Recent Advances in the use of GNSS-RO Observations in NWP at NASA's GMAO

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IROWG-10

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Introduction and Overview

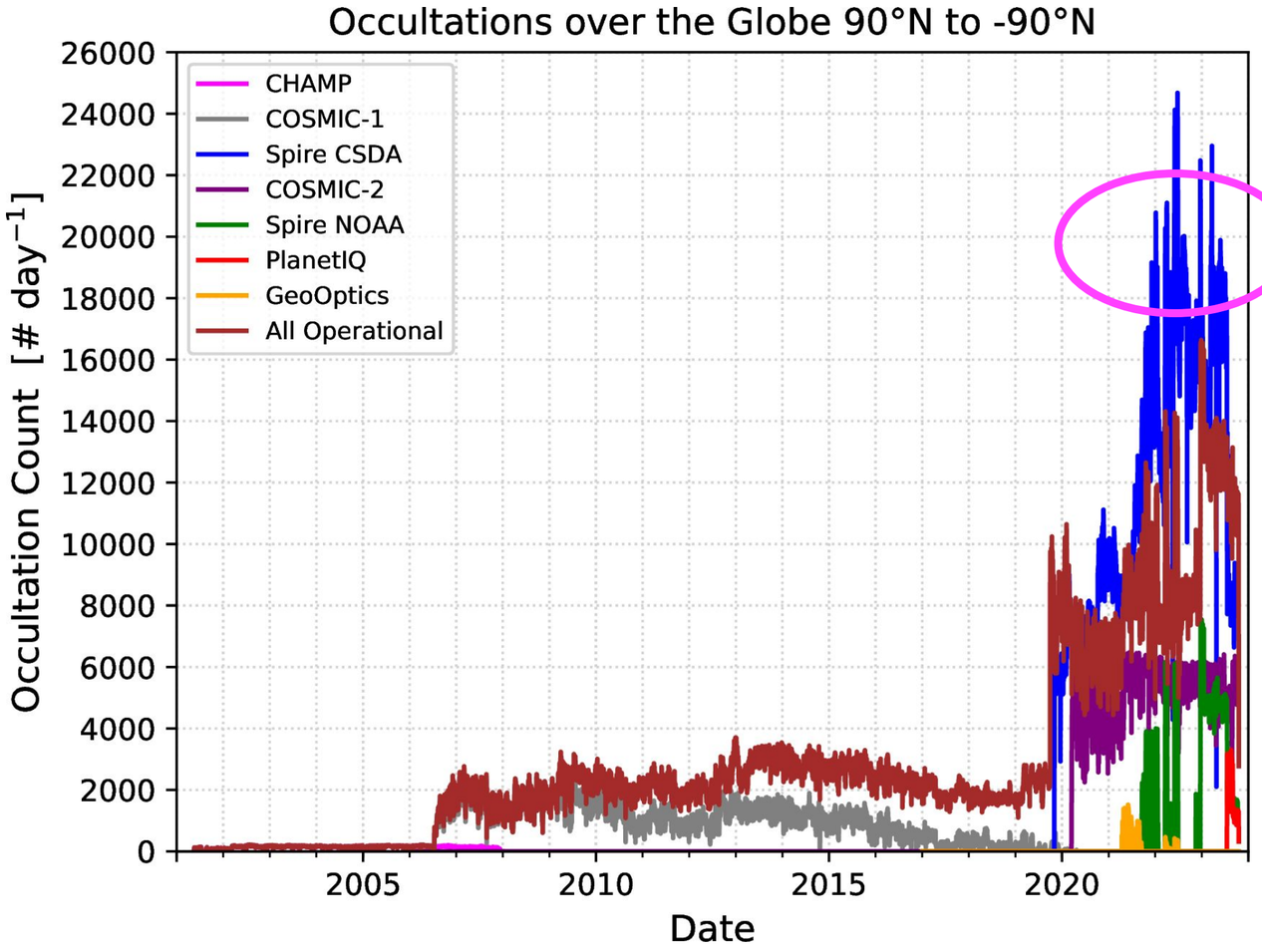
GNSS-RO Related work at GMAO

- Operational NWP
  - Assimilation of RO in real-time into Goddard Earth Observing System (GEOS) model
  - Using available suite of operationally available RO including commercial

- Reanalysis
  - Development of the new MERRA-21C product
    - Bridge between current MERRA-2 and upcoming MERRA-3
    - Covers the "satellite era" i.e. the 21st Century
    - Assimilating high-volume Commercial RO from CSDA archive
    - Globally 5-20 thousand profiles/day from Spire alone

Outline of Presentation

1. Evaluation of GNSS-RO Observation Uncertainty (Error) Model & QC Methods in GEOS
2. Progress & initial results from GMAO's contribution to Radio Occultation Modeling Experiment (ROMEX)



Evaluation of GNSS-RO Observation Uncertainty Model & Quality Check Method in GEOS

Observation Uncertainties in NWP

In data assimilation (DA) the following cost function is minimized:

$$J(x) = \frac{1}{2}[(x_b - x)^T \mathbf{B}^{-1}(x_b - x) + (y - \mathcal{H}(x))^T \mathbf{R}^{-1}(y - \mathcal{H}(x))]$$

Obs error (uncertainties) are contained in the **R** matrix

where:
- x = analysis to be found
- x_b = model 1st guess
- y = observation
- H(x) = forward model

- **B** = background error covariance
- **R** = observation error covariance

The larger the uncertainty assigned to a given observation, the less closely the model analysis produced by DA draws to the given observation.

An *observation uncertainty model* is the method of estimating the uncertainty used in the above cost function for a given observation.

The *quality control (QC) method* applied to the observations is also an important factor in how observations are actually used by the NWP system.

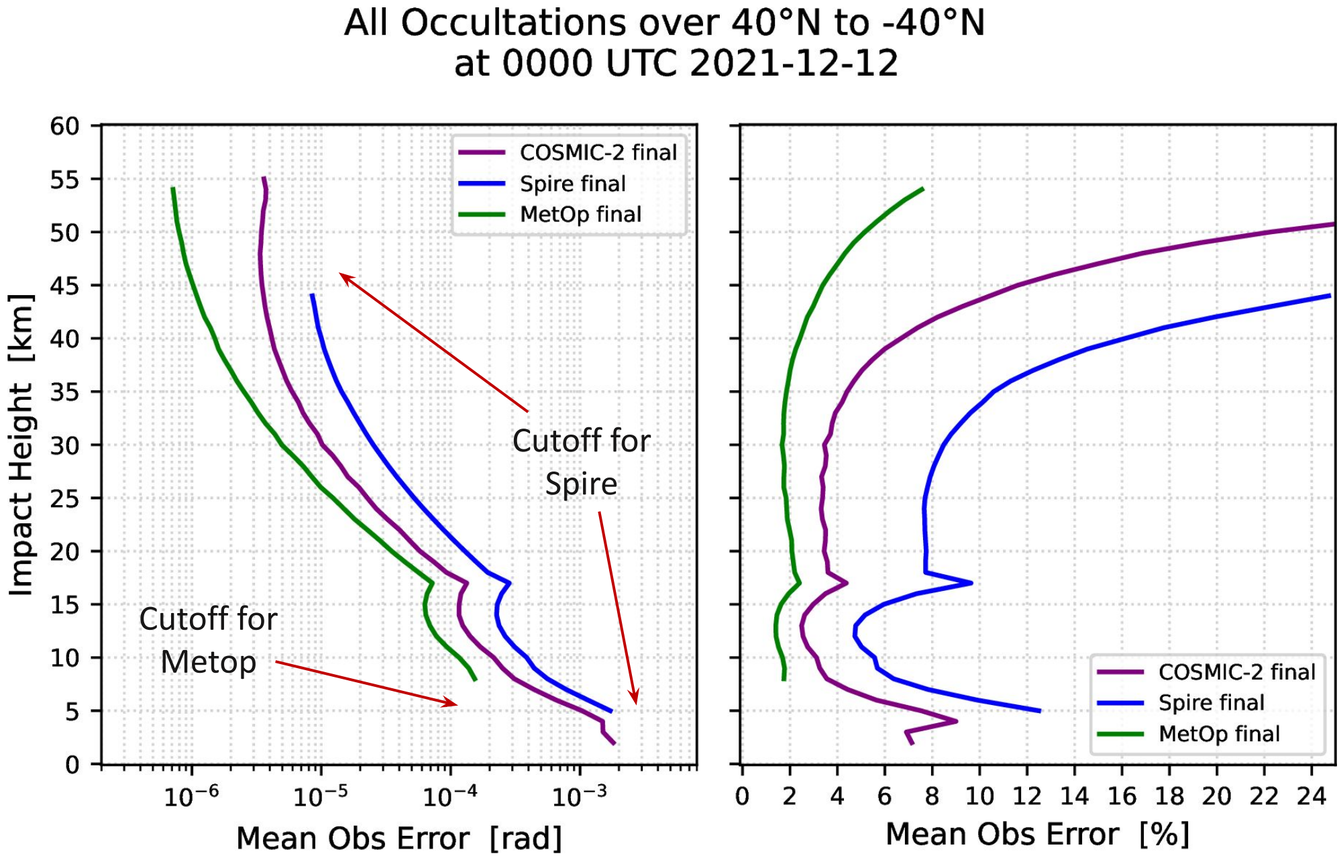
Current Obs Uncertainty & QC Method at GMAO

The Current obs uncertainty model in GEOS

- Based on fit to estimated error using Desroziers method
- Varies by impact height, latitude, & processing center
- Inflated obs errors (factor of 2) for commercial constellations
- “superobbing” inflated by $N^{1/2}$ where N is the number of RO obs in a single layer

The Current Quality Control method in GEOS includes:

- Gross error check
  - innovations/E > 10
- Statistical check:
  OMB/O > X σ (σ varies with 3 regions, transition zones +/- 1 km between regions. σ specified via statistical fit to observed σ based on two months of data)
- Mission specific height cutoffs
  - No MetOp below 8 km
  - No commercial below 5 km & above 45 km



