RO Impacts and Advances in NOAA NWP Operation

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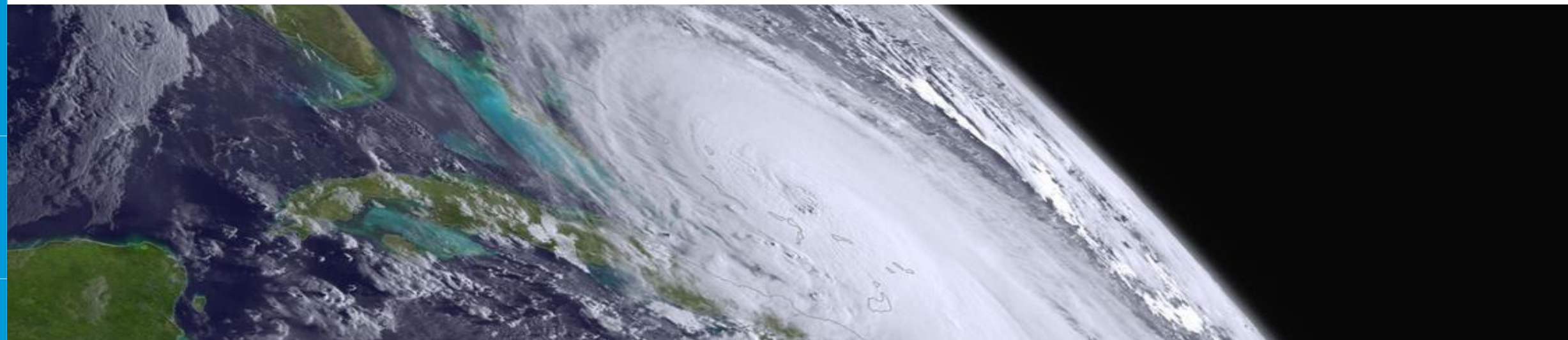
IROWG10
September 13, 2024

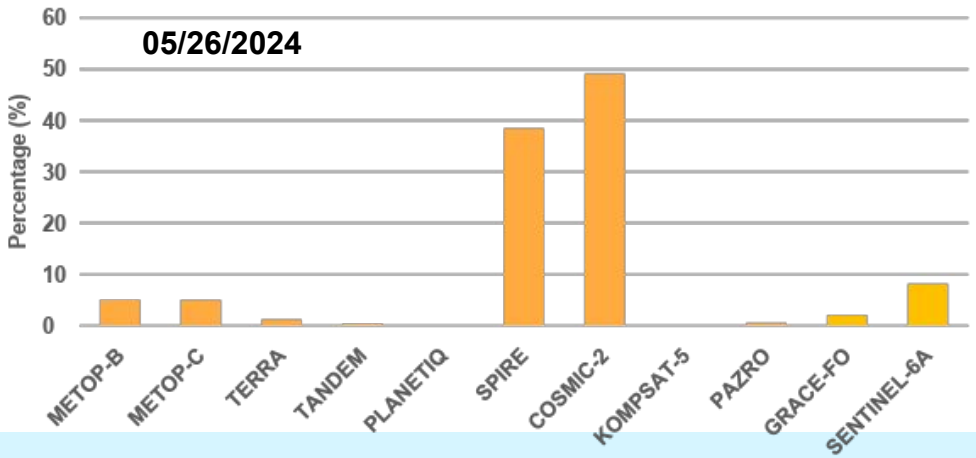


Outline

- 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

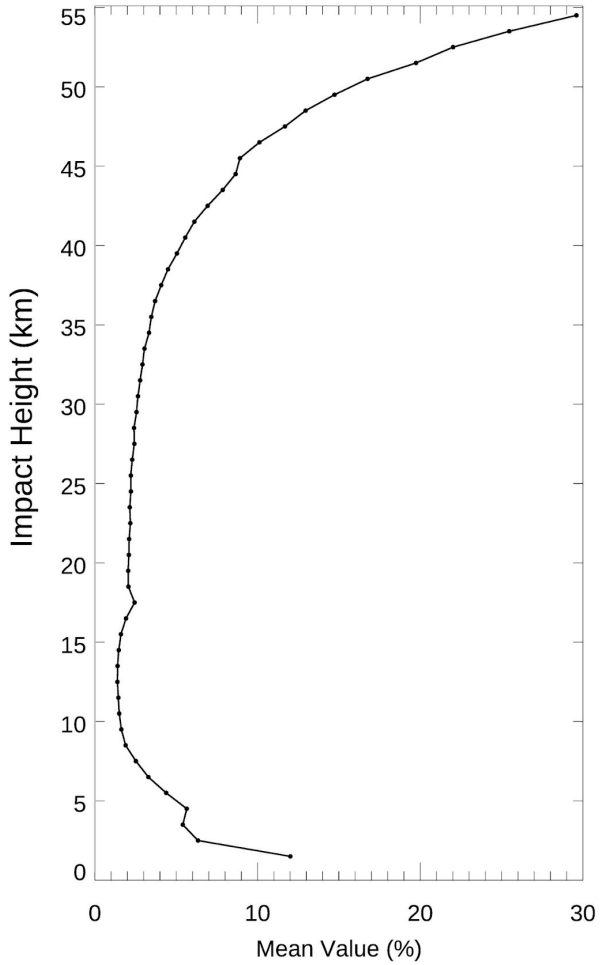
- **Total refractivity N (Rueger 2002):**

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

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

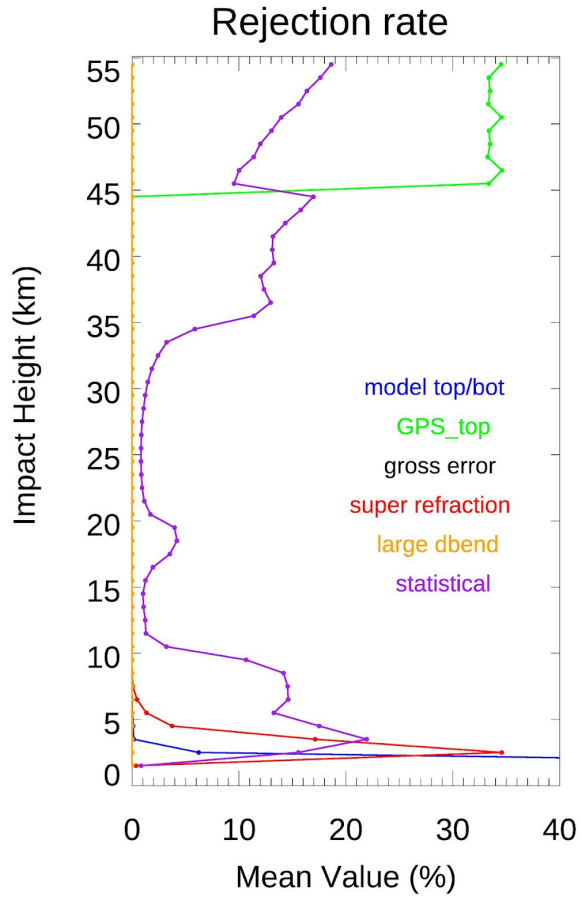
$$\alpha(a) = -2a \int_a^{\infty} \frac{d\ln n/dx}{\sqrt{(x^2 - a^2)}}\, dx, \quad x = nr$$

