Recent Progress in GNSS RO Data Assimilation in NCEP GFS

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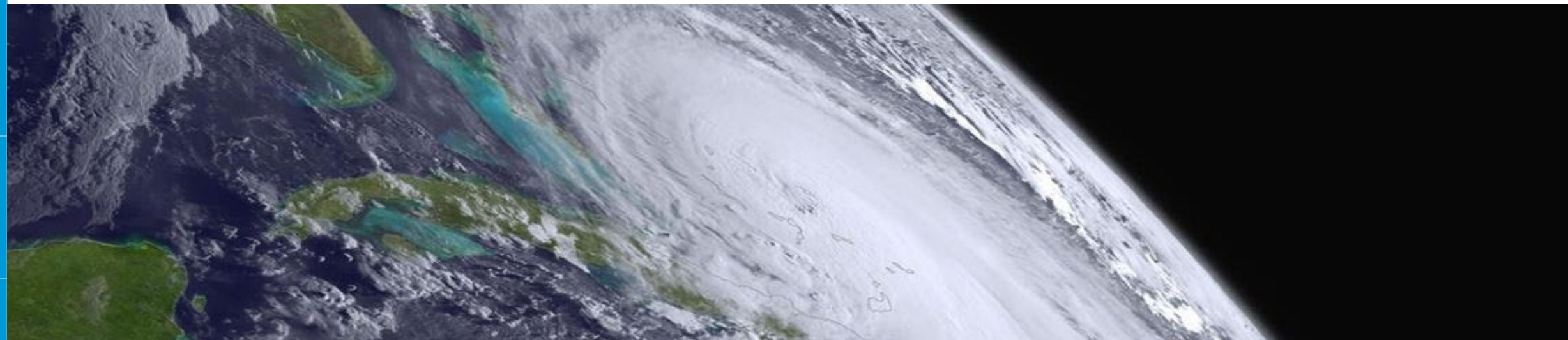
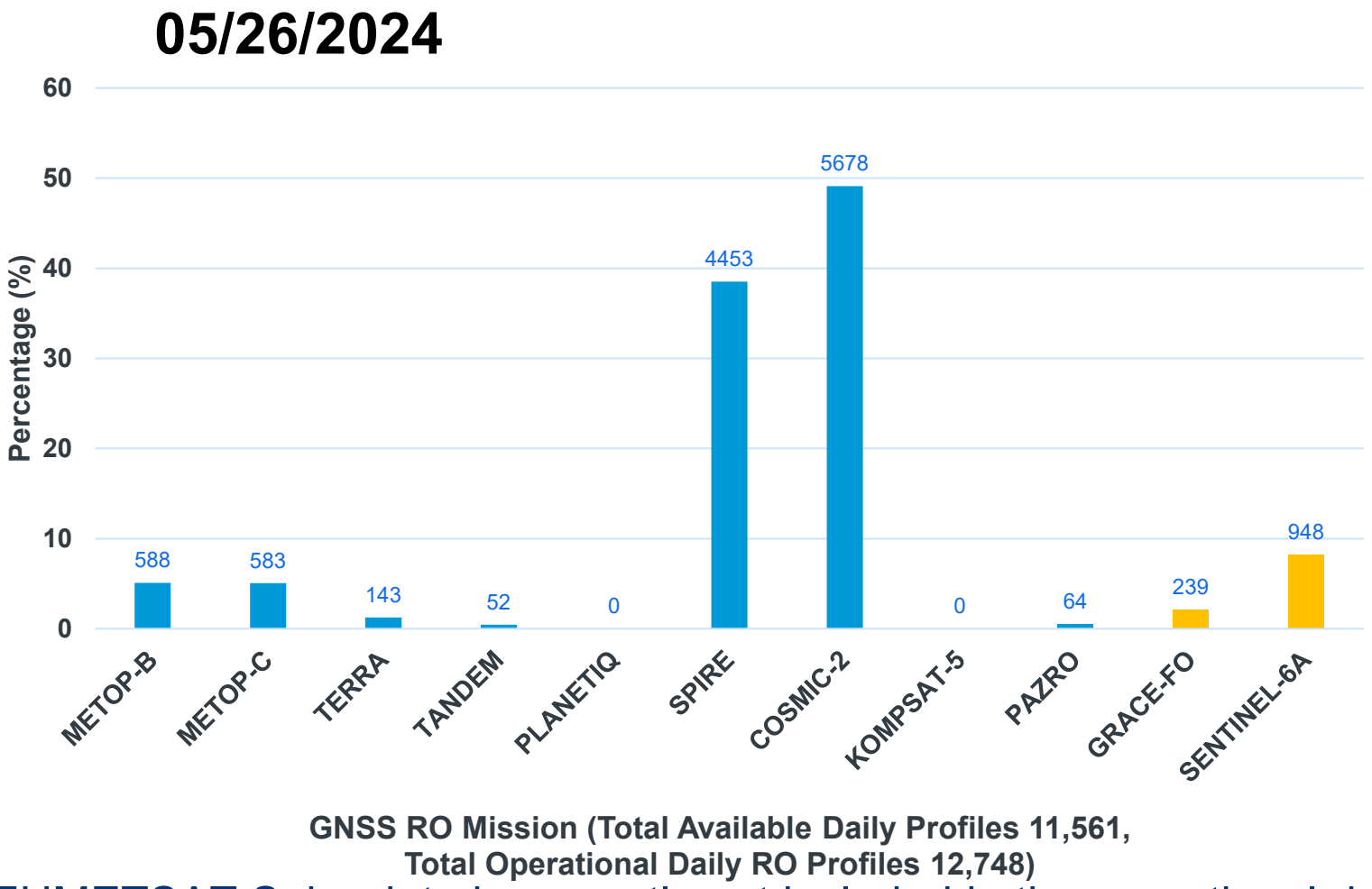
8th ROM SAF Workshop
June 11-13, 2024



Outline

- Impact of commercial RO data
- GFSv17 overview and preliminary result from ROMEX
- RO optimization
- Future directions

Daily GNSS RO Count in NCEP Operational Data



- EUMETSAT Spire data is currently not included in the operational dump, but will resume soon

CWDP and CDP

- In 2017, Taiwan and the U.S. decided not to proceed with the high-inclination polar orbit component of COSMIC-2
- Commercial Weather Data Pilot (CWDP) program: To assess the potential viability of commercial weather data in NOAA's weather modeling and forecasting
- CWDP Round 1 in 2016-2017:
  - Bring radio occultation data from commercial companies to NOAA
  - Awarded to GeoOptics, Inc. and Spire Global, Inc.
  - Focus: Provide space-based GNSS RO data, to demonstrate data quality and potential value to NOAA's weather forecasts and warnings.
- CWDP Round 2 in 2018:
  - Awarded to GeoOptics, Inc., Spire Global, Inc., and Space Sciences and Engineering LLC
  - Results: Commercial sector capable of providing RO data supporting NOAA's operational products and services.
- CDP Radio Occultation Data Buy (RODB) contracts:
  - RODB-1: Awarded to GeoOptics, Inc., and Spire Global with a series of delivery orders (DOs) in 2020-2023
  - RODB-2: Awarded to Spire Global and PlanetiQ in 2023 with a 5-year ordering period

Commercial RO Data

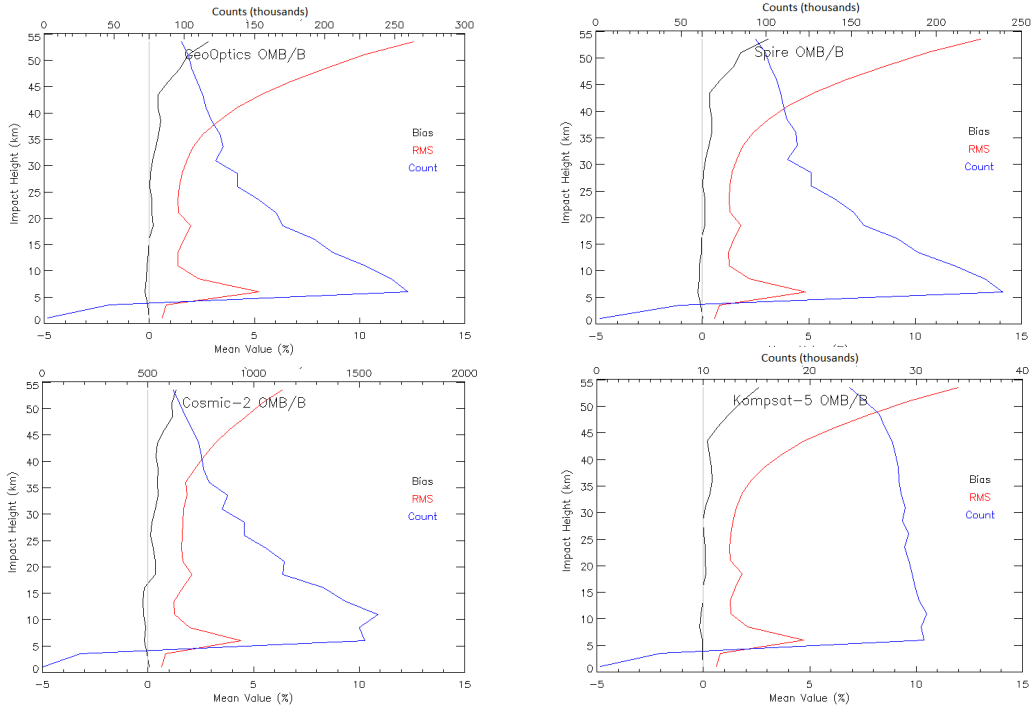
- NOAA NESDIS CDP Radio Occultation Data Buy (RODB) contracts:
  - **RODB-1:** Awarded to GeoOptics and Spire with a series of delivery orders (DOs) in 2020-2023
  - **RODB-2:** Awarded to Spire and PlanetiQ in 2023 with a 5-year ordering period

Delivery Order	Vendors	Period of Performance
DO-1	GeoOptics 500 Profiles/day Spire 500 Profiles/day	Dec 2020 - Jan 2021
DO-2	GeoOptics 1,300 Profiles/day	Mar – Sept 2021 (**Implemented May 2021**)
DO-3	Spire 3,000 Profiles/day	Sept 2021 – Mar 2022 (**Implemented September 2021**)
DO-4	GeoOptics 500 Profiles/day Spire 5,500 Profiles/day	Mar 2022 – Jan 2023
DO-5	Spire 3,100 Profiles/day EUMETSAT Spire 1,600 Profiles/day	Jan – July 2023

Findings from RODB-1 DO-1 to DO-2

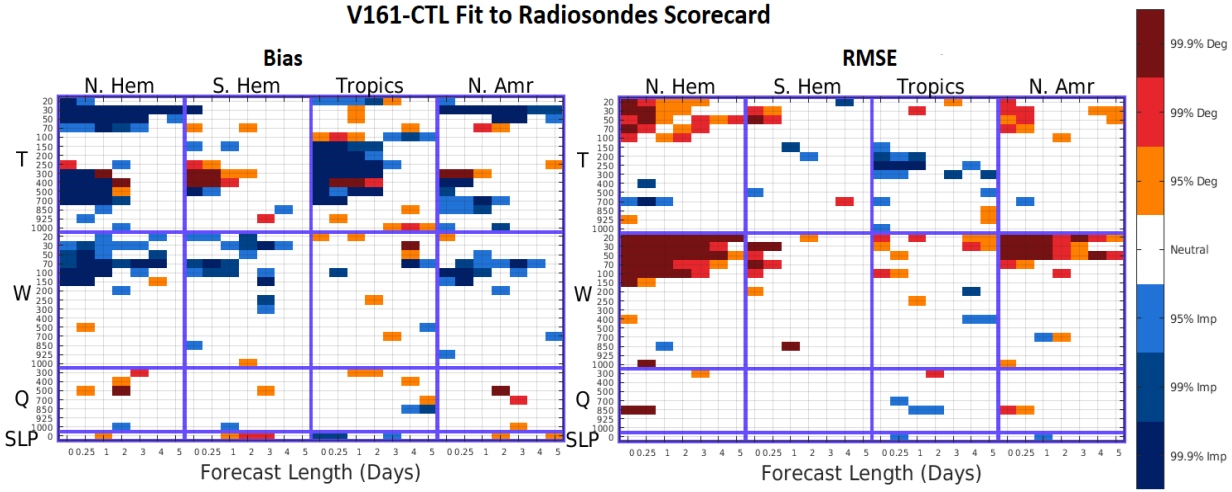
DO-1:

- Neutral to negative forecast impact
- Similar quality and error characteristics as other non-commercial operational RO data
- Improvements in fits to temperature, but degradation in the upper layers



DO-2:

- Cutoff height: 45 km
- Data impact is statistically neutral
- Degradation in upper layer wind and temperature RMSE
- Improvement in temperature bias and tropical tropospheric temperature RMSE

