Trends (2000 to 2022) from TOAR II/HEGIFTOM Global Ground-based Tropospheric Measurements: A Reference Dataset for Satellite Products & Models

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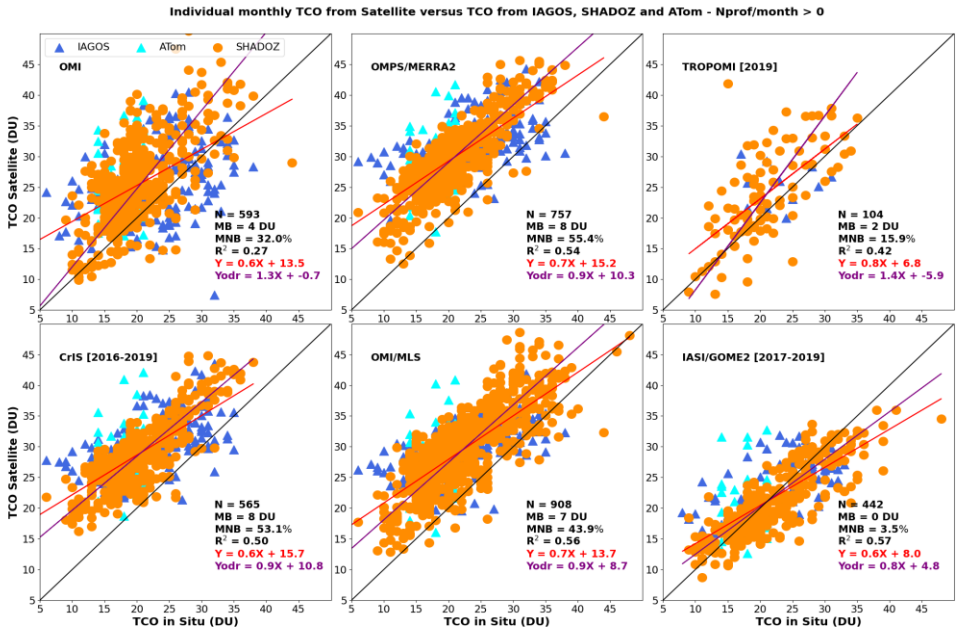
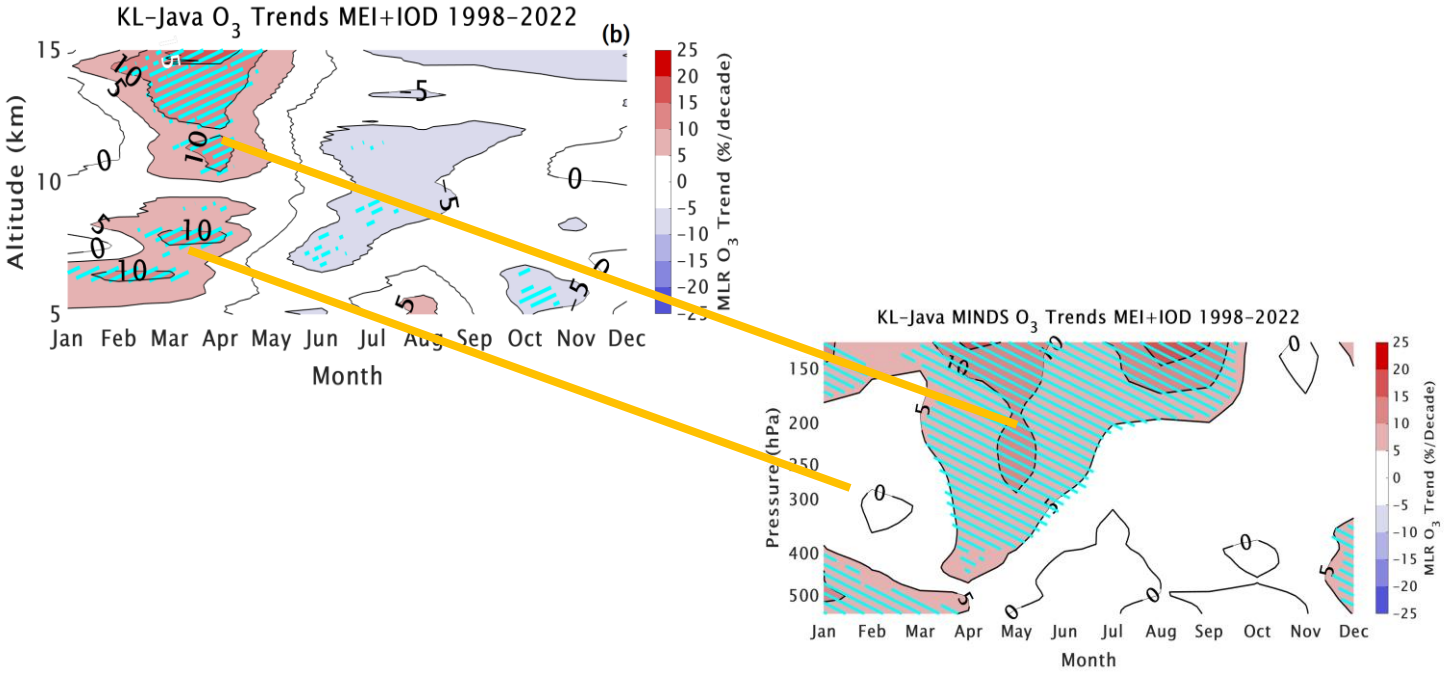
SHADOZ=So. Hemisphere Additional Ozonesondes
IAGOS = In-service Aircraft for a Global Observing System
HEGIFTOM = Harmonization and Evaluation of Ground-based Instruments for Free Tropospheric Ozone Measurements

Outline

- **WHY Is HEGIFTOM (**Harmonization and Evaluation of Ground-based Instruments for Free Tropospheric Ozone Measurements) **so important in Ozone (TOAR II) & Climate Assessments?**
- **HEGIFTOM: WHAT, HOW, WHERE. Data Status.**
- **Present "Total tropospheric ozone column" (TrOC, surface to 300 hPa) trends**
  - **Focus on 55 station/instrument time-series from 2000-2022**
  - **Five instrument types with TrOC measurements included in calculations**
  - **Compare trends by 2 standard statistical methods (QR, MLR)**
  - **Free Tropospheric (FT) ozone column trends computed (not shown)**
- ***Summary: Trends to date for 2000-2022 show*:**
  - ***All sites within ± 3 ppbv/dec ➔ equivalent to ±(1-8)%/dec, for TrOC, depending on location, and independent of statistical method***
  - ***HEGIFTOM data = *the* independent reference for satellite, model evaluation***

Why Does IGAC/TOAR II Need HEGIFTOM?





- **Tropospheric ozone (TCO) satellite products (Keppens, next Talk) struggle to match aircraft, ozonesondes, each other! New tropical comparisons (Gaudel et al., 2024 for TOAR II) illustrate noise, varying biases, correlation, r^2 0.3-0.6 (Left)**
- **Typical CCM puts positive FT O_3 trend, greatest radiative forcing region, in wrong months. BL O_3 trend too low. (Right, update of Stauffer et al., 2019)**

WHAT & HOW: HEGIFTOM Data to the Rescue!

HEGIFTOM: IGAC/TOAR II Activity, Co-Leads: R. Van Malderen & H. G. J. Smit

Alternative to still-evolving satellite TrOC (tropospheric ozone column) products:

- **Ozone from 5 ground-based instrument types, most from NDACC & related networks: in-service aircraft [IAGOS], ozonesondes, FTIR, Brewer/Dobson Umkehr, Lidar (Photos, Right)**
- **All instrument types in HEGIFTOM database. *Reprocessed data based on rigorous protocols and absolute standards*, thus ensuring harmonized time-series with minimal artifacts. Contributing networks**
- **Each measurement is delivered with *uncertainty* and a *quality flag***

