Comparison of COSMIC-2 Radio Occultation Retrieval Products with Vaisala RS41 and RS92 Radiosonde Measurements

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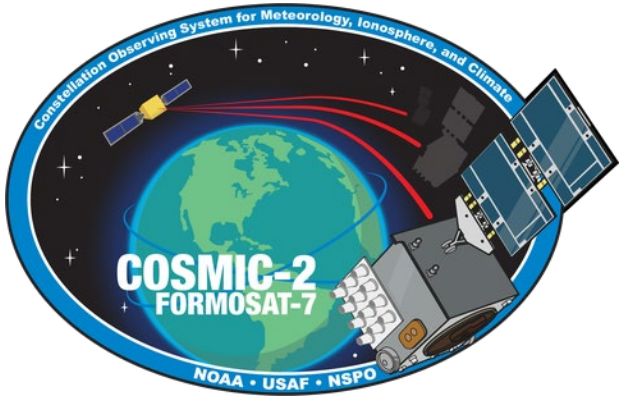
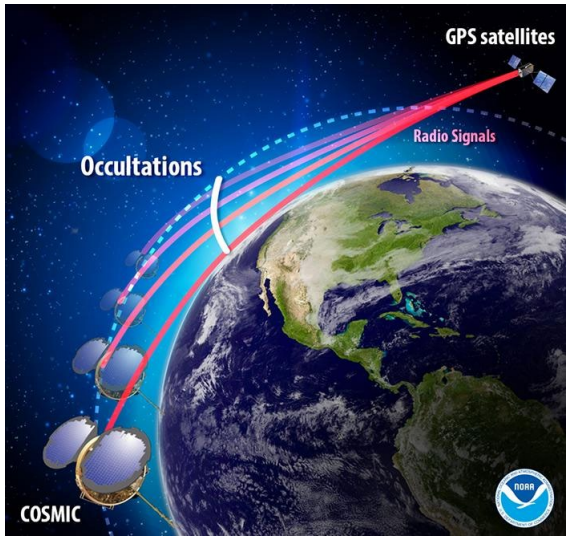
Motivation and Outline

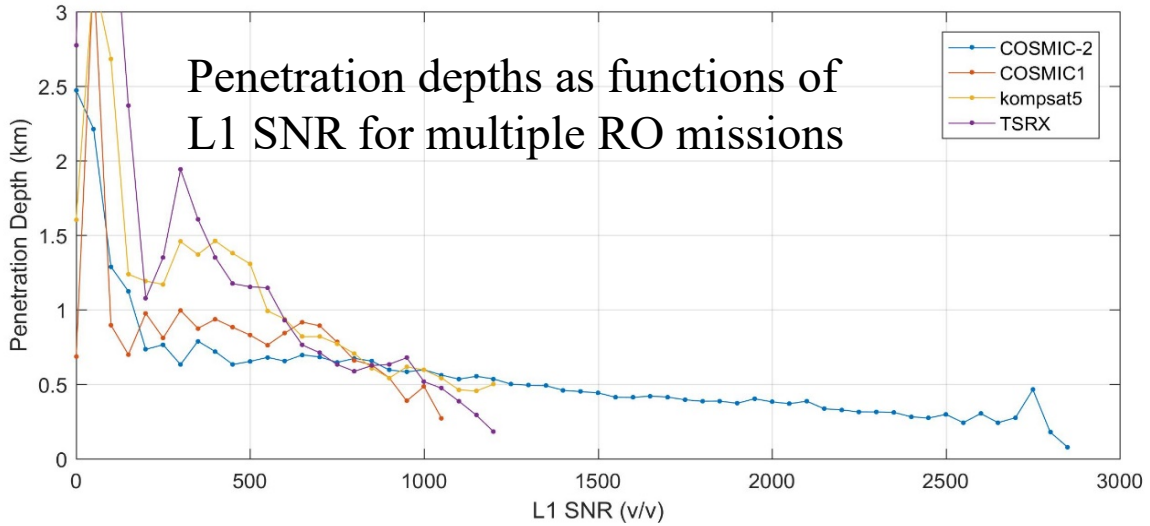
- Understanding the bias and uncertainty between radio occultation (RO) retrievals and radiosonde observations (RAOBs) directly impacts climate studies and numerical weather predictions.
- Comparison of temperature and humidity profile data between
  - Retrieved by University Corporation for Atmospheric Research (UCAR) and NOAA Center for Satellite Applications and Research (STAR) from COSMIC-2 RO data
  - In-situ Vaisala RS41 and RS92 radiosonde observations (RAOB).
- Comprehensive evaluations of the temperature and humidity bias and uncertainty
  - RS41/RS92 RAOB data vs. COSMIC-2 RO data
  - Differences between two COSMIC-2 wet profile retrievals
  - Investigate height and day-night (solar zenith angle) dependence of temperature and humidity biases

