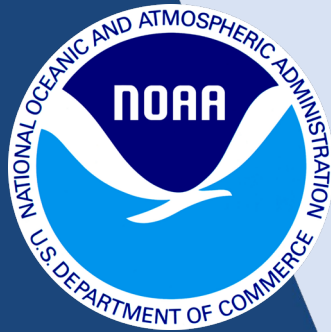


# Advancements in ROMEX Data Processing and Evaluation: Lessons from NOAA/STAR



NOAA National  
Environmental Satellite, Data,  
and Information Service

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William Miller<sup>2</sup>

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Studies (CISS), ESSIC, University of Maryland

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# Outlines

## 1. Summary and Goals

Q1. What lessons we had learned from preparation and processing ROMEX data? COSMIC-2, Spire, PlanetiQ

Q2. RO-RO differences among Missions

Q3. Why viewing geometry is important ?

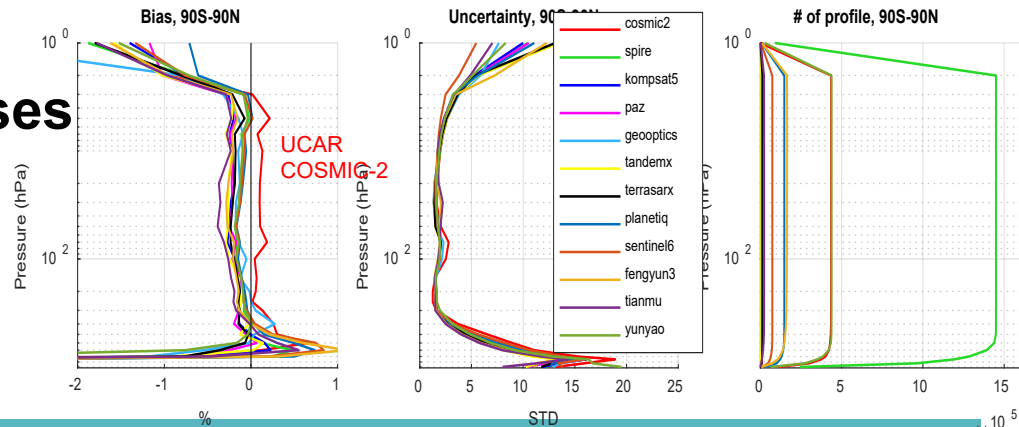
My results shows negative biases of  $\sim -0.1$  to  $-0.4$  from about 4 km up to 35 km for all ROMEX missions except C2, which shows a positive bias of about 0.05 to 0.10 %. So C2 appears to have a positive bias compared to the other missions by about 0.3% (Heights are approximate)

## 2. Approaches and Results

A. RO-RO differences

B. the Causes of RO-RO Biases

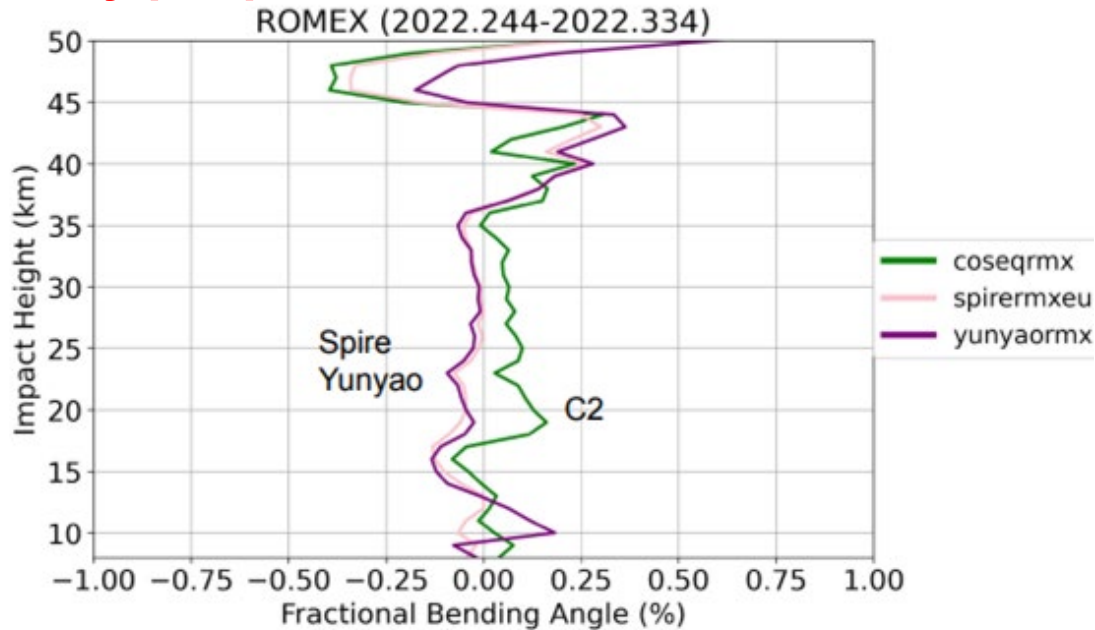
## 3. Conclusions and Recommendations



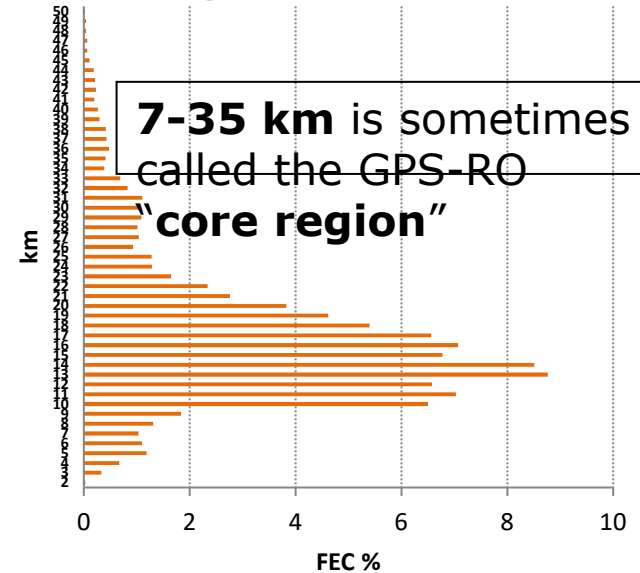
Questions need answer:  
Rick's result (from ROMEX)

RO-RO biases? Processing Errors?

Many people identified the COSMIC-2 biases



Heights where GNSS-RO is reducing the 24hr forecast errors

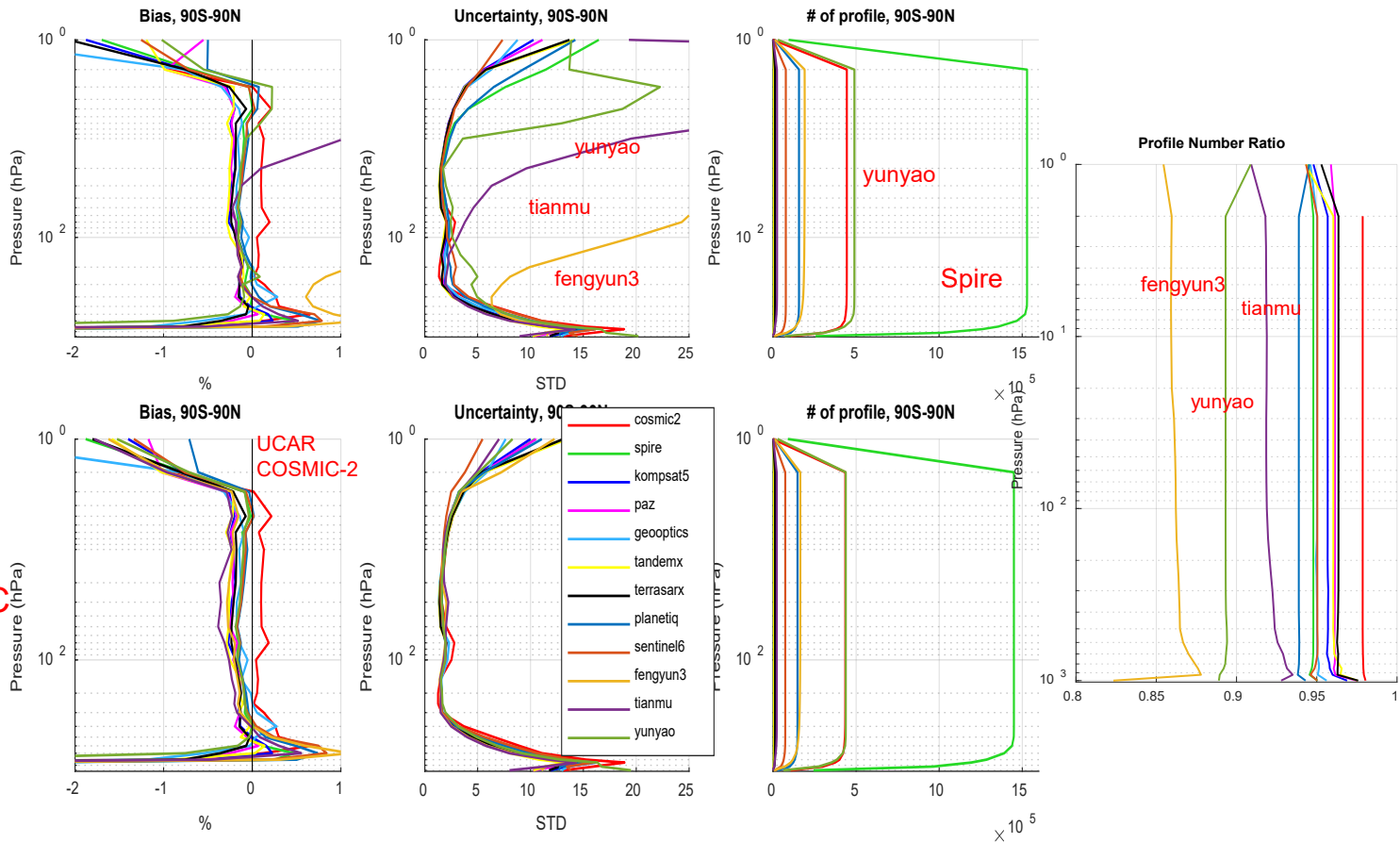


Why these small difference are critical for NWP impact studies and climate applications ?

- A. RO data are used as anchors for other data sets
- B. The 10 km to 30 km ranges are the most accurate and impactful region for NWP and climate
- C. COSMIC-2 and Metop etc data are used as controls for all the other experiments

# ROMEX O-B Bending angle ROMEX before and after additional QC applied at different pressure levels (Global)

Internal QC only



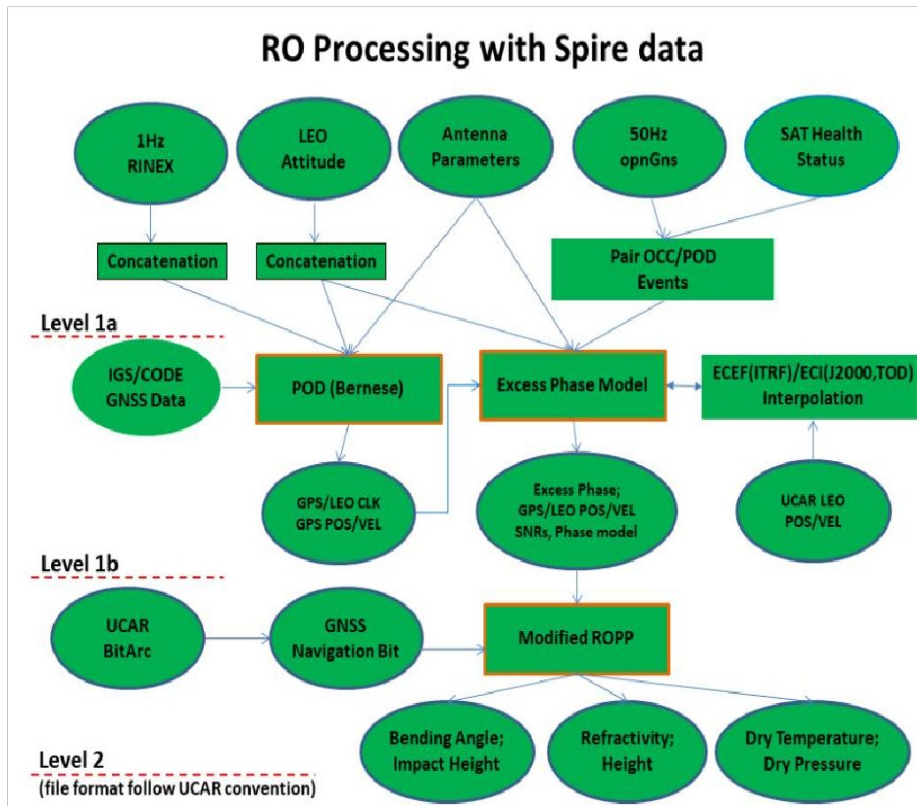
Additional QC



## 2. Approaches and Results

What lessons we had learned from preparation and processing ROMEX data?