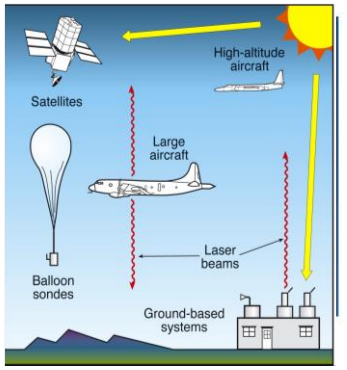
IAGOS


Ozonesondes


Brewer/Dobson Umkehr


FTIR


Lidar



TrOC= surface -300 hPa

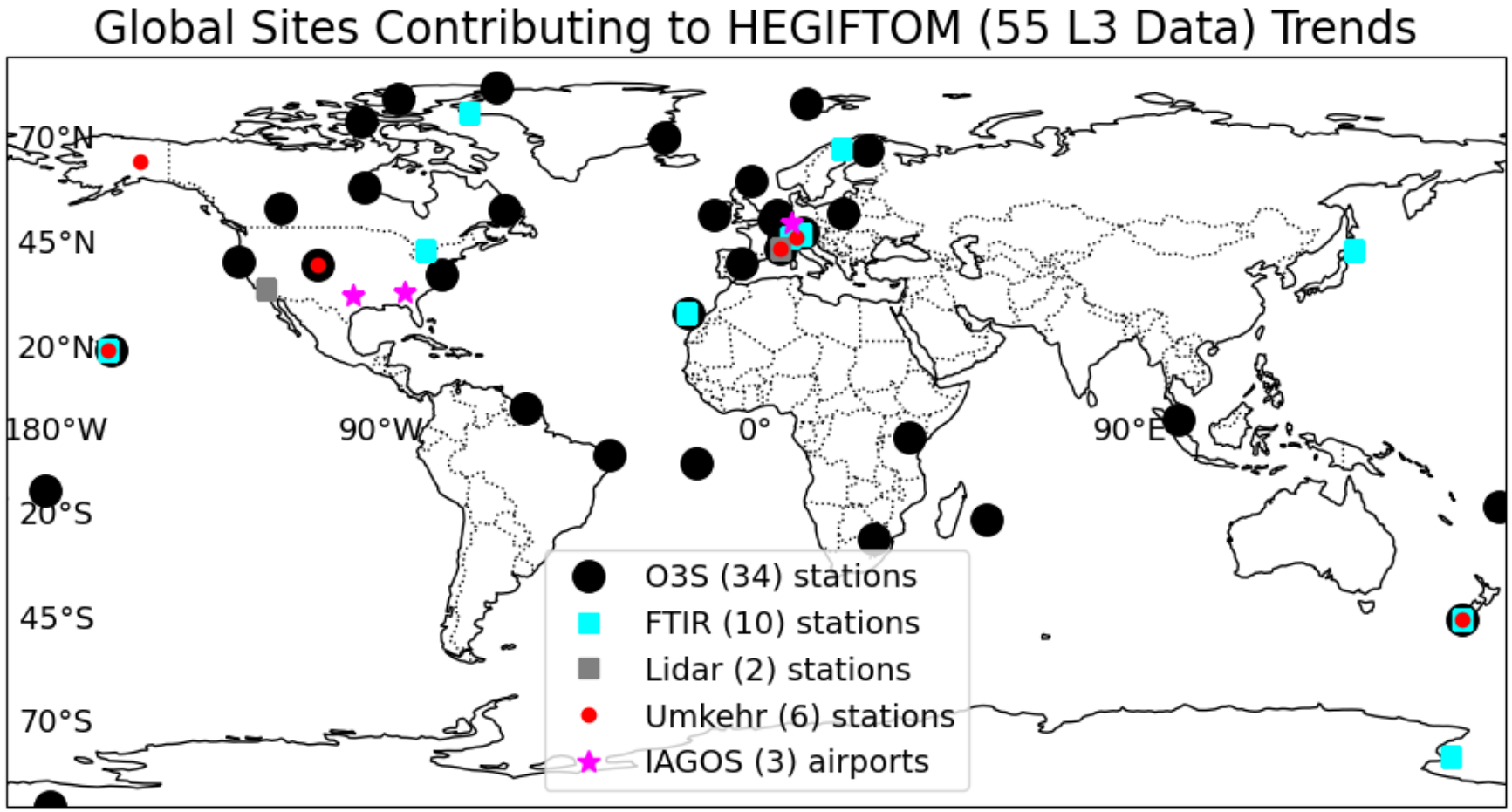
FT, 700-400 hPa

NDACC

GAW

http://hegiftom.meteo.be/datasets

HEGIFTOM Sites/Datasets for 2000-2022 Trends



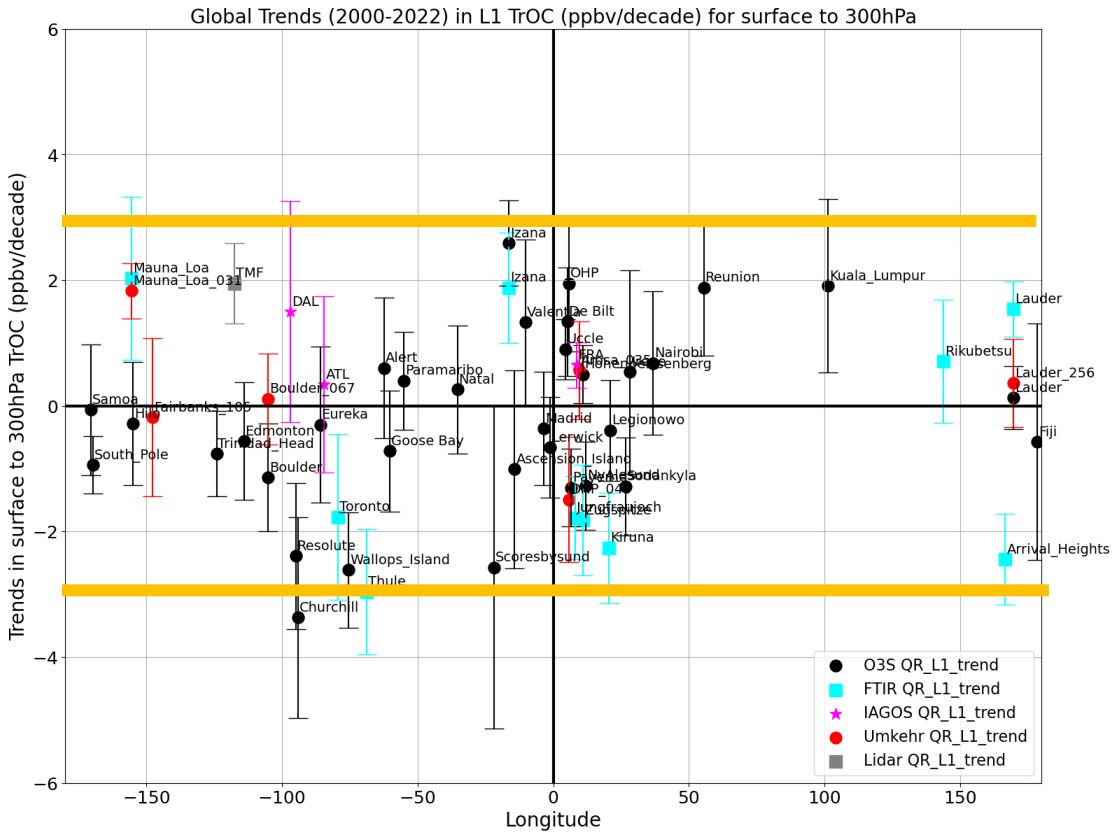
TOAR II Protocol: Minimum Sample No. to reduce trends uncertainty, start in 2000-2002, end 2020-2022 QR (Quantile Regression) analyses use all data ("L1") from 55 sites; **only 50%-ile results shown**. Monthly means (L3) from 55 sites are analyzed with QR and MLR (multiple linear regression)

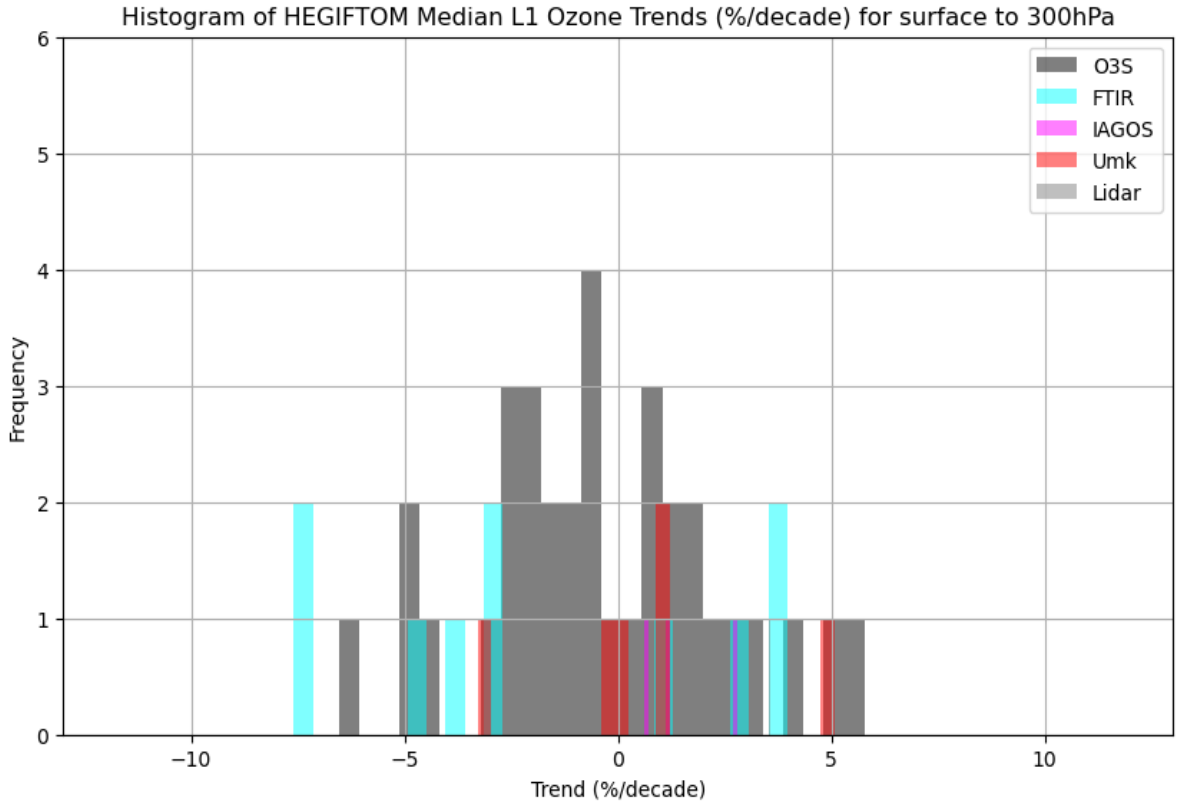
Trends Questions Addressed with HEGIFTOM Data

Phase II

1. What do TrOC trends (surface to 300 hPa) for 2000-2022 look like? *Examine "all-site" QR trends & median distribution at 55 sites*
2. How do TrOC trends computed with QR and MLR compare? *Answer with analysis of L3 (monthly mean) TrOC from 55 stations*
3. How do TrOC trends from the various instrument types (sondes, IAGOS, FTIR, Dobson Umkehr, Lidar) compare? *Examine trends at colocated stations*
4. How do TrOC trends vary by region? *Examine trends on map*

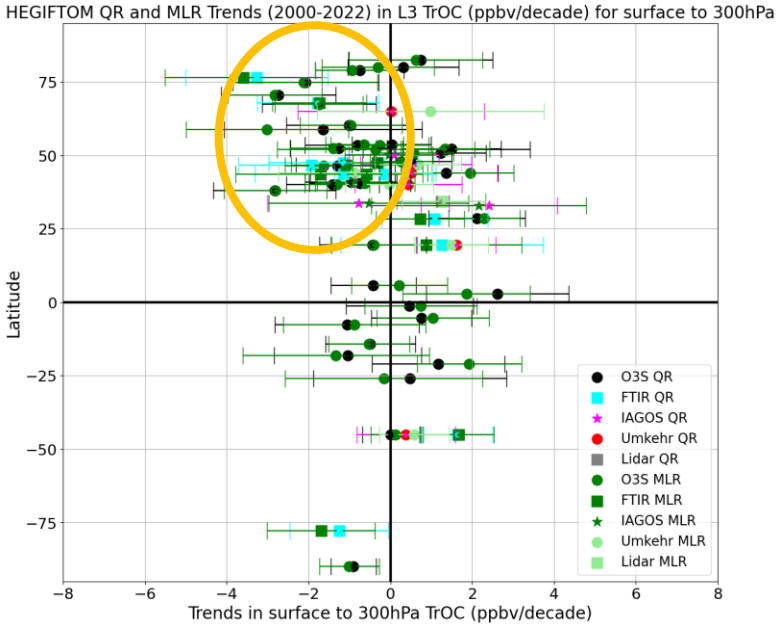
Ques 1. TrOC QR "All-Site" Trends, 5 Instrument Types

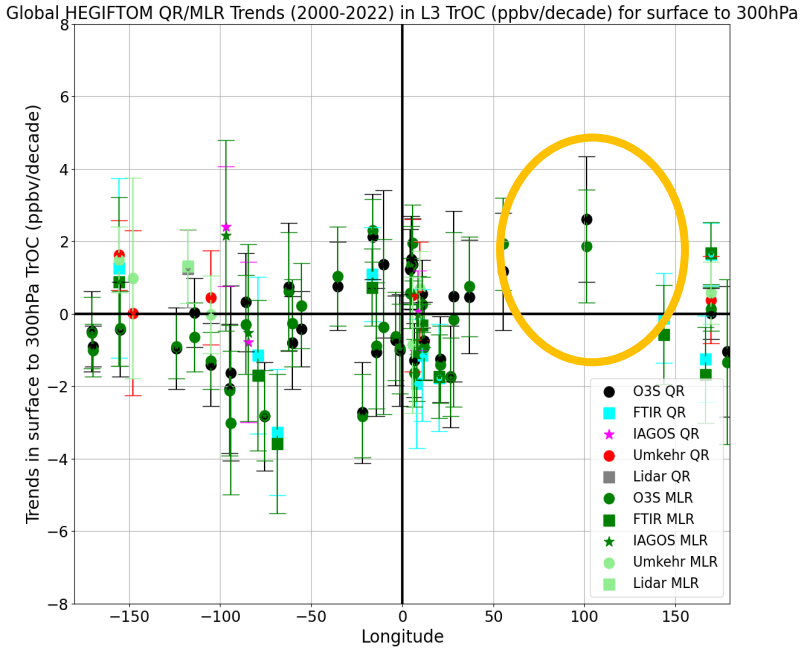


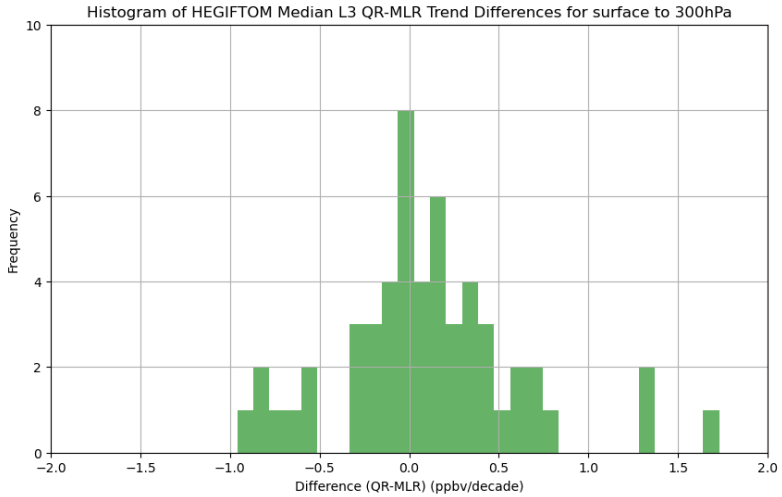


- **Left:** QR L1 trends for TrOC in TOAR-preferred ppbv/decade (2σ). (1) **Median trends nearly all within +/- 3 ppbv/decade.** (2) Medians for most stations ~0. (3) Positive and negative trends appear at all longitudes
- **Right:** Medians in %/decade suggest possible instrument bias. More negatives than positives

Ques 2. TrOC QR, MLR Trends Similar







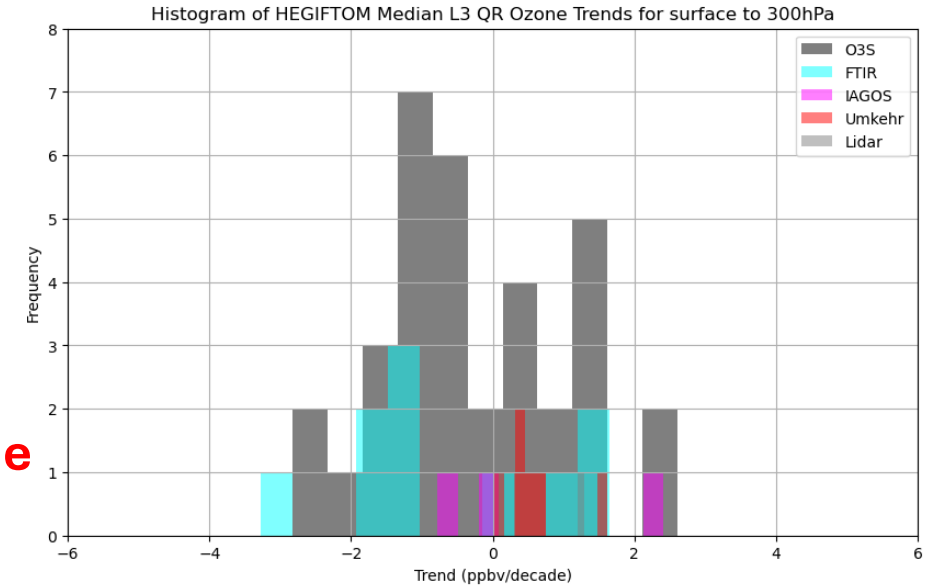
QR-MLR trends, ppbv/dec

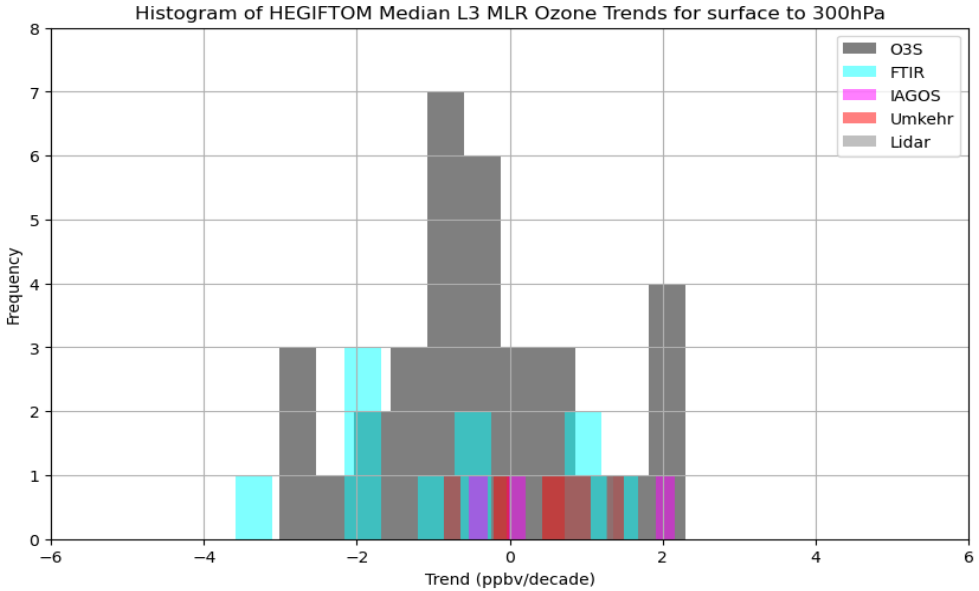
- **Left & Center:** **TrOC trends, QR= color-coded for 5 instruments. MLR= green shades for 5 instrument types. QR trends tend to be higher than MLR (Right)**
- **Left: Preponderance of negative trends in No. Hemisphere. Center: few Asian data**

