An overview of 17 years of radio occultation development and assessment at NOAA

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Outline

- Data assimilation algorithms and early COSMIC impacts
- Expected impact from RO with OSSEs (originally planned COSMIC-2)
- Ongoing efforts to optimize RO data assimilation impact
- Concluding thoughts

RO data assimilation algorithms

A forward operator for **refractivity** (*N*) was initially used to assimilate RO observations from the COSMIC mission into the NCEP's operational global model starting in May 2007 (COSMIC launched in April 2006). Operational assimilation of other operational and research missions followed.

Inverse compressibility factors (~ 1)

Pressure of the dry air

$$N = k_1\left(\frac{P_d}{T}\right)Z_d^{-1} + k_2\left(\frac{P_w}{T}\right)Z_w^{-1} + k_3\left(\frac{P_w}{T^2}\right)Z_w^{-1},$$

Water vapor pressure

Atmospheric refractivity constants

Absolute temperature

Quality control procedures and observation error structures were developed and implemented according to the forward operator

Several "flavors" of *N* were implemented operationally over time

Limitations of a refractivity forward operator

- *Relatively* easy to implement: interpolation of modeled pressure, water vapor and temperature values from the model grid points to the location of the observation. [Dependence of the geometric height of model levels on the model variables needs to be taken into account as well.]

- The resulting modeled refractivity would only match the *observation* (assuming perfect model and retrieval algorithms) if the atmosphere were strictly spherically symmetric.

- Ignores the existence of horizontal gradients of refractivity in the atmosphere (global spherical symmetry approximation).

- <u>Refractivity observations</u>
  - require the use of some climatology or auxiliary information, which affects profiles above ~ 30 km.
  - negatively biased below the PBL height under very large gradients of atmospheric refractivity (super-refraction conditions).

Motivation for a bending angle forward operator

- Retrieval of bending angles makes use of approximation of bilateral symmetry around the ray path tangent height (not global).
- Not weighted with climatology information.
- Bending angles do not suffer from the negative bias in the lower troposphere caused by super-refraction conditions.
- Errors are vertically less correlated than in refractivity profiles because there is no use of an Abel transform.
- Retrieved earlier than refractivity in the processing of the GNSS-RO observations, which makes it more attractive from a data assimilation point of view.
- However, their use in data assimilation algorithms is more challenging due to the large variability of the vertical gradients of refractivity (water vapor).

NCEP Bending Angle Method (NBAM)

Operational assimilation of RO at NCEP switched from soundings of refractivity to soundings of **bending angle** in May 2012. Top of the profiles raised from 30 to 50 km and compressibility factors were introduced in the forward operator. Updated versions with improved quality controls and error characterization procedures were implemented in subsequent operational upgrades.