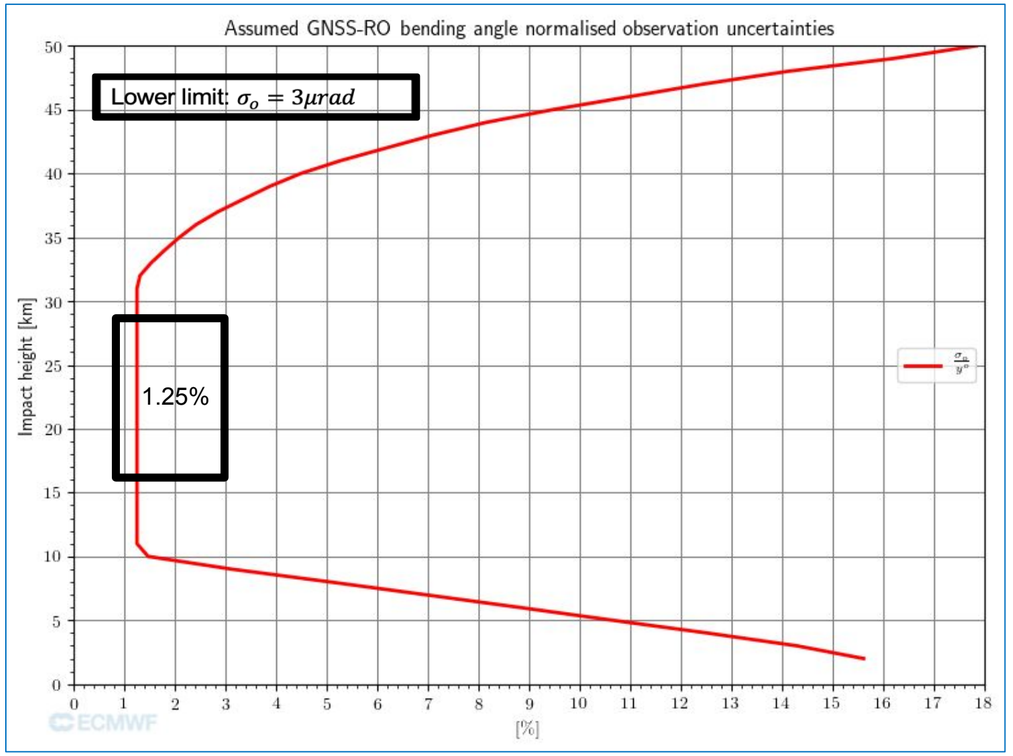
The ECMWF Obs Uncertainty & QC Method

The ECMWF RO observation uncertainty model

- Dependent only on impact height
- Independent of mission/latitude etc
- Error correlations in vertical are ignored

The ECMWF RO Quality Control method includes:

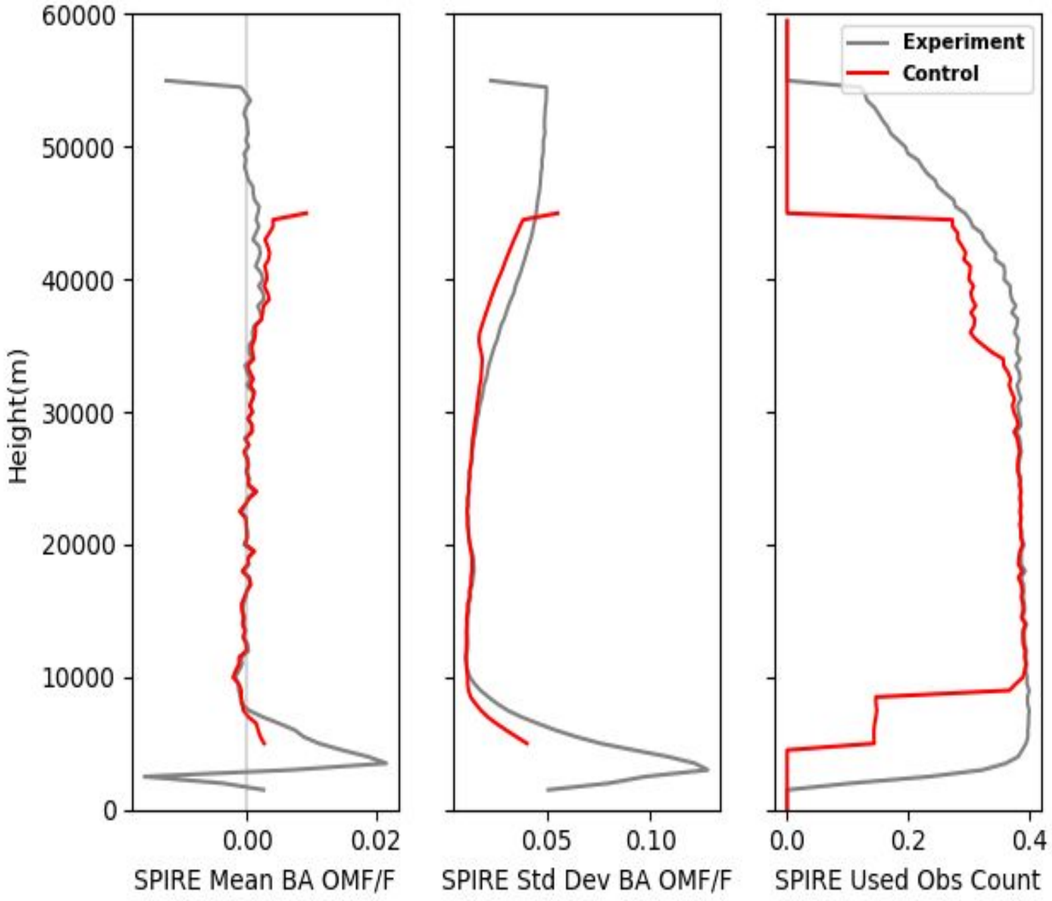
- Reject if the innovation is larger than 7 times standard dev of the obs (σ_o)
  - abs(o-b) > 5 $\sqrt{(\sigma_o^2 + \sigma_b^2)} = 5\sqrt{2}\sigma_o^2 \cong 7\ \sigma_o$.
- No upper/lower boundary cutoffs.



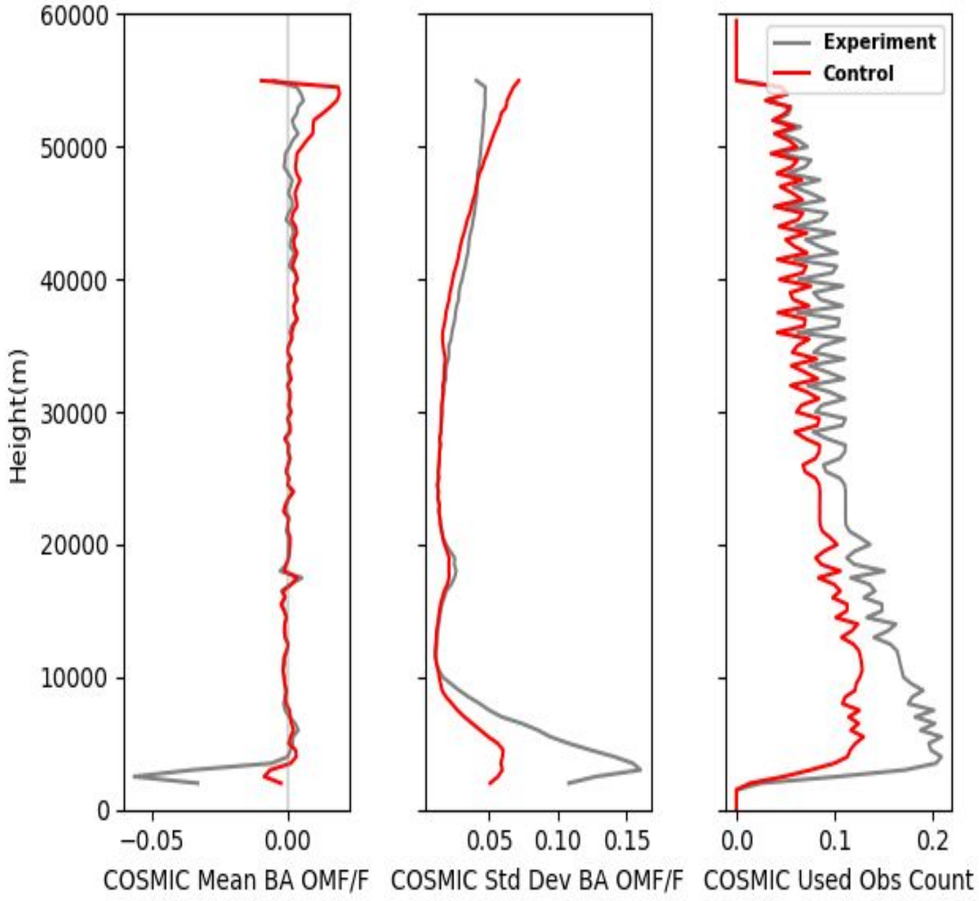
$$\frac{\textbf{Observation error std}}{\textbf{Observation}}\ (\%)$$