- **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(α) > 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 > Xσ (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

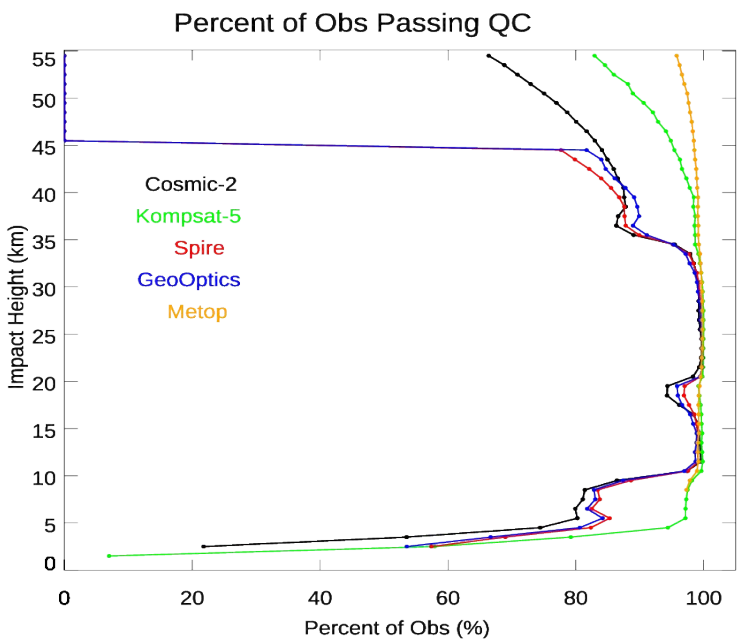


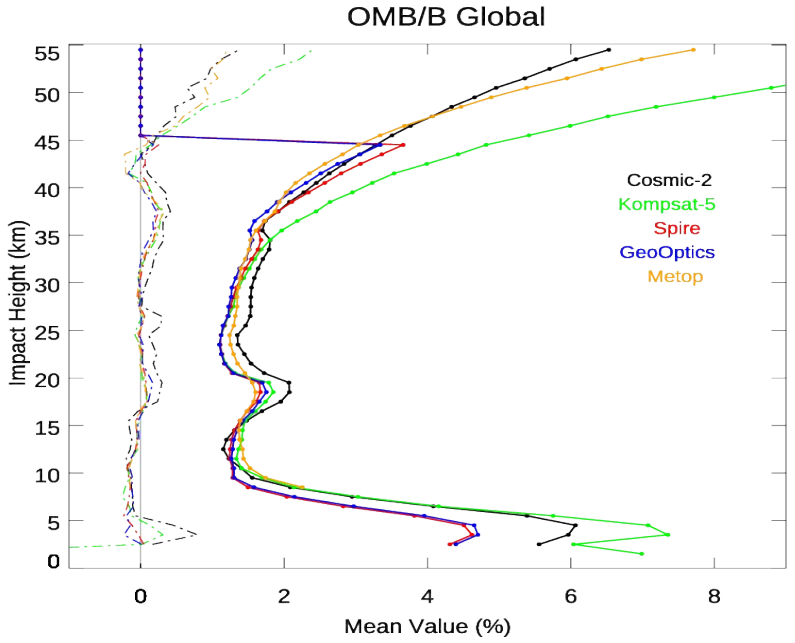
Commercial RO Data

- 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

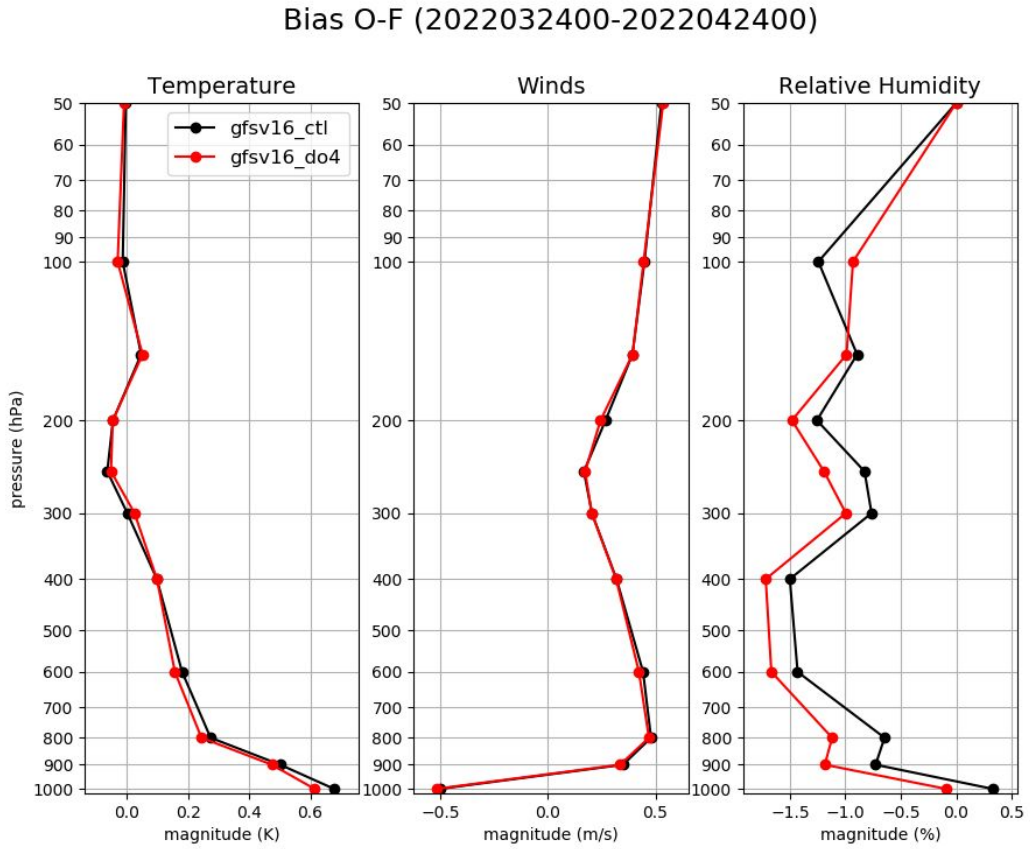


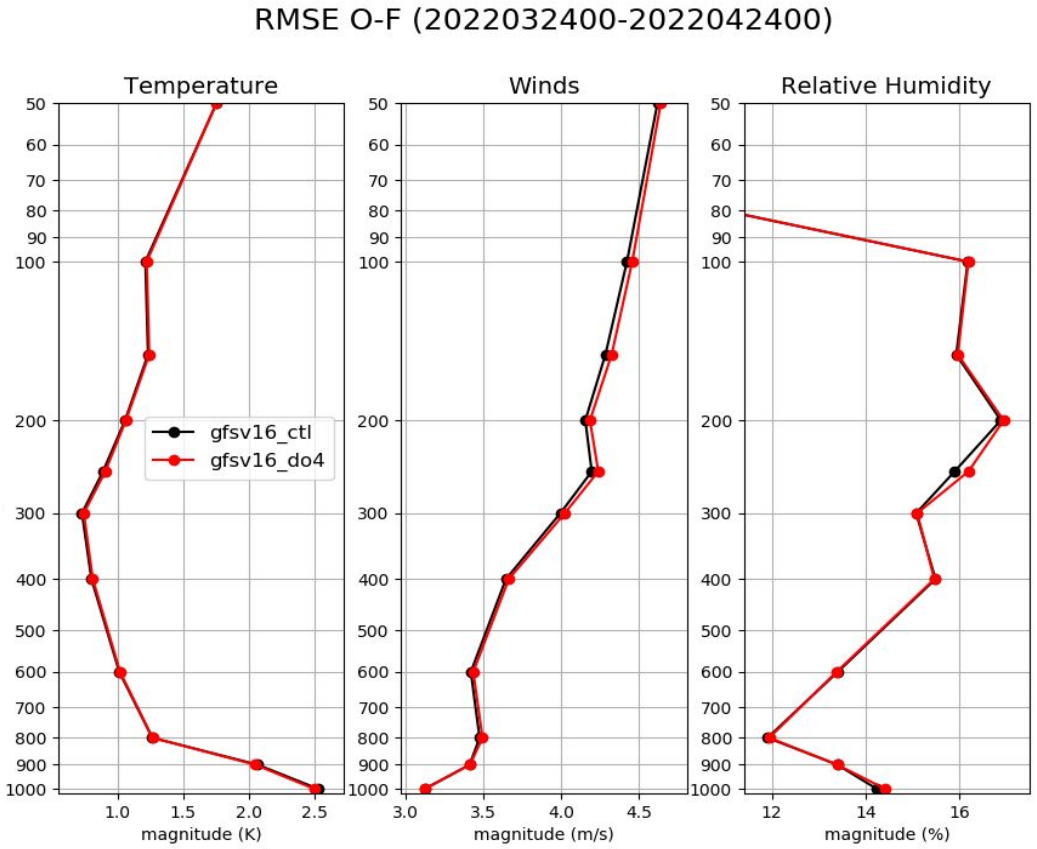


20220324 - 20220424

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

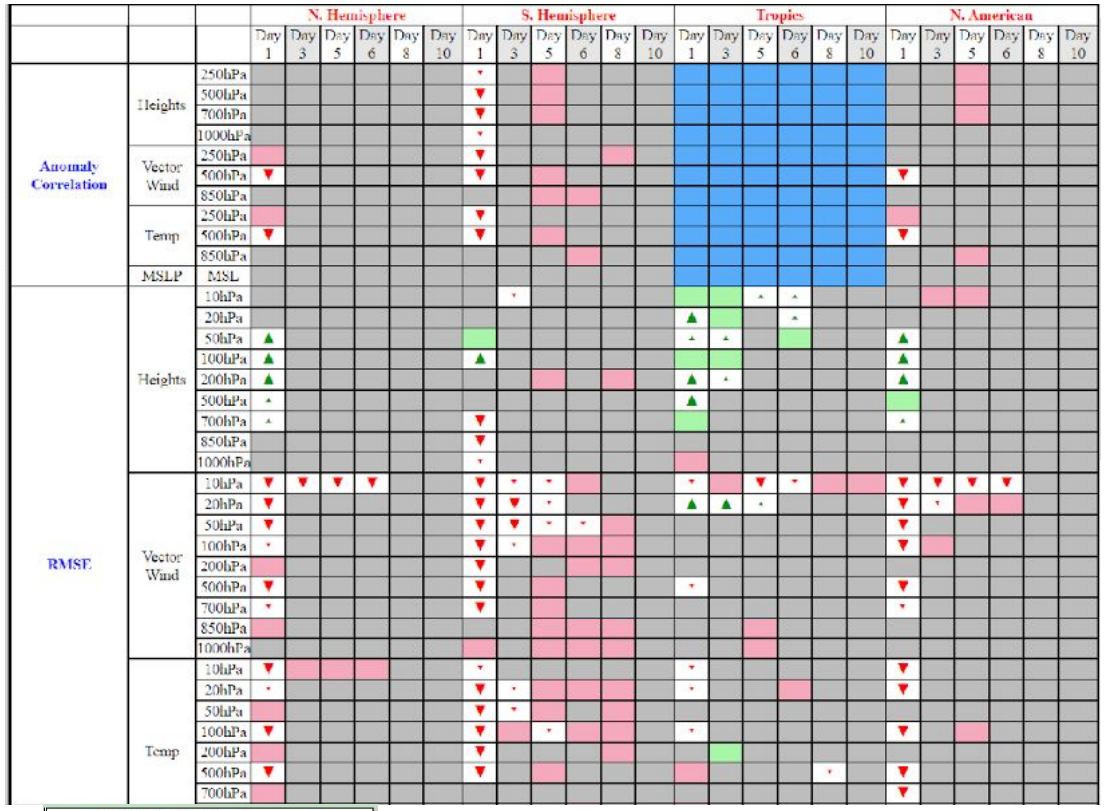
Data Impact - Fit to Radiosondes

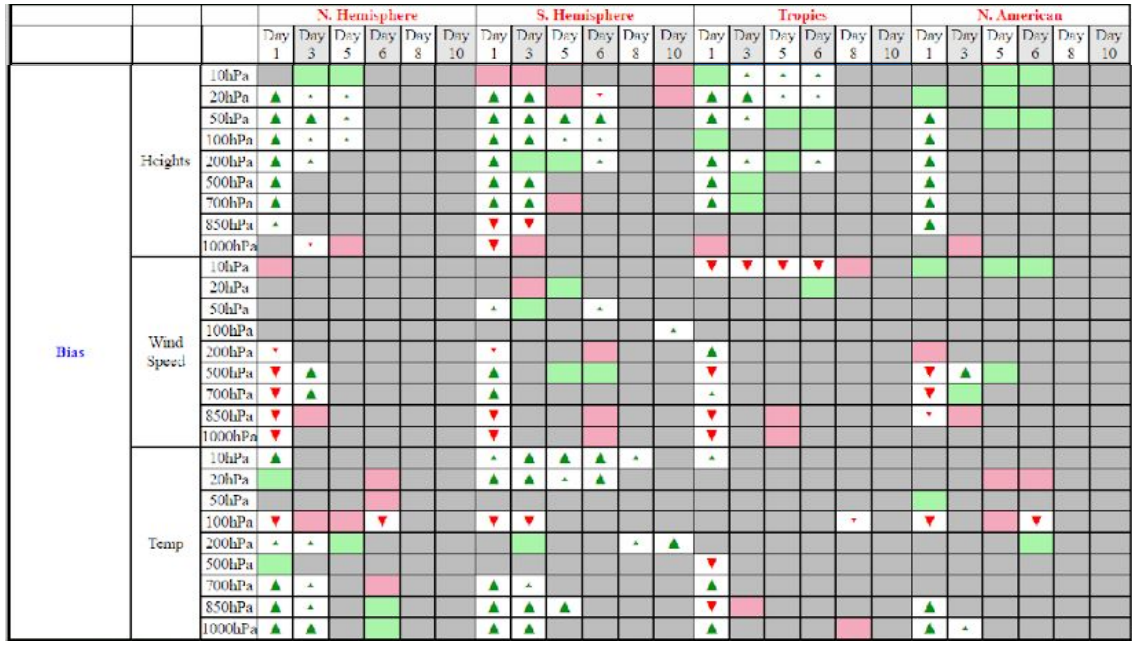




- Slightly larger bias in temperature below 500 hPa; Less bias in relative humidity from 900 to 150 hPa
- Slightly smaller RMSE in wind above 300 hPa; Smaller RMSE in RH at 250 hPa

Scorecard: Fit to ECMWF Analysis





EMC Verification Scorecard
Symbol Legend
▲ V16_DO4 is better than V16_CTL at the 99.9% significance level
▵ V16_DO4 is better than V16_CTL at the 99% significance level
V16_DO4 is better than V16_CTL at the 95% significance level
No statistically significant difference between V16_DO4 and V16_CTL