Ques 2, Cont'd. TrOC QR, MLR Trends Similarity

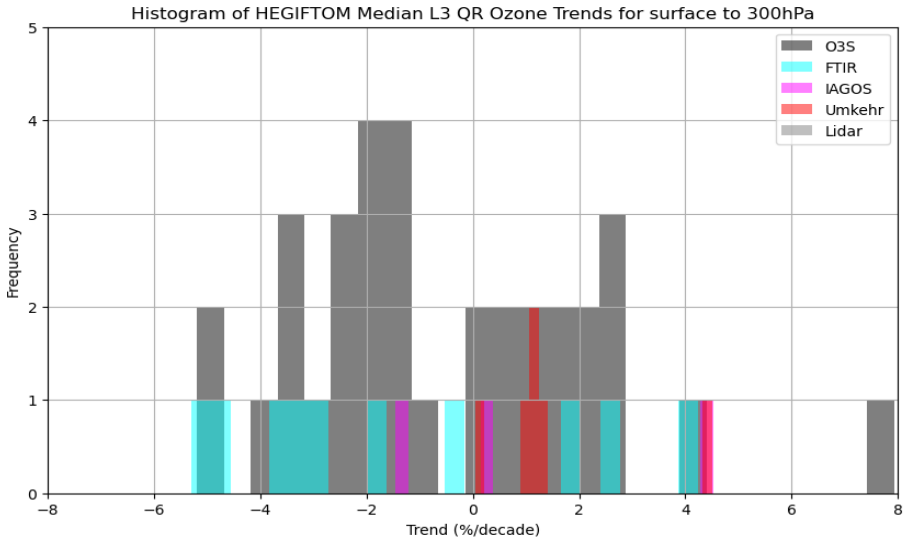
TOAR Phase II

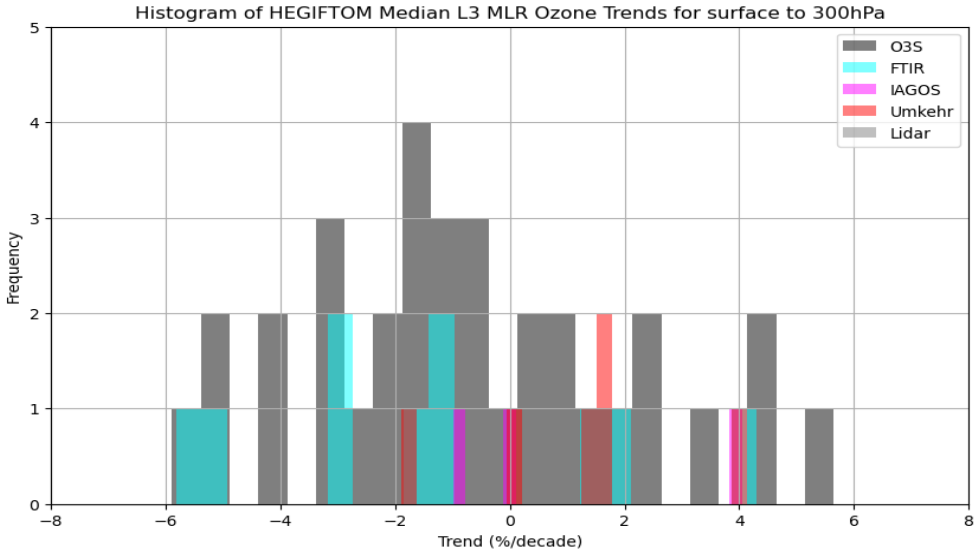
QR, MLR trends, +/-3 ppbv/decade range



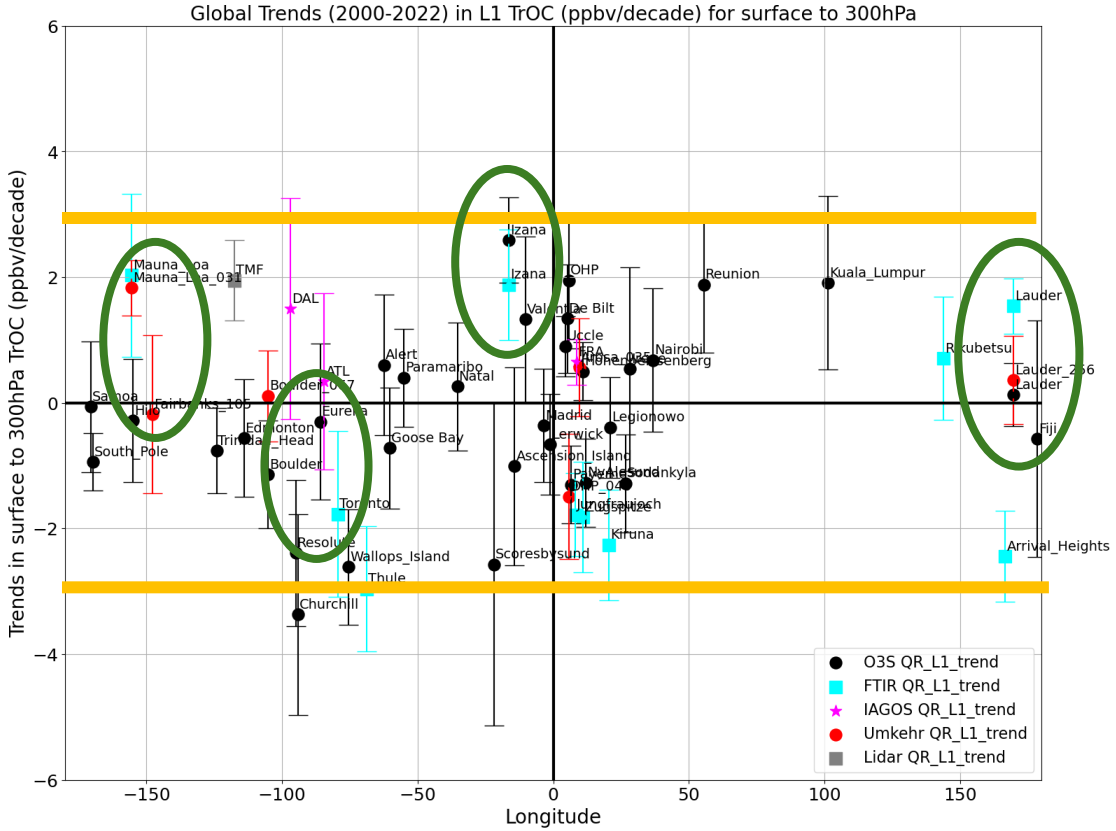


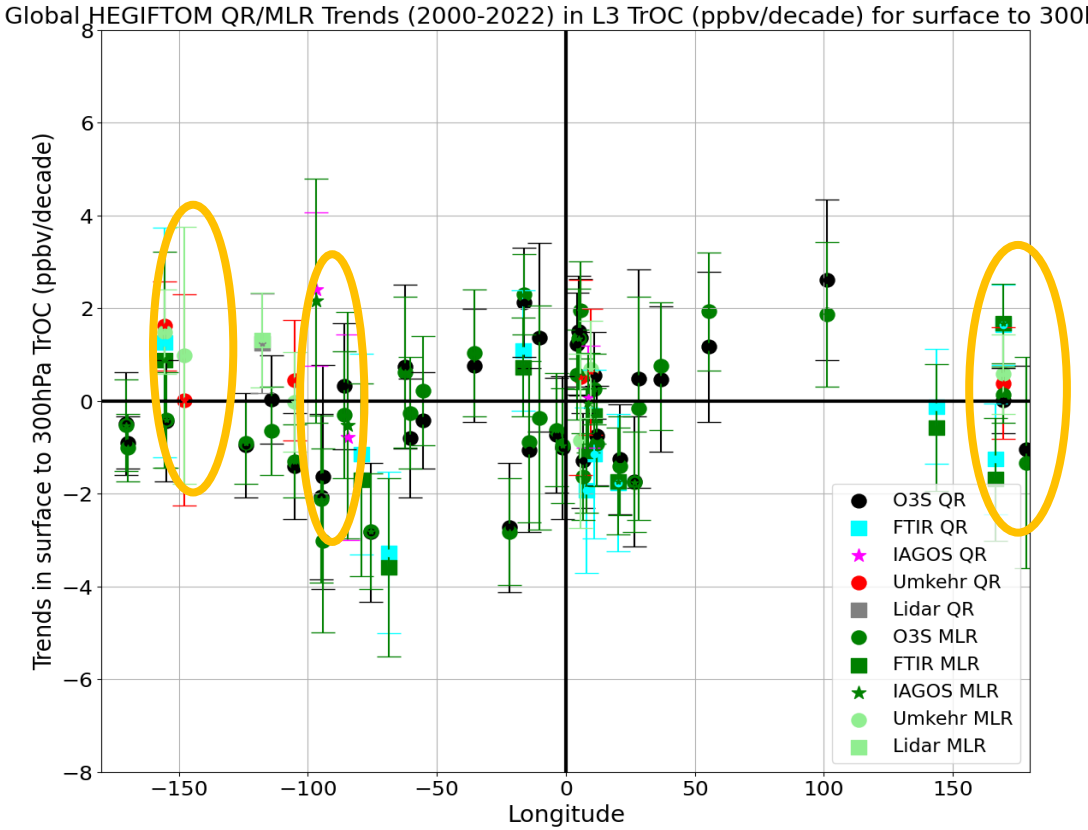
QR, MLR trends, %/decade, -6 to +8%/dec range





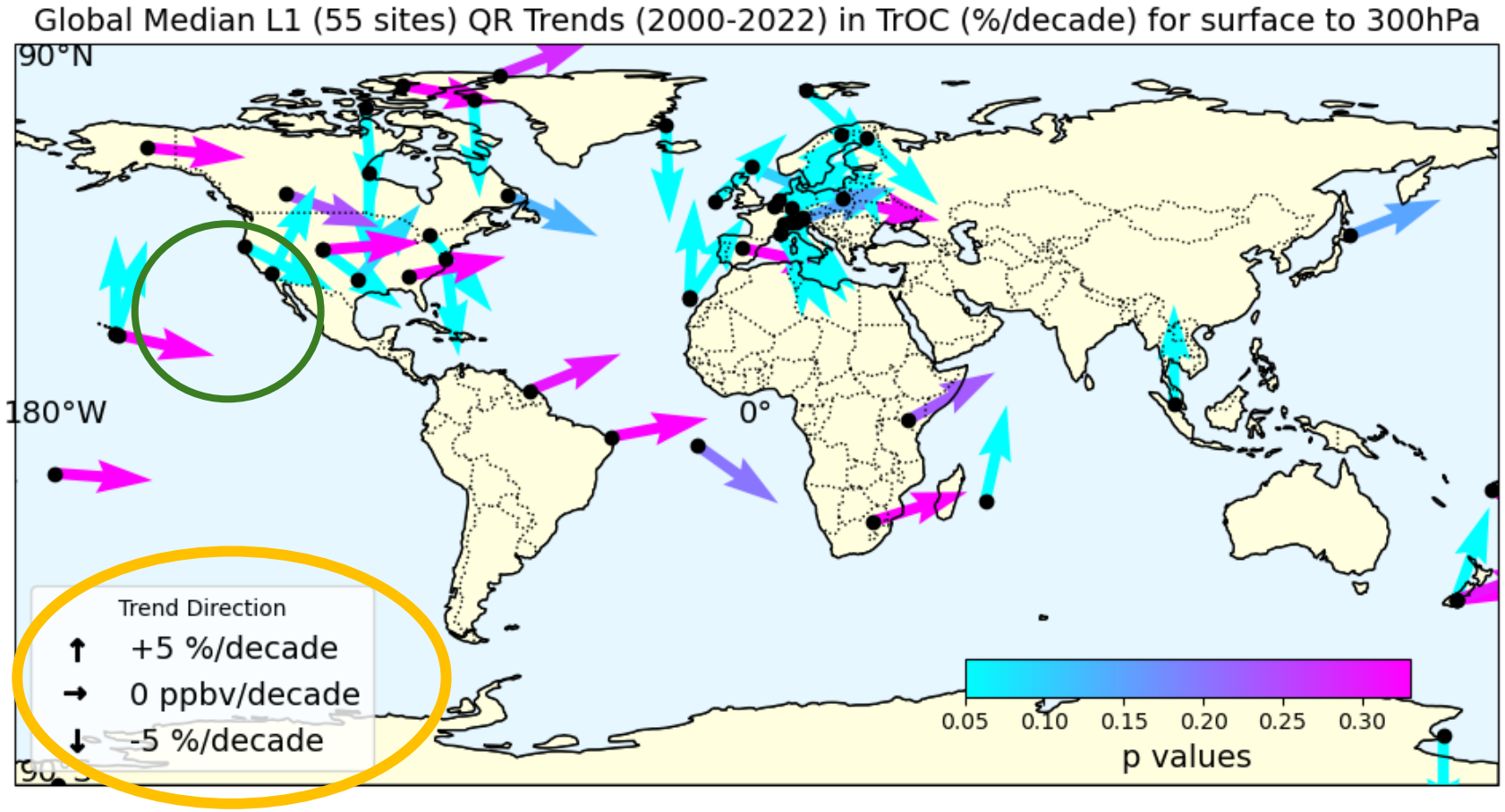
Ques 3. TrOC Trends from 5 Instruments Compared