### Approach: STAR ROMEX RO data processing



#### Data Download

##### Option 1: Access Data from HTTP server

RO mission	L2: Bending Angle and Refractivity		L2: Temperature and Humidity
	STAR ROPP atmPrf (ATBD)	STAR RFSI atmPrf (Reference)	STAR 1Dvar wetPrf (Reference, ATBD)
COSMIC-2	Data	Data	Data
PlanetQ	Data	Data	Data
Spire	Data	TBD	Data
KOMPASAT-5	<a href="#">Data</a>	<a href="#">Data</a>	<a href="#">Data</a>
PAZ	<a href="#">Data</a>	<a href="#">Data</a>	<a href="#">Data</a>
GRAS Metop-C	<a href="#">Data</a>	TBD	<a href="#">Data</a>
GRAS Metop-B	<a href="#">Data</a>	TBD	<a href="#">Data</a>
GRAS Metop-A	<a href="#">Data</a>	TBD	<a href="#">Data</a>
COSMIC-1	<a href="#">Data</a>	<a href="#">Data</a>	<a href="#">Data</a>
TerraSAR-X	TBD	TBD	TBD
TanDem-X	<a href="#">Data</a>	TBD	TBD
GRACE-A/B	TBD	TBD	TBD
SACC	TBD	TBD	TBD
CNOFS	TBD	TBD	TBD
CHAMP	TBD	TBD	TBD

##### Option 2: Access Data from FTP server

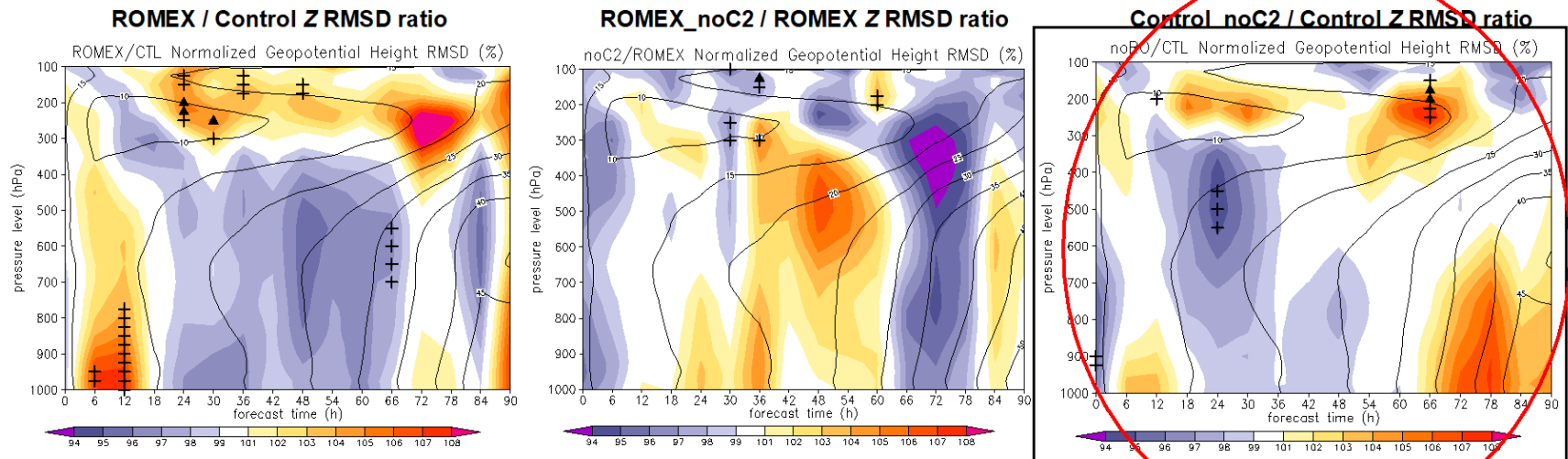
```
ftp starro.umd.edu
username: anonymous
cd starro/data/
## The directory structure is the same as on the HTTP server in option 1
```

Data are available from : <https://gpsmet.umd.edu/gnssro/download.php>

# A. Are C2 biases the reasons for geo-potential height biases in DA? Approaches: Using HAFS to quantify the TC forecast impacts of four experiments

Control\_noC2  
Control  
ROMEX  
ROMEX\_NoC2

## ROMEX and COSMIC-2 DA Impacts on Forecast GPH RMSD



**Adding the ROMEX data on top of C2 (left) reveals mixed impacts:**

- improves lower- and middle-tropospheric geopotential height RMSD for medium-range forecasts
- degrades geopotential height RMSD for short-range forecasts, especially in the lower troposphere

**•When removing C2 but keeping the ROMEX data (middle) or without ROMEX data (right), effects are also mixed:**

- for both cases, removing C2 data improves lower-to-middle tropospheric height RMSD in the analysis/short-range forecasts

**Miller et al., Does Assimilating PlanetIQ and Spire GNSS RO Bending Angles Improve HAFS Atlantic Hurricane Forecasts? An Evaluation in Support of the ROMEX Experiment. AMS 2025, Jan. 13-17, New Orleans, USA.**

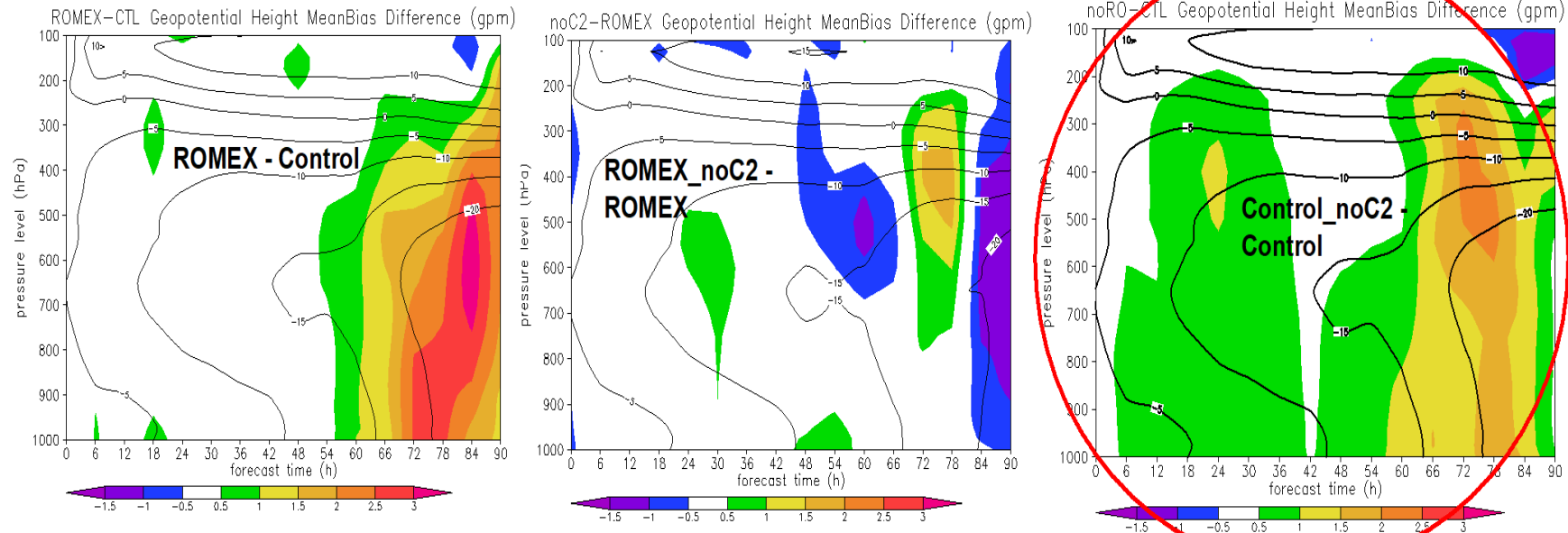
# ROMEX and COSMIC-2 DA Impacts on Forecast GPH Bias

Control\_noC2  
Control  
ROMEX  
ROMEX\_NoC2

Contours: Control Z bias (g/kg)  
Shading: Change in Z bias after adding CWD (g/kg)

Contours: ROMEX Z bias (g/kg)  
Shading: Change in Z bias after removing C2 (g/kg)

Contours: Control Z bias (g/kg)  
Shading: Change in Z bias after removing C2 from Control (g/kg)



- All HAFS configurations forecast a negative Z bias below 300 hPa and a positive Z bias above 300 hPa
- Adding the ROMEX commercial RO data to COSMIC-2 helps mitigate HAFS's negative Z bias after  $t = 60$  h (left)
- Removing COSMIC-2 data from Control also helps mitigate HAFS's negative Z bias for most forecast periods (right), which suggests that assimilated **COSMIC-2 RO data contributes to HAFS's negative Z bias below 300 hPa**

Miller et al., Does Assimilating PlanetIQ and Spire GNSS RO Bending Angles Improve HAFS Atlantic Hurricane Forecasts? An Evaluation in Support of the ROMEX Experiment. AMS 2025, Jan. 13-17, New Orleans, USA.