$$\alpha(a) = -2a\int_a^{\infty} \frac{d\ln n / dx}{(x^2 - a^2)^{1/2}}\, dx$$

$$(x = nr)$$

Refractional radius

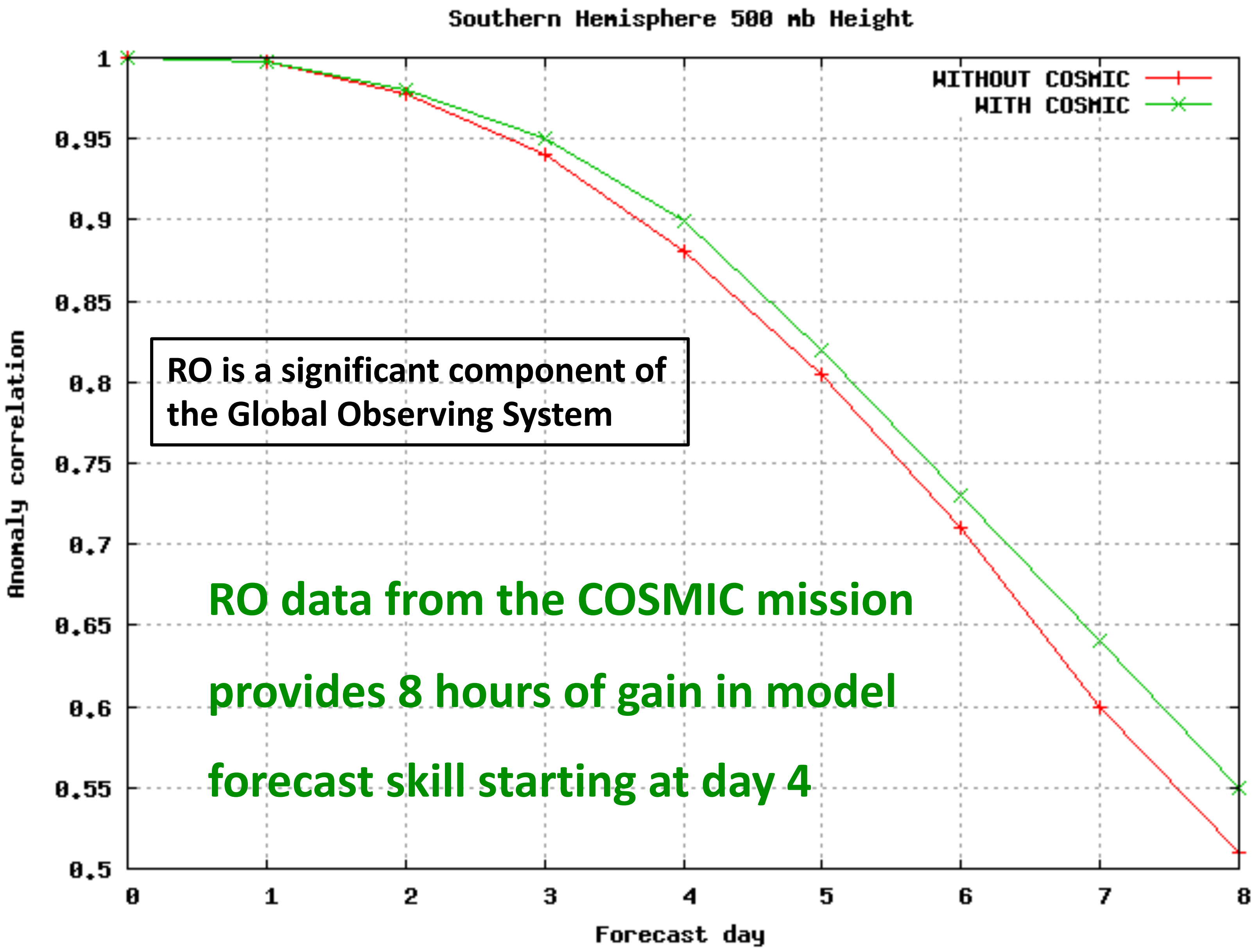
Index of refraction

Impact parameter

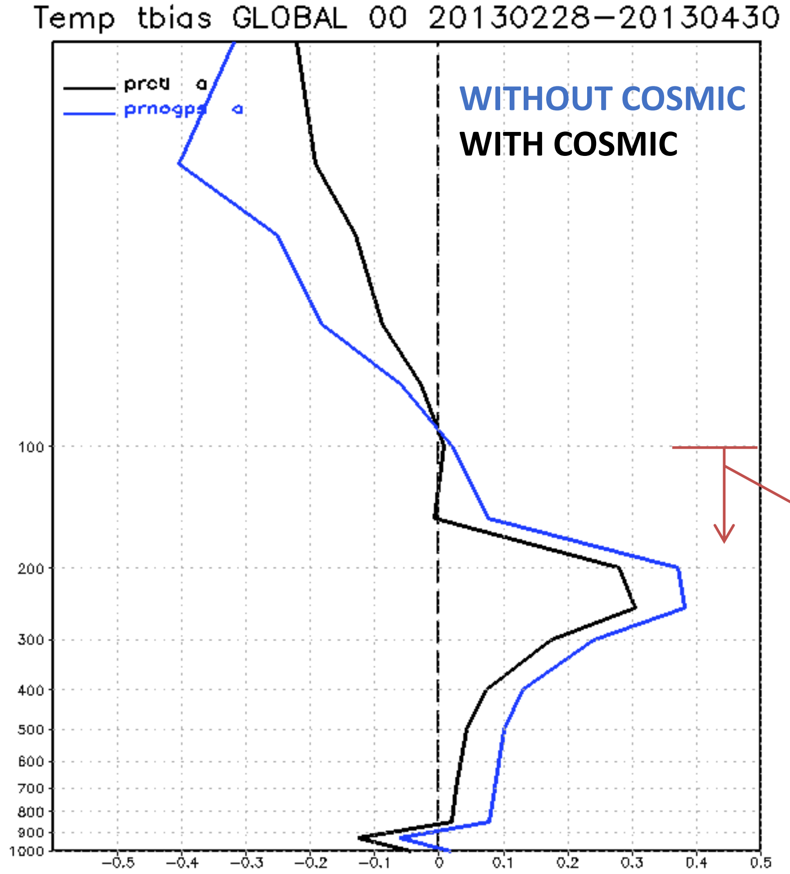
NBAM is still the operational forward operator for RO observations at NOAA

