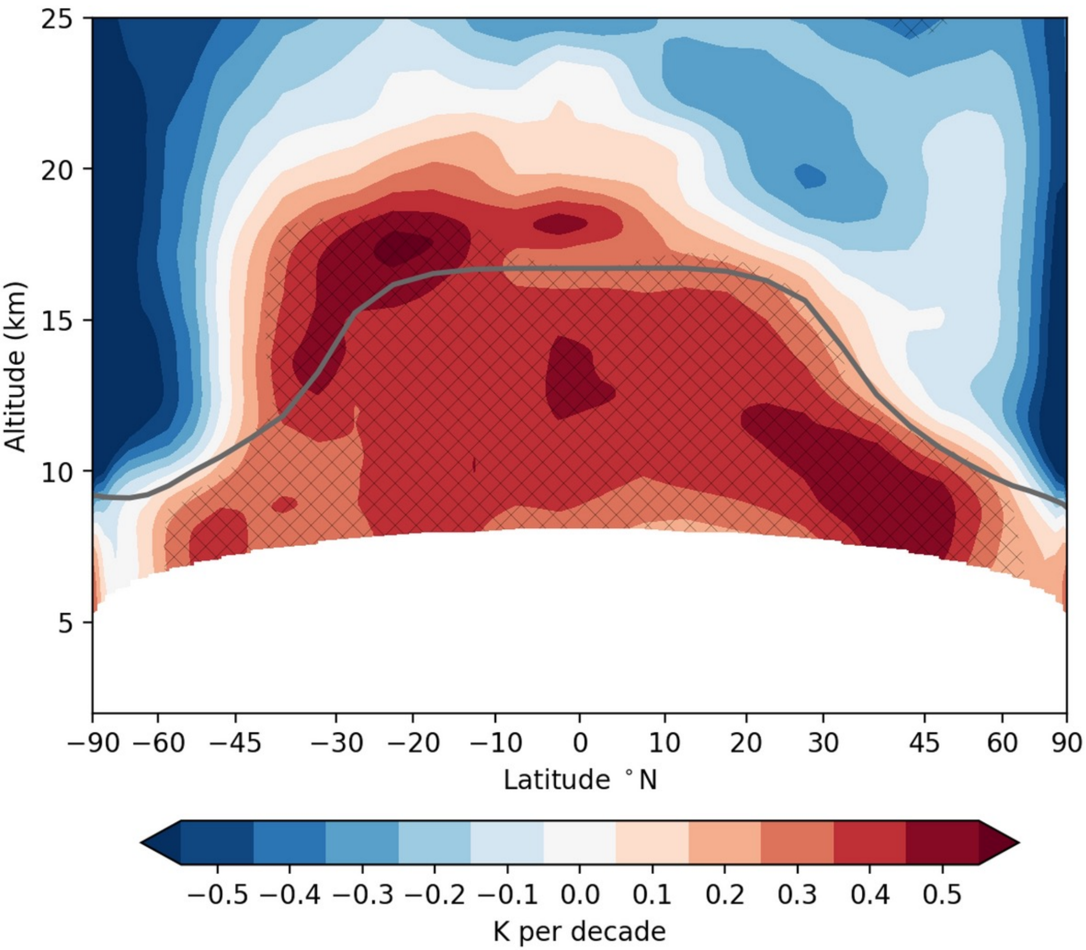


From IPCC AR6 WG 1, Technical Summary

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

Florian Ladstädter, Andrea K. Steiner & Hans Gleisner

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

(Slides, Estel Cardellach).

