Tropospheric ozone trends at Boulder (2000-2022):

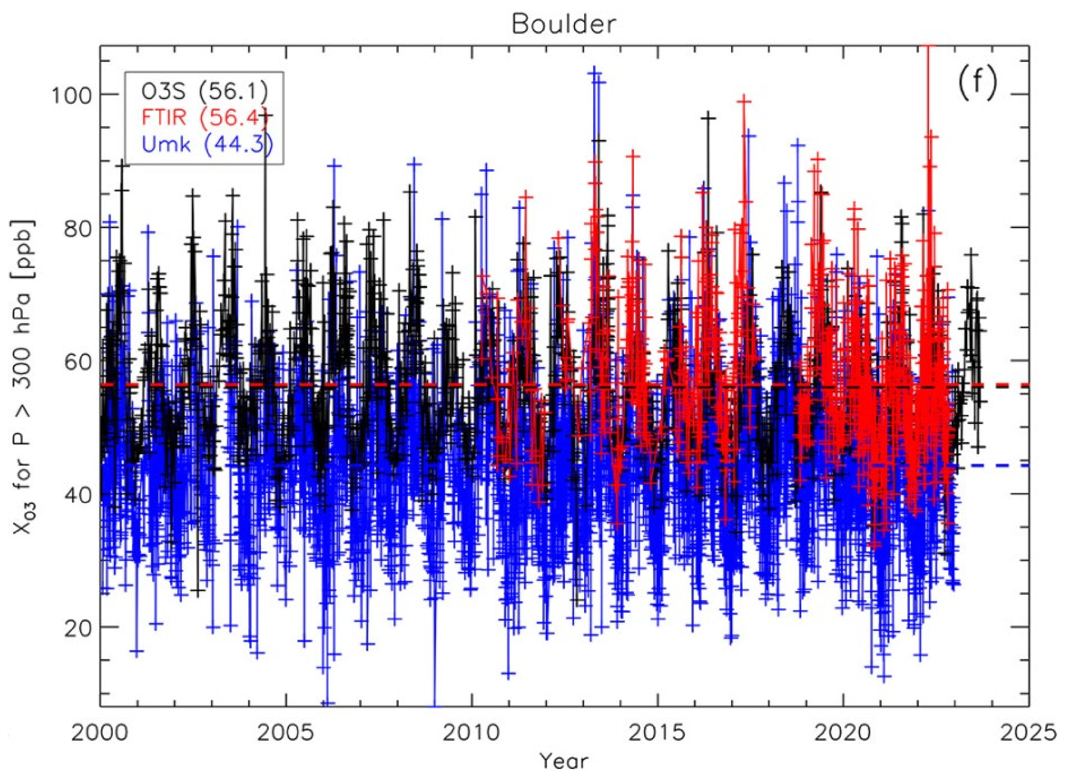
Insights from multiple NDACC instruments

I. Petropavlovskikh (CIRES/NOAA), P. Effertz (CIRES/NOAA); B. Noirot (CIRES/NOAA), G. McConville(CIRES/NOAA), J. Hannigan (NCAR); I. Ortega (NCAR); E. Maillard Barras (MeteoSwiss, Switzerland); R. Van Malderen (RMI, Belgium); P. Cullis (NOAA); G. Morris (NOAA); R. Stauffer (NASA/Goddard), A. Thomson (U. of Maryland)

