GNSSRO Assimilations for NOAA Operations

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Joint efforts with NCEP/EMC, NOAA/AOML, COSMIC-2 Cal/Val teams, and NOAA/NWS

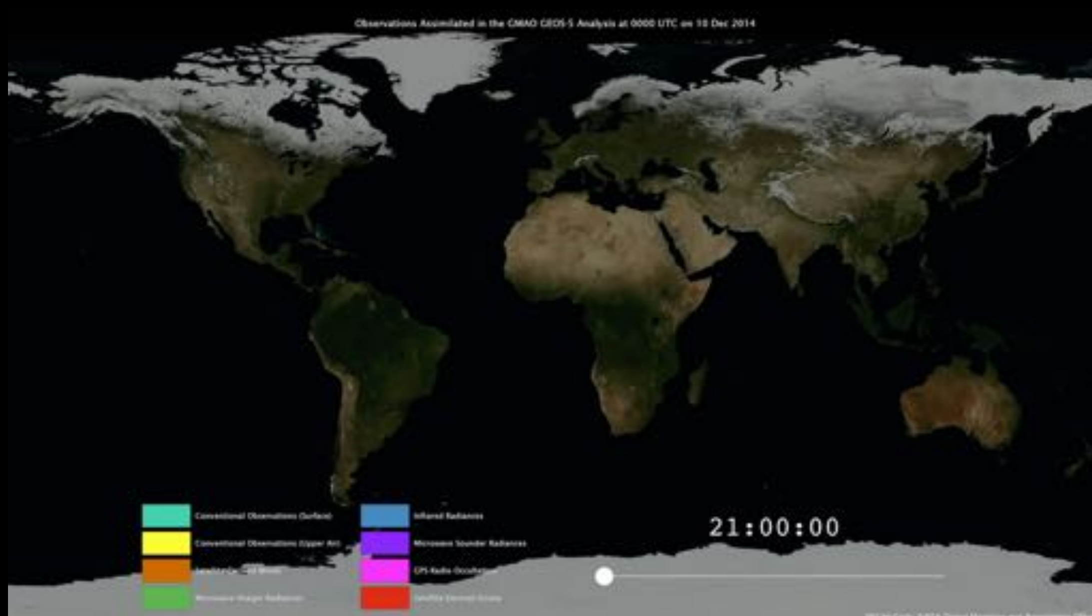
8th International Radio Occultation Working Group Meeting (Virtual)
7-13 April 2021

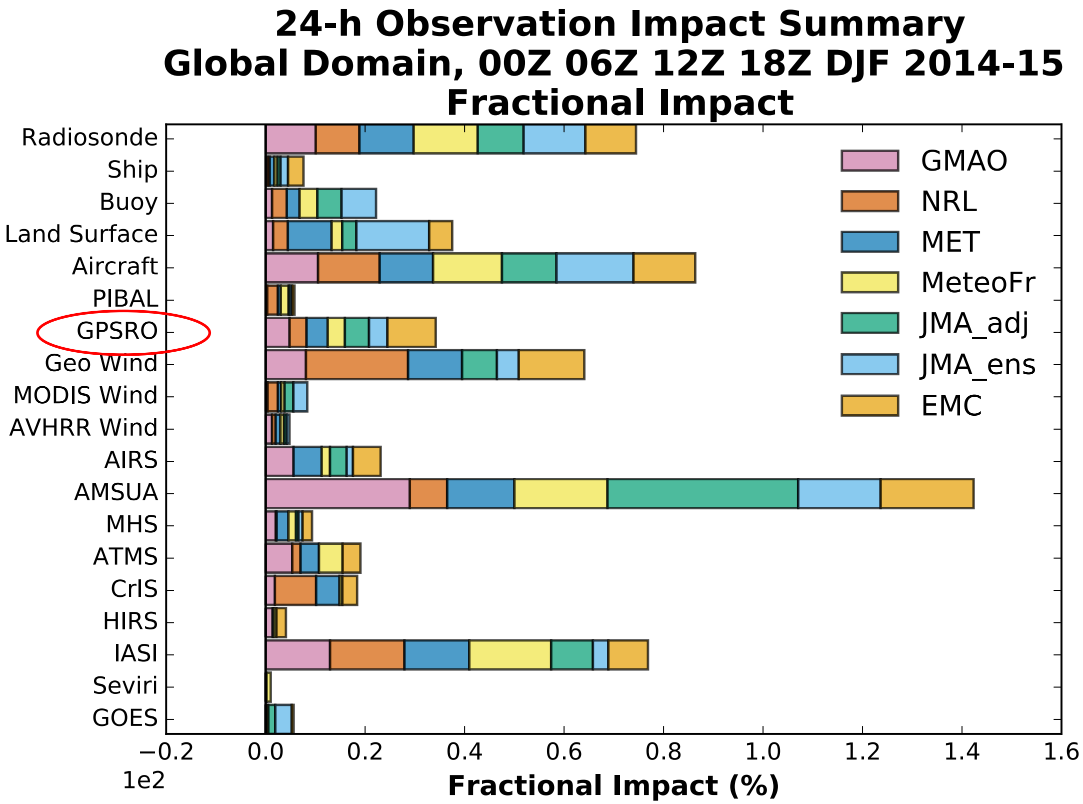
Outline

- Introduction of NCEP Global Data Assimilation System (GDAS)
- COSMIC-2 assessment and implementations
- Commercial data evaluations
- Lessons learned and ongoing efforts
- Summary

Current Operational GDAS (Hybrid 4DEnVar)

- **Background from C768L127 (~12km)** FV3-based GFS (cubed sphere dynamic core)
- Deterministic analysis using Gridpoint Statistical Interpolation (GSI)
- 80 member **C384L127 (~25km)** EnSRF with stochastic physics to represent model uncertainty
- Analysis increment at ensemble resolution
- Ensemble perturbations centered about hybrid analysis
- Assimilate conventionaland other satellite data and retrievals (e.g., radiance, satwinds, ozone, GNSSRO)
- Also adopted for NASA GEOS forecast system





(Rahul Mahajan, EMC)

GNSSRO is one of the critical satellite data resources for NWP improvements

GDAS GNSSRO Forward Operator

- GDAS uses 1D bending angle operator (L. Cucurull, 2007)

$$\alpha = -2a\int_a^{\infty}\frac{\partial \ln n}{\partial x}\frac{a}{\sqrt{x^2-a^2}}dx$$

$$x = nr$$

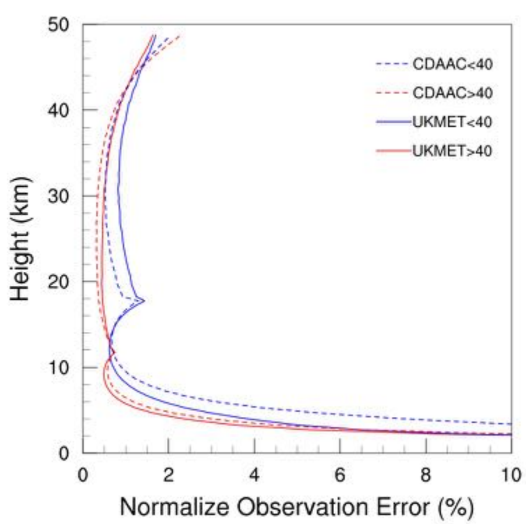
n: refractive index, as a function of model state variables pressure, temperature and humidity

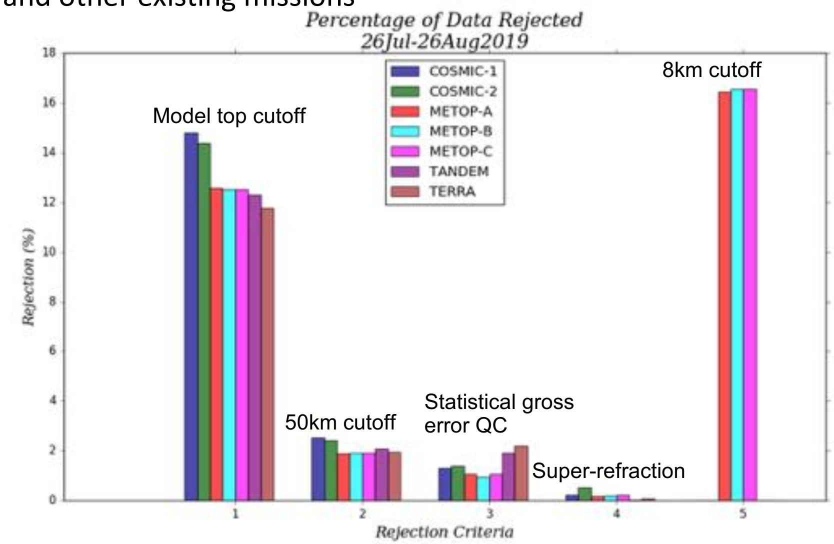
r: radius of a point on the trajectory of the ray

α : bending angle

a: impact parameter

- Assimilate obs up to 50km (v15.3)/55km (v16, implemented on March 22, 2021)
- Observation errors are defined by three latitudinal bands (40S-40N, >40N, > 40S) as polynomial functions of impact heights. Observation errors are also slightly different based on processing centers
- Five QC procedures from original configurations, including lower and upper boundary check, gross error check, statistical gross error check, super refraction check, plus the Jacobian QC added in v16.
- These default configurations have been used for COSMIC-1 and other existing missions