- Technical implementation details
  - The bending angle forward operator is singular at the lower limit of the integral and under super-refraction conditions.
  - NBAM avoids the numerical singularity by evaluating the integral in a new grid.
  - The integral is then evaluated in an equally spaced grid, so the trapezoidal rule can be easily and accurately applied.
  - NBAM does not require the refractivity to decay exponentially with height (only above the model top).
  - NBAM makes use of a quadratic interpolator that preserves continuity of the refractivity values and their derivatives in both the model model vertical grid and the new integration grid.
  - QC and observation errors have been tuned similarly to refractivity.
  - As all the implemented FO at NCEP, the drift of the tangent point is taken into account

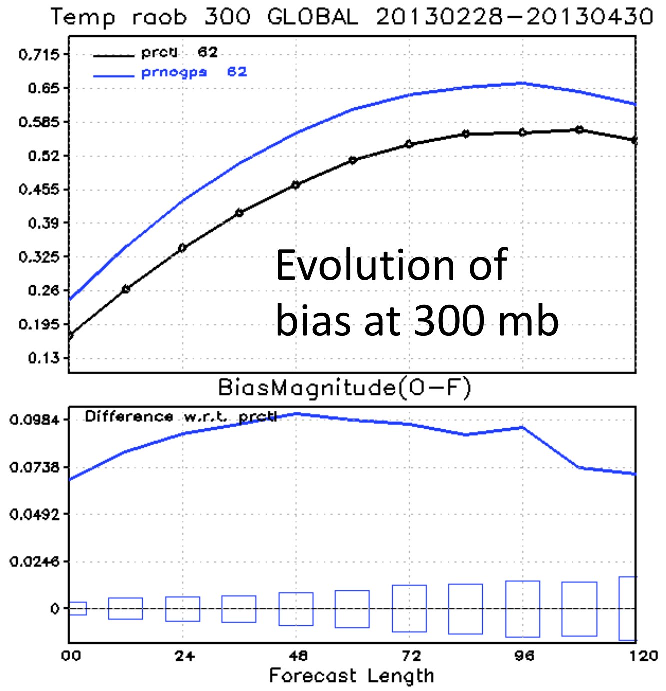
Early impact of COSMIC at NCEP

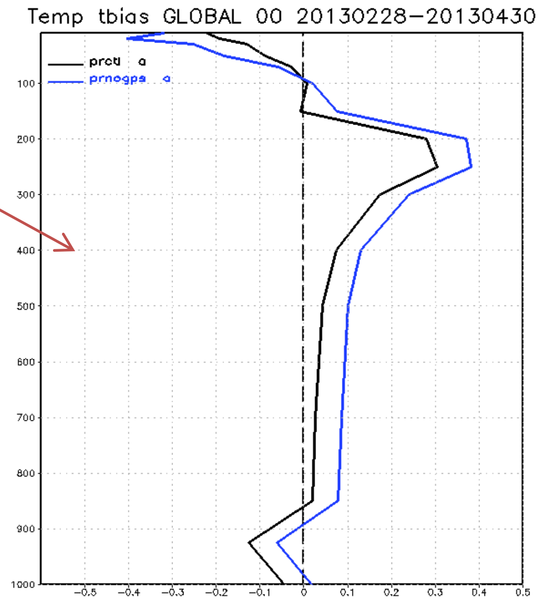


Fit to radiosondes



F-O temperature (K)



