Errors in RO observations: what causes them and how can we estimate them?

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OPAC-7 and IROWG-9
8-14 September 2022
Seggau Castle, Leibnitz, Austria

Contributions from Nouredine Semane and Ricardo Todling

Outline

- Methods of estimating random error statistics
- Sources of RO errors and their estimates
- Estimation of errors of individual RO profiles
  - “stdv” standard deviation of BA from climatology 60-80 km
  - Local spectral width in troposphere (LSW)
  - Horizontal gradients of N (violation of spherical symmetry assumption)

Estimating random error statistics (uncertainties) of observations (O)

- Comparison with one trusted data set X
  - Apparent or perceived error method
    - Hollingsworth and Lönnberg (1986)
    - NMC method (Parrish and Derber 1992)
  - (O-B)/B B=Background in model data assimilation
- Comparison to two data sets simultaneously
  - Desroziers et al. 2005 (O, model background B and analysis A)
  - Three-cornered hat (3CH) (O and any two data sets, obs or models)
  - 3CH and Desroziers equivalent with model B and A as 3CH ancillary data
- Comparison to three or more data sets simultaneously
  - N-cornered hat (O and three or more data sets, obs or models)

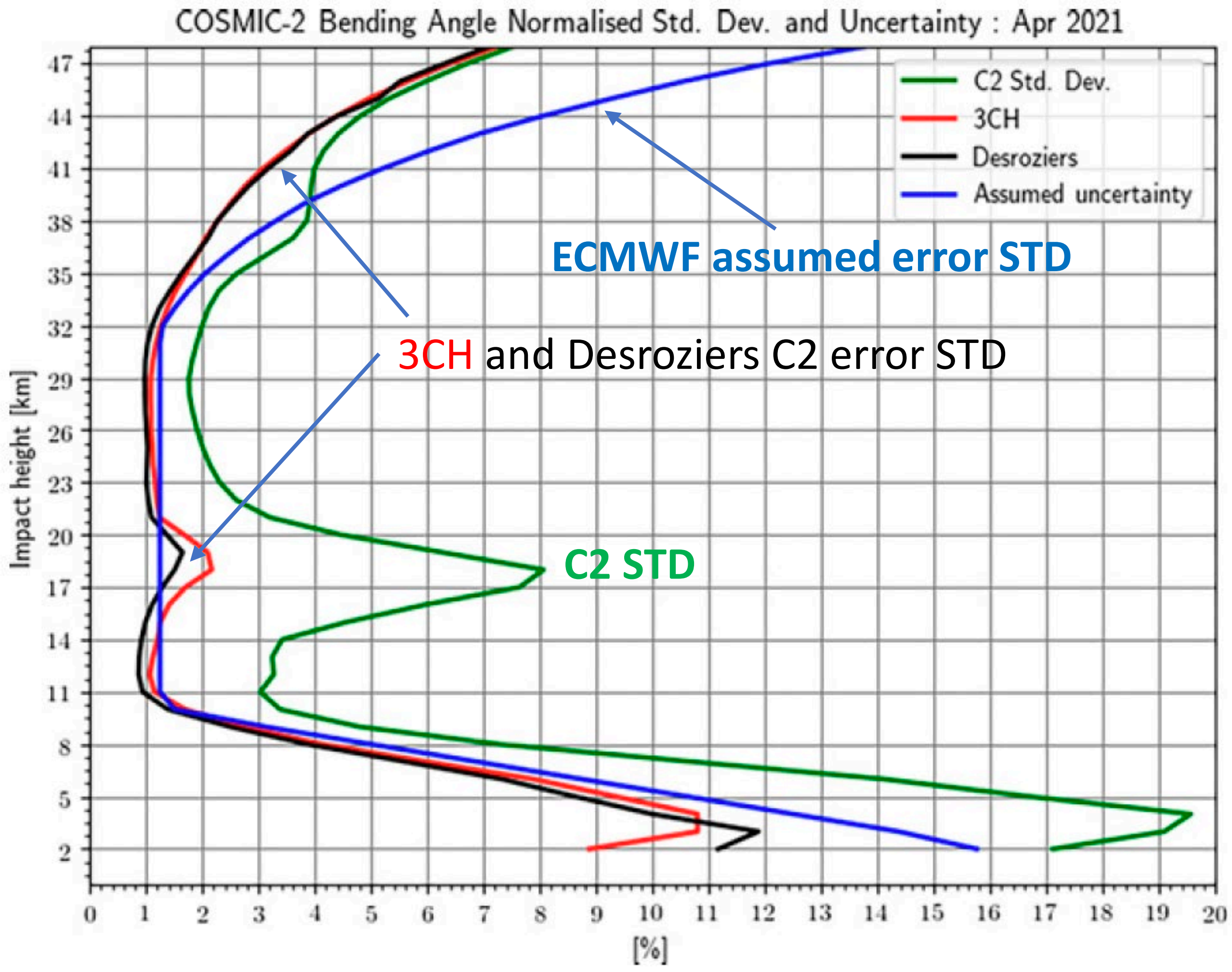
All methods require collocated independent data sets and can be heavily influenced by different horizontal and vertical footprints of the data sets, especially when radiosondes are one of data sets.

3CH and Desroziers estimate of C2 uncertainties

ERA5 and GFS time lagged data used in 3CH estimates

C2 standard deviations given for comparison

Fig. 2 of Semane et al. 2022



RO Observation Uncertainties

- Observation errors consist of
  - Fundamental (intrinsic) measurement errors, i.e. phase and amplitude errors (important mainly above 30 km)
  - Atmospheric effects and errors in retrievals and processing (e.g. violation of assumption of local spherical symmetry)
- In estimating RO errors, observations are compared with at least one other data set. This comparison introduces additional "errors."
  - Forward model errors for data sets other than RO
  - Collocation errors (time and space)
  - Correlations of errors in data sets
  - Representativeness errors due to different scales represented by RO and other data sets (horizontal and vertical footprints)
  - Vertical smoothing
  - QC-more stringent QC results in smaller error estimates

Anthes, R., J. Sjoberg, X. Feng and S. Syndergaard, 2022: Comparison of COSMIC and COSMIC-2 Radio Occultation Refractivity and Bending Angle Uncertainties with latitude in August 2006 and 2021. *Atmosphere* **13**, 5. https://doi.org/10.3390/atmos13050790

