Investigating the Impact of Residual Ionospheric Error and Other Factors on GNSS RO Temperature Climate Data Records in the UTLS

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Abstract

GNSS RO measurements have been widely used for climate studies owing to their high vertical resolution, global coverage, and intrinsic long-term stability. Since RO climatology is generated based on a combined data record from different RO missions, the data consistency among these missions is essential to enable RO climatology to detect and monitor weak climate trends. In this study:

(1) We assessed the RO mission consistency by comparing their collocated profiles;
(2) Quantified the impact of mission inconsistency on the trend estimation through sensitivity studies;
(3) Discussed the possible causes of the bias among RO missions.

This study is based on the dry temperature profiles processed by the GNSS RO Science and Data Center (SDC) at the NOAA Center for Satellite Applications and Research (STAR) (STAR-ROPP version 1.0 ATBD). The multiple RO missions include Metop-A, -B, -C, COSMIC-1, COSMIC-2, and SPIRE. Data is publicly available on NOAA/STAR/SDC website: https://gpsmet.umd.edu/star_gnssro/download.html.

Assessment of the Consistency among RO Missions

Considering Metop data consists of the current most extended RO time series (from late 2006 to the current) from the same receiver (GRAS) at almost the same altitude (~820 km), we use Metop data as references to validate the consistency of other missions. The collocation criteria are set by a time difference of no more than 30 minutes and a horizontal spatial separation of less than 150 km at around 19 km altitude of the tangent point.

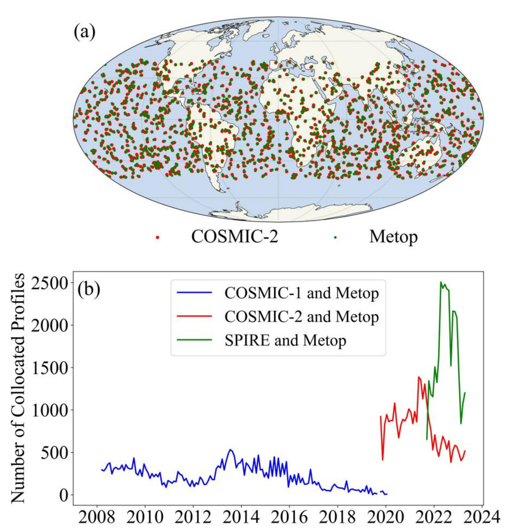


Fig.1 Statistics on the collocated pairs. (a) Global distribution of COSMIC-2 and Metop pairs for May 2021. (b) The monthly number of each collocated mission pair.