- **Left:** L1 QR trends, 4 of 6 sites with > 1 instrument show large offsets: MLO/Hilo, Boulder, Izaña, Lauder (Zeng et al., 2024; Björklund et al., 2024)
- **Right:** Pronounced offsets observed at same sites (MLO/Hilo, Boulder, Lauder) with both statistical methods. Causes unclear – different sampling frequency, protocols, diurnal, seasonal effects investigated

Ques 4. TrOC Trends – Global Map View



Summarizes: 55 station Trends, moderately positive to negative trends with more confidence (lower p-value) in no. hemisphere (NH). More negative trends in NH. Large divergences at multi-instrument stations. Lack of SH and Asian data in HEGIFTOM limits "global" assessment

Conclusions – HEGIFTOM TOAR II Trends

SUMMARY

- TrOC trends (2000-2022) determined from 55 Ground-based Instruments display *moderately* positive and negative median trends; many with no detectable change!
- Results are independent of QR, MLR statistical method. D. Kollonige SHADOZ talk illustrates outstanding MLR application to equatorial SE Asia trends!

SIGNIFICANCE: HEGIFTOM data are *the* Definitive TOAR Reference. Use them!

- Recommend TOAR Model Comparison project with these values, site by site
- If model (or satellite TOC) disagree, HEGIFTOM can guide improvements

WORK IN PROGRESS:

-Understand instrument trend offsets
-Nearby site trend disagreements- why?
-Investigate COVID-19 impact on trends
-"Merge" stations for robust "regional trends" – examine 5%-ile, 95%-ile trends

Thank you! Acknowledgments. Bibliography

- **Acknowledgments: Dozens of funding organizations. Hundreds of researchers who have operated and collected ozone ground-based data over the past 30 years! Ozonesonde Funding by NASA UACO (K. Jucks), SAGE III (R. Eckman) and NOAA/OAR - GML**

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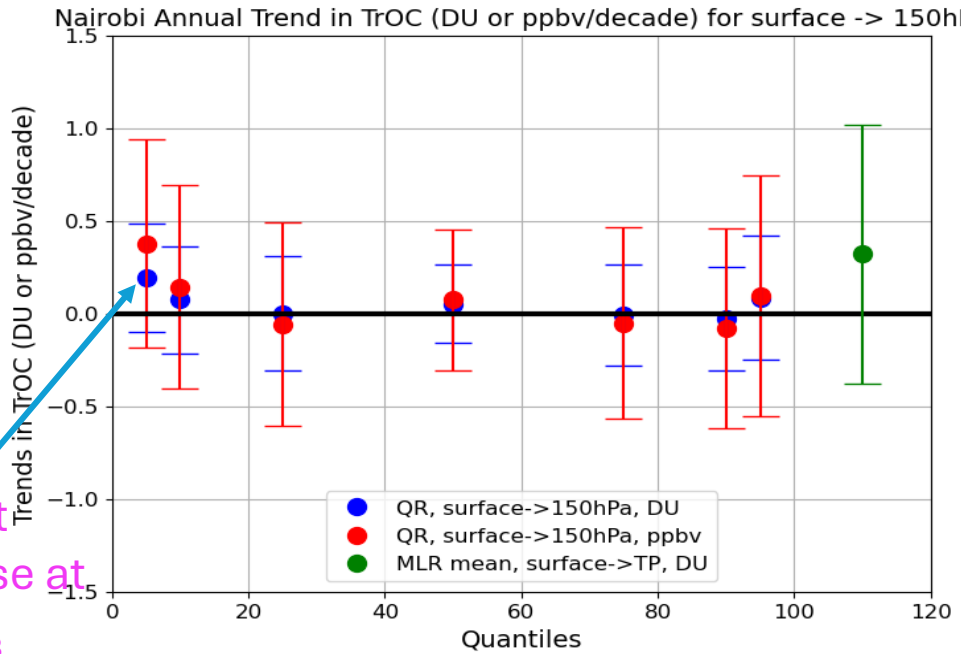
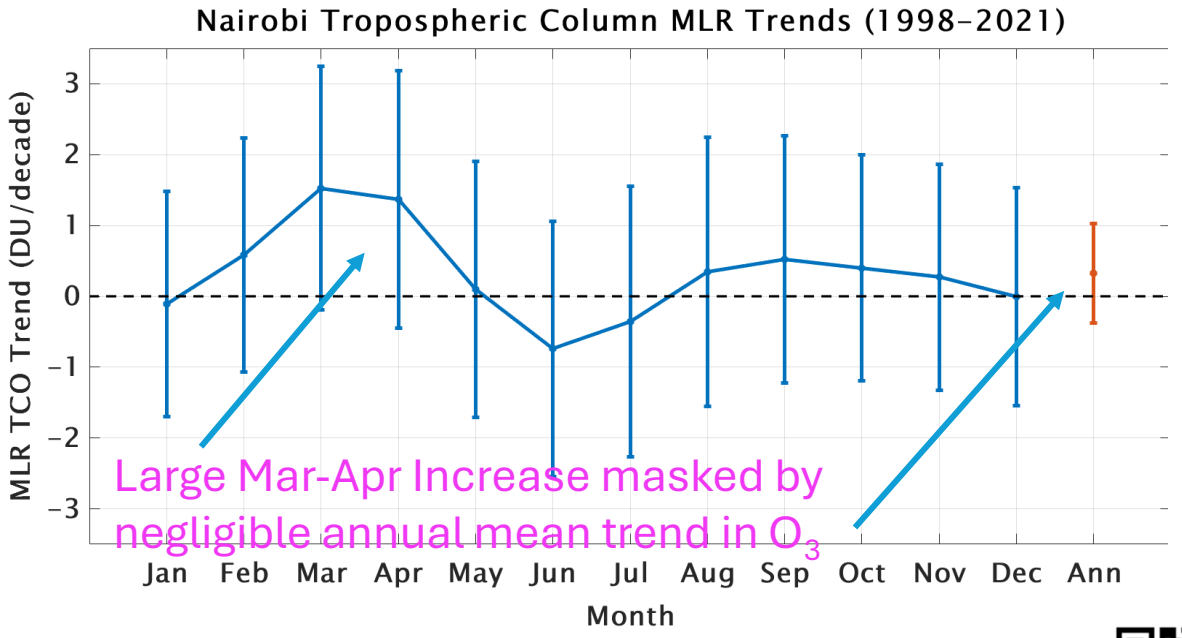
HEGIFTOM Trends. Input & Guidelines

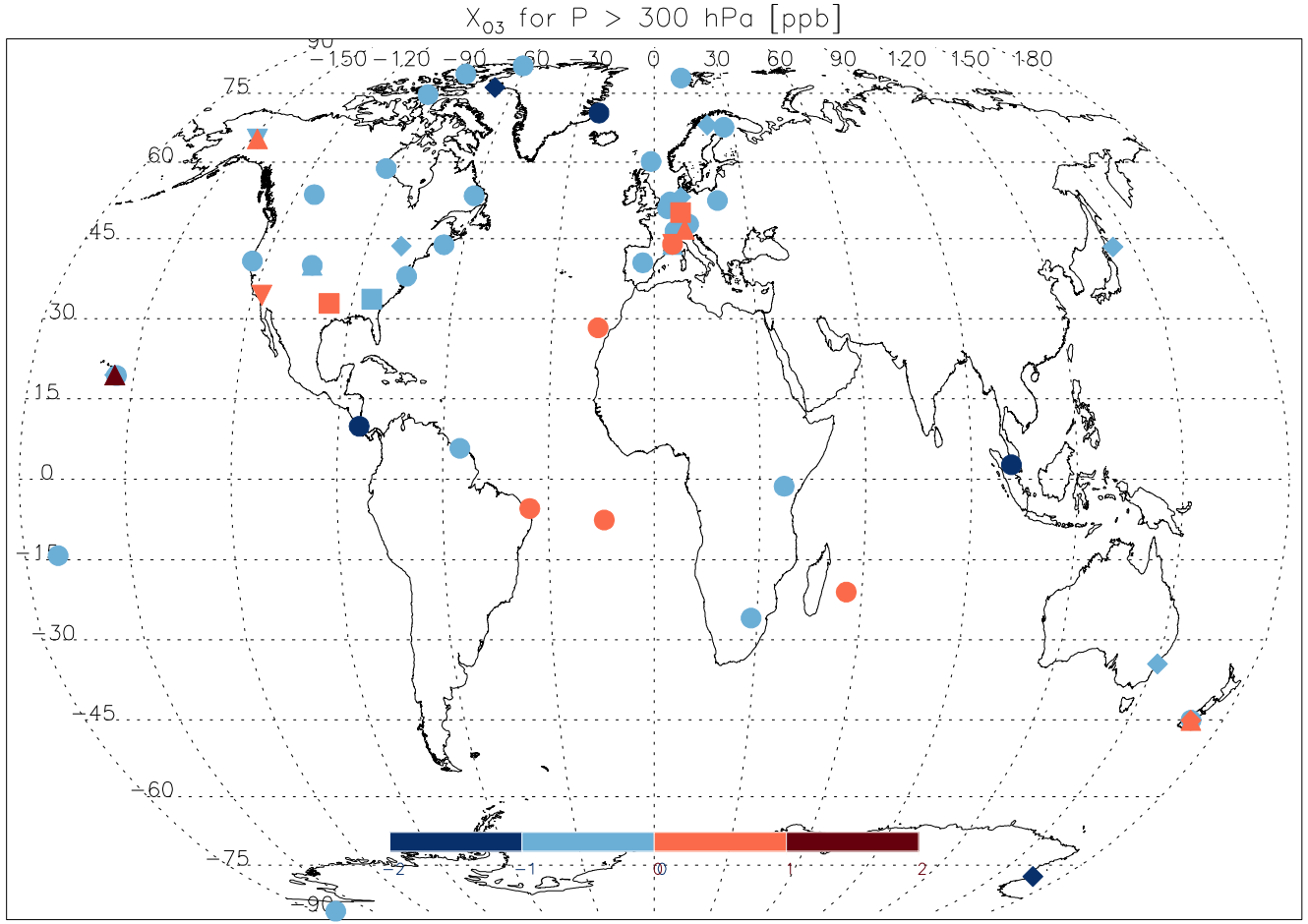


Largest Increase at Low O_3



- **Recommended TOAR II statistical approach is Quantile Regression (QR) with NOAA-provided test code, e.g., K-L Chang et al., (2023; JGR; 10.1029/2022JD038090)**
- **Alternative: Multiple-Linear Regression (MLR) as used in Thompson et al., 2021 & Stauffer et al., *ACP*, 2024. MLR is standard of stratospheric ozone Assessment community**
- **Above example for a typical SHADOZ station shows merits of each approach. QR gives insights into low-mid-ozone-O_3 profiles. Monthly means from MLR give insight into meteorological or chemical signatures responsible for O_3 trends**