COSMIC-2 Radio Occultation (RO) Sensor

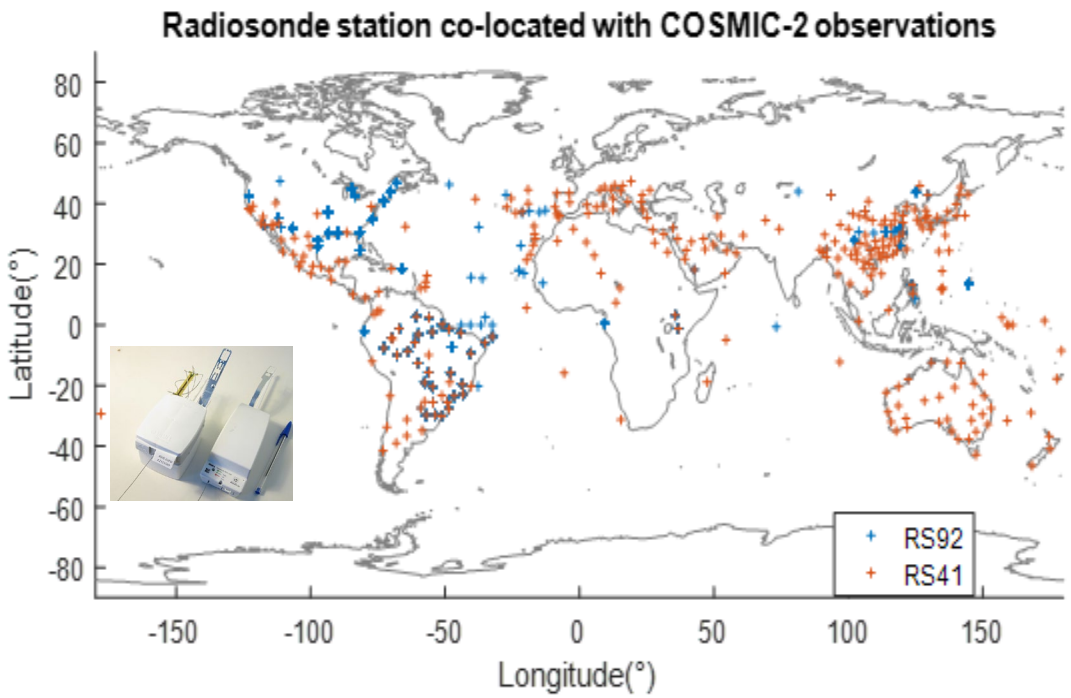
- GNSS-RO data are collected by measuring the changes in a radio signal as it is refracted through the atmosphere, allowing derivation of temperatures and moisture in atmosphere's layers.
- COSMIC-2 was launched on June 25, 2019 as COSMIC-1 follow on.
- Six small satellite-constellation; 24-degree inclination LEO
- Tri-GNSS Radio-occultation System (TGRS) payload; GNSS: GPS and GLONASS
- Enhanced RO signal quality and deeper penetration depth
- On March 16, 2020, data became available for atmospheric and climate studies and NWP applications .







RS41 and RS92 Radiosonde



- Vaisala RS92 was a primary radiosonde type in the global operational upper-air network
  - Provided the backbone temperature and moisture measurements for NWP and satellite-based sounding senor validation.
  - Over the past two decades, RS92 was used as a reference sonde in GRUAN.
- Starting in late 2013, RS92 was gradually replaced by Vaisala RS41.
  - Vaisala RS41 is equipped with advanced temperature and humidity sensor technologies
  - Provide improvements in measurement accuracy for temperature, humidity, and pressure and wind parameters throughout the atmosphere.
- Collocated 7-month of COSMIC-2 RO and RS41/RS92 RAOB data are analysed.

References: He et al. 2009; Ho et al. 2010; Jauhiainen et al. 2014; Jensen et al. 2016; Kawai et al. 2017; Sun et al. 2019.