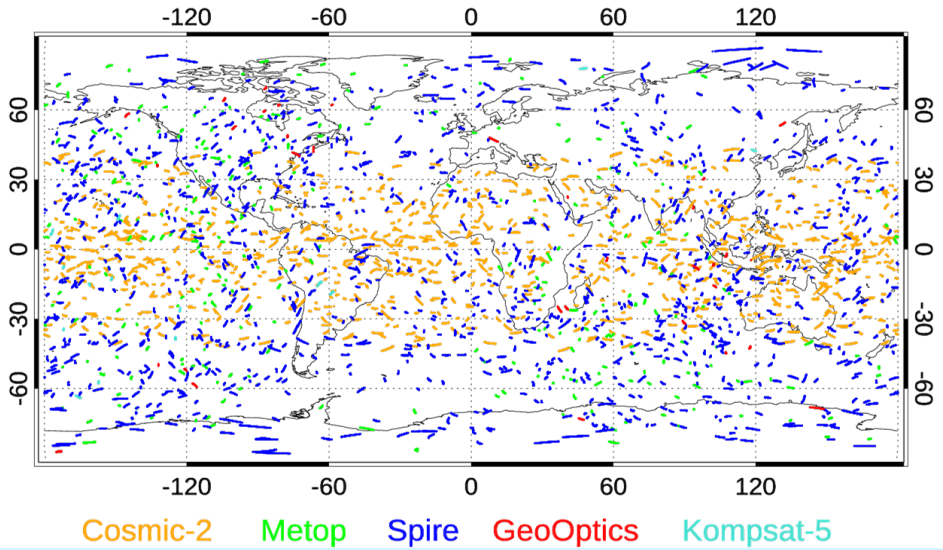


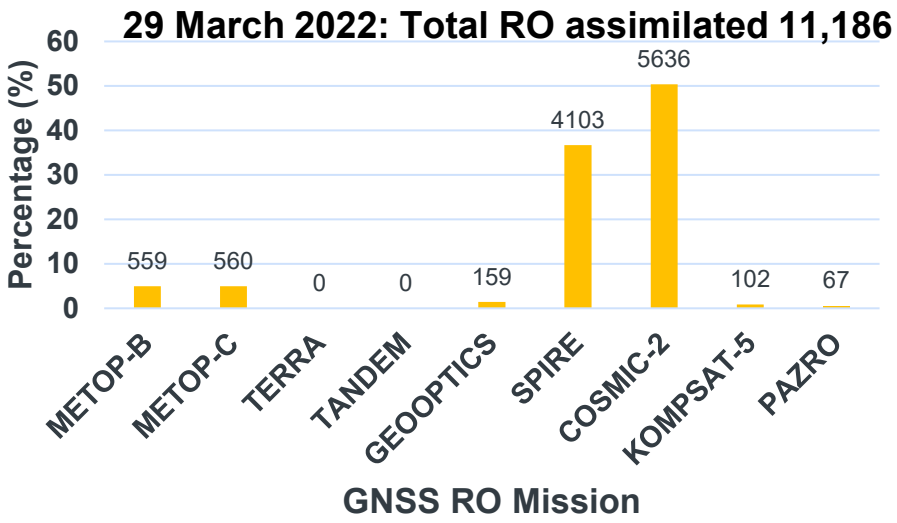
Red: Degradation

Blue: Improvement

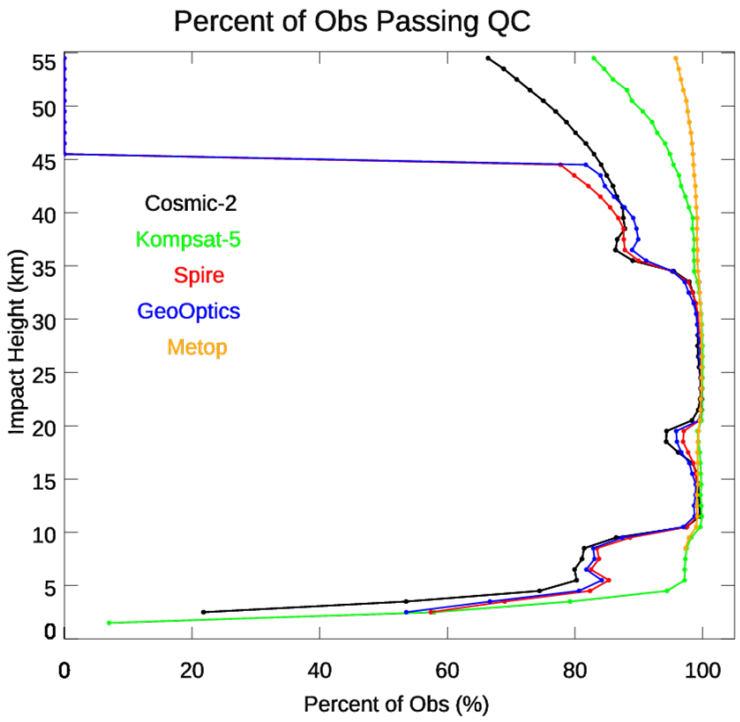
DO-3 and DO-4 Assessment

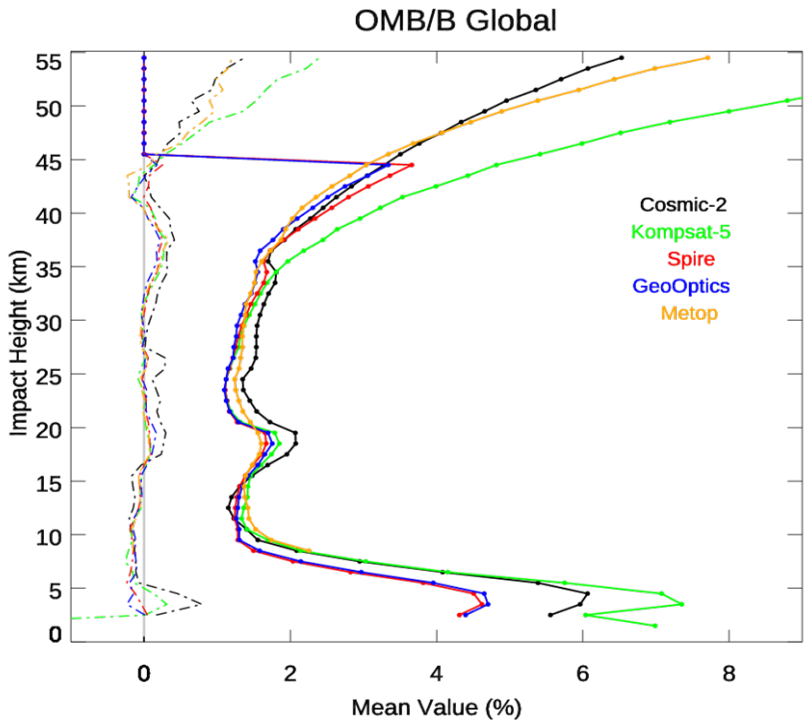
- **DO-3:** Applied more strict statistical QC: O-B/Err cutoff threshold values were reduced by 1/2 at all vertical levels, except for 11-34 km; Addressed two issues within the RO bending angle observation operator
- **DO-4 Data Denial Experiment:** 24 March – 24 April 2022
  - **v16_ctl**: Control run **with** DO-4 data
  - **v16_do4**: Data denial experiment **without** DO-4 data
- **Configuration:** Global parallel experiments GFS v16.1.6, 80 ensemble members, C384 (25 km) resolution





Data Quality – DO-4



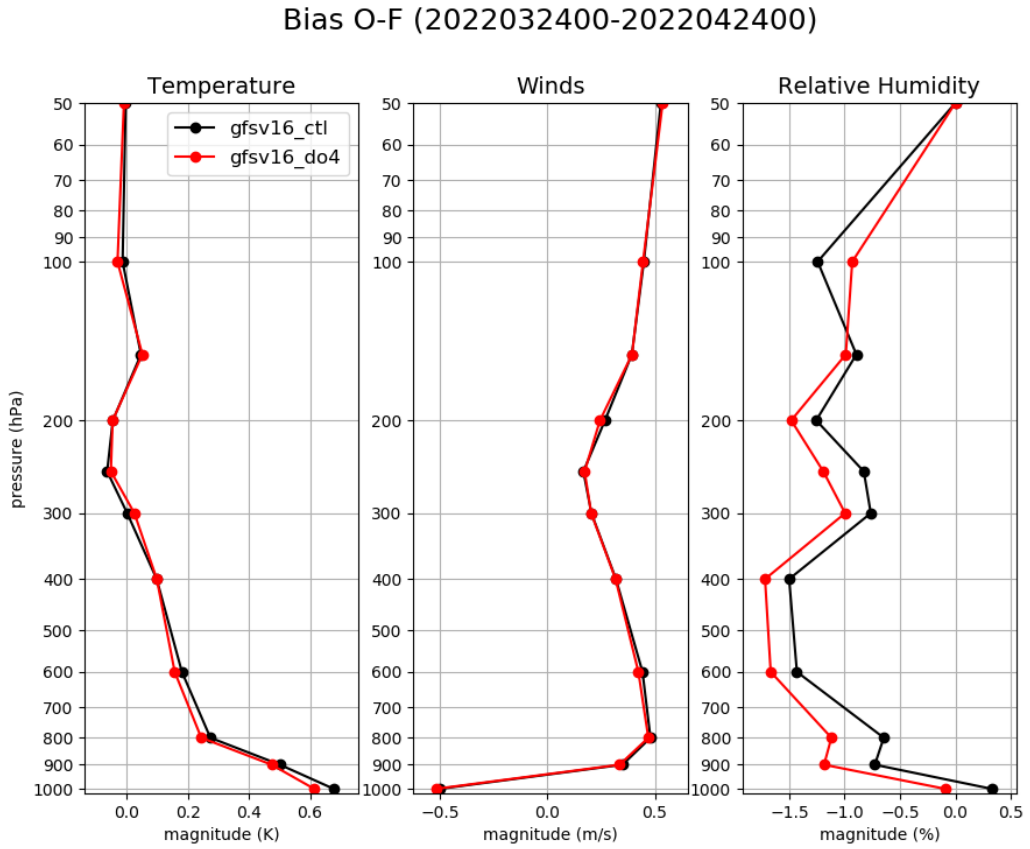


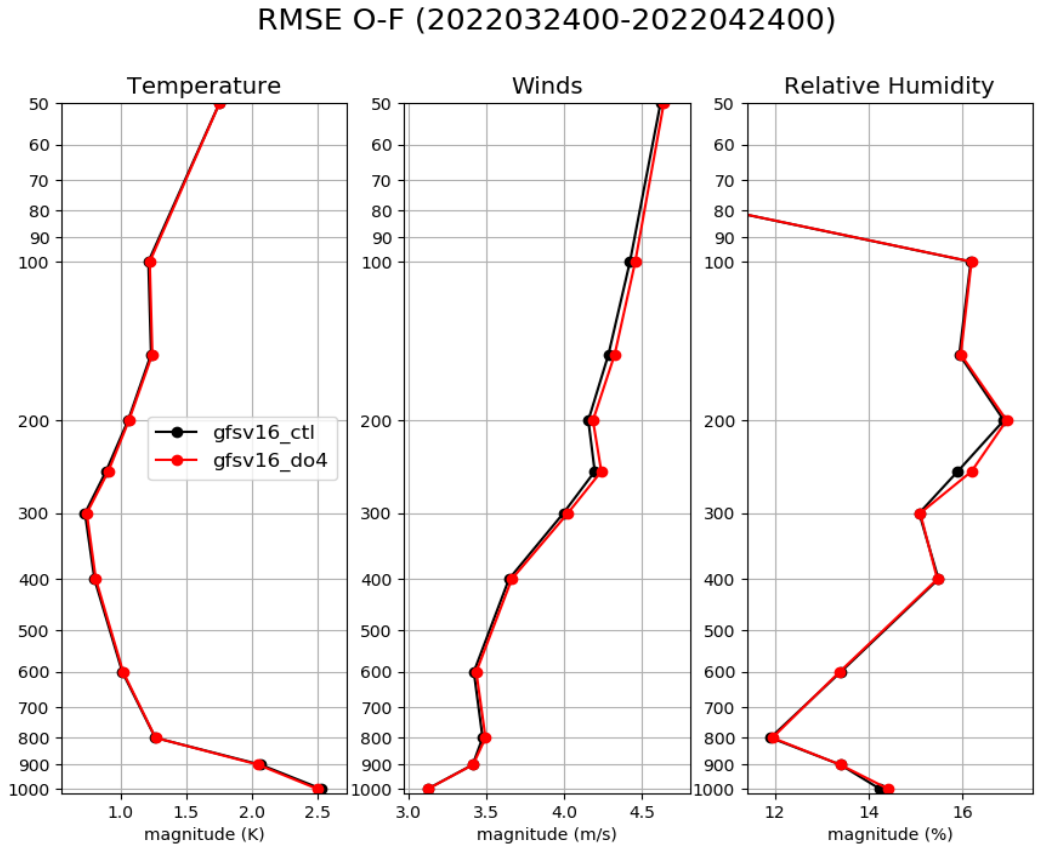
- O-B/O Statistic QC: 2D polynomial function of latitude and impact height
- Stricter statistic QC for COSMIC-2 and commercial RO data utilizing smaller O-B/O threshold values results in a lower percentage of obs passing QC below 10 km and above 35 km
- Commercial data: Rejected above 45-km impact height

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

			N. Hemisphere						S. Hemisphere						Tropics						N. American					
			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	Heights	250hPa							▼																	
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	Vector Wind	250hPa							▼																	
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RMSE	Heights	10hPa								▼					▲	▲	▵	▵								
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			N. Hemisphere						S. Hemisphere						Tropics						N. American					
			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
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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**

Improvement in SH: AC for HGT, wind, and T; RMSE for wind, T, and low level HGT; Bias for low level HGT and WSPD. **Degradation in SH:** bias for HGT and T.

