

NOAA

IROWG10

September 13, 2024

RO Impacts and Advances in NOAA NWP Operation

**Xuanli Li¹, Christopher Riedel², Catherine Thomas³,
Jeremiah Sjoberg⁴, Haixia Liu⁵, Daryl Kleist³,
Lidia Cucurull⁶, Richard Anthes⁴, Xin Jin¹, Andrew Collard³**

¹ SAIC @ NOAA/NWS/NCEP/EMC

² UCAR/CAPESS@OAR/ORTA/QOSAP

³ NOAA/NWS/NCEP/EMC

⁴ UCAR COSMIC

⁵ Lynker @ NOAA/NWS/NCEP/EMC

⁶ NOAA/OAR/QOSAP





Outline



- RO data assimilation in GFS and GDAS v16 at NCEP EMC



- RO data impact on forecast



- RO optimization

- Future directions

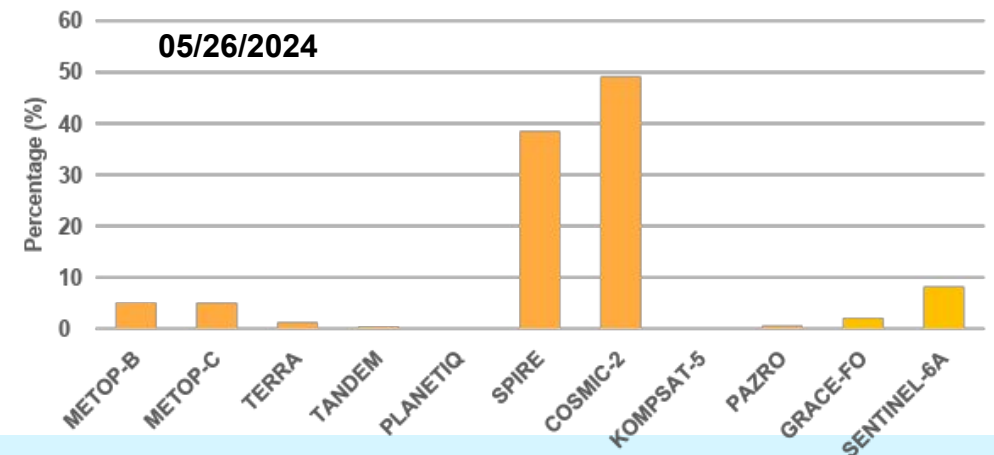




GFS and GDAS



- FV3 dynamic core
- Operational: C768 (13 km), 127 vertical levels, 80 km model top
- GFDL microphysics
- GDAS v16
 - Gridpoint Statistical Interpolation (GSI) based hybrid 4D-EnVar system
 - 25 km ensemble analysis, 80 members, 13 km deterministic forecast
 - 4D Incremental Analysis Update, LETKF ensemble update
- **Numerous types of observations assimilated including:**
 - Satellite radiances (using CRTM)
 - Satellite-based ozone and winds
 - Conventional
 - GNSS-RO



RO Observation Operator and Observation Error

- **Total refractivity N (Rueger 2002):**

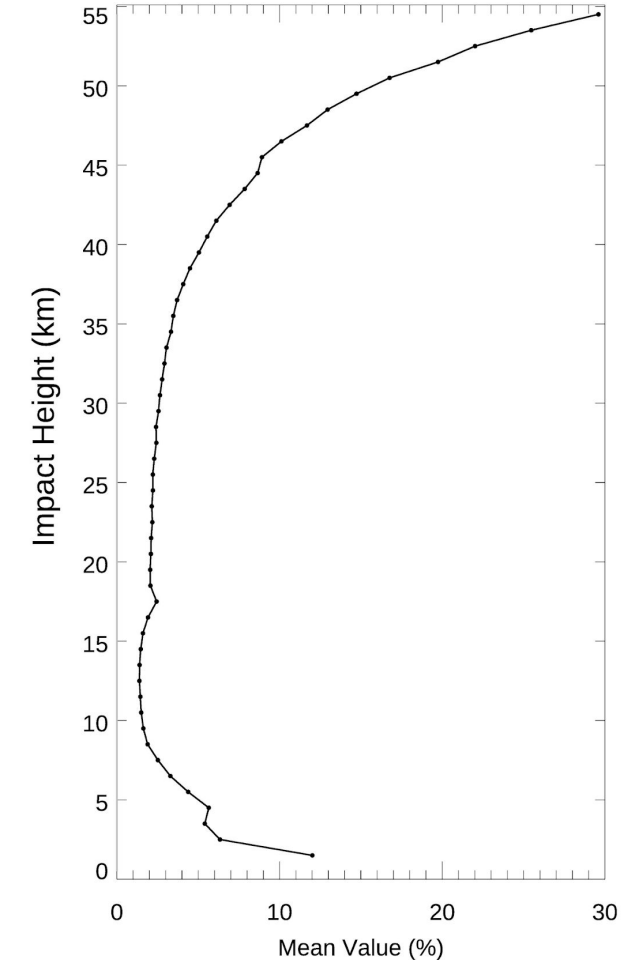
$$N = k_1 \left(\frac{P}{T}\right) Z_d^{-1} + k_2 \left(\frac{e}{T}\right) Z_w^{-1} + k_3 \left(\frac{e}{T^2}\right) Z_w^{-1}$$

- **NBAM 1-D bending angle (Cucurull et al. 2013):**

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

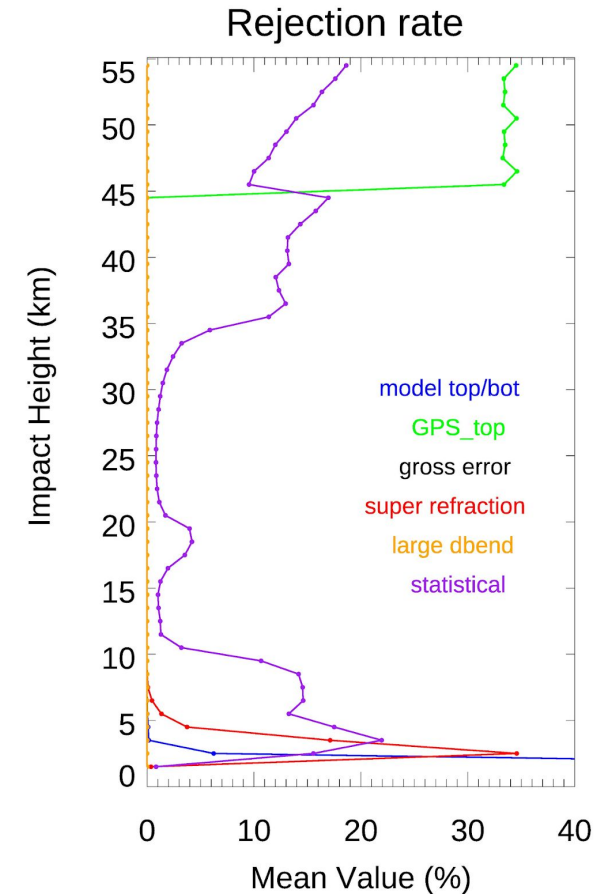
- **RO observation error (Desroziers et al. 2005)**