Comparison Between EC Obs Uncertainty Method and Control

SPIRE

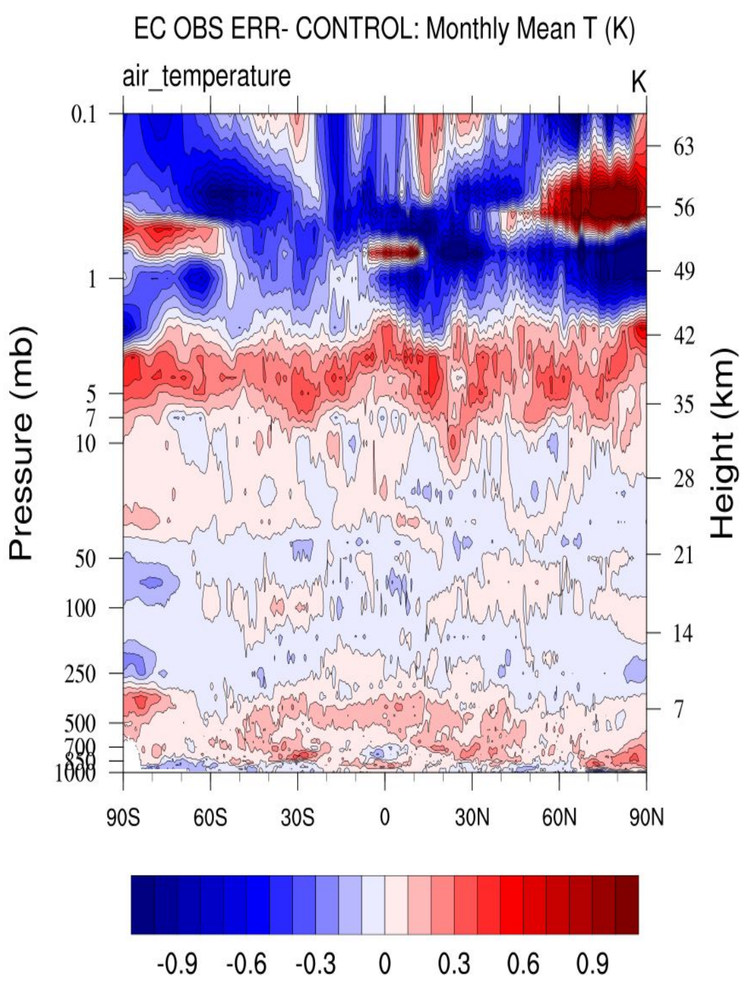


COSMIC2

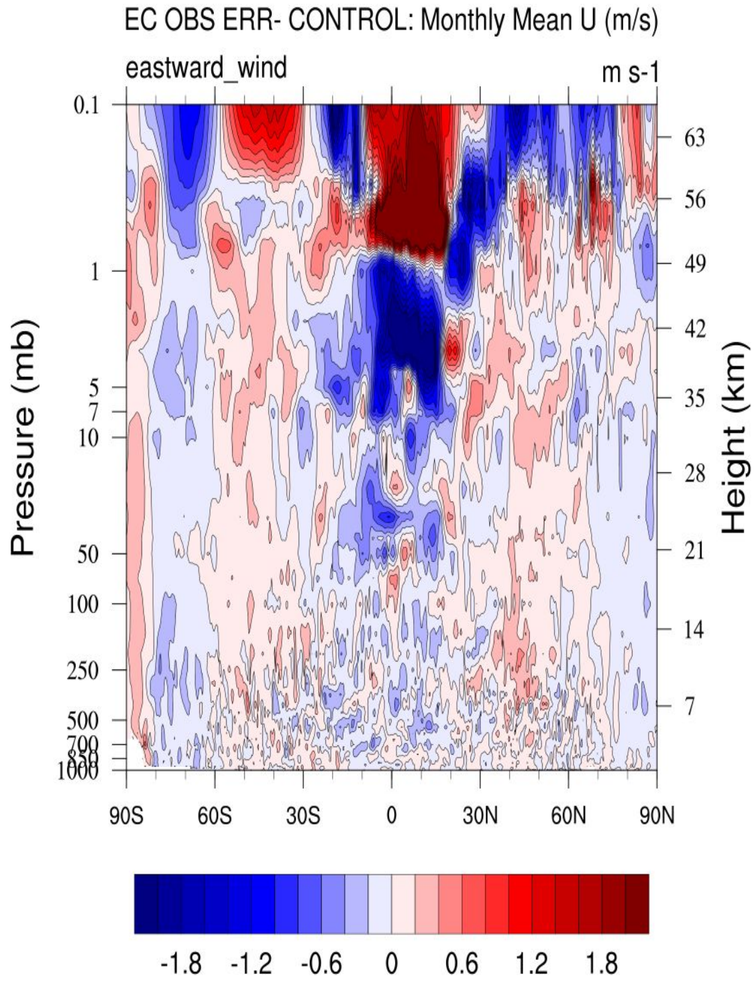


Monthly Mean Comparison: ECMWF Obs Uncertainty Method - Control

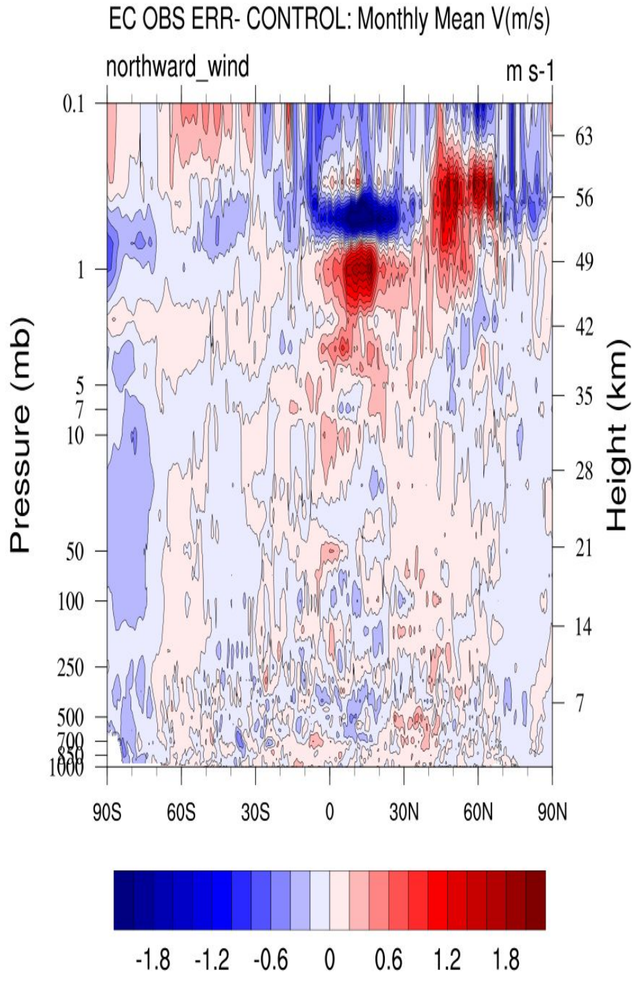
Temperature



U Wind Comp



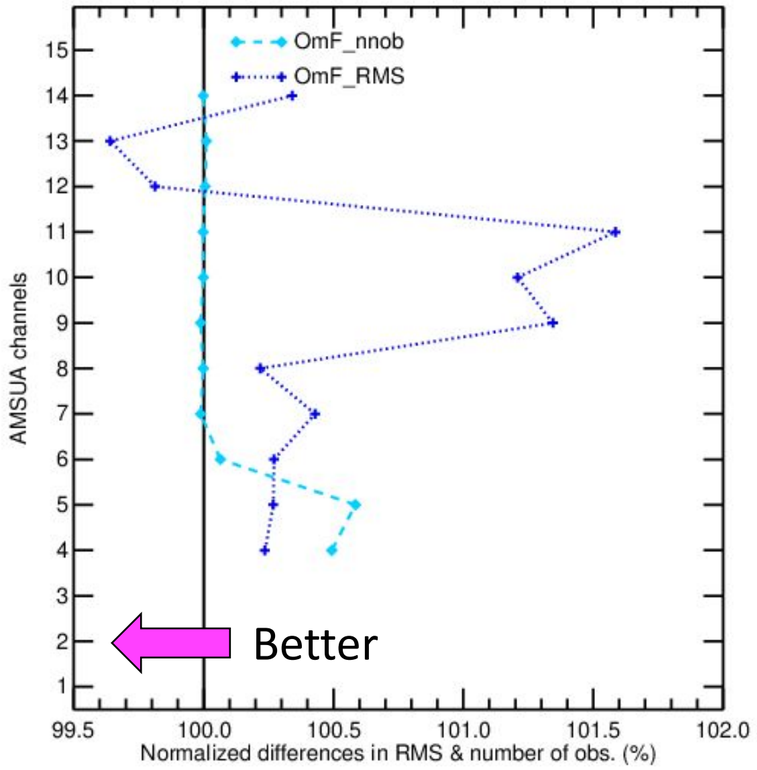
V Wind Comp



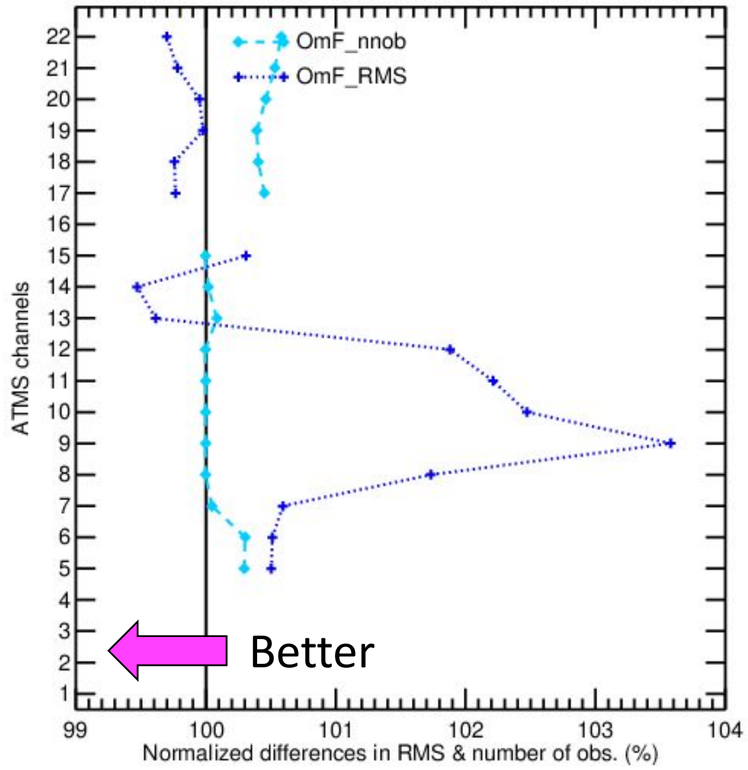
Large differences in the analyses between the experiment (using the ECMWF method) and the Control. Especially above ~35 km

Validation against Microwave Instruments

AMSU-A



ATMS



Degraded performance with experiment using EC Obs Uncertainty & QC Model with both instruments

Progress & initial results from GMAO's contribution to ROMEX

ROMEX experiments

ROMEX seeks to answer

- What is the impact of greatly increased volume of RO observations on NWP forecasts?