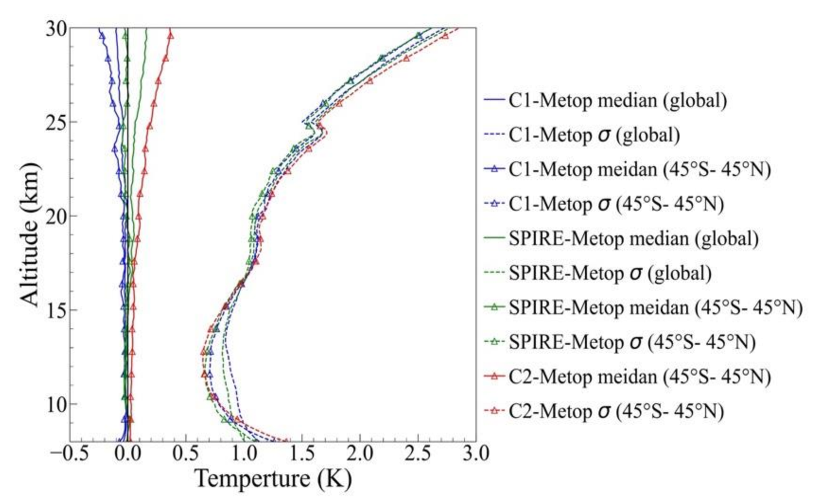


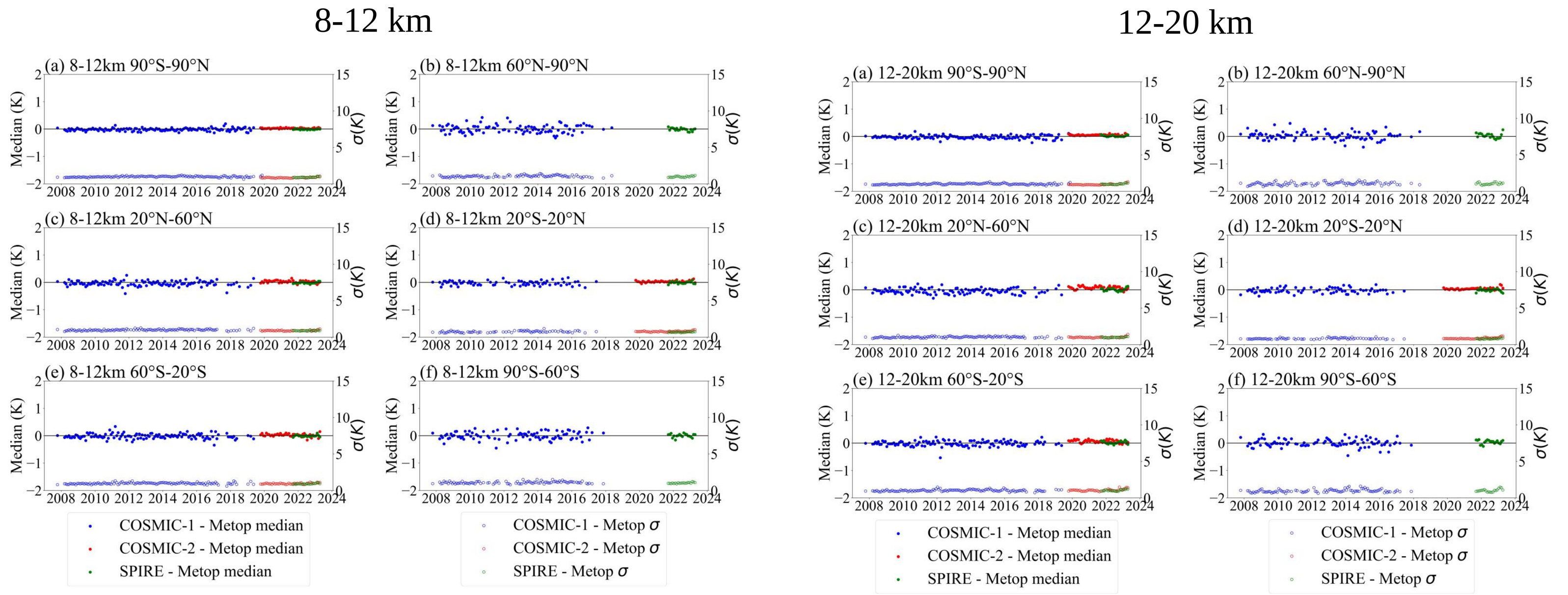
Fig.2 Measures of consistency between COSMIC-1 and Metop, SPIRE and Metop, and COSMIC-2 and Metop pairs as a function of height for the entire globe and 45°S-45°N region.

- COSMIC-1 and SPIRE have bias less than 0.2 K.
- COSMIC-2 has 0.1-0.4 K positive bias against Metop above 20 km.
- Within 45°S-45°N, SPIRE temperatures are consistent with those from Metop, indicating that SPIRE's positive bias primarily concentrates in high latitudes.
- Overall, the mean mission differences are less than 0.1 K at all latitudes and heights below 20 km, increasing with altitude. σ is around or below 1K below 20 km and increases to about 2K above 20 km.

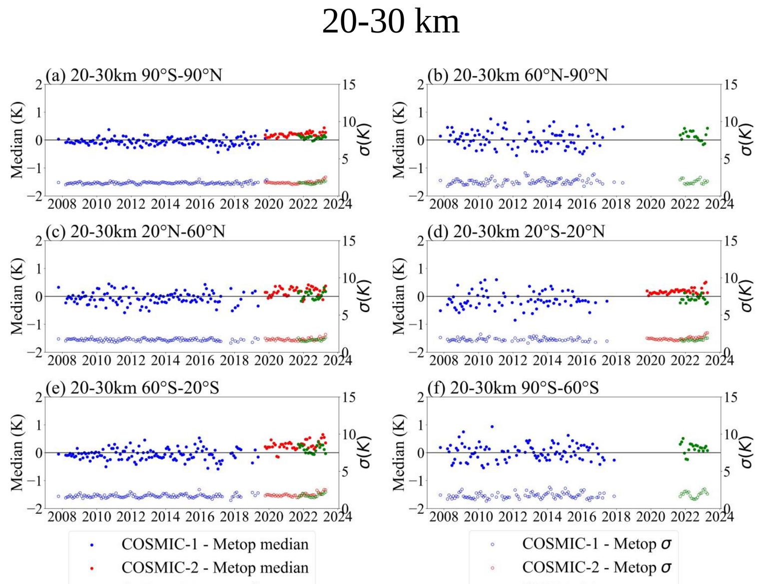
Fig.3 Measures of Consistency between COSMIC-1 and Metop, COSMIC-2 and Metop, and SPIRE and Metop Pairs at Six Latitude Zones