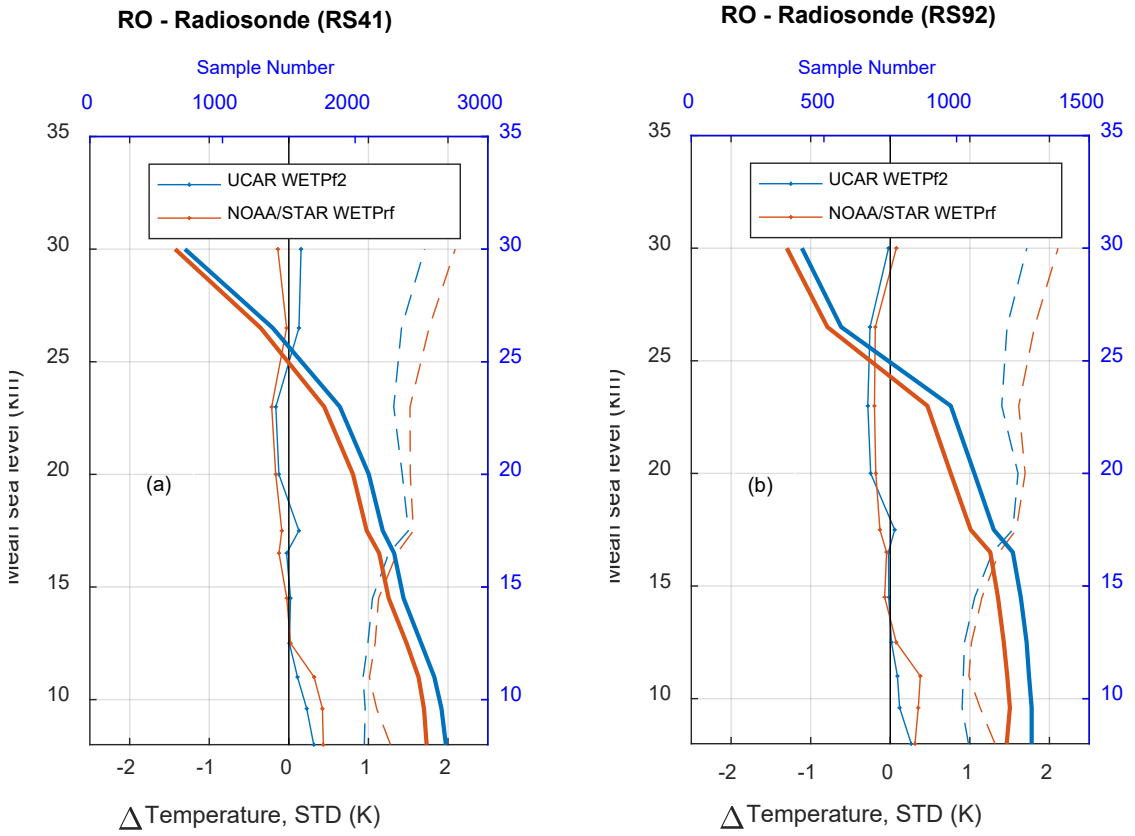
COSMIC-2 Temperature/Humidity Data Products from 1DVAR Retrieval

	NOAA/STAR 1DVAR	UCAR NRT WETPrf2 1DVAR
Observation Error	Scaled monthly variability of refractivity	Statistical
Background Error	Monthly variability of T,Q profiles	Consistent with Observation Err.
Background Error Correlation	Off-diagonal elements set to be zero	Multivariate
Error Covariance Matrix Resolution and Construction	Five latitude bins; Monthly precomputed on fixed levels	Lat/Lon (10^ox10^o); Monthly Precomputed on fixed levels
Observation Operator	Refractivity	Variational Abel Transform
Initialization a priori model	Global Forecasting System (GFS)	Global Forecasting System (GFS)

Data Set Name	Provided by	Time Coverage
UCAR-WETPf2	UCAR	2019/10/01 to 2020/04/30
NOAA/STAR WETPrf	NOAA/ STAR	2019/10/01 to 2020/04/30

- UCAR WETPf2 (https://data.cosmic.ucar.edu/gnss-ro/cosmic2/nrt/)
- NOAA/STAR WETPrf (ftp://ftp.star.nesdis.noaa.gov/pub/smcd/scda/GNSSRO/COSMIC2/wetPrf/)
- Difference in 1DVAR retrieval algorithms can cause difference in RO-retrieved temperature and humidity profile.
- Inter-comparison with RS41 or RS92 radiosonde measurements helps evaluate such difference.