GMAO's Model Configuration

- NASA's GEOS Atmospheric Data Assimilation System (ADAS) version 5.30.3 (X0048)
- Resolution of 25 km in horizontal & 72 layers in vertical
- Primary model initialization at 00 & 12 UTC (longer forecasts)
- Additional model initialization at 06 & 18 UTC (shorter forecasts)

GMAO's RO Specific Configuration

- NBAM Observation operator
- Standard GEOS Observation Error Model & QC

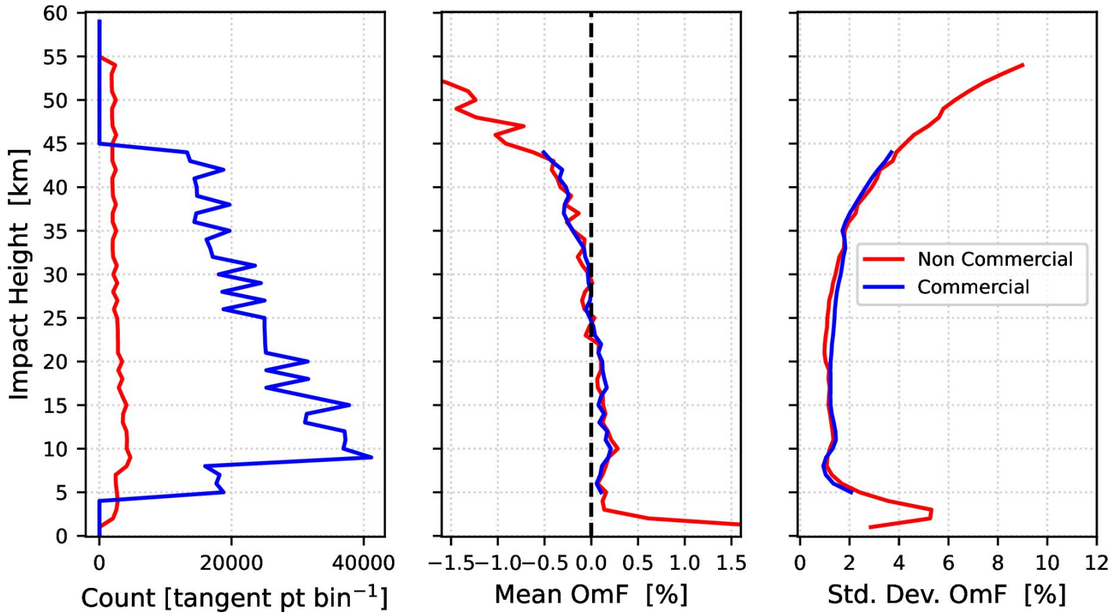
Current status of NWP runs

- Completed the first month (September 2022) of the 3 month ROMEX period

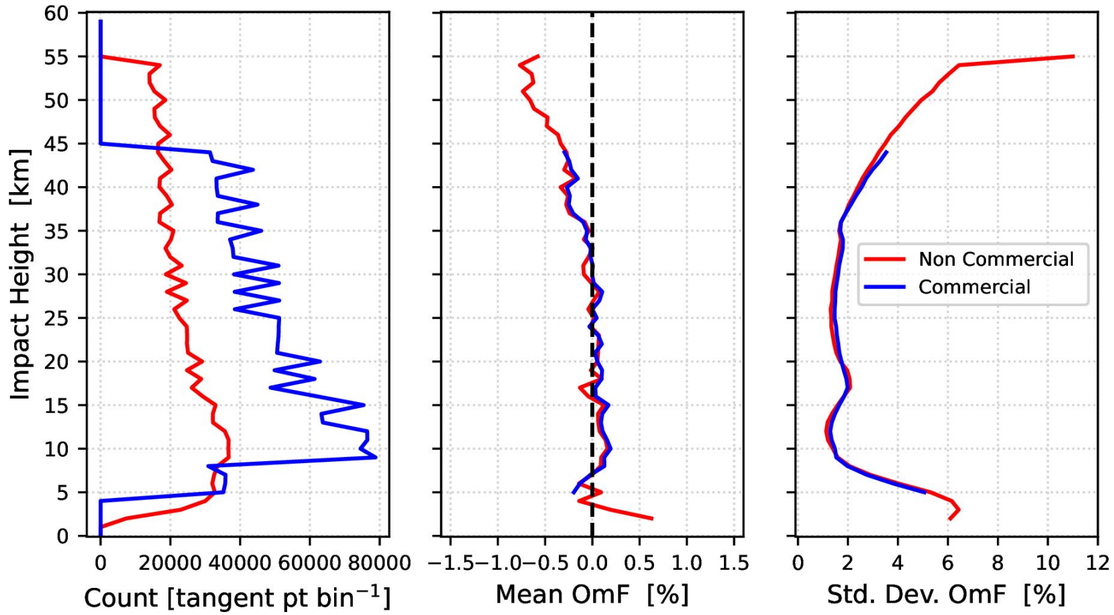
ROMEX Data Volume (estimated)			For 20220906	
Mission	RO/day	Control	Control	Experiment
GRAS	1,200	y	1194	1194
COSMIC-2	6,000	y	5220	5220
Spire	17,000	n		17337
GNOS	2,100	n		2080
PlanetiQ	3,200	n		2900
Yunyao	6,200	n		4165
Tianmu	100	n		305
KOMPSAT-5	300	y	175	175
PAZ	200	y	124	124
TerraSAR-X	100	y	120	120
TanDEM-X	100	y	93	93
Sentinel-6	800	y	838	838
Sum control	8700	y	7771	
ROMEX supplemental	28600	n		26782
Sum ROMEX	37300	n		34553

OmB Statistics for ROMEX
Commercial vs Public Sourced RO

Extra tropics (Southern)

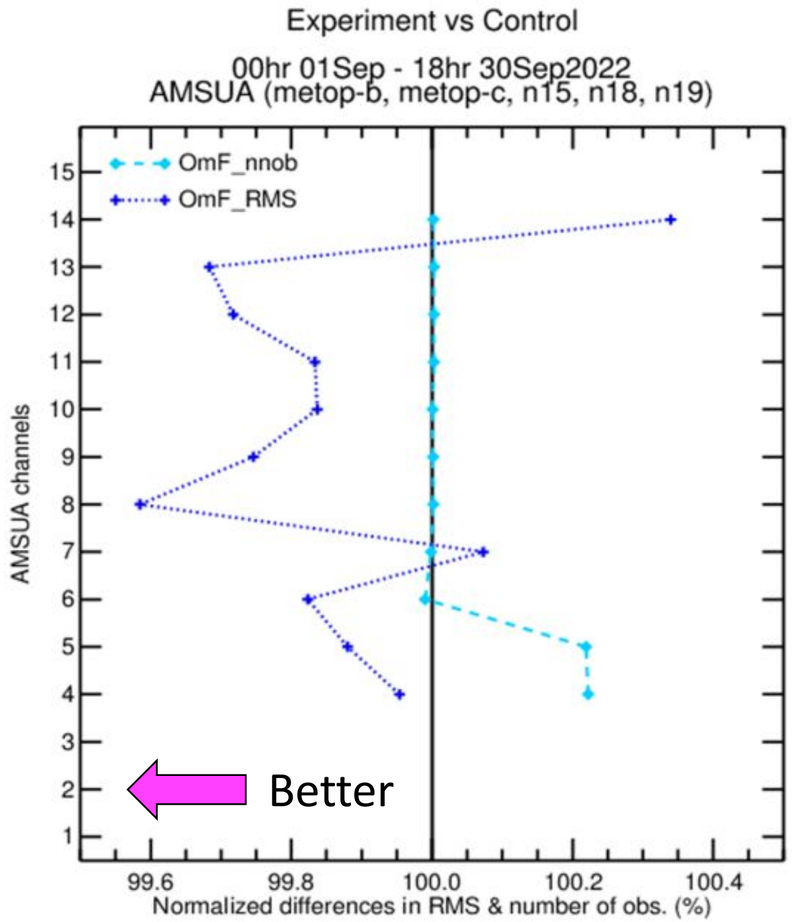


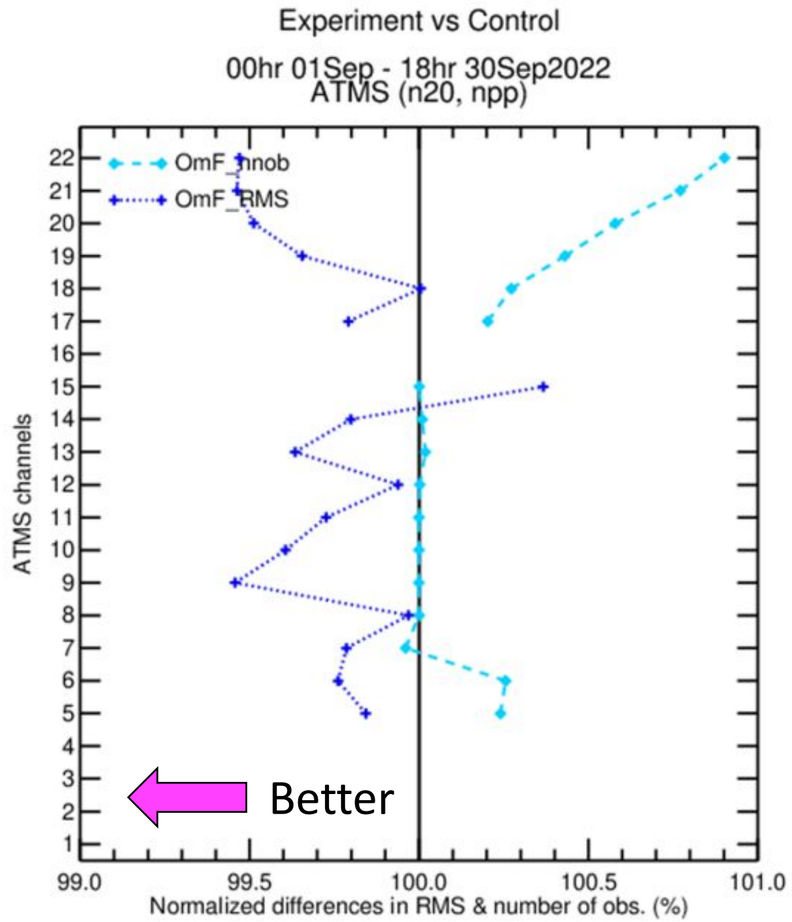
Tropics (40N to 40S)