Sources of RO Errors

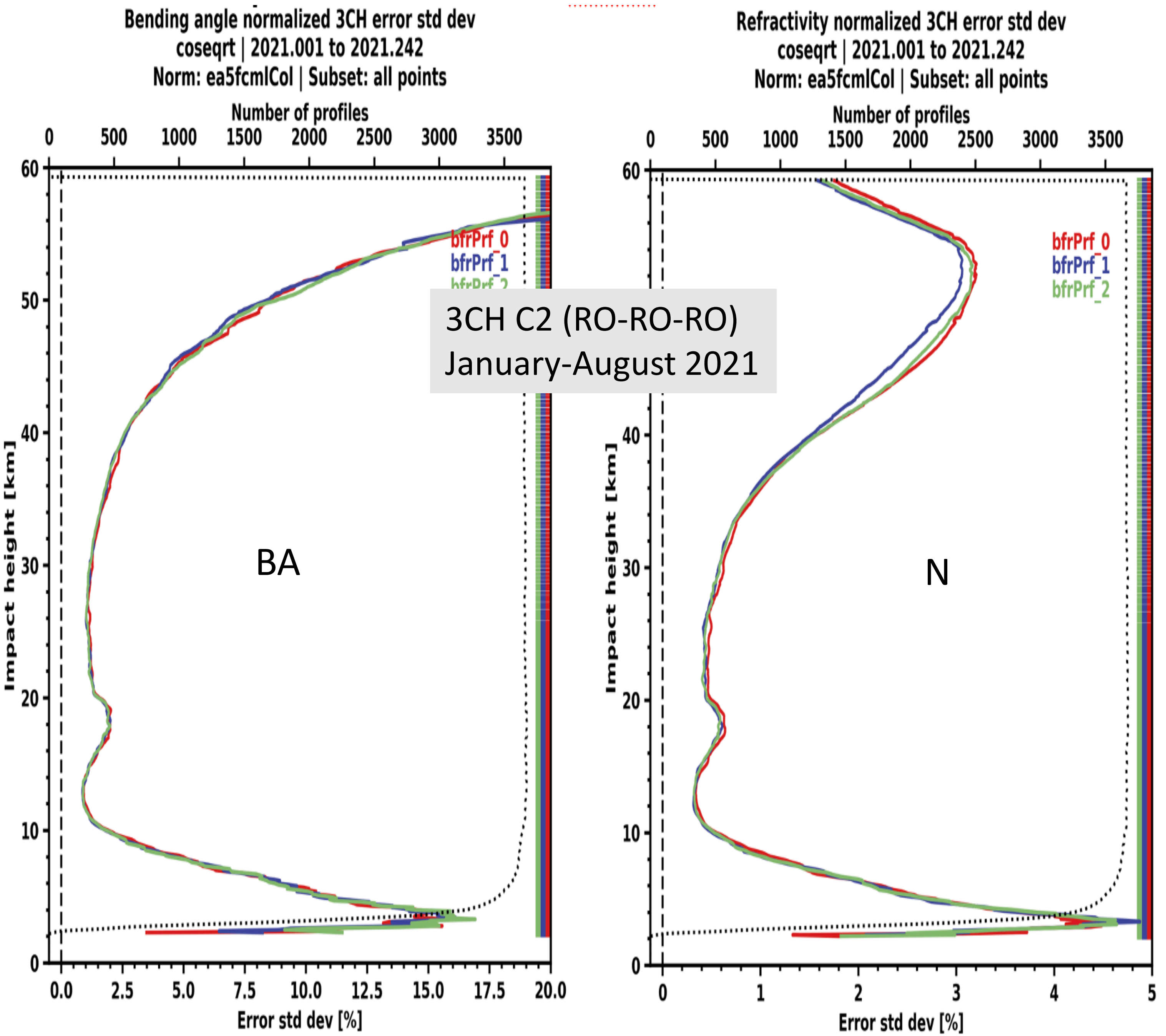
- Measurement errors
  - Orbit uncertainties
  - Receiver errors (e.g. thermal noise)
  - Clock errors of GNSS and receivers
  - Multipath on satellite
- Atmospheric effects
  - Ionospheric residuals (incomplete correction for ionospheric effects)
  - Horizontal gradients of refractivity and violation of spherical symmetry assumption
    - Atmospheric multipath
    - Retrieval errors
    - L1 and L2 tracking errors
  - Super-refraction (ducting)

Dominant source of RO uncertainties

Residual ionosphere errors
GNSS and LEO clock errors

Horizontal gradients of T
and footprint effects

Horizontal inhomogeneities of N,
with q dominant in lower
troposphere. SNR has little effect.



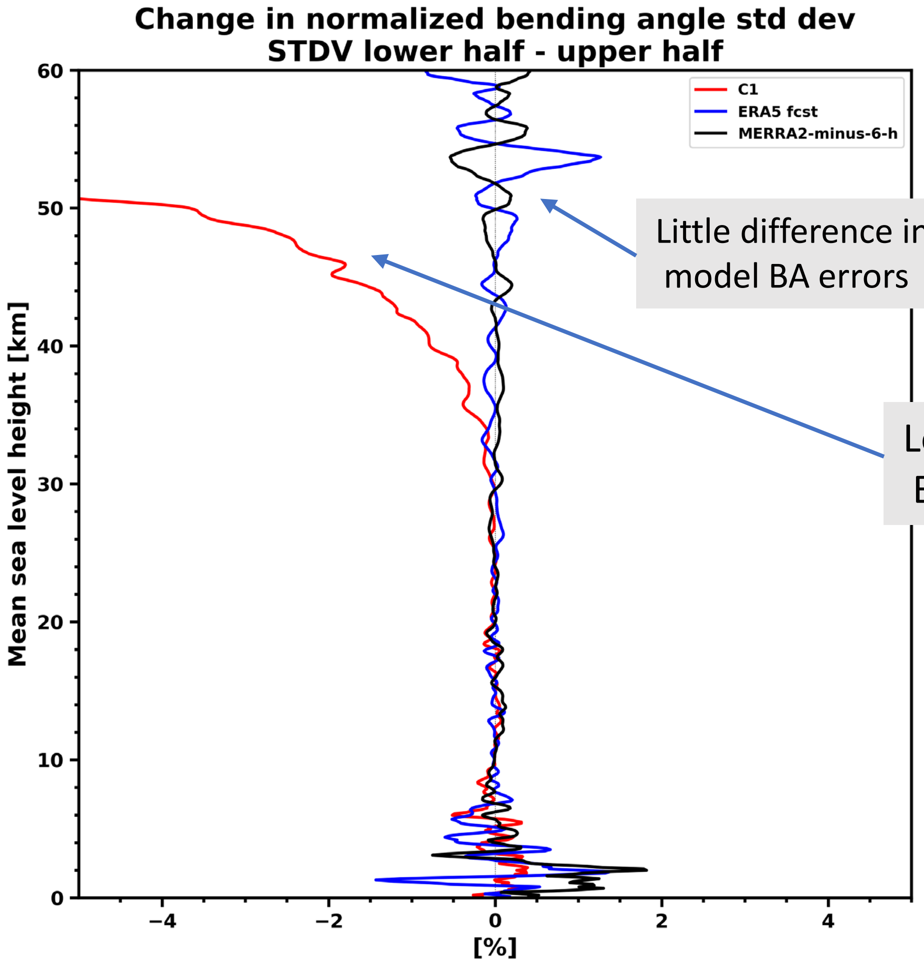
Estimating uncertainties of individual profiles