V16_DO4 is worse than V16_CTL at the 95% significance level
▿ V16_DO4 is worse than V16_CTL at the 99% significance level
▼ V16_DO4 is worse than V16_CTL at the 99.9% significance level
Not statistically relevant
Start Date: 20220324
End Date: 20220424

- **Green: Degradation**
- **Red: Improvement**

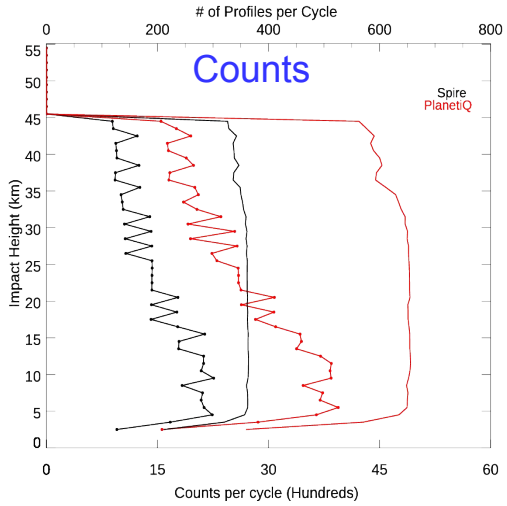
Mostly neutral

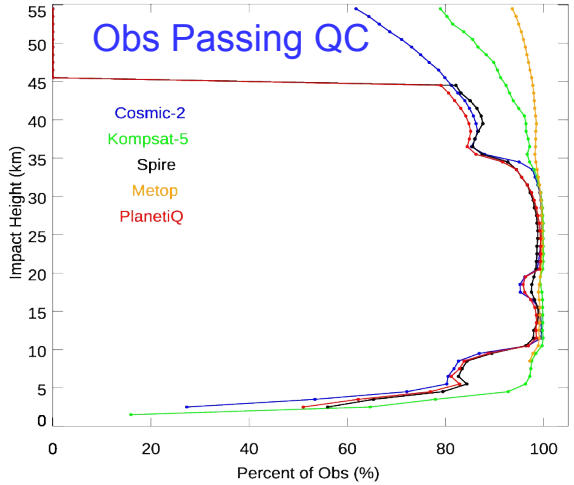
Improvement: AC for HGT, wind, and T in SH; RMSE for wind and T in SH; RMSE for wind and T in Tropics.

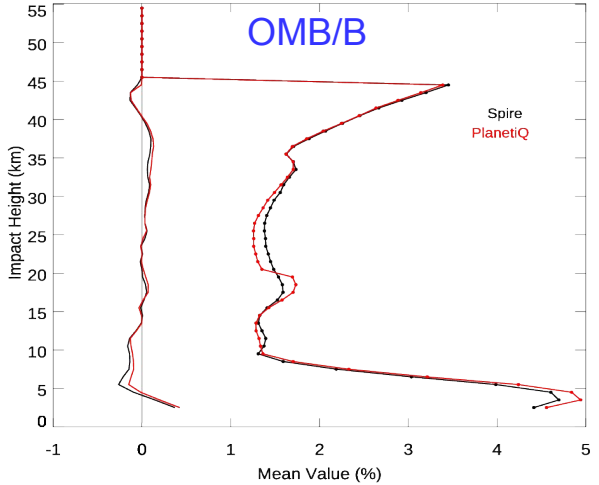
Degradation: Height bias in NH, SH, and tropics; T bias at low troposphere in NH and SH.

ROBD-2 DO-2 PlanetiQ Verification Experiment

- **RODB-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						M
		500hPa						M						M						M						M
		700hPa						M						M						M						M
		1000hPa						M						M						M						M
	Vector Wind	250hPa						M						M						M						M
		500hPa						M						M						M						M
		850hPa						M						M						M						M
	Temp	250hPa						M						M						M						M
		500hPa						M						M	▲					M						M
		850hPa						M						M						M						M
