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

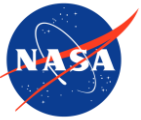**Anne M. Thompson*[1,2], Debra E. Kollonige[1,3], Ryan M. Stauffer[1]**

Roeland Van Malderen[4], Herman GJ Smit[5,6], Bryan J. Johnson[7], Kai-Lan Chang[6,8]

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(4) RMI, Uccle, Belgium; (5) FZ-Juelich, Germany; (6) CIRES, U. of Colorado, Boulder, CO;
(7) NOAA/Global Monitoring Lab, Boulder, CO; (8) NOAA Chemical Sciences Lab, Boulder, CO
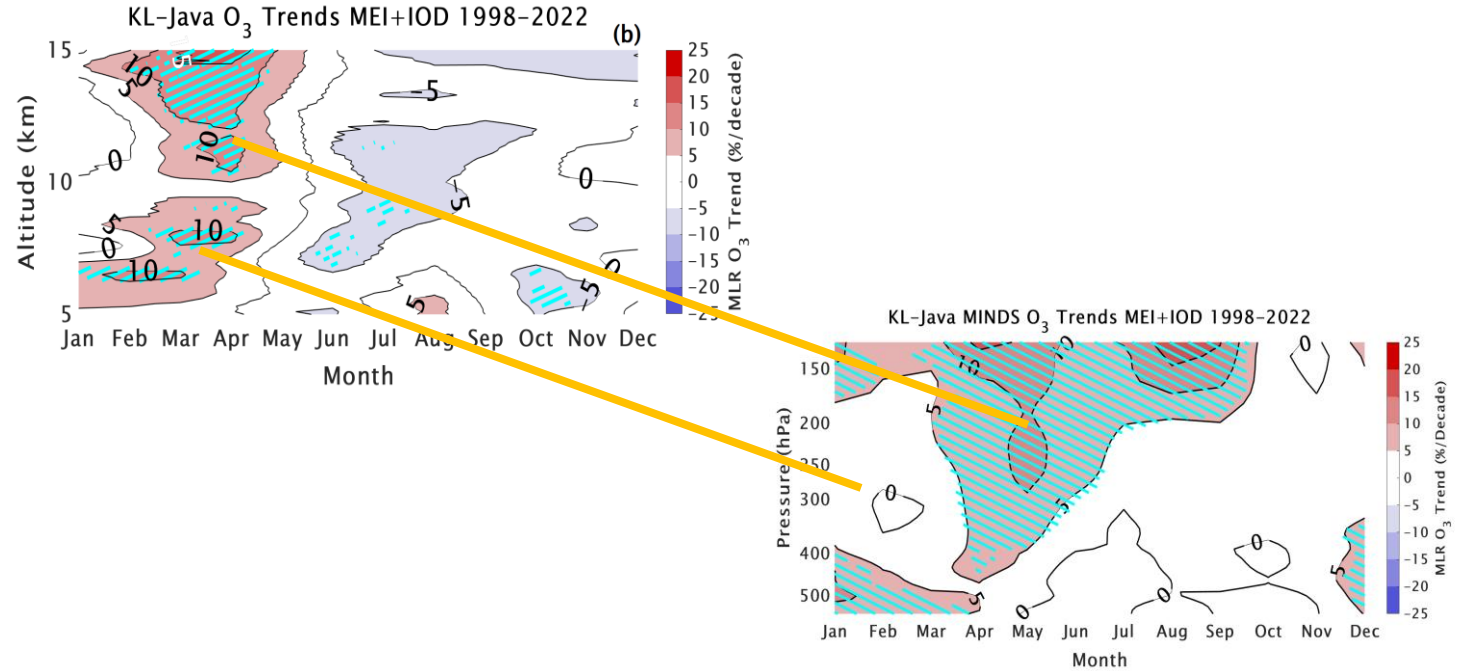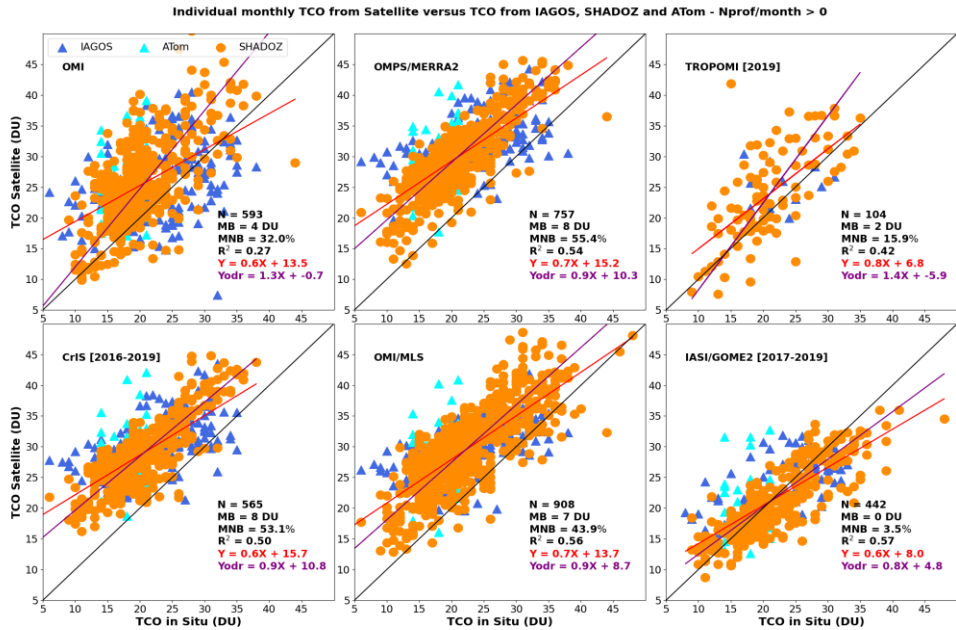
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SHADOZ=So. Hemisphere Additional Ozonesondes
IAGOS = In-service Aircraft for a Global Observing System
HEGIFTOM = Harmonization and Evaluation of Ground-based Instruments for Free Tropospheric Ozone Measurements