- Characterize the uncertainty of individual RO profiles as a function of some characteristic of each profile, rather than a statistical model
- Based on RO observations
  - “STDV”: standard deviation of BA difference from climatology between 60-80 km (a measure of SNR)
  - Local spectral width (LSW, Liu et al 2018; Chen et al. 2018; Chang and Yang, 2022)
- Based on model fields
  - Horizontal gradients of N from model (proposed here)-related to LSW

Standard deviation of BA difference from climatology

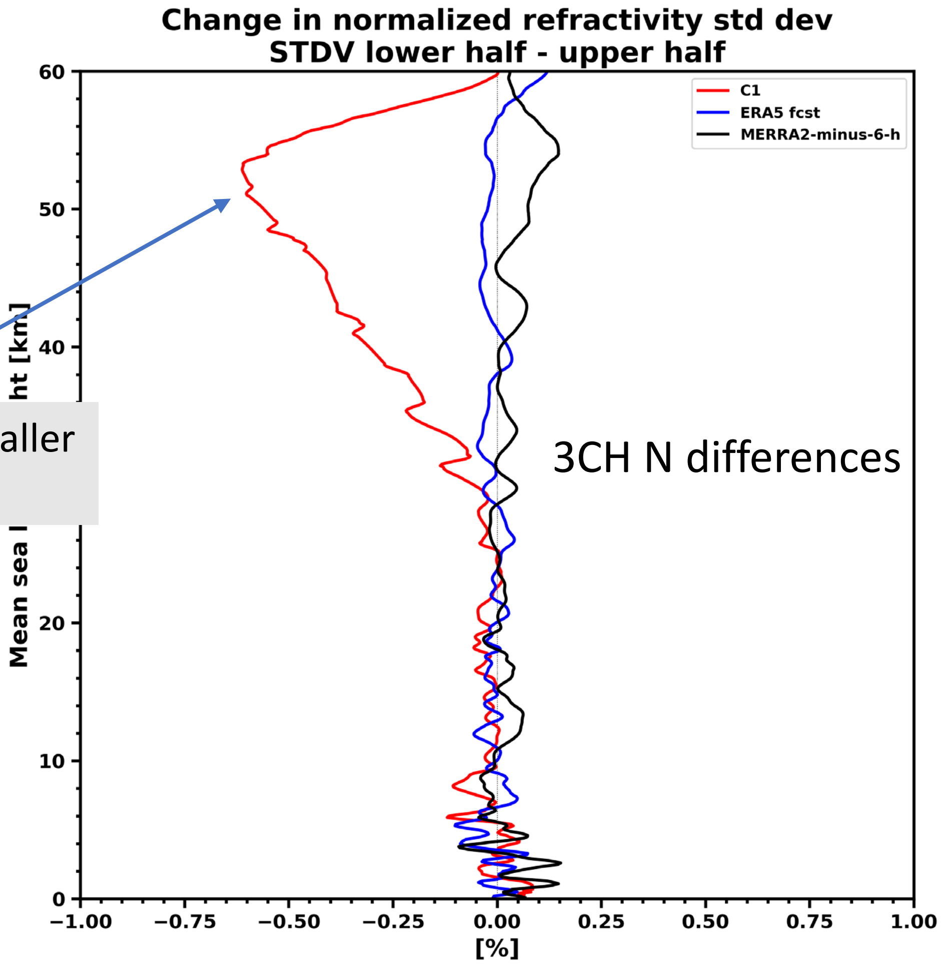
- “STDV”: standard deviation of BA difference from climatology between 60-80 km
- STDV is determined by clock errors, receiver thermal noise (SNR), and ionospheric residuals
- Provided by CDAAC for each RO profile
- STDV is good predictor of uncertainty above 40 km (next slide)