	MSLP	MSL						M						M						M						M
RMSE	Heights	10hPa						M						M						M						M
		20hPa						M						M						M						M
		50hPa						M						M						M	▾					M
		100hPa						M						M						M						M
		200hPa						M						M	▲					M						M
		500hPa						M						M						M						M
		700hPa						M						M						M						M
		850hPa	▾					M						M						M						M
		1000hPa						M						M						M						M
	Vector Wind	10hPa						M						M						M						M
		20hPa						M						M	▲	▵				M	▾		▼			M
		50hPa	▲	▵	▲			M	▲	▲	▲			M	▲	▲				M						M
		100hPa						M						M	▲	▲				M						M
		200hPa						M						M						M						M
		500hPa						M						M						M		▲	▲			M
		700hPa						M						M						M						M
		850hPa						M						M						M			▲			M
		1000hPa						M						M						M						M
	Temp	10hPa						M						M						M	▾	▾			▾	M
		20hPa		▵		▵		M	▵	▵				M	▵	▵				M						M
		50hPa	▲	▵	▲	▵		M	▲	▲	▲	▵		M	▲	▲				M						M
		100hPa						M						M	▲	▲				M						M
		200hPa						M						M						M						M
		500hPa						M						M	▲					M		▲				M
		700hPa						M						M						M						M
		850hPa						M						M						M						M
		1000hPa						M						M						M						M