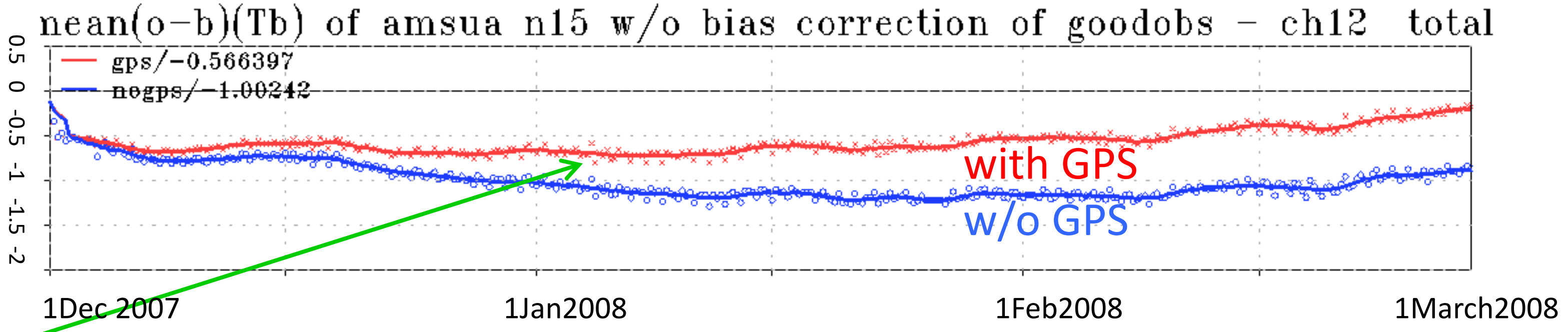


Satellite radiance assimilation

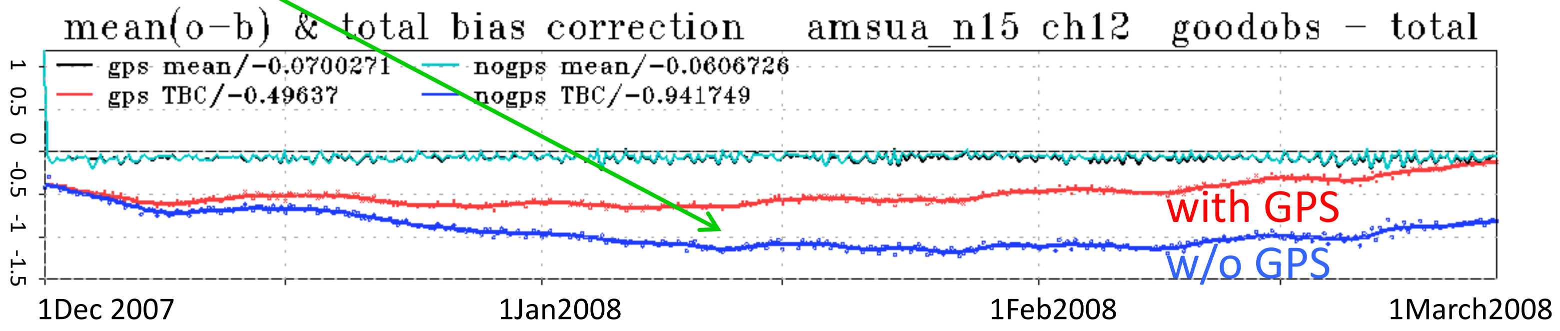
- Satellite radiance observations contain systematic errors (i.e. biases), either in the retrievals, instruments and/or forward models.
- These biases can be larger than the signal, so the use of radiances in DA require the utilization of significant bias corrections.
- Typically, these biases corrections do not account for biases that might exist in the model, which requires some measurements to be assimilated without bias correction to ‘anchor’ the model, avoiding a drift of the bias correction algorithms.
- RO is an anchor measurement: unbiased observations – or at least their bias is small enough, so they do not need to be bias corrected.
- Experiments showed that given good quality satellite radiances and a less biased forecast model – due to the assimilation of unbiased RO observations, the amount of bias correction applied to radiance observations over time was found to be significantly lower and more information was extracted from the satellite radiances.