Example from a single day (06 September 2024)

Comparison Between ROMEX Control and Experiment: Microwave Instruments

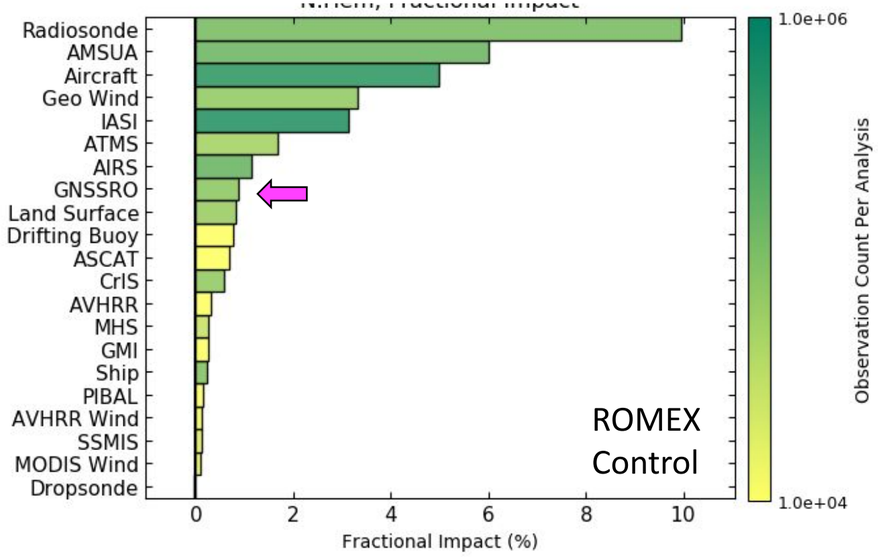


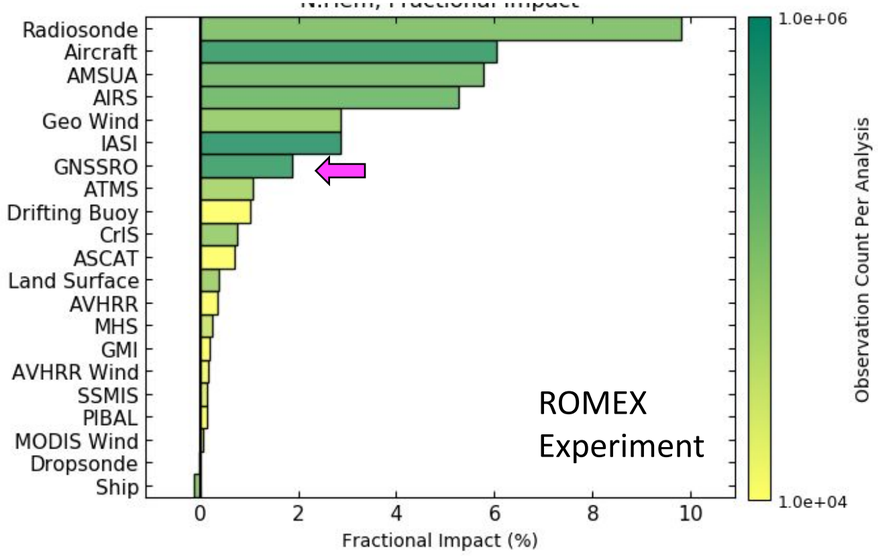


There is an improvement in the performance of the MW instruments with the assimilation of commercial GNSS-RO data where the RMSE is reduced for mostly all channels, except Channel 14. Channel 14 is not bias corrected in the GMAO systems.

Preliminary Results on ROMEX: FSOI in Northern Hemisphere

- Forecast Sensitivity-based Observation Impacts (FSOI)
  - Utilizes the components of a variational DA system
  - Provides impact of any observation or group of obs
  - Impact is on accuracy of short-term (usually 24 hour forecast)
  - Computationally inexpensive (relatively)
- Potential applications
  - Impact of commercial RO as a whole
  - Impact of individual constellations/satellites
- Initial results are promising for ROMEX
  - Larger fraction impact for Experiment





Results for Northern Hemisphere 20N to 90N

Preliminary Results on ROMEX: FSOI in Tropics

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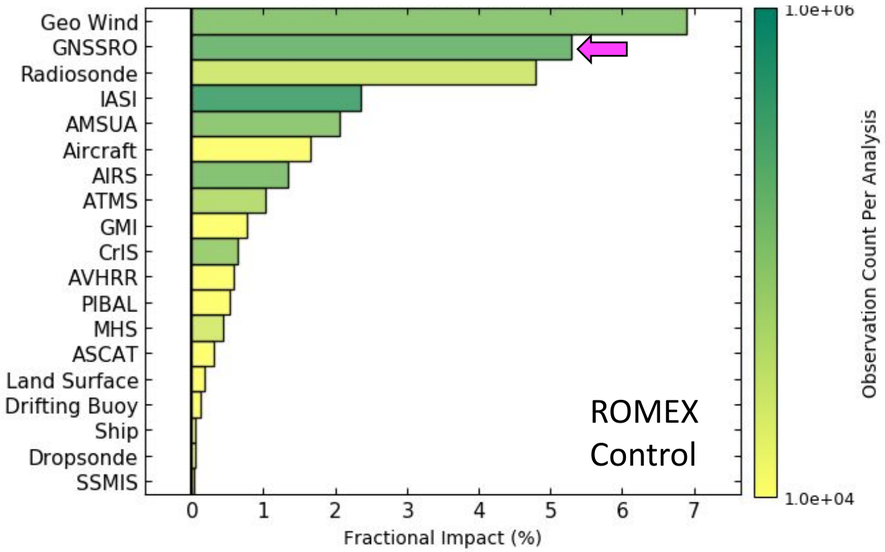
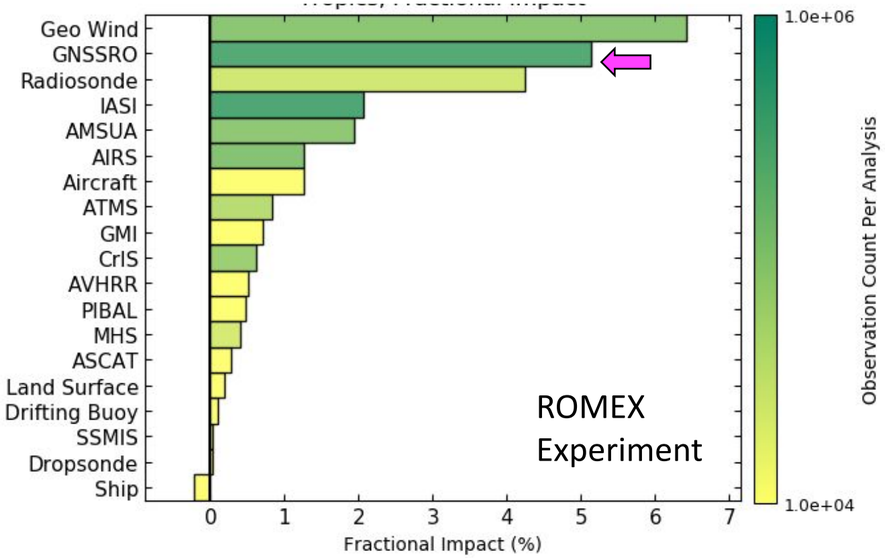
  - Computationally inexpensive (relatively)
- Potential applications
  - Impact of commercial RO as a whole
  - Impact of individual constellations/satellites
- Initial results are promising for ROMEX
  - Larger fraction impact for Experiment
    - Less in tropics





Results for Tropics 20N to 20S

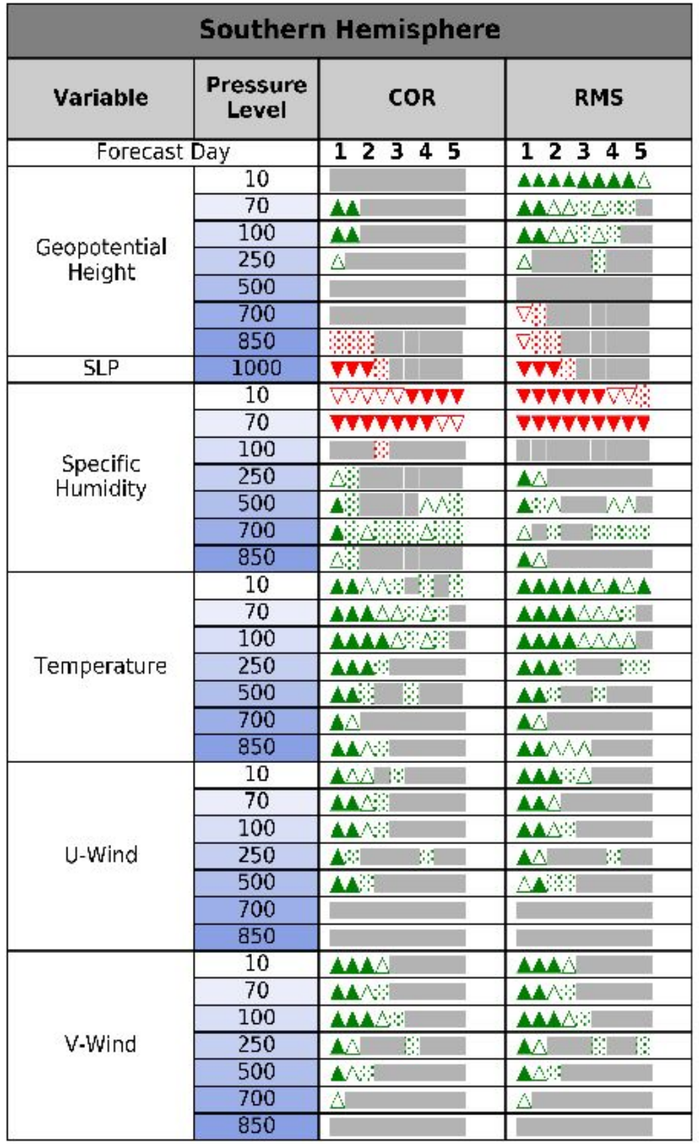
Future Work on ROMEX: Forecast Impact

Example of type of forecast evaluation

- Forecast skill card
  - Southern Hemisphere only
  - Forecasts out to 5 day
  - Main pressure levels