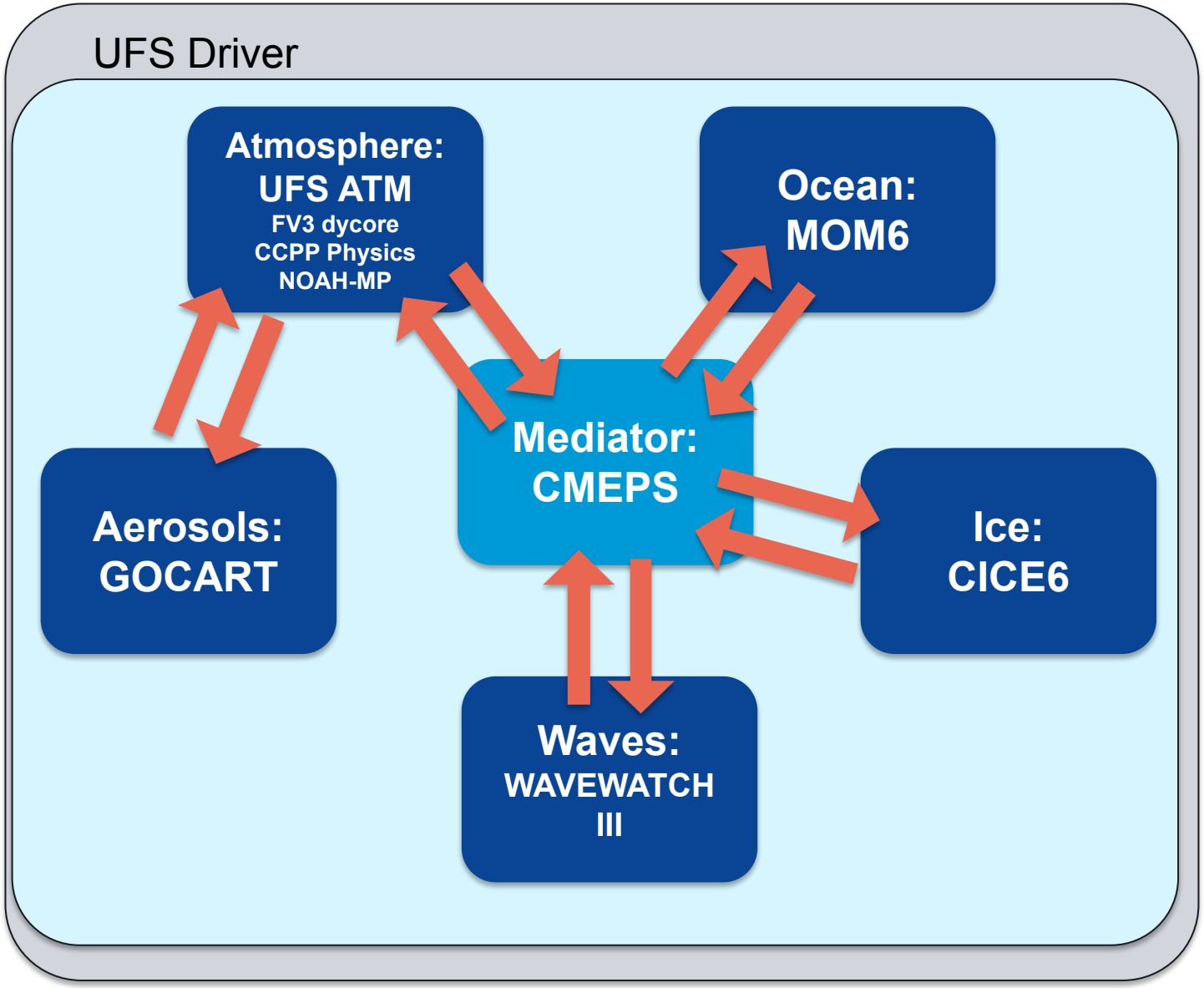
Scorecard Symbol Legend			
▲	v1637piq is better than gfs at the 99.9% significance level	▼	v1637piq is worse than gfs at the 99.9% significance level
▵	v1637piq is better than gfs at the 99% significance level	▾	v1637piq is worse than gfs at the 99% significance level
	v1637piq is better than gfs at 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			

			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						M
		20hPa						M						M						M						M
		50hPa						M						M	▼			▾		M						M
		100hPa						M						M	▾					M						M
		200hPa	▾					M						M	▼					M						M
		500hPa						M						M						M		▵				M
		700hPa						M						M						M						M
		850hPa						M						M						M		▾				M
		1000hPa						M						M						M		▼				M
	Wind Speed	10hPa						M						M						M						M
		20hPa						M						M						M						M
		50hPa						M						M						M						M
		100hPa						M						M						M						M
		200hPa						M						M						M						M
		500hPa						M						M						M						M
		700hPa						M						M						M						M
		850hPa						M						M						M						M
		1000hPa						M						M						M						M
	Temp	10hPa						M						M						M						M
		20hPa						M						M						M						M
		50hPa						M						M						M						M
		100hPa						M						M						M						M
		200hPa						M						M						M	▾					M
		500hPa						M						M						M		▲				M
		700hPa						M						M						M						M
		850hPa						M						M	▾					M	▾	▾	▾	▾		M
		1000hPa						M						M	▾					M						M