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*

Individual monthly TCO from Satellite versus TCO from IAGOS, SHADOZ and ATom - Nprof/month > 0

KL-Java O_3 Trends MEI+IOD 1998–2022

KL-Java MINDS O_3 Trends MEI+IOD 1998–2022

- **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)**

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
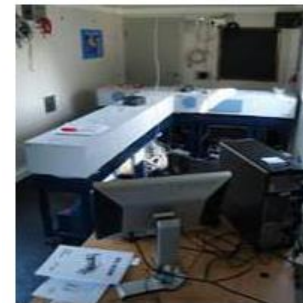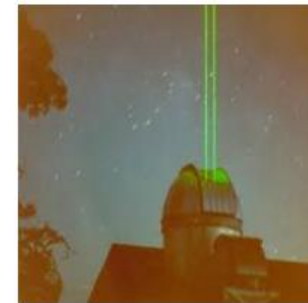
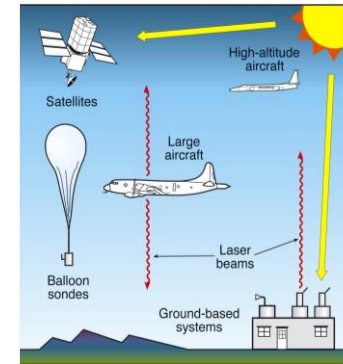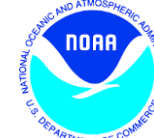- Each measurement is delivered with *uncertainty* and a *quality flag*