3CH Uncertainty differences based on STDV



Little difference in model BA errors

Low STDV have smaller BA and N errors

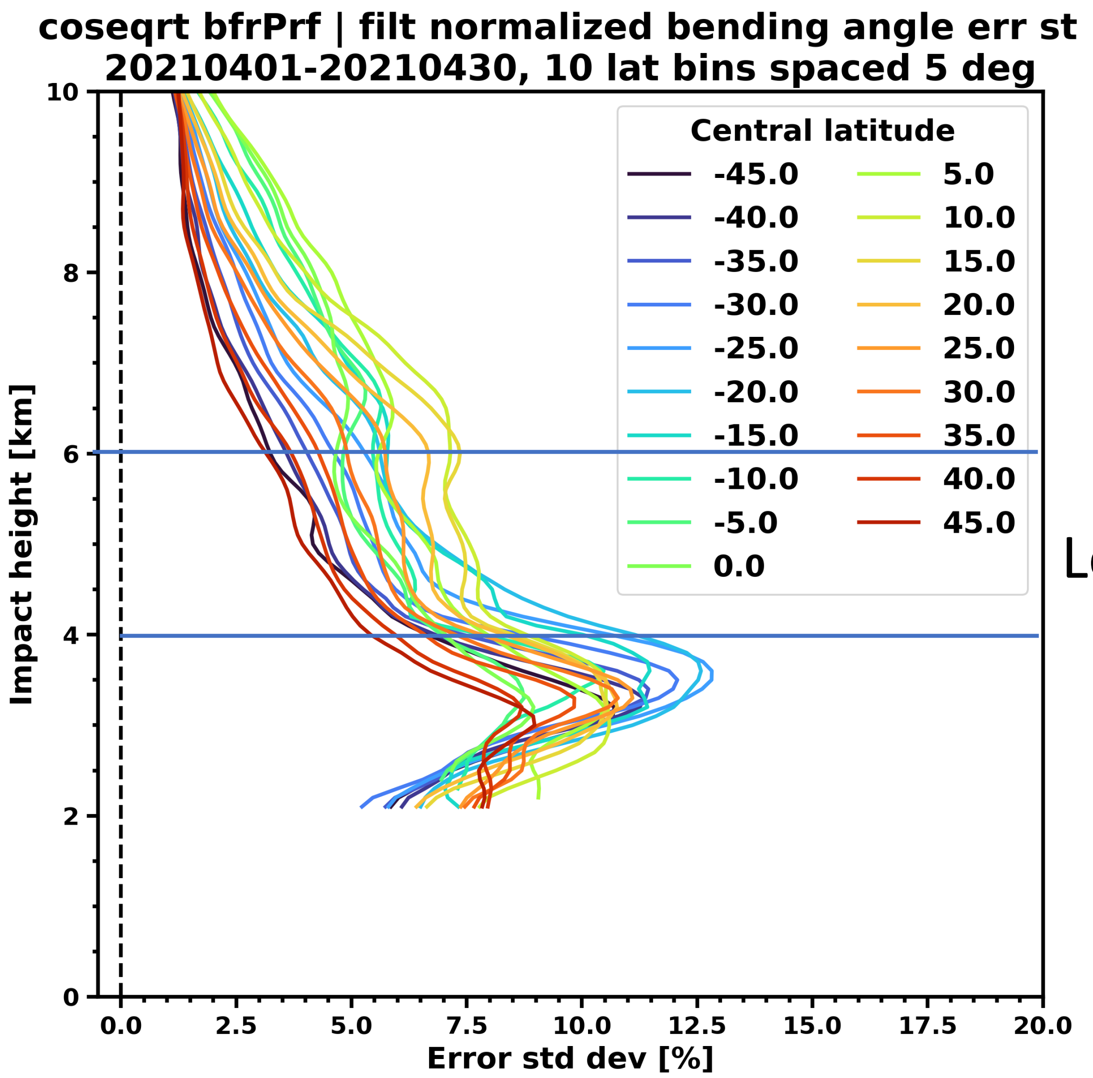


3CH N differences

3CH error estimates of low and high LSW

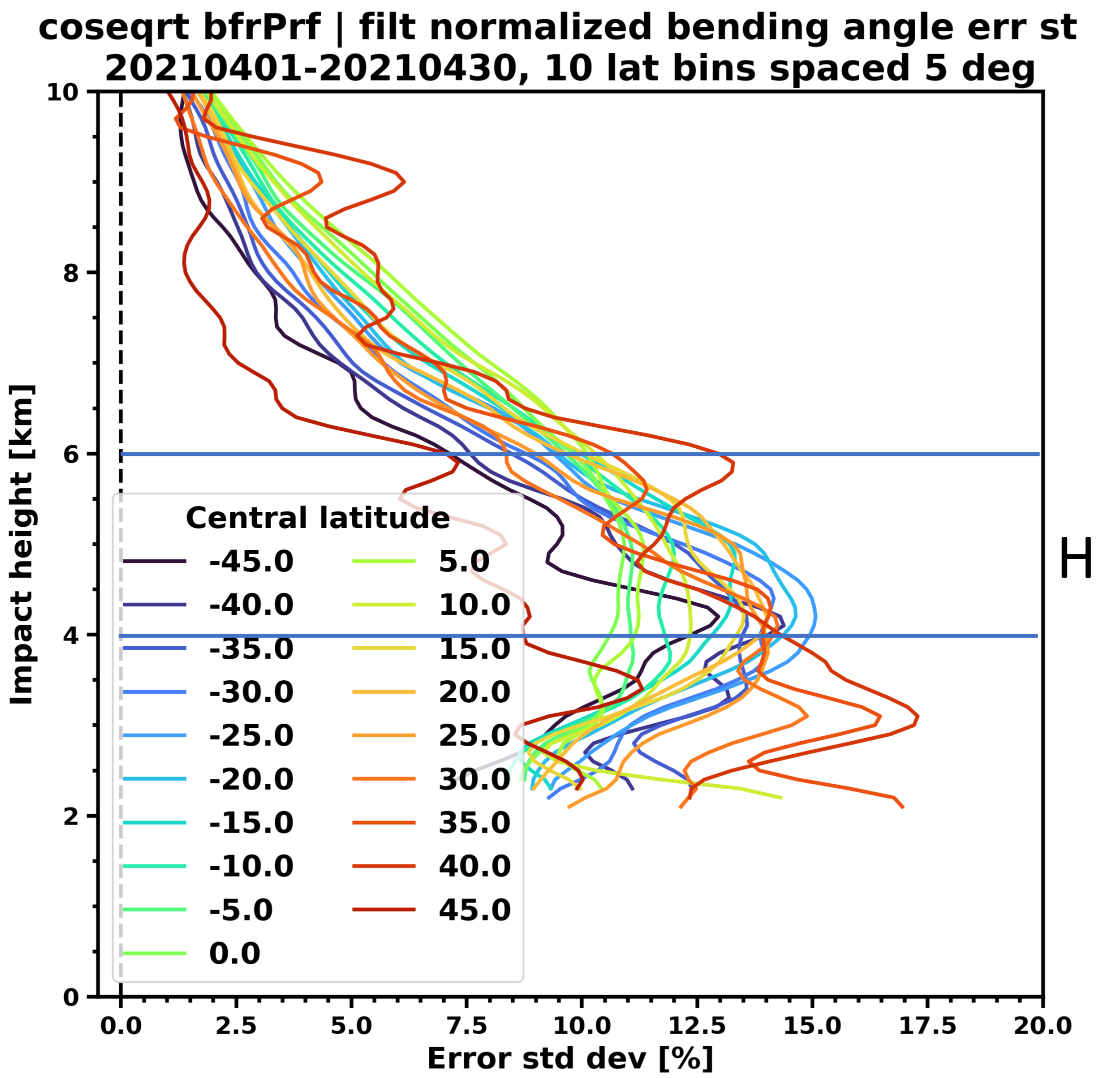
- LSW here is taken as the LSW RMS between 4-6 km impact height
- C2 ERA5 and GFS short-term forecasts for April 2021
- Two LSW bins represent upper and lower ~25% of LSW values
- Low LSW profiles clearly have smaller uncertainties than high LSW profiles below 10 km impact height, and impact is greatest in the range chosen for the LSW differences (Not entirely local)