# B. The distribution of UCAR C2 biases

## The UCAR COSMIC-2 biases change with time

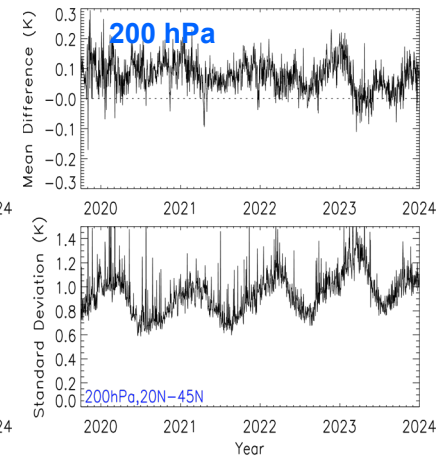
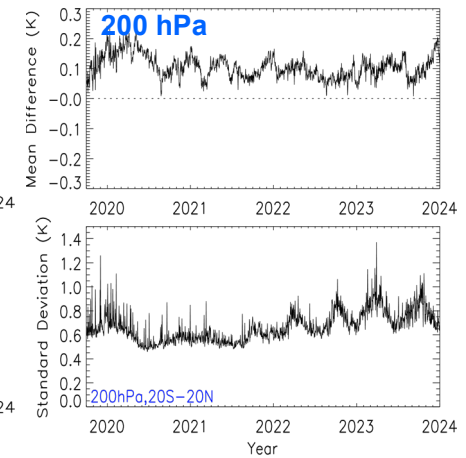
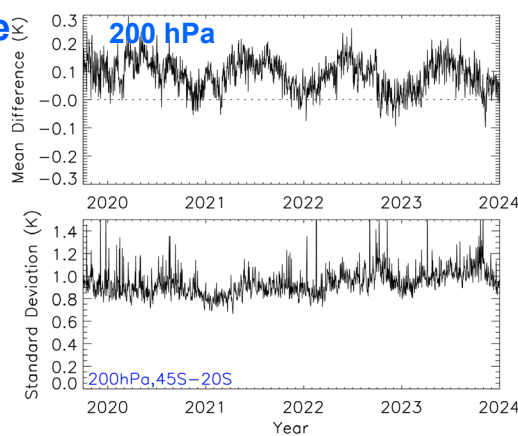
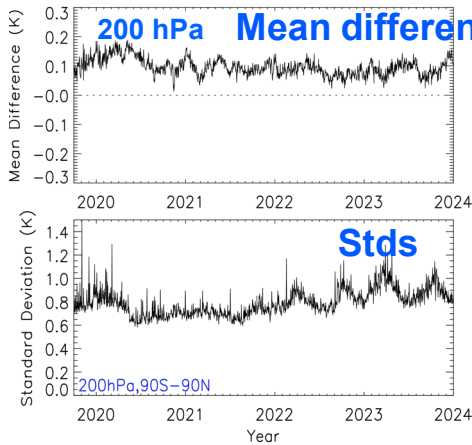
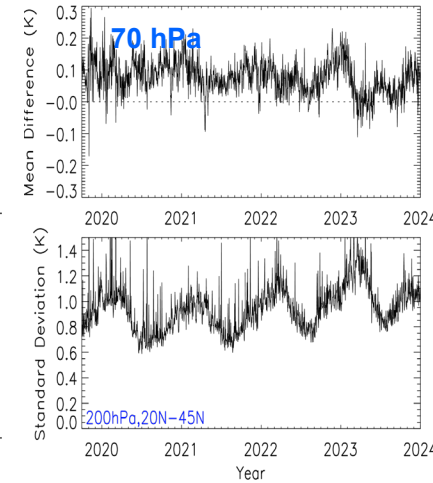
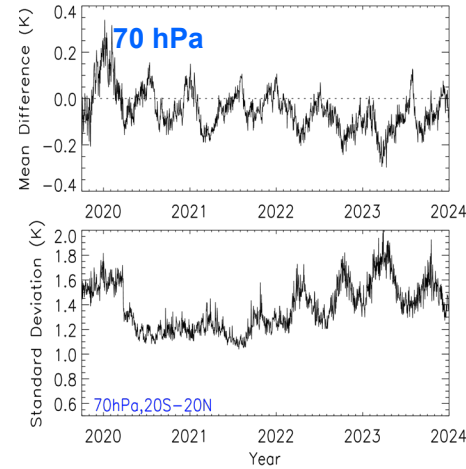
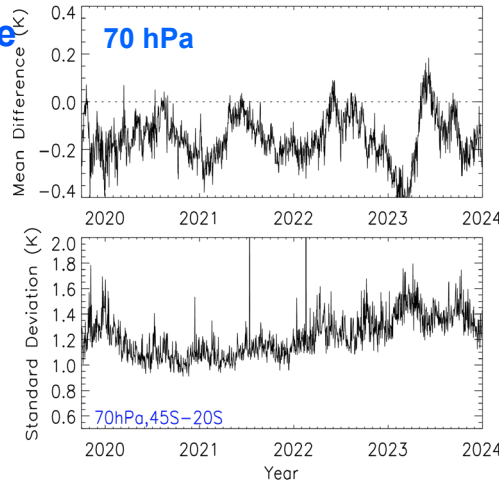
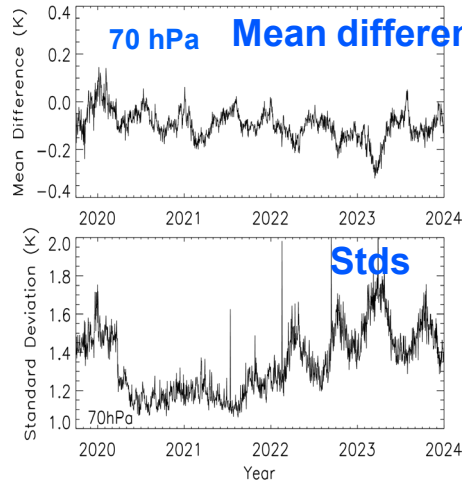
UCAR COSMIC-2 – ERA5

Temperature 45S-45N

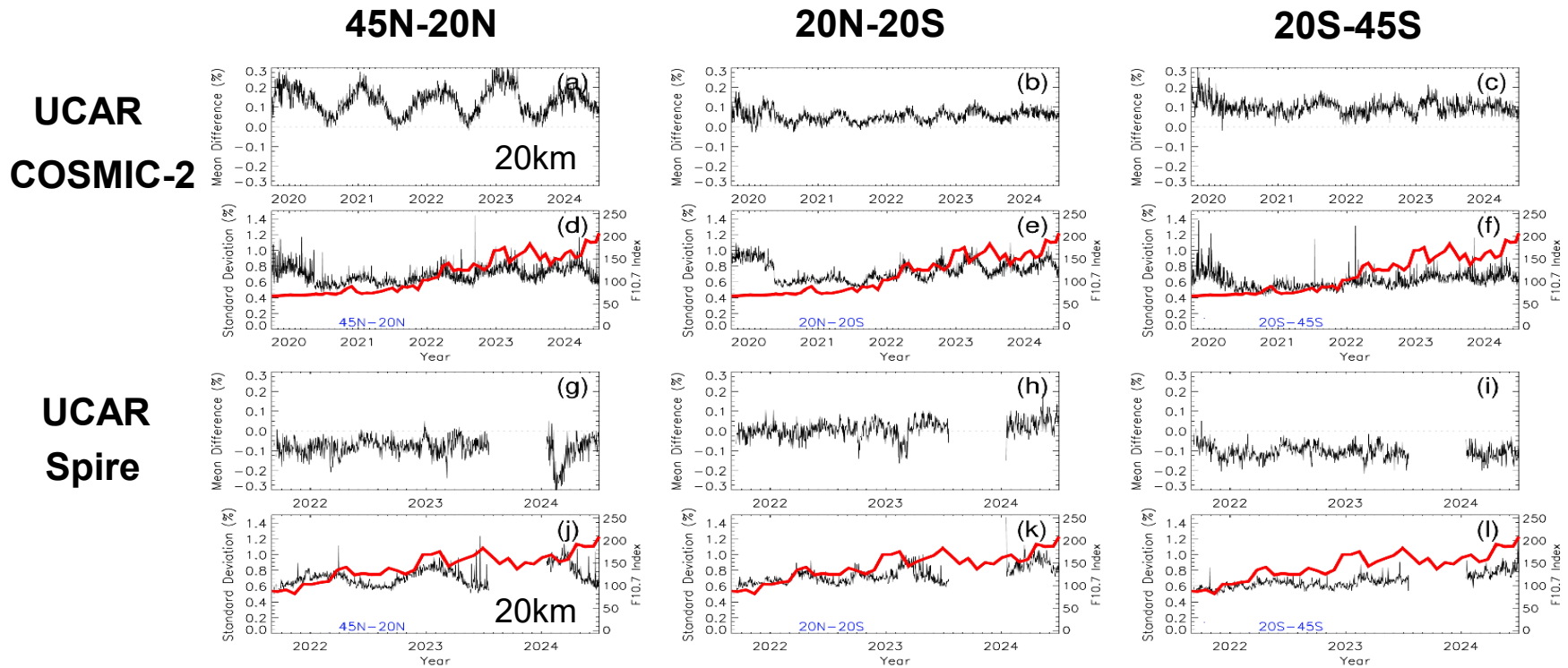
Temperature 45S-20S

Temperature 20S-20N

Temperature 20N-45N

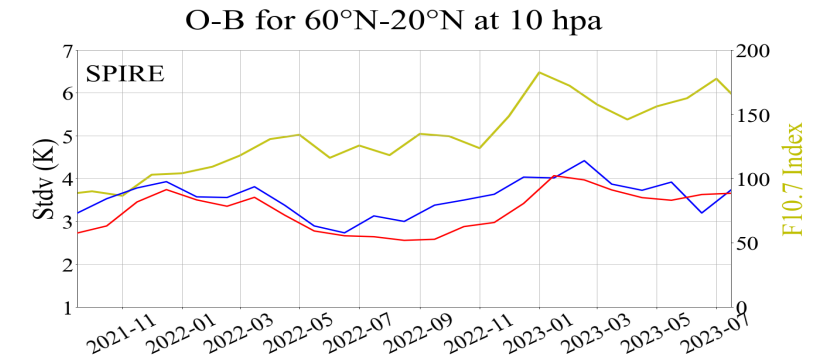
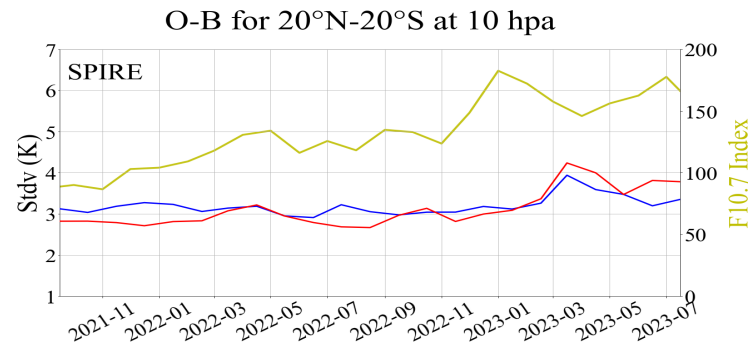
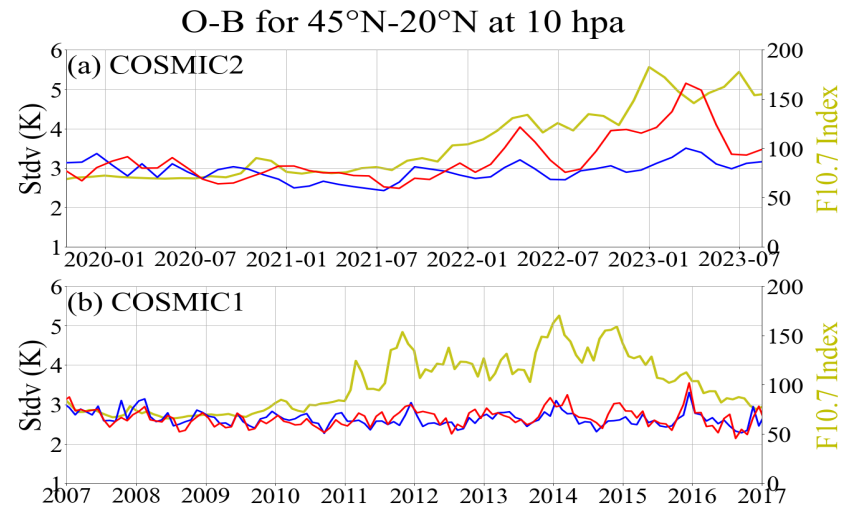
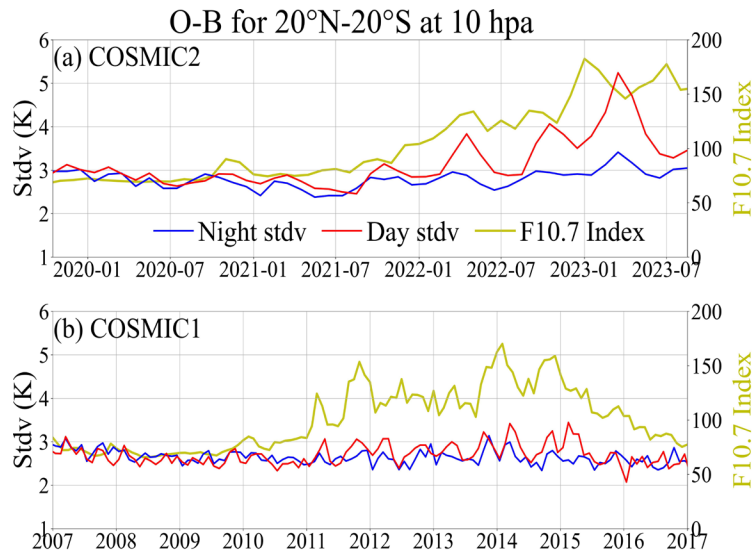