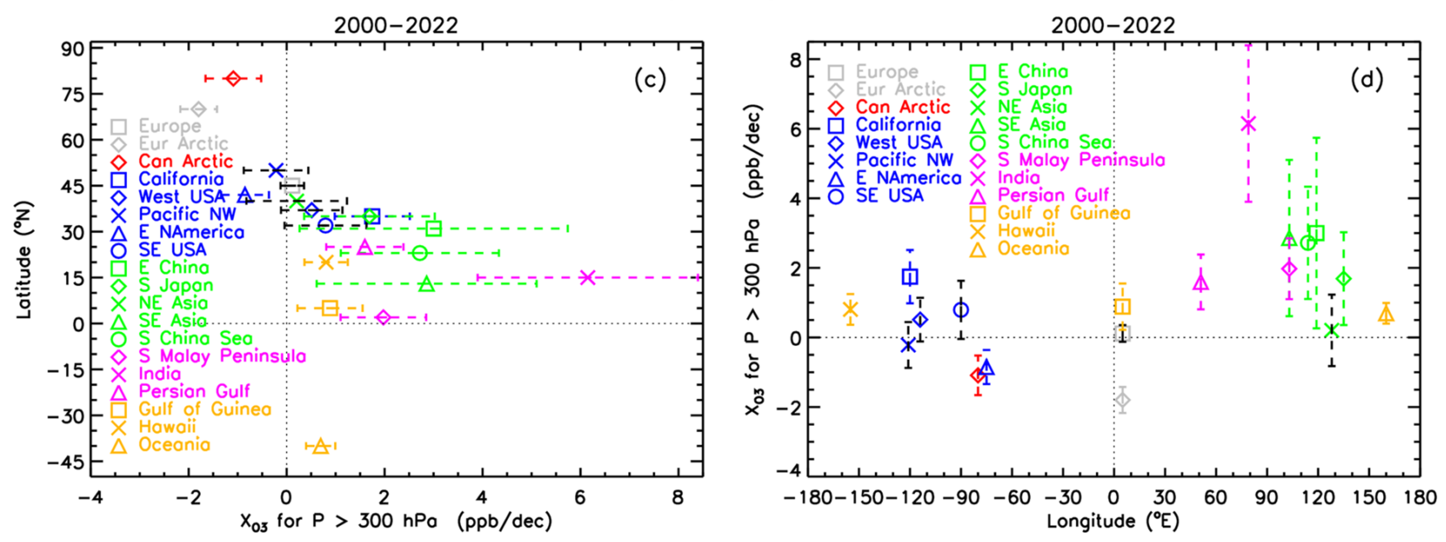
Introduction

The TOAR-II Harmonization and Evaluation of Ground-based Instruments for Free-Tropospheric Ozone Measurements (HEGIFTOM) project evaluated changes in partial tropospheric ozone columns (<300 hPa, TrOC) using 2000-2022 globally distributed ozone records using Quantile Regression (QR) and Multiple Linear Regression (MLR) methods (Van Malderen et al, 2025). The trends over Boulder were derived from ozonesondes, Fourier-Transform Infrared spectrometer (FTIR), and Dobson Umkehr records that are of high quality and maintained according to the Network for Detection of Atmospheric Composition Change protocols (www.ndacc.org). Still, the intermittent biases and gaps were found in instrumental records that likely lead to the differences in the derived trends.

In this paper we investigate mean ozone biases related to the instrument-related temporal sampling and to the vertical sensitivity of retrieved ozone by FTIR and Umkehr methods as determined by their respective Averaging Kernels. The strategy for future intercomparisons between surface-based instruments measuring ozone is discussed.



VM2025a. Figure 2 (f) 2000-2022 TrOC daily ozone data in Boulder from ozonesonde (O3S), FTIR, and Dobson Umkehr.



VM2025b, Figure 10 (c,d) 2000-2022 trends for different regions. Boulder is part of the US-West region.