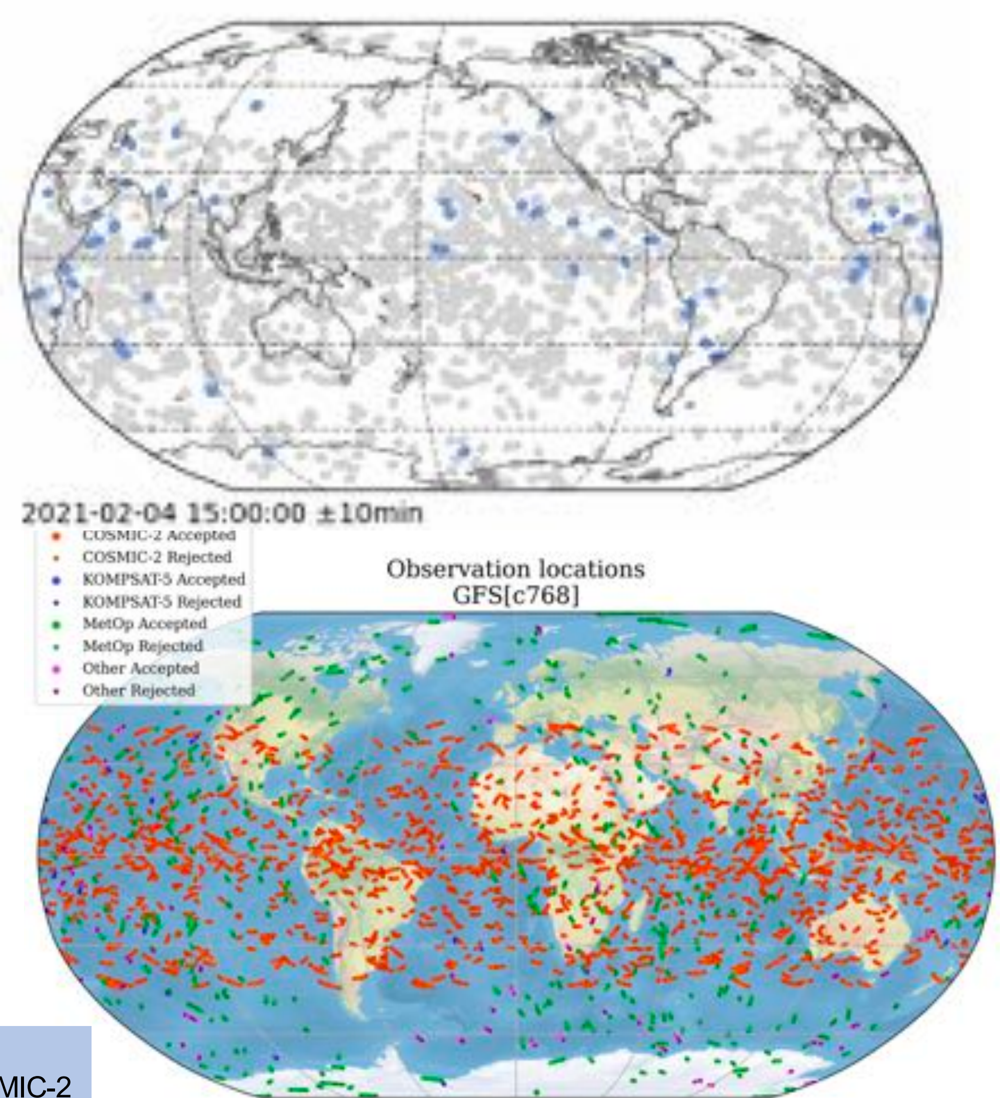


GDAS GNSSRO Updates

- GFSv15.1 (June 2019)*
  - Initial implementation of FV3-based GFS
- GFSv15.2 (November 2019)
  - KOMPSAT-5
- GFSv15.3 (May 2020)
  - COSMIC-2 with QC and observation error updates
- *GFSv16 (March 2021)**
  - 127 Layers, ~80km model top
  - Metop-C
  - Updated QC for GNSSRO
- GFSv16.1 (May 2021)
  - Commercial GNSSRO

*significant model updates

New GNSSRO missions improve data coverage significantly, especially in tropics-mid latitudes due to the inclusion of COSMIC-2



GNSSRO observations in NOAA operations @20210204

COSMIC-2

FORMOSAT-7/COSMIC-2

Part of a joint agreement between the American Institute in Taiwan and the Taipei Economic and Cultural Representative Office in the United States, with NOAA and the Taiwan National Space Organization as designated representatives

- A constellation of six satellites, providing data concentrated between 45S-45N latitude.
- Launched on June 25, 2019
- ~5000 occultations per day
- Higher SNR and deeper penetrations than COSMIC-1 and other missions

As part of COSMIC-2 Cal/Val team, JCSDA and NOAA partners provided NWP assessment using GDAS

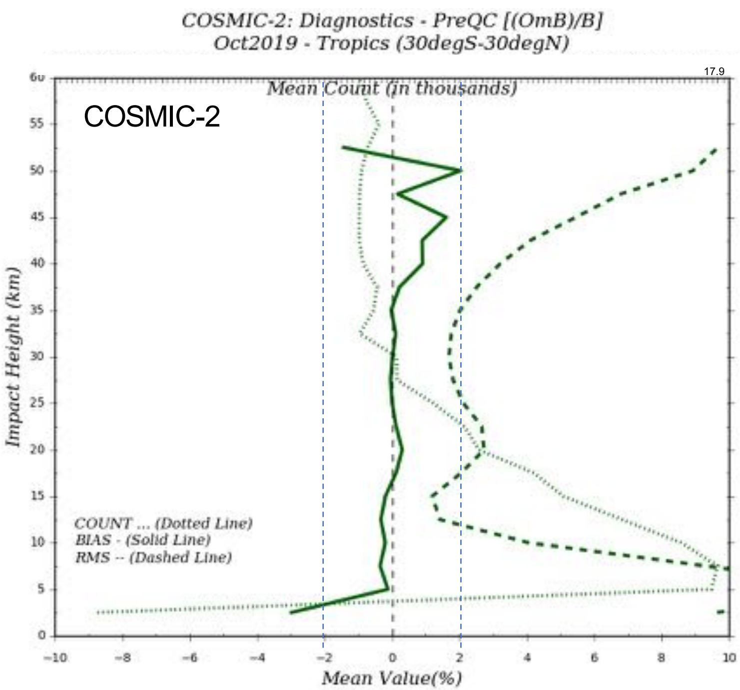
- Initial data assessment -> COSMIC-2 data releases
- Assimilate COSMIC-2 following COSMIC-1 configurations:
  - Improvement for tropical and NH but degradation for wind in SH
- Optimize the COSMIC-2 data assimilation with updated obs error and QC

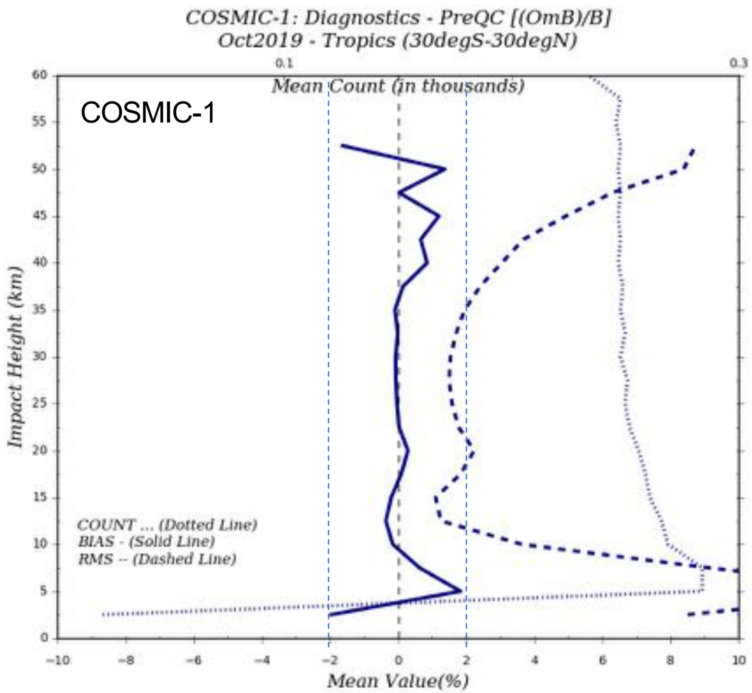
✓ COSMIC-2 implementations at NCEP (v15.3) on May 26, 2020

✓ GFS v16.0 with COSMIC-2 updates on March 22, 2021

Mean Bias and Standard Deviation

Mean bias and standard deviation against GFS 6hr forecasts (background)
October 1-31, 2019 (before COSMIC-2 assimilated in GDAS)

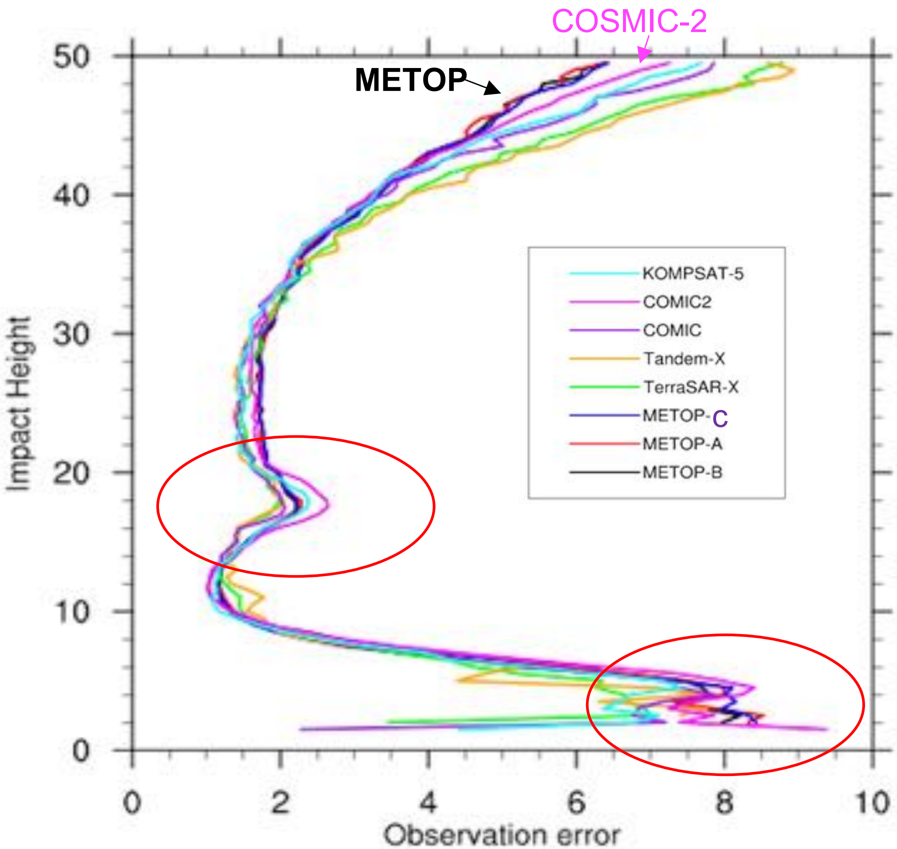




Comparing COSMIC-2 with COSMIC-1 without any QC for 30S-30N (results are similar for 30-60N/S)

- Larger biases near surface and above 40km
- Similar for core regions
- Larger standard deviation, expected given the much larger data counts

Estimation of Observation Errors



Global averaged Observation error computed using GFS/FV3

Observation errors

- Was estimated based on the initial assessment and analysis using the default COSMIC-1 configurations and tuned using Derosiers's method (Desrosiers and Ivanor , 2001)
- A combination of measure errors and representativeness errors
  - Different data sets since the default errors were implemented
  - Different forecast models (for background)