- 2-D function of latitude and impact height
- Latitude: 40° N - 40° S and > 40°
- Height: <12 km, 12-18 km, and > 18 km (2 additional regions for COSMIC-2 and commercial data: <4 km and 4-8 km)
- Inflated by square root of number of obs within a grid



RO Data Quality Control

- Reject data with quality flags
- Super-refraction: impact height < 5 km (Cucurull et al. 2013)
 - $\left| \frac{dN}{dr} \right| \geq 0.75 CV$ or
 - $\left| \frac{dN}{dr} \right| \geq 0.5 CV$ and $\max(\alpha) > 30$ mrad
- Model level 3 – 55 km (45 km for commercial data)
- Maximum value: 50 mrad
- |O-B|/Error gross check
- MetOp data below 8 km
- Statistic QC $|O-B|/O > X\sigma$ (Cucurull et al. 2013):
 - σ specified via statistical fit to observed σ
 - > 35 km: 1σ COSMIC-2/commercial, 2σ others
 - 10-35 km: 2σ COSMIC-2/commercial, 3σ others
 - < 10 km: 1σ COSMIC-2/commercial, 2σ others



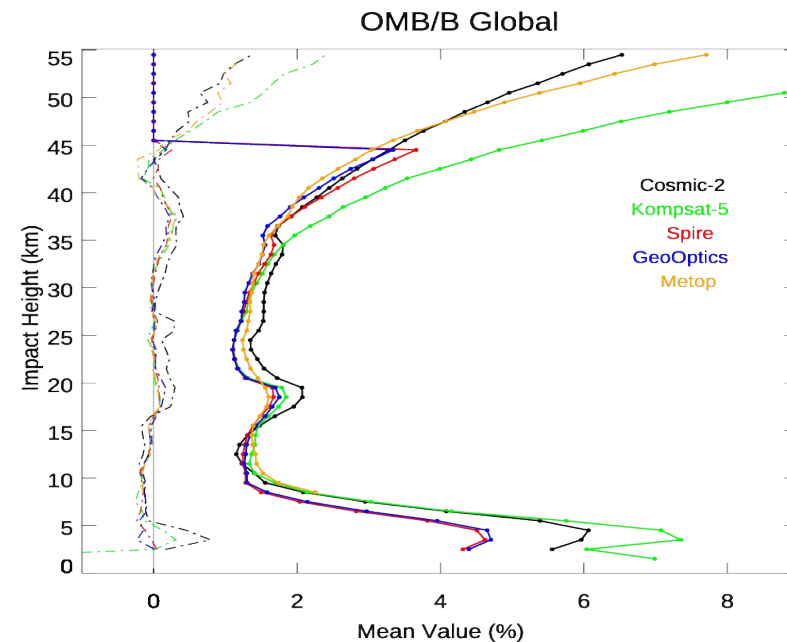
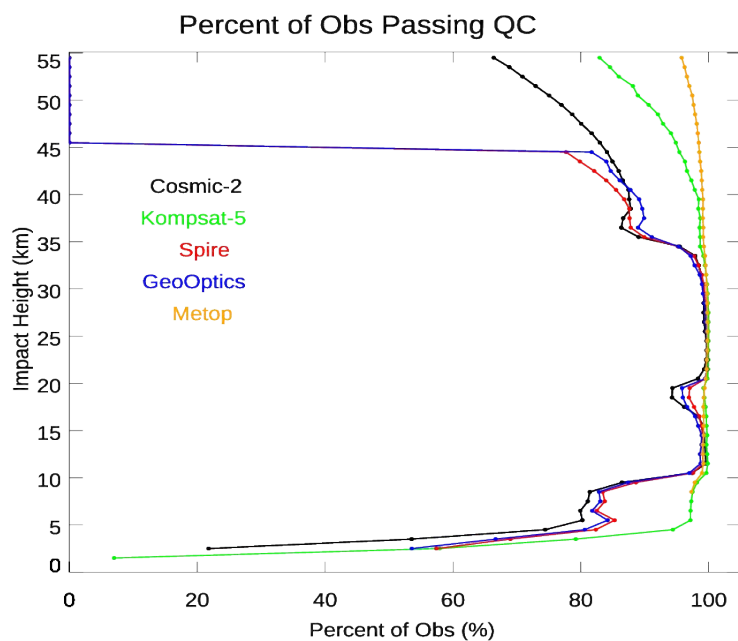


Commercial RO Data

- NOAA NESDIS CDP Radio Occultation Data Buy (RODB) contracts:
 - **RODB-1:** 5 delivery orders (DOs) in 2020-2023
 - Implemented May 2021 and September 2021
 - DO-1: GeoOptics 500 Profiles/day and Spire 500 Profiles/day
 - DO-2: GeoOptics 1,300 Profiles/day
 - DO-3: Spire 3,000 Profiles/day
 - DO-4: GeoOptics 500 Profiles/day and Spire 5,500 Profiles/day
 - DO-5: Spire 3,100 Profiles/day + EUMETSAT Spire 1,600 Profiles/day
 - **RODB-2:** Awarded to Spire and PlanetiQ in 2023 with a 5-year ordering period
 - Implemented September 2023
 - DO-1T: PlanetiQ 500 Profiles/day and Spire 500 Profiles/day
 - DO-2: PlanetiQ 3,100 Profiles/day
 - DO-3: Spire ~~6,000~~ 3,000 Profiles/day (<1,000 in August 2024) + EUMETSAT Spire 1,600 Profiles/day

RODB-1 DO-4 Assessment

- **DO-4** : March 2022 – January 2023
- **Data Denial Experiment**: 24 March – 24 April 2022
 - **v16_ctl**: Control run **with** DO-4 data (~500 GeoOptics and ~5,500 Spire)
 - **v16_do4**: Data denial experiment **without** DO-4 data
- **Configuration**: Global parallel experiments GFS v16.1.6, C384 (25 km) resolution