Range (4-6 km) Low LSW C2



Low LSW mean ~6%

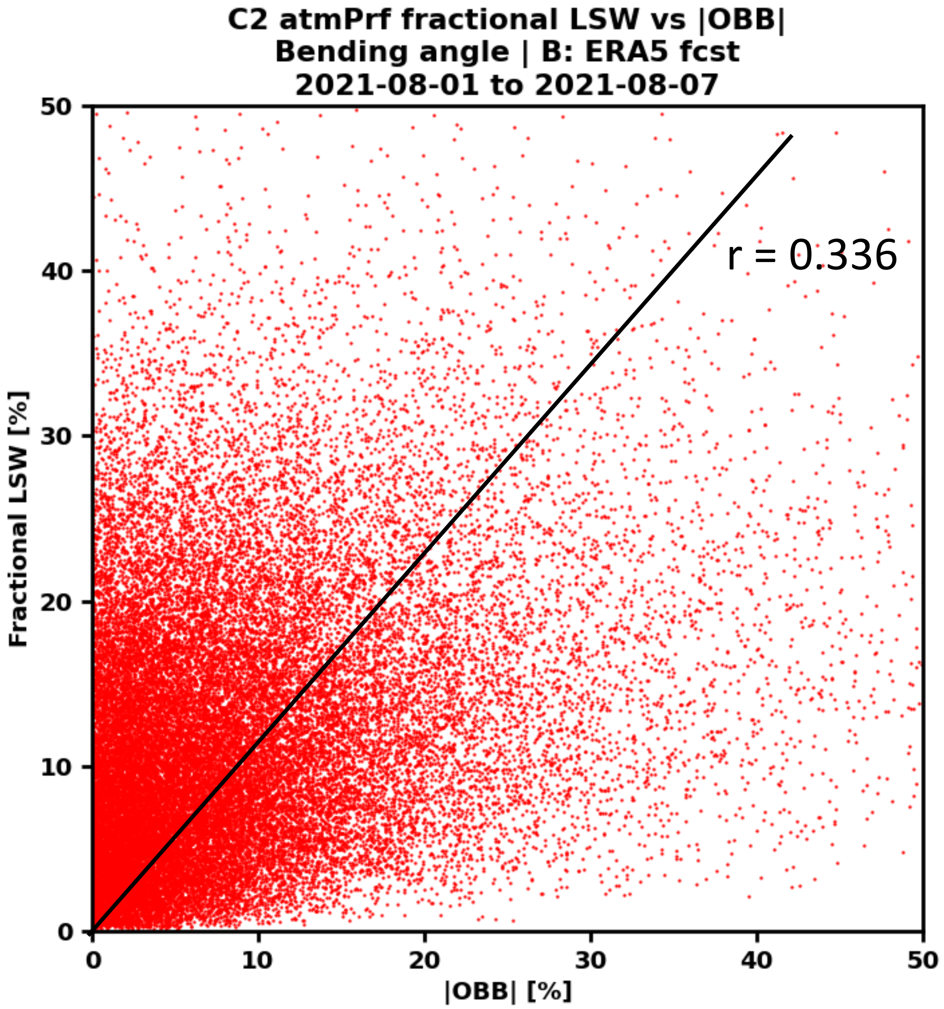
Range 4-6 km High LSW C2

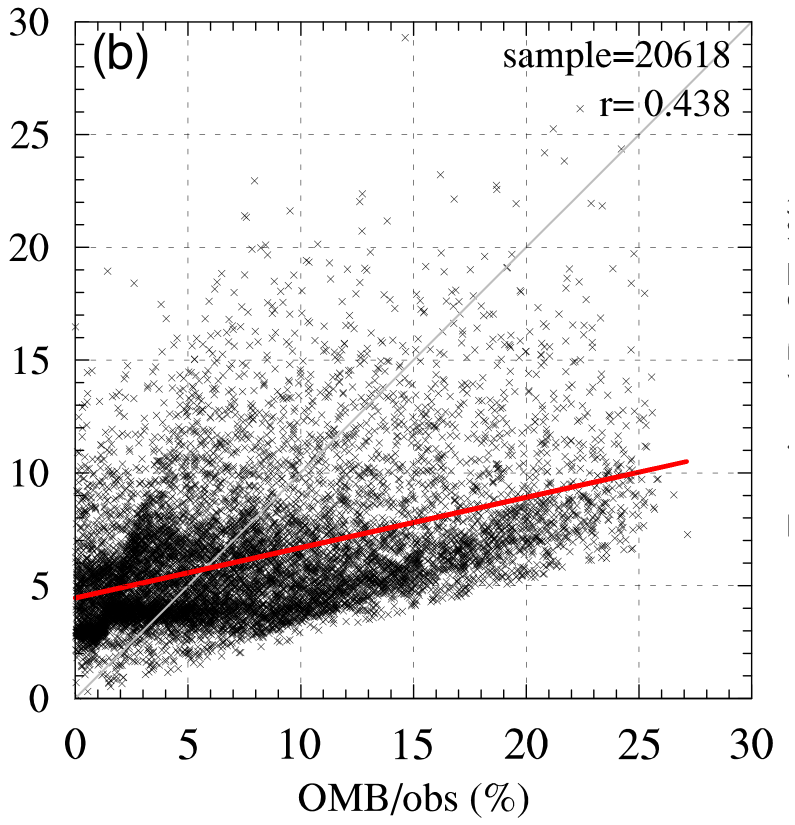


High LSW mean ~ 12%

LSW vs |OBB| for COSMIC-2 compared to DBOE vs OBB (H. Zhang)

r = 0.336 for C2, 0.438 for C1. These seem small?