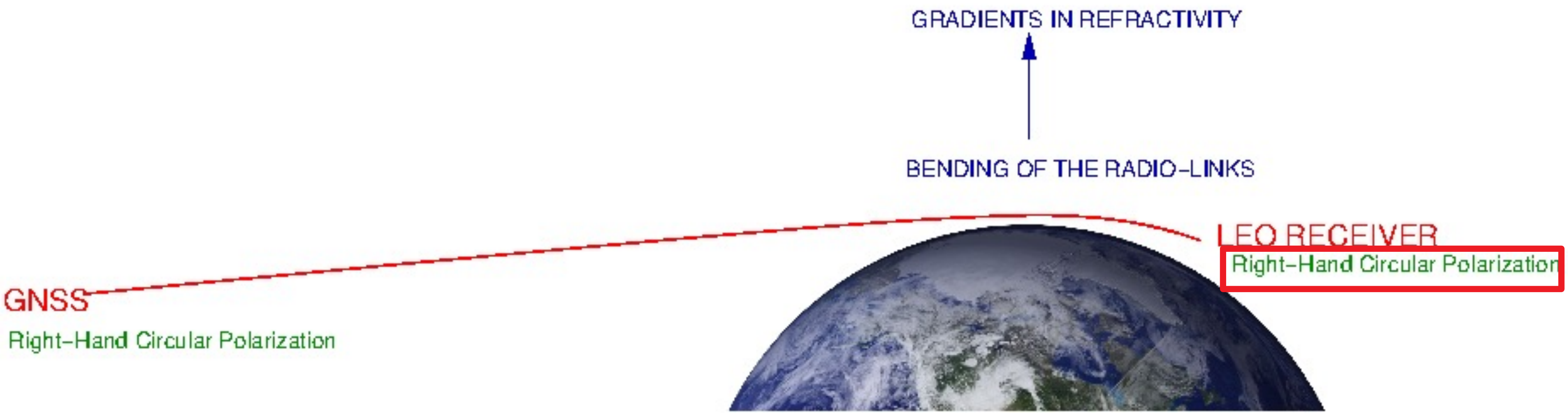
Geophysical Research Letters

Research Letter | Open Access

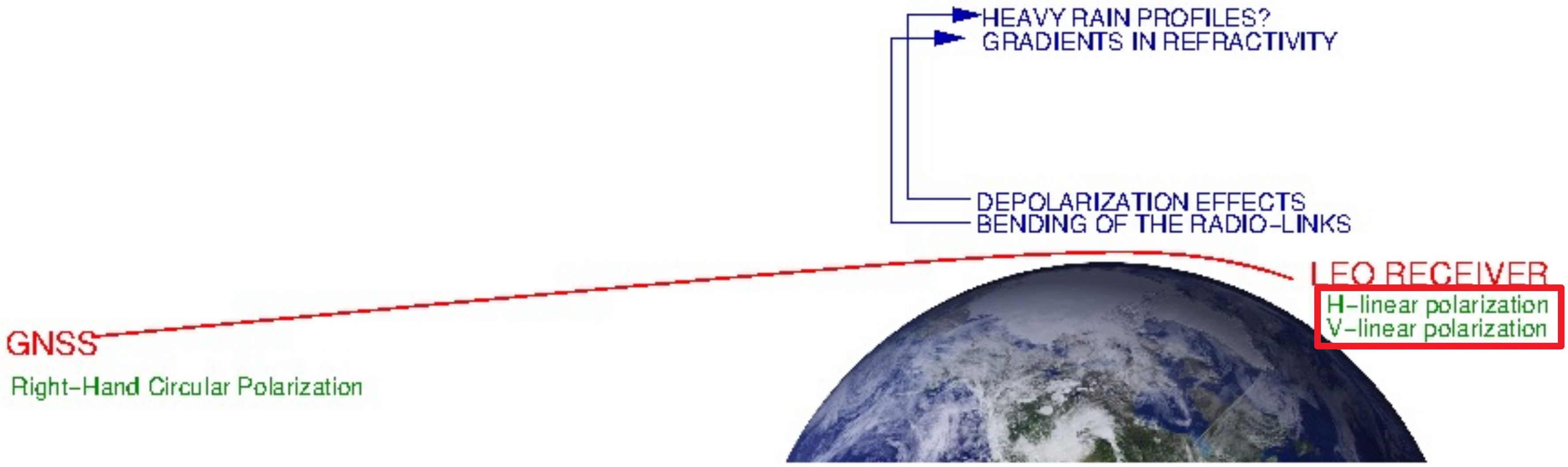
Sensing Heavy Precipitation With GNSS Polarimetric Radio Occultations

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



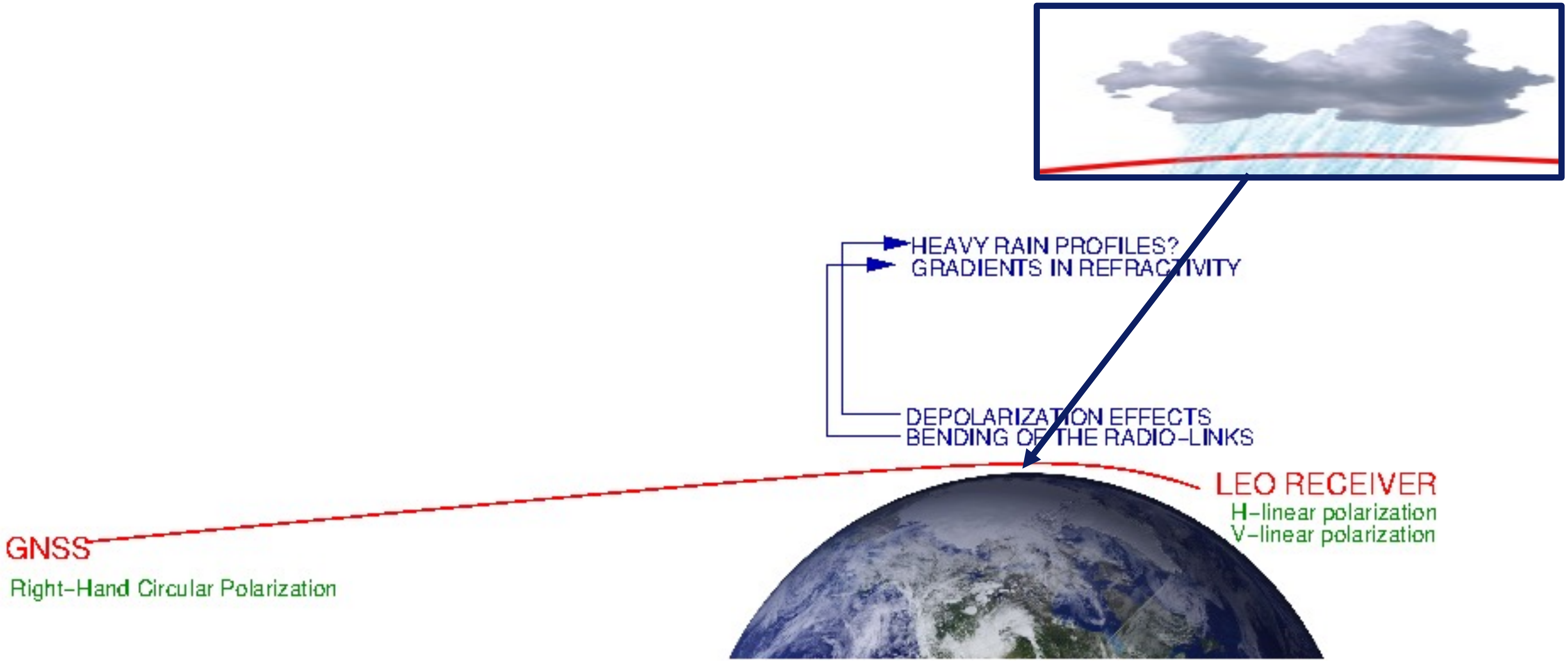
***'TYPICAL' GNSS RO PRODUCTS:** VERTICAL PROFILES OF THERMODYNAMIC VARIABLES at the tangent point (typically temperature, pressure, humidity)*



'NEW' GNSS-PRO PRODUCTS:

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

*+ **VERTICAL PROFILES OF INTENSE RAIN***



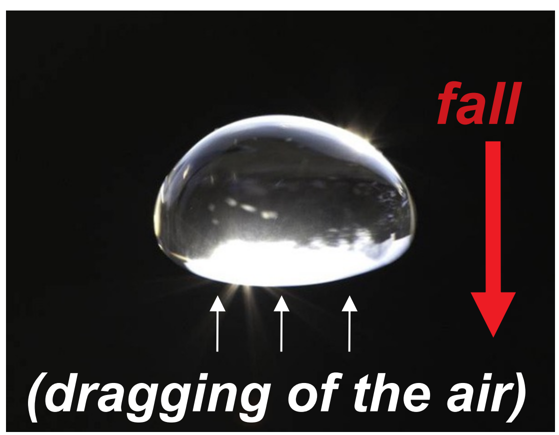
'NEW' GNSS-PRO PRODUCTS:

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

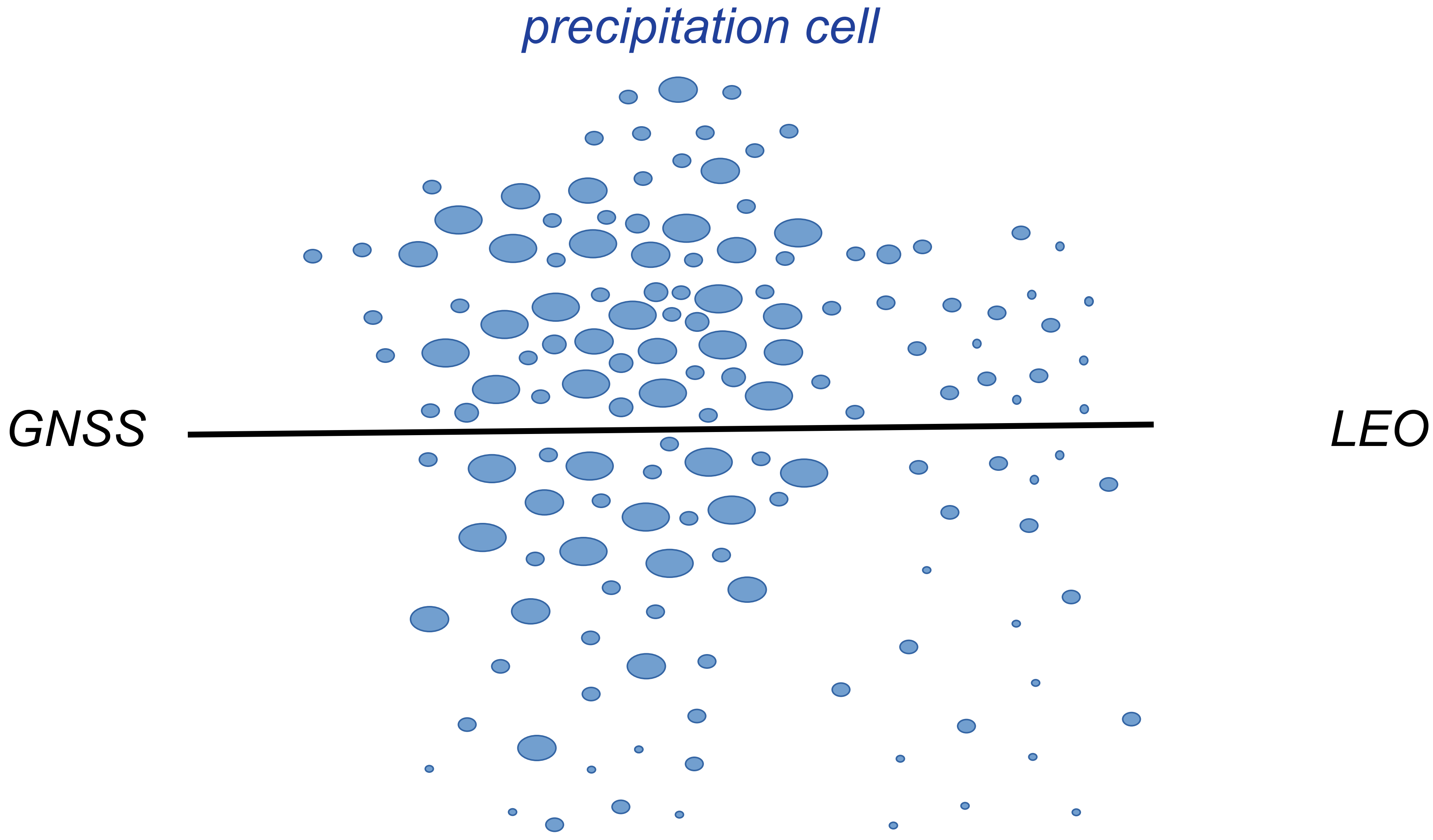
*+ **VERTICAL PROFILES OF INTENSE RAIN***

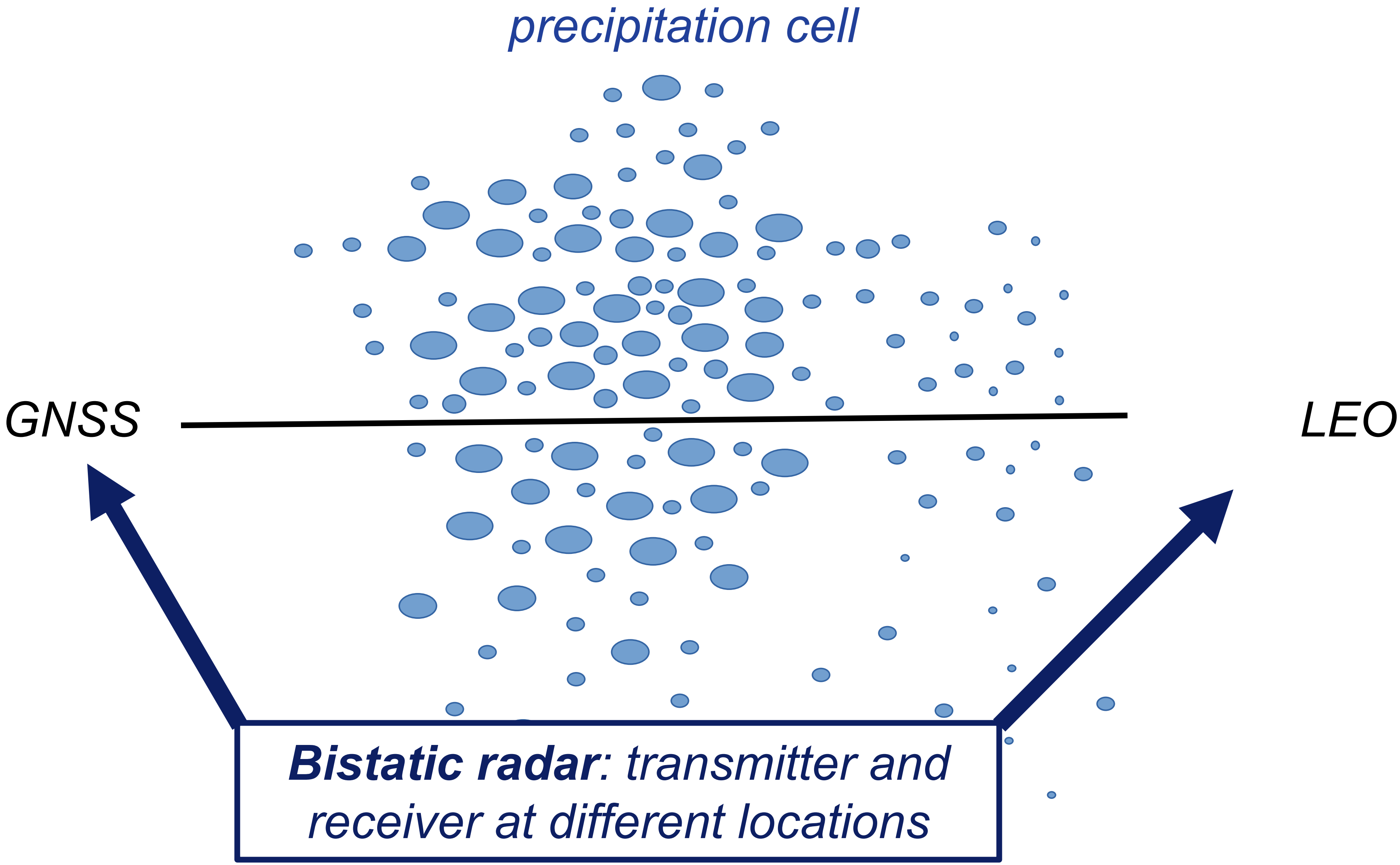
To understand this concept it is important to keep in mind that the big falling rain drops ARE NOT like this