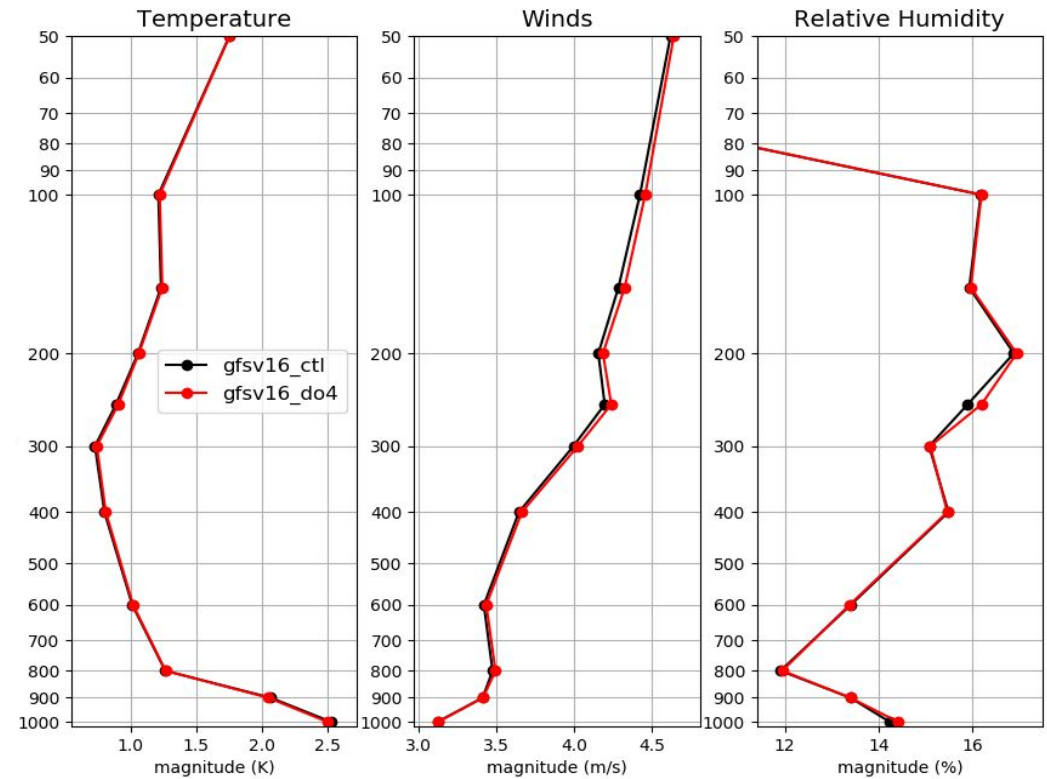
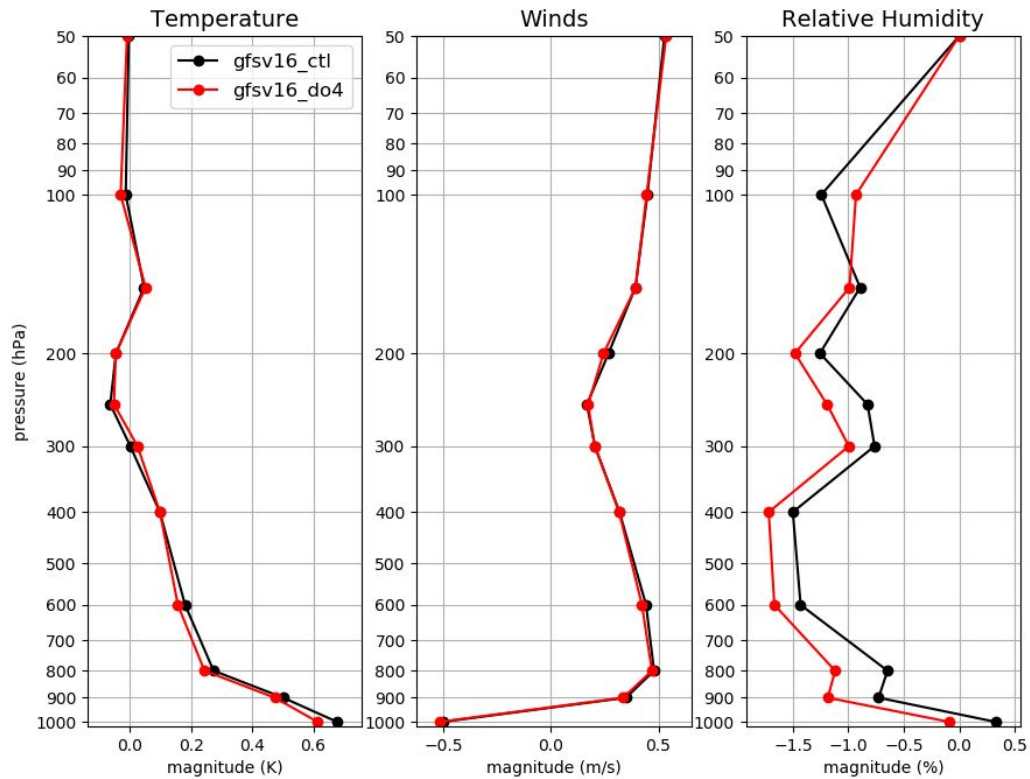
20220324 - 20220424

Data from both Spire and GeoOptics show quality comparable to existing missions

Data Impact - Fit to Radiosondes

Bias O-F (2022032400-2022042400)

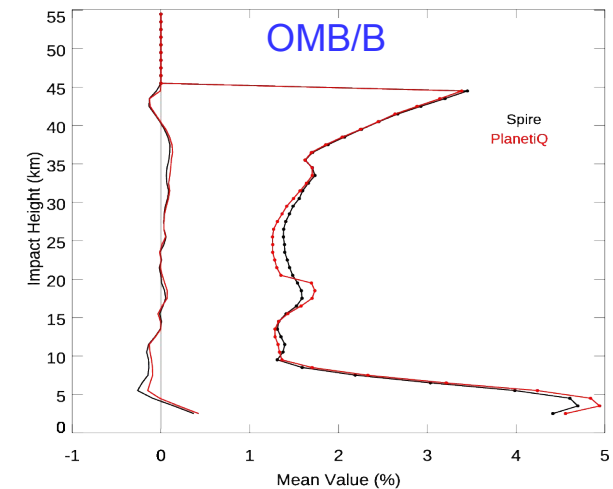
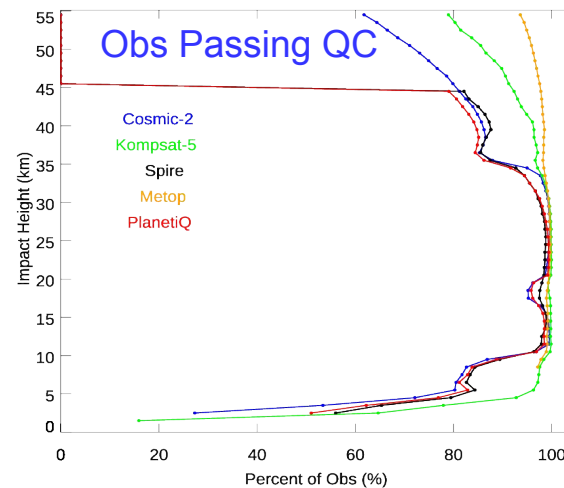
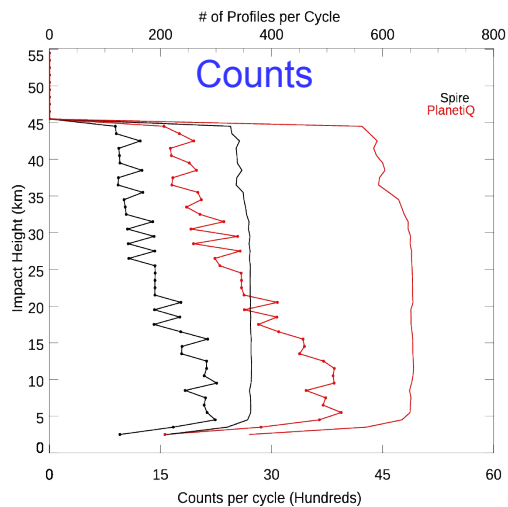
RMSE O-F (2022032400-2022042400)