8-12 km

12-20 km



20-30 km



- From the upper troposphere to the lower stratosphere, COSMIC-1, COSMIC-2, and SPIRE are consistent with Metop at all latitude zones.
- In the mid-stratosphere:
  - COSMIC-1 is still consistent with Metop with bias less than 0.1 K.
  - SPIRE has a positive bias (0.16 K) at polar areas.
  - COSMIC-2 has obvious positive bias relative to Metop at all latitude zones from 45ºS to 45ºN. The bias is larger (~0.28K) in the 45ºS-20Sº than in the 20ºN-45ºN (0.17K) and 20ºS-20ºN (0.17K) at the same height.

Impact of COSMIC-2 and SPIRE Bias on Temperature Trend Estimation

- Using the dry temperature profiles from multiple missions processed by the GNSS RO SDC at the NOAA STAR, we develop a new monthly zonal mean climatology (STAR-ROPP MMC) on latitude-height grids with a resolution of 5º in latitude by 0.2 km in height in the UTLS from April 2006 to July 2023.
- The sampling error of the MMC is estimated and removed by applying the ERA5 reanalysis .
- Temperature anomalies and trends are estimated from the sampling error corrected MMC.
- We carried out the following sensitive experiments to investigate the potential impacts of COSMIC-2 and SPIRE bias on MMC and trend estimates. The temperature anomalies and trends are calculated based on:
  - All RO missions (STAR-ROPP with COSMIC-2)
  - All missions excluding COSMIC-2 data (the current STAR-ROPP MMC)
  - All missions excluding COSMIC-2 and SPIRE (STAR-ROPP without SPIRE) at 20-30 km.
- The impact of the mission bias is regarded as significant if the trend difference exceeds the measurement stability required by the Global Climate Observing System (GCOS), 0.05 K/Decade.

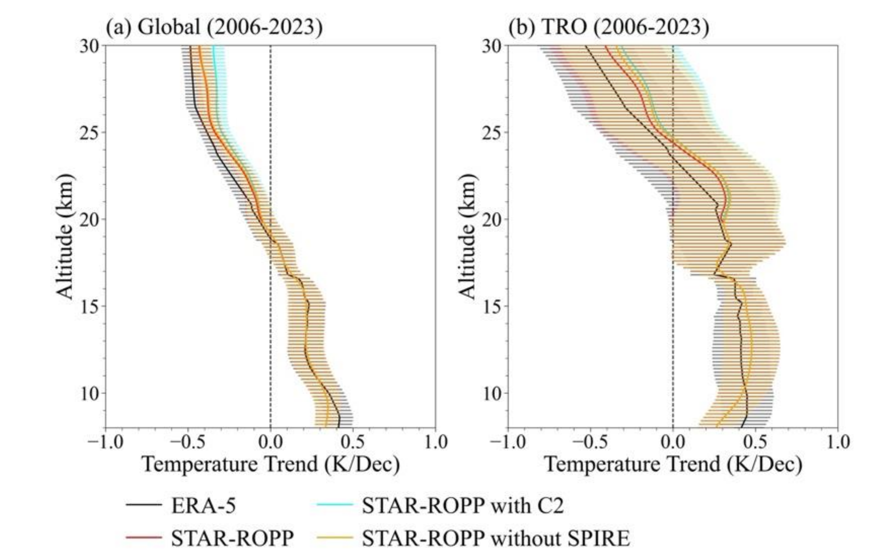


Fig.4 Vertically resolved temperature trends estimated from ERA-5, STAR-ROPP, STAR-ROPP with COSMIC-2, and STAR-ROPP without SPIRE for (a) global (90ºS-90ºN) and (b) the TRO (20ºS-20ºN) regions. Error bars represent the trend uncertainty at the 95% confidence level.