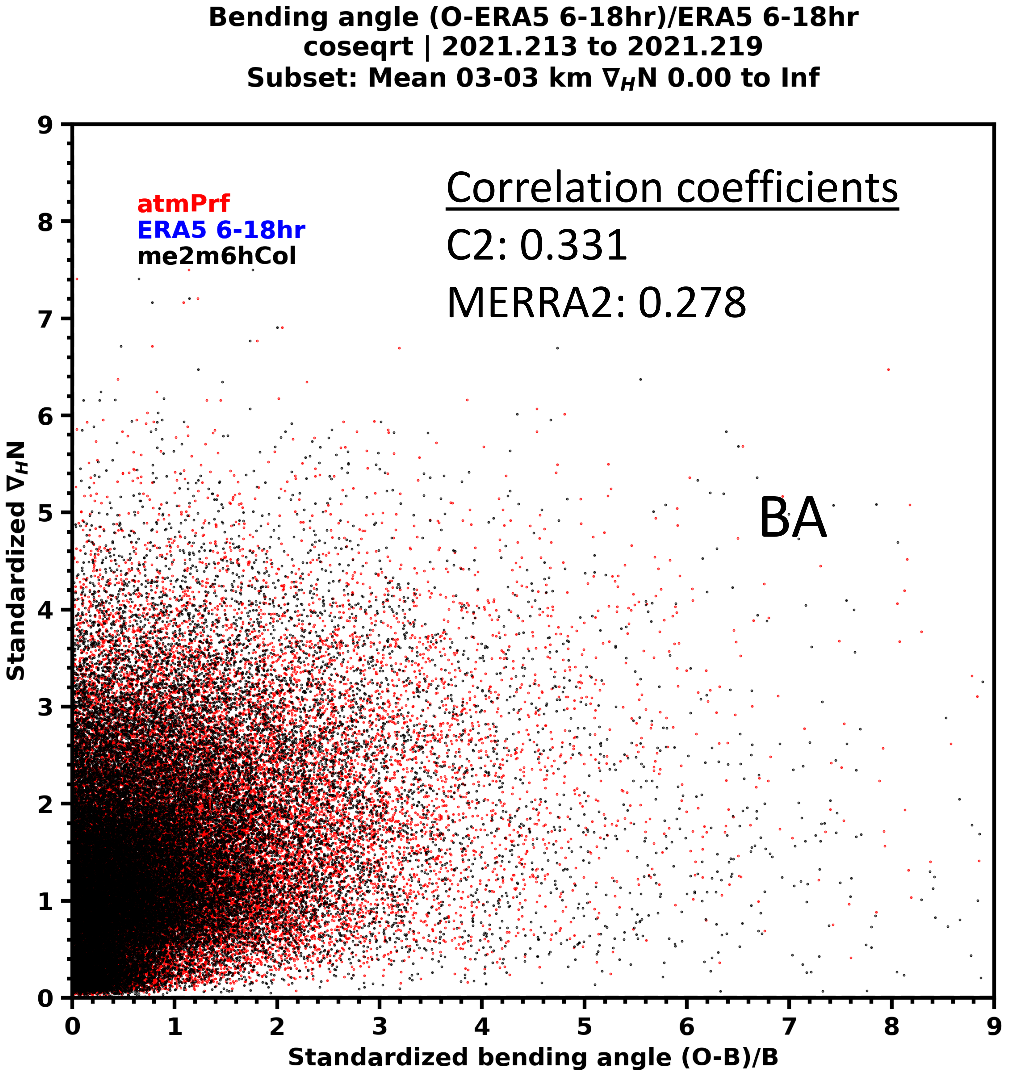
Comparison between the normalized background departure from observation (OMB/obs) and fractional DBOE at about 700-hPa)~3 km MSL) from 1 to 15 September 2008. (Hailing Zhang)

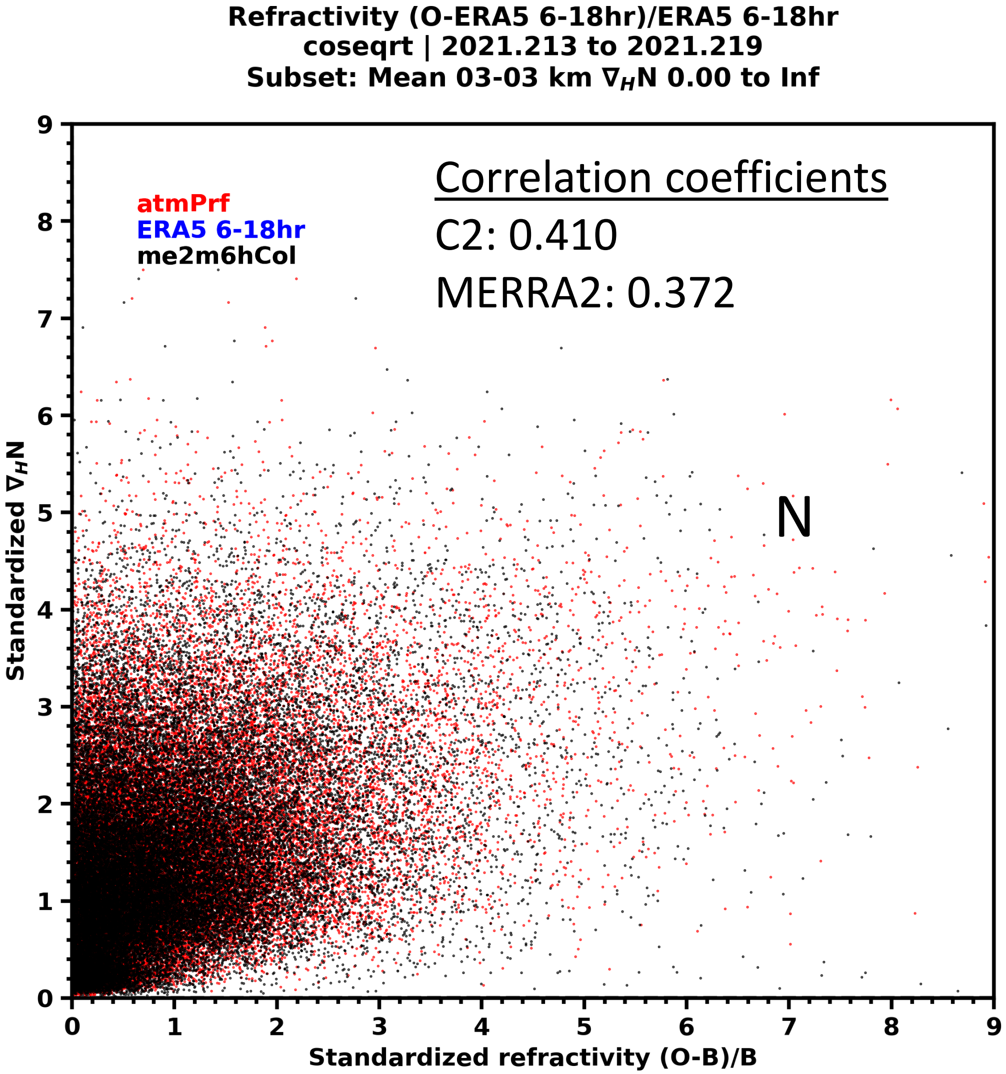
Model $\nabla_H N$ as predictor of individual RO profile uncertainty?