# C. What are the time series of UCAR C2-ERA5 and Spire –ERA5 biases at different latitudes? C2-ERA5 vs Spire –ERA5 differences



Time series of daily mean and standard deviation of the differences between COSMIC-2 and ERA-5 fractional refractivity at 20 km from Oct. 2019 to June 2024 ((a)-(f)), and between SPIRE and ERA-5 fractional refractivity differences from June 2021 to June 2024 at 20 km ((g)-(l)), for 45°N-20°N (left), 20°N-20°S (middle), 20°S-45°S (right). The overplotted red lines represent the 15-day average of the F10.7 index (1 sfu= $10^{-22}$ Wm<sup>-1</sup>Hz<sup>-1</sup>). (Zhou et al., 2025, JGR)

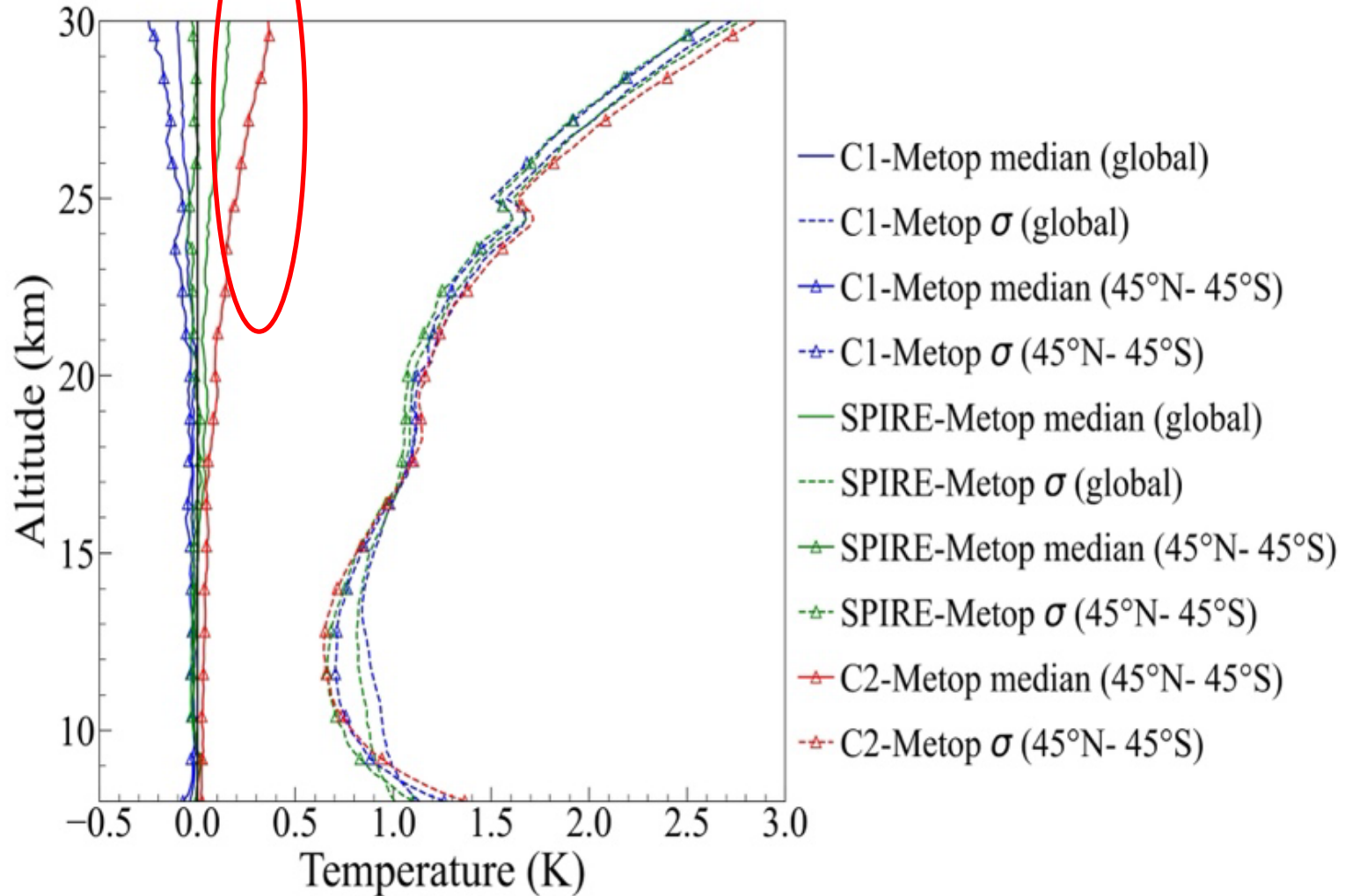
## D. What are the time series of UCAR C2-ERA5 and Spire –ERA5 biases at daytime vs nighttime ? C2-ERA5 vs Spire –ERA5 differences



Daytime (red) and nighttime (blue) standard deviation of COSMIC-2 minus ERA-5 (a) and COSMIC-1 minus ERA-5 (b) over the Tropics at 10 hpa. Overplotted is the F10.7 index (yellow).

## F. What are the UCAR C1, Spire, C2 minus Metop differences at different latitudes?

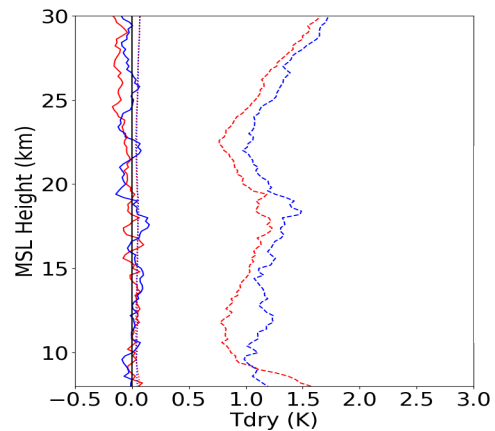
Using UCAR Metop GRAS as references



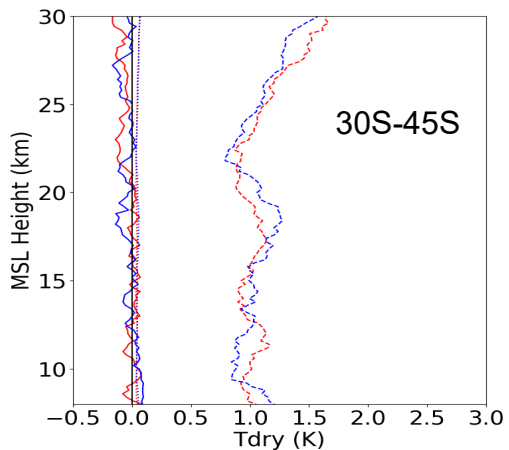
# UCAR COSMIC-1 - Metop

45N-30N

UCAR cosmic1 vs. metop  
45N-30N (2007-10\_2019-1)



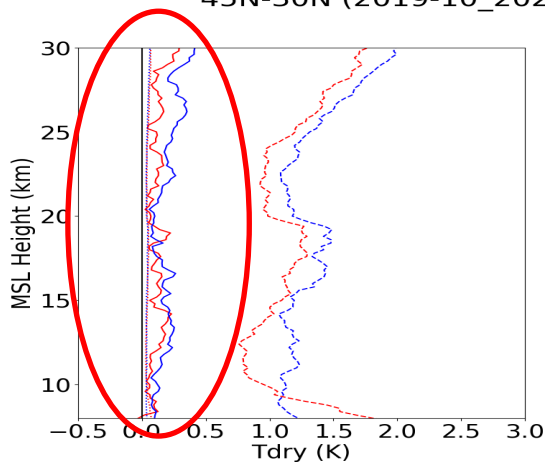
UCAR cosmic1 vs. metop  
30S-45S (2007-10\_2019-1)



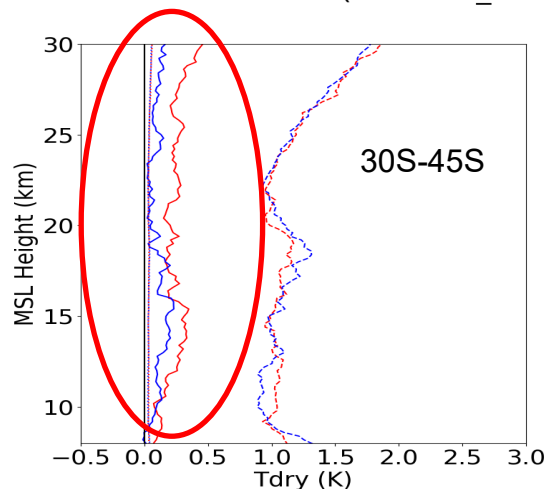
# UCAR COSMIC-2 - Metop

45N-30N

UCAR cosmic2 vs. metop  
45N-30N (2019-10\_2023-04)



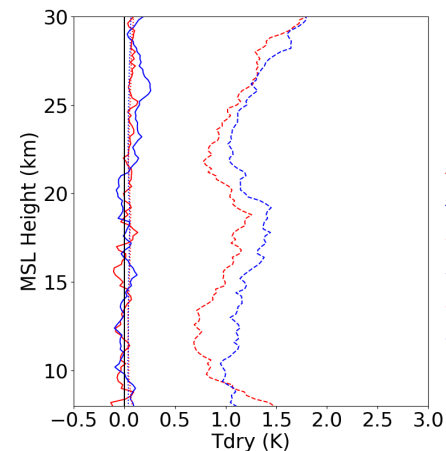
UCAR cosmic2 vs. metop  
30S-45S (2019-10\_2023-04)



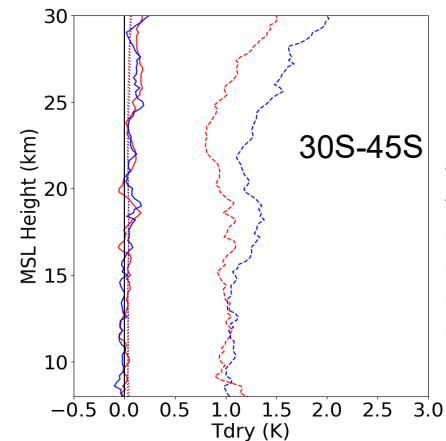
# UCAR Spire - Metop

45N-30N

UCAR spire vs. metop  
45N-30N (2020-12\_2023-04)

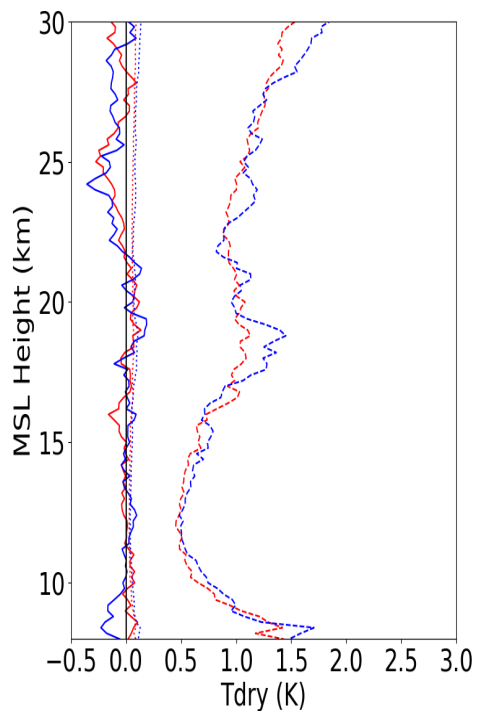


UCAR spire vs. metop  
60N-45N (2020-12\_2023-04)