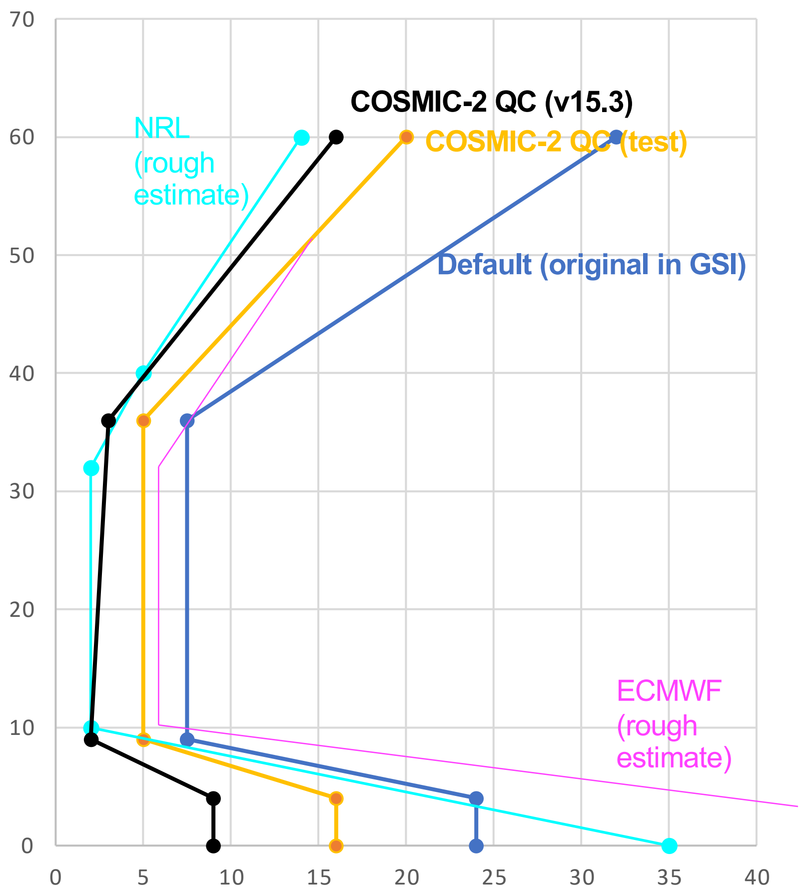
COSMIC-2 has

- Larger obs errors below 5km and around 20km
- Smaller obs errors above 45km than other missions except for Metop series

Compared with the default obs errors (slide 5), the new obs errors have smaller values near surface (more weighting) and larger obs errors above 35km (less weighting for data assimilation)

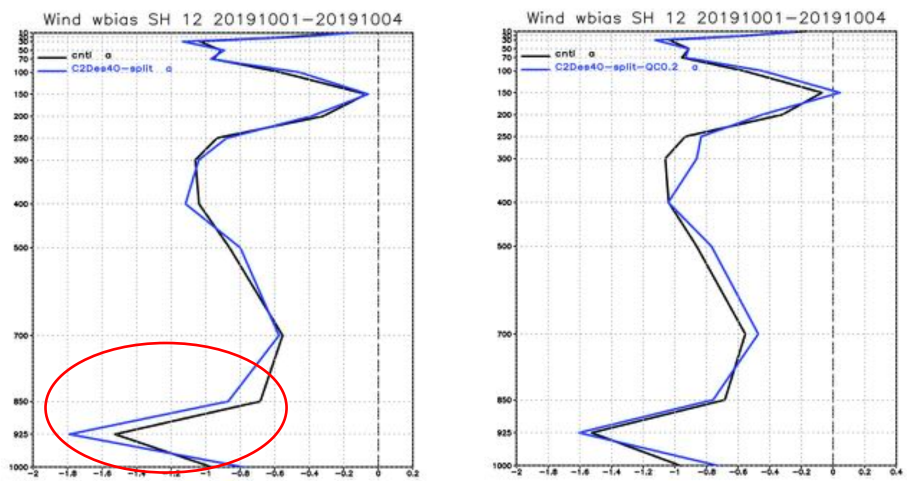
- Initial assessment shows the new COSMIC-2 errors slightly reduced standard deviation of short term forecasts for T, q and wind (not shown)

Statistical Gross Error QC



Gross error QC threshold for latitude=0

12Hr wind forecast biases - Southern Hemisphere



Original

New

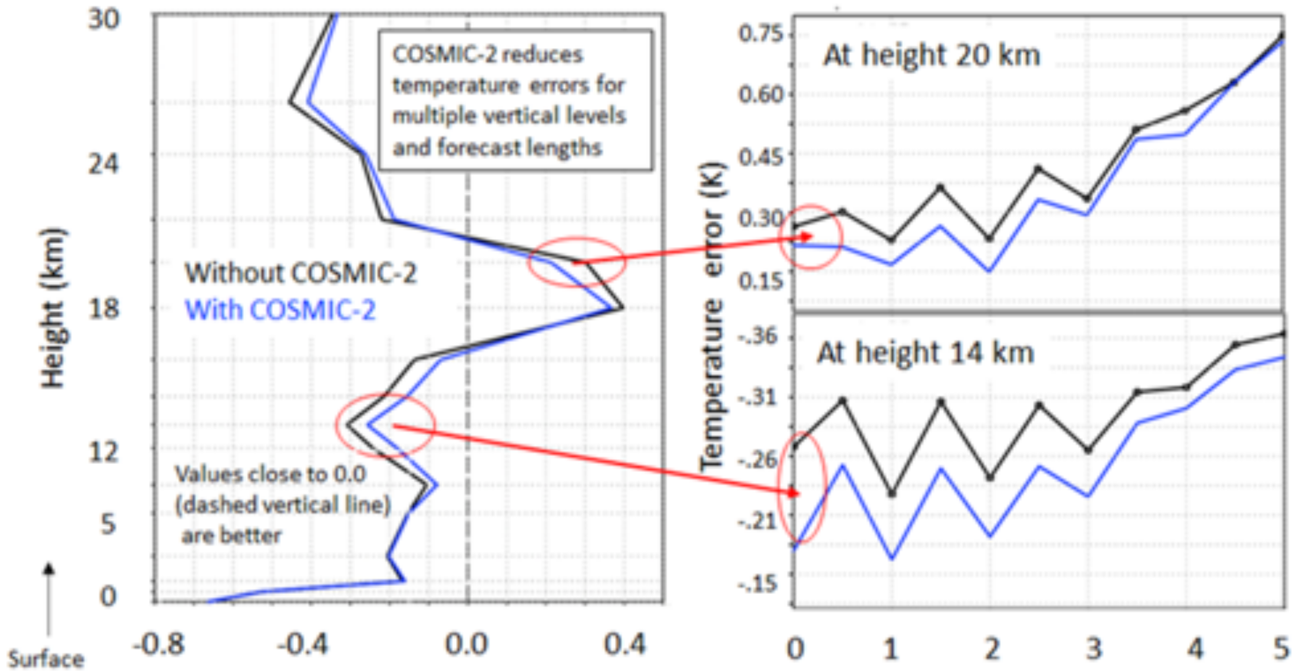
Assessment using the default GSI QC shows positive impacts for NH and tropical areas. However, the SH wind was degraded

Different gross (statistical) QC threshold values were tested by JCSDA and AOML

- Current operations adopted the stricter QC for COSMIC-2 to improve wind analyses and forecasts
- QC threshold values are relatively consistent with the updated observation errors

Forecast Impacts of COSMIC-2

Comparison of forecast temperature errors with and without assimilating COSMIC-2 data in the Tropics

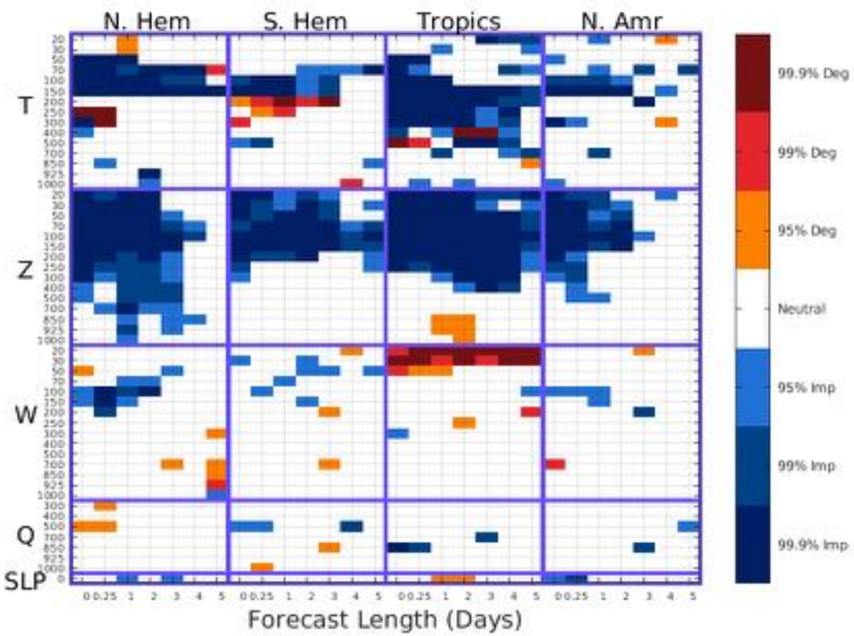


In-Situ Temperature Fits (F00)

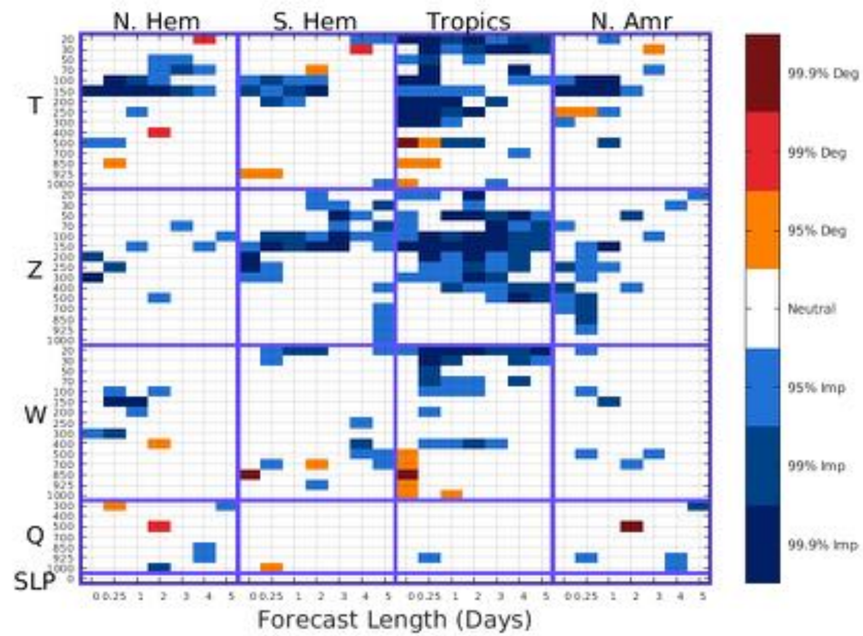
Forecast Length (Days)