IAGOS

Ozonesondes

Brewer/Dobson Umkehr

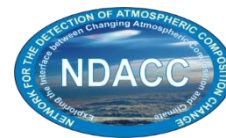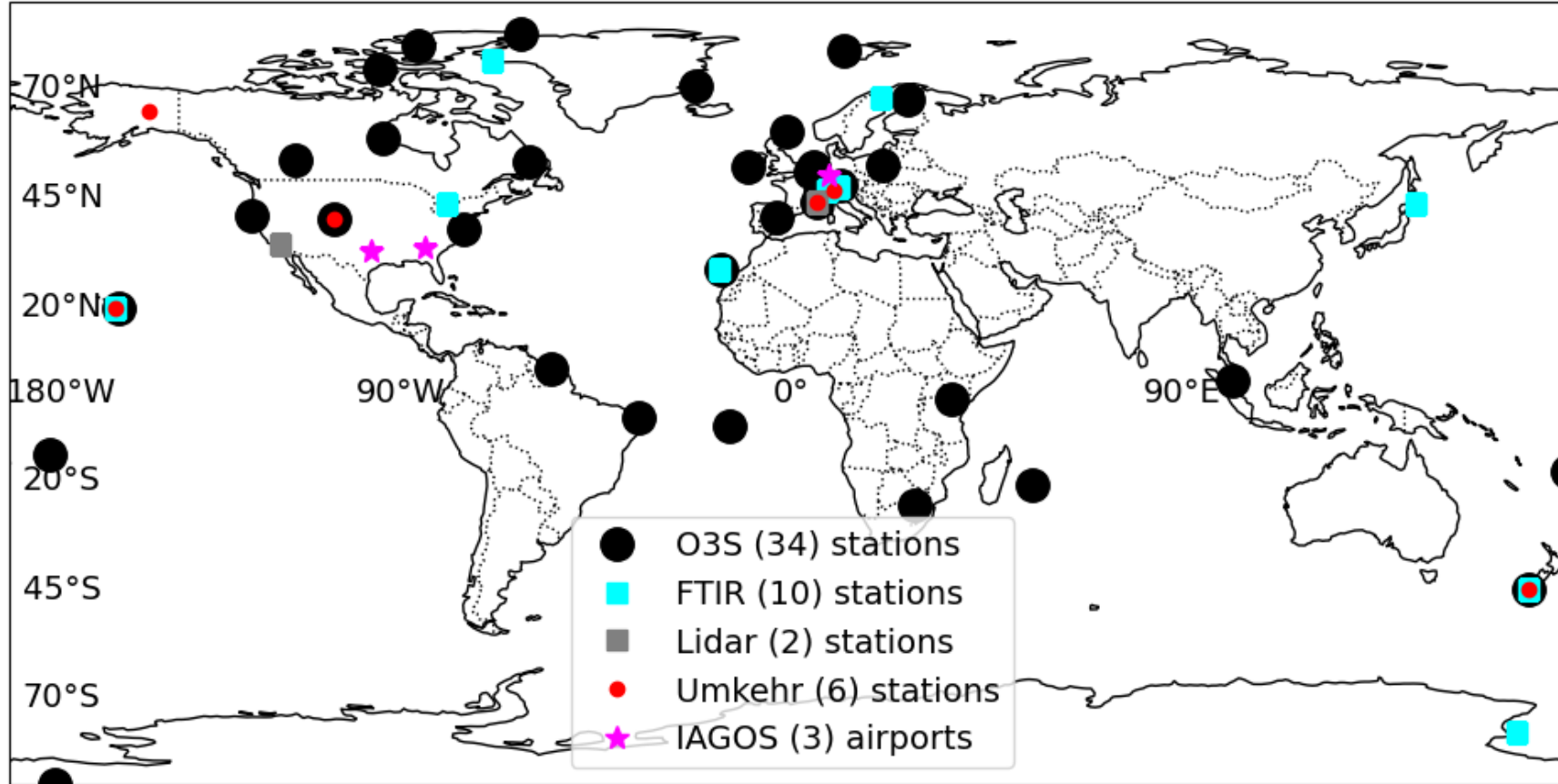FTIR