Benefits of RO on satellite radiance assimilation

Radio Occultation keeps the weather model from drifting away from reality



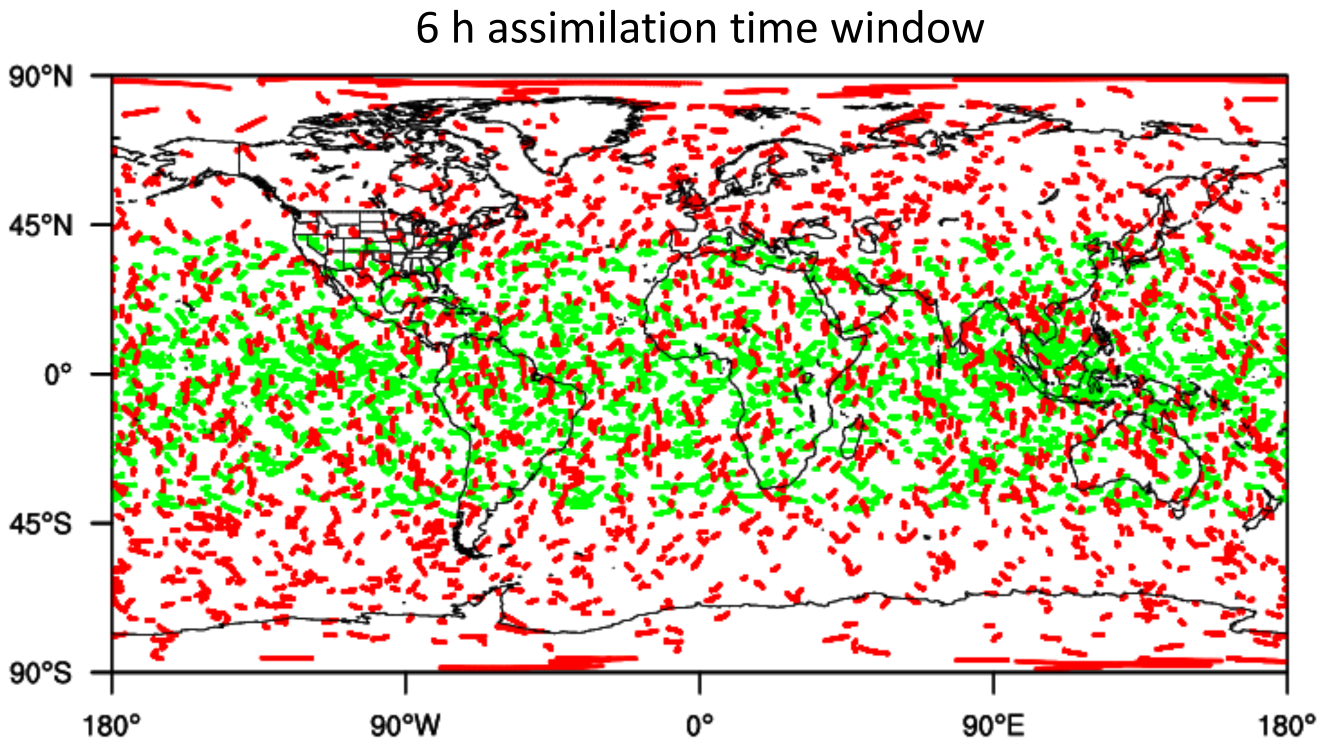
Difference of ~ 0.5 K



Originally proposed “COSMIC-2” spatial distribution

COSMIC-2A (Equatorial)

COSMIC-2B (Polar)



Observing System Simulation Experiments (OSSEs) with COSMIC-2

- Request for OSSEs to determine the potential value of proposed RO constellations (including COSMIC-2A and COSMIC-2B) for current operational numerical weather prediction systems – requested by NWS, NESDIS, and the U.S. Congress.

- NOAA conducted a series of OSSEs with COSMIC-2A and COSMIC-2B, as well as tradeoff studies in the design and configuration of COSMIC-2B.
  - Earlier OSSEs with GFS showed that the largest benefit in NWP skill from COSMIC-2A (”equatorial” component) was to improve tropical winds, and that global RO coverage was necessary to improve weather forecast skill globally. (“Polar” component was needed).
  - Recent OSSEs with FV3GFS show increased impact from COSMIC-2A, particularly in the NH. This improvement is attributed to changes in the data assimilation system. Earlier findings indicating that globally distributed RO observations are more important than denser sampling of the tropical latitudes in order to improve weather prediction globally remain valid (*Cucurull and Casey, MWR, 2020*).

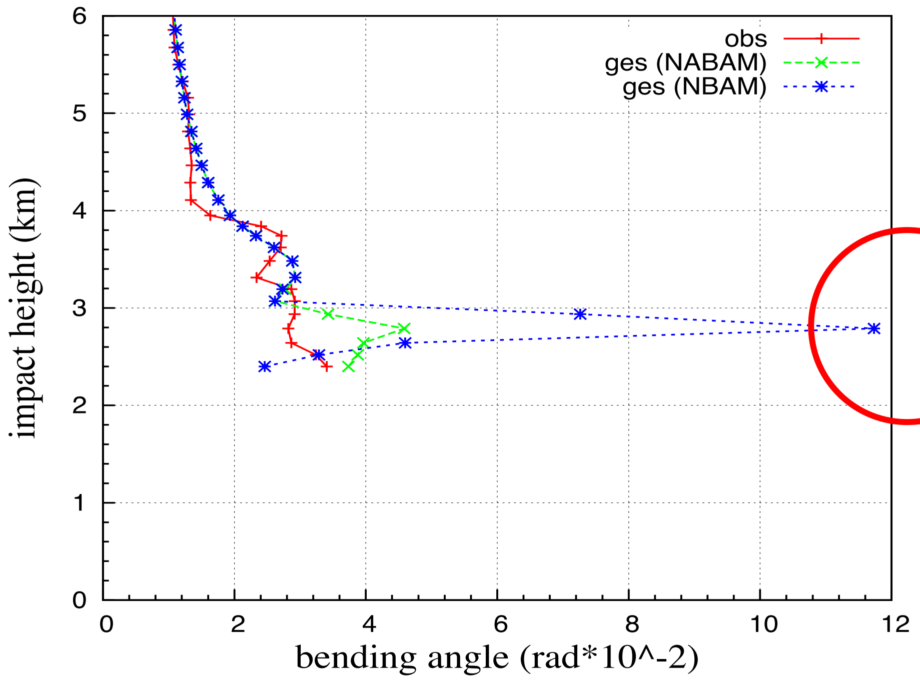
Optimization of the use of RO in the troposphere