Scorecard for Forecast Impacts

Blue indicates COSMIC-2 reduced forecast errors
Red indicates COSMIC-2 degraded forecast errors



Bias



RMSE

- COSMIC-2 significantly reduces mean bias of the temperature above 300hPa and geopotential height (GH) above 500hPa and reduces RMSE for temperature, GH and wind mostly in tropical areas
- Changes in humidity are not statistically significant

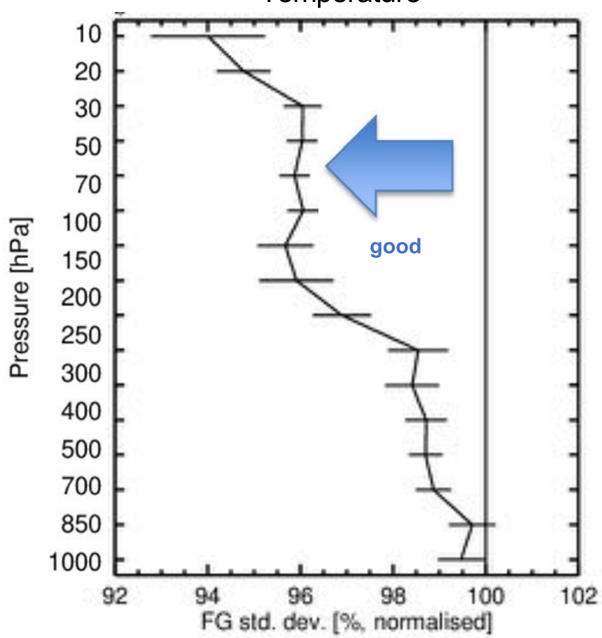
One month real-time runs (using results up to May 18, 2020)

Comparing with ECMWF Results

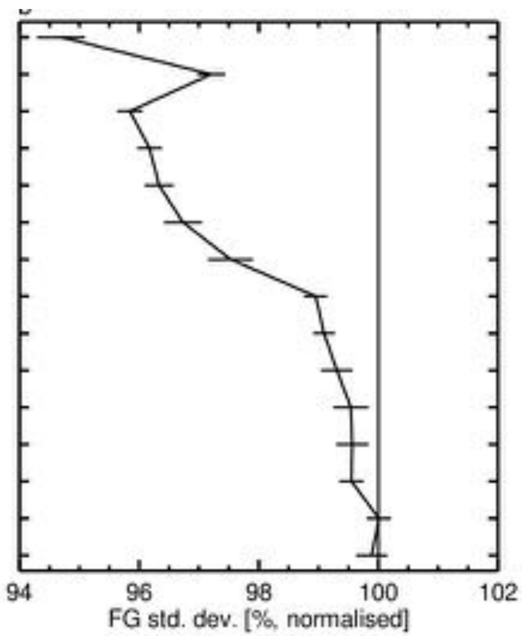
Early results from ECMWF shows similar improvement for short term forecasts, including temperature, wind, and humidity. The largest changes are over upper levels. Similar results were presented from other centers

$100*(\sigma_{cosmic2}-\sigma_{control})/\sigma_{control}$

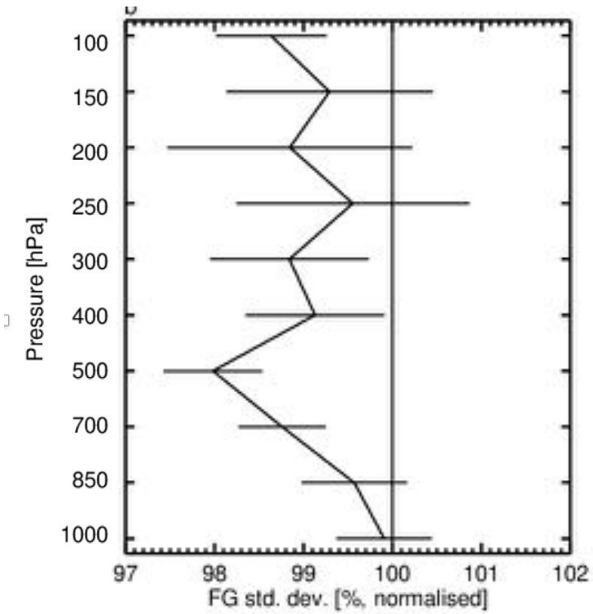
Temperature



Wind



Humidity



Sean Healy, 2020

Commercial GNSSRO

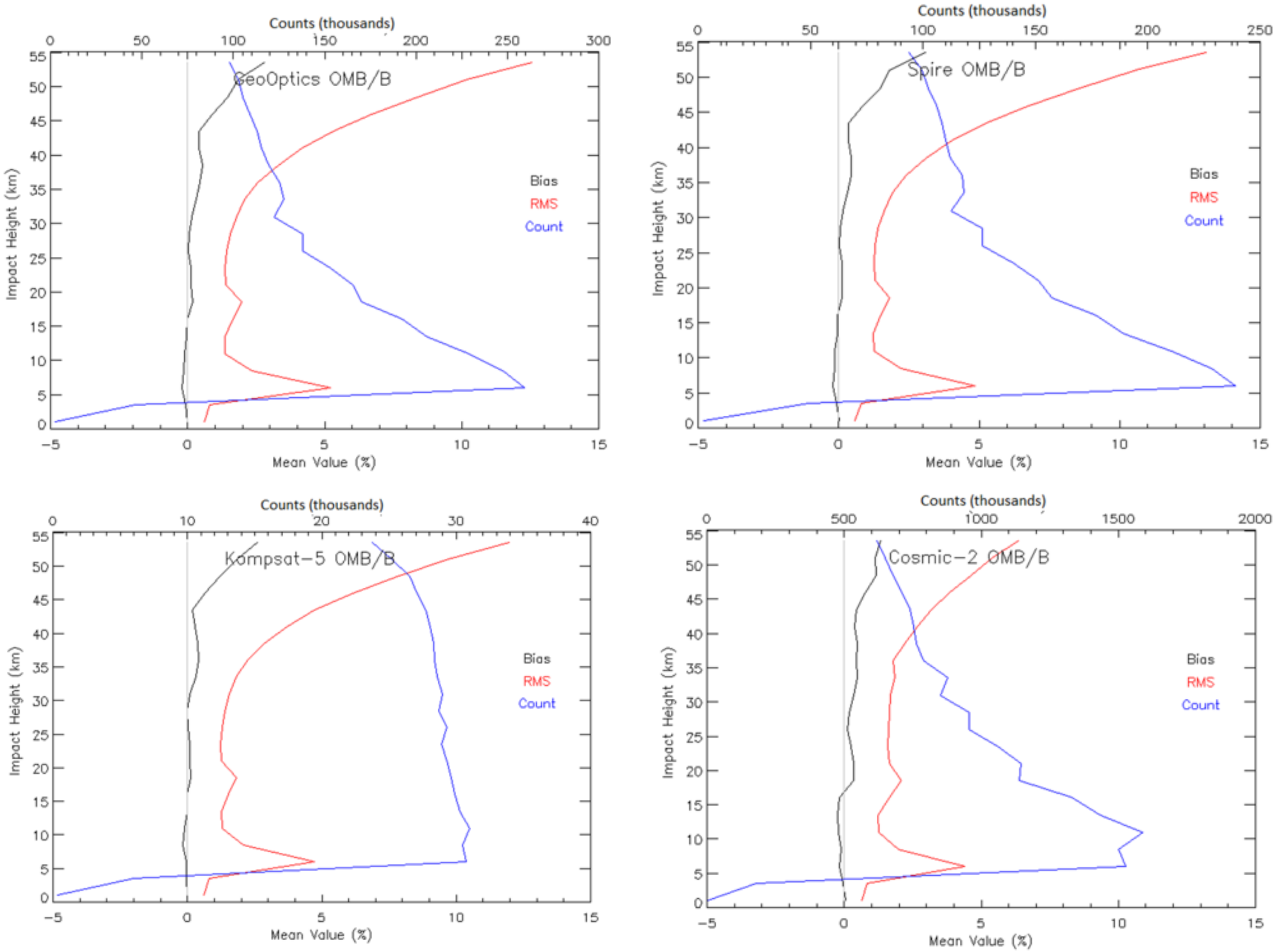
Commercial GNSSRO at NOAA

- NOAA's Commercial Weather Data Pilot (**CWDP**): GNSS radio occultation was selected as the most suitable data type for the first two rounds of the CWDP
  - Round 1 (2016-2018)
  - Round 2 (2018-2019)
- On Friday, November 20, 2020, NOAA awarded its first contracts to purchase commercially available space-based radio occultation (RO) data for use in NOAA's operational weather forecasts (**DO-1**):
  - GeoOptics and Spire Global
  - 500 occultations/day for 30days
- On February 19, 2021, NOAA awarded Delivery Order 2 (**DO-2**) for radio occultation (RO) data
  - GeoOptics
  - 1300 occultations/day for six months
  - Shared with US gov agencies

NOAA CWDP Round 2 Findings

Evaluation	GeoOptics	Spire
Neutral Atmosphere Products	Noise and bias is comparable to C1 and K5. Error assessment is within range of other governmental RO platforms.	Noise and bias is slightly higher than C1 and K5, especially at high altitudes. Error assessment is within range of other governmental RO platforms.
NWP Impact	Comparable to government assets recently evaluated, such as C1.	Comparable to government assets recently evaluated, such as C1.
Ionospheric Products	Useful for space weather products. Scintillation data could improve situational awareness.	Noisy, but adequate for space weather products. Electron density profiles may also be useful.
Geographical Coverage	Polar orbits provide global coverage and complement C2, but local-time coverage is limited.	Polar orbits provide global coverage and complement C2, but local-time coverage is limited.
Support for Problem Resolution	Responsive to all requests and flexible on changing requirements.	Responsive to all requests and flexible on changing requirements.
Delivery Latency	Did not sign up for near-real-time deliveries in Round 2.	Did not sign up for near-real-time deliveries in Round 2.