- Slightly larger bias in temperature below 500 hPa; Less bias in relative humidity from 900 to 150 hPa
- Slightly smaller RMSE in wind above 300 hPa; Smaller RMSE in RH at 250 hPa

ROBD-2 DO-2 PlanetiQ Verification Experiment

- **ROBD-2 DO-2:** in July 2023 with PlanetiQ 3,100 Profiles/day
- Global workflow v16.3.7; 80 ensemble members; C768 (13 km) resolution
- Verification Time Period: 19 July – 29 August 2023
- **gfs:** Operational run without PlanetiQ data
- **v1637piq:** Experiment with operational RO data + PlanetiQ data (~650 profiles/cycle)



- The statistics of PlanetiQ were similar to Spire

Scorecard – Fit to ECMWF Analysis

		N. America					N. Hemisphere					S. Hemisphere					Tropics								
		Day 1	Day 3	Day 5	Day 6	Day 8	Day 10	Day 1	Day 3	Day 5	Day 6	Day 8	Day 10	Day 1	Day 3	Day 5	Day 6	Day 8	Day 10	Day 1	Day 3	Day 5	Day 6	Day 8	Day 10
Anomaly Correlation Coefficient	Heights	250hPa					M					M	▲					M							
		500hPa					M					M						M							
		700hPa					M					M						M							
		1000hPa					M					M						M							
	Vector Wind	250hPa					M					M						M							
		500hPa					M					M						M							
		850hPa					M					M						M							
	Temp	250hPa					M					M						M							
		500hPa					M					M	▲					M							
		850hPa					M					M						M							
MSLP	MSL					M					M					M									
RMSE	Heights	10hPa					M					M					M								
		20hPa					M					M					M								
		50hPa					M					M					M								
		100hPa					M					M					M								
		200hPa					M					M	▲				M								
		500hPa					M					M					M								
		700hPa					M					M					M								
		850hPa					M					M					M								
		1000hPa					M					M					M								
		Vector Wind	10hPa					M					M					M							
	20hPa						M					M	▲	▲			M								
	50hPa		▲	▲	▲		M	▲	▲	▲		M	▲	▲			M								
	100hPa						M					M	▲	▲			M								
	Temp	10hPa					M					M					M								
20hPa						M					M	▲	▲			M									
50hPa		▲	▲	▲	▲	M	▲	▲	▲	▲	M	▲	▲			M									
100hPa						M					M	▲	▲			M									
200hPa						M					M					M									
500hPa						M					M	▲				M									
700hPa						M					M					M									
850hPa						M					M					M									
1000hPa						M					M					M									

		N. America					N. Hemisphere					S. Hemisphere					Tropics								
		Day 1	Day 3	Day 5	Day 6	Day 8	Day 10	Day 1	Day 3	Day 5	Day 6	Day 8	Day 10	Day 1	Day 3	Day 5	Day 6	Day 8	Day 10	Day 1	Day 3	Day 5	Day 6	Day 8	Day 10
Bias	Heights	10hPa					M					M					M								
		20hPa					M					M					M								
		50hPa					M					M					M								
		100hPa					M					M					M								
		200hPa					M					M					M								
		500hPa					M					M					M								
		700hPa					M					M					M								
		850hPa					M					M					M								
		1000hPa					M					M					M								
		Wind Speed	10hPa					M					M					M							
	20hPa						M					M					M								
	50hPa						M					M					M								
	100hPa						M					M					M								
	Temp	10hPa					M					M					M								
20hPa						M					M					M									
50hPa						M					M					M									
100hPa						M					M					M									
200hPa						M					M					M									
500hPa						M					M					M									
700hPa						M					M					M									
850hPa						M					M					M									
1000hPa						M					M					M									

▲	v1637piq is better than gfs at the 99.9% significance level	▼	v1637piq is worse than gfs at the 99.9% significance level
▲	v1637piq is better than gfs at the 99% significance level	▼	v1637piq is worse than gfs at the 99% significance level
▲	v1637piq is better than gfs at the 95% significance level	▼	v1637piq is worse than gfs at the 95% significance level
■	No statistically significant difference between v1637piq and gfs	■	Not statistically relevant
Dates: 20230719-20230829			