Tropospheric ozone column: COVID impact



○ ozonesondes

△ Umkehr

◇ FTIR

□ IAGOS

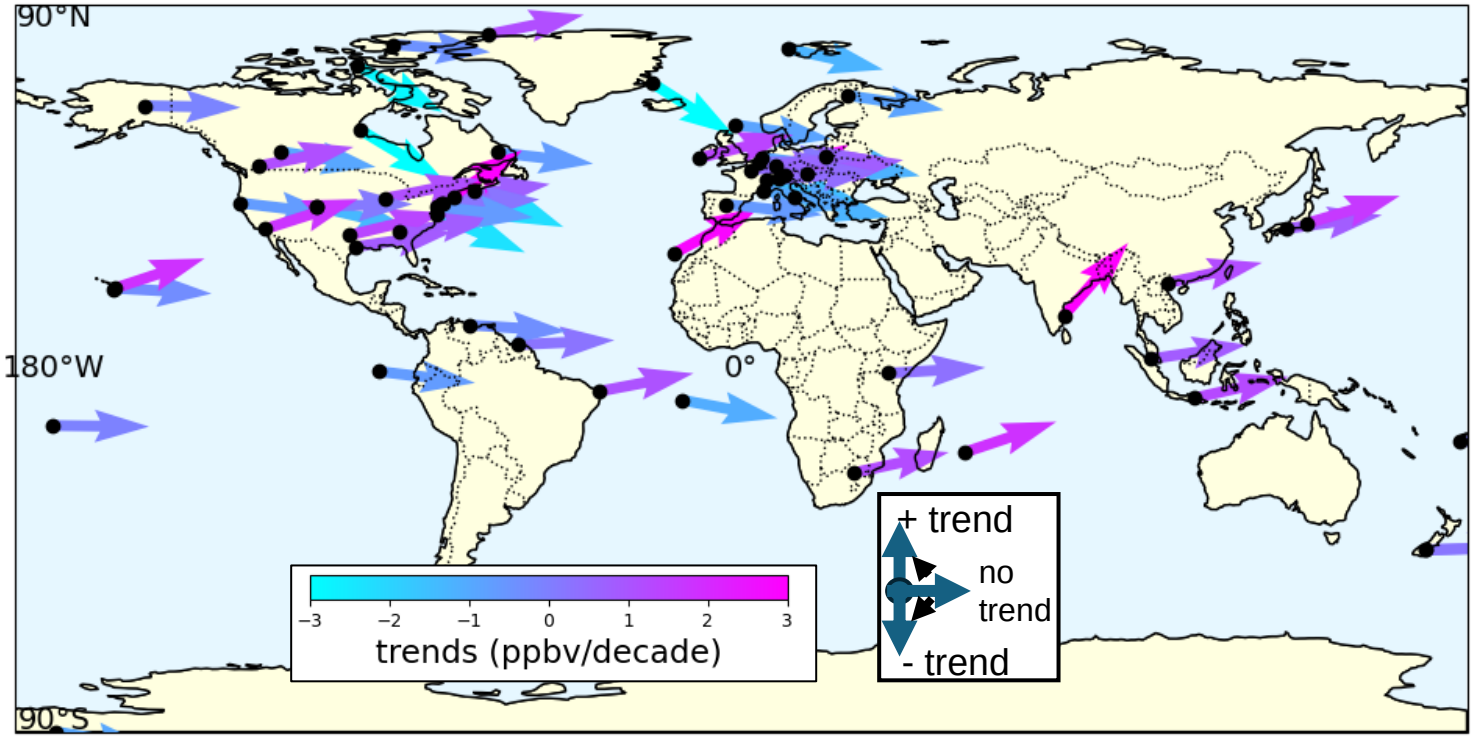
▽ Lidar

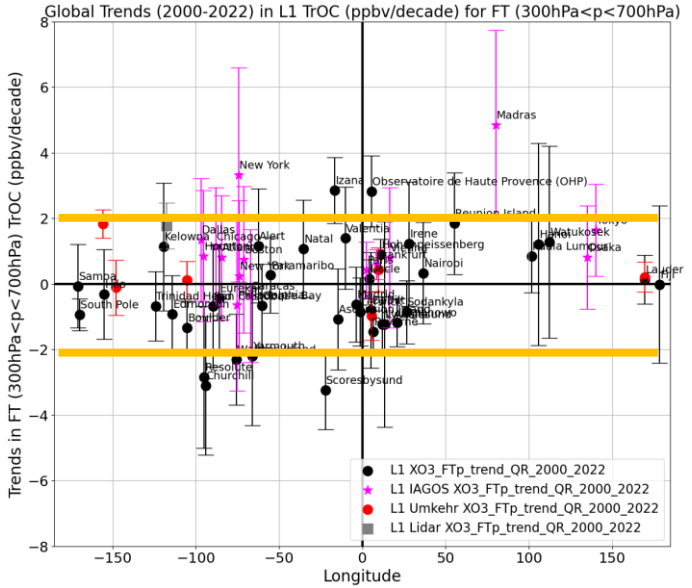
- Relative change of mean TrOC for the time period 2000-2022 vs. 2000-2019
  Blue: 2000-2022 < 2000-2019
  Red: 2000-2022 > 2000-2019
- Decline in 75% of the sites,
  on average -0.3%
  prominent in NH (spring + summer),
  stronger in FT.
- From R. Van Malderen, RMI
- Impact on trends!

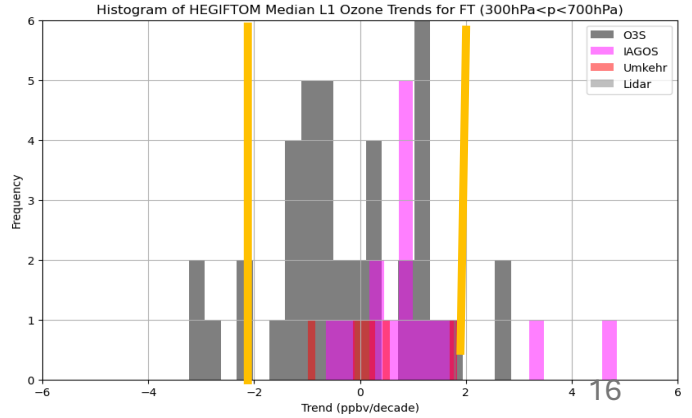
Ques 3. All-Site FTOC Median Trend Variability

- **Left**: Sites (sondes, IAGOS, Umkehr, lidar), **50-%ile median** profiles, L1 analyzed with QR, 2000-2022. **Upper Right:** FT OC, 700-300 hPa, mostly smaller than TrOC trends; several exceptions in tropics.
- **Changes mostly ≤ 2.0 ppbv/dec, positive OR negative**

Global Median All Instruments L1 Trend (2000-2022) in TrOC (ppbv/decade) for FT (300hPa<p<700hPa)

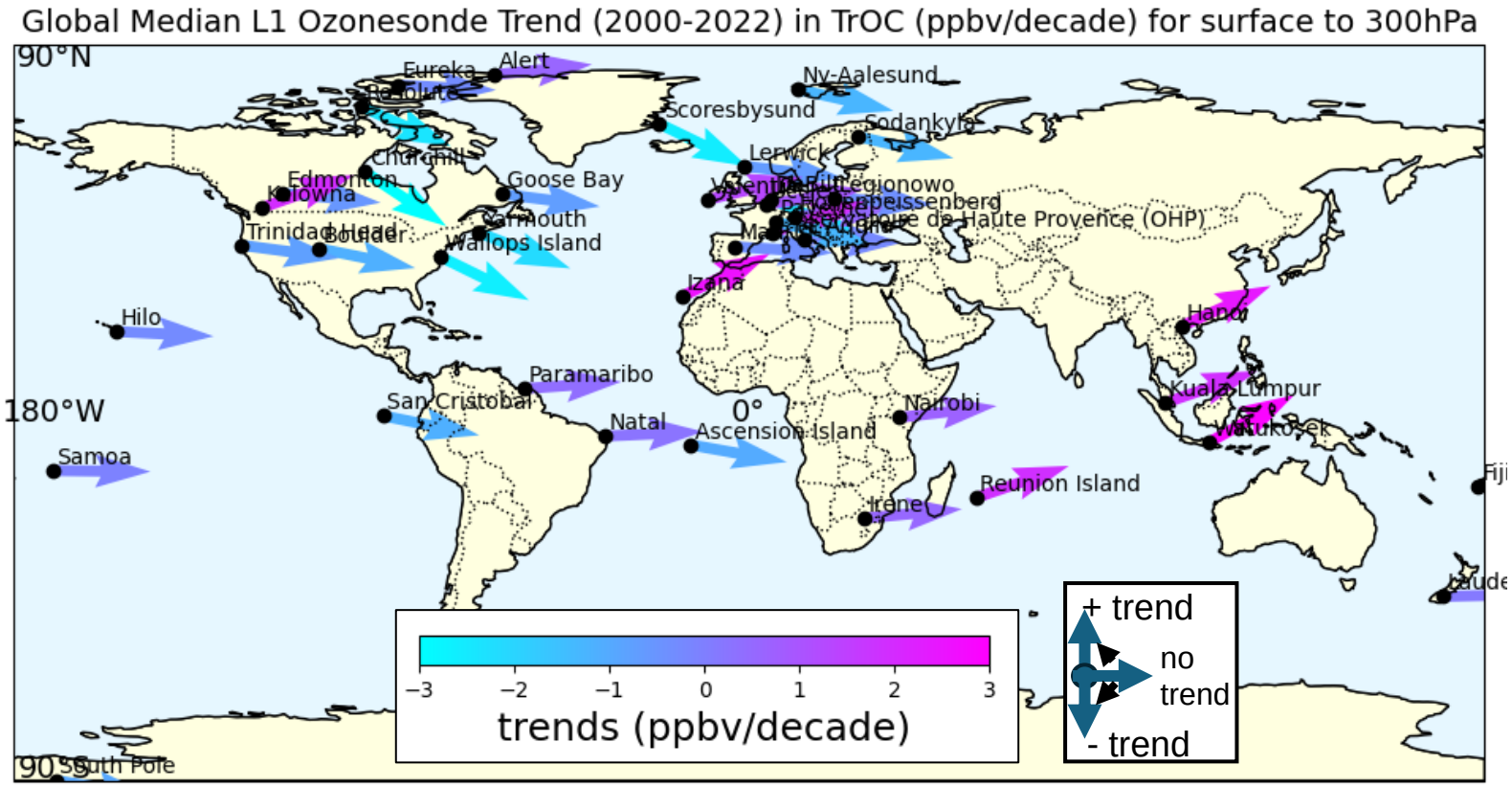


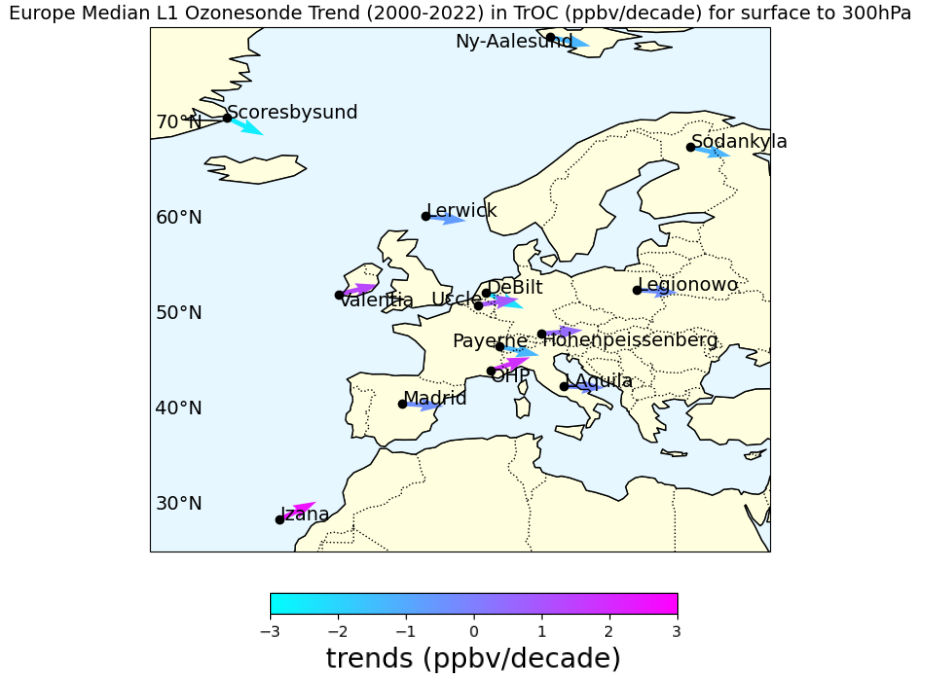




Ques 2. Ozonesonde TrOC Regional Trends

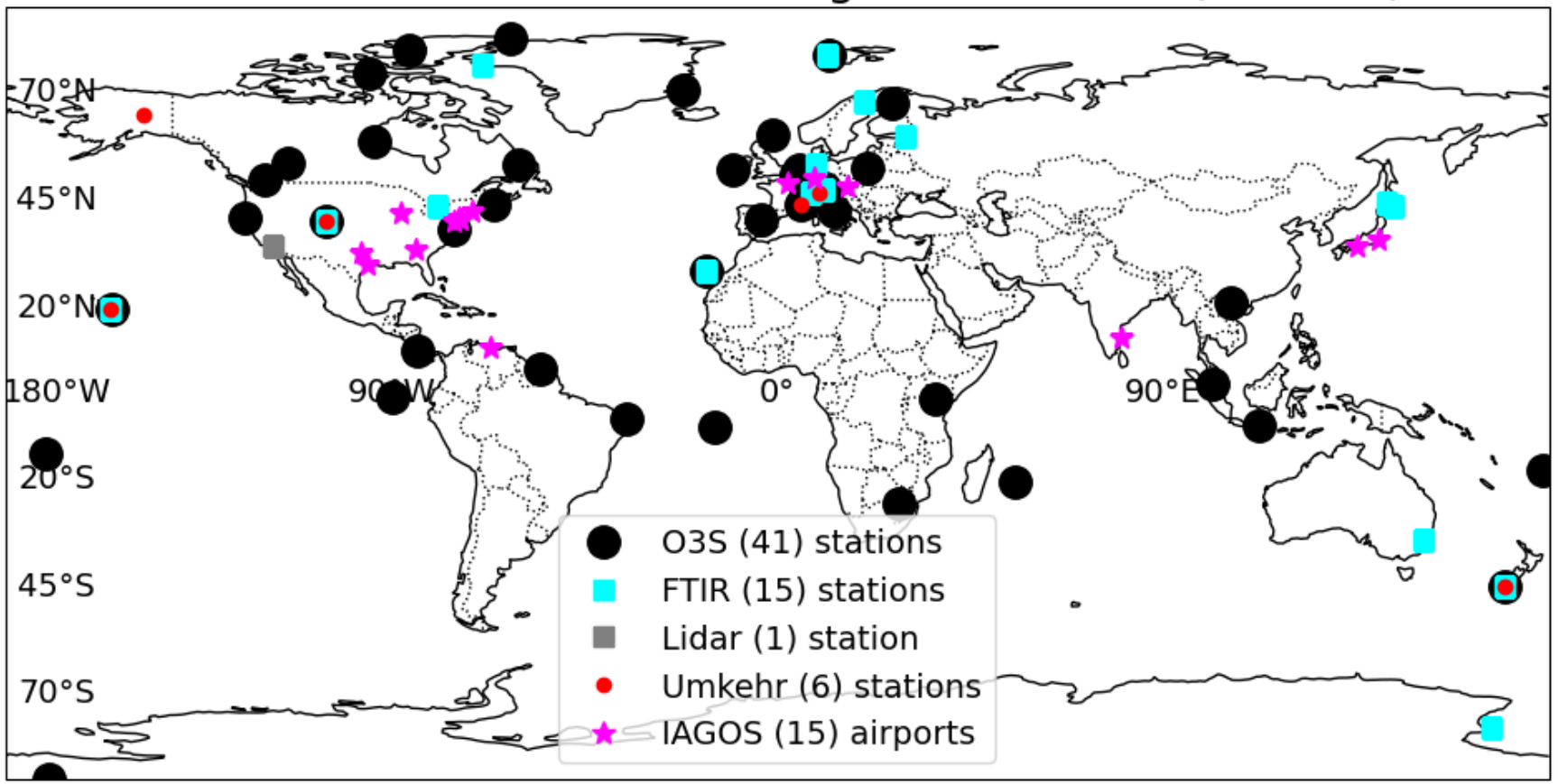
- Sonde (black points), **50-%ile median** profiles, L1 data analyzed with QR, 2000-2022
- **Left**: TrOC (surf-300 hPa) column, negative-> zero trends, blue shades
- **Trends ≤ 3 ppbv/dec, positive or negative,** *all lat, long (2 outliers)*. **Right:** Western Europe sonde trend zoom