NOAA CW DO-1 Findings



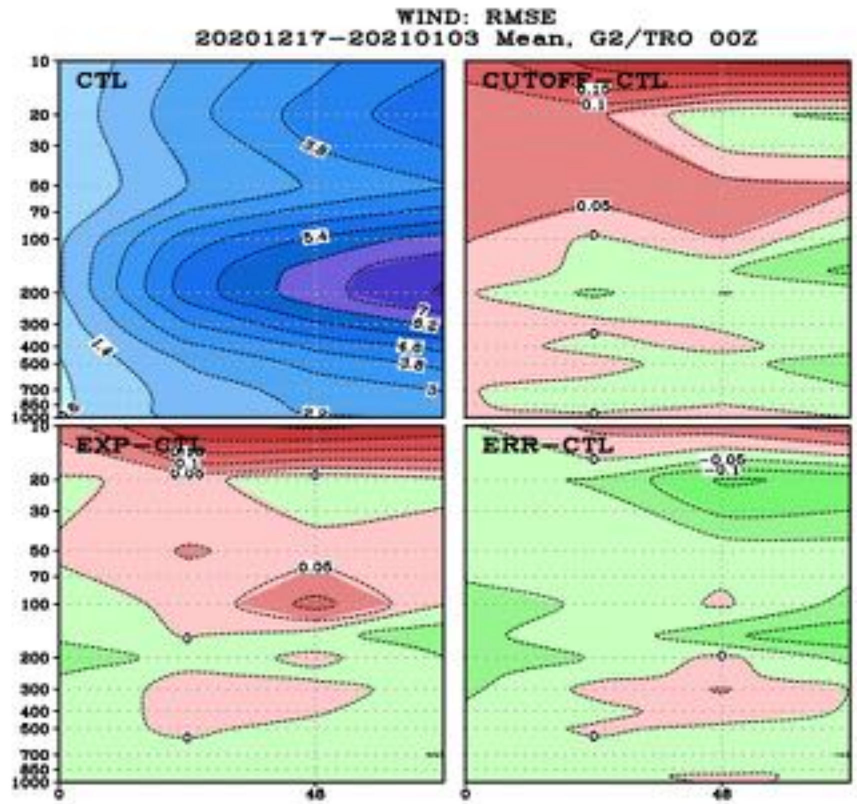
Averaged for 2020122000- 2021011600

- GeoOptics and Spire occultations are found to have similar error characteristics as other operationally assimilated RO data
- Relatively larger STD above 45km

NOAA CW DO-1 findings

- Initial experiment assimilating the commercial RO data using the default obs error and QC (COSMIC-1 configurations) had neutral to negative forecast impact in low resolution GFS testing
  - Indications of improvements in fits to temperature, but degradation was seen in the upper layers, especially for wind above 45km

- Two mitigation measures were tested: cut off the commercial RO data above 45 km and inflate the observations errors by 50% (further optimized obs error is under way)
- Preliminary results show that both methods improve background fits to temperature and wind measurements. Inflating observation errors improves forecast metrics impact at higher levels.



Green indicates improvement over CTL

Lessons Learned and Ongoing Efforts

Review

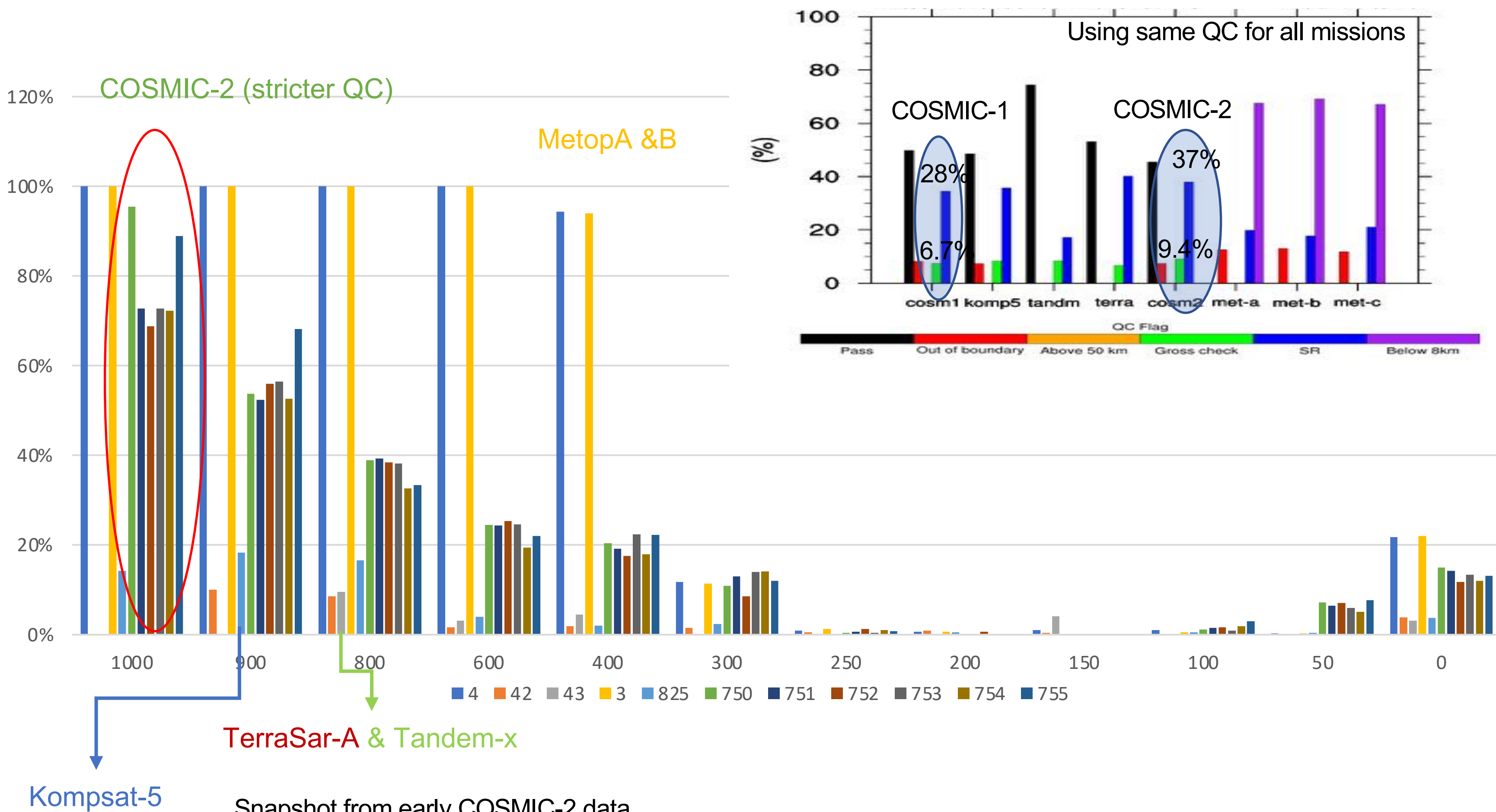
What have been done?

- New missions (COSMIC-2, Metop-C, commercial, etc) have significantly increased data counts and coverage in operations in past couple of years
- Consistent (even better) data quality has been confirmed
- Positive impacts with appropriate error models/quality controls on NWP

What are still missing?

- We are still far away from the target of 20000 occultations/day
- Mid-high latitudes coverage is not as good as those in (sub)tropical areas (attributed to COSMIC-2)
- High rejection rates for lower level data - “Penalties” on data with higher SNR/deeper penetration?
- Less impacts for lower level atmosphere – moisture rich areas
- Less focus on regional impacts – partially due to availability in specific regions

Rejection Rates

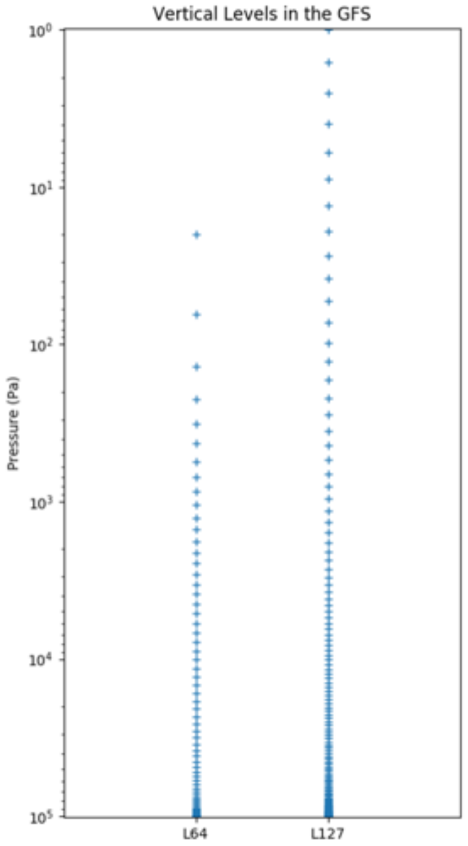


Snapshot from early COSMIC-2 data

Stricter QC is adopted due to the SH wind degradation for COSMIC-2

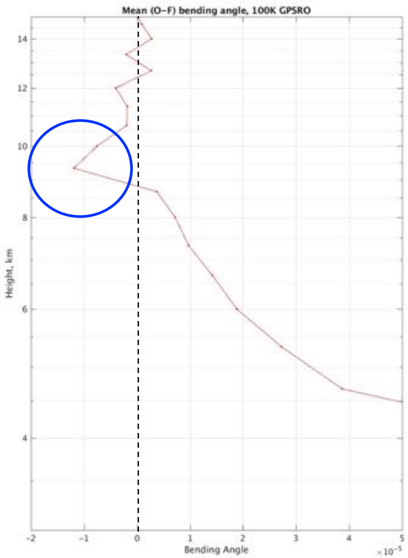
GDAS Specifics

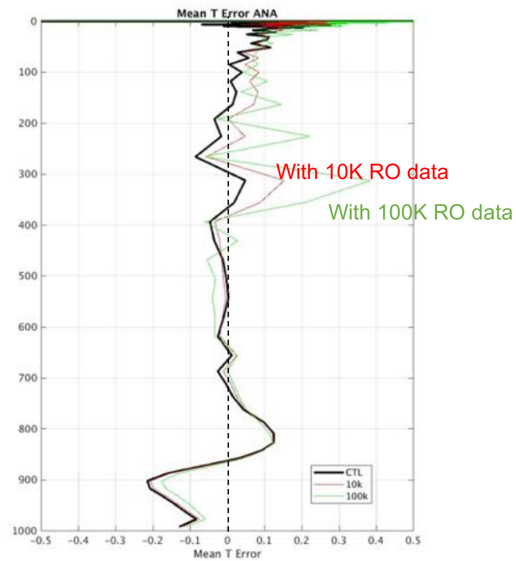
- Observation errors: not fully optimized for other missions/model upgrades
- Need additional studies on obs error models (setting/rising, transmitter/receiver, other methods…)
- Model upgrade: The GFSv16 moves from 64 layers to 127 layers, raising the model top from **55 km** to **80 km,** along with many other changes. These changes require another look at the current GNSSRO assimilation
- Larger obs errors around 20km impact height
- Source of SH degradation during initial studies (while NH and tropical areas show improvement due to COSMIC2)
- Forward operator updates