Legend

- ▲ far better, significant (99.99% confidence)
- △ better, significant (99% confidence)
- ⁘ slightly better, significant (95% confidence)
- ■ no significant difference
- ⁘ slightly worse, significant (95% confidence)
- ▽ worse, significant (99% confidence)
- ▼ far worse, significant (99.99% confidence)



Example of Forecast Skill Card

Summary & Conclusions

Observation uncertainties & QC method for RO

- GMAO is experimenting with different methods
  - One goal is to use more of the available RO observations in the DA system
- Initial results suggest the method used by the ECMWF is not improving over the method currently used in GEOS
  - Further investigation is currently being carried out
  - Potentially related to QC criteria

The Radio Occultation Modeling Experiment (ROMEX)

- GMAO is participating in ROMEX along with multiple operational NWP centers
- Initial results are encouraging
  - Commerical RO obs are of good quality
  - Increased volume of RO obs appears to be improving the analyses and short term forecast
- Further work investigating the impact of the forecast will be carried out
  - Results will be compared with other operational NWP centers

The End

Contact:
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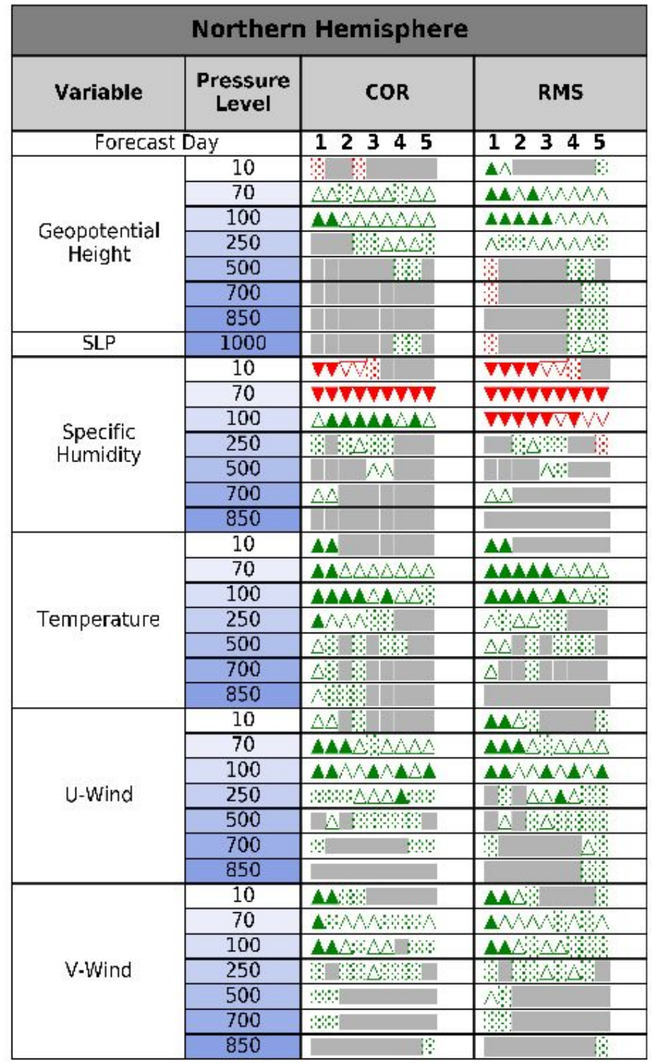
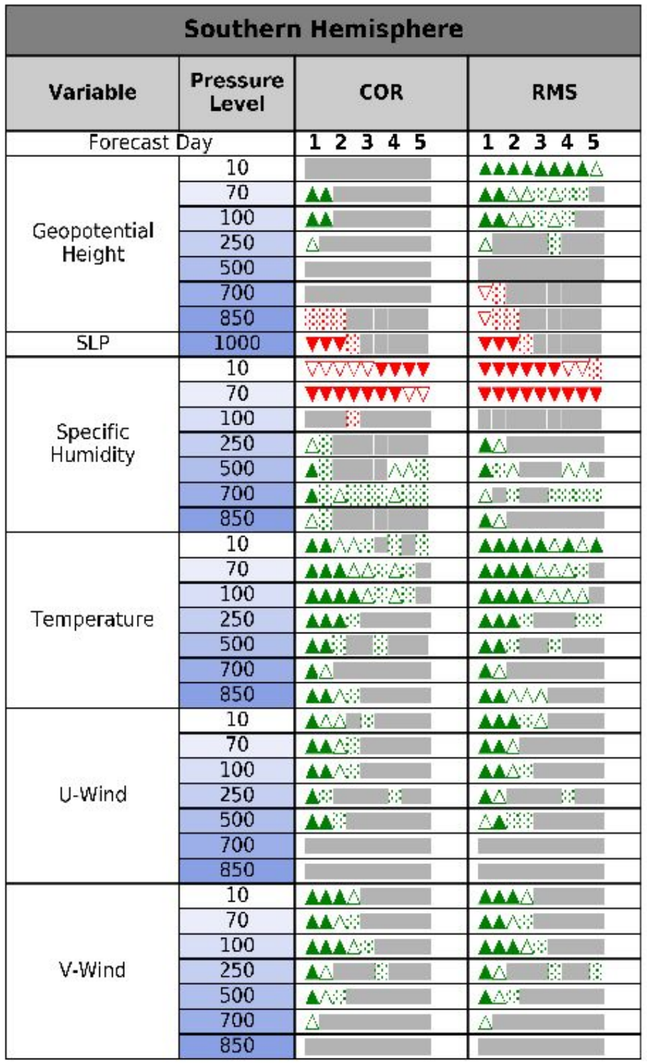
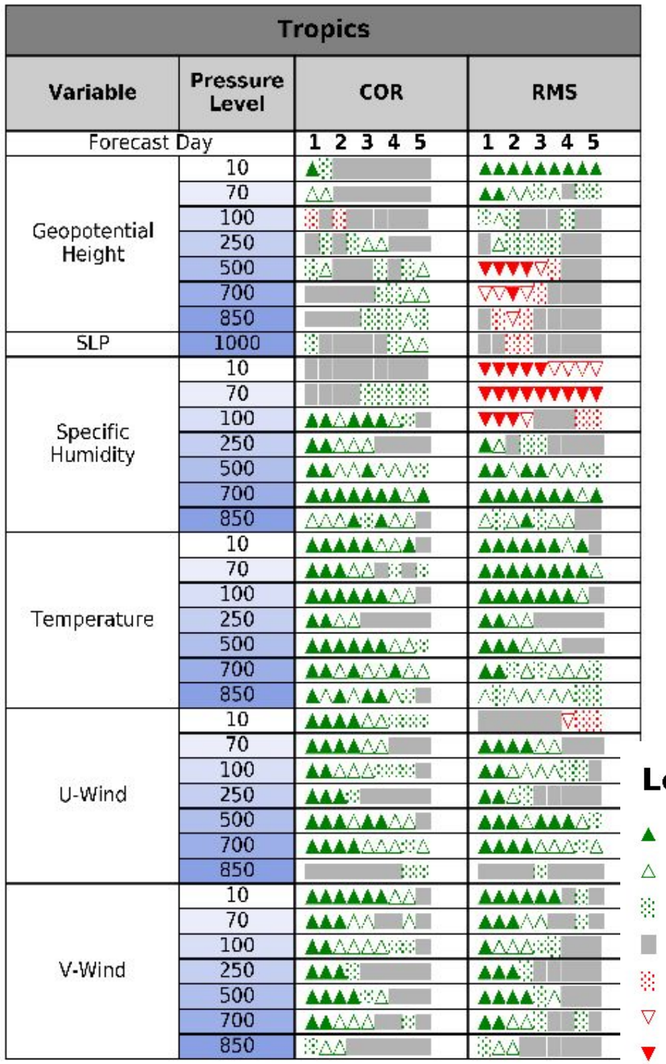
Forecast Skill Card Example