Overall comparison of COSMIC-2 Temperature Retrievals with RS41 and RS92 RAOB Measurements



COSMIC-2 vs. RS41

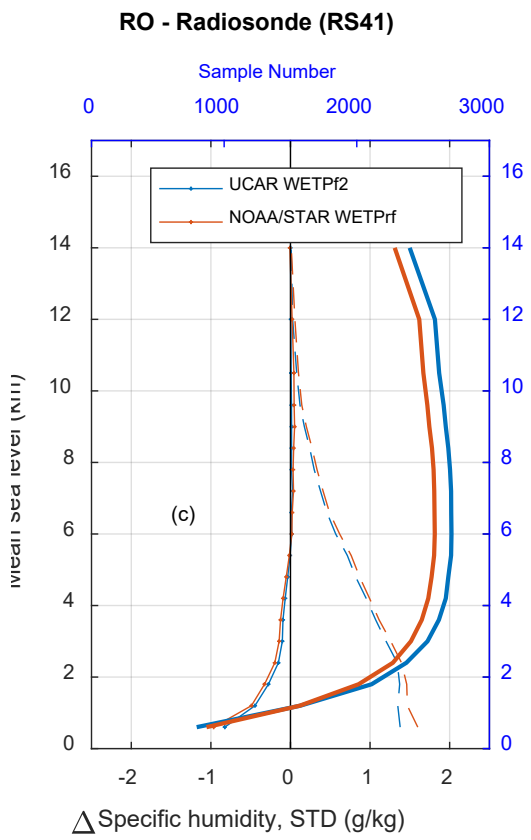
COSMIC-2 Retrieval	μ(ΔT) (σ(ΔT))(K) (8-11 km)	μ(ΔT) (σ(ΔT)) (K) 12.5-16.5(km)	μ(ΔT) (σ(ΔT)) (K) (17.8-26.4 km)
UCAR WETPf2	0.22(0.95)	0.00(1.10)	-0.01(1.42)
STAR WETPrf	0.39(1.13)	-0.04(1.19)	-0.12(1.59)

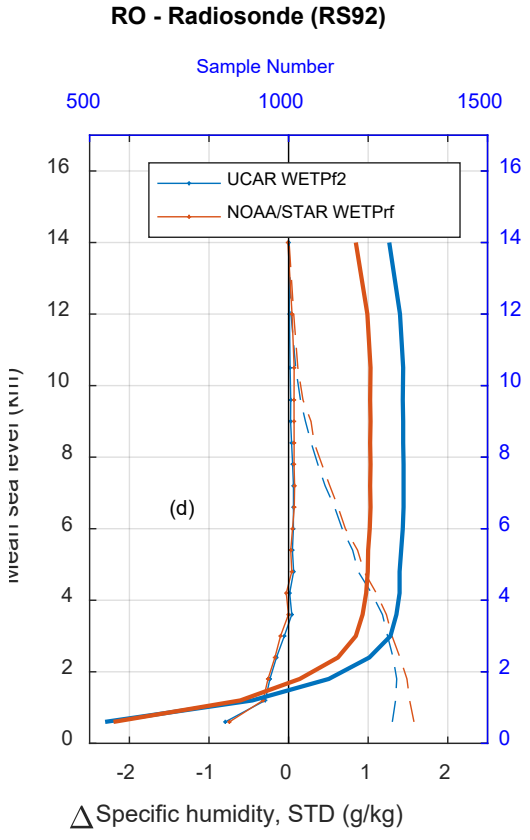
COSMIC-2 vs. RS92

COSMIC-2 Retrieval	μ(ΔT) (σ(ΔT))(K) (8-11 km)	μ(ΔT) (σ(ΔT)) (K) 12.5-16.5(km)	μ(ΔT) (σ(ΔT)) (K) (17.8-26.4 km)
UCAR WETPf2	0.16(0.93)	-0.01(1.09)	-0.18(1.50)
STAR WETPrf	0.35(1.14)	-0.01(1.18)	-0.17(1.68)

- UCAR vs. NOAA/STAR COSMIC-2 temperature retrievals
  - Very consistent at height above 12.5 km.
  - Main difference occur over the height range 8-11 km with a net difference of ~0.1-0.2 K
- Between 17.8 km and 26.4 km, RS92 RAOB has a warm bias of around 0.1 K in comparison with RS41 RAOB
  - Confirmed by both UCAR and NOAA/STAR COSMIC-2 temperature retrieval

Overall comparison of COSMIC-2 Humidity Retrievals with RS41 and RS92 RAOB Measurements