- Improve the assimilation of the RO observations in the mid and lower troposphere, particularly under large gradients of refractivity, including super-refraction (SR) conditions (top of the PBL, tropical latitudes).
- Critical development work COSMIC-2, but also for all RO missions.
- Addressing the problem from a model and observation space perspective.
- Is there any NWP useful information in the observations below a model layer with a large vertical gradient of refractivity?.
- Given the larger uncertainty associated with observations affected by SR conditions, can the analysis benefit from their assimilation?.
- Improvement on the water vapor field is expected.

Operational vs new forward operator

NBAM (operational)

NABAM (new forward operator)



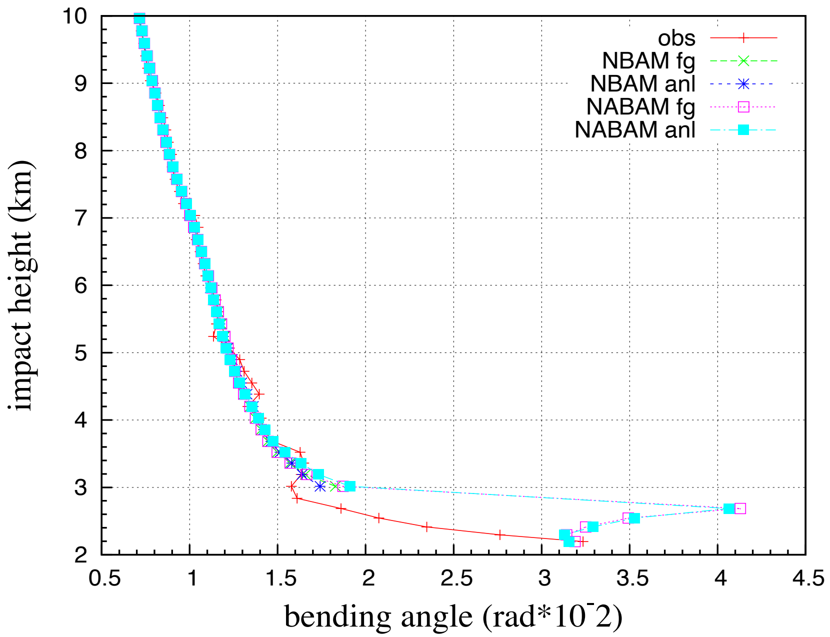
unrealistic simulated bending angle value

Existing QCs would reject this observation and observations below this observation within the same profile