## UCAR COSMIC-1 - Metop

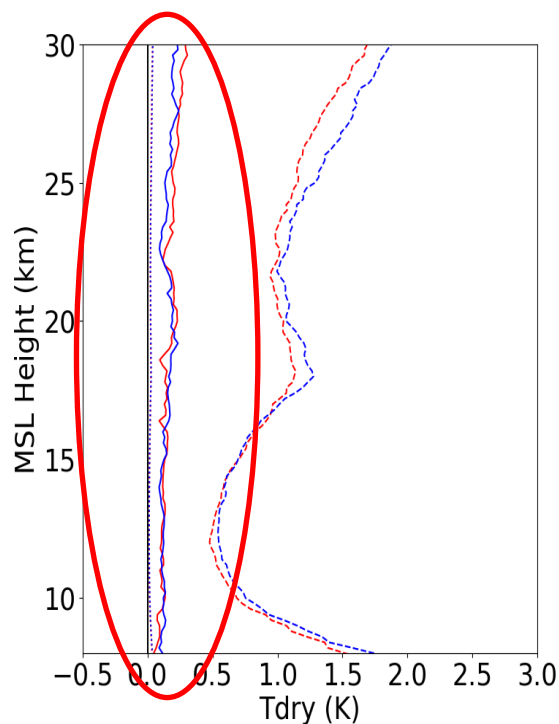
UCAR cosmic1 vs. metop  
10N-10S (2007-10\_2019-12)



## UCAR COSMIC-2 - Metop

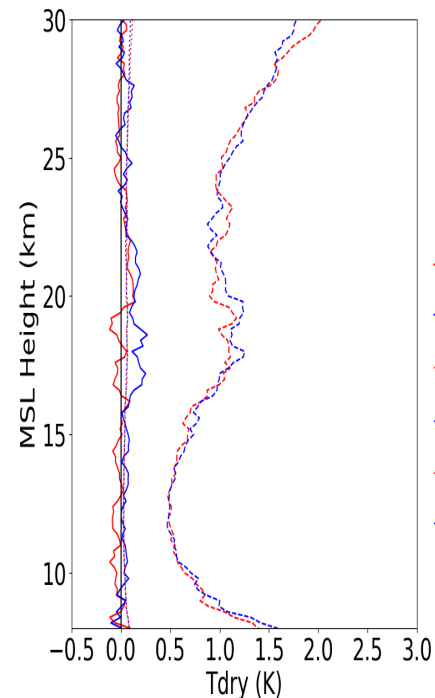
### 10N-10S

UCAR cosmic2 vs. metop  
10N-10S (2019-10\_2023-04)



## UCAR Spire - Metop

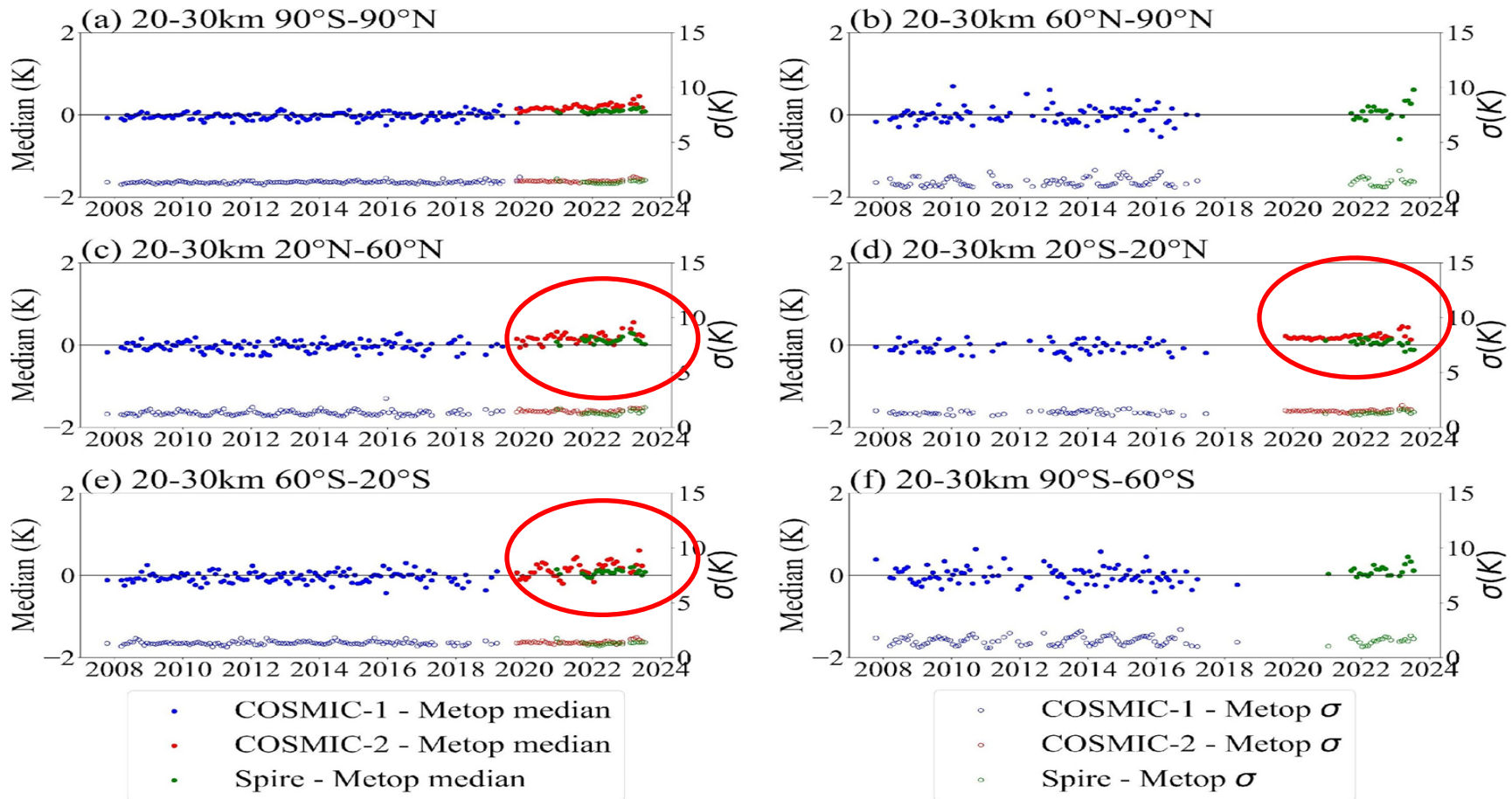
UCAR spire vs. metop  
10N-10S (2020-12\_2023-04)



- median JunJulAug
- median DecJanFeb
- - -  $\sigma$  JunJulAug
- - -  $\sigma$  DecJanFeb
- ⋯ Stderr JunJulAug
- ⋯ Stderr DecJanFeb

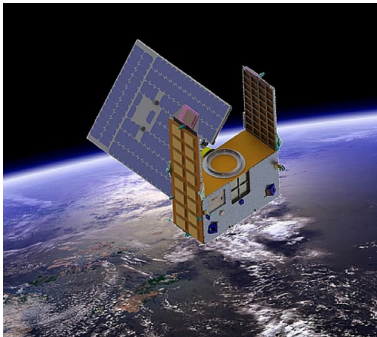
# No satellite-to-satellite bias? RO-RO difference

## UCAR COSMIC-2 – Metop GRAS

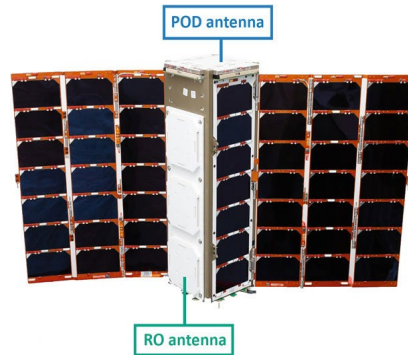


# Causes of the RO-RO biases?

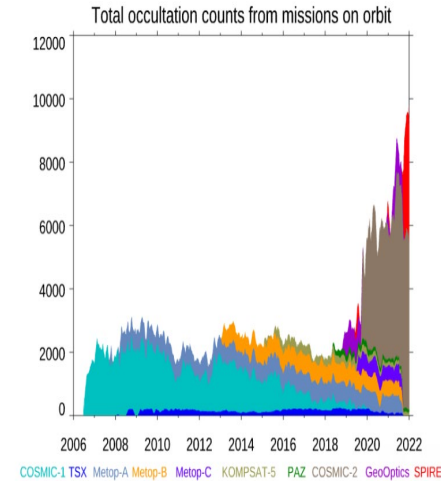
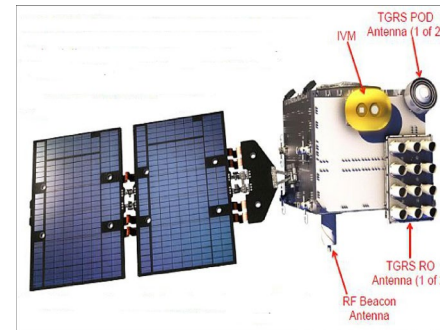
PlanetiQ Patch Antenna Array



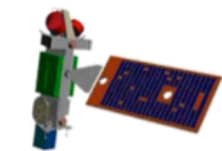
Spire RO 3-Patch Antenna Array



COSMIC-2 Helical Antenna Array

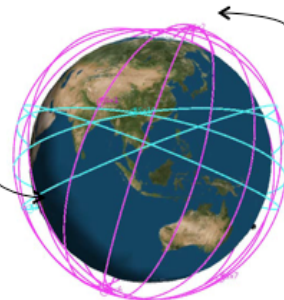


## The Antenna design and Viewing Geometry



6 satellites  
24° inclination  
520 km alt  
5-year life

TriG Radio Occultation System  
Space science payloads



6 satellites  
72° inclination  
800 km alt  
5-year life

TriG Radio  
Occultation System  
Additional payloads  
TBD

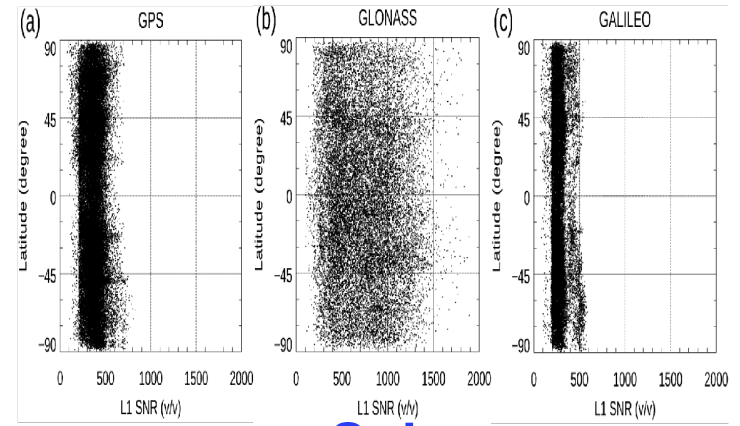
- **High Precision?**
- **No satellite-to-satellite bias?**
- **How high SNR help to decrease observation errors and improve the retrieval accuracy?**