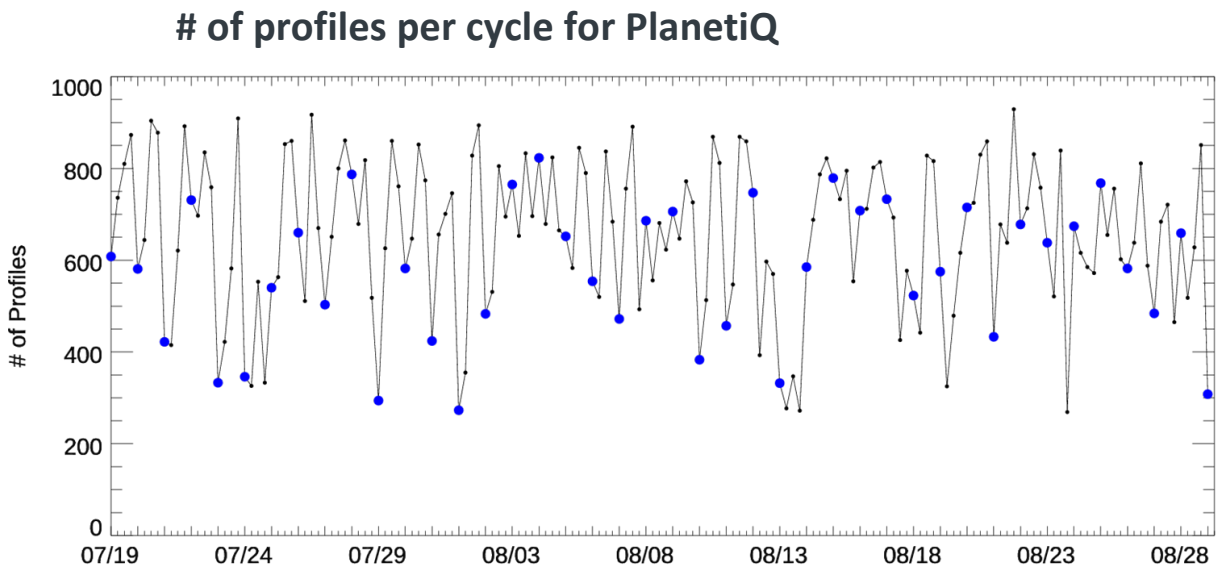
Improvement in NH: AC for mid-level wind and T; RMSE for wind and T; Bias for mid to low level wind. **Degradation in NH:** RMSE for upper level HGT; Bias for HGT and low level T.

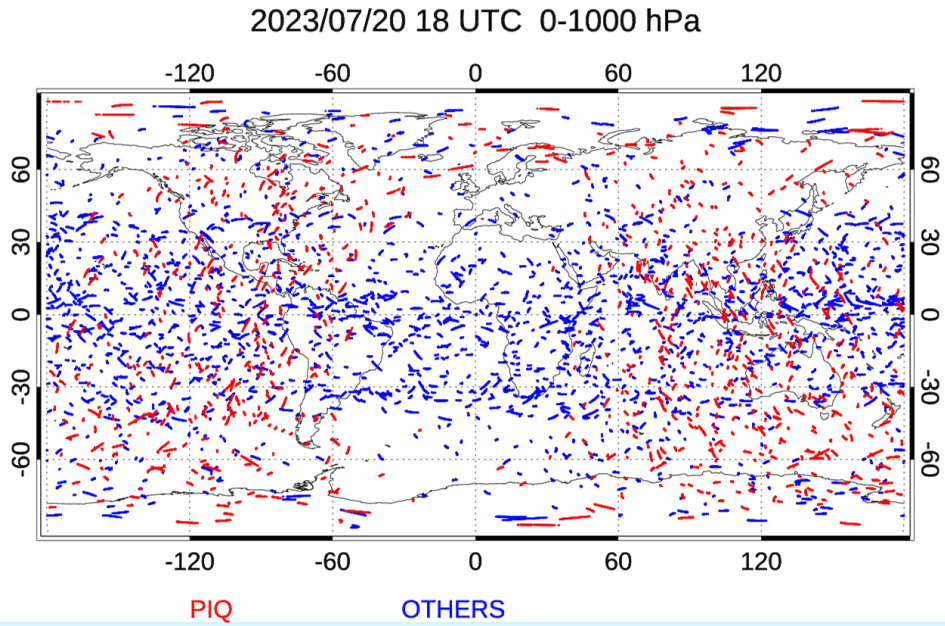
ROBD-2

Delivery Order	Vendors	Period of Performance
DO-1T	PlanetiQ 500 Profiles/day Spire 500 Profiles/day	Apr - May 2023
DO-2	PlanetiQ 3,100 Profiles/day	July 2023 – Jan 2024 (**Implemented Sept 2023**)
DO-3	Spire ~~6,000~~ 3,000 Profiles/day	Jan – Sept 2024

PlanetiQ Verification Experiment

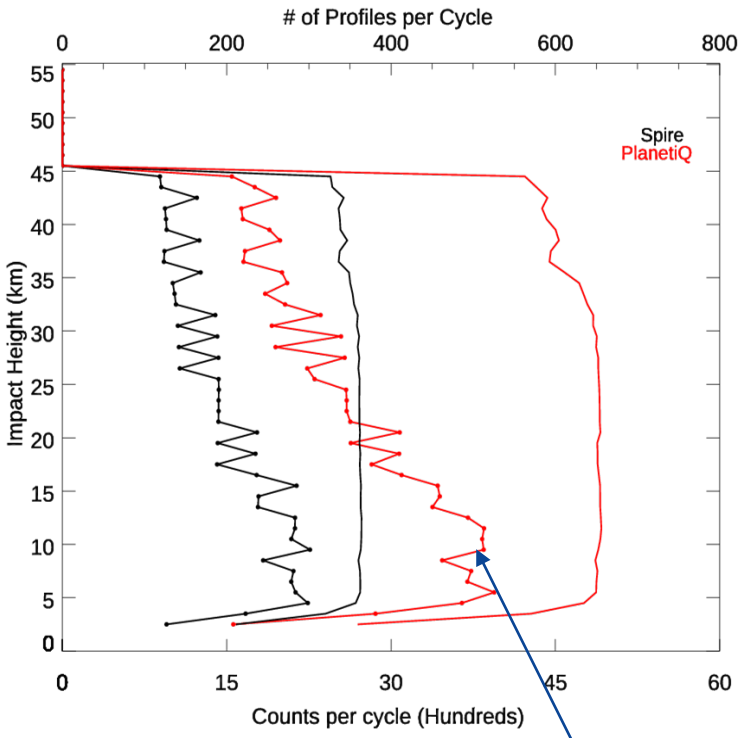
- Global workflow v16.3.7; 80 ensemble members; C768 (13 km) resolution
- Verification Time Period: 19 July – 29 August 2023
- **gfs:** Operational run without PlanetiQ data
- **v1637piq:** Experiment with operational RO data + PlanetiQ data (~650 profiles/cycle)



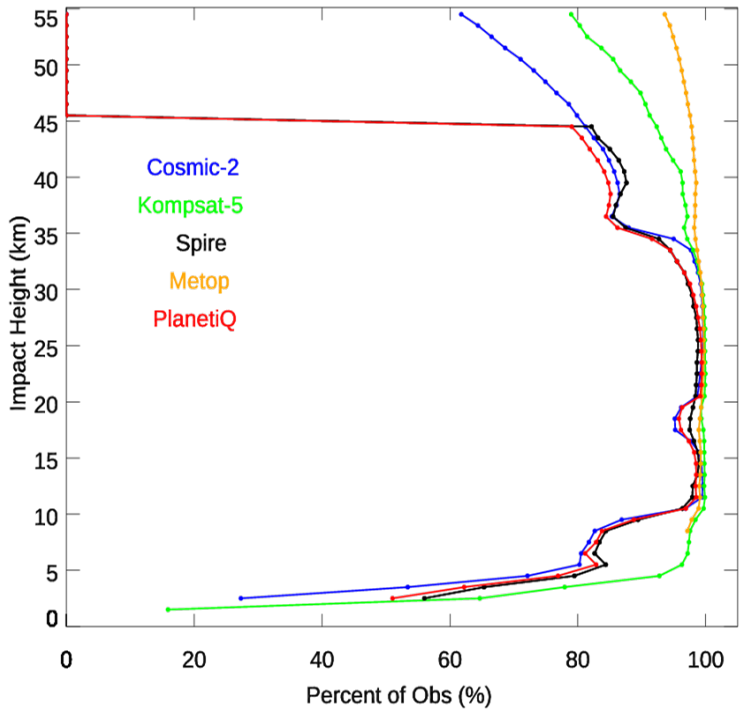


RODB-2 DO-2 PlanetiQ vs. EUMETSAT Spire

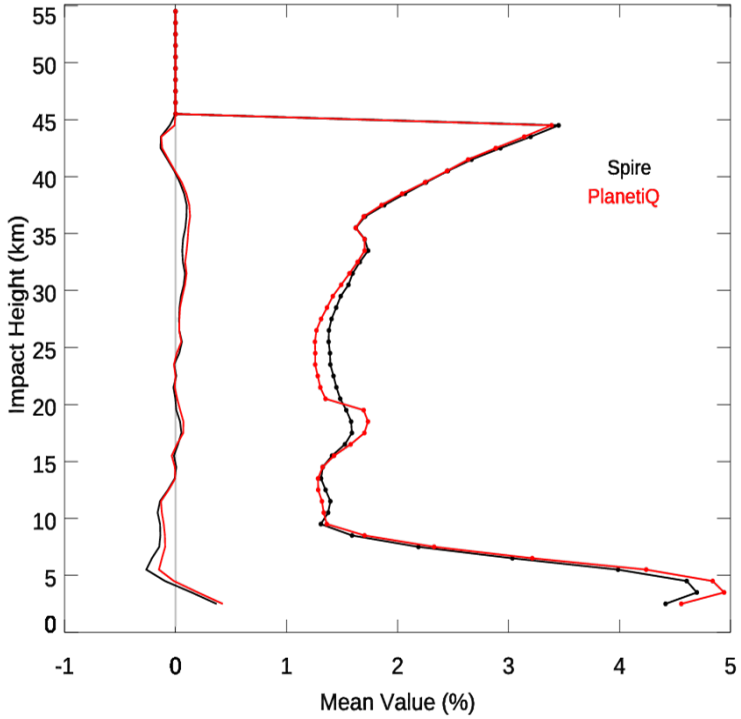
Count and # of Profiles



Obs Passed QC



Bias and RMS of OMB/B



PlanetiQ was roughly twice
the amount of EUMETSAT Spire

- 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
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		850hPa						M						M						M						M
	MSLP	MSL						M						M						M						M
RMSE	Heights	10hPa						M						M						M						M
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		100hPa						M						M						M						M
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	Vector Wind	10hPa						M						M						M						M
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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
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		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
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- **Green: Improvement** **Red: Degradation**
- Neutral to slightly positive impact
- Positive impact was found in RMSE for both wind and temperature near 50 hPa and low level T
- Less significant impact when compared to DO-4, partly due to smaller data volume