- Look at scatter plots of (O-B)/B vs $\nabla_H N$ for individual RO BA at 3 km
- (O-B)/B a measure of uncertainties of individual profiles (good assumption?)
- $\nabla_H N$ from model computed on 150 km scale; no small scale inhomogeneities

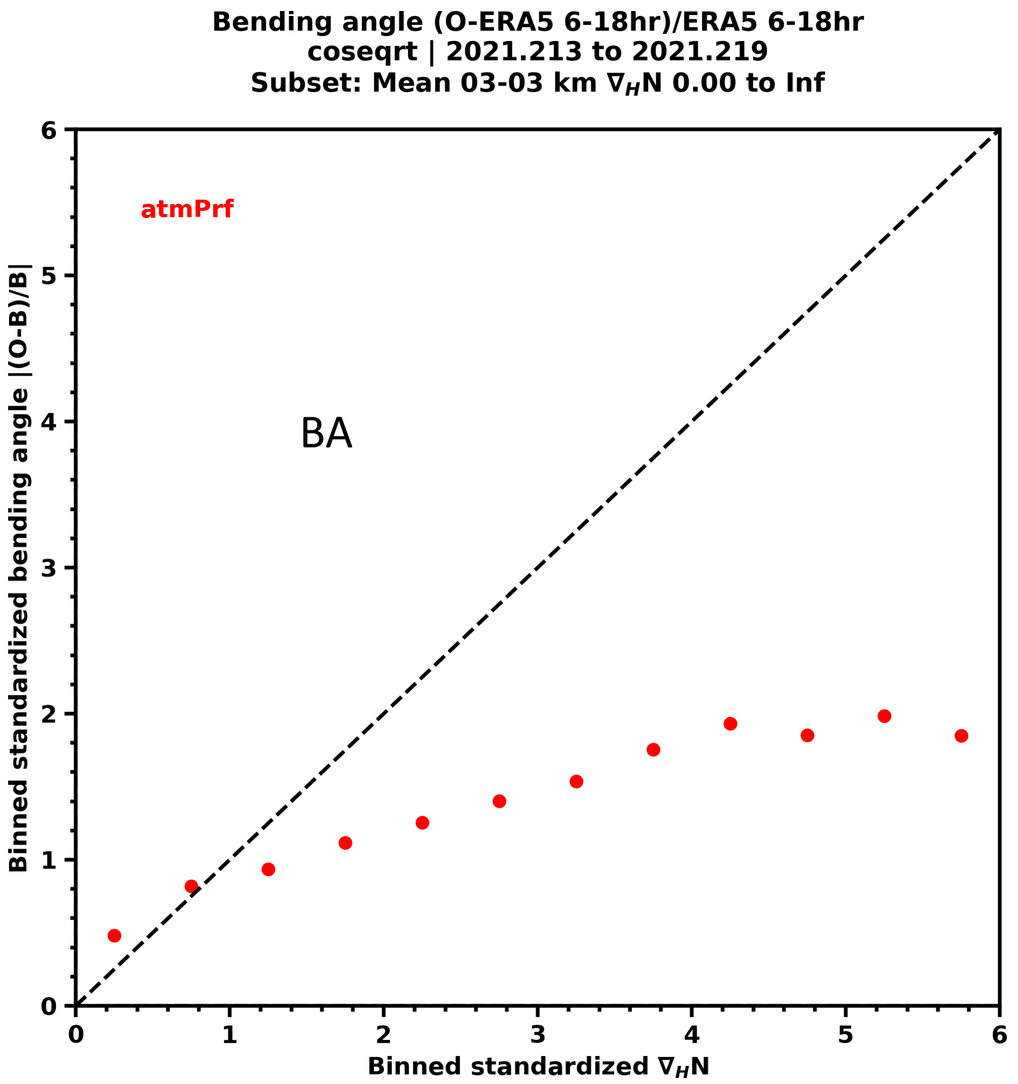
$\nabla_H N$ vs. OBB (BA and Refractivity)