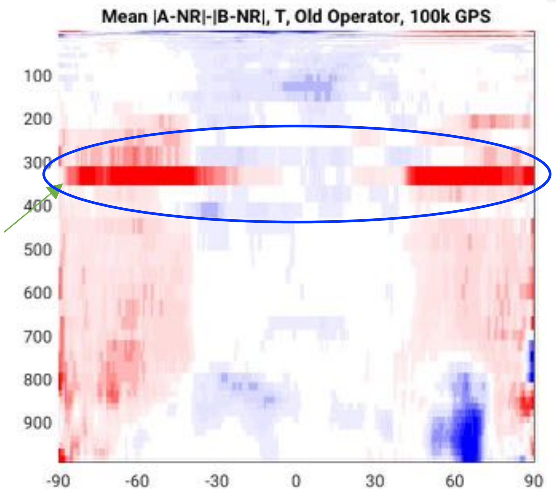


Ongoing efforts at NOAA/AOML, NESDIS, JPL, JCSDA and other partners

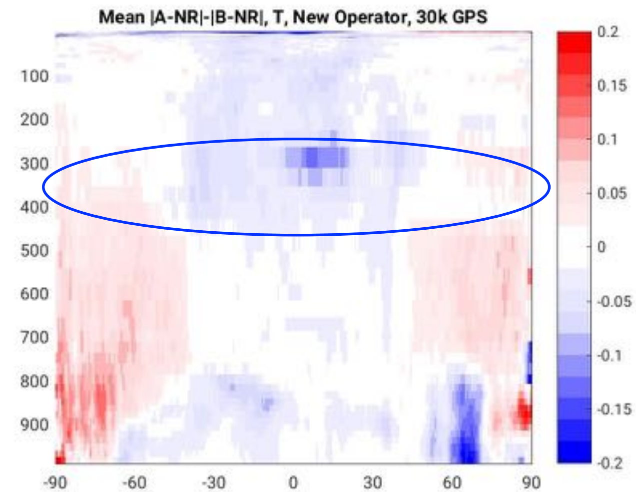
Interpolation around Tropopause







Old (default)

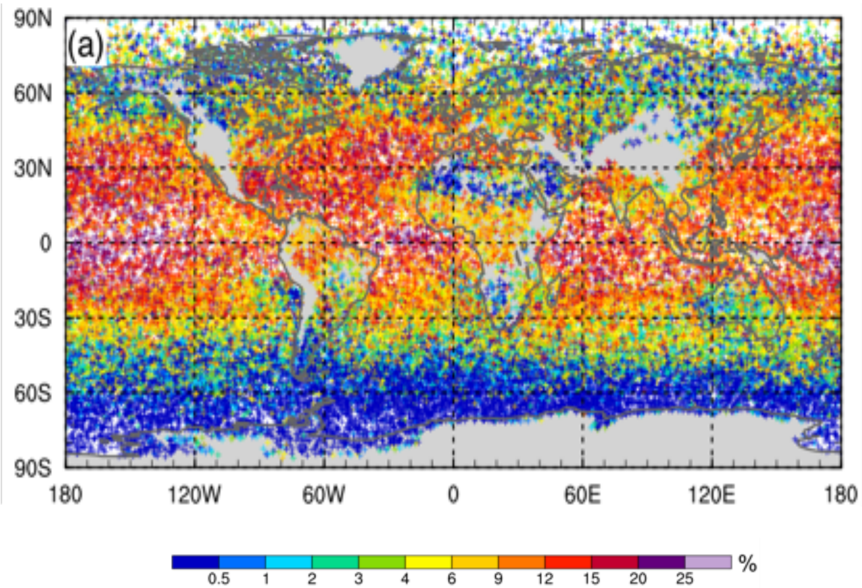


New

- Similar spikes around 20km impact height were found for COSMIC-2 and other missions -> around tropopause, especially in tropical areas
- OSSE studies show such biases would lead to significant temperature biases with increasing observation numbers
- Changes to the interpolation from model space to observation space help alleviate the biases

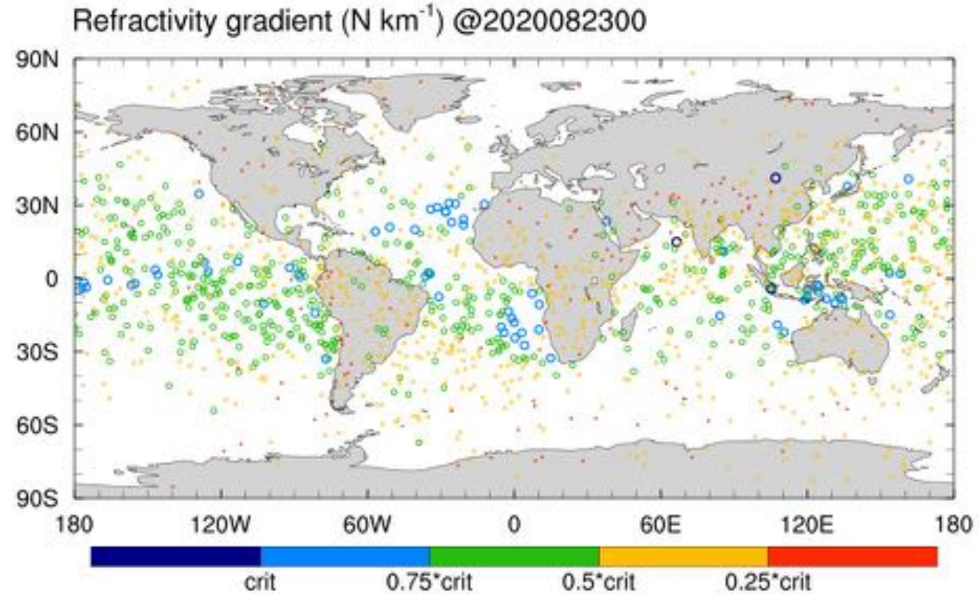
(Collaboration with NASA/GMAO)

Lower Level Uncertainty



Distribution of fractional local spectral width (LSW) (unit: %) at 2 km MSL for (a) August 2008

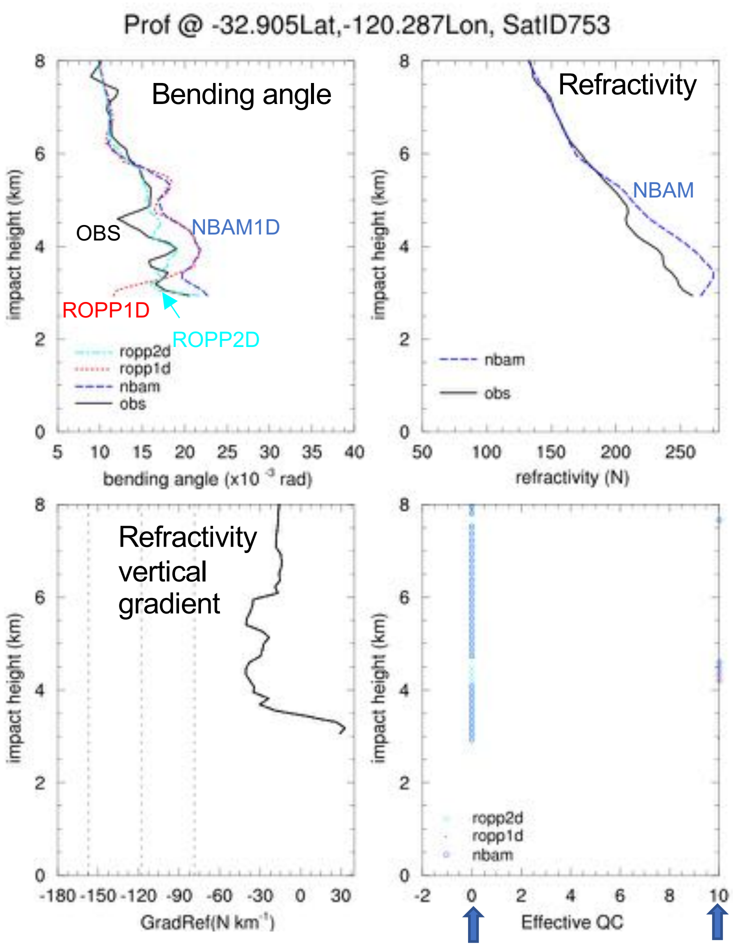
(Hailing Zhang, et al, 2021, submitted to MWR)



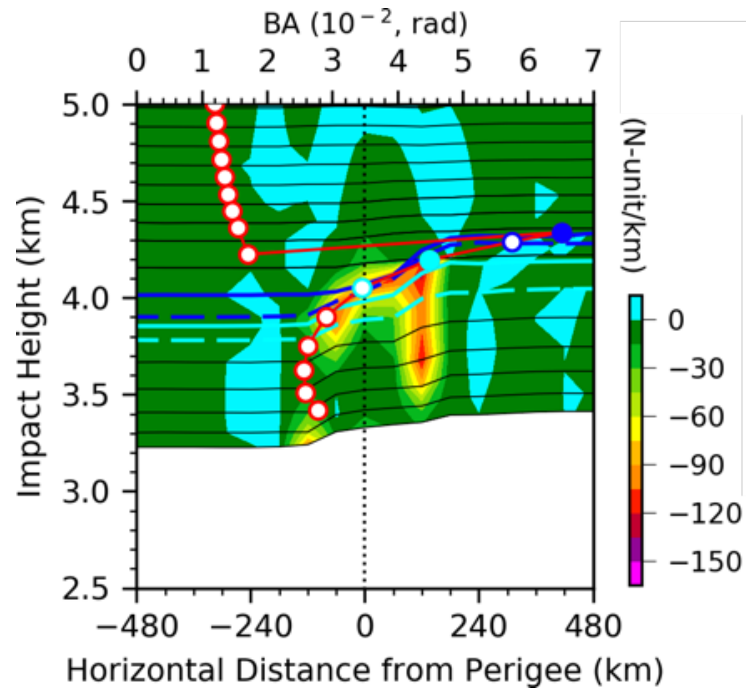
Vertical refractivity gradient computed using model background at 00Z 23 August, 2020. Values are grouped based on values used for GSI super-refraction QC