Lidar

TrOC= surface-300 hPa

FT, 700-400 hPa

http://hegiftom.meteo.be/datasets

4

Global Sites Contributing to HEGIFTOM (55 L3 Data) Trends

Legend:
- O3S (34) stations
- FTIR (10) stations
- Lidar (2) stations
- Umkehr (6) stations
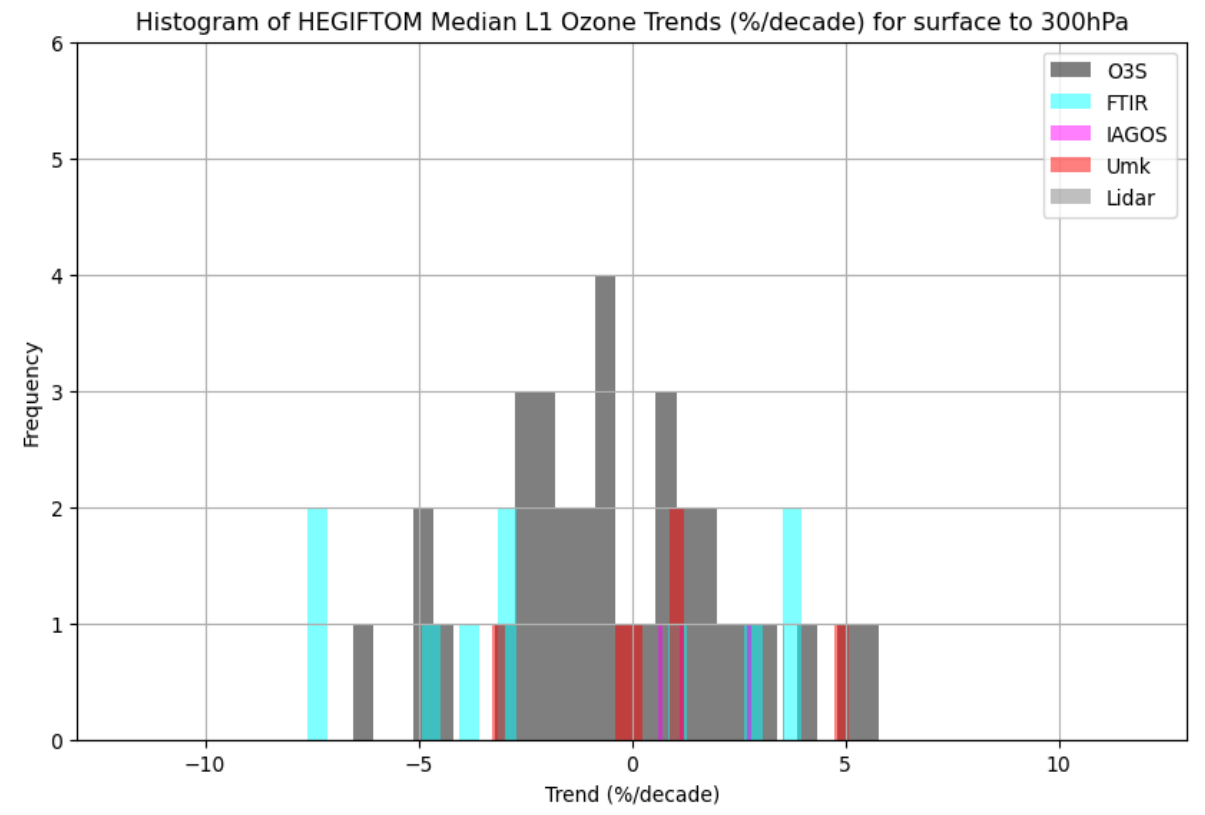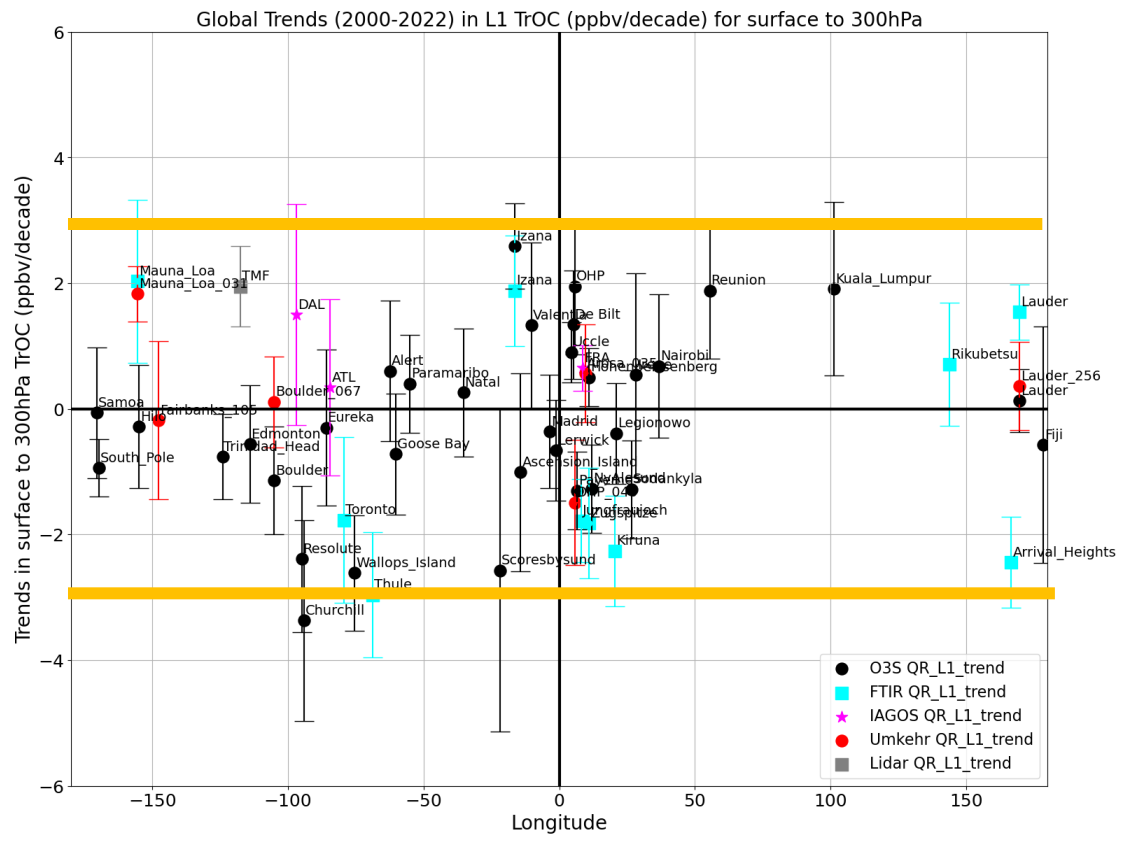- IAGOS (3) airports