COSMIC-2 vs. RS41

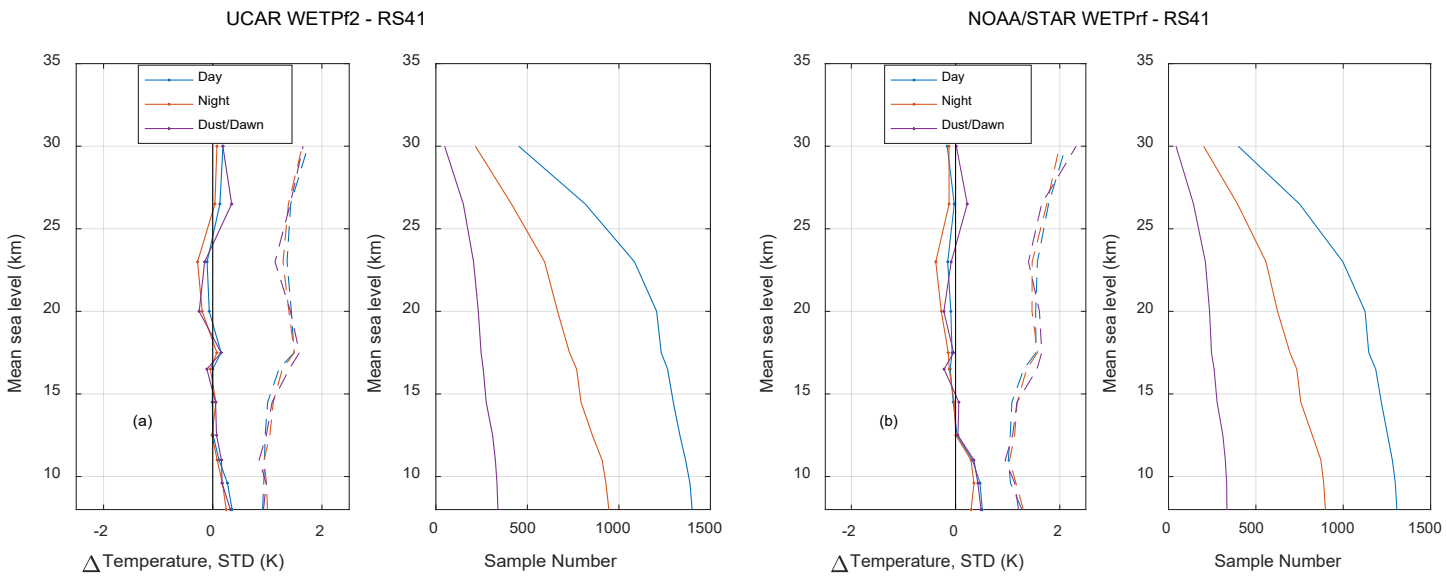
COSMIC-2 Retrieval	μ(ΔH) (σ(ΔH)) (g/kg) (below 4.2 km)	μ(ΔH) (σ(ΔH)) (g/kg) (4.8-8.4 km)
UCAR WETPf2	-0.28(1.24)	0.01(0.50)
STAR WETPrf	-0.33(1.33)	0.01(0.54)

COSMIC-2 vs. RS92

COSMIC-2 Retrieval	μ(ΔH) (σ(ΔH)) (g/kg) (below 4.2 km)	μ(ΔH) (σ(ΔH)) (g/kg) (4.8-8.4 km)
UCAR WETPf2	-0.21(1.25)	0.05(0.58)
STAR WETPrf	-0.23(1.37)	0.06(0.63)

- UCAR and NOAA/STAR COSMIC-2 humidity retrievals are in general consistent in the troposphere, especially above 4.8 km.
- Systematic near-surface (below 4.2 km) wet biases in the RO retrievals relative to RS41/RS92 RAOB humidity data
  - May indicate the negative refractivity biases owing to super-refraction in RO retrievals (Ho et al., 2020)