Comparing Operational GNSSRO Operators

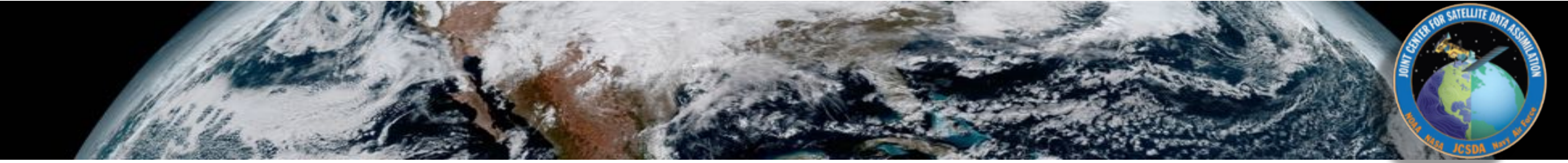
JCSDA incorporates multiple GNSSRO operators under the **Joint Effort for Data assimilation Integration (JEDI)** system: COSMIC-2 data are simulated using: NBAM (NCEP GSI), ROPP 2D (ECMWF), and ROPP1D (NRL) using the same FV3 background (UKMet operator is underway). This enables in-depth studies on the GNSSRO assimilation.



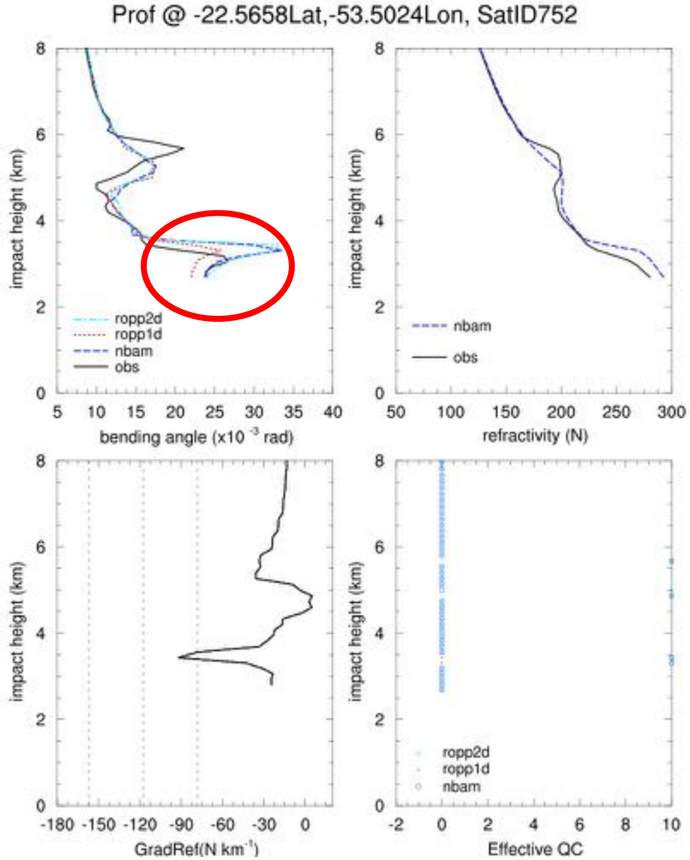
Dashed lines: NBAM Super-refraction(SR) check values



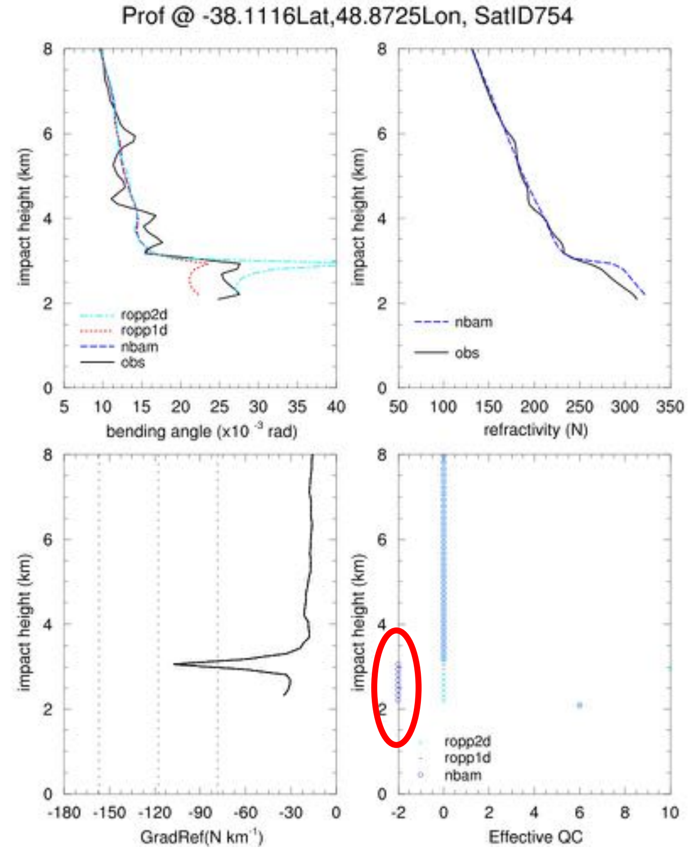
Simulated ray paths (black, cyan, and blue curves) and vertical gradients of wet refractivity (N-units km-1, shaded in color). The vertical profile of bending angle (using 2D operator) is shown by the red curves with open circles. (S. Yang, et al. 2020)



All passed QC, but large discrepancies with bending angle obs



NBAM failed SR, while ROPP passed

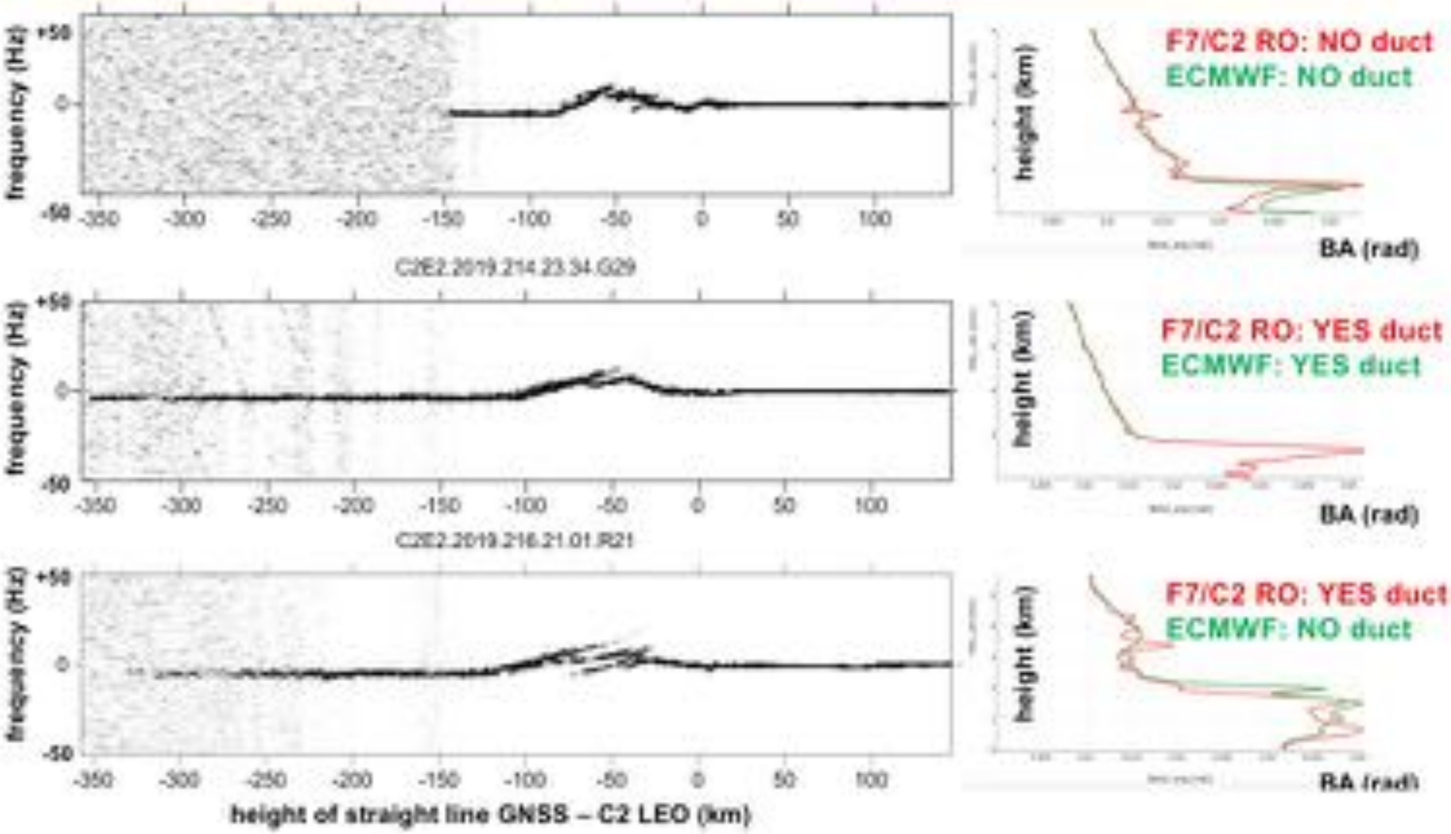


- Super-refraction QC is based on background values
- QC variables and criteria are different in these operators
- ✓ Ongoing work to check and test QC procedures (and observation errors) from our partners (e.g., UKMet, NRL, ECMWF)
- ✓ Operator comparison -> better understanding what is the critical/missing and how to improve the GNSSRO assimilation in JEDI, our next generation data assimilation system

F7/C2 High SNR (> 2000 V/V) allows detection of ducting on top of ABL

- Detection of ducting is based on presence of RO signals tracked down to -350 km.
- Information about ducting is important for assimilation of BA.