More information about TOAR II HEGIFTOM trends can be found in VM2025a: Van Malderen et al (2025a)), DOI:10.5194/acp-25-7187-2025

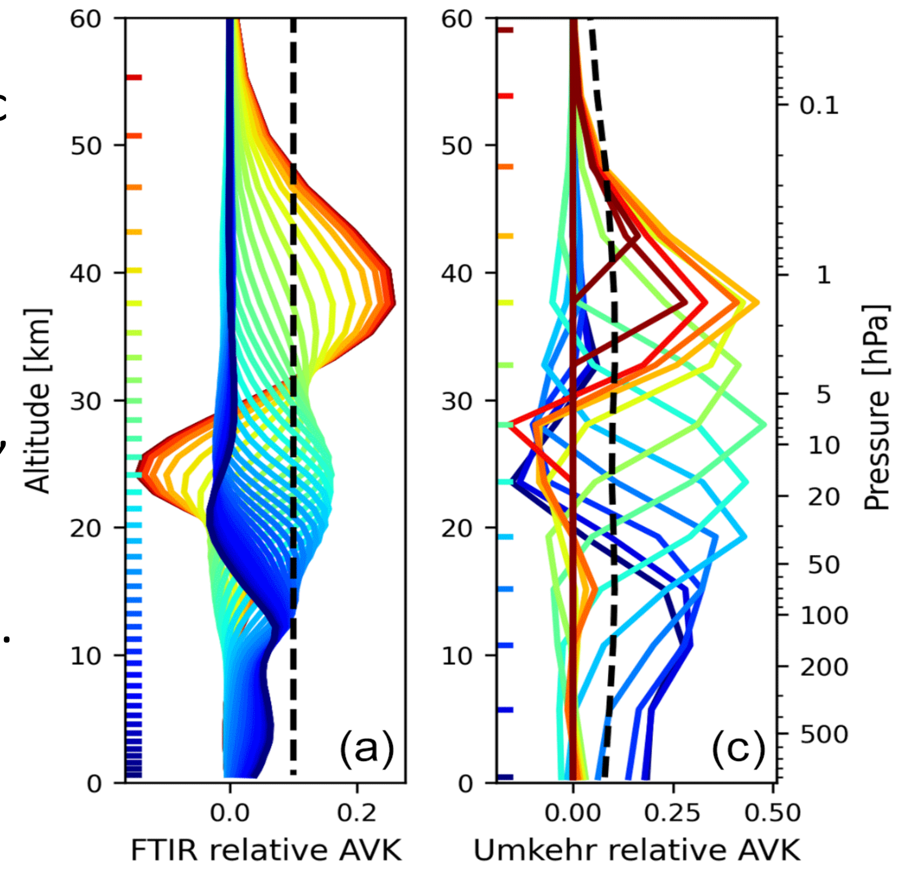
and VM2025b: Van Malderen et al. (2025b), DOI:10.5194/egusphere-2024-3745

Datasets

Ozonesondes (NDACC)	Sterling et al (2018), Stauffer et al (2022)
Dobson Umkehr (NOAA)	Petropavlovskikh et al. (2024)
FTIR (NDACC)	Hase et al. (2004), Vigouroux et al. (2015)

Please contact Irina Petropavlovskikh for Umkehr data irina.Petropavlovskikh@colorado.edu

Averaging Kernels



Bjorklund et al. 2024: Figure 2(a-c) Averaging kernel of the FTIR (left) and Dobson Umkehr (right). The color corresponds to the altitude marked on the left-hand side of the figures. The dashed black line shows the sensitivity (divided by 10 to better fit on the scale of the figure): zero means only a priori contributes to RT.