HEGIFTOM Sites/Datasets for 2000-2022 Trends

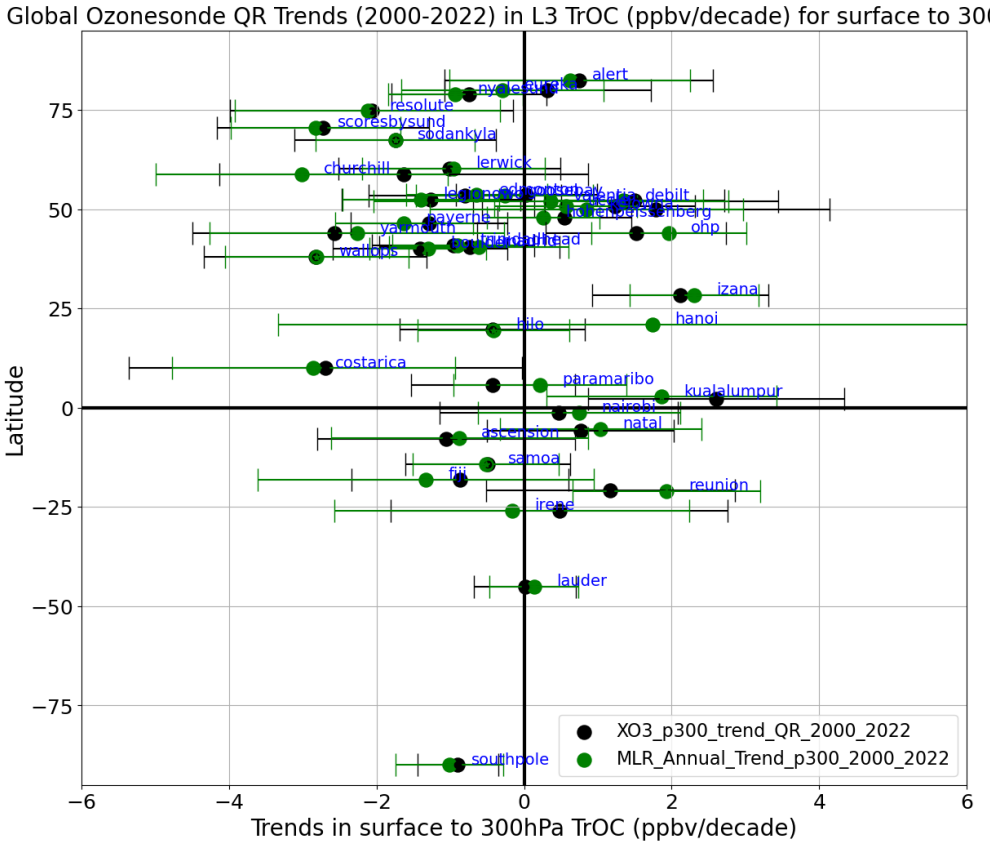
Global Observation Sites Contributing to HEGIFTOM (L1 Data) Trends

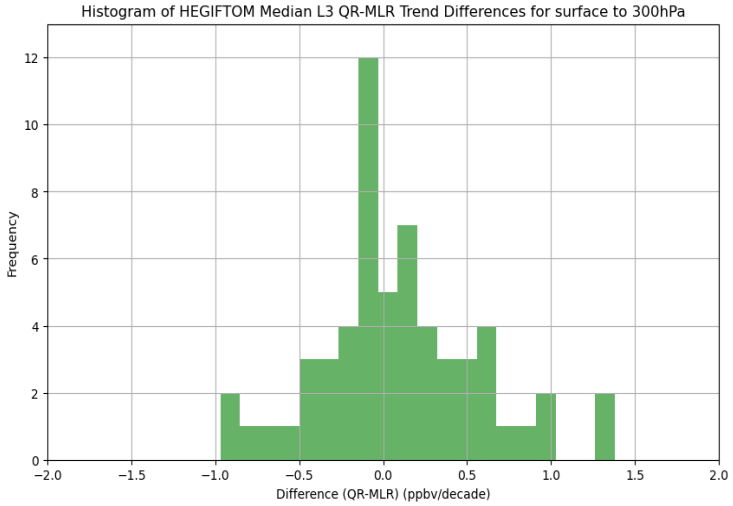


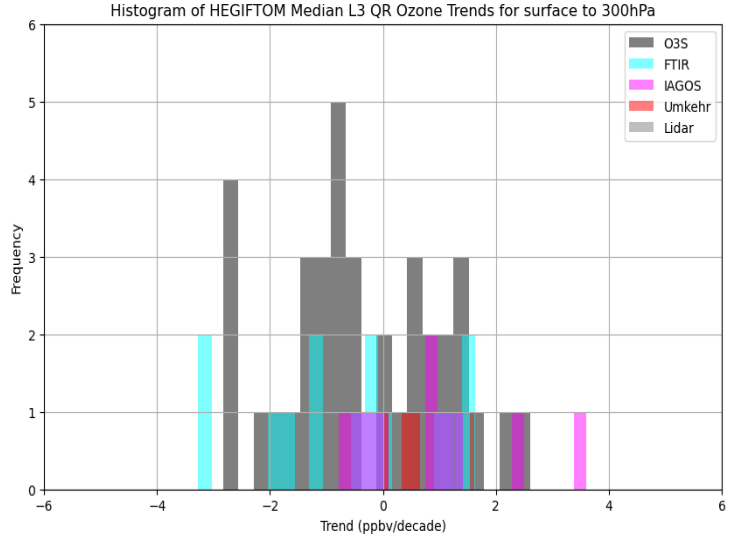
- **L1 QR Data Trends (78):**
  - O3Sonde (41)
  - FTIR (15)
  - IAGOS (15)
  - Umkehr (6)
  - Lidar (1)
- **L3 QR Data Trends (68):**
  - O3Sonde (37): excludes Hanoi, San Cristobal, LaQuila, Watukosek
  - FTIR (14): excludes Boulder
  - IAGOS (10)
  - Umkehr (6)
  - Lidar (1)
- **L3 MLR Data Trends (62):**
  - O3Sonde (38): excludes San Cristobal, LaQuila, Watukosek
  - FTIR (14): excludes NyAlesund
  - IAGOS (3)
  - Umkehr (6)
  - Lidar (1)

TOAR II Protocol: Require Minimum Sample No. to reduce trends uncertainty. L1 QR analyses use all data from 78 sites; only 50%-ile results shown. Monthly means (L3) are subject to more gaps so fewer sites (68, 62) are analyzed

Ques 1. MLR & QR TrOC TRENDS SIMILAR







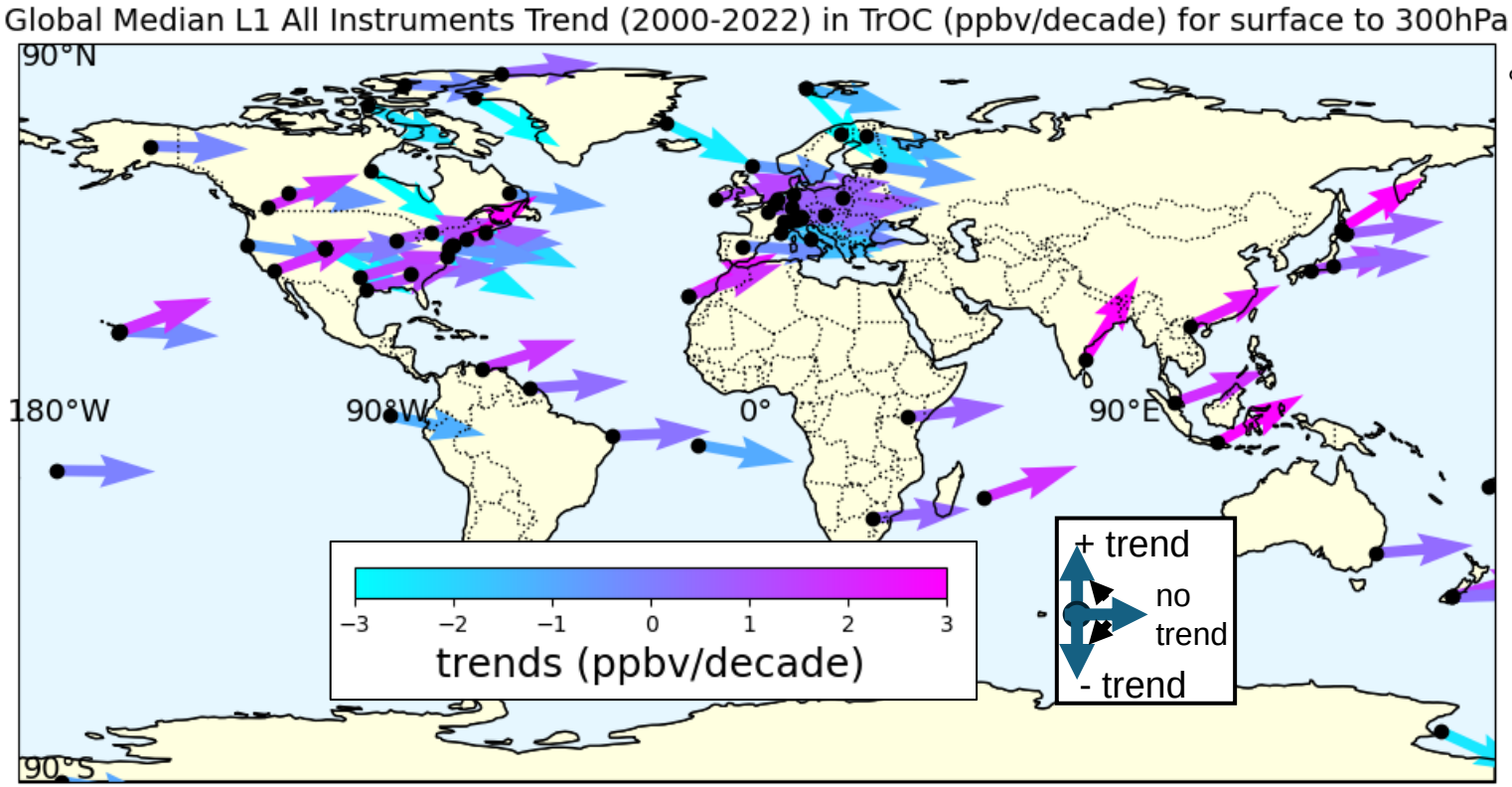
60 sites w/ MLR & QR trends

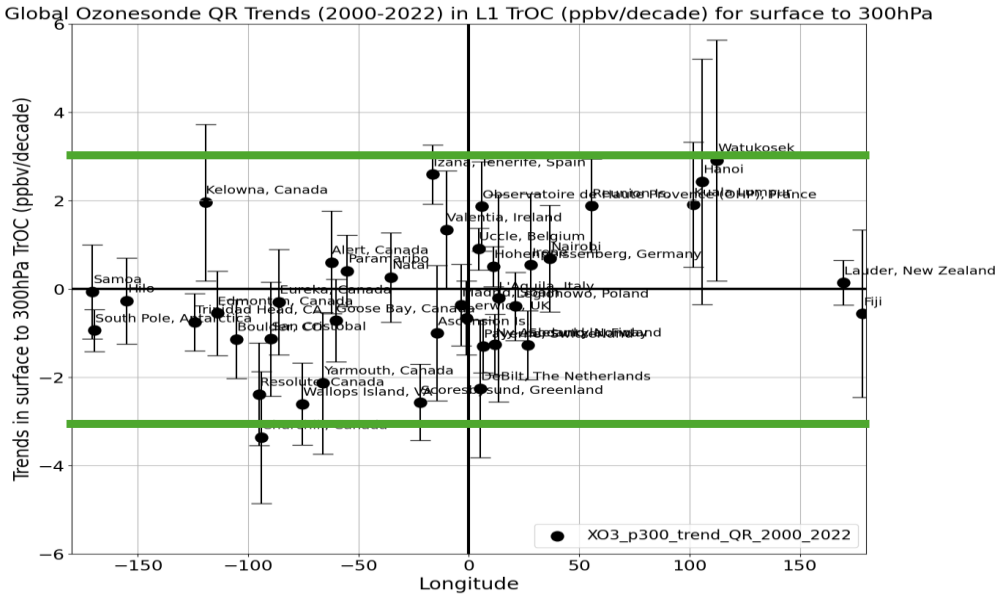
Sonde trends in Gray

- **Left:** Sonde trends for trop. column (surface-300 hPa, ppbv/dec) with L3 data mostly overlap within uncertainty (**black=QR, green=MLR**). **Center:** Small bias toward larger MLR trend
- **Right:** Positive: negative trends ~50:50. Given uncertainty, ~50% of sites show no trend!