F7/C2 has detected super-refractive ducts with an accuracy of 100 m

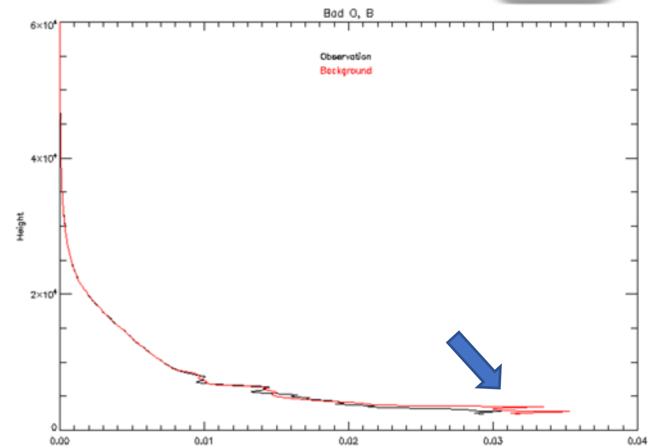


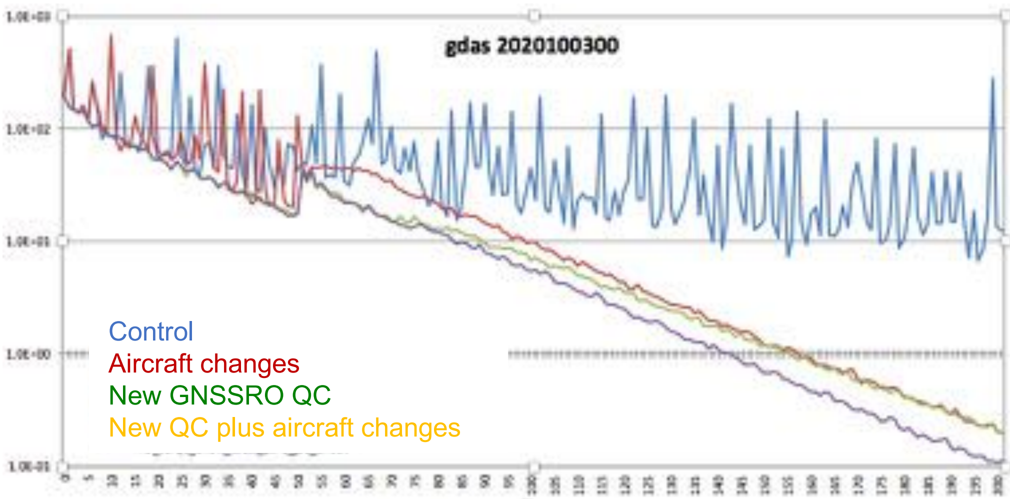
Can we use it in our DA?

John Brown (UCAR), COSMIC-2 FOC review, 2021

QC Fix for Lower Level Issues

- JCSDA added a QC to v16 using the Jacobian terms. The new QC helps to remove the anomalies during the minimization process (to find the optimal solution, analysis) and increase the assimilated observation numbers by improving the background





Gradient of cost function (converged to smaller values means the DA system is able to find the optimal analysis). No convergence (blue) means the system can't achieve the analysis

Fit to GNSSRO

Exp	Number of GNSSRO data assimilated		Bias	RMS
	outloop1	outloop1		
Cntl	217116	219924	0.19	2.66
With New QC	217057 (-59)	220705 (+781)	0.19	2.59

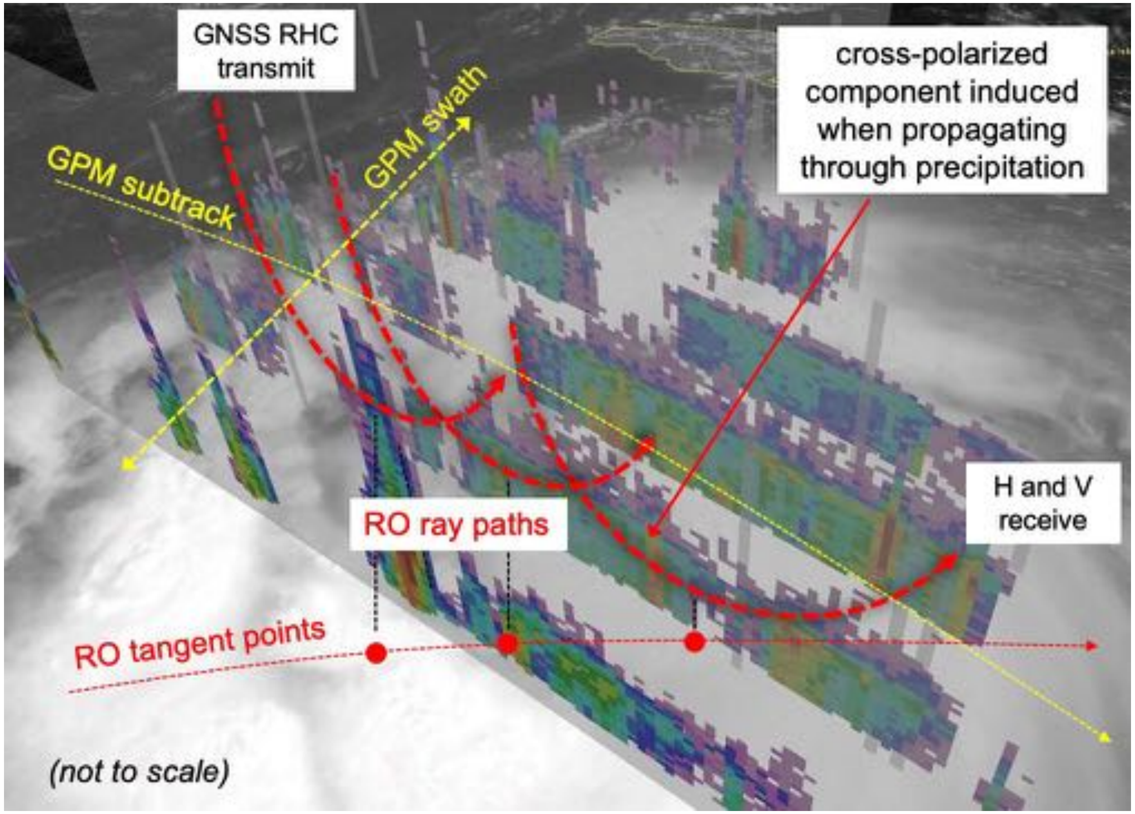
Fit to in-situ temperature, wind and humidity is also improved (not shown)

New Observation types

Polarimetric RO (PRO):

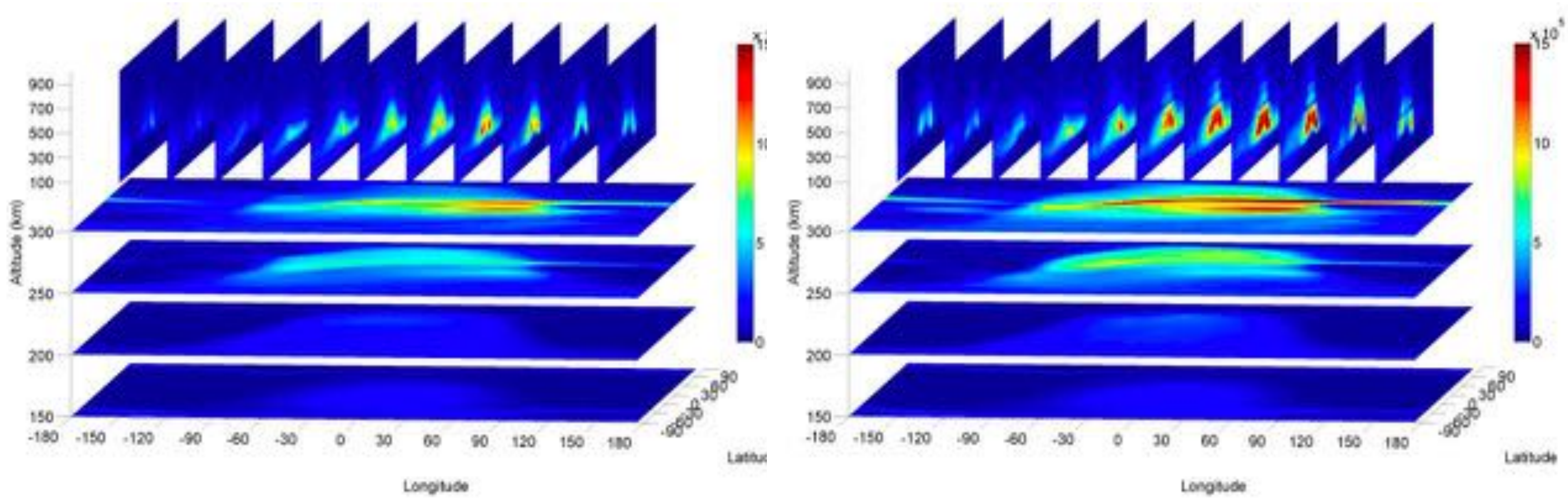
New GNSS products: Vertical profiles of thermodynamic variables + **vertical profiles of precipitation**

GNSS-R(flectometry) or hydroGNSS:
Surface roughness, vegetation, precipitation



Plot from Vertical Structure Content of Polarimetric Radio Occultations and and Applications to Weather Modeling, F. Joseph Turk, Friday, April 9, 10:30ET

Assimilating COSMIC-2 for Space Weather Studies



The electron density distribution before (left) and after (right) assimilating synthetic slant TEC data simulated by using the COSMIC-2 satellite configuration into GIP using the GDAS-EnSRF

(Tomoko Matsuo, University of Colorado)

Summary and Plans

- JCSDA and NOAA has been working together to incorporate new GNSSRO data into NOAA operations
  - COSMIC-2 was implemented at NCEP in May 2020. It shows significant impacts for the mid-upper troposphere/stratosphere, especially in tropical areas
  - Initial assessment of commercial data was performed during the NOAA pilot study and DO1. Currently NCEP is performing real-time evaluation and preparing implementation for DO-2 (~May 2021).
- It remains an issue how to better use of RO, especially in the gradient-sensitive areas, like tropopause or lower troposphere. Some of the ongoing studies (QC, interpolation, etc.) have shown their potential to further improve the forecasts
- Studies are also being performed on advanced forward operators for GNSSRO using our next generation data assimilation system. The system includes multiple operational operators, which stimulates inter-agency collaborations on improving GNSSRO data assimilation
- Ongoing efforts to explore additional information from new missions (e.g., PAZ RO/PRO, Setinel-6, GNSS-R, etc)