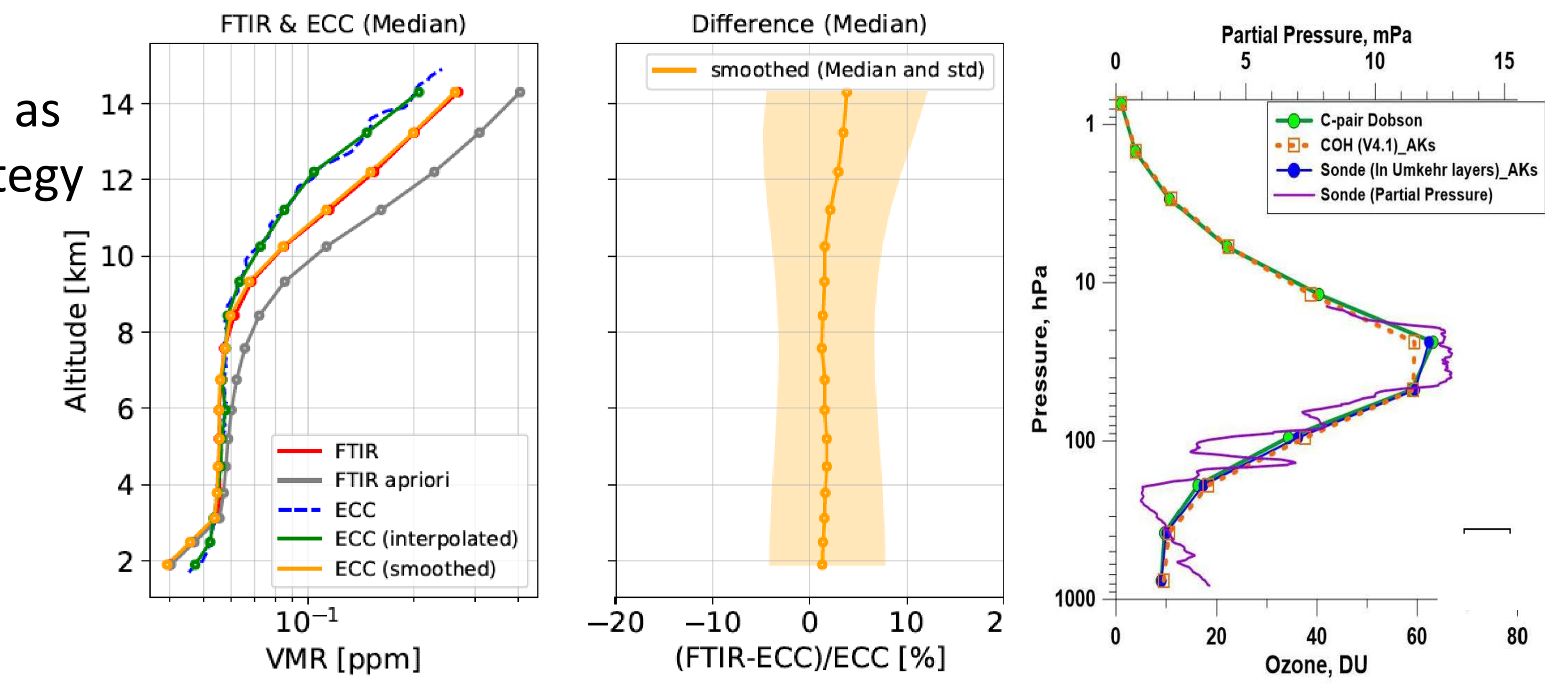


FIG 1. Example of ozonesonde (ECC) profiles compared to the co-incident FTIR and Dobson observations in Boulder, CO. Left panel: Mean (2018-2024) FTIR ozone VMR (ppm), FTIR a priori, 100-m averaged ECC, interpolated ECC, and smoothed ECC below 15 km. Middle panel: relative difference (%) between FTIR and ECC smoothed. Right panel: Dobson Umkehr, COH (satellite), AK-smoothed ozonesonde O3 partial columns (DU) and 100-m binned ozonesonde profile (mPa) taken in Boulder on 11/13/2018 .