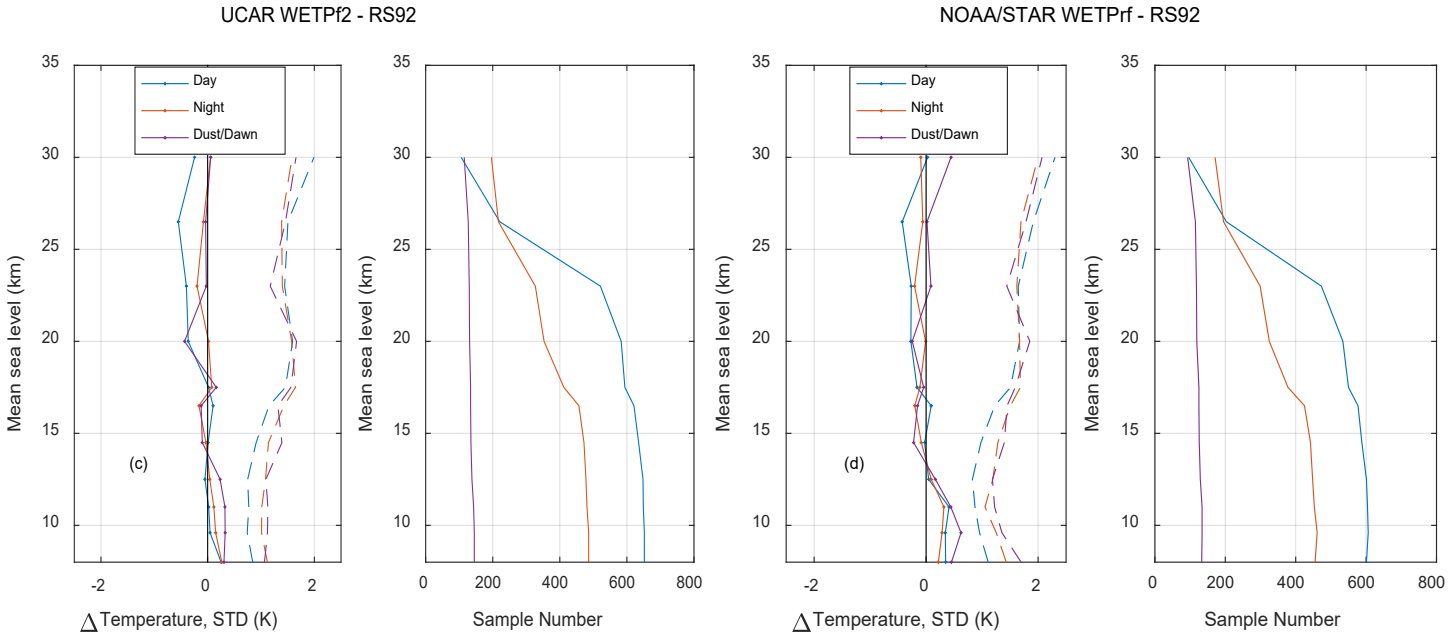
Day and Nighttime Temperature Bias Comparison: UCAR and NOAA-STAR COSMIC-2 Temperature Retrieval vs. RS41 Measurement



Height Range	RO Retrievals	Day	Night	Dawn/Dusk
8-11 km	UCAR WETPrf2	0.25(0.93)	0.15(0.98)	0.22(0.93)
	STAR WETPrf	0.43(1.11)	0.31(1.17)	0.39(1.11)
12.5-16.5 km	UCAR WETPrf2	-0.00(1.06)	-0.02(1.15)	0.03(1.14)
	STAR WETPrf	-0.04(1.15)	-0.06(1.24)	-0.02(1.25)
17.8-26.4 km	UCAR WETPrf2	0.03(1.43)	-0.10(1.38)	0.02(1.40)
	STAR WETPrf	-0.08(1.61)	-0.25(1.56)	-0.05(1.58)

- Compared with both UCAR and NOAA/STAR COSMIC-2 temperature retrievals
  - ~0.1 K warm biases in the RS41 nighttime measurements over the height from 17.8 to 26.4 km.
- The day-night difference for RS41 and RS92 measurements compared with UCAR and NOAA/STAR retrievals are both small (mean temperature bias difference < 0.1 K) over 17.8 to 26.4 km.
- Temperature bias difference below 11 km between UCAR and NOAA/STAR retrievals can be mainly due to the difference in the 1DVAR retrieval algorithms, particularly the treatment of the a priori background model over this height region.