- **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

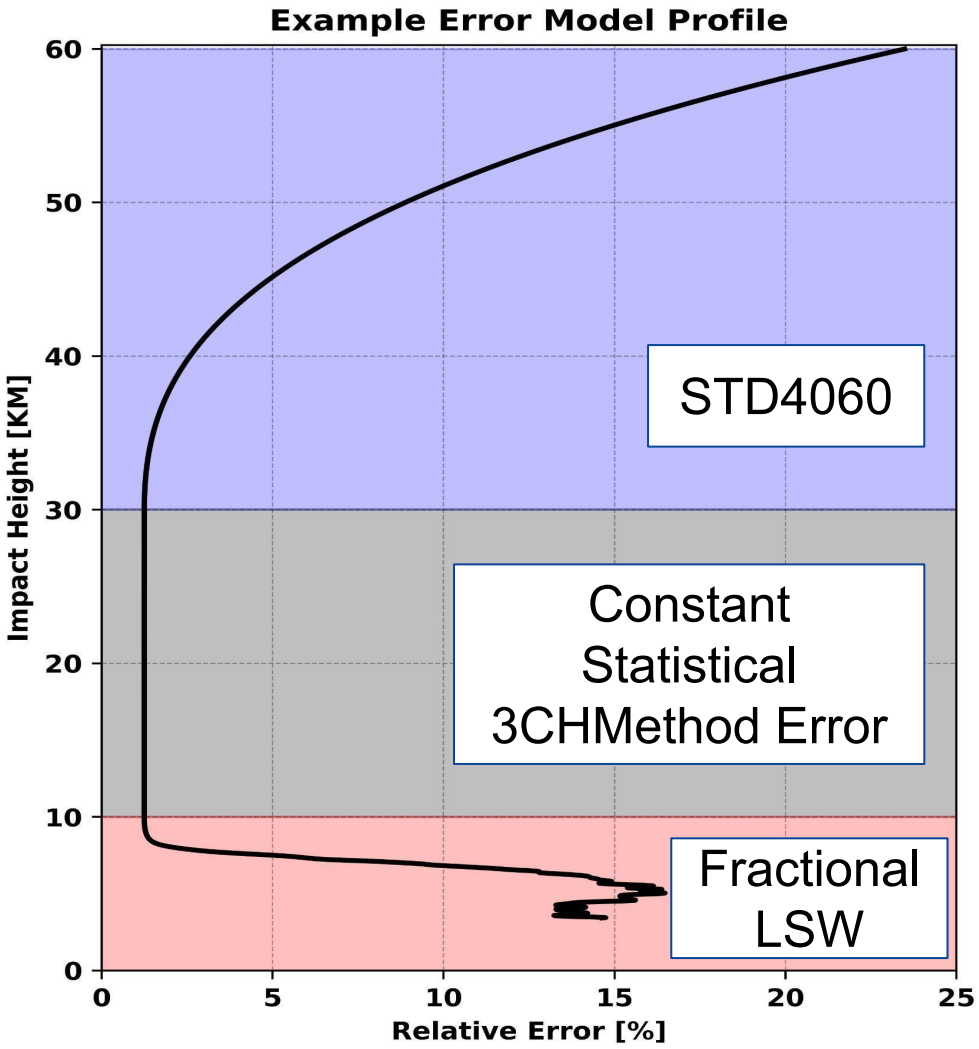
GFSv17 Overview

- 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



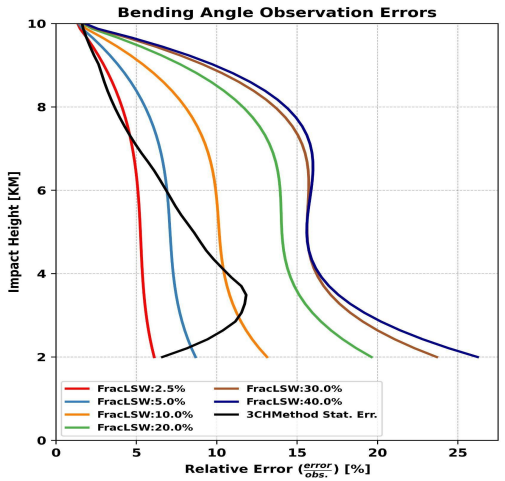
New Hybrid Obs Error Model

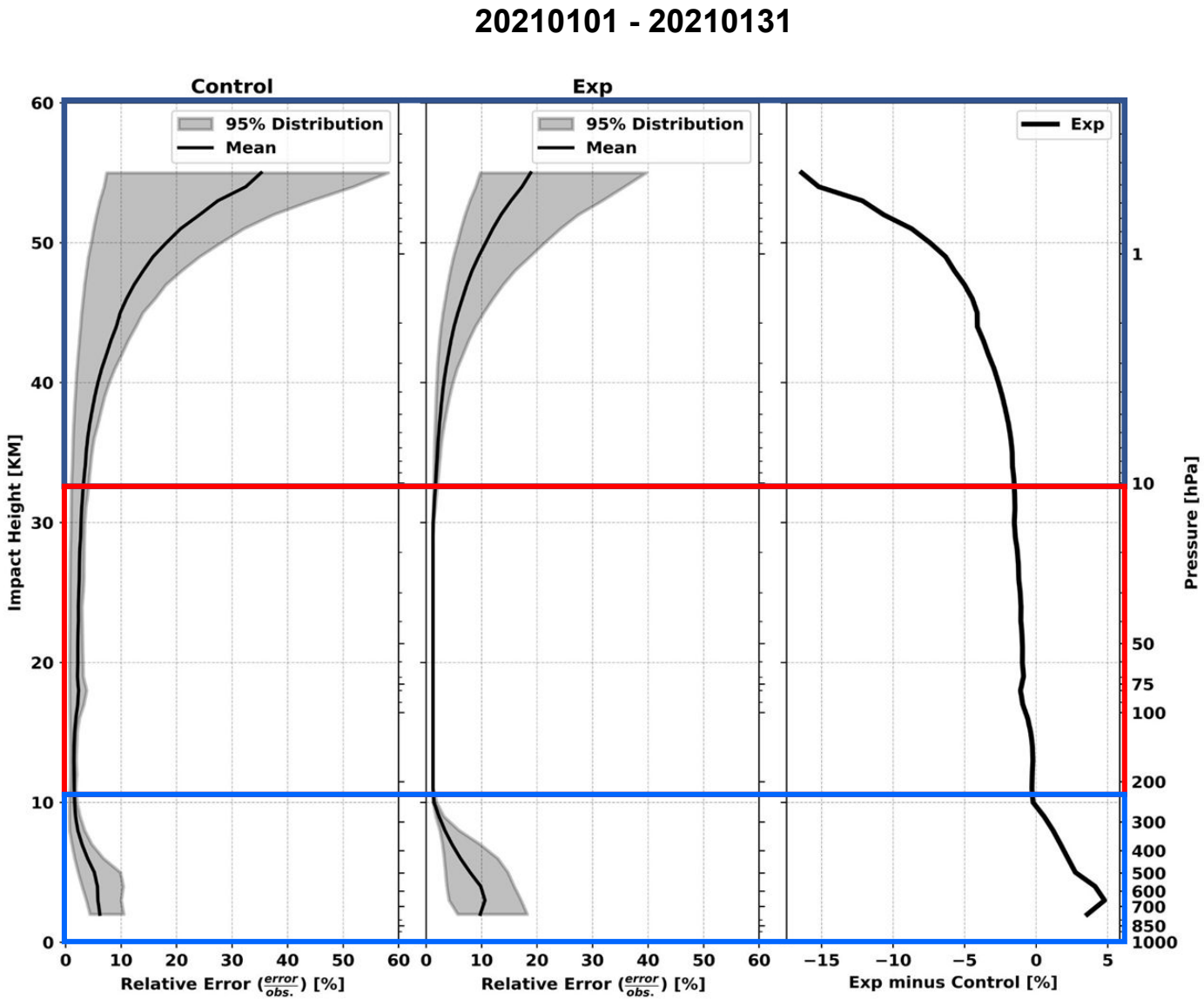
- Error model is defined in 3 vertical regions
- STD4060 => Blue Region (30-60 km)
  - Standard deviation between observation values and an exponential fit for impact heights between 40-60 KM
- Constant Statistical 3CHMethod Error => Grey Region (10-30 km)
  - Relative error of 1.25%
- Fractional LSW => 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