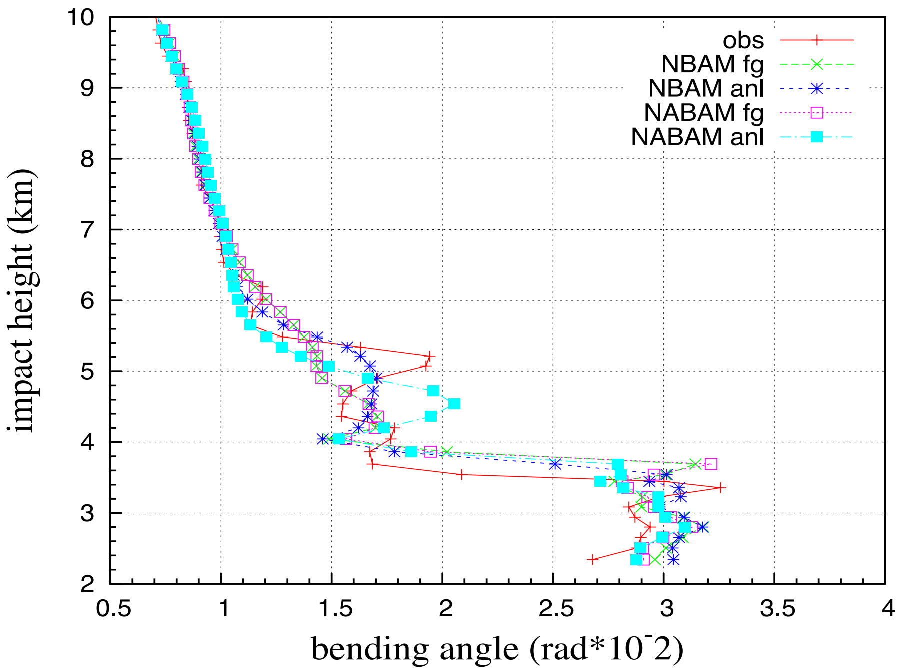
Cucurull and Purser, 2020

Operational vs new forward operator

COSMIC profile that flagged model SR quality controls



COSMIC profile that flagged observation SR quality controls

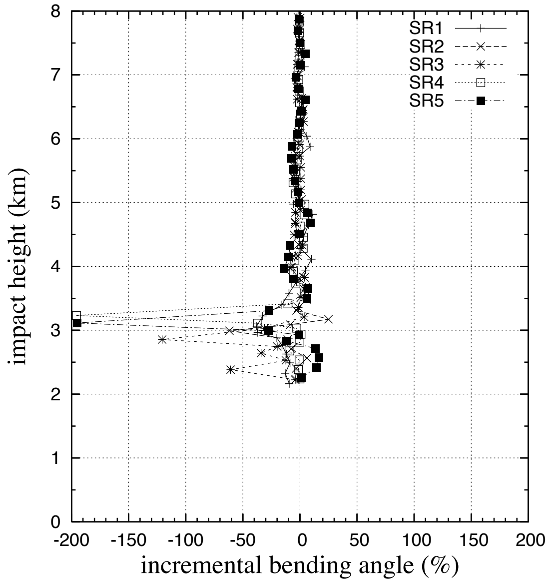


Cucurull and Purser, 2020

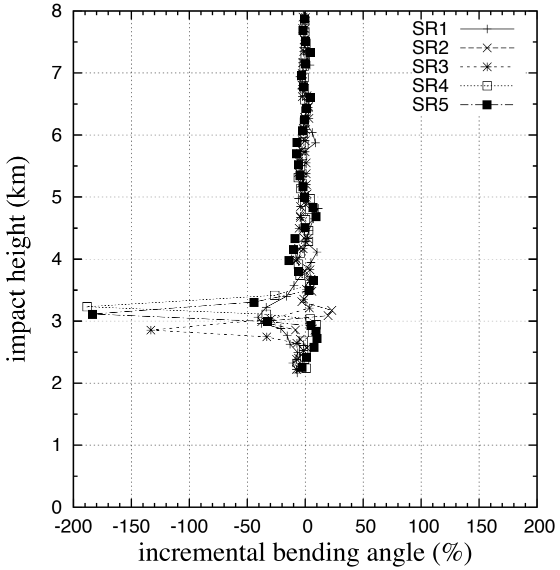
PBL height

- Large differences between observed and simulated bending angles might still occur with the use of NABAM when a mismatch in PBL height exists between then modeled and observed profiles.
- However, the smaller zig-zag structures as compared to the use of NBAM (see for example profile SR3) indicates that NABAM does a better job in capturing the PBL height.