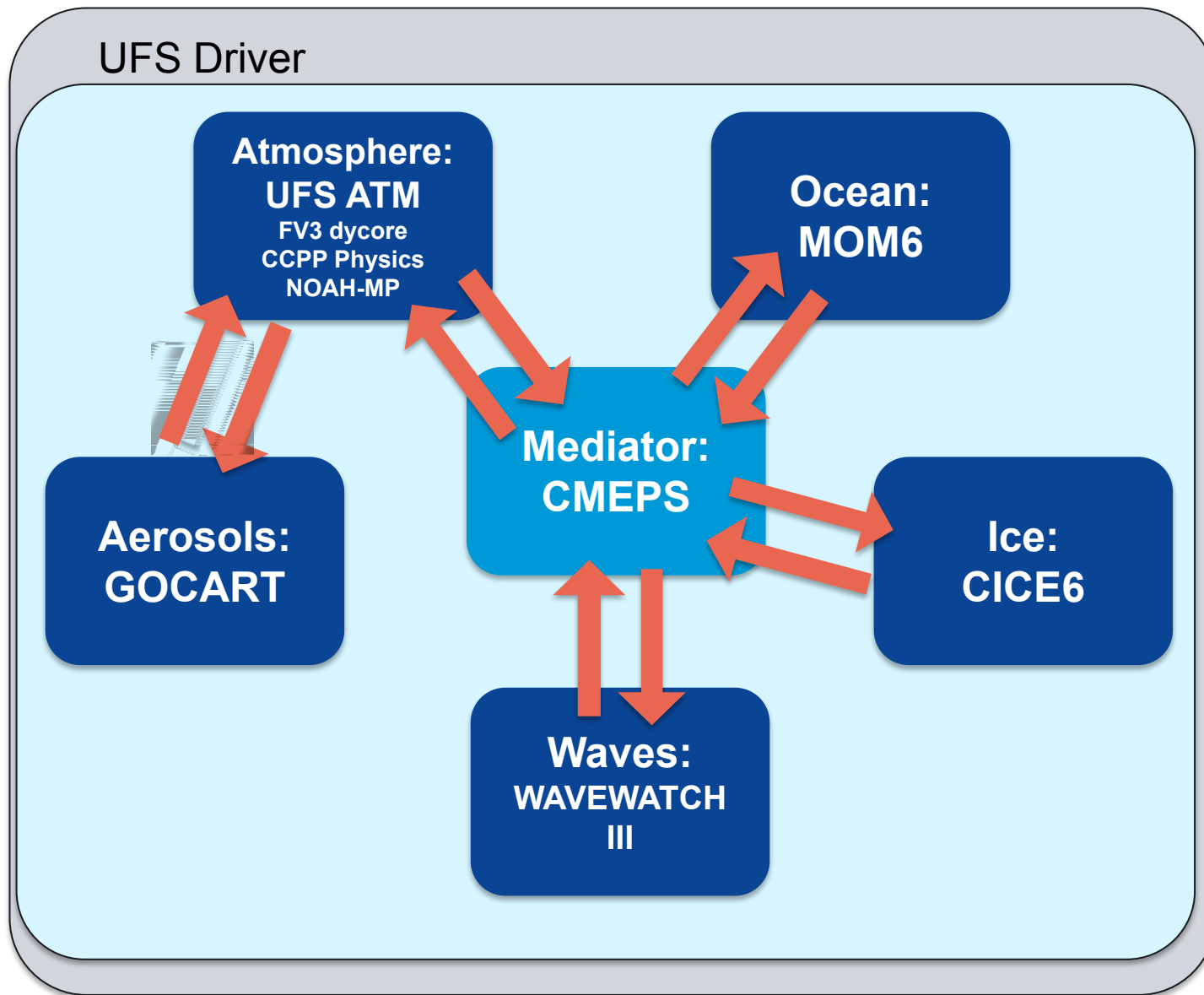
- **Green: Improvement** **Red: Degradation**
- Neutral to slightly positive impact
- **Improvement:** RMSE for both wind and temperature near 50 hPa in NH and SH
- Less significant impact when compared to DO-4, partly due to smaller data volume





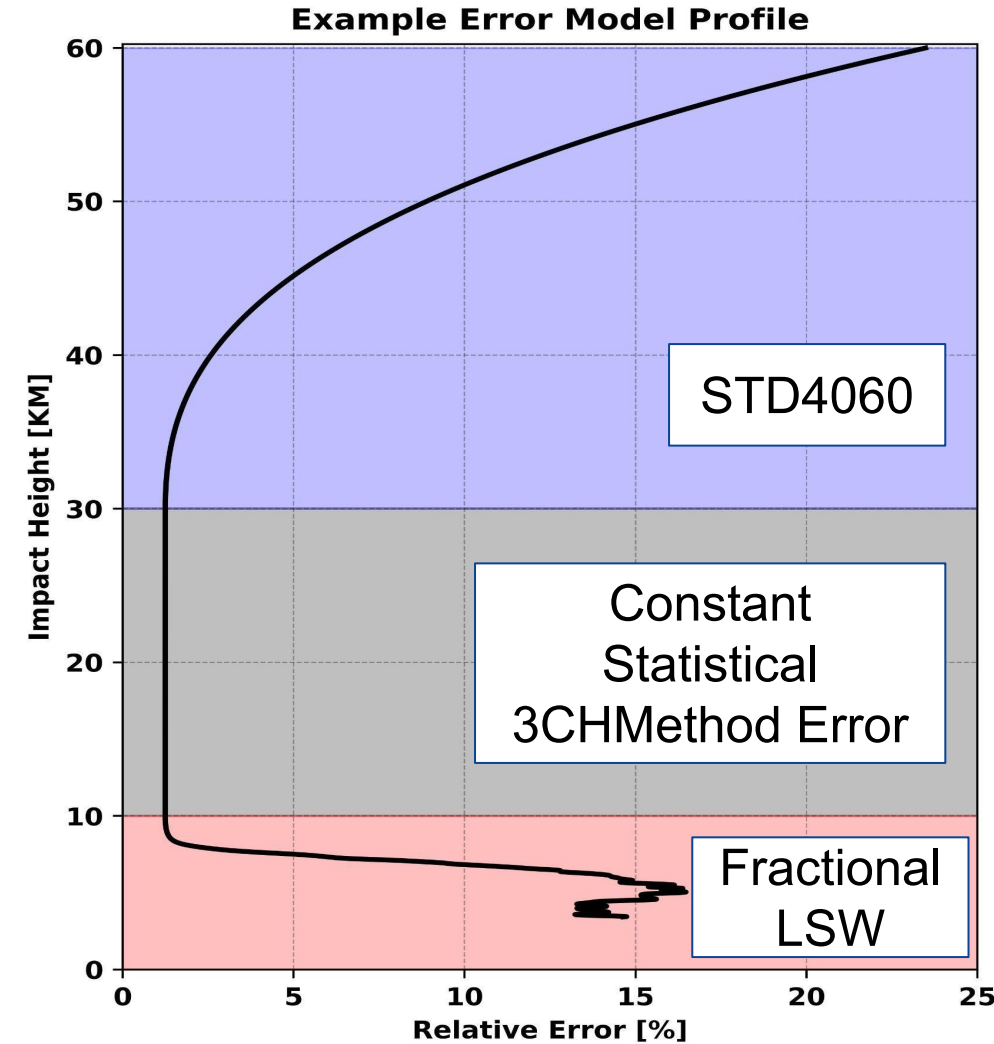
GFSv17 Overview

- 5-way weakly coupled system
 - Atmosphere
 - Ocean and Sea ice
 - Land
 - Waves
 - Aerosol (Non-interactive in GDAS deterministic forecast only)
- ATM DA updates
 - Thompson microphysics/all sky upgrades
 - Scale-Dependent Localization
 - New observations: satellite radiance, GNSS RO, satwind, saildrones