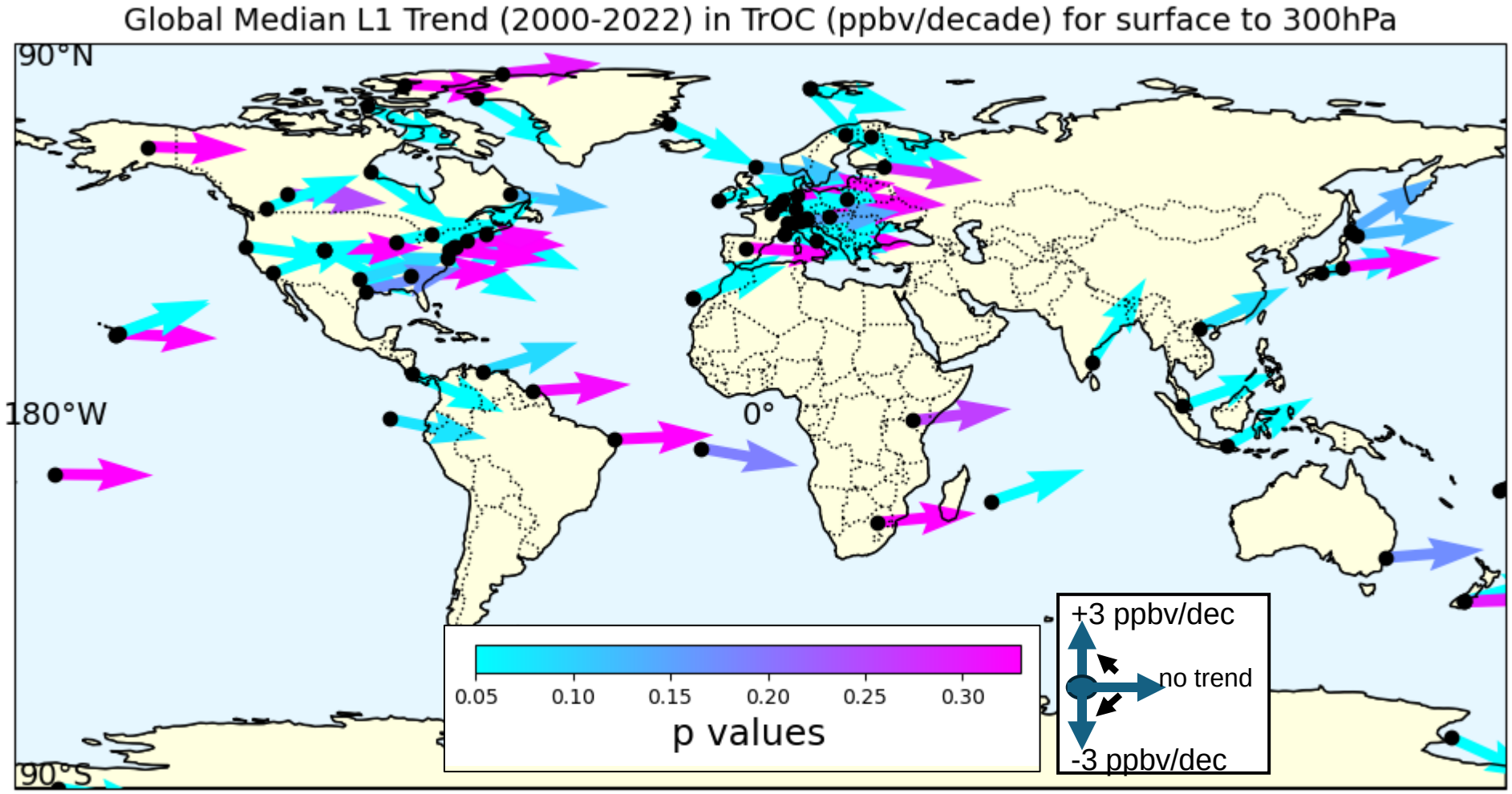
Ques 2. B. All-Site TrOC Regional Trends

- Sonde (black points), **50-%ile median** profiles, L1 data analyzed with QR, 2000-2022
- **Left**: TrOC (surf-300 hPa) column, with multi-instrument data for several sites. Note divergent trends at Hilo/MLO: Umkehr sees FT pollution increase, sonde TrOC declines
- **Right: Trends ≤ 3 ppbv/dec, positive or negative,** *all lat, long (only 2 sonde outliers)*





Ques 1. QR TrOC Trends: All instruments w/ p-values Surface to 300hPa - All Sites within +/- 3 (ppbv/decade)

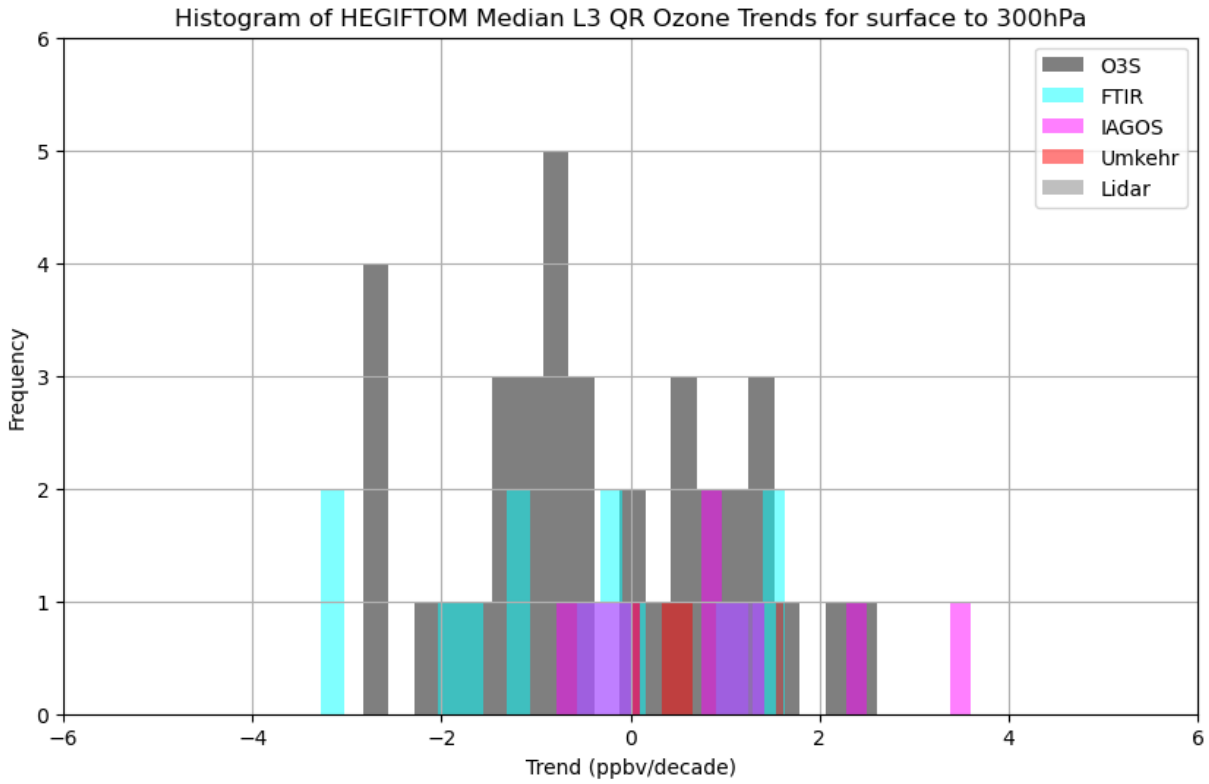


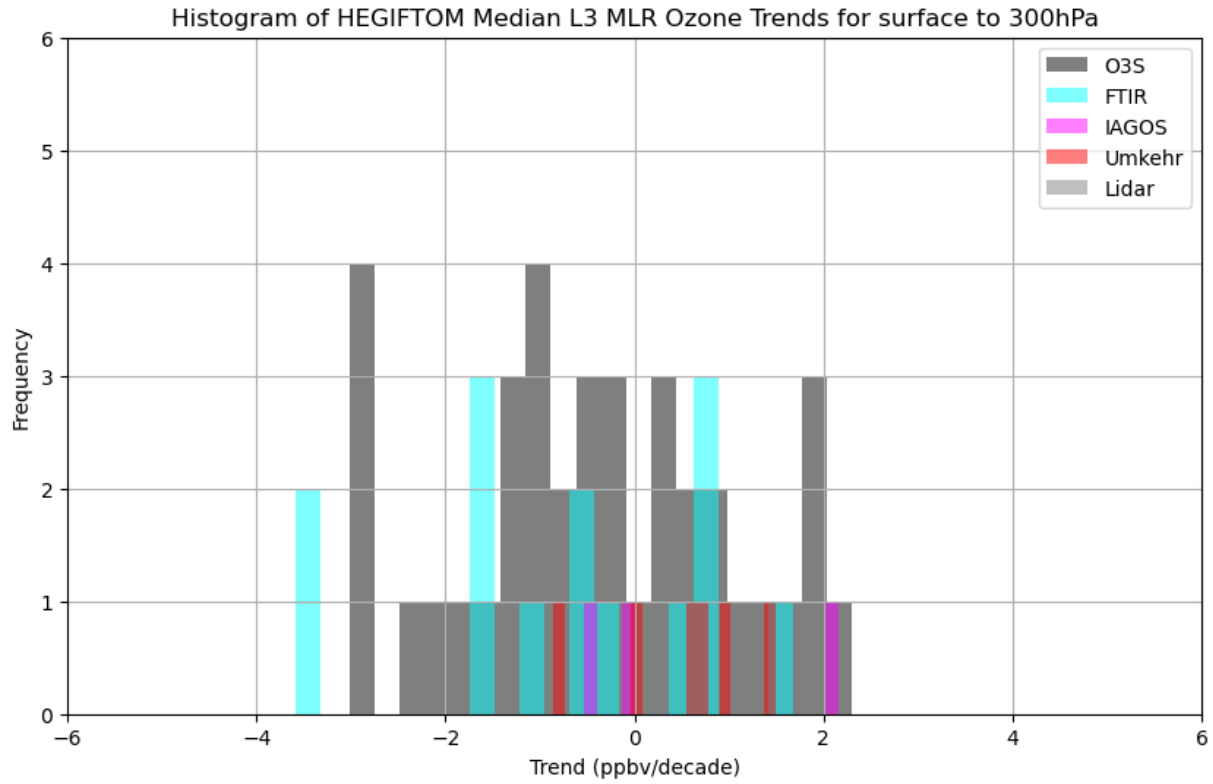
Biases visible here? Maybe QR & FTIR sl more negative

Left **QR L3 Trends for all datasets , surface to 300hPa**

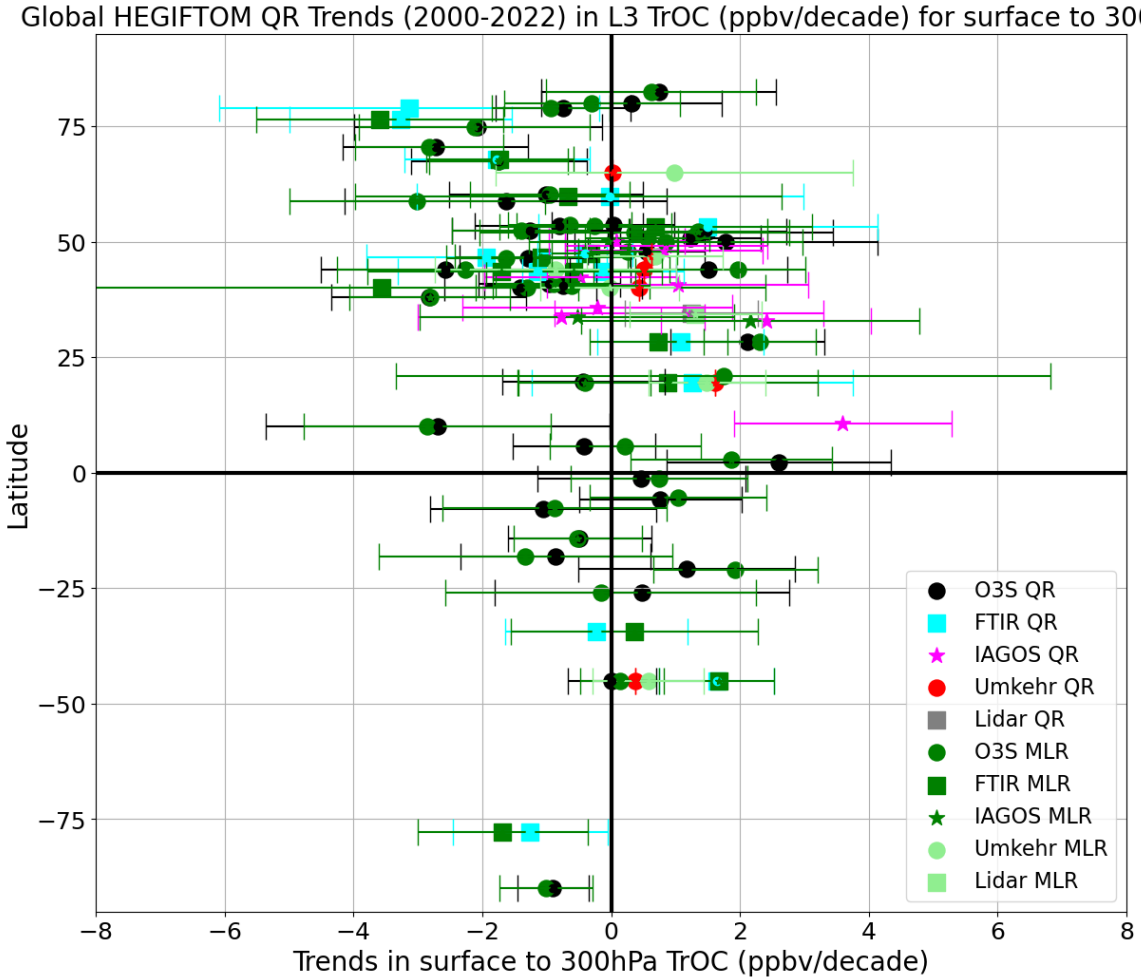
Right **MLR L3 Trends for all datasets , surface to 300hPa**