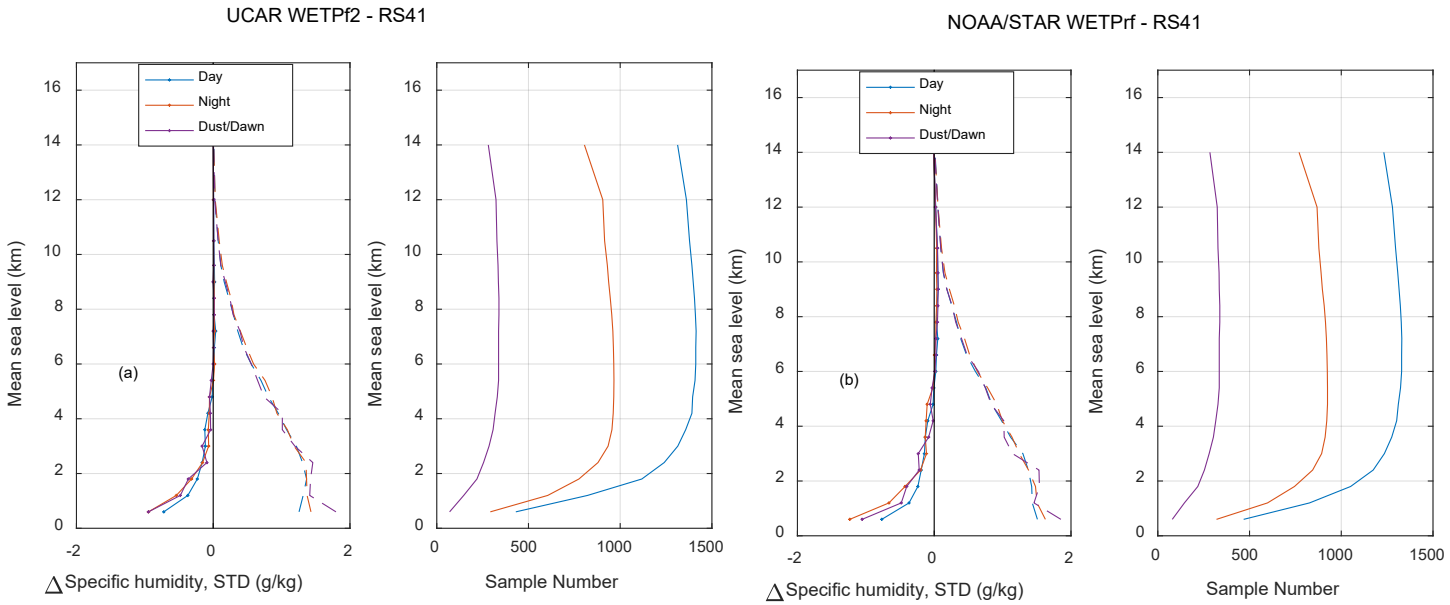
Day and Nighttime Temperature Bias Comparison: UCAR and NOAA-STAR COSMIC-2 Temperature Retrieval vs. RS92 Measurement



Height Range	RO Retrievals	Day	Night	Dawn/Dusk
8-11 km	UCAR WETPrf2	0.11(0.79)	0.16(1.00)	0.30(1.16)
	STAR WETPrf	0.37(0.98)	0.22(1.21)	0.54(1.42)
12.5-16.5 km	UCAR WETPrf2	0.02(0.94)	-0.06(1.19)	-0.01(1.29)
	STAR WETPrf	0.04(1.01)	-0.09(1.28)	-0.02(1.41)
17.8-26.4 km	UCAR WETPrf2	-0.32(1.50)	-0.08(1.52)	-0.02(1.46)
	STAR WETPrf	-0.28(1.68)	-0.13(1.70)	-0.01(1.63)

- The RS92 warm biases (~0.15–0.25K) between 17.8 km and 26.4 km occur mainly during the daytime.
  - May be traceable to the remnant error after applying the correction to the daytime temperature for RS92.
- Over the height region from 12.5 to 16.5 km, the temperature bias difference among UCAR and NOAA/STAR temperature retrievals and RS41/RS92 RAOB measurements are minimal (mostly < 0.05 K) with no significant (< 0.05 K) daytime and nighttime difference.
  - Consistency in temperature data among two COSMIC-2 retrievals and two RAOBs over this height region.
- Below 11 km, RS92 does show day-night bias difference while RS41 does not.

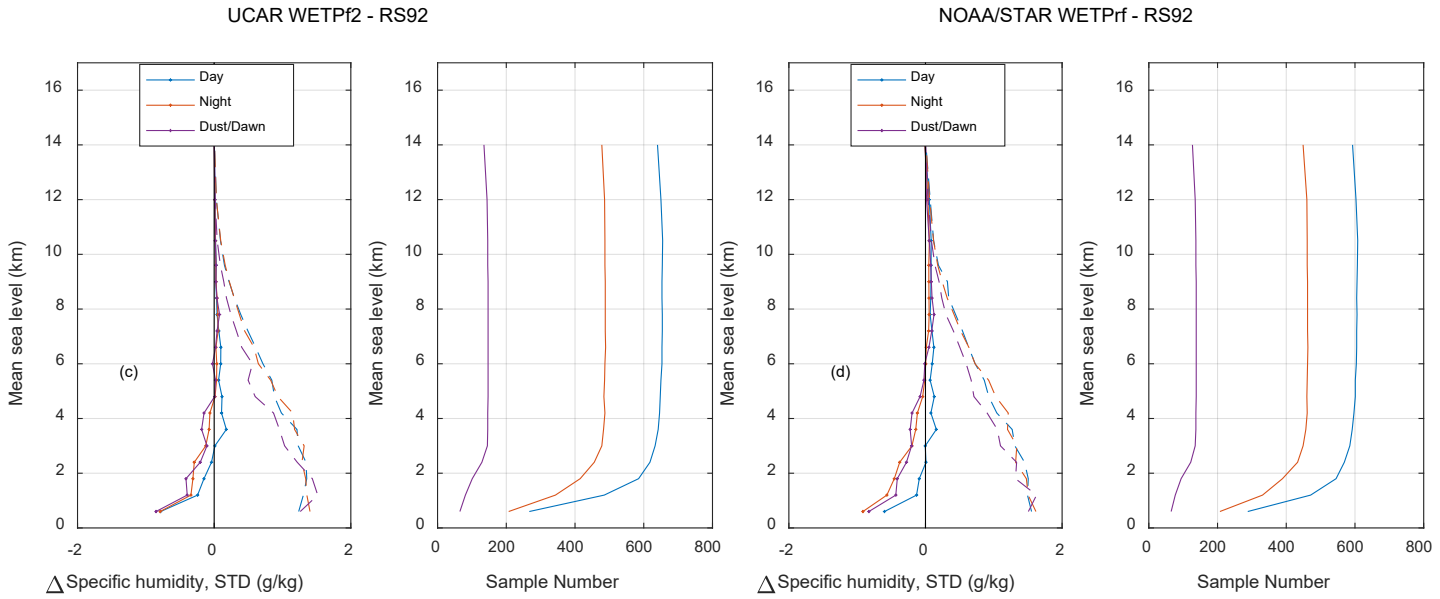
Day and Nighttime Humidity Bias Comparison: UCAR and NOAA-STAR COSMIC-2 Humidity Retrieval vs. RS41 Measurement