**Challenges to compare multiple RO missions**

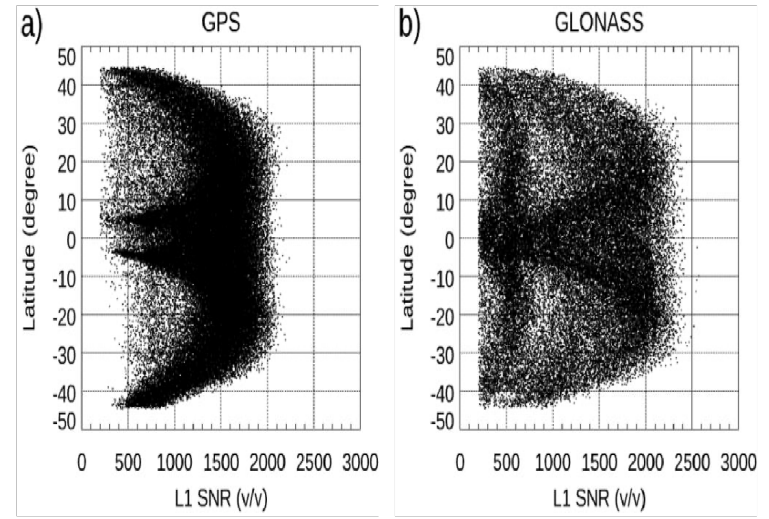
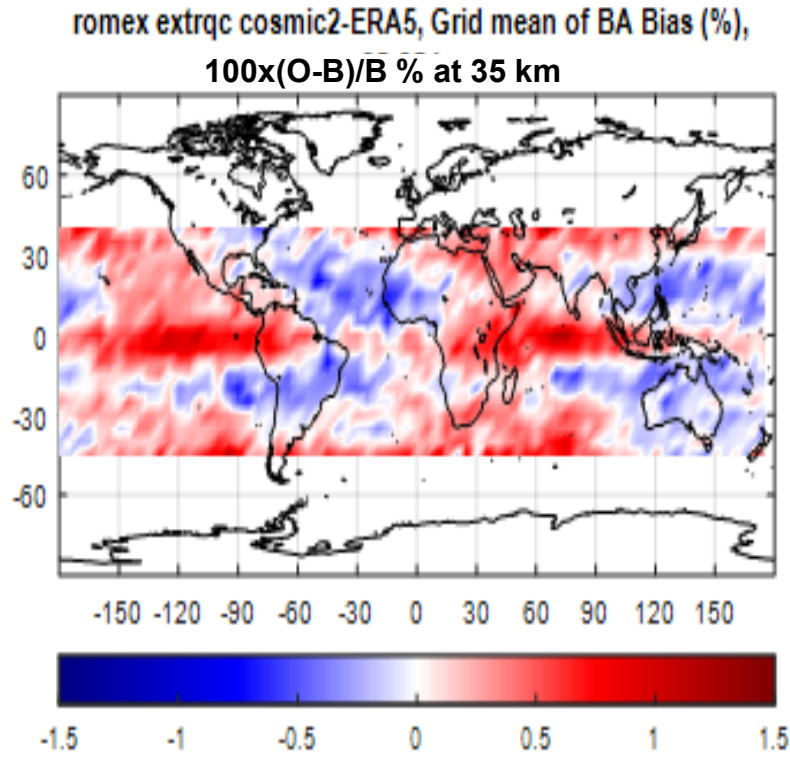
**We need more than one independent RO center to process the same data**

Steiner and Ho et al., (2020); Ho et al., 2010a,b, 2011, 2012, 2013, 2015, 2017, 2018, 2001)

# A. The latitudinal distribution C2 biases may be related to SNR distribution



Spire



COSMIC-2

Ho et al., (2023)

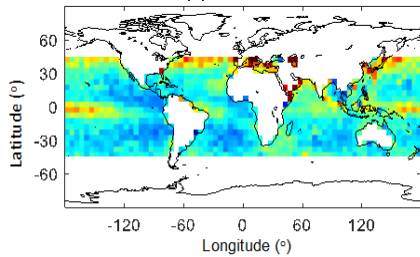


## B. Signal-Noise-Ratio RO data vs. penetration height

The global mean of the lowest penetration height in June 2022 binned into 5°x 5° grid

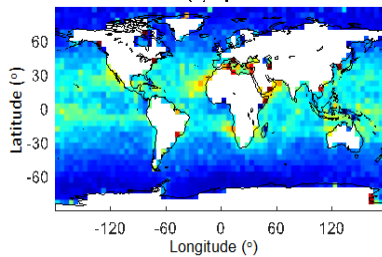
### COSMIC-2

(a) COSMIC-2



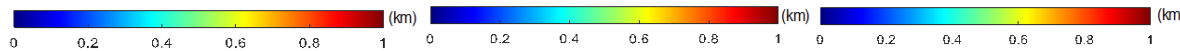
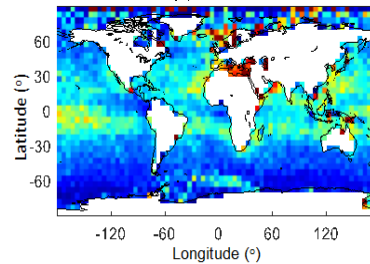
### Spire

(b) Spire



### PlanetiQ

(c) PlanetiQ



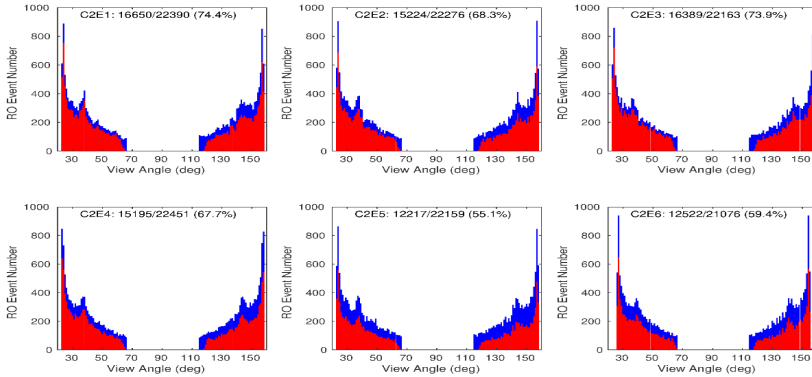
	10°N–10°S	30°N–10°N	10°S–30°S	45°N–30°N	30°S–45°S	60°N–45°N	45°S–60°S	90°N–60°N	60°S–90°S
COSMIC-2	0.79	0.64	0.54	0.99	0.60				
Spire	0.64	0.71	0.55	0.58	0.35	0.38	0.22	0.18	0.11
PlanetiQ	0.72	0.73	0.61	0.59	0.35	0.38	0.22	0.24	0.10

### Penetration Height

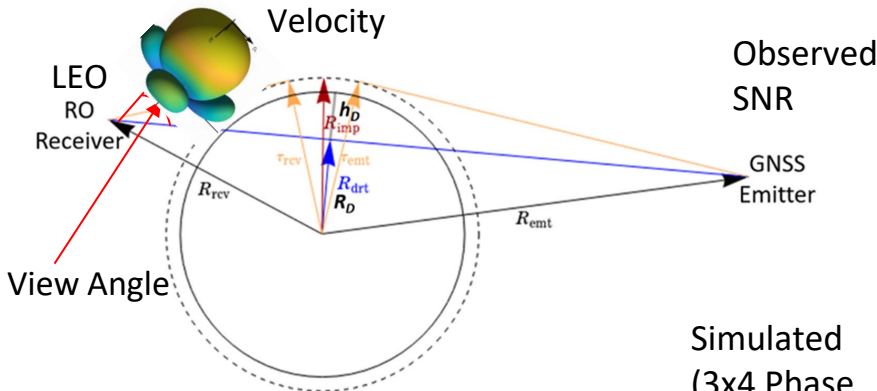
The lowest penetration height of 80% of the total data for different RO missions at different latitudinal zones.

We usually use the SNR to indicate the strength of RO signals in penetrating the lower troposphere (Ho et al., 2023). The lowest penetration height of RO tracking is usually related to the data's SNR and the atmosphere's dryness. However, because the high SNR signals still cannot resolve the combination of i) complexity of water vapor along the track, ii) the turbulence effects, iii) the instrument effect (see Ao et al., 2022), we did not see high SNR RO data improv i) retrieval accuracy, and ii) retrieval uncertainty in the lower troposphere (Ho et al., 2022, 2023).

# COSMIC-2 latitudinal distribution SNR distribution

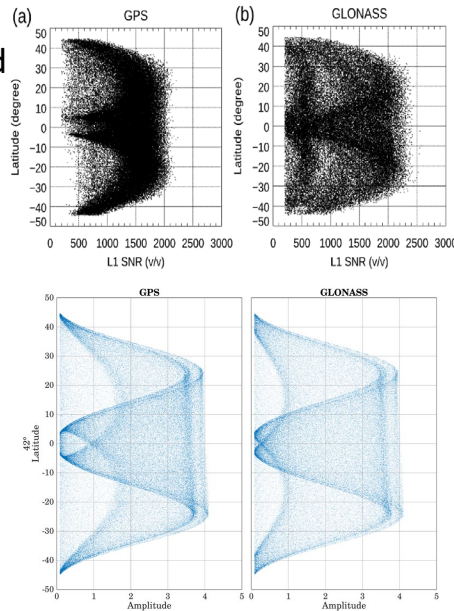


COSMIC-2

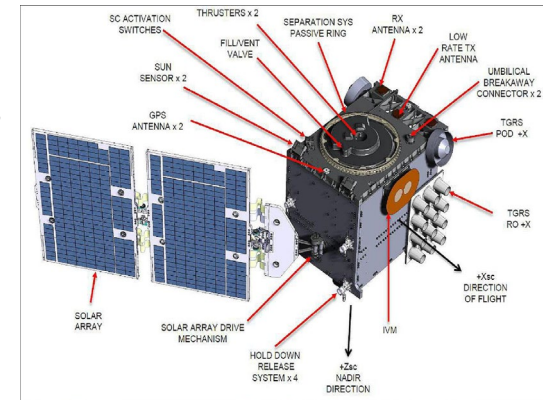
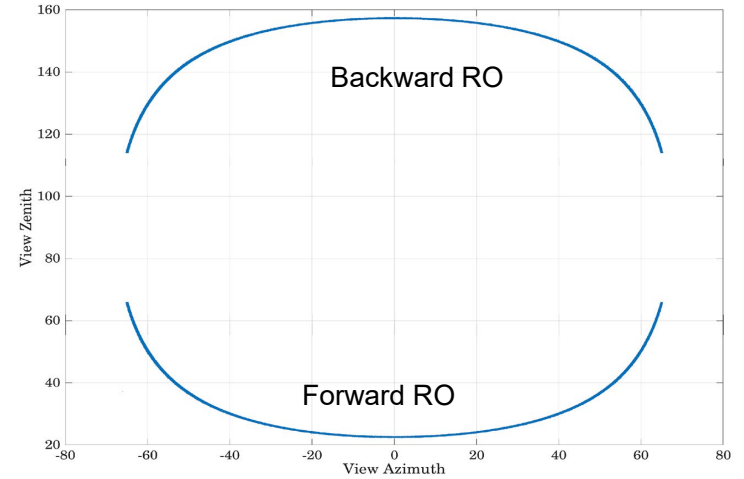


Poster 798: Wed 3:00 pm – 4:30 pm  
 T. Liu: An Antenna-Coupled Simulation Tool to Explore the Optimal Configuration for the NOAA's Future GNSS RO Architecture Missions

Simulated (3x4 Phase Array Antenna)