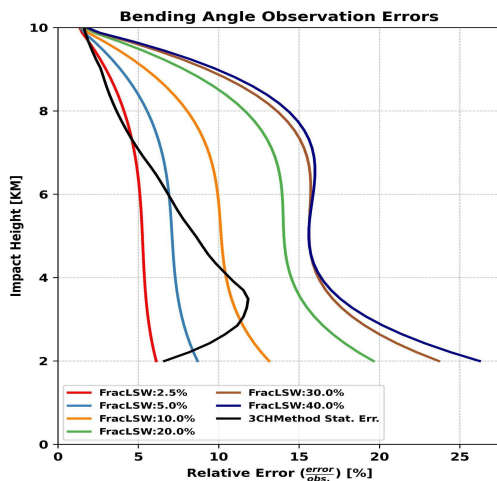
New Hybrid Obs Error Model

- Error model is defined in 3 vertical regions
- STD4060 => **Blue Region (30-60 km)**
 - Standard deviation between observation values and an exponential fit for impact heights between 40-60 KM
- Constant Statistical 3CHMethod Error => **Grey Region (10-30 km)**
 - Relative error of 1.25%
- Fractional LSW => **Red Region (<10 km)**
 - Use fractional LSW (LSW/Bending-angle) to compute relative error
 - Special treatment:
 - Fractional LSW > 40 => Fractional LSW = 40

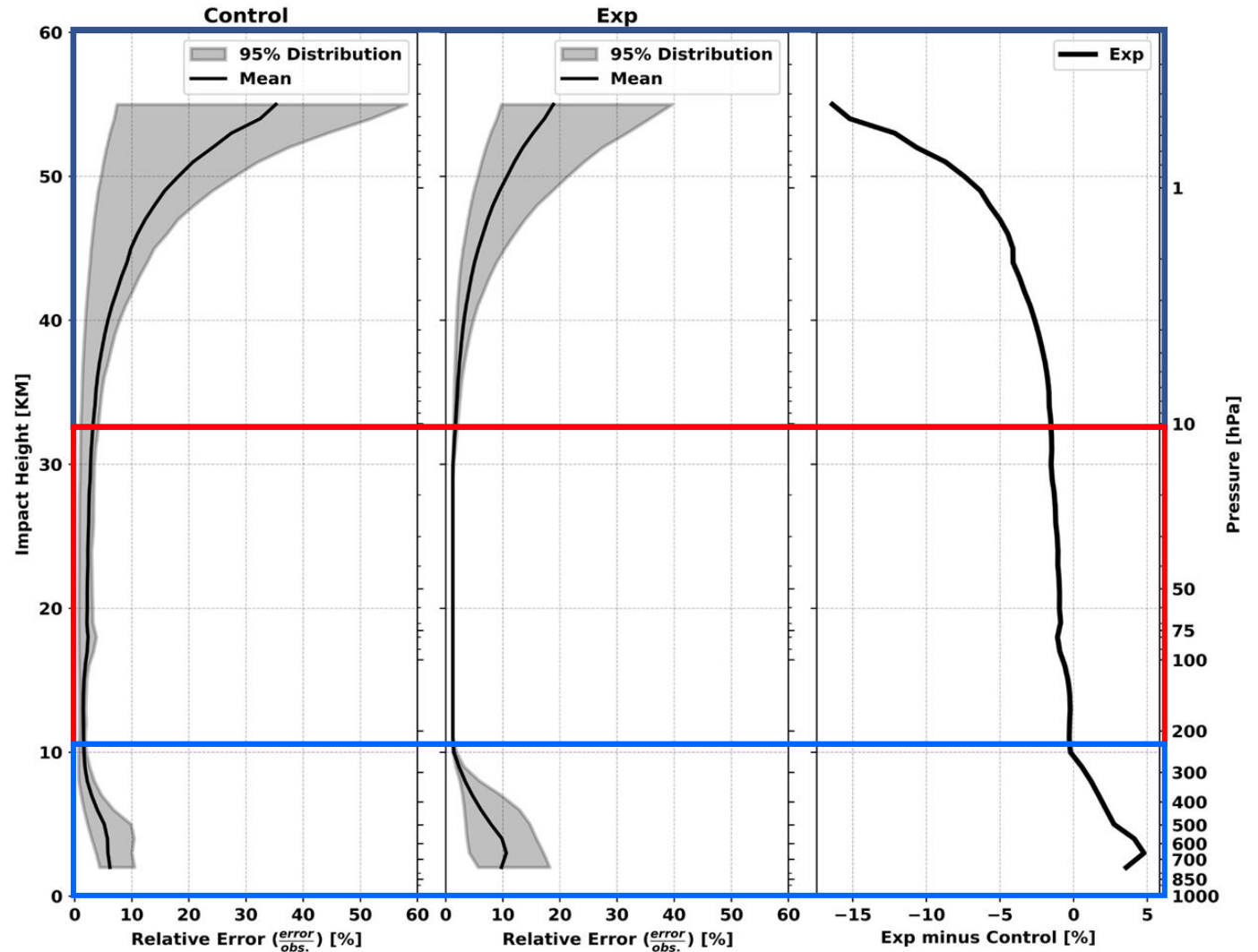


GSI Obs Error vs. New Hybrid Error Model

- On average, the hybrid error model increases the obs error at <10 km, while decreasing the error above 15 km
- More variation in obs error in hybrid error model