Height Range	RO Retrievals	Day	Night	Dawn/Dusk
Below 4.2 km	UCAR WETPf2	-0.26(1.21)	-0.32(1.24)	-0.28(1.31)
	STAR WETPrf	-0.28(1.31)	-0.42(1.34)	-0.36(1.36)
4.8-8.4 km	UCAR WETPf2	0.01(0.48)	0.01(0.52)	-0.01(0.49)
	STAR WETPrf	0.02(0.52)	-0.00(0.56)	0.00(0.54)

- UCAR and NOAA/STAR COSMIC-2 humidity retrievals are, in general, very consistent in the troposphere, significantly above 4.2 km over lands.
- Systematic wet biases below 4.2 km in the RO retrievals relative to RAOB humidity data.
- Consistency in Day/Night humidity difference below 4.2 km between UCAR COSMIC-2 and RS41 RAOB data.

Day and Nighttime Humidity Bias Comparison: UCAR and NOAA-STAR COSMIC-2 Temperature Retrieval vs. RS92 Measurement



Height Range	RO Retrievals	Day	Night	Dawn/Dusk
Below 4.2 km	UCAR WETPf2	-0.13(1.24)	-0.30(1.32)	-0.28(1.16)
	STAR WETPrf	-0.08(1.37)	-0.41(1.43)	-0.35(1.18)
4.8-8.4 km	UCAR WETPf2	0.07(0.60)	0.04(0.61)	0.03(0.41)
	STAR WETPrf	0.09(0.64)	0.00(0.68)	0.06(0.48)

- Day-night humidity difference below 4.2 km in RS92 RAOBs when compared to COSMIC-2 retrievals, mainly due to the wet biases in the nighttime RS92 data.
- The mean humidity difference between RS41 and RS92 below 4.2 km is about 0.07-0.10 g/kg, due to a slight daytime dry bias in RS92 relative to RS41.

Summary

- In this study, the temperature and humidity data independently retrieved by UCAR and NOAA/STAR from COSMIC-2 RO data are compared with in-situ Vaisala RS41 and RS92 RAOB data.
- Collocated 7-month of COSMIC-2 RO and RS41/RS92 RAOB data are analyzed to investigate the height and day-night dependence of temperature and humidity biases.
  - UCAR and NOAA/STAR COSMIC-2 temperature retrievals are consistent above 12.5 km.
  - Warm biases in RS92 data compared to RS41 data over the height region above 17.8 km, mainly due to the warm daytime bias in RS92 data.
  - Main temperature difference between UCAR and NOAA/STAR retrievals is 0.1-0.2 K over 8-11 km, which is due to difference in the variational retrieval algorithms.
  - Over 8-11 km, the relative temperature difference between COSMIC-2 retrievals and RS41/RS92 RAOBs are more significant than other heights.
  - UCAR and NOAA/STAR COSMIC-2 humidity retrievals are in general consistent in the troposphere, especially above 4.8 km.
  - Systematic wet biases below 4.2 km in the RO retrievals relative to RAOB humidity data.
  - Day-night humidity bias difference below 4.2 km due to wet biases in the night-time RS92 data.
- The RO vs. RAOB comparison helps quantify the temperature and humidity biases among different radiosonde sensor types and different RO retrieval algorithms.