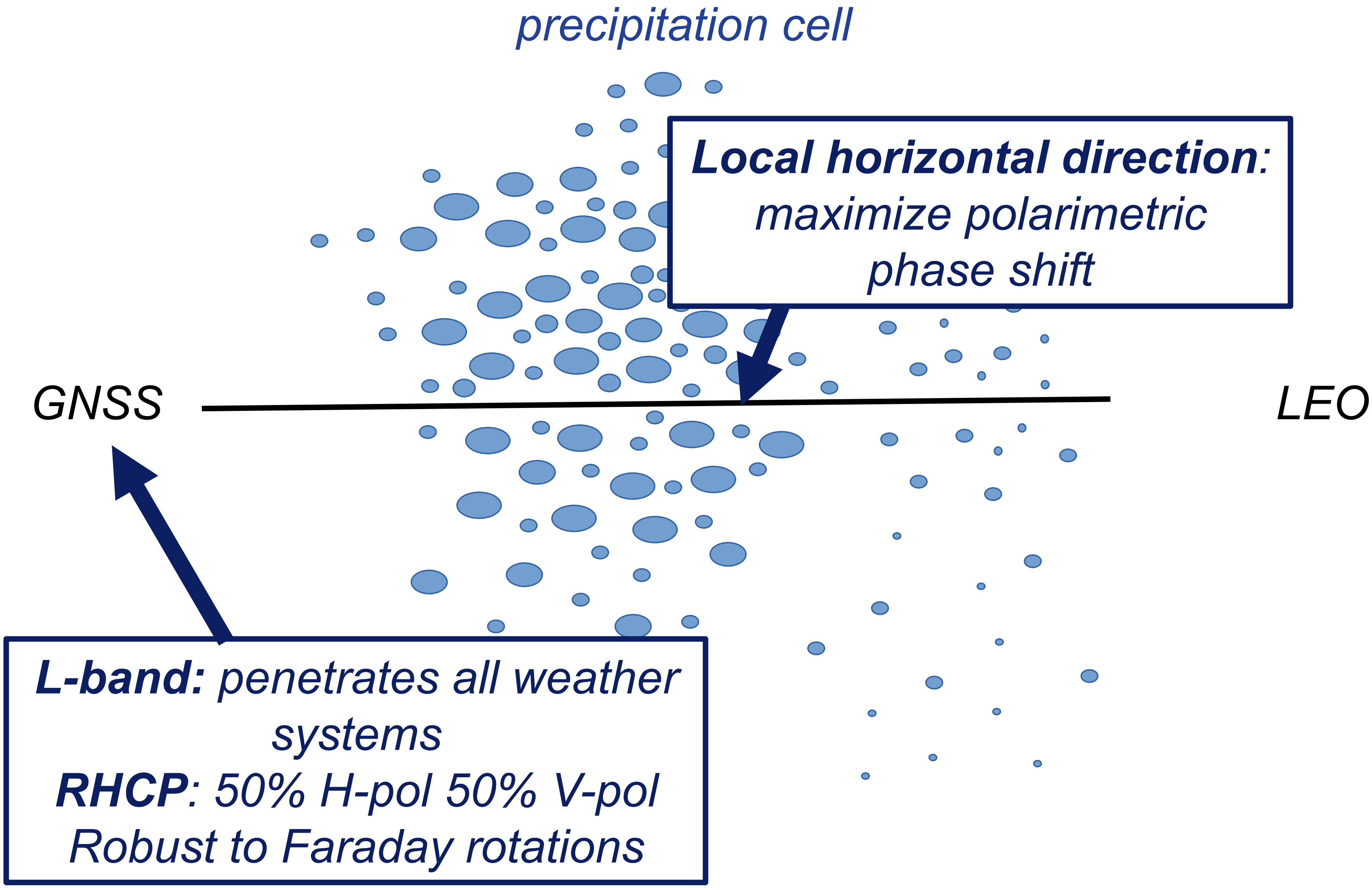
but rather LIKE



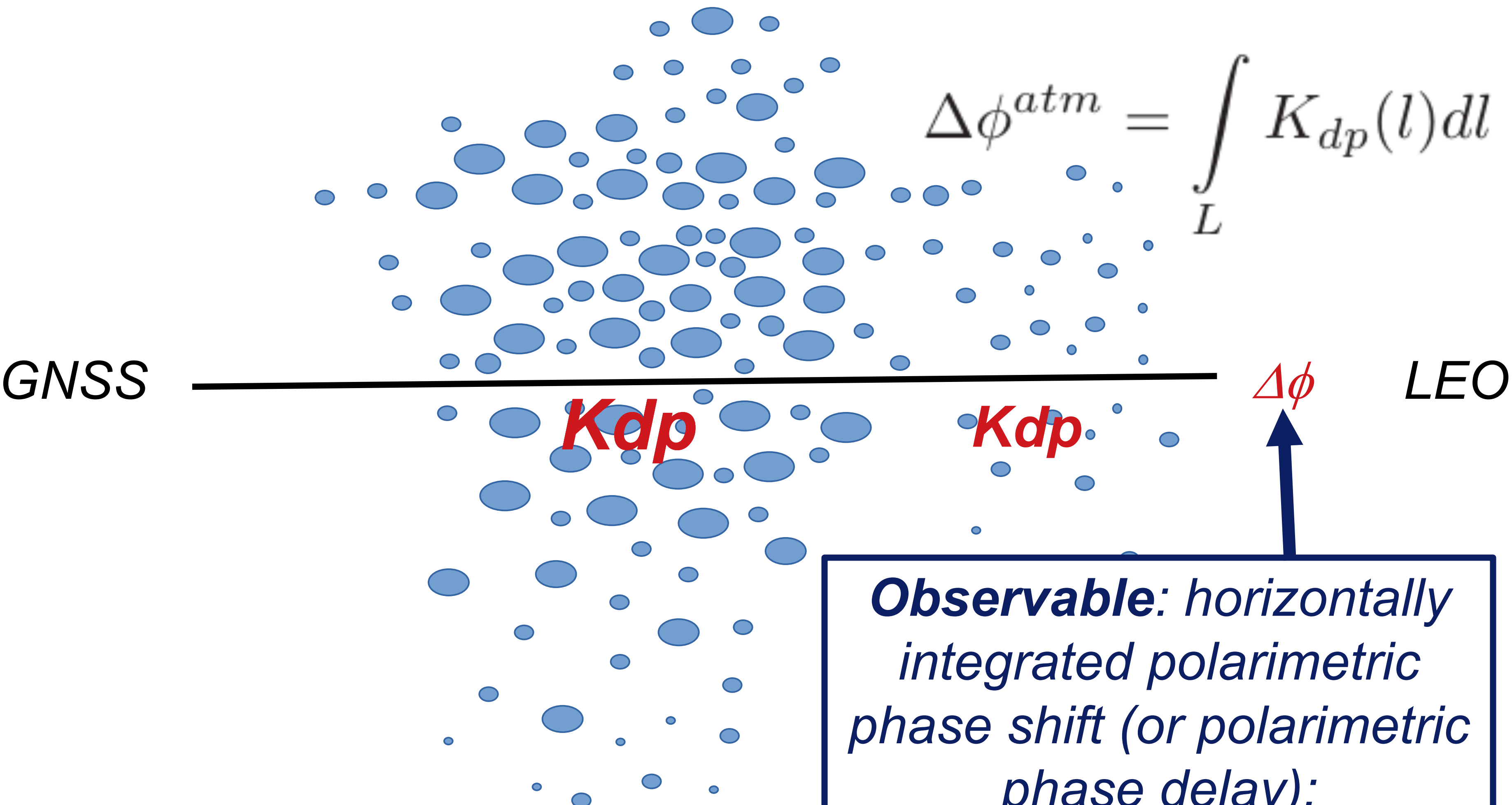
Vertical dimension shorter than Horizontal dimension → different propagation delays


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