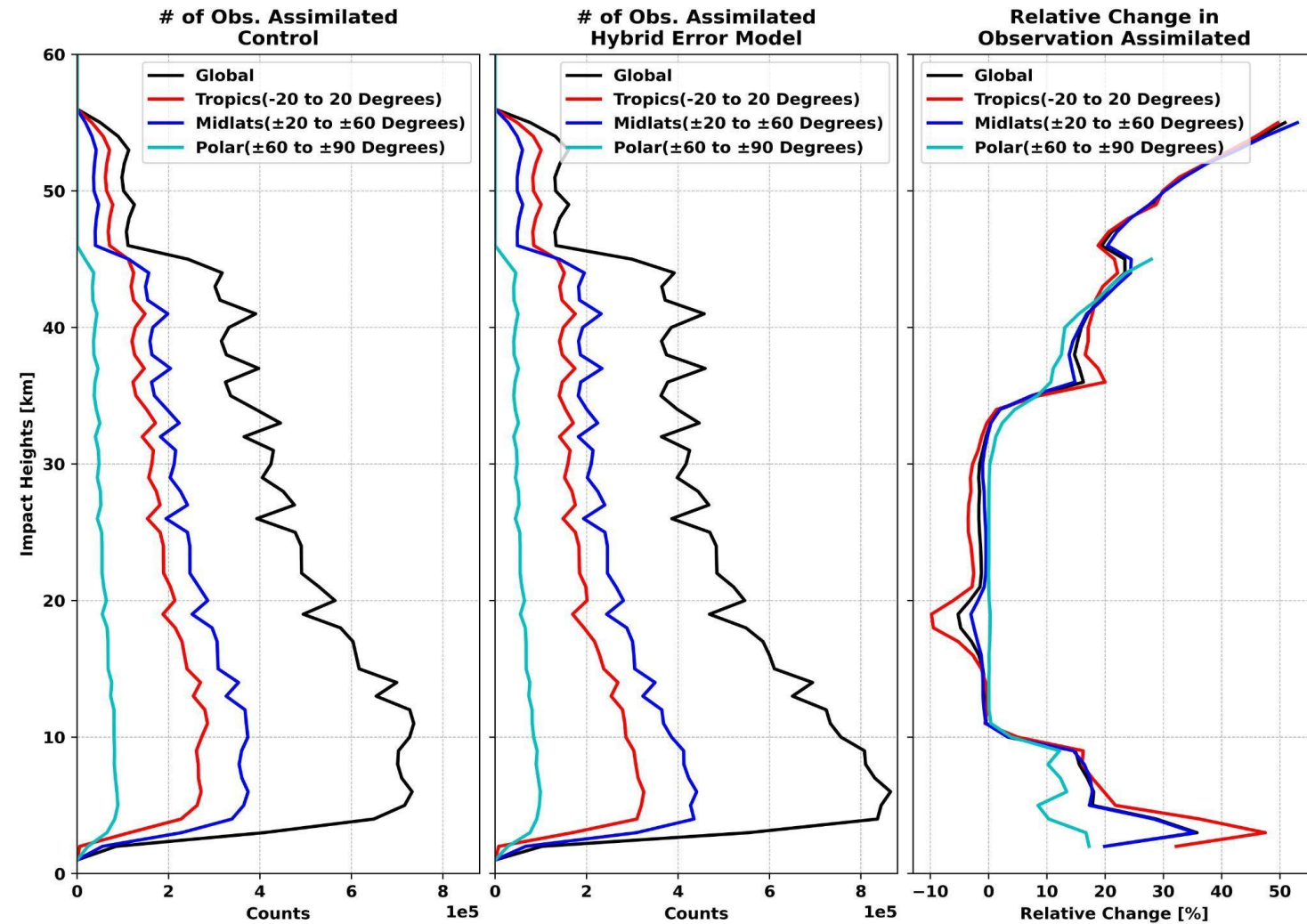
20210101 - 20210131



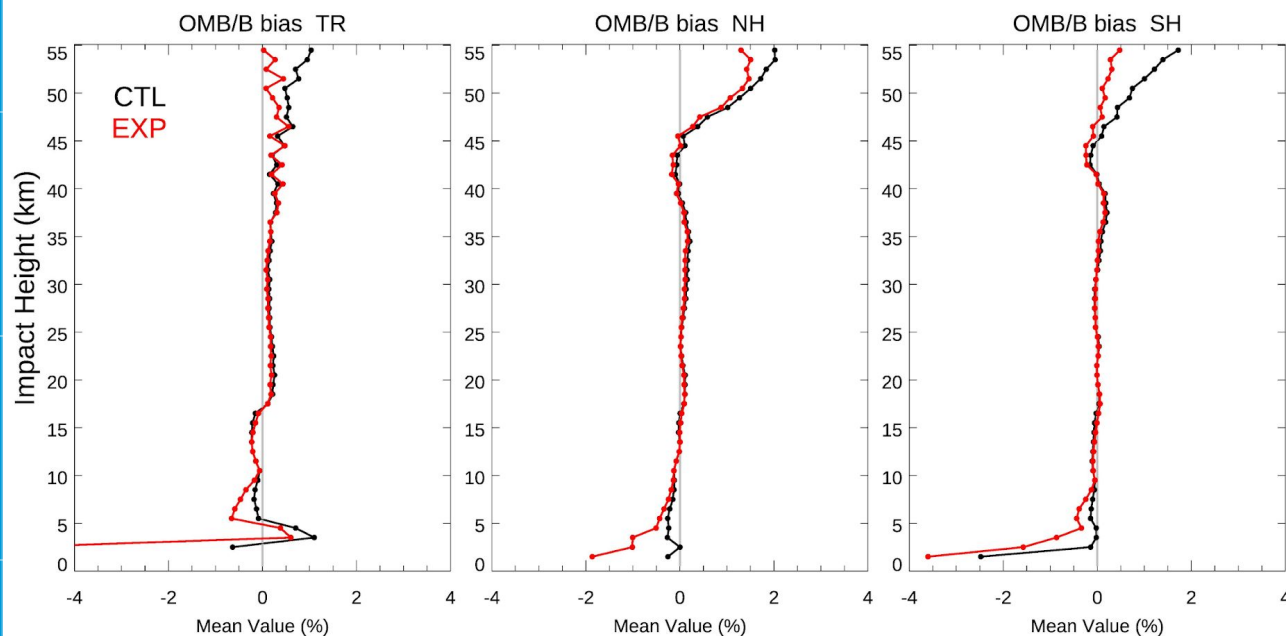
New QC

20210101 - 20210131

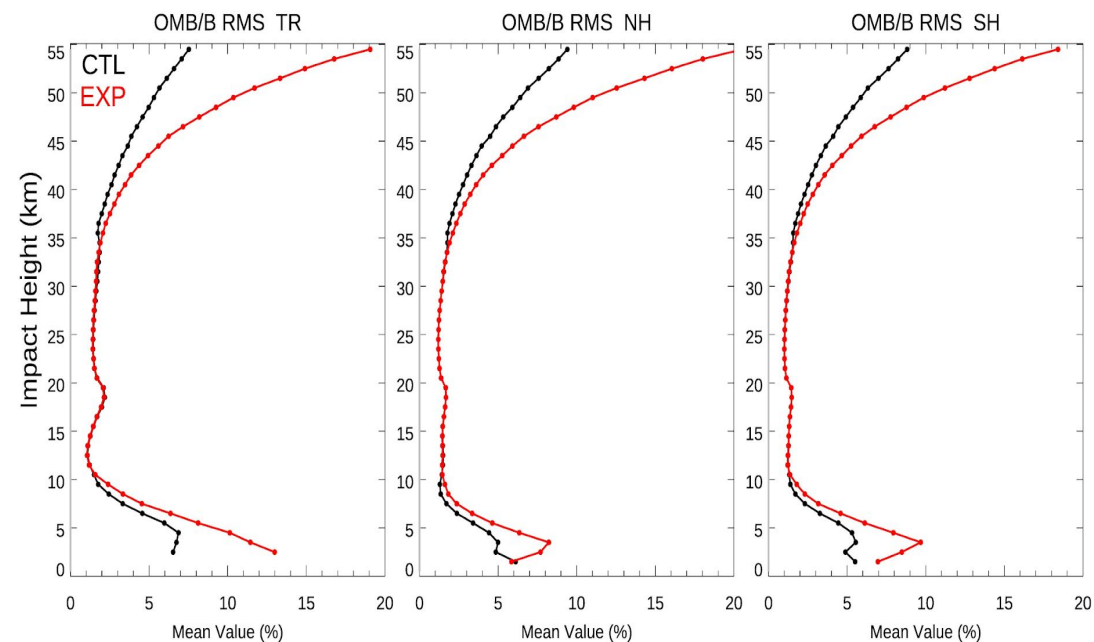
- New QC:
 - $(O-B)/B > 3\sigma$ (σ is the 3CH global statistical uncertainty)
 - May eliminate too many observations between 10-30 km.
- Increase in the number of assimilated observation > 30 km and < 10 km
- Tropics: largest reduction between 15-30 km. Large increase < 5 km.
- 10-30 km: Reduction of 2-10% in the number of assimilated observations