Global Data Assimilation System

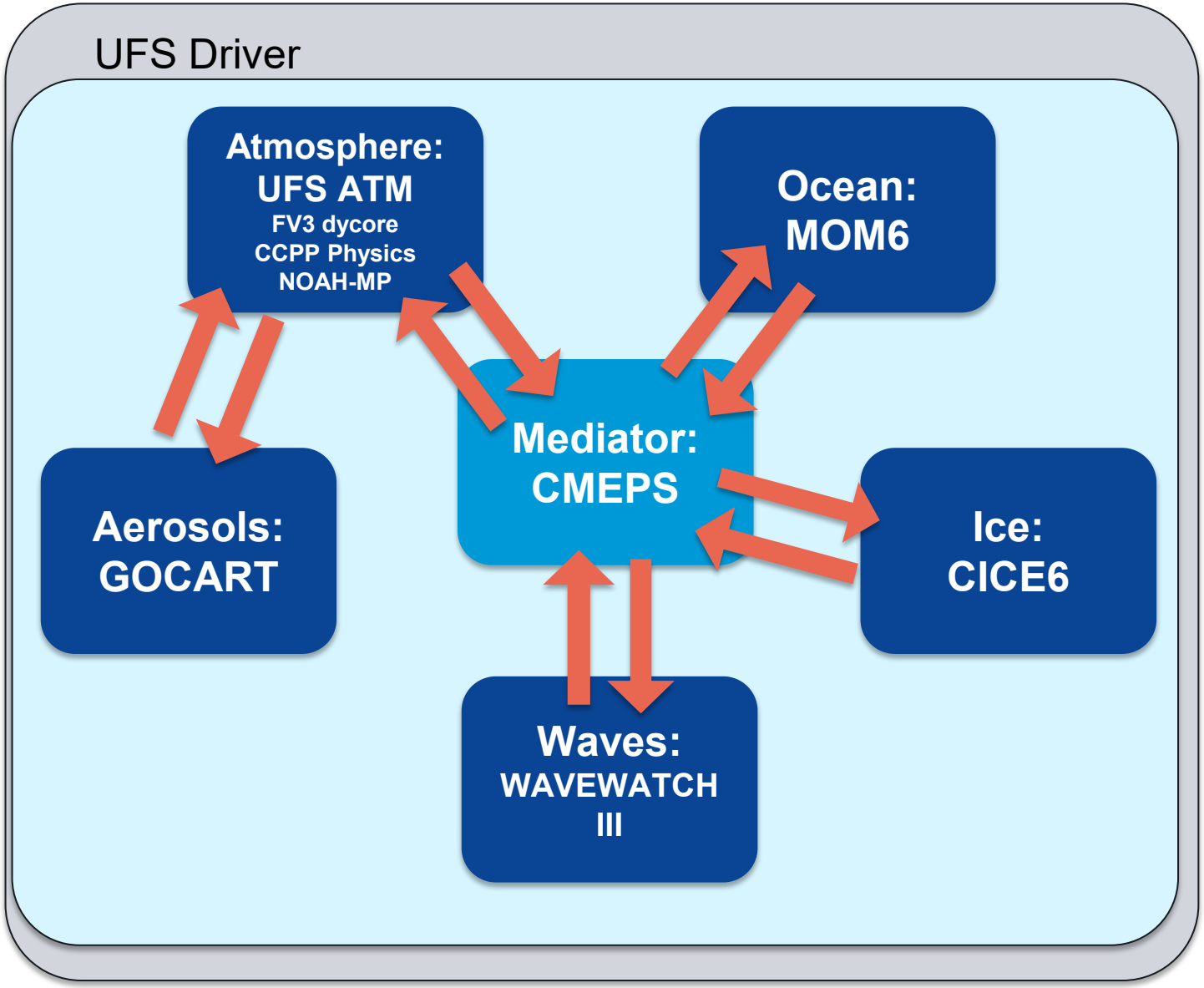
- **Current major version (v16) operational since March 2021**
  - Most notable change to L127 from L64
  - EnSRF to LETKF for ensemble update
  - 4D Incremental Analysis Update
- **Gridpoint Statistical Interpolation (GSI) based hybrid 4D-EnVar system**
  - GSI used for GDAS since 2007
  - ~25 km analysis for ~13km forecast
- **Numerous types of observations assimilated including:**
  - satellite radiances (using CRTM)
    - numerous platforms/instruments/channels
  - satellite-based ozone and winds
  - radiosondes
  - aircraft-based observations
  - surface station pressure
  - GNSS-RO

GFSv17

- **Coupled forecast model (atm, ocn, ice, wav)**
- **Improved DA with marine JEDI**
- **Consolidation of NCEP production suite**
  - GODAS combined in Coupled GDAS
- **Improvement expected when comparing to GFSv16**
  - TC genesis False Alarm Rate
  - TC right-of-track bias
  - Low instability bias
  - Bias in wave height
  - Ice coverage in wave model

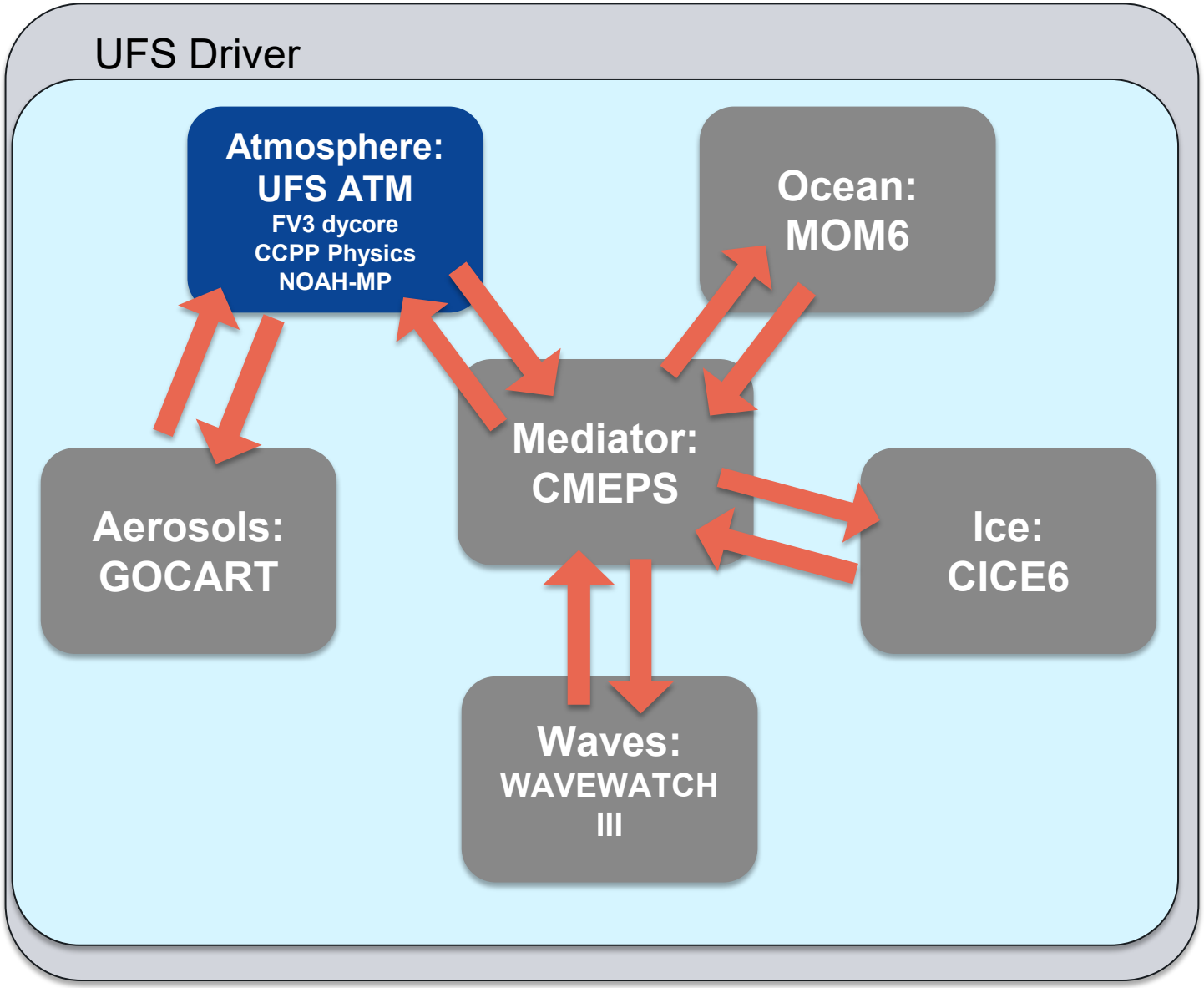
GFSv17 Overview

- 5-way weakly coupled system
  - Atmosphere
  - Ocean
  - Sea ice
  - Land
  - Waves
  - Aerosol (Non-interactive in GDAS deterministic forecast only)
- GFSv17 and GEFSv13 will be separate systems
  - Infrastructure will be as unified as possible
  - Implementation planned for the same day
- New DA components will use JEDI software

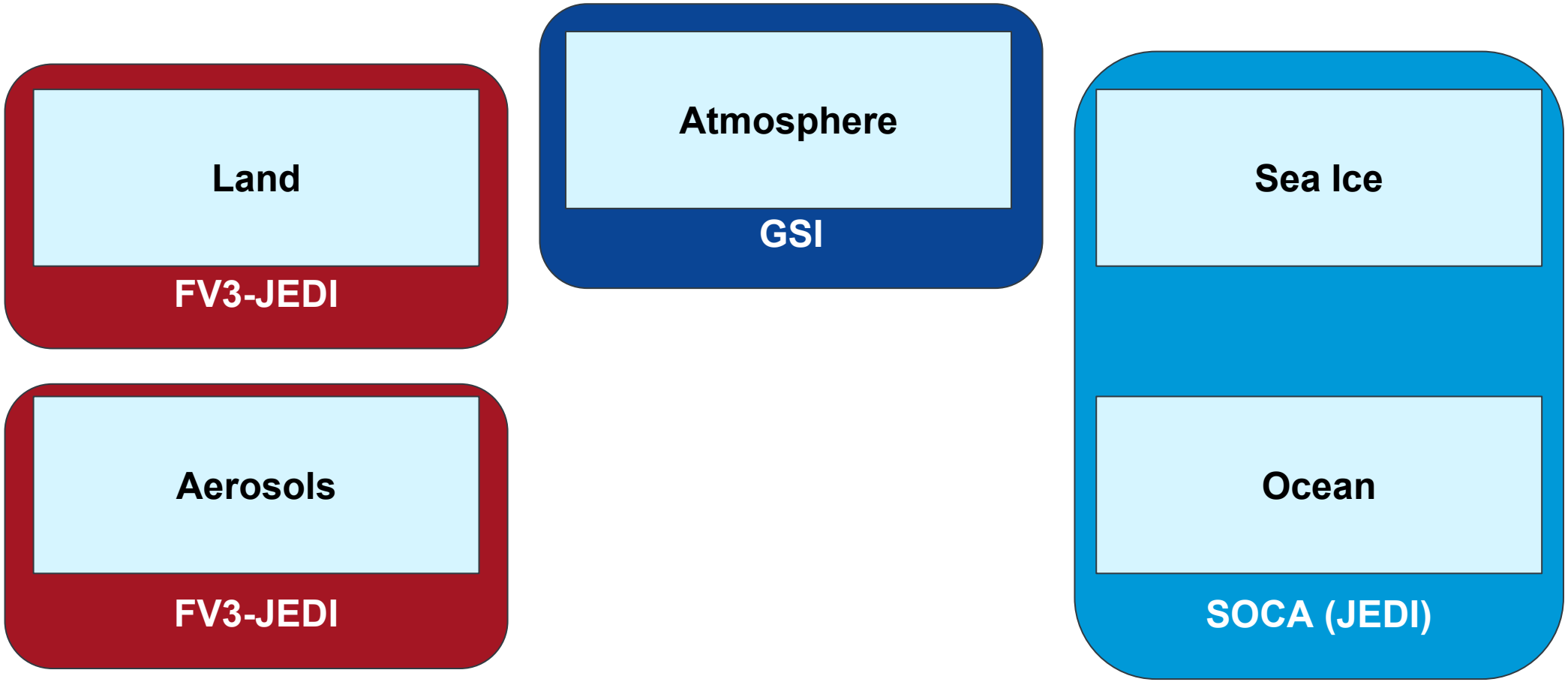


UFS ATM Overview

- Atmosphere
  - Increase in horizontal res for deterministic forecast (C1152)
  - Upgrade to Thompson microphysics
  - **GSI-based hybrid 4DEnVar** deterministic analysis
  - **GSI-based 4D-LETKF** ensemble analysis
  - Additional early cycle ensemble analysis for GEFS initialization (if resources allow)
- Land
  - Upgrade model to Noah-MP
  - **JEDI-based 2D OI** for snow
  - **GSI-based LETKF** for soil



New Coupled Model, New Coupled DA



Currently, GDAS is atmosphere only, with basic offline land surface updates. With GFSv17, weakly coupled (strongly between sea ice and ocean) DA will be introduced for all Earth system components except for waves.