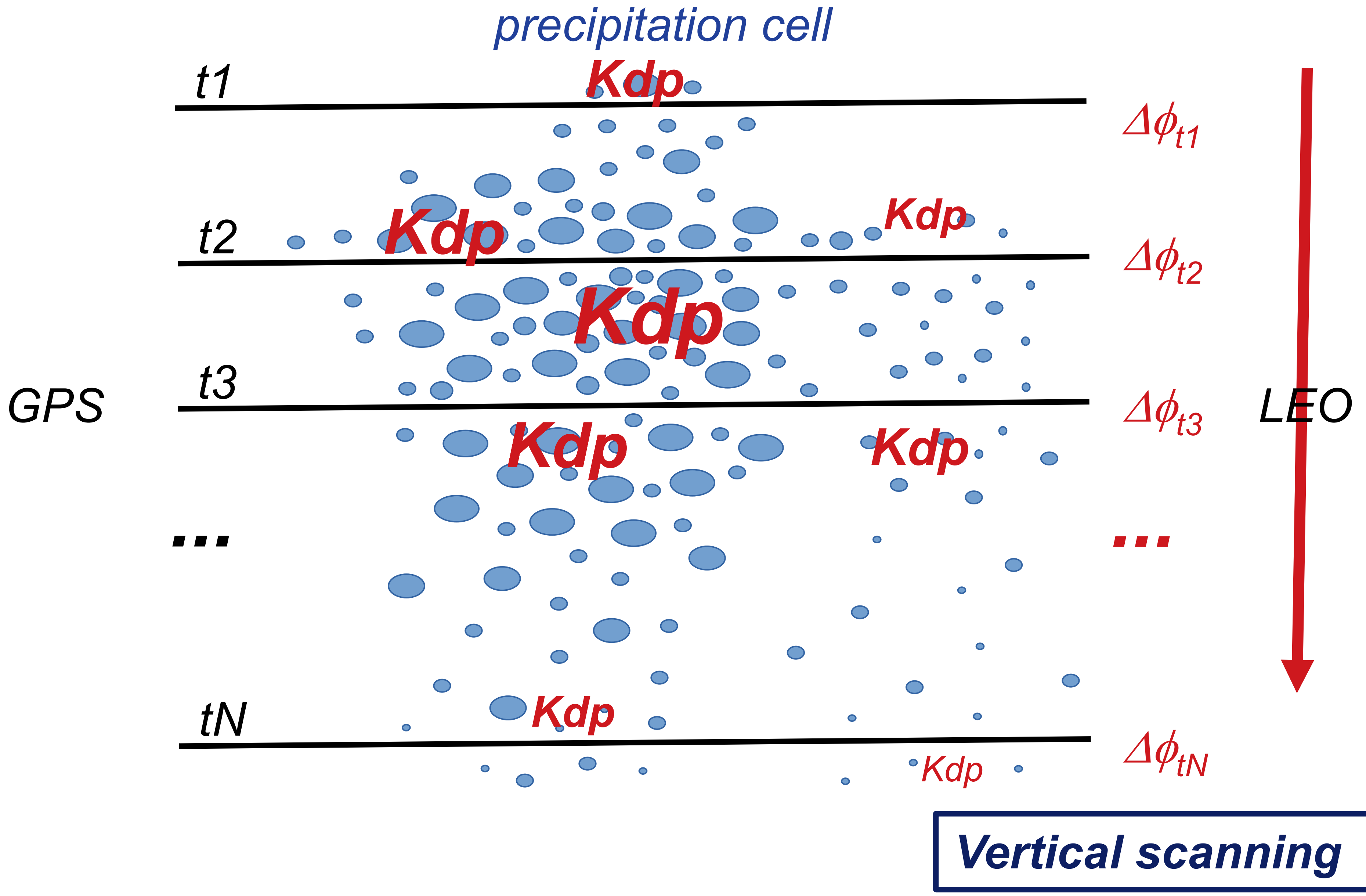


$$\Delta\phi^{atm} = \int_L K_{dp}(l)dl$$

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

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

Delay of H-pol longer than V-pol!