- The STAR-ROPP temperature trends present a transition from a prominent warming of 0.309 ± 0.085 K/Decade in the upper troposphere to a robust cooling of -0.281 ± 0.044 K/Decade in the mid-stratosphere.
- Above 20 km, by removing COSMIC-2, the temperature trends in global and tropical areas become cooler, up to -0.1 K/Dec, and closer to ERA-5 trends.
- By further removing SPIRE, global trends change less than 0.01K/Dec while tropical trends change less than 0.05 K/Dec except above 29 km.

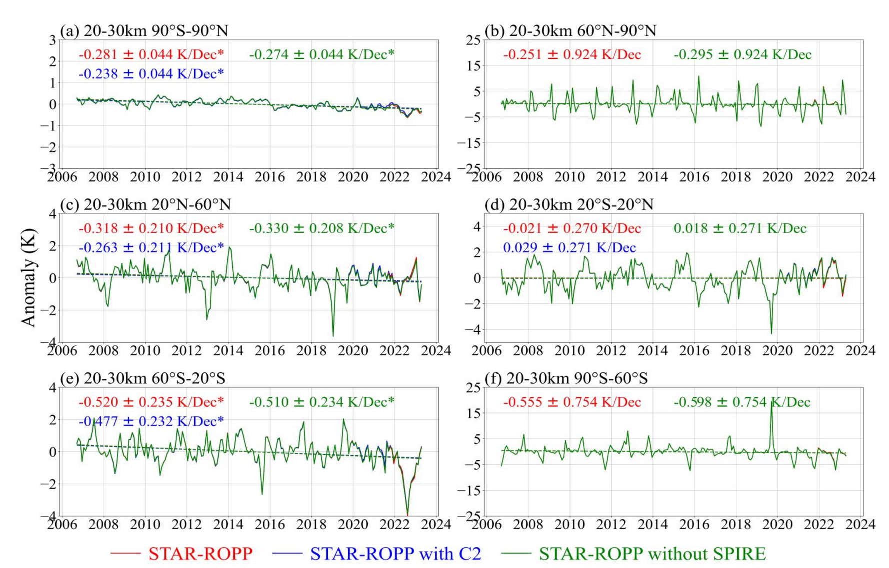


Fig.5 Temperature anomalies estimated from STAR-ROPP, STAR-ROPP with COSMIC-2, and STAR-ROPP without SPIRE at 20-30 km layer for six latitude zones. The trend and its uncertainty at a 95% confidence level are listed on each panel with the same color as the legend.

- Based on the temperature trends calculated from six latitude zones, removing the COSMIC-2 data declines the estimated temperature trends by around 0.05 K/Dec-0.06 K/Dec, exceeding the GCOS required measurement stability.
- While further removing SPIRE, the temperature trend change is less than 0.04 K/Dec.
- Therefore, SPIRE data are included, and COSMIC-2 data are excluded when generating the multi-mission MMC above 20 km.
- SPIRE has only contributed for two and a half years. More SPIRE data covering a more extended period is needed to accurately estimate its bias and impact on temperature trend estimation. We will continue closely monitoring SPIRE observations.

Possible Causes of COSMIC-2 Bias in the UTLS

(1) the 25th solar cycle from the end of 2019 to the current

- During RO limb sounding, the total phase delay is contributed from both neutral atmosphere and the ionosphere. For the study of neutral atmospheric parameters, it is essential to correct the ionospheric contribution.
- The linear combination of the two GNSS L-band signals is routinely used to remove the first-order ionospheric error.
- Nevertheless, high-order ionospheric errors remain due to neglecting the high-order terms in the Appleton-Hartree equation, the vertical gradient of the square of the electron density, and the L1/L2 ray path separation.
- LEO satellites in lower altitude tend to have higher ionospheric residuals due to the lack of topside/bottomside bending cancellation and the violation of the commonly used assumption that refractive index is unity at the receiver (Mannucci et al. 2011).