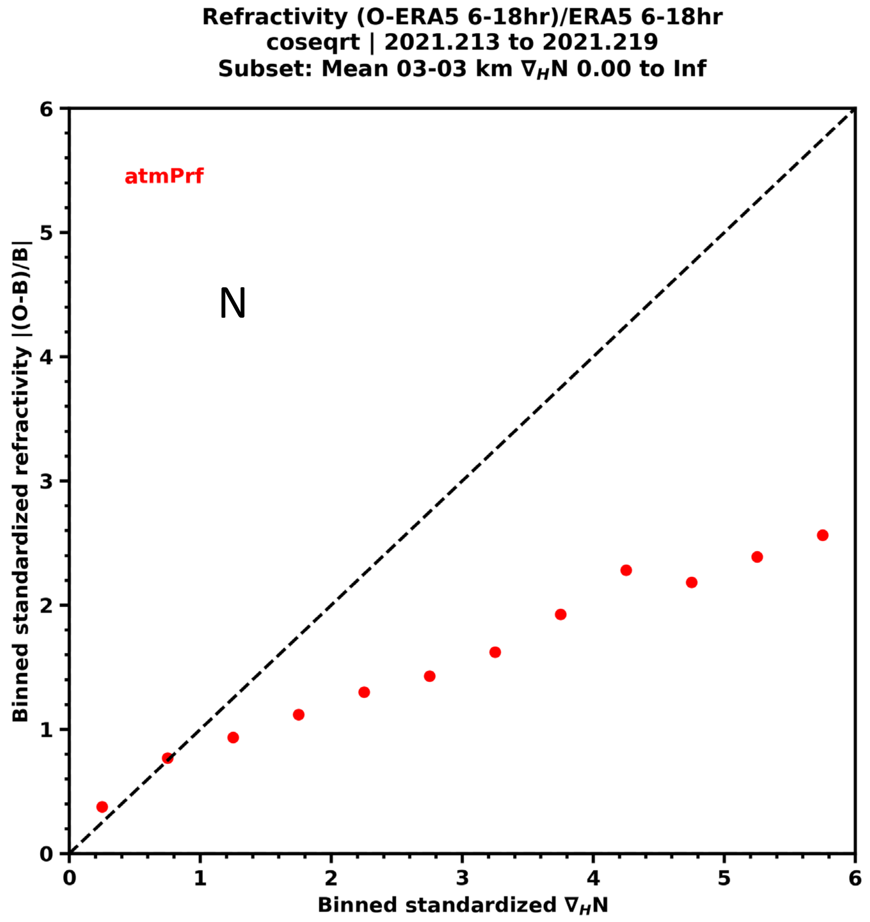
1-7 August 2021





Binned 3 km BA and N OBB vs $\nabla_H N$





Summary

- Instrument and other intrinsic errors important above 30 km
- Horizontal gradients of N and small-scale turbulence dominate uncertainties in troposphere
- Uncertainties of individual profiles may be estimated by
  - STD of BA from climatology above 30 km
  - LSW below 10 km
  - $\nabla_H N$ below 10 km
  - Fairly weak correlations of OBB vs. LSW and $\nabla_H N$
    - Why?
    - How much does this affect the use of LSW and $\nabla_H N$ as predictors of RO uncertainties?

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Extra slide

3CH estimates of radiosonde Uncertainties

Ancillary data sets

C2
ERA5
MERRA-2
JMA-55

Dominant: Representativeness differences-horizontal and vertical footprints!

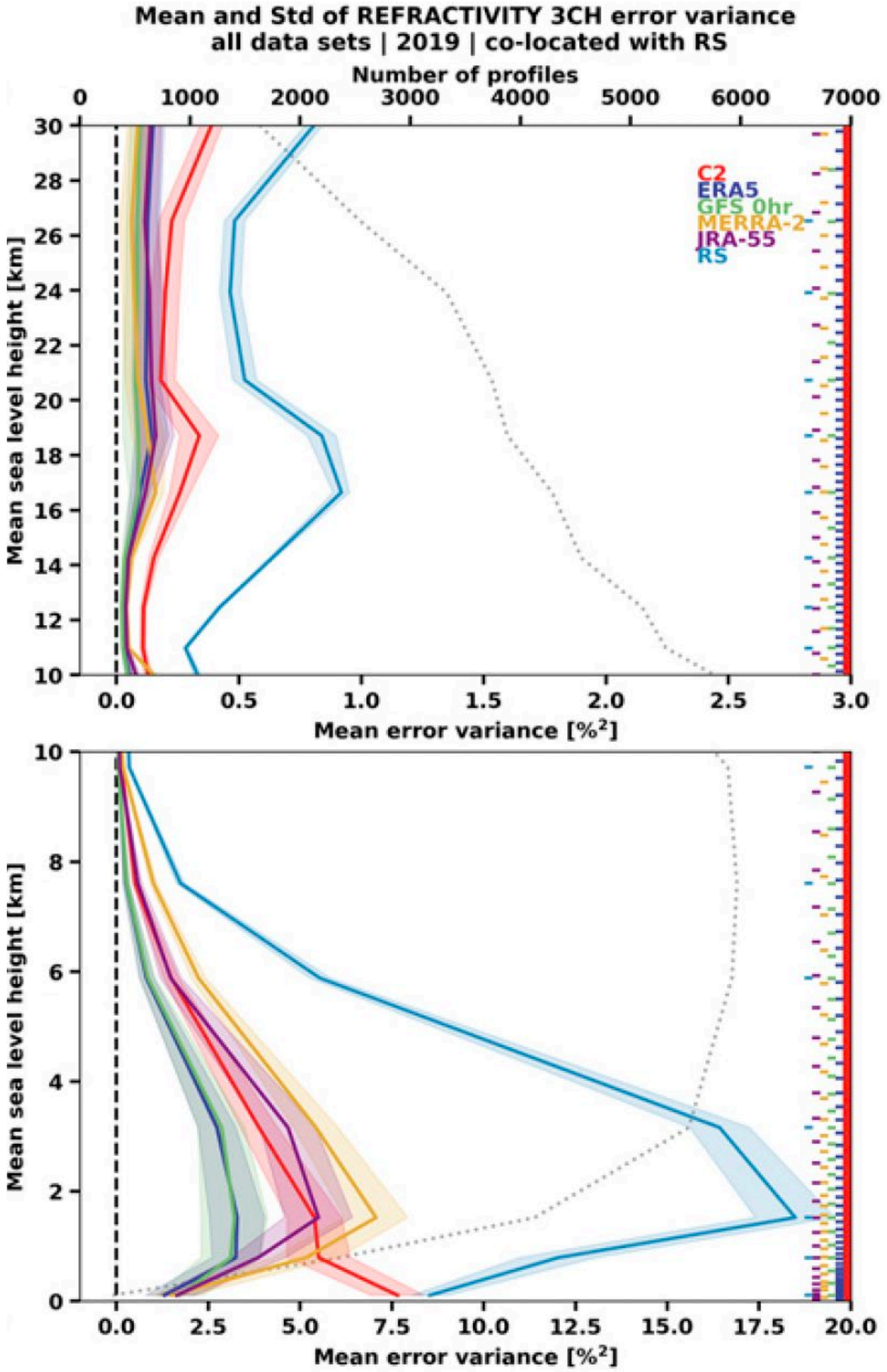

Fig. 5 Rieckh et al. 2021