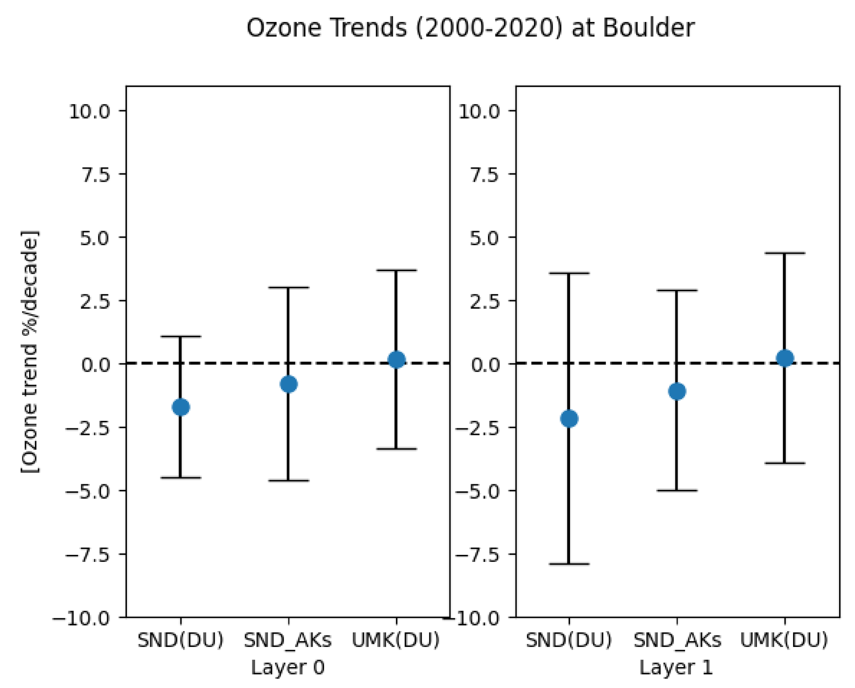


FIG 2. Ozone trends in ozonesonde (SND), Umkehr (UMK) and AK-smoothed sonde (SND_AKs) data in Umkehr layers 0 (surface-506 hPa) and layer 1 (506-253 hPa). The impact of the AK-smoothing is to reduce negative trends in SND data (non-stat significant)

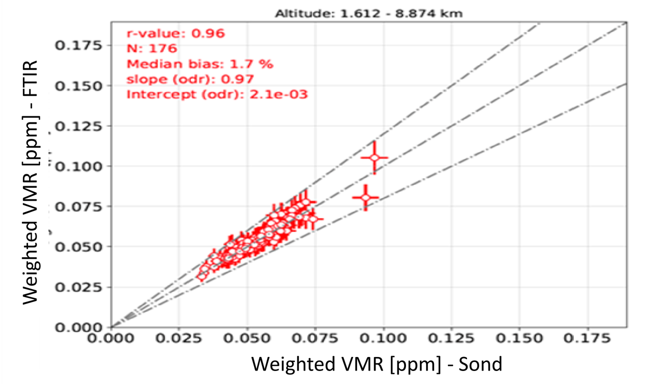
Conclusions

- **Co-incident and co-located tropospheric ozone records collected by ozonesonde, FTIR and Dobson Umkehr instruments in Boulder provide opportunity for in-depth assessment of long-term trends, instrumental drifts and biases.**
- **We find that three measuring systems observing tropospheric ozone during 2019-2024 assessment period agree well on capturing the variability on monthly to annual scales (i.e. reduced ozone in 2020). Agreement is improved when the co-incident criteria and AK-smoothing methods are applied.**
- **Further analyses are needed to characterize sampling biases.**

Tropospheric ozone in Boulder (2019-2024)

We investigate how FTIR, Umkehr and O3S tropospheric ozone in Boulder compare in 2019-2024. Coincident data (within 30 min) are used to assess trends, biases and correlation. AK are applied to smooth ozonesonde profiles.