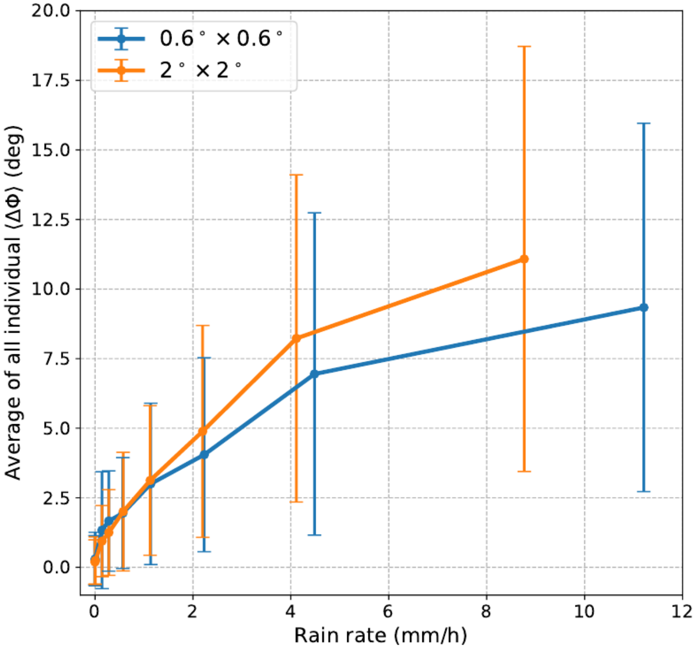
precipitation cell
t1
Kdp
$\Delta\phi_{t1}$
t2
Kdp
Kdp
$\Delta\phi_{t2}$
Kdp
GPS
t3
$\Delta\phi_{t3}$
LEO
Kdp
Kdp
...
...
tN
Kdp
$\Delta\phi_{tN}$
Kdp
Vertical scanning

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

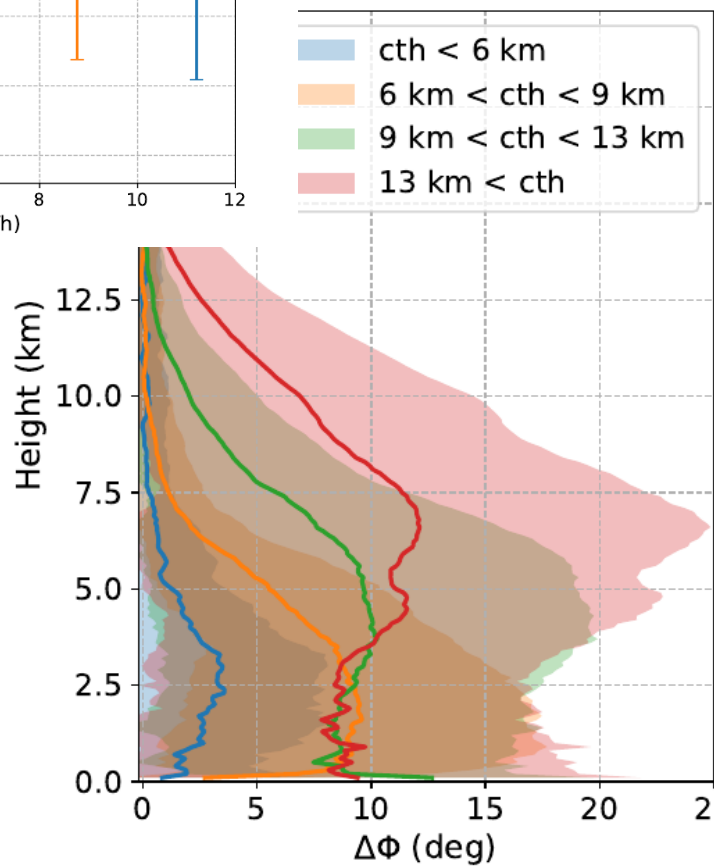
*Sucessful launch on **February 22, 2018**, by SpaceX (Falcon9).*

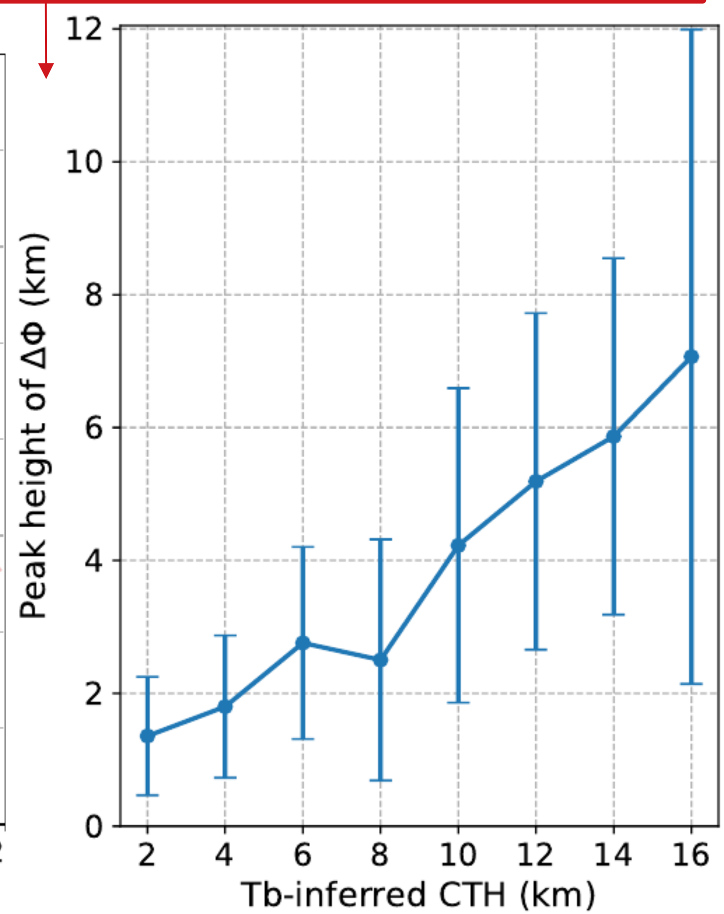
*GNSS RO experiment **activated on May 10**, 2018.*