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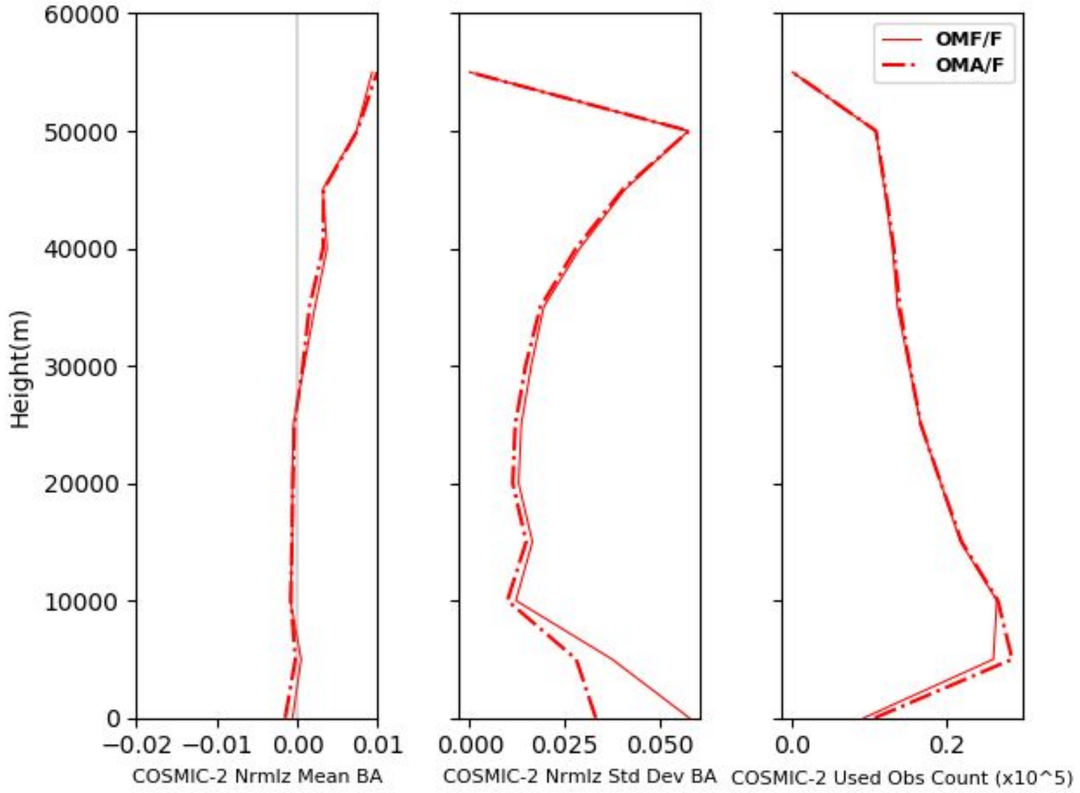
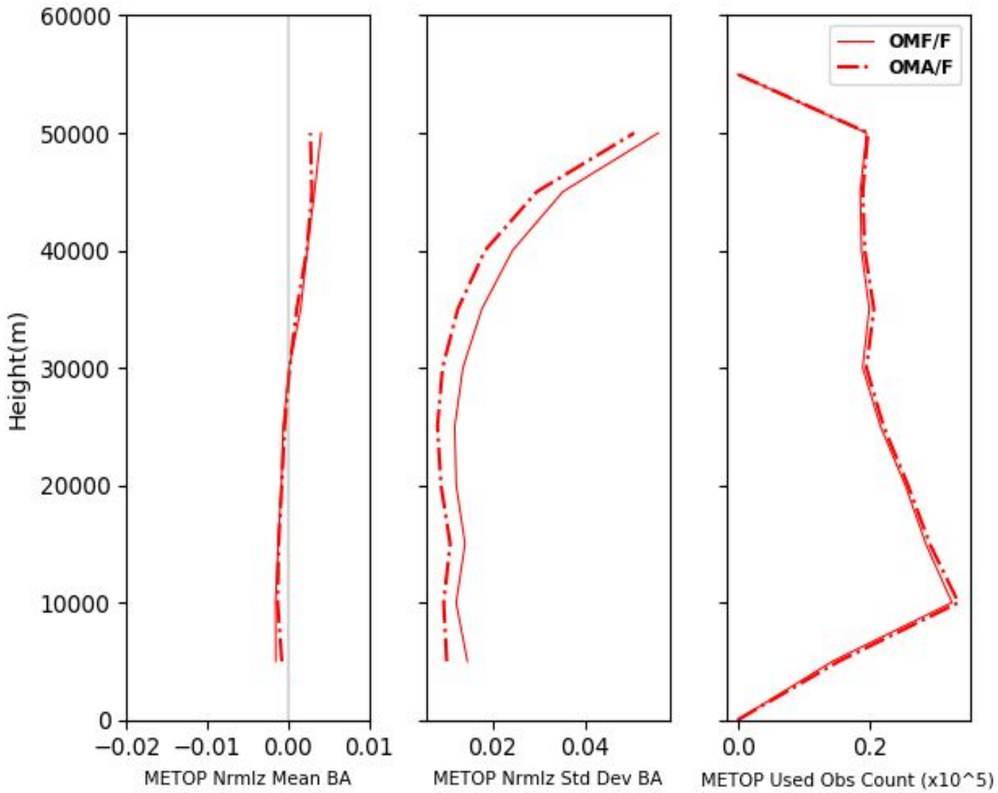
Comparison of Bending Angle OMF/F and OMA/F : Mean, Std Dev and Counts

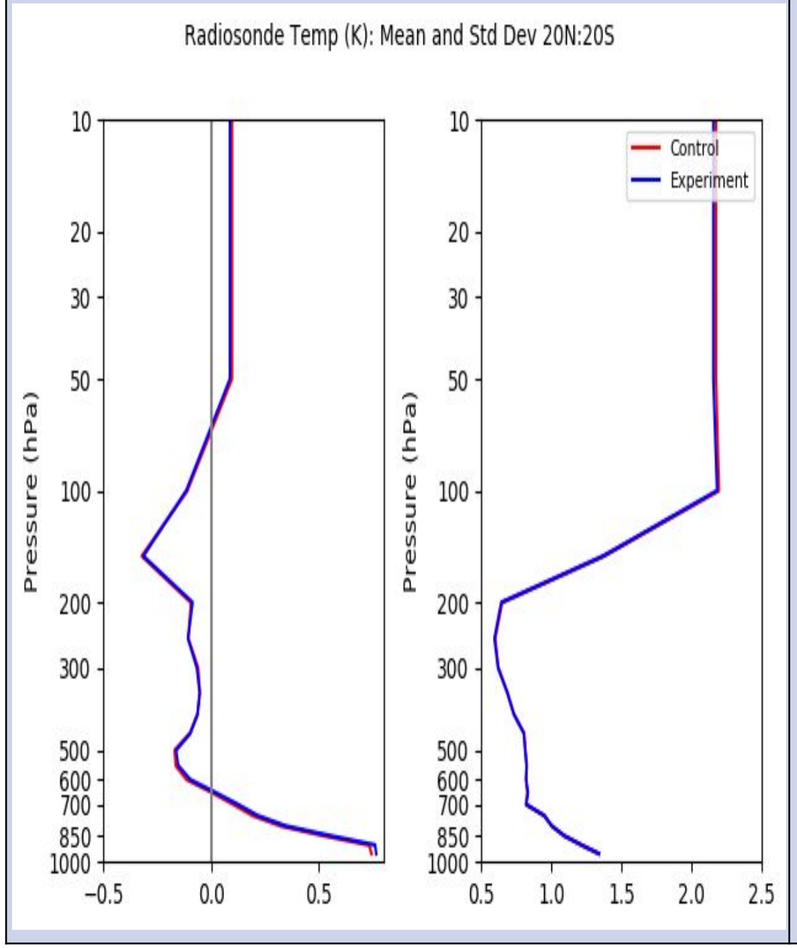
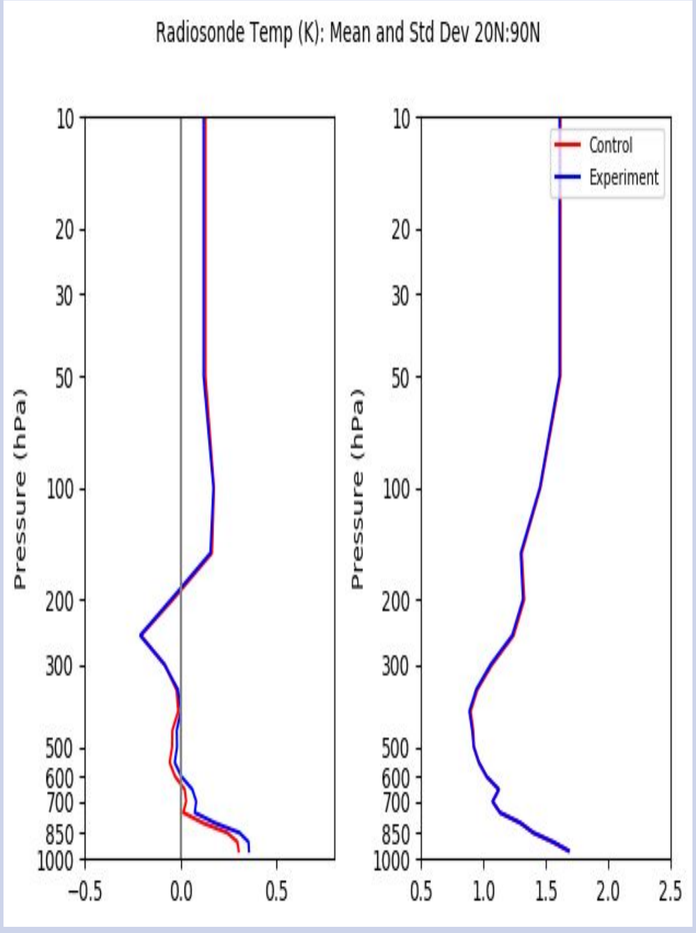
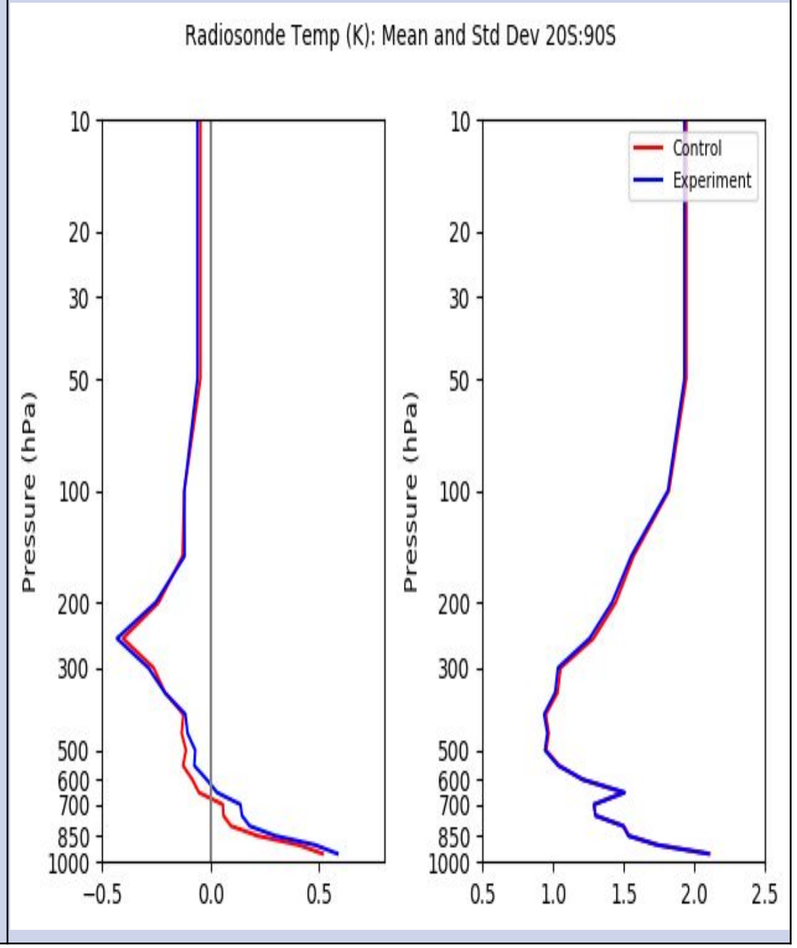
COSMIC-2