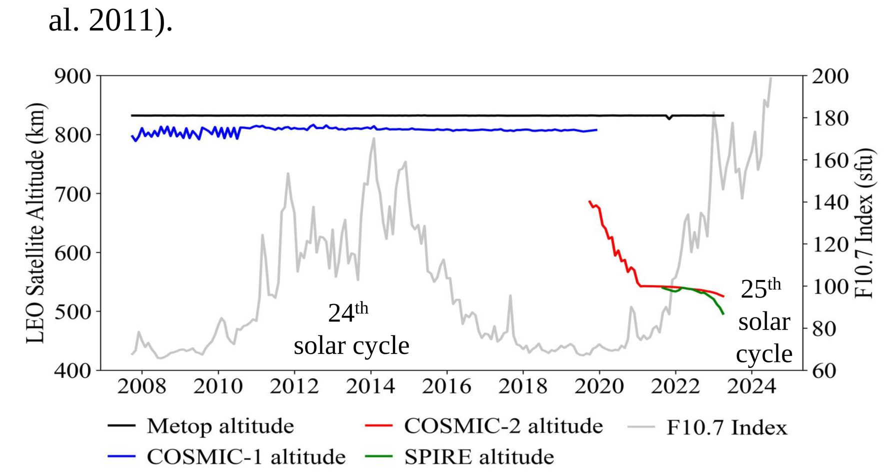


Fig. 6 Monthly mean of LEO satellite orbit altitudes and solar radio flux (F10.7 index) during 24th and 25th solar cycles (1 sfu=10^{-22}Wm^{-1}Hz^{-1}).

- With the high and stable orbital altitude (~800 km), COSMIC-1 dry temperature is consistent with Metop even during the 24th solar maximum.
- As CubSat, SPIRE's orbital altitude gradually dropped from 550 km to 500 km.
- During the 25th solar cycle, COSMIC-2 altitude declines sharply from 700 km to 550 km and gradually down to 520 km.
- The orbital altitude change of COSMIC-2 might be a possible cause of its slightly positive bias against Metop and ERA-5.

(2) STAR-ROPP Inversion Implementations

The possible inversion procedures that affect RO trend analysis include i) precise orbit determination and clock synchronization, ii) the approach to convert Doppler to bending angles, iii) ionospheric correction, iv) the initialization of the Abelian integral to covert bending angles to refractivity profiles, and v) quality control. This section compared the bending angles and refractivity retrieved by STAR ROPP and STAR ROPP Full Spectrum Inversion (RFSI), and UCAR.

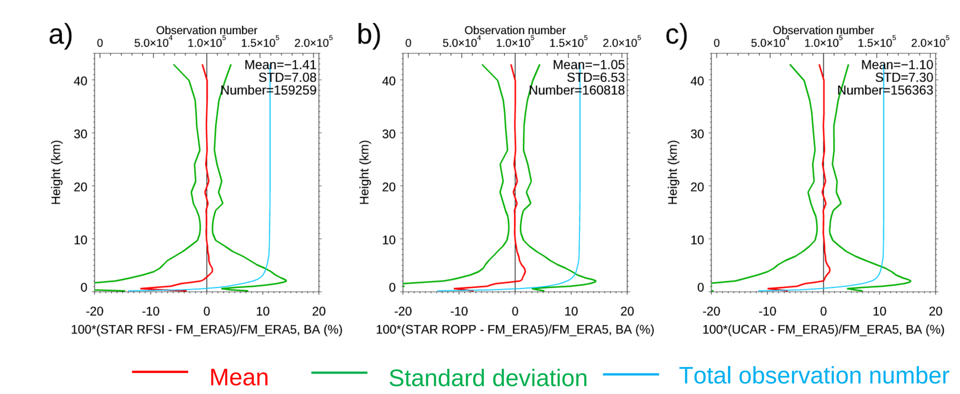


Fig. 7 Comparison of height-dependent fractional bending angle difference between COSMIC-2 and ERA5 simulations (O-B) in July 2022. (a) STAR RFSI against ERA5 forecast, (b) STAR ROPP against ERA5 forecast, and (c) UCAR against ERA5 forecast.

- The quality of STAR-ROPP COSMIC-2 bending angle profiles is very consistent with those inverted from STAR RFSI and UCAR when compared with the ERA-5 forecast.
- With similar comparisons, we confirmed that the STAR-ROPP Metop-A-B-C and SPIRE are also of very high quality as those of COSMIC-2.
- These validation results give us confidence in the quality of STAR-ROPP refractivity and temperature profiles from multiple RO missions.