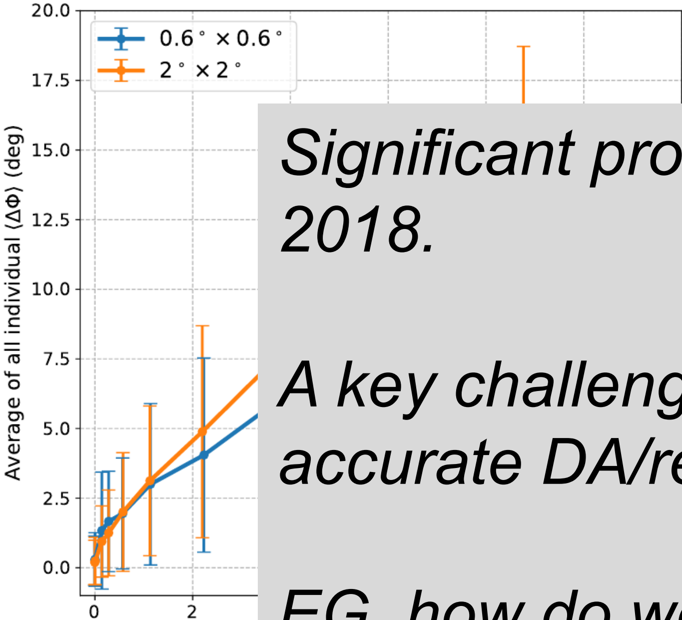
Rain rate vs polarimetric delay



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







Rain rate vs polarimetric delay

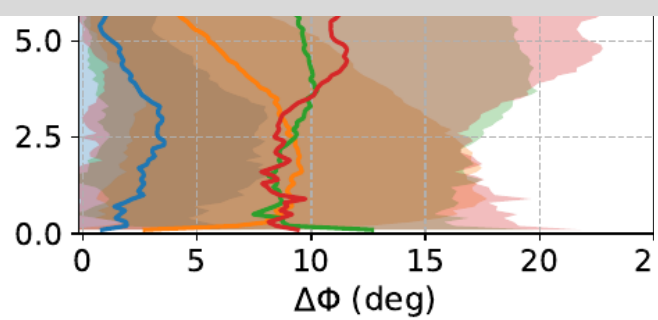
th)

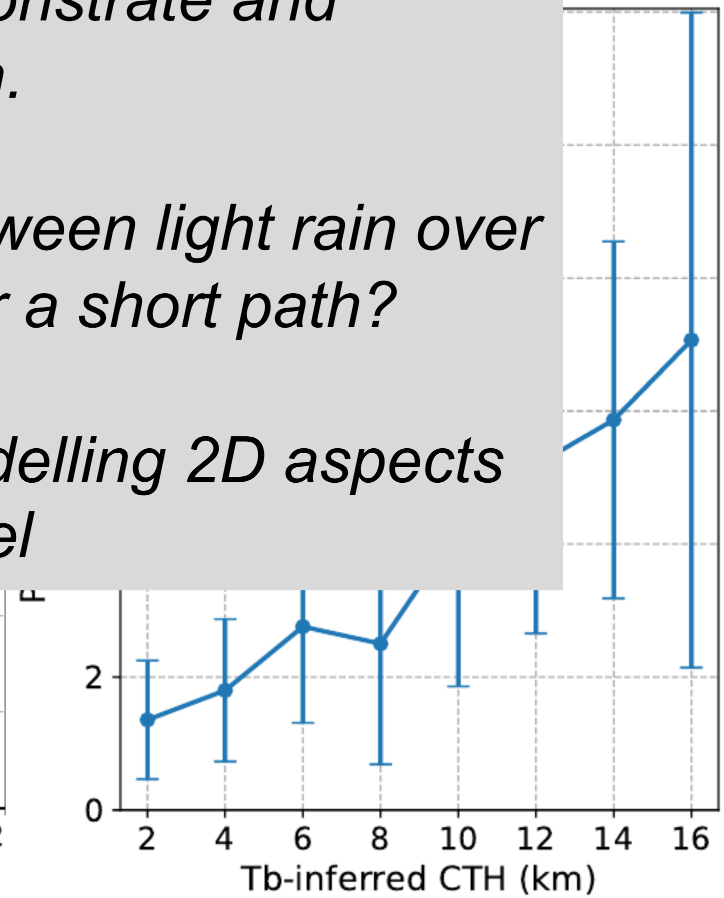
Significant progress since the launch of PAZ in 2018.

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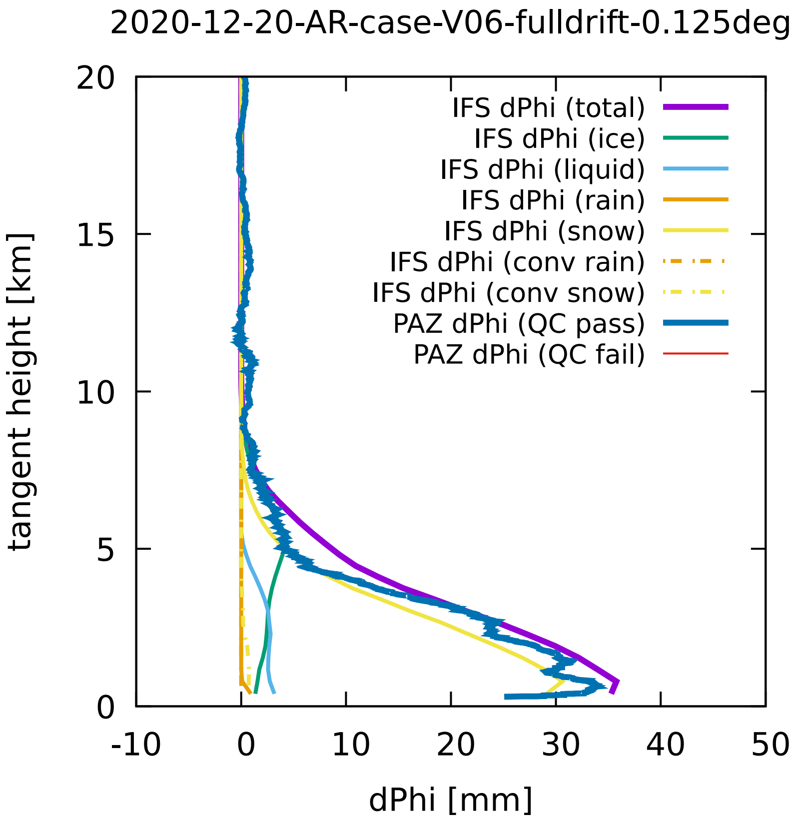
Forward model https://amt.copernicus.org/articles/17/1075/2024/