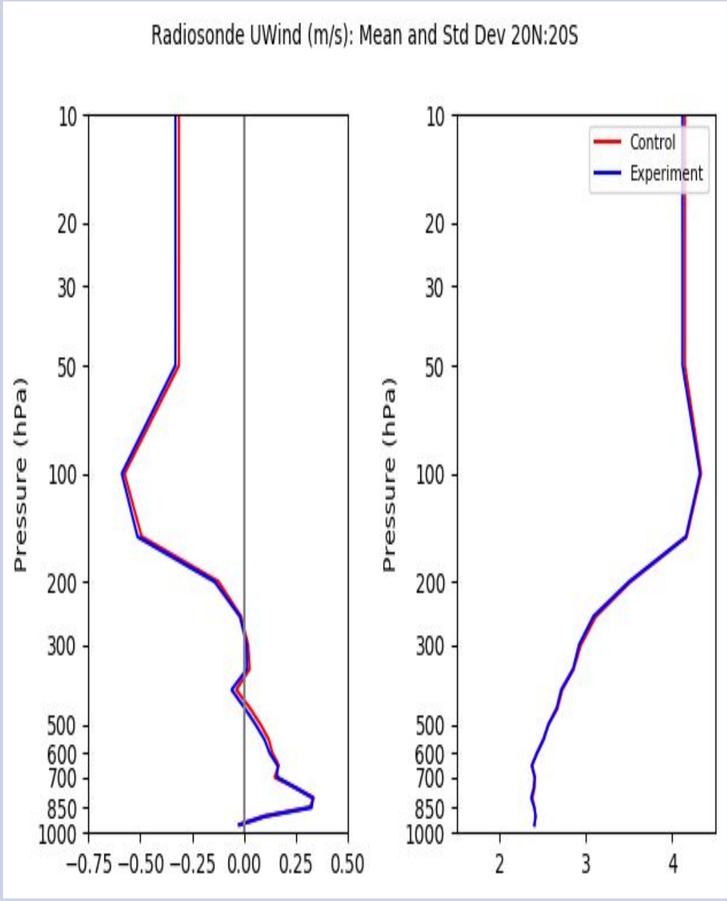
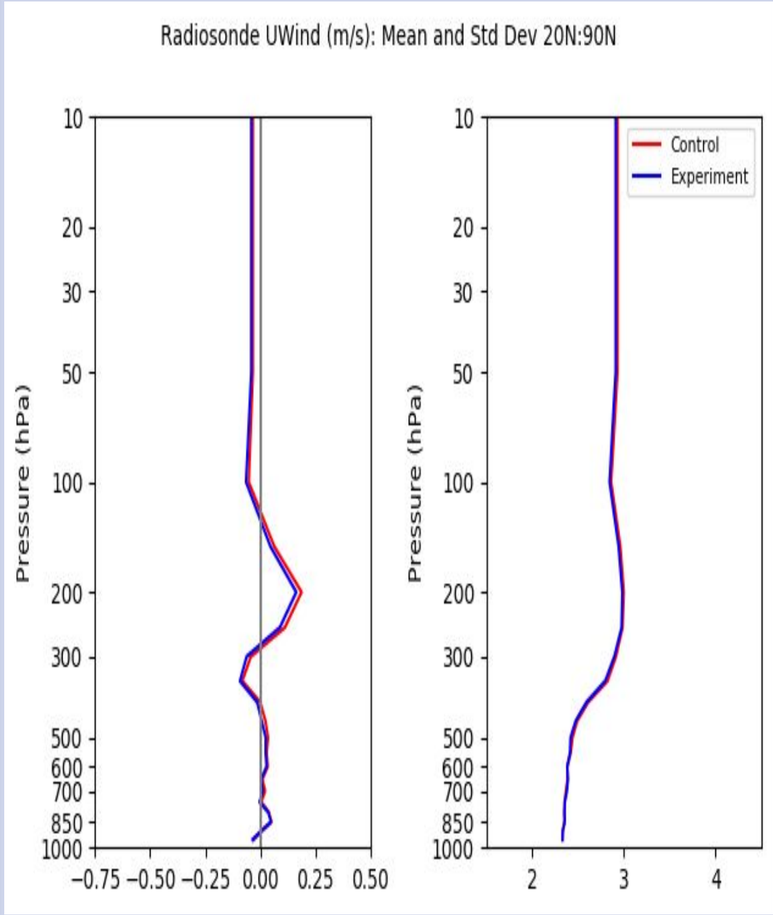
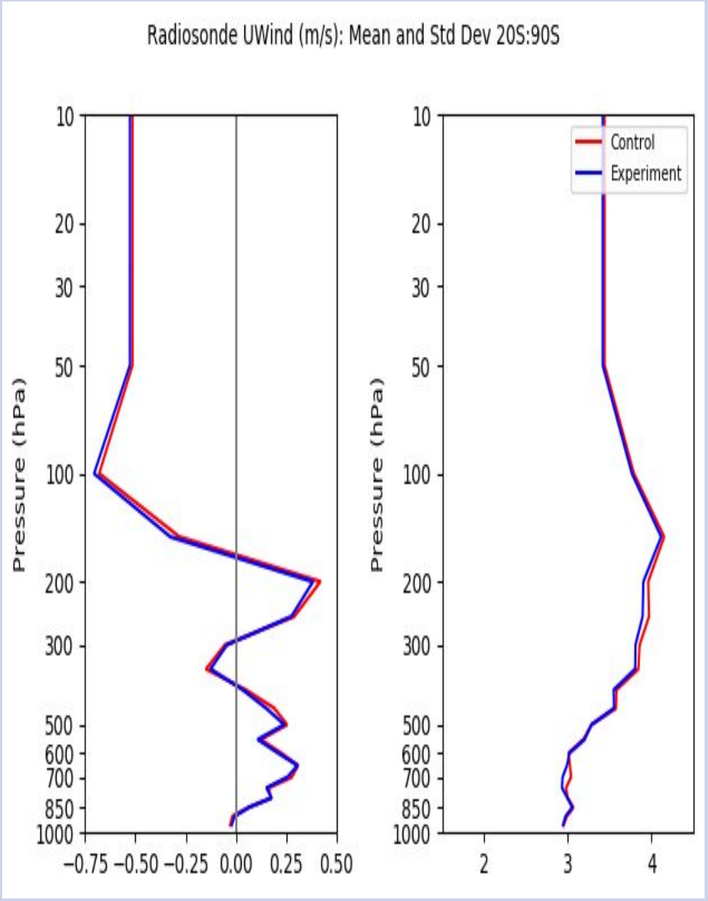
Metop



Comparison Between ROMEX Control and Experiment: Radiosonde Temperature

Tropics	N-Hem	S-Hem
		

Comparison Between ROMEX Control and Experiment: Radiosonde Zonal Wind

Tropics	N-Hem	S-Hem
		

Preliminary Results on ROMEX: FSOI in Southern Hemisphere

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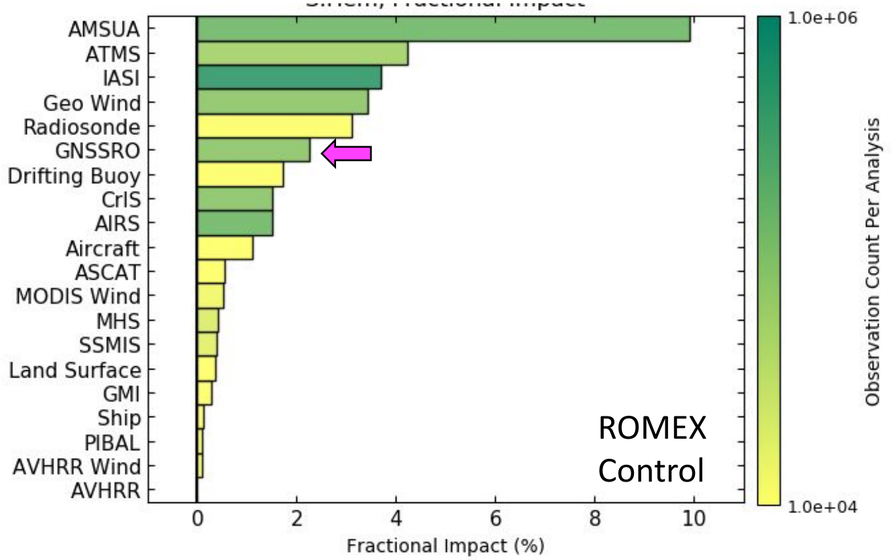

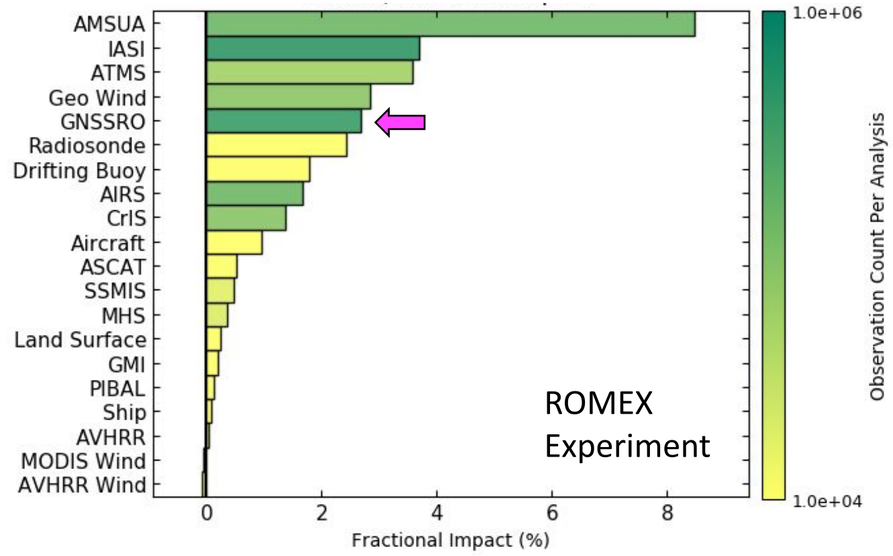

Results for Southern Hemisphere 20S to 90S

Future Work on ROMEX: FSOI

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