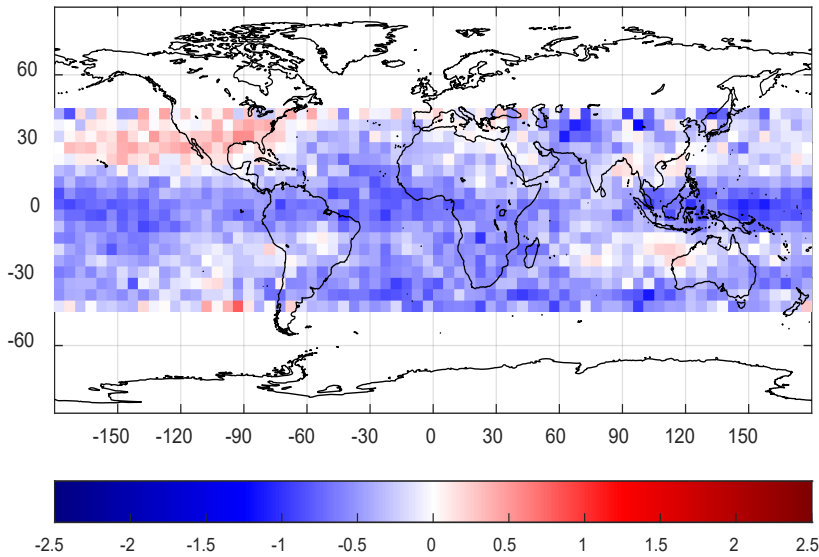
Relationship between View Zenith and View Azimuth Angle for RO Limb Sounding



# C. The latitudinal distribution of C2 biases vs. SNR

Positive fractional BA biases lead to negative temperature biases

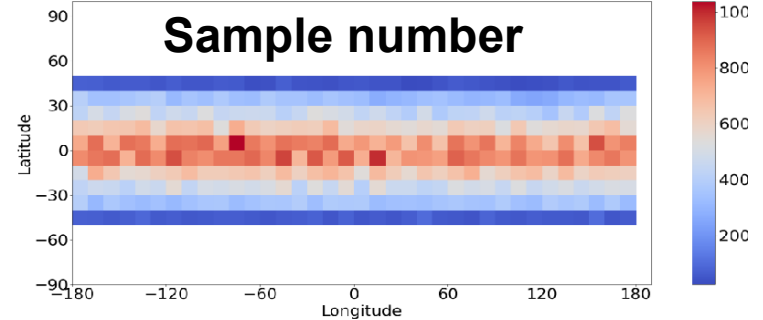
ucar cosmic2-ERA5, Grid mean of T Bias (K), 25-30 km



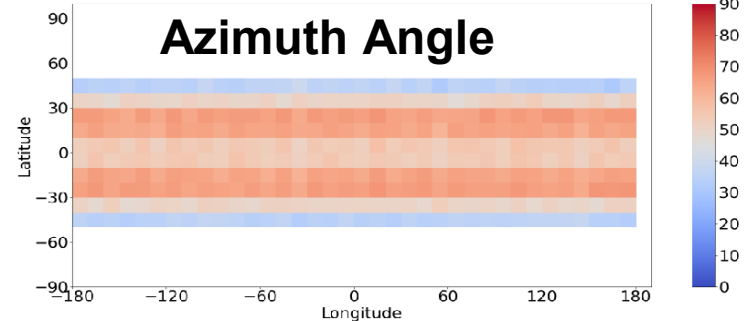
Ho et al., (2023)

# COSMIC-2

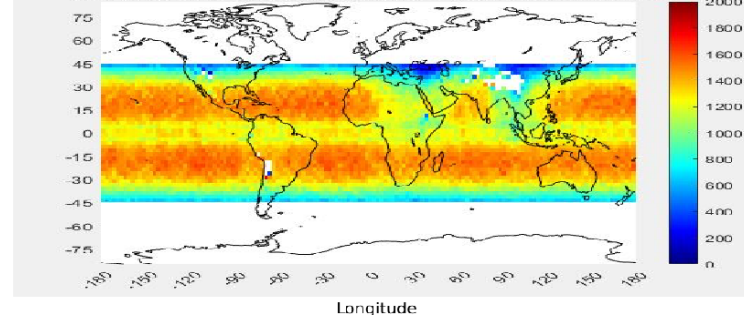
(a) Sample number



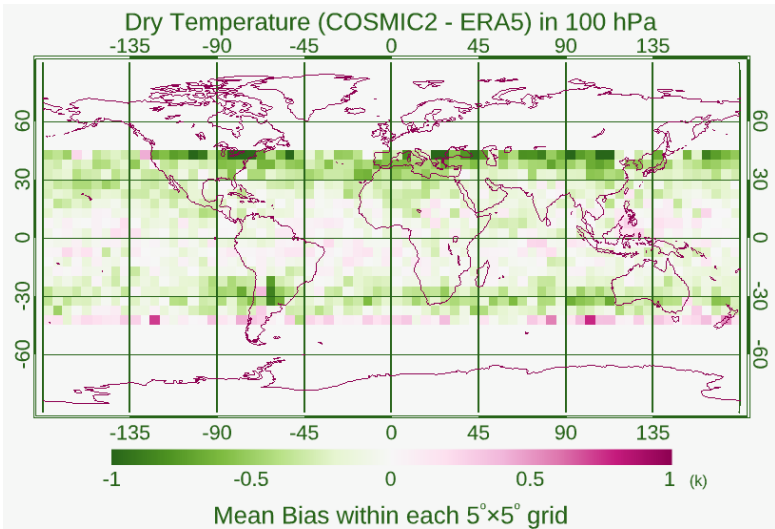
(b) Azimuth angle mean (degree)



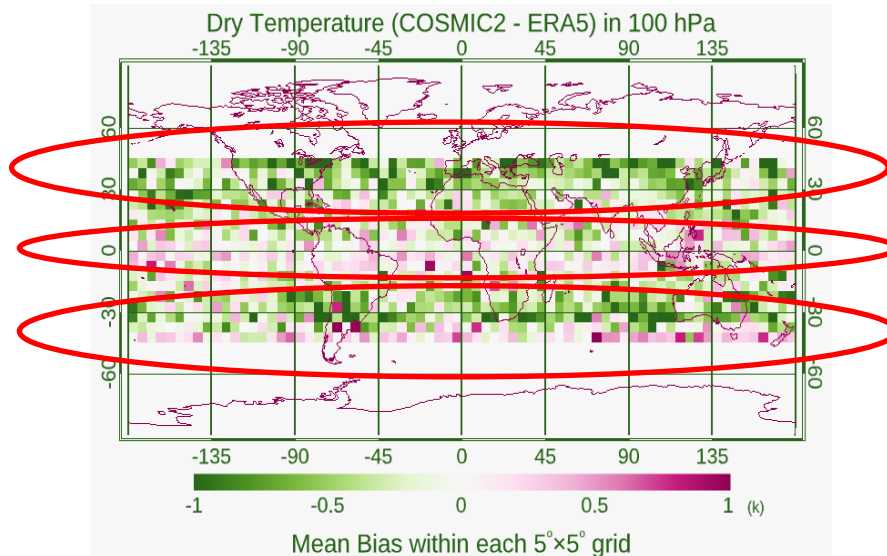
Mean L1 SNR Day+Night ocean only June-Oct2022-COSMIC-2



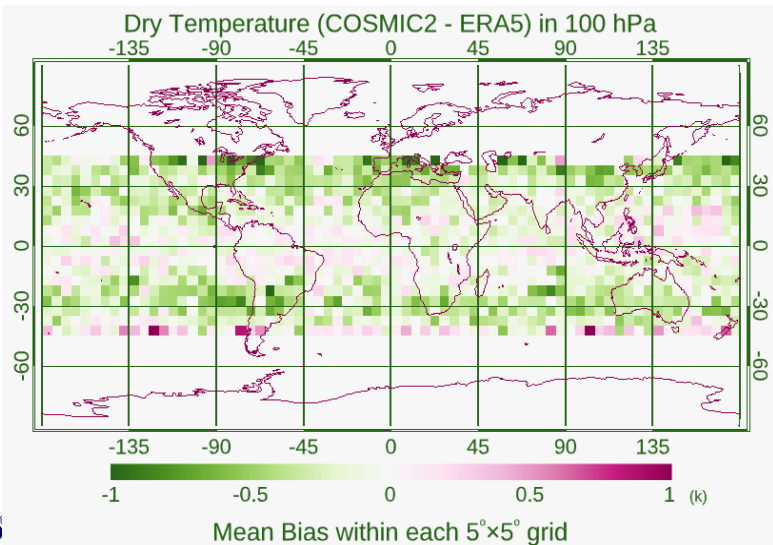
### 100 mb all the COSMIC-2 – ERA5



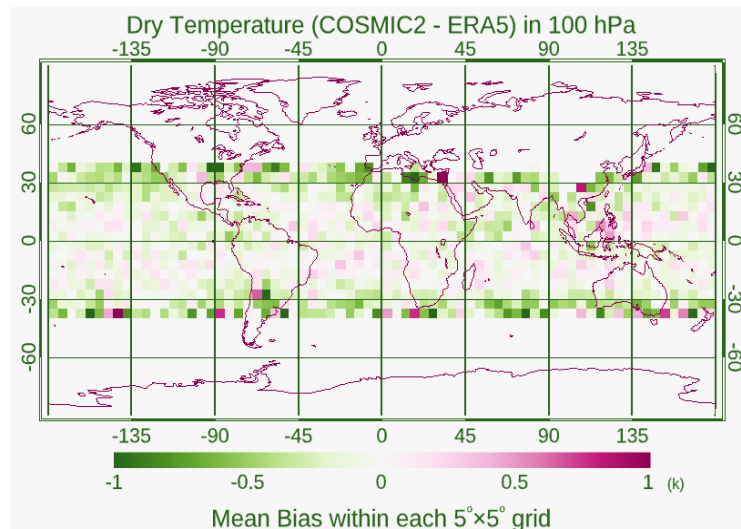
### SNR < 700 V/V



### 750 V/V < SNR < 1500 V/V



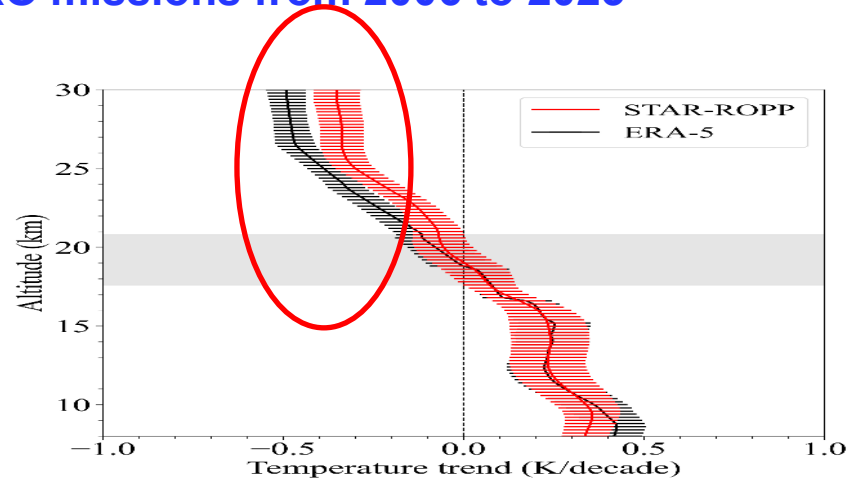
### SNR > 1500 V/V



# Construction of temperature climate data records in the upper troposphere and lower stratosphere using multiple RO missions from 2006 to 2023