Atmospheric DA Upgrades for GFSv17

- Early cycle EnKF for GEFS initialization
- Thompson microphysics/all sky upgrades
  - New number concentration variables
  - New optimization on obs error, cloud optical table
  - CRTM 3.0
- Scale-Dependent Localization
- New observations
  - NOAA-21 VIIRS, OMPS-NP, OMPS-TC
  - MetOp-C GOME
  - Sentinel-6
  - MetOp Second Generation, Meteosat Third Generation
  - GMI
  - Saildrones

ROMEX Experiments with GFSv17

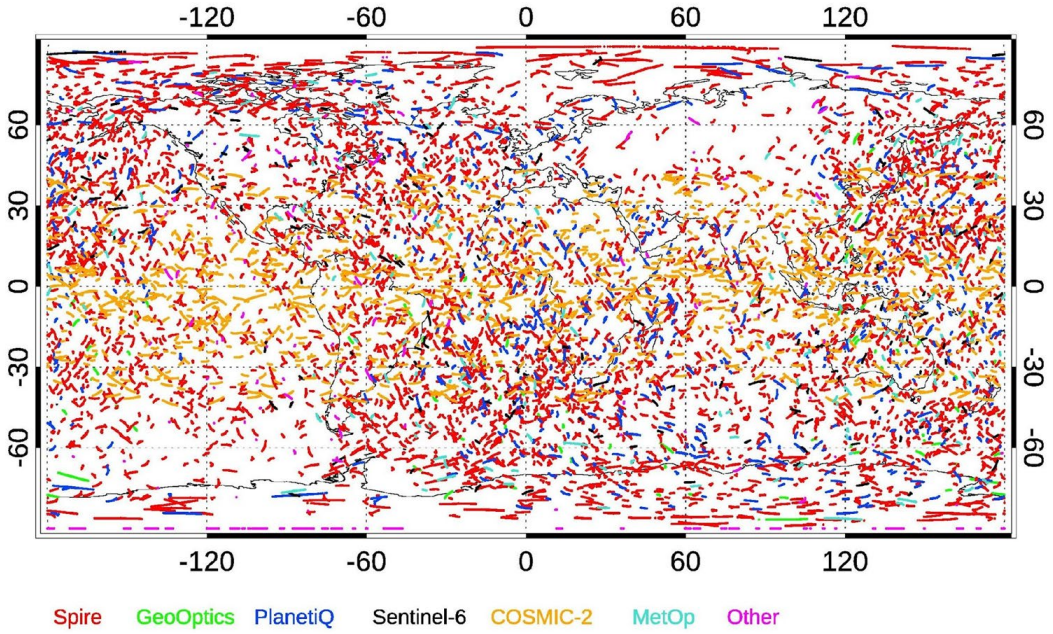
- Global parallel experiments using GFSv17
- 80 ensemble members, half resolution C384 (25 km) + C192
- Thompson microphysics scheme employed in model forecast
- Noah-MP Land Surface Model
- Model is not coupled

- Atmosphere-only DA
- Atmosphere DA has been updated to Thompson microphysics scheme, but was not available at the time of the experiments
- Scale-Dependent Localization is not incorporated

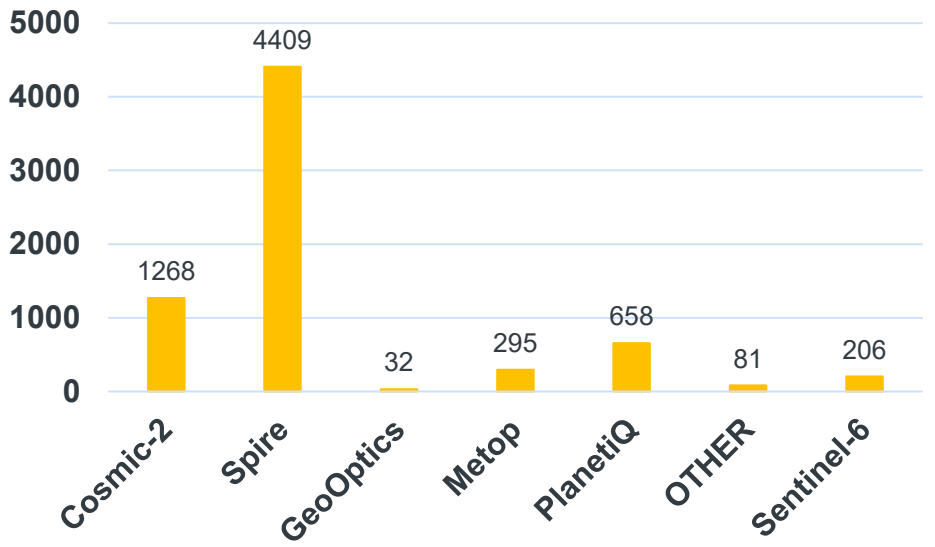
ROMEX Experiments

- **Verification:** September 1 - October 1, 2022
  - **baseline**: COSMIC-2, MetOp, Kompsat-5, TandemX, TerraSarX, PAZ, and Sentinel-6 (~7,000 profiles/day)
  - **supplement**: baseline data + Spire, GeoOptics, and PlanetiQ (~28,000 profiles/day)