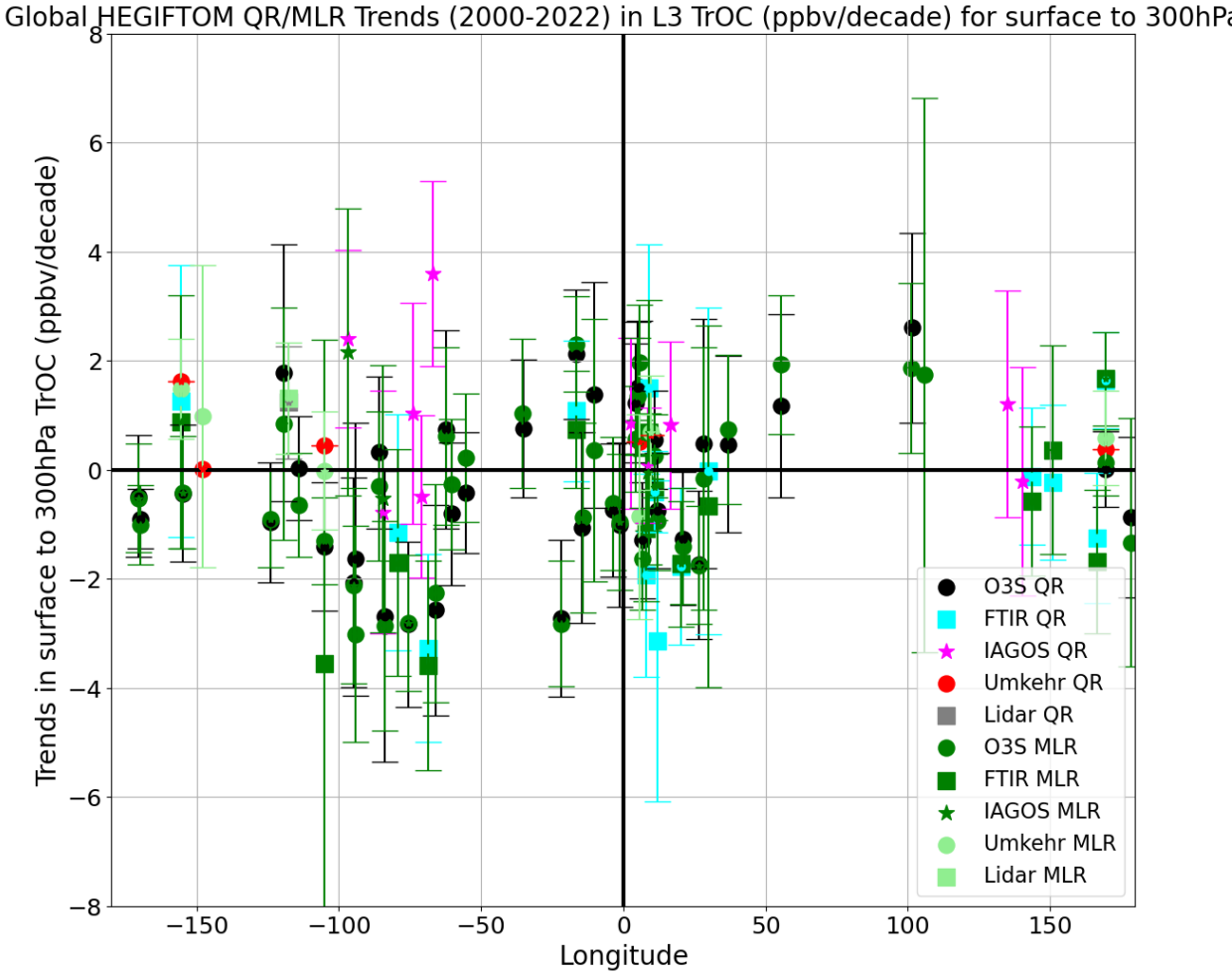
For L3 there are slightly fewer stations than for L1



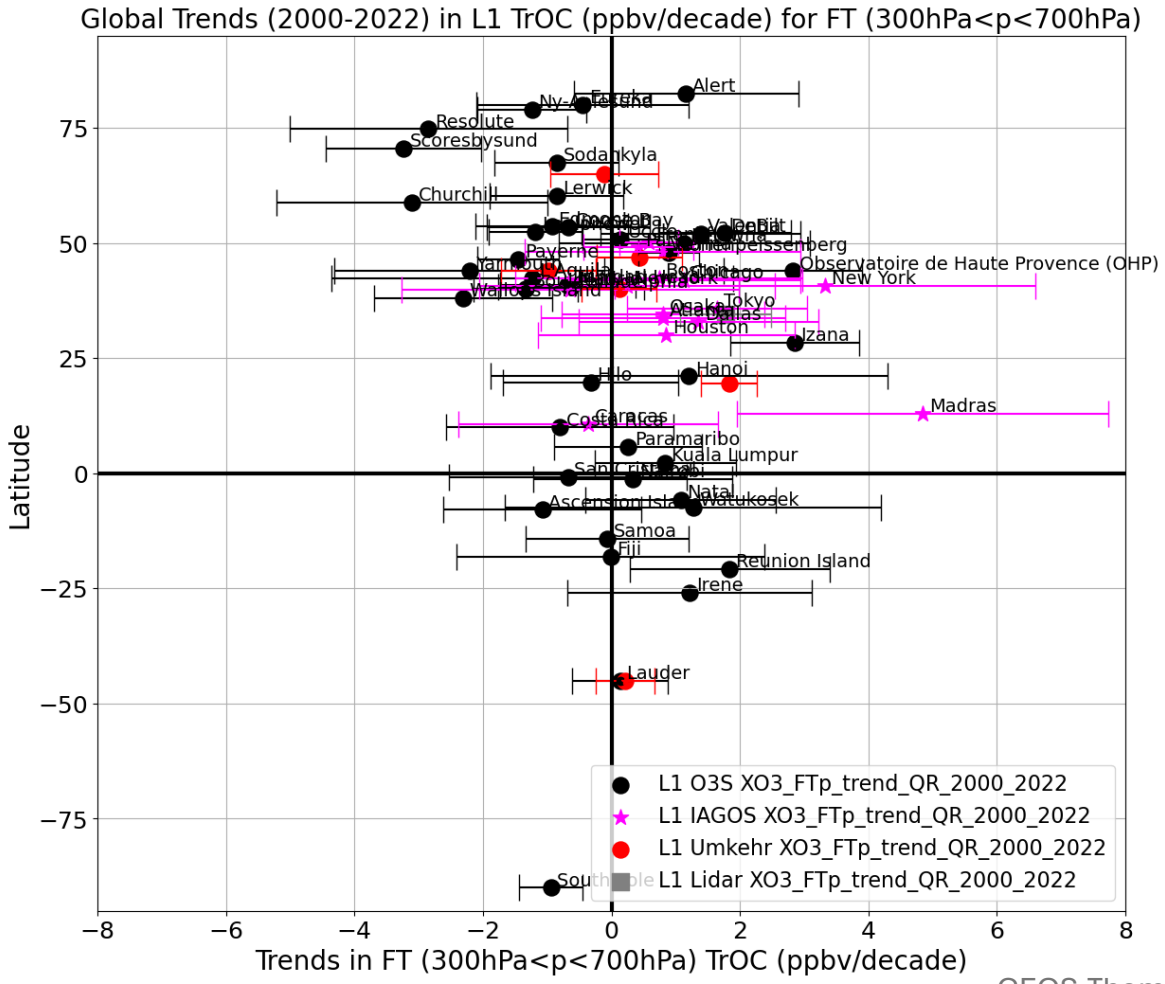


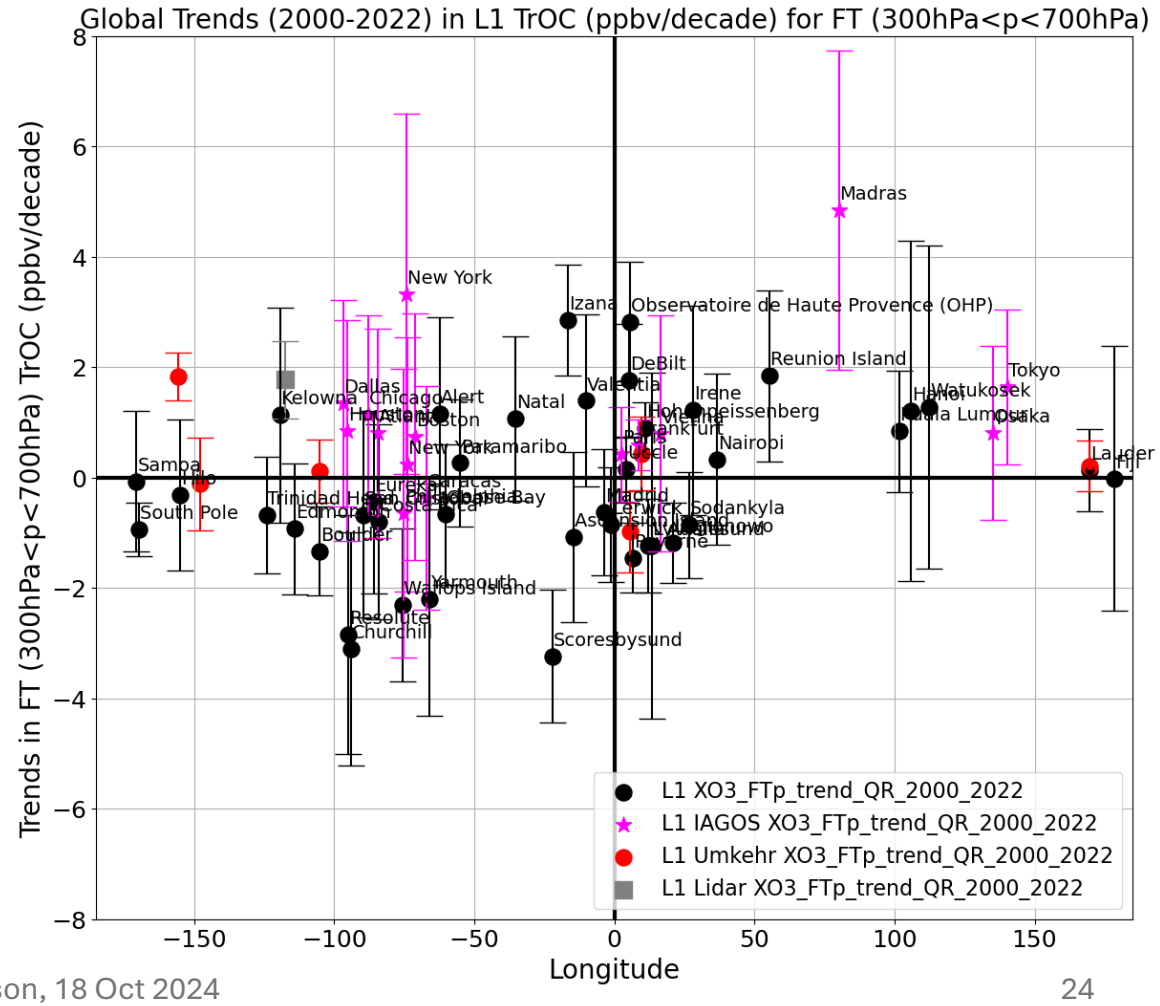
Ques 4- 22/April HEGIFTOM QR and MLR L3 Trends-
All TrOC Data: Surface to 300hPa Most stations within +/- 3 (ppbv/decade)





FT – data from 3 inst QR L1 Trends for all , for ~60 sites FT (300<p<700hPa). Most stations within +/- 2 (ppbv/decade)





QR Trends for Ozonesondes/IAGOS/lidar, ie same as Fig 3 except for LT (0-4km). Most stations within +/- 3 (ppbv/decade). *This is for L3 and needs to be updated to L1.*