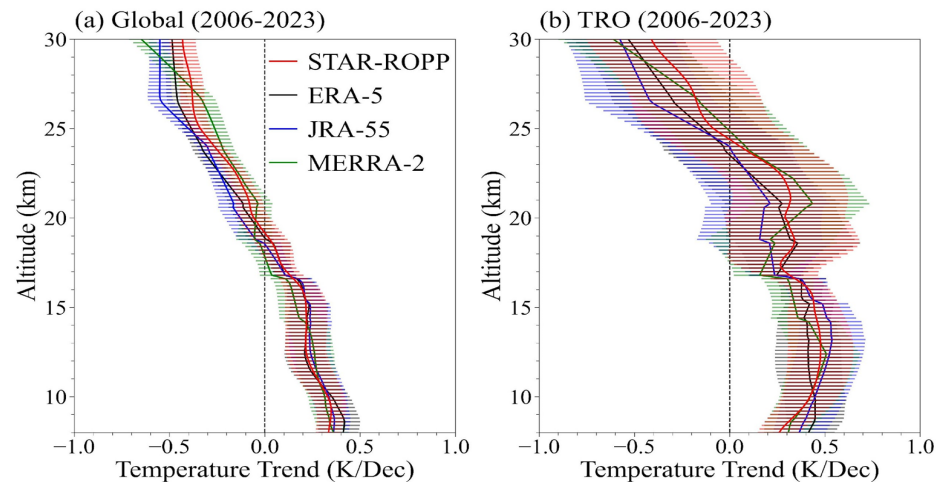
RO mission	Data coverage
SPIRE	Sep 2021 to Jul 2023
COSMIC2	Oct 2019 to Jul 2023
COSMIC1	Apr 2006 to Apr 2020
Metop-A	Oct 2007 to Nov 2021
Metop-B	Feb 2013 to Mar 2023
Metop-C	Jul 2019 to Feb 2023

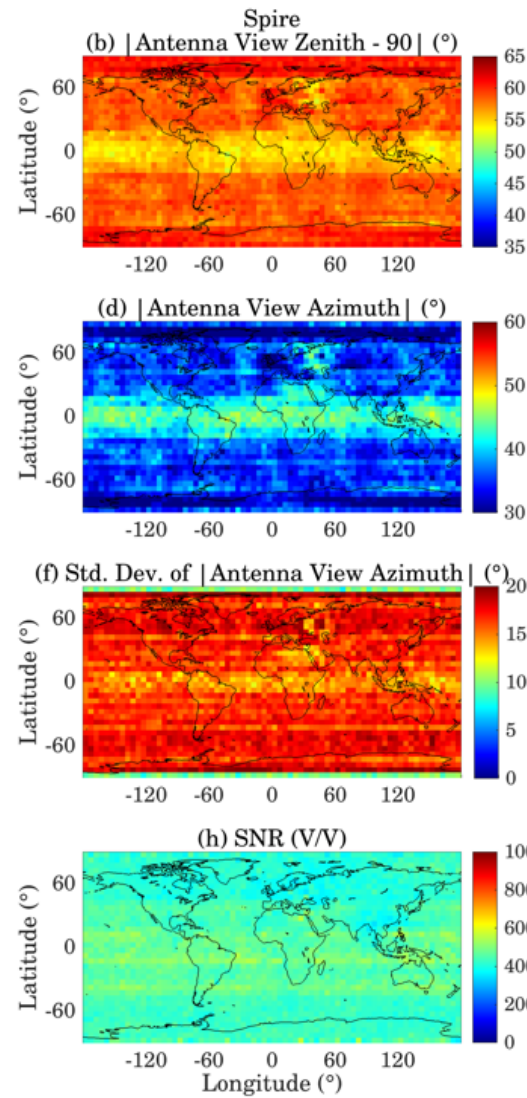
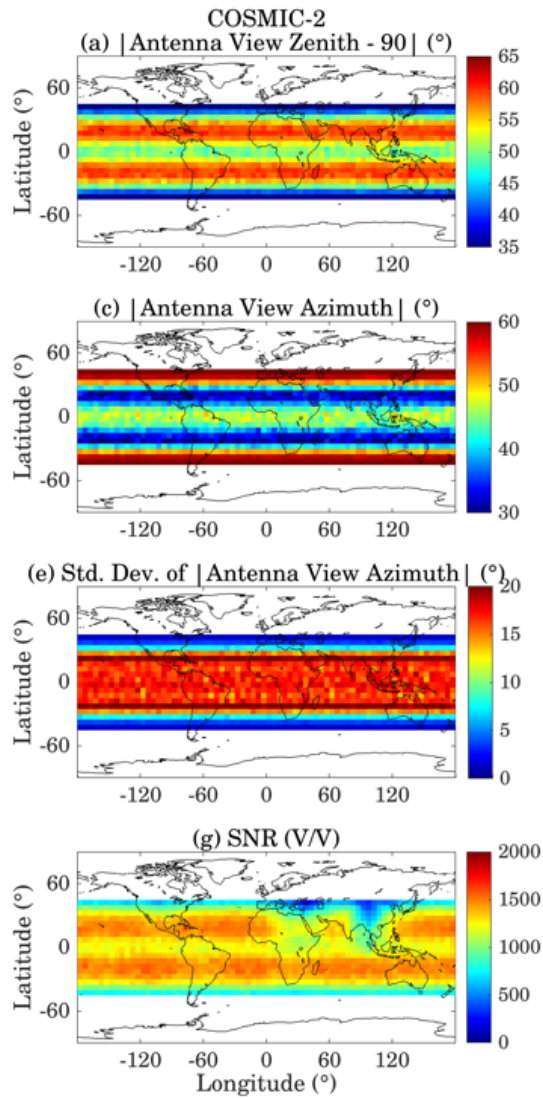
**With COSMIC-2**



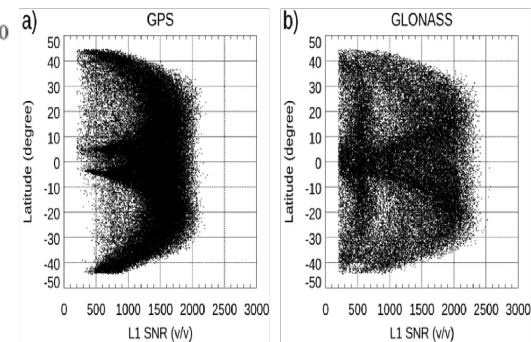
Vertically resolved temperature trends were estimated from STAR-ROPP (red) and ERA-5 (black) data sets. Error bars represent the trend uncertainty at the 95% confidence level. The shaded area denotes the altitude levels where temperature trends are insignificant.

**No COSMIC-2**

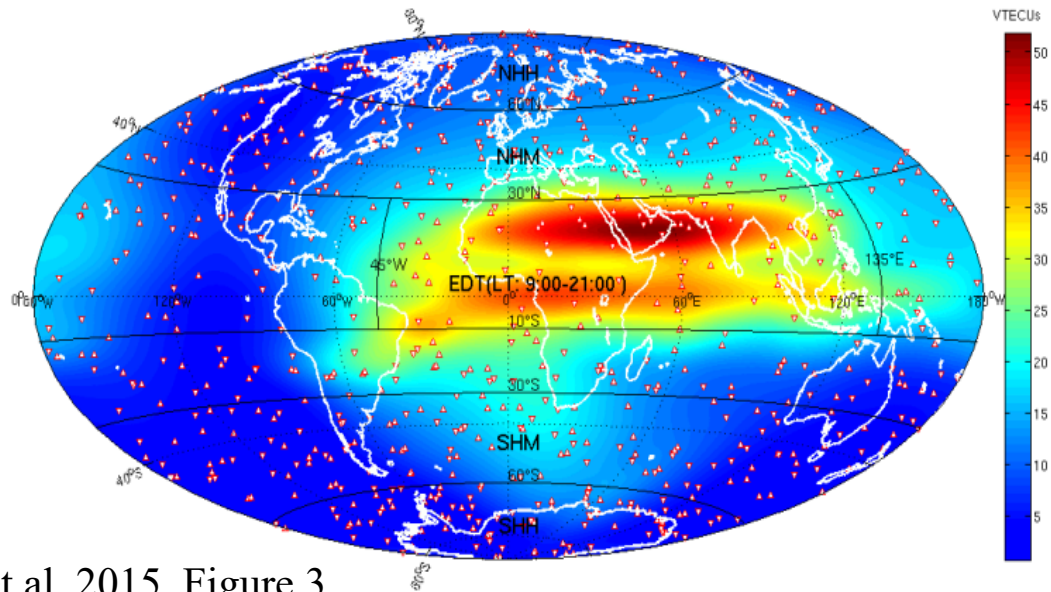




Mean of the absolute antenna view zenith angle (related to the North) minus 90 degrees (a-b) and the absolute azimuth angle (c-d), the standard deviation of antenna view azimuth angle (e-f), and SNR (g-h) on  $5^\circ \times 5^\circ$  grid for COSMIC-2 (left) and SPIRE (right) from 2022/09-2022/12



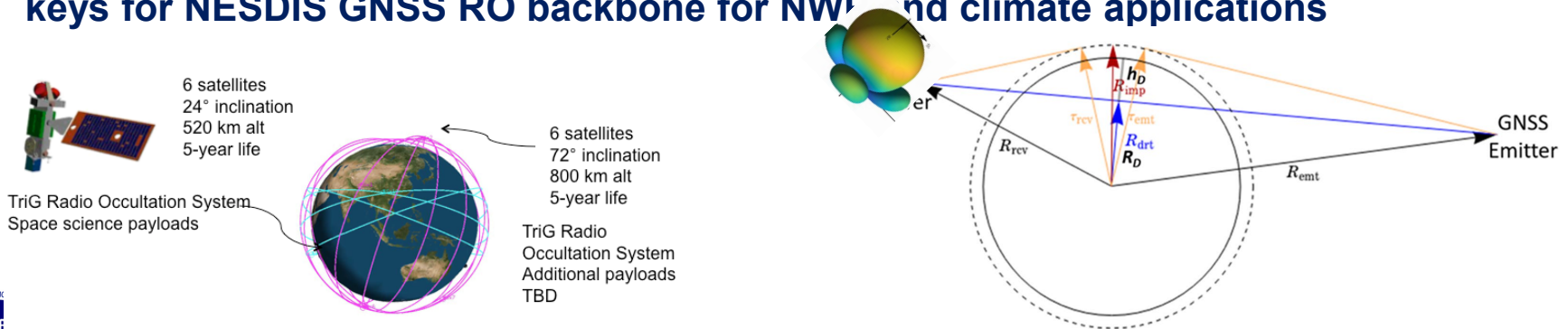
Global distribution of the vertical total electron content (VTEC) at  
12:00 UTC on 15 July 2008  
 $F_{10.7} = 140$  1 VTEC =  $10^{16}$  electrons /m<sup>2</sup>



Liu et al. 2015, Figure 3

## 4. Conclusions and Recommendations

- QCs are very important for RO data processing and validation
- SNRs do affect the RO penetration, precision, observation uncertainty, and data accuracy in the upper troposphere to lower stratosphere
- With low inclination angle (24 degree), COSMIC-2 SNR distribution are highly dependent on the view azimuth angles
- COSMIC-2 latitudinal dependent biases (compared to background and other RO missions) have obvious seasonal variation and may be the cause of the geopotential height degradation in the global NWP
- The data quality (accuracy and uncertainty) for low inclination angle is affected by residual ionosphere Error (RIE) more than those data from high inclination angle missions
- Commercial RO data do improve the TC forecasts
- NOAA-owned RO data with high stability and precision with all location time are keys for NESDIS GNSS RO backbone for NWP and climate applications



## 15A.4 Jun Zhou: Construction of Temperature Climate Data Records in the Upper Troposphere and Lower Stratosphere Using Multiple RO Missions from 2006 to 2023 at NESDIS/STAR

Jun Zhou et al., 2024 (JGR): Construction of Temperature Climate Data Records in the Upper Troposphere and Lower Stratosphere Using Multiple RO Missions from 2006 to 2023 at NESDIS/STAR

Ho, S.-p.; Zhou, X.; Shao, X.; Chen, Y.; Jing, X.; Miller, W. Using the Commercial GNSS RO Spire Data in the Neutral Atmosphere for Climate and Weather Prediction Studies. *Remote Sens.* 2023, 15, 4836. <https://doi.org/10.3390/rs15194836>

Disclaimer: The scientific results and conclusions, as well as any views or opinions expressed herein, are those of the authors and do not necessarily reflect those of NOAA or the Department of Commerce.

# UCAR COSMIC-2 vs. STAR ROPP and STAR FSI COSMIC-2

## COSMIC-2 Time Series Refractivity Compared to ERA-5