NBAM



NABAM

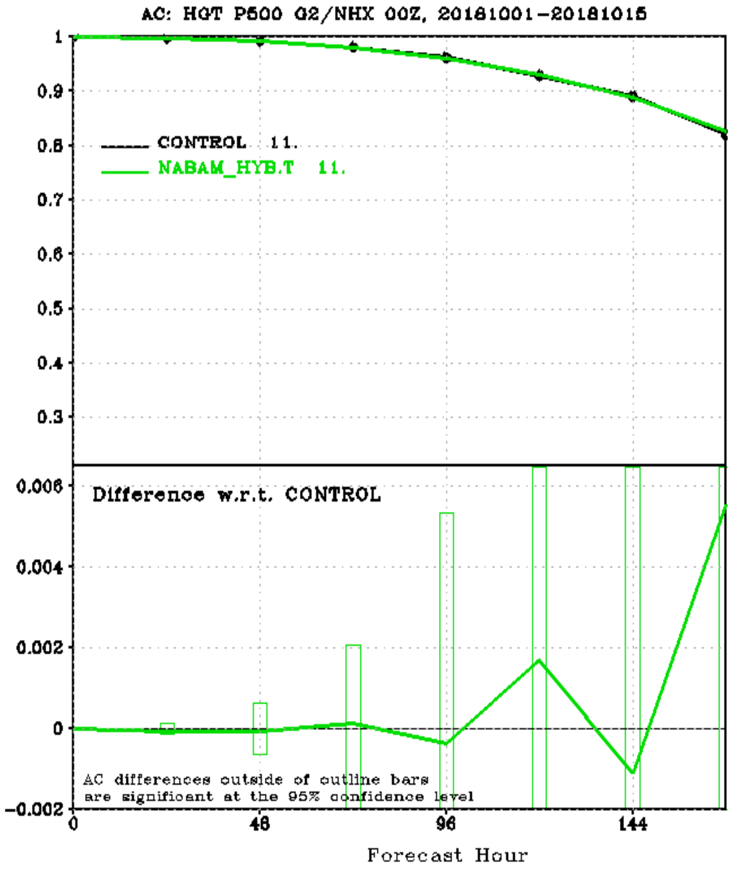


Differences between the observed and simulated bending angle profiles (in percentage) for five profiles likely affected by atmospheric super-refraction conditions with the use of NBAM and NABAM forward operators.

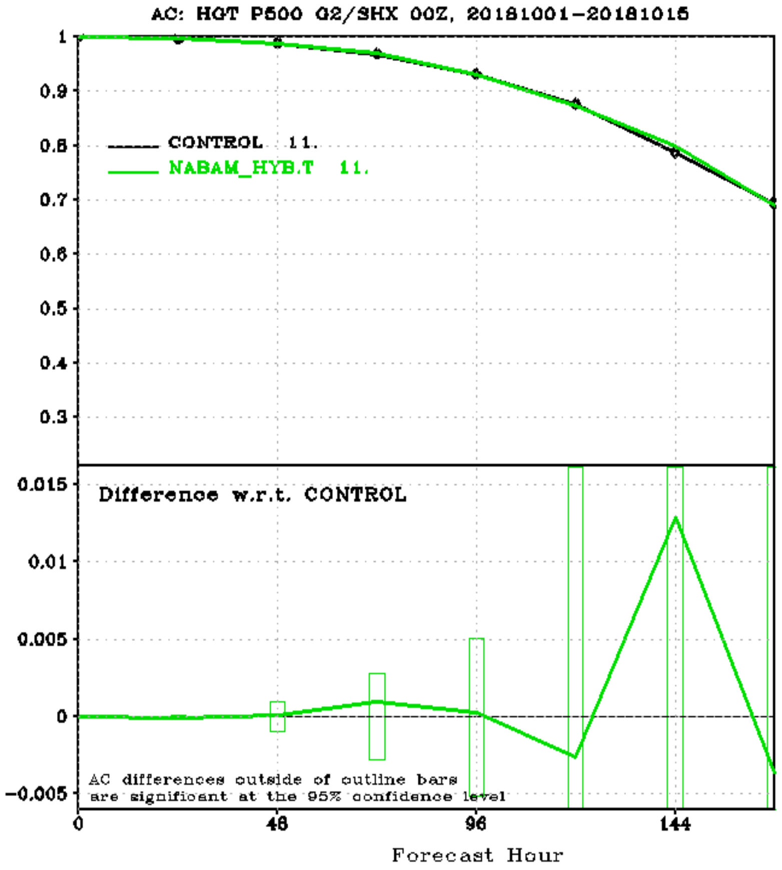
NABAM hybrid baseline configuration (ongoing work)

no COSMIC-2 assimilation, no Quality Control changes

Anomaly correlation 500-hPa geopotential heights
Northern Hemisphere extratropics



Anomaly correlation 500-hPa geopotential heights
Southern Hemisphere extratropics



Next steps
in coordination with EMC, JCSDA, STAR, UCAR

- Continue to support to operational implementation/optimization of COSMIC-2.
- Further evaluation of RO (non-COSMIC-2 + COSMIC-2) impacts with newer model versions - RO statistics appear to have changed.
- Identify geographical regions for potential improvement.
- Implement enhanced forward operator (baseline configuration) and investigate initial impact.
- Tune new forward operator according to current configuration (RO + COSMIC-2 separately and combined).
- Continue to improve RO DA methodologies (forward operators, quality controls and observation error structures).