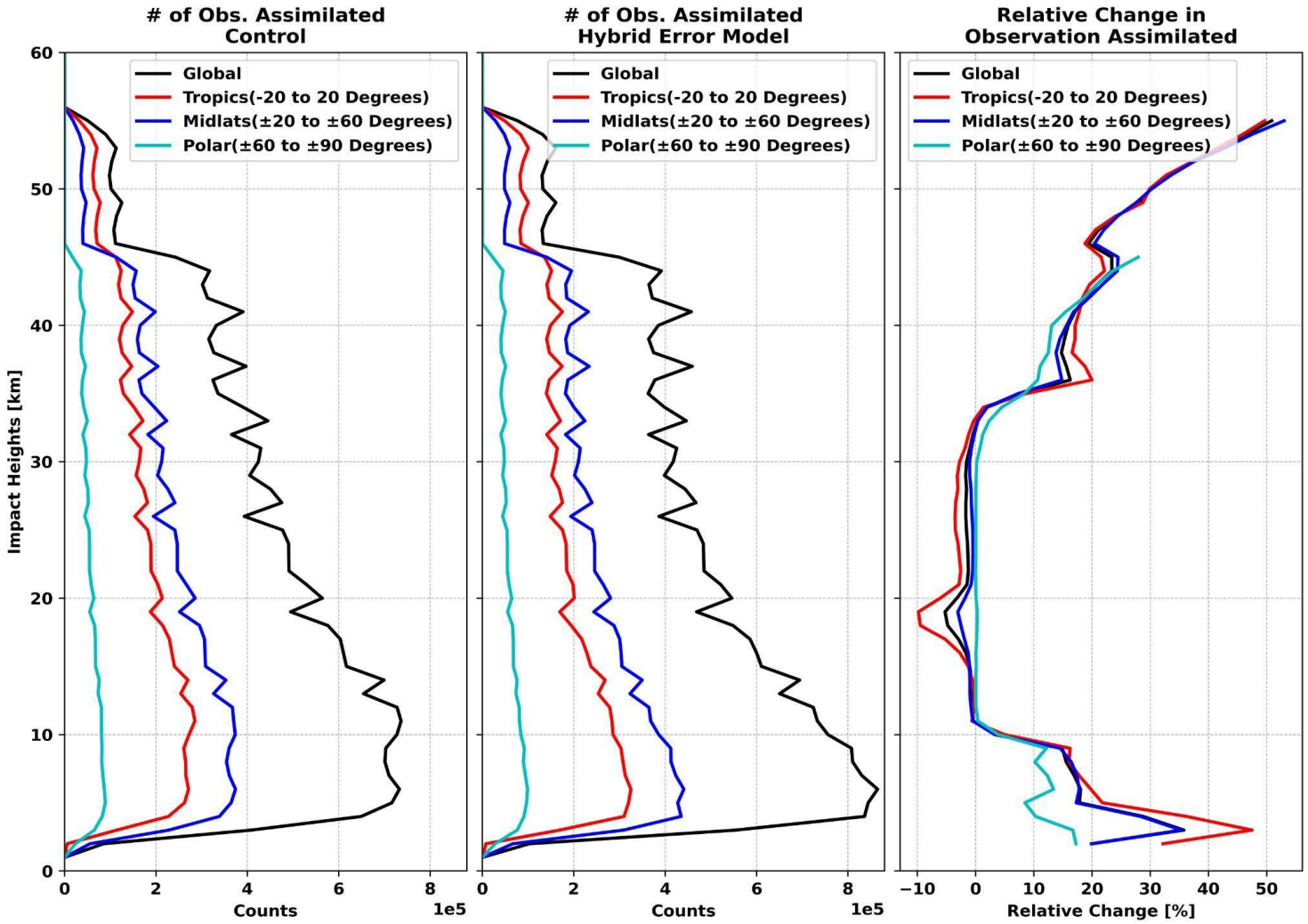




New QC

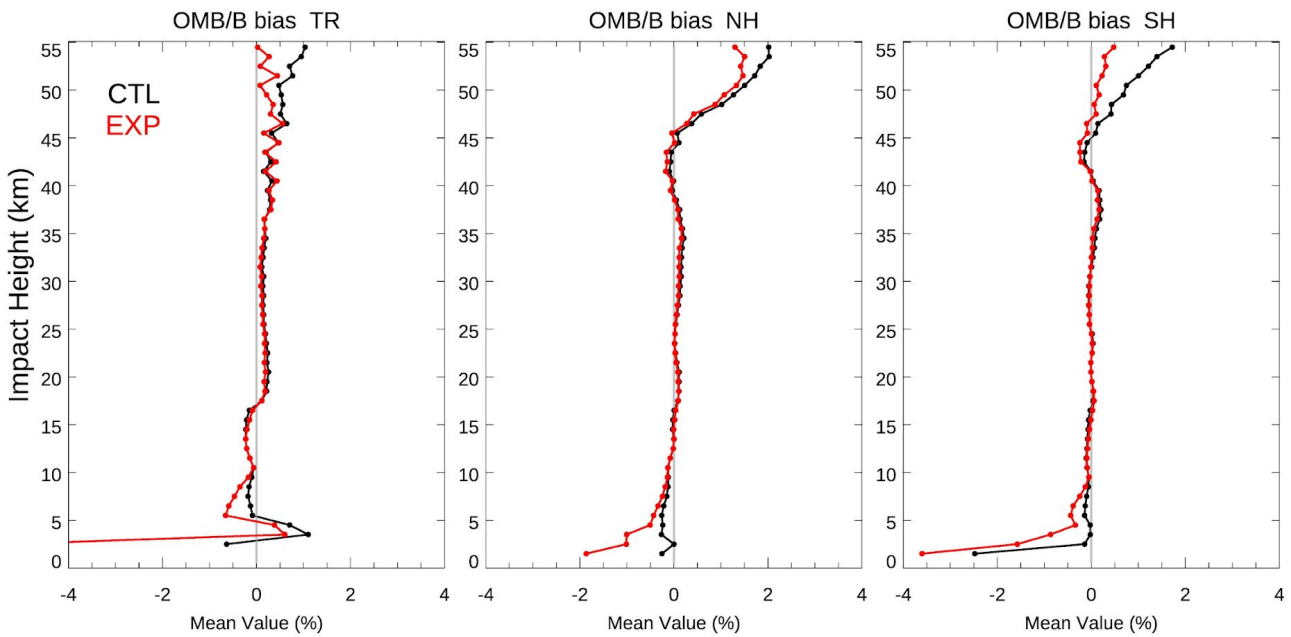
- New QC:
  - (O-B)/B > 3σ (σ is the 3CH global statistical uncertainty
  - May eliminate too many observations between 10-30 km.
- Increase in the number of assimilated observation > 30 km and < 10 km
- Tropics: largest reduction between 15-30 km. Large increase < 5 km.
- 10-30 km: Reduction of 2-10%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