00 UTC 2022/09/04

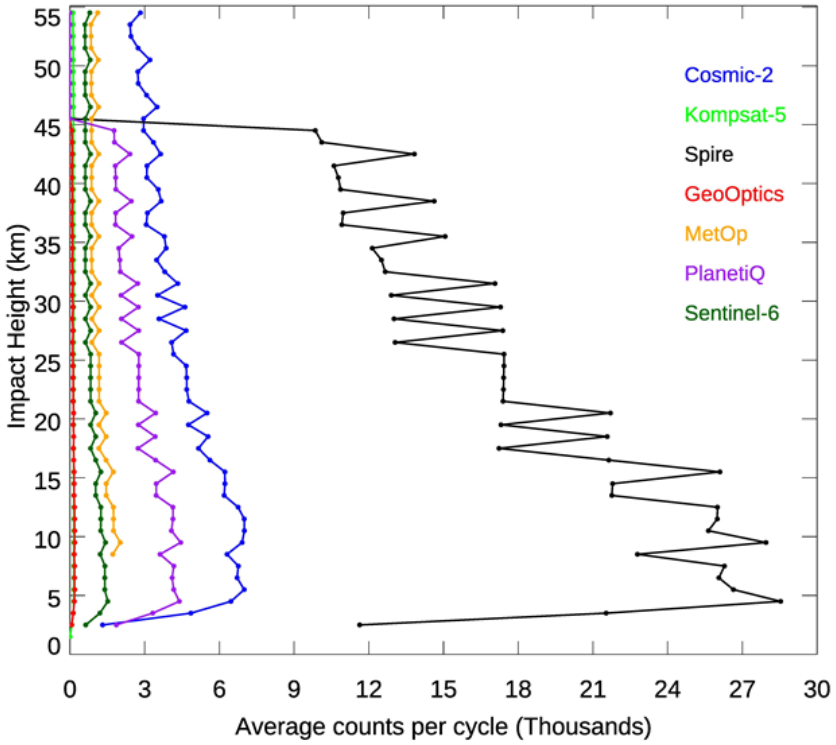


Average number of profiles per cycle: Total RO 6,949

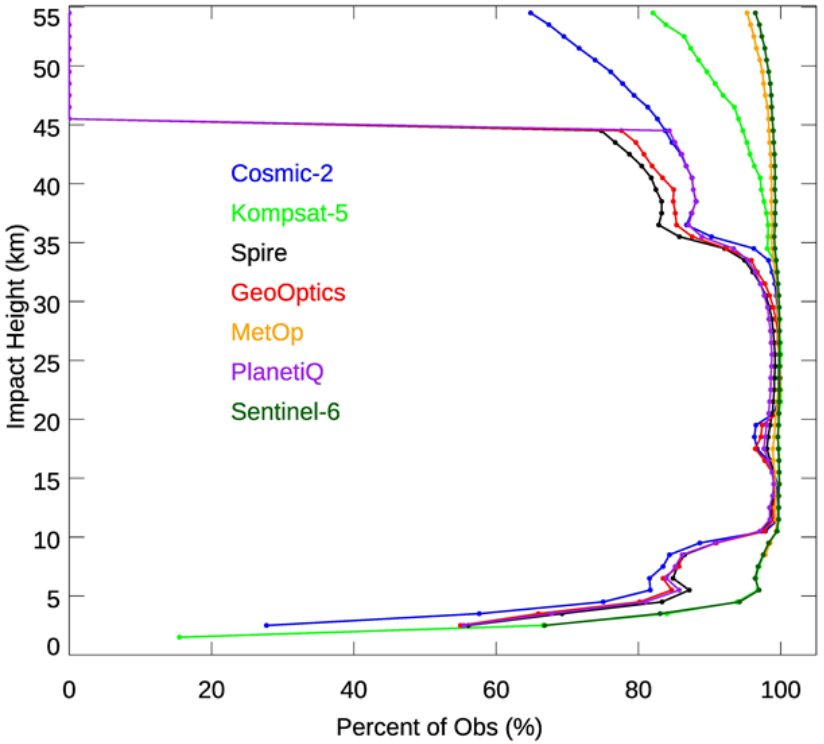


Data Quality

Counts



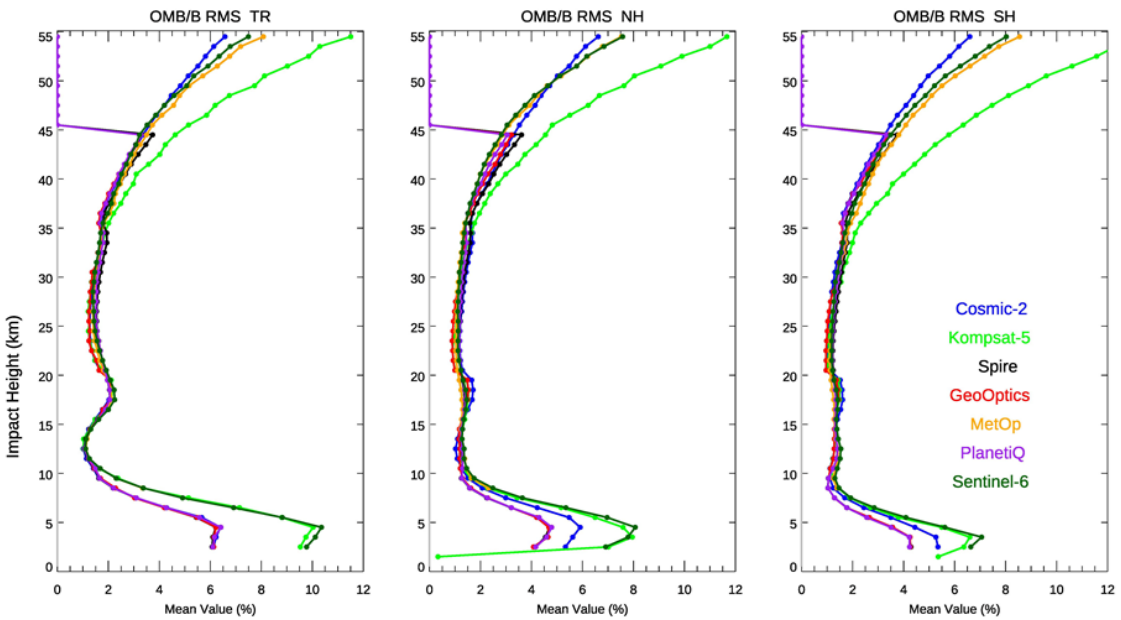
Percent of obs passing QC



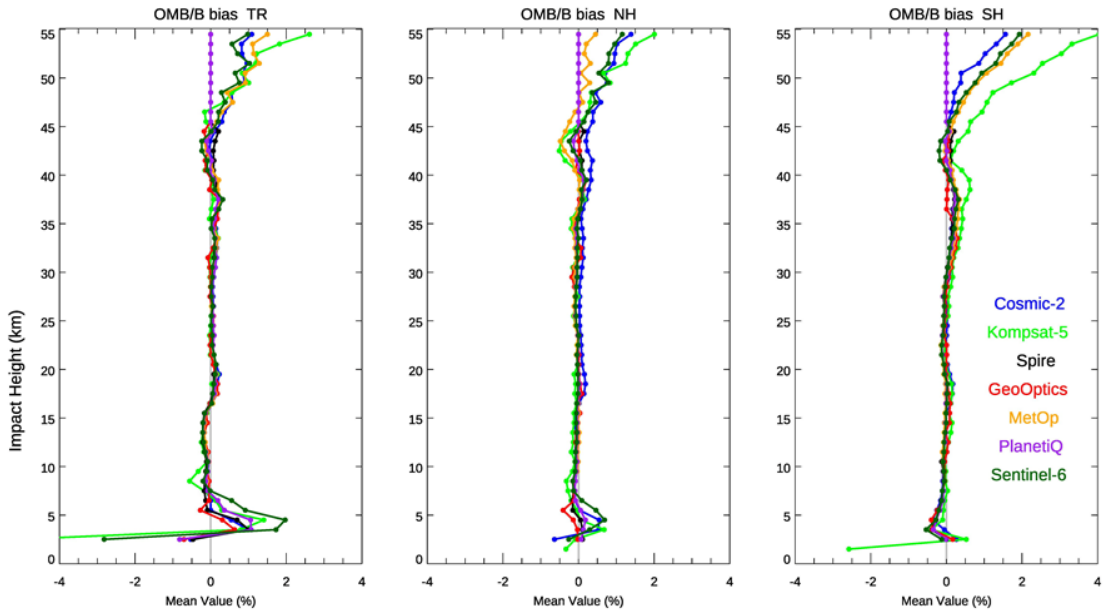
20220901 - 20220921

Data Quality – OmB/B

RMS



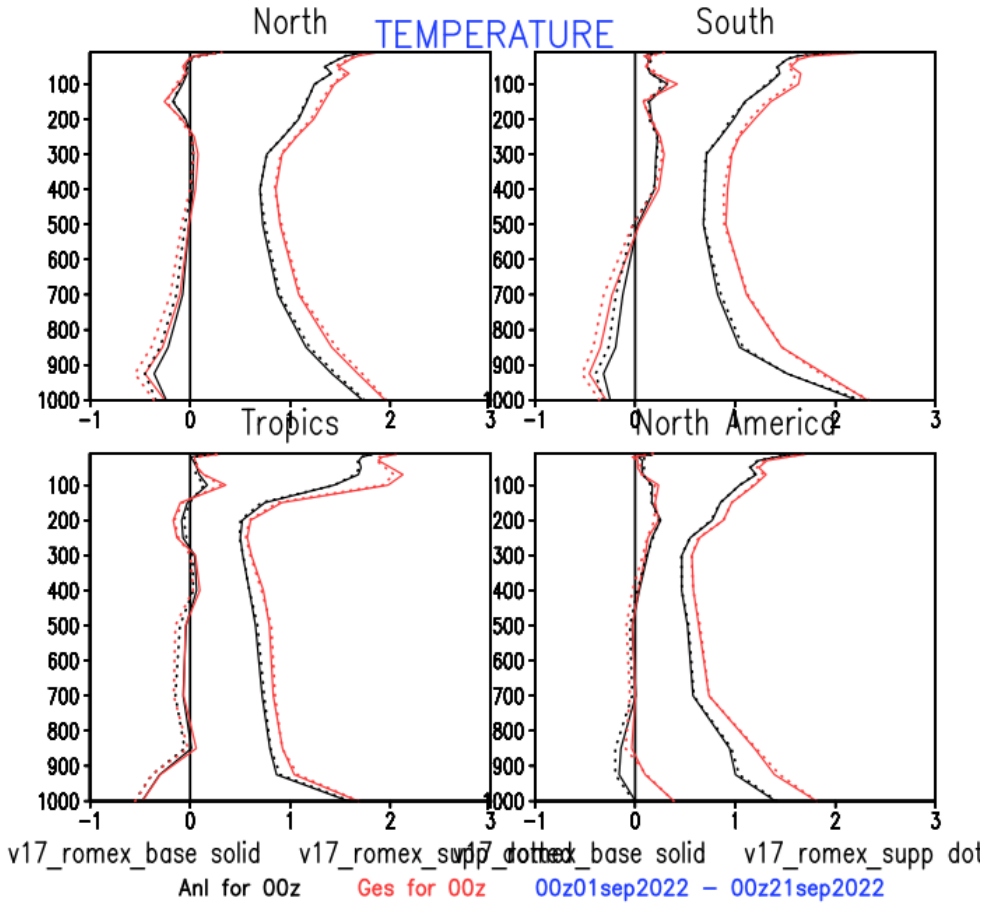
Bias

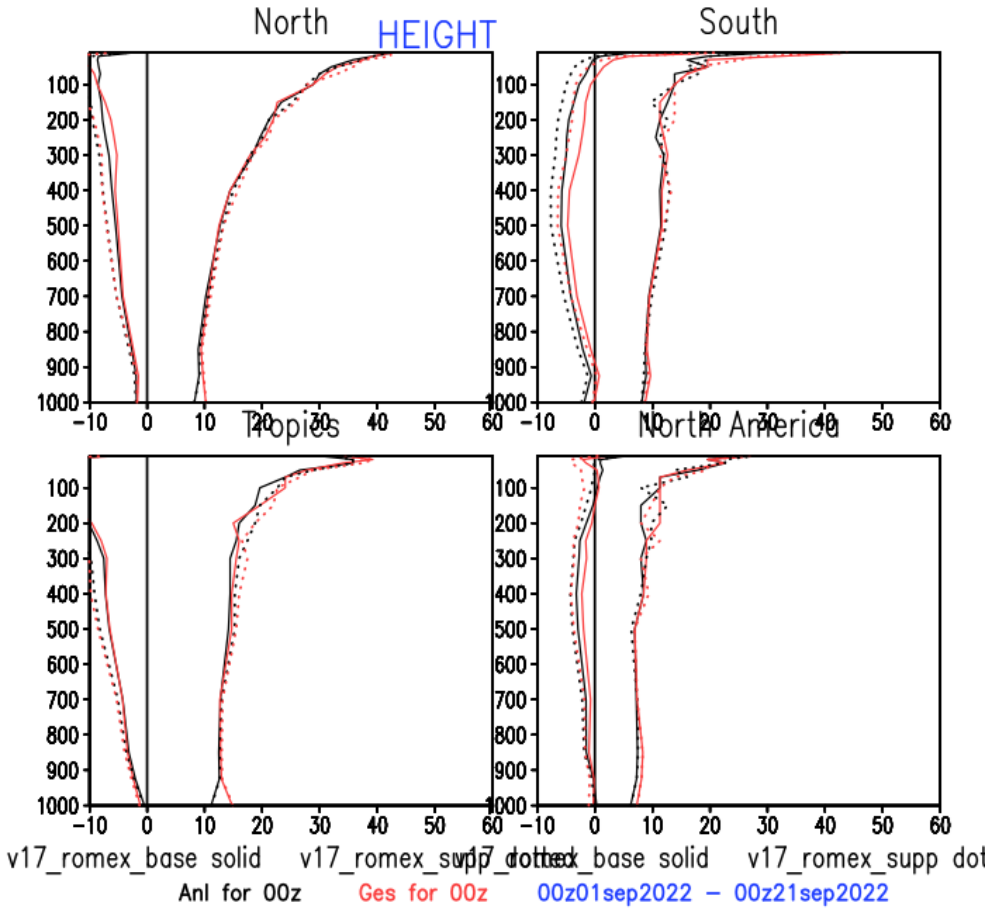


20220901 - 20220921

- Larger RMS and bias for Kompsat-5 and Sentinel-6 data
- Larger RMS in SH above 40 km impact height and larger RMS in Tropics below 10 km impact height

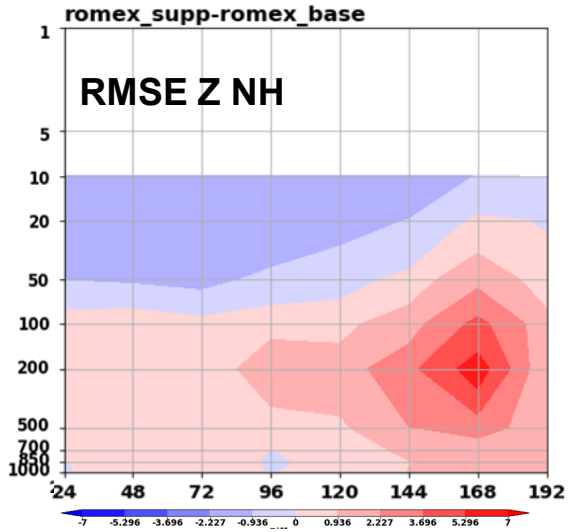
Data Impact - Fit to Radiosonde Data

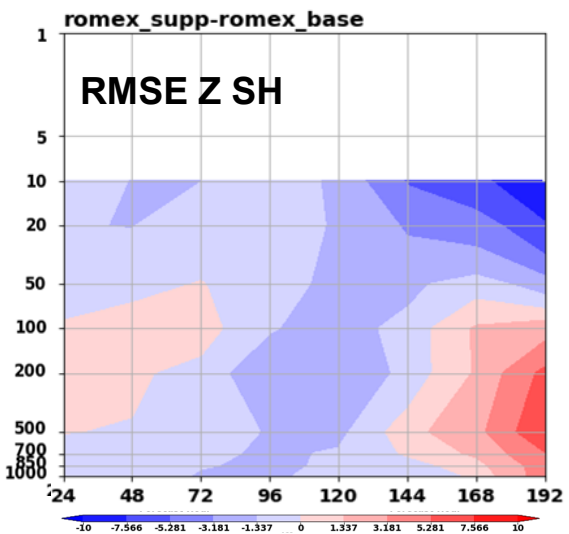


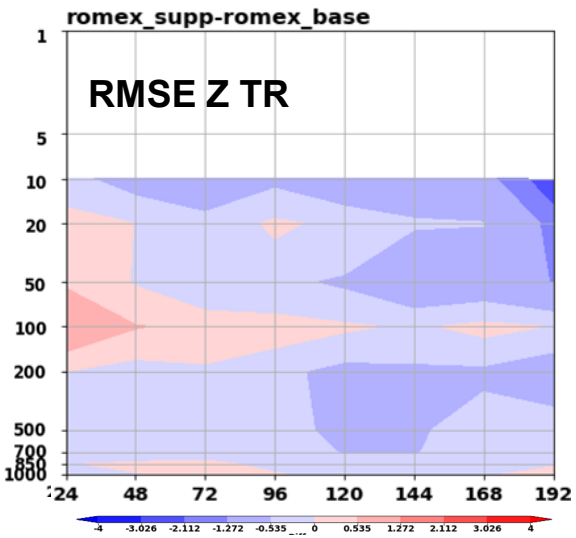


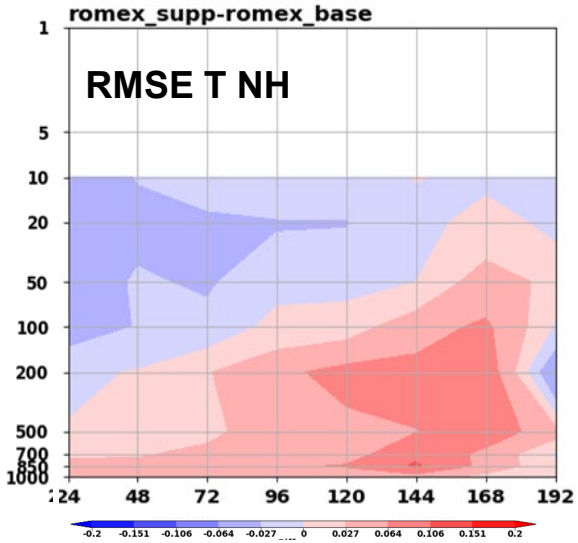
- Cold bias in T at mid to low troposphere and slightly larger T RMSE in v17_romex_supp
- Lower Z bias and larger Z RMSE in troposphere in v17_romex_supp

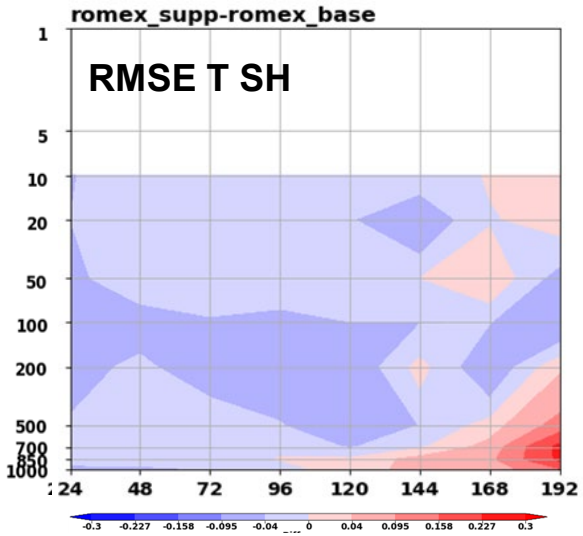
Verification against IFS

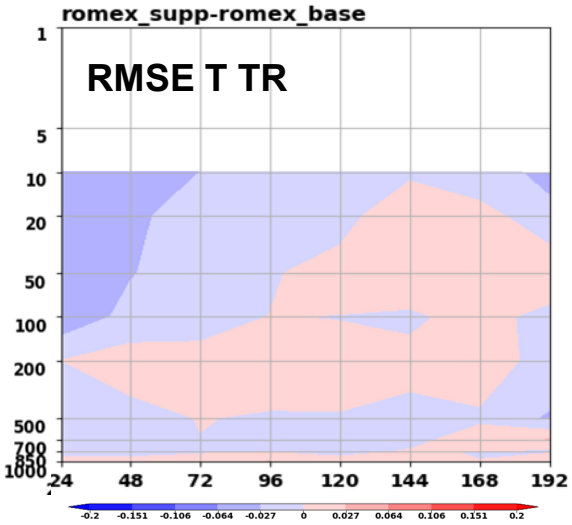












- Red: Degradation in Z RMSE and T RMSE over NH
- Blue: Improvement in T RMSE over SH and Tropics