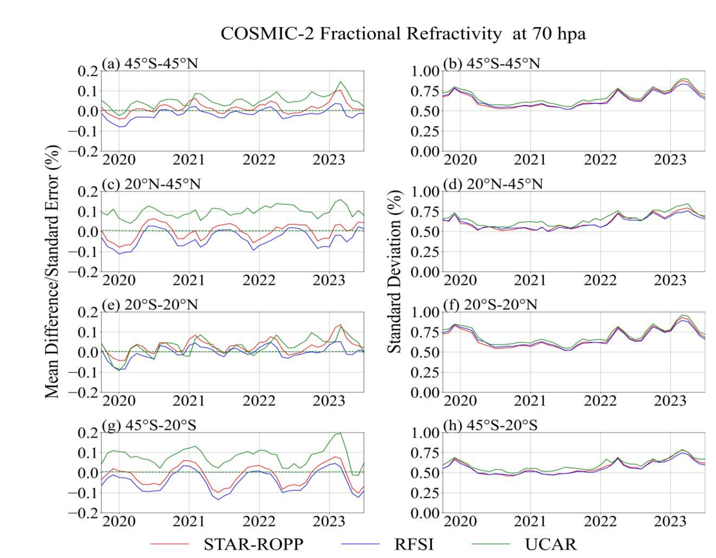


Fig.8 Time series of mean COSMIC-2 minus ERA-5 fractional difference/standard error (left column) and the standard deviation (right column) for four latitude zones at 70 hPa.

- UCAR, STAR-ROPP, and RFSI COSMIC-2 minus ERA-5 fractional refractivity differences reflect the seasonal variation, especially in the North/South mid-latitudes, which might be related to solar event-induced ionospheric perturbation.
- UCAR refractivity profiles are 0.1-0.2% consistently higher than those from STAR-ROPP and RFSI, and are positively biased compared to ERA-5, partly due to the different ionospheric error correction methods and the different bending angle initializations used by STAR and UCAR.
- The standard deviation reached minimum values in March 2020, when ECMWF started assimilating RO data. However, after that, both fractional refractivity biases and the standard deviation increase with time, which seems to reflect the rise of the F10.7 Index over the same period.

(3) COSMIC-2's smaller SNR in the mid-latitude regions

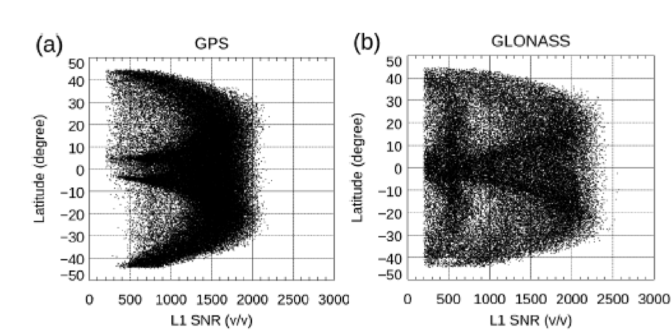


Fig. 9 Latitudinal distribution for COSMIC-2 L1 SNR from 15 February to 15 March 2022, for (a) GPS and (b) GLOSNASS. (Fig. 5 in Ho et al. 2023)

- Ho et al. (2023) stated that while COSMIC-2 forward and backward antenna viewing angles are within [23º, 66º] and [115º, 158º], their viewing azimuth angles are within [-75º, -20º] and [20º,75º].
- Because the antenna gain is smaller at the side viewing direction (the viewing azimuth is not zero degrees, which is over the midlatitudes), the related SNR over the midlatitudes is smaller than those in the tropical region.
- Relatively smaller SNR may be the reason for the slight positive bias of COSMIC-2 in the midlatitudes than in Tropics.

Summary

- The comparison of the collocated dry temperature profiles from multiple missions exhibits good agreement in the UTLS region, except above 20 km, SPIRE shows a slight positive bias up to 0.16 K in polar areas, and COSMIC-2 has a larger positive bias ranging from 0.17-0.28 from 45ºS-45ºN.
- Sensitivity studies demonstrate that the COSMIC-2 positive bias in the mid-stratosphere can increase the temperature trend by about 0.05 K/Decade in this region. Therefore, COSMIC-2 data above 20 km has been excluded from the construction of STAR-ROPP MMC.
- Preliminary investigation indicates that the residual ionospheric error due to the drop of COSMIC-2 orbital altitude and the smaller SNR in the mid-latitudes owing to the antenna viewing geometry might contribute to the COSMIC-2 positive bias above 20 km.
- We will continue quantifying the COSMIC-2 biases using other datasets and investigate their causes in a future study.
- For the details, please refer to Zhou et al (2024)

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Acknowledgments

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