Forecast Bias



Forecast RMS



20230101 - 20230228

- Larger bias and RMS of O-B/B in troposphere and > 35 km due to changes in QC
- Atmosphere-only DA

v17 Testing

- Verification: 20230101-20230128 against ECMWF Analysis
- Impact is mostly neutral
- Degradation in RMSE for heights over Tropics
- Improvement in wind bias over Tropics
- Green: Improvement
Red: Degradation

▲ EXP1-NewErr-NewQC is better than V17-CleanCtI at the 99.9% significance level	▼ EXP1-NewErr-NewQC is worse than V17-CleanCtI at the 99.9% significance level
- EXP1-NewErr-NewQC is better than V17-CleanCtI at the 99% significance level	- EXP1-NewErr-NewQC is worse than V17-CleanCtI at the 99% significance level
■ EXP1-NewErr-NewQC is better than V17-CleanCtI at the 95% significance level	■ EXP1-NewErr-NewQC is worse than V17-CleanCtI at the 95% significance level
□ No statistically significant difference between EXP1-NewErr-NewQC and V17-CleanCtI	□ Not statistically relevant

Dates: 20230101-20230228

		N. America					N. Hemisphere					S. Hemisphere					Tropics											
		Day 1	Day 3	Day 5	Day 6	Day 8	Day 10	Day 1	Day 3	Day 5	Day 6	Day 8	Day 10	Day 1	Day 3	Day 5	Day 6	Day 8	Day 10	Day 1	Day 3	Day 5	Day 6	Day 8	Day 10			
Anomaly Correlation Coefficient	Heights	250hPa				M	M					M	M					M	M									
		500hPa				M	M					M	M					M	M									
		700hPa				M	M		▲				M	M				M	M									
		1000hPa				M	M		▲				M	M				M	M									
	Vector Wind	250hPa				M	M						M	M				M	M									
		500hPa				M	M						M	M				M	M									
		850hPa				M	M						M	M				M	M									
	Temp	250hPa				M	M						M	M				M	M									
		500hPa				M	M		■				M	M				M	M									
		850hPa				M	M		▲				M	M				M	M									
	MSLP	MSL				M	M		▲				M	M				M	M									
	RMSE	Heights	10hPa	-				M	M					M	M	▲	▲	-	▲	M	M	▼	▼	■		M	M	
			20hPa					M	M					M	M	▲		■	■	M	M	▼	▼	▼	■	M	M	
50hPa							M	M					M	M			■	■	M	M	▼	▼	▼	■	M	M		
100hPa							M	M			■			M	M			■	■	M	M	▼	▼	▼	■	M	M	
200hPa							M	M			▼			M	M			▼	▼	M	M	▼	▼	■		M	M	
500hPa							M	M			■			M	M			▼	▼	M	M	▼	▼	■		M	M	
700hPa							M	M						M	M				M	M	▼	▼	■		M	M		
850hPa					■									M	M			▲	▲	M	M					M	M	
1000hPa					■									M	M			▲	▲	M	M					M	M	
Vector Wind			10hPa					M	M					M	M				M	M	▲	▲	▲	▲		M	M	
		20hPa					M	M					M	M				M	M	▲	▲	▲	▲		M	M		
		50hPa	▼				M	M			▼			M	M			■	■	M	M	▼	▼	■		M	M	
		100hPa					M	M						M	M			■	■	M	M	▼	▼	■		M	M	
		200hPa					M	M						M	M			■	■	M	M	▼	▼	■		M	M	
		500hPa					M	M						M	M			■	■	M	M	▼	▼	■		M	M	
		700hPa					M	M						M	M			■	■	M	M	▼	▼	■		M	M	
		850hPa			■									M	M			▲	▲	M	M					M	M	
		1000hPa	■		■									M	M			▲	▲	M	M					M	M	
		Temp	10hPa					M	M			▲			M	M			▲	▲	▲	▲	M	M	▲	▲	M	M
20hPa							M	M						M	M				M	M	▲	▲	▲	▲		M	M	
50hPa			▼				M	M			▼	▼			M	M				M	M	▲	▲	▲	▲		M	M
100hPa							M	M							M	M				M	M	▲	▲	▲	▲		M	M
200hPa							M	M							M	M			■	■	M	M	▼	▼	■		M	M
500hPa							M	M							M	M			■	■	M	M	▼	▼	■		M	M
700hPa							M	M							M	M			■	■	M	M	▼	▼	■		M	M
850hPa							M	M							M	M			■	■	M	M	▼	▼	■		M	M
1000hPa							M	M							M	M			■	■	M	M	▼	▼	■		M	M
Wind Speed			10hPa	▲	■			▲	▲			▲	▲			▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲
		20hPa	▲	■			▲	▲			▲	▲			▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	
		50hPa			■																							
	100hPa																											
	200hPa																											
	500hPa																											
	700hPa																											
	850hPa																											
	1000hPa																											
	Temp	10hPa	▲	■			▲	▲			▲	▲			▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲		
20hPa		▲	■			▲	▲			▲	▲			▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲			
50hPa				■																								
100hPa		▼																										
200hPa																												



Future Directions

- ROMEX experiments with GFSv17
- Optimization of obs error and QC
- Joint Effort for Data assimilation Integration (JEDI)
 - Collaborative effort on next generation of DA infrastructure
 - GFSv18: JEDI-based atmosphere DA (complete transition away from GSI)
 - JEDI T2O
 - Exploring the multiple observation operators for RO, improved quality control and observation error specification
 - Begin exploring the assimilation of GNSS-R products, including OSW and potentially soil moisture within the coupled DA context
 - Monitoring advancements in the utilization of GNSS PRO data and the development of PRO assimilation