FTIR vs. ozonesondes



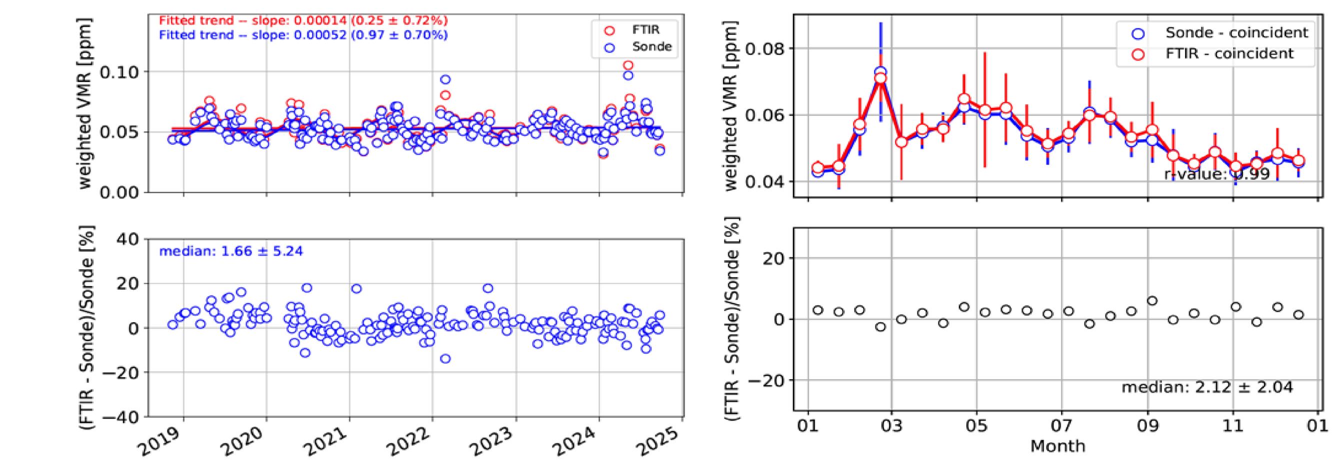


FIG 4. FTIR and sondes averages (1.61-8.87 km) show small positive trends in 2019-2024 that are likely driven by episodic wildfires. FTIR TO3 record has high median bias (~2 %) and high correlation (R^2=0.96) relative to ozonesondes. Also an interesting seasonal pattern is found over Boulder with highest ozone at the end of February, May and July.