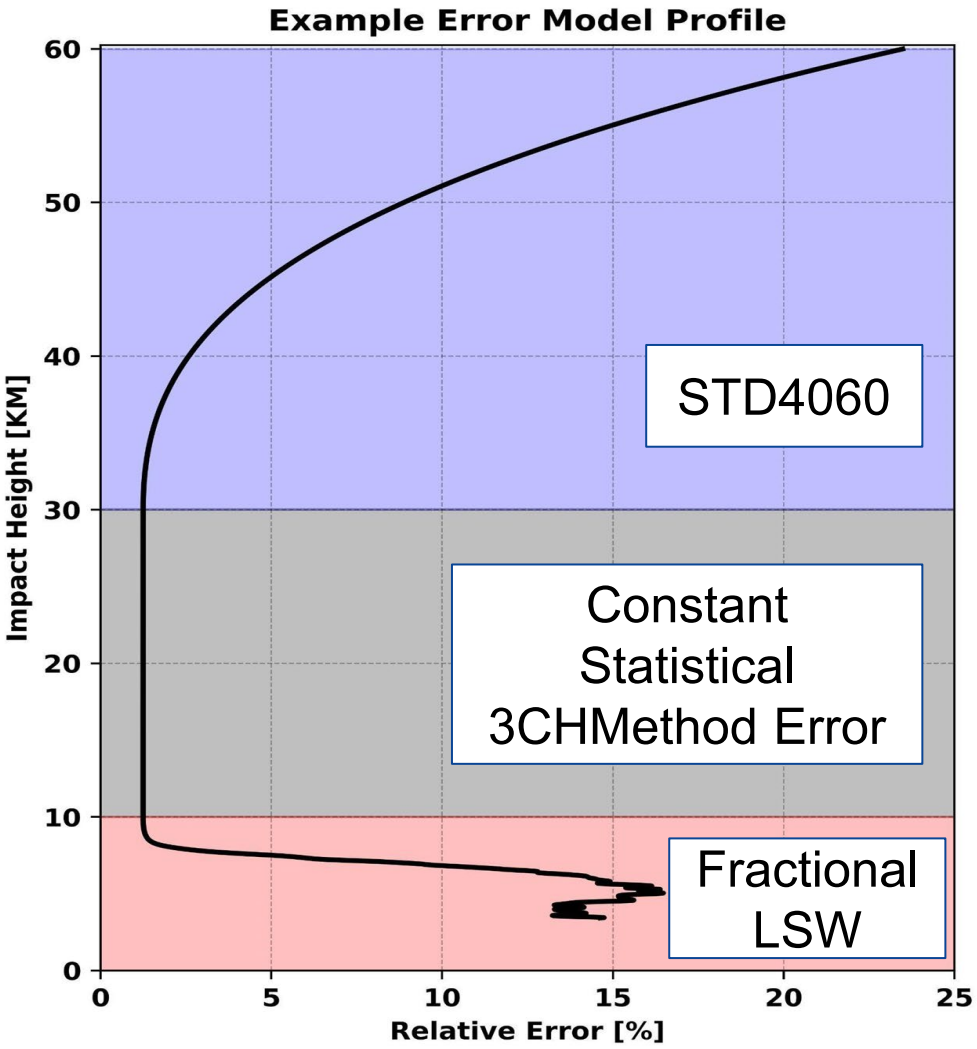
RO Optimization for GSI

- GSI RO obs error and QC was developed 15 years ago when much less RO data was available
- GSI RO obs error: 2D polynomial function of latitude and impact height
  - Latitude is defined in two regions: 40º N - 40º S and > 40º
  - Height is defined in three regions: <12 km, 12-18 km, and > 18 km (2 additional regions for COSMIC-2 and commercial data: <4 km and 4-8 km)

- Current statistic QC in GSI: Statistical QC OMB/O > X σ (σ varies in 3 vertical regions, transition zones +/- 1 km between regions)
  - σ specified via statistical fit to observed σ
  - >35 km: 1σ COSMIC-2/commercial, 2σ other
  - 10-35 km: 2σ COSMIC-2/commercial, 3σ other
  - 0-10 km: 1σ COSMIC-2/commercial, 2σ other

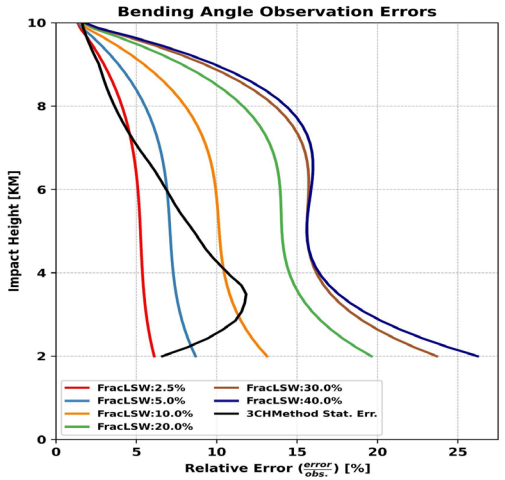
New Hybrid Error Model

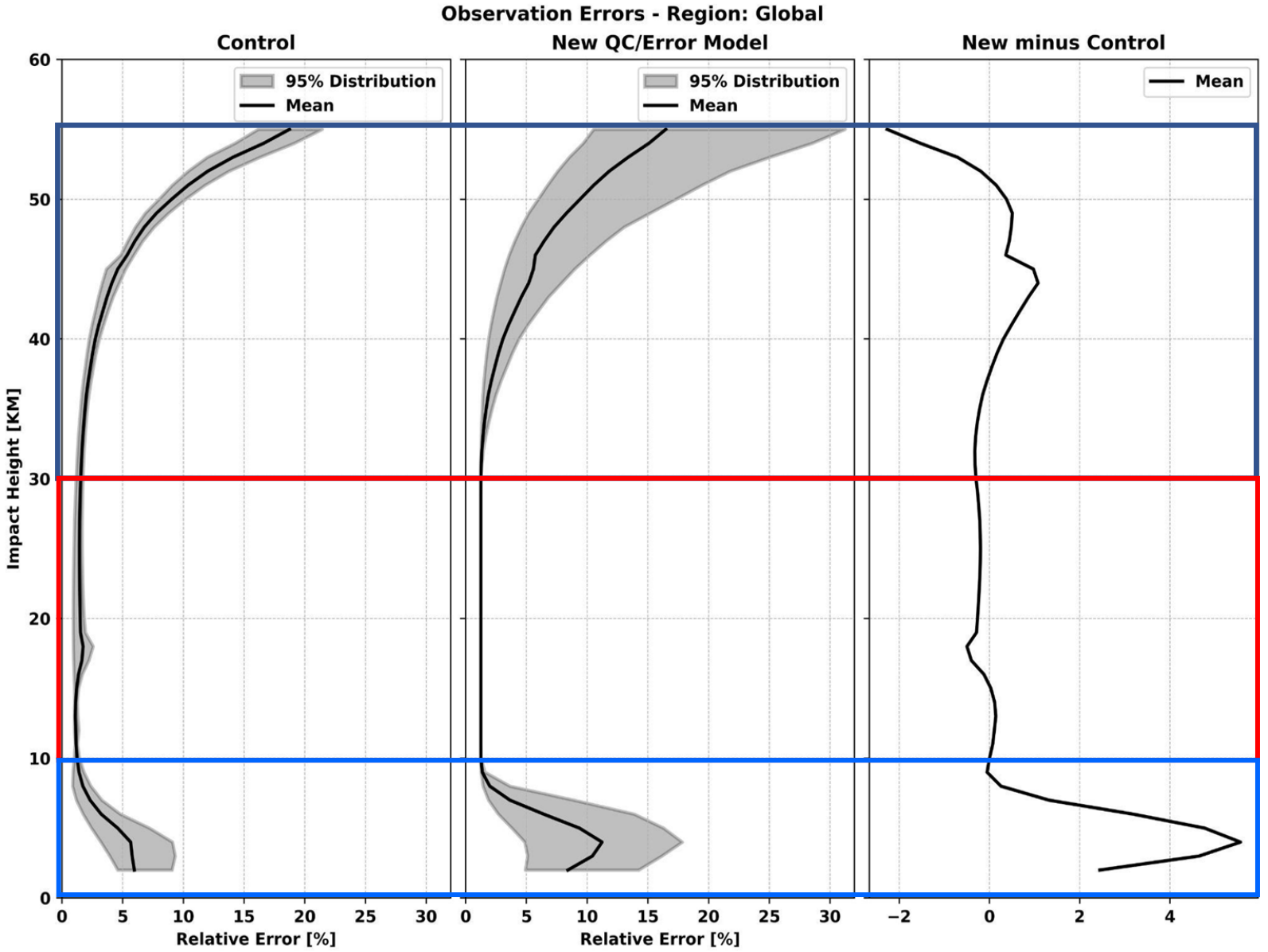
- Error model is defined in 3 vertical regions
- STD4060 => Blue Region
  - Standard deviation between observation values and an exponential fit for impact heights between 40-60 KM
- Constant Statistical 3CHMethod Error => Grey Region
  - Relative error of 1.25%
- Fractional LSW => Red Region
  - Use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

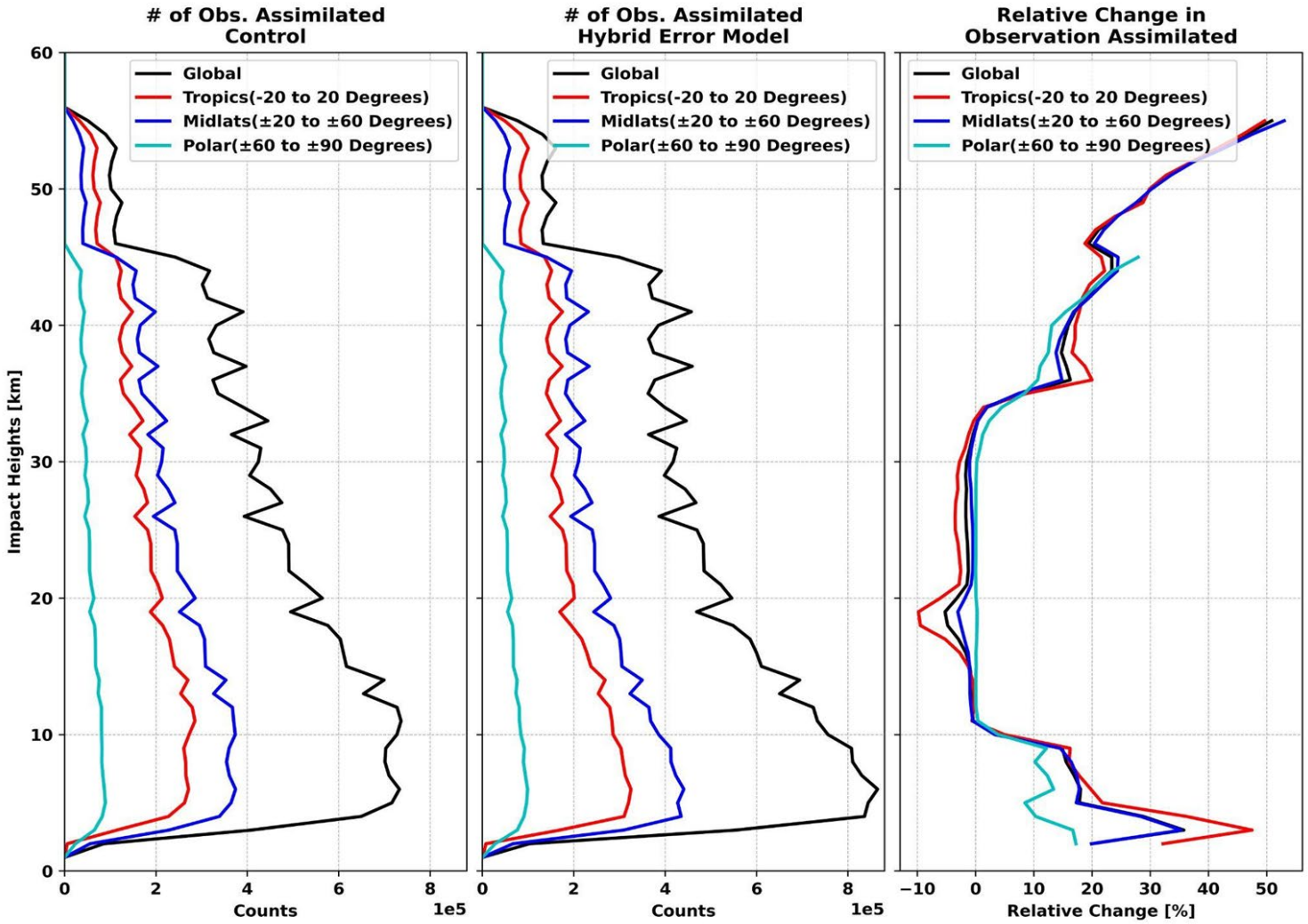
- On average, the hybrid error model increases the obs error at <10 km and 40-50 km, while decreasing the error at 15-37 km and above 52 km
- More variation in obs in hybrid error model