20210101 - 20210131

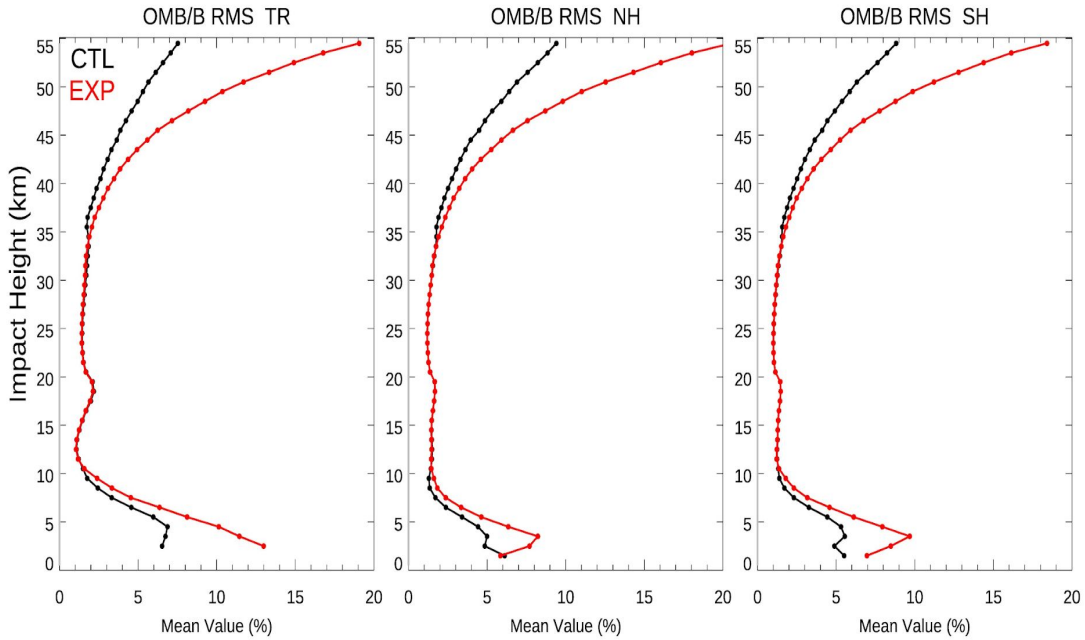


v17 Testing

Forecast Bias



Forecast RMS

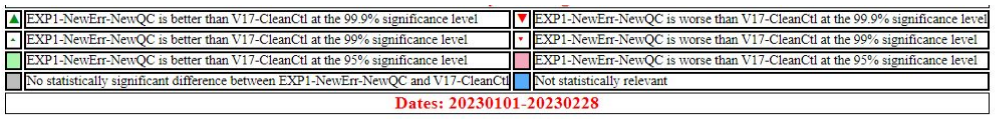


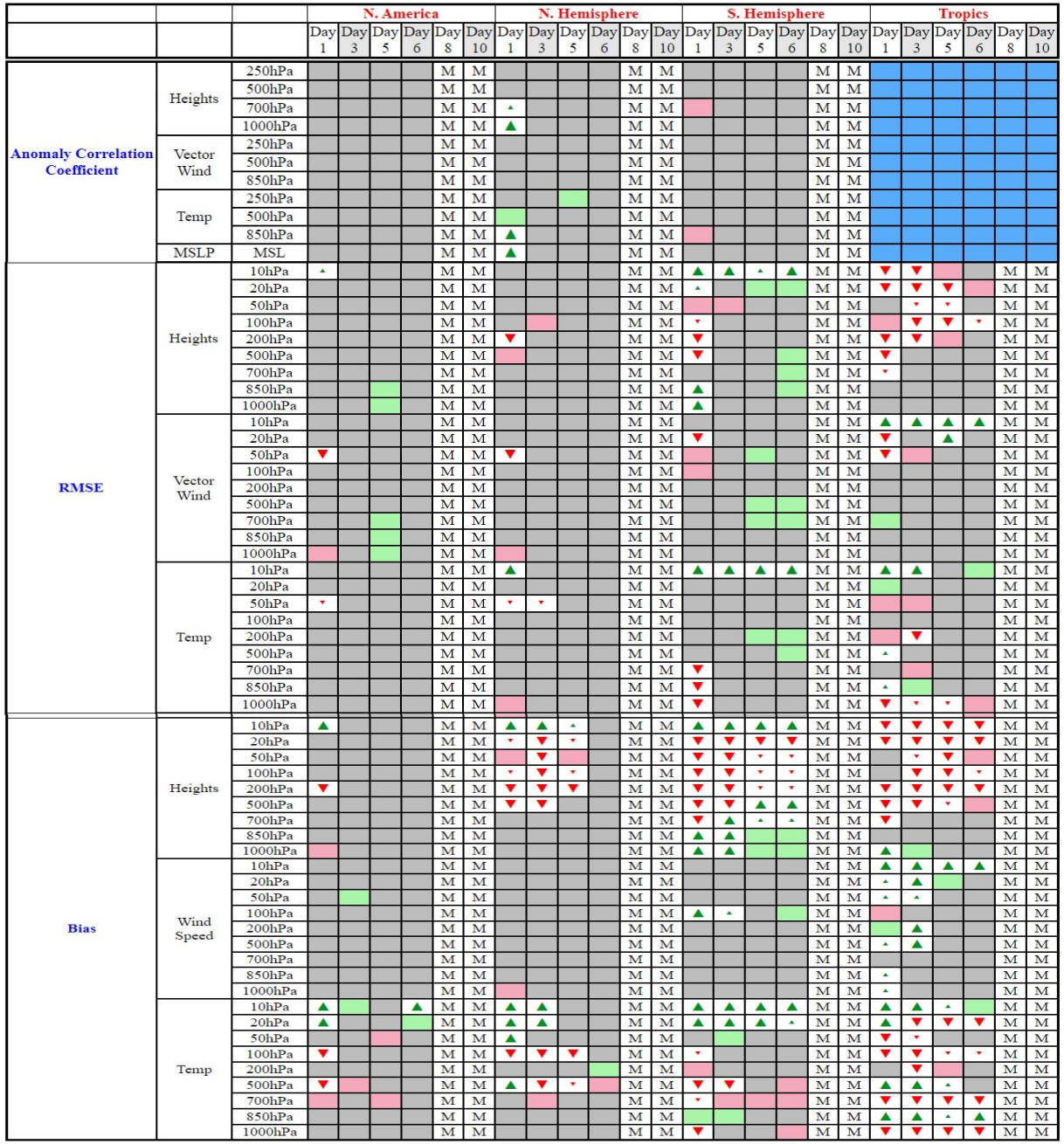
20230101 - 20230228

- 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





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