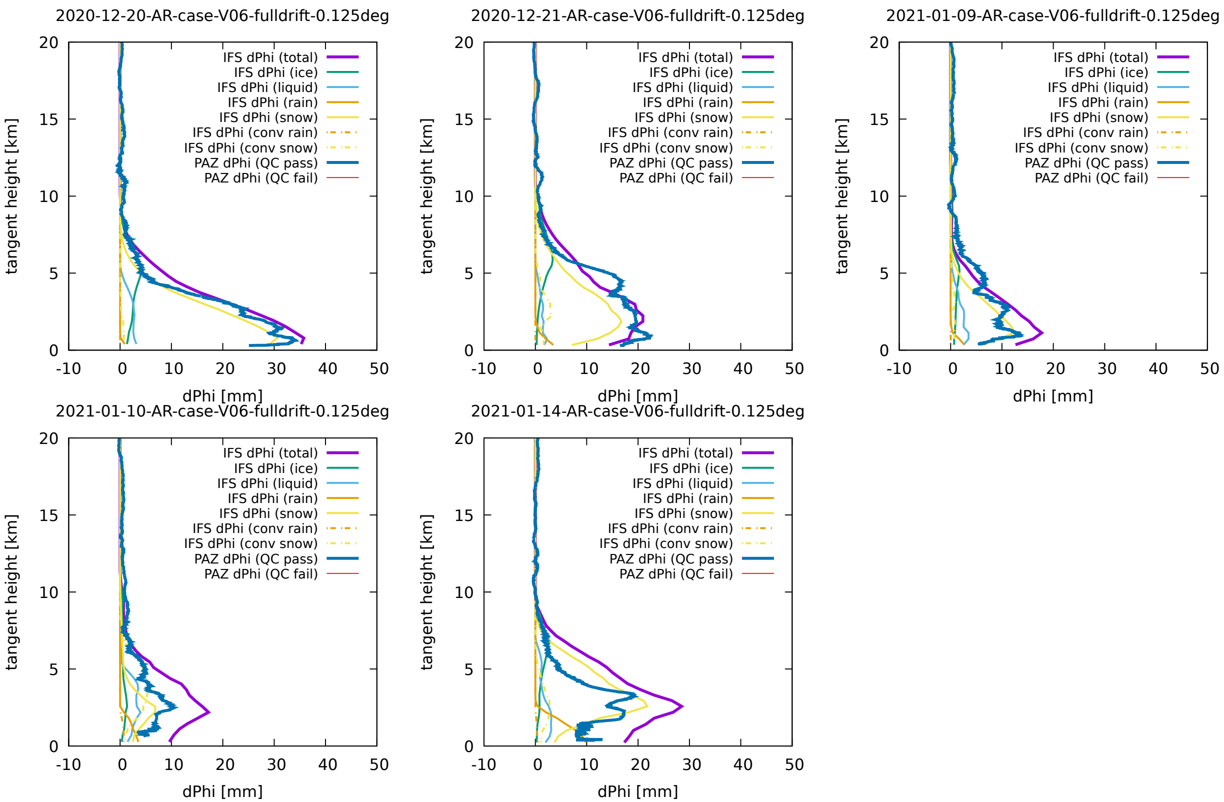
ECMWF

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



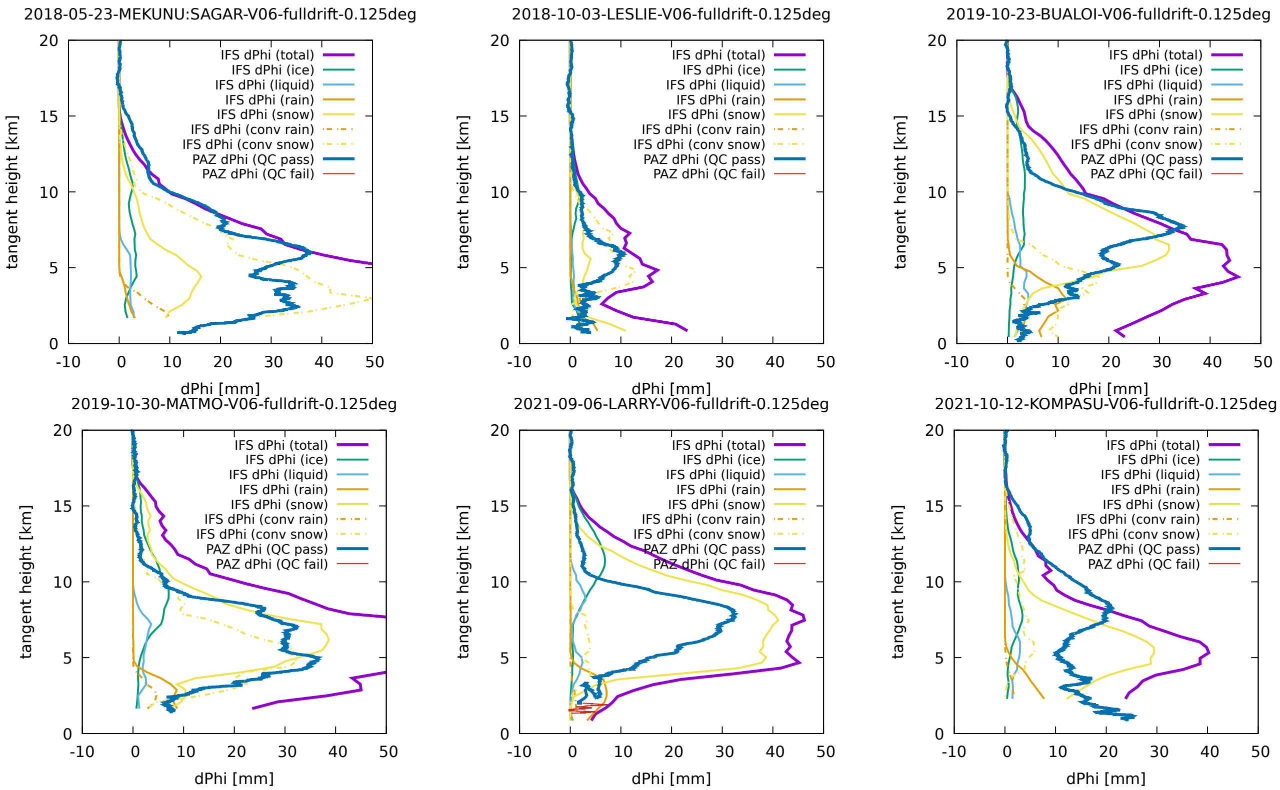
- *Result for an Atmospheric River (AR) case*
- *Very good agreement between simulated total (blue) and observed (purple) profiles.*
  - *despite many simplifying assumptions!*
- *Resolved-scale snow (yellow solid) is the dominant contribution*

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
  - Impact on stratospheric winds in the tropics

- 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 the polarimetric RO concept and recent forward modelling work