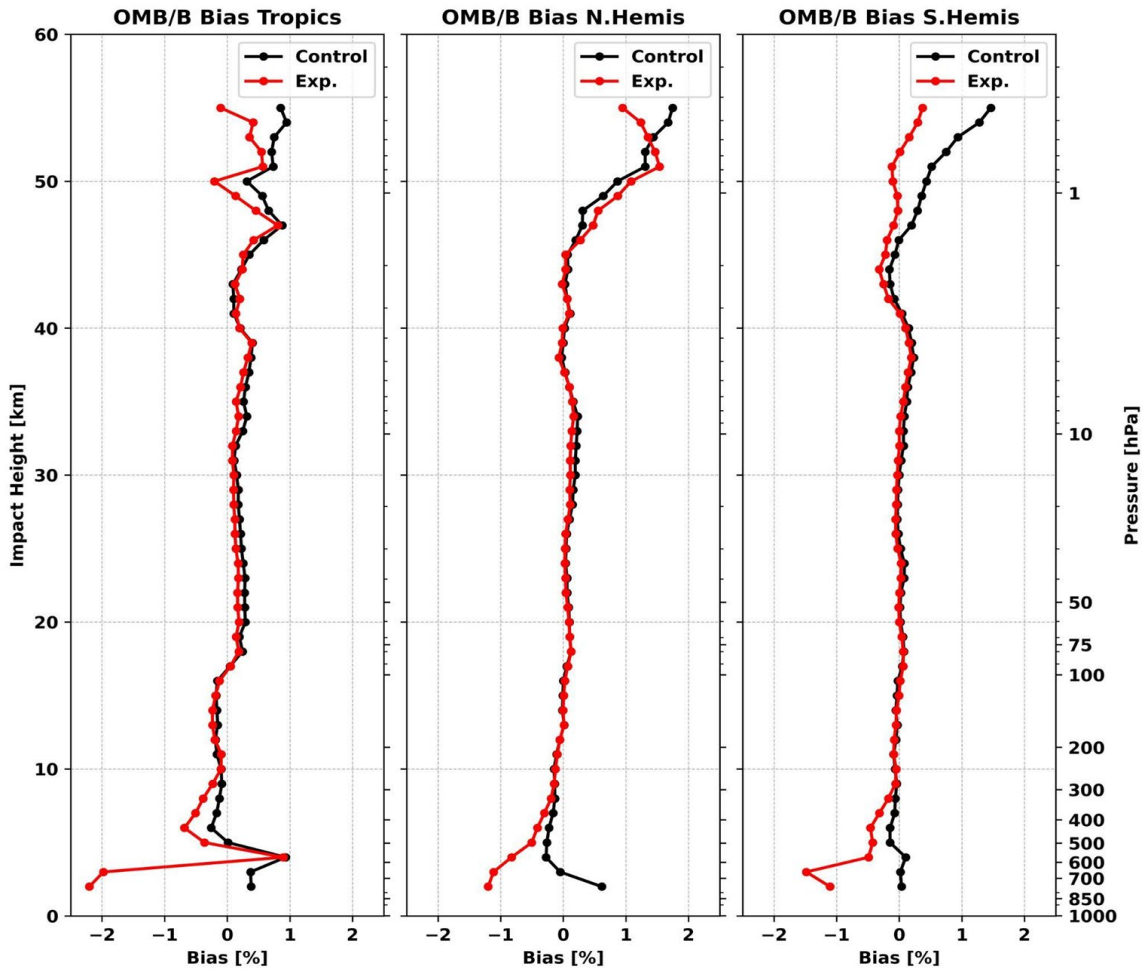
New QC

- 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

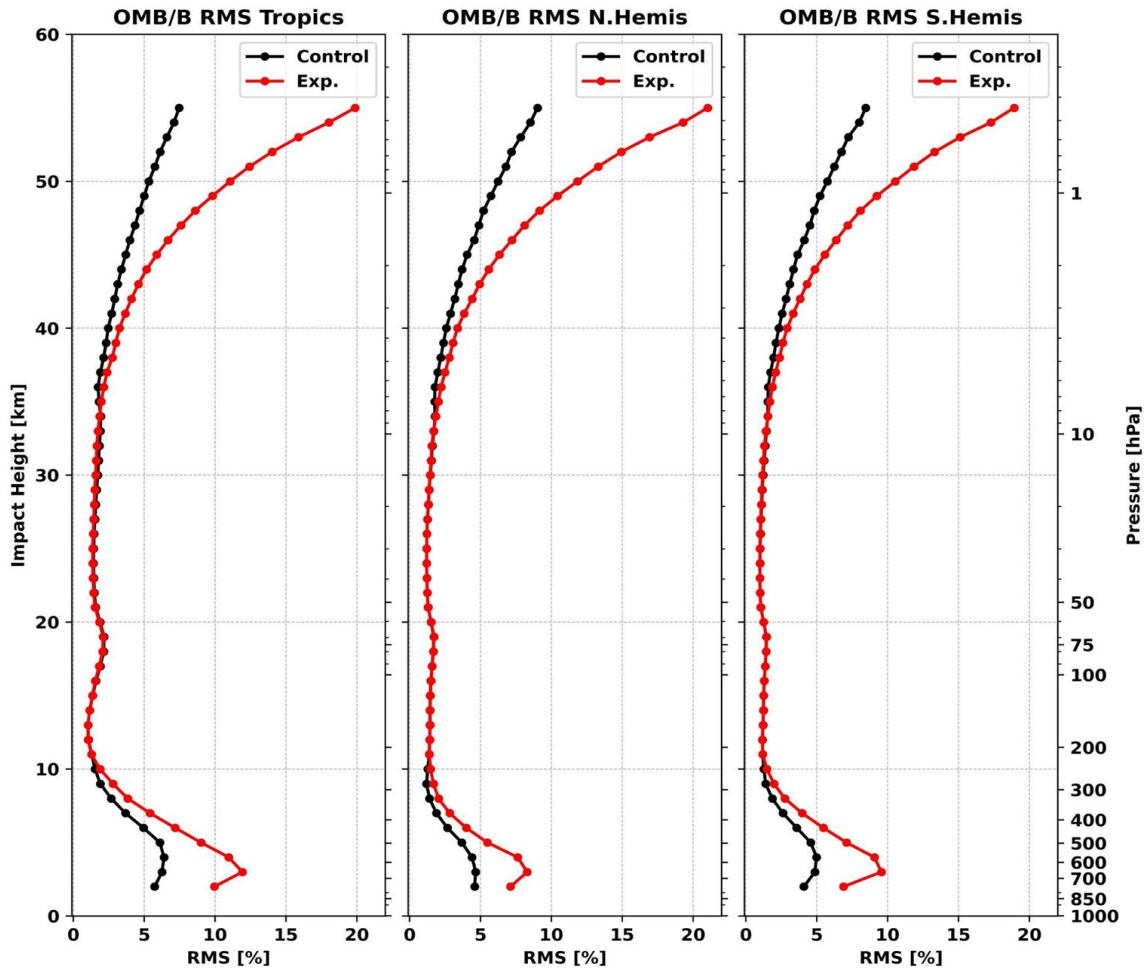


v17 Testing

Forecast Bias



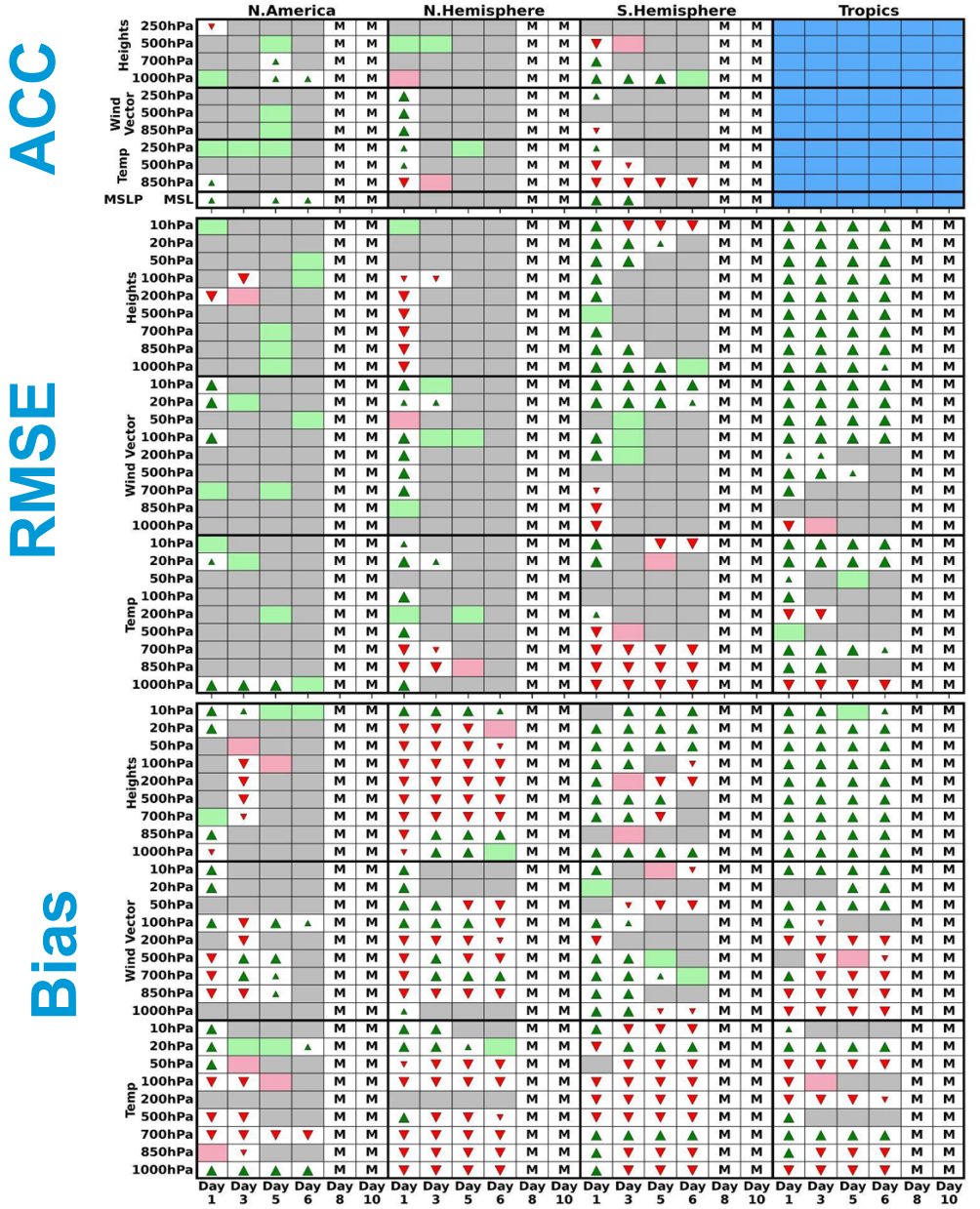
Forecast RMS



- Larger bias and RMS of O-B/B in troposphere and > 35 km due to changes in QC
- ***One Caveat:*** Control was run using **v16** and experiment is using **v17**

v17 Testing

- **Verification**: 20230105-20230128 against ECMWF Analysis
- Significant improvements in RMSE of height and wind over SH and Tropics
- Degradation in RMSE and bias in height over NH
- Degradation in temperature in low troposphere
- ***One Caveat:*** Control was run using **v16** and experiment is using **v17**



Future Directions

- Development and testing of GFSv17
  - Coupled mode of v17
  - SDL on

- Joint Effort for Data assimilation Integration (JEDI) Transition
  - Collaborative effort on next generation of DA infrastructure
  - GFSv18: JEDI-based atmosphere DA (complete transition away from GSI)
  - Testing different components of JEDI system within our environment
  - 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