Umkehr vs ozonesondes

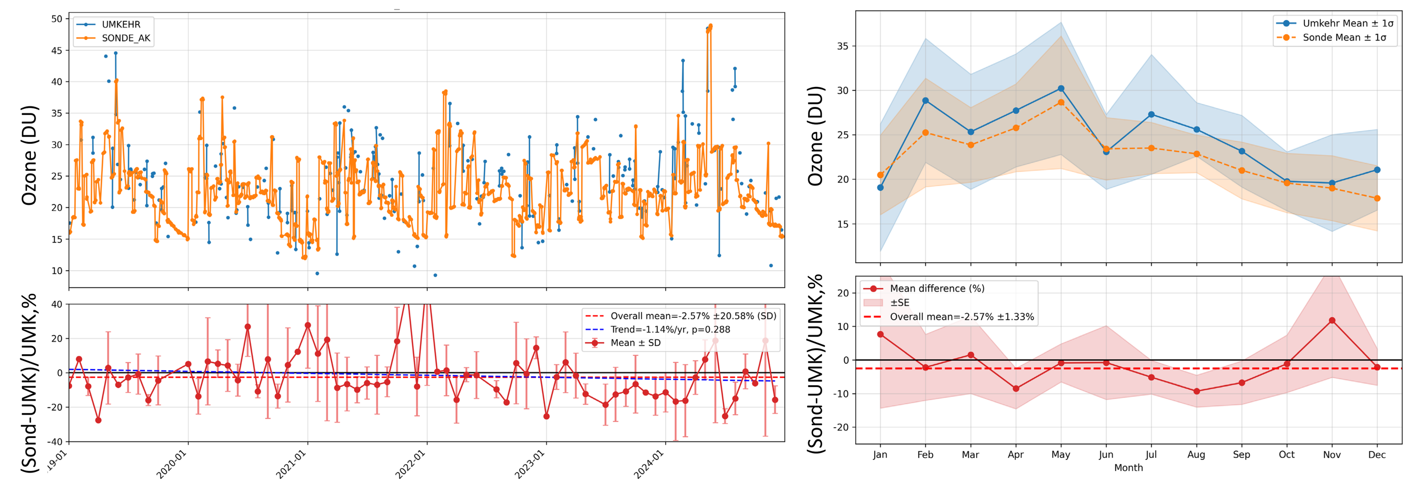


FIG 5. The correlation between monthly averaged Umkehr and AK-smoothed ozonesonde (2019-2024) in the troposphere is 0.65 with low mean bias ~2.6 %. The larger bias is found in April likely impacted by active strat./trop. exchange that Umkehr has difficulty to isolate. Larger bias is found in August due to enhanced pollution in the lower troposphere where Umkehr has lower sensitivity.

FTIR vs. Umkehr

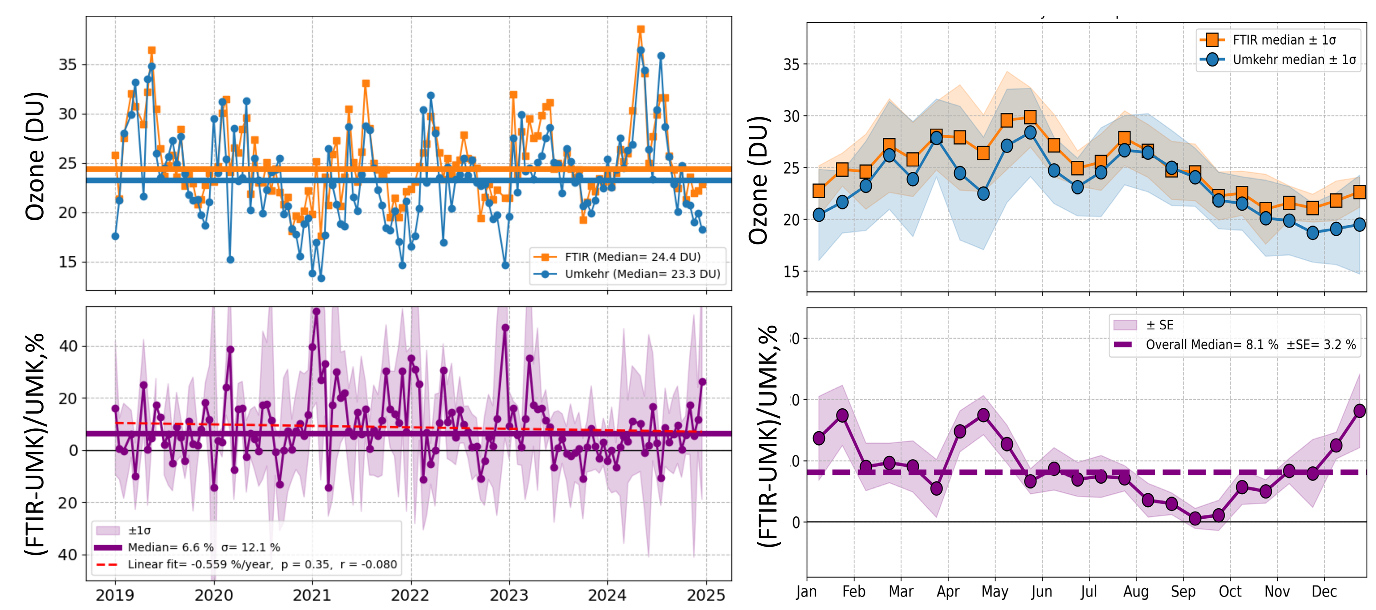


FIG 6. FTIR and Umkehr MM (co-incident) partial ozone columns (surface-253 hPa) comparisons, 2019-2024. On average, FTIR is ~8 % higher than Umkehr, including occasional MM biases > 15 % (Umkehr uncertainty). FTIR/Umkehr correlation R2 is 0.8 and the scatter plot slope is 0.76.