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

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*

Global Trends (2000-2022) in L1 TrOC (ppbv/decade) for surface to 300hPa

Histogram of HEGIFTOM Median L1 Ozone Trends (%/decade) for surface to 300hPa

- **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 <u>and</u> negative trends appear at all longitudes

- **Right:** Medians in %/decade suggest possible instrument bias. More negatives than positives

HEGIFTOM QR and MLR Trends (2000-2022) in L3 TrOC (ppbv/decade) for surface to 300hPa

Global HEGIFTOM QR/MLR Trends (2000-2022) in L3 TrOC (ppbv/decade) for surface to 300hPa
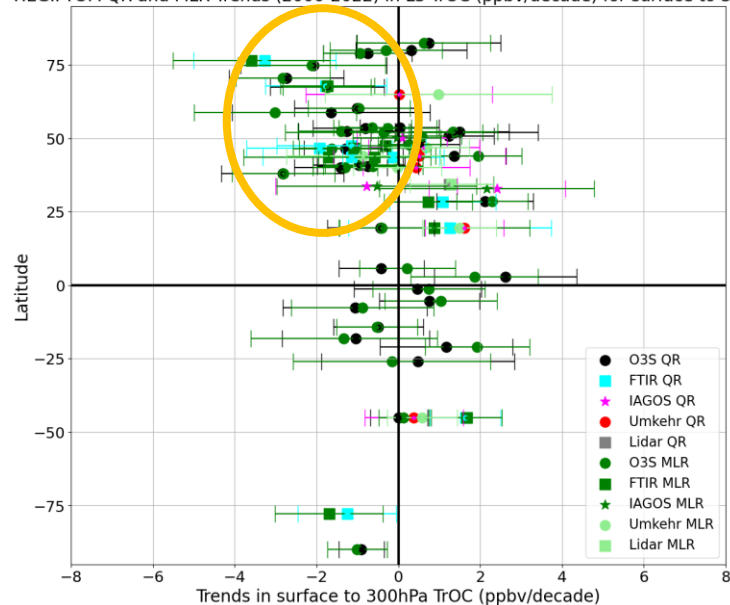
Histogram of HEGIFTOM Median L3 QR-MLR Trend Differences for surface to 300hPa
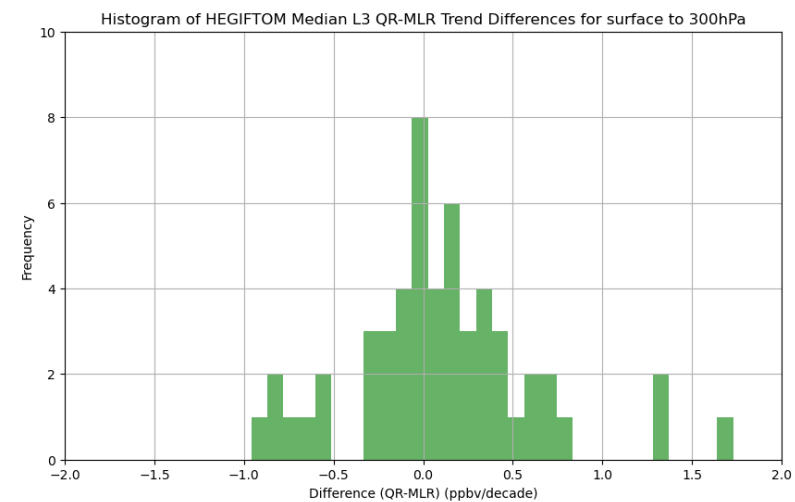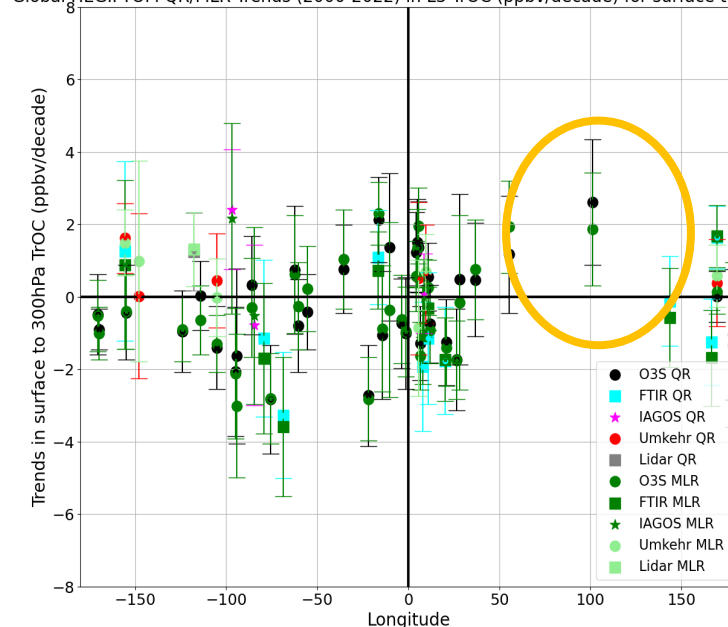
QR-MLR trends, ppbv/dec

- **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

Phase II

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

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

Histogram of HEGIFTOM Median L3 QR Ozone Trends for surface to 300hPa

Histogram of HEGIFTOM Median L3 MLR Ozone Trends for surface to 300hPa

Histogram of HEGIFTOM Median L3 QR Ozone Trends for surface to 300hPa

Histogram of HEGIFTOM Median L3 MLR Ozone Trends for surface to 300hPa

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9

Global Trends (2000-2022) in L1 TrOC (ppbv/decade) for surface to 300hPa

Global HEGIFTOM QR/MLR Trends (2000-2022) in L3 TrOC (ppbv/decade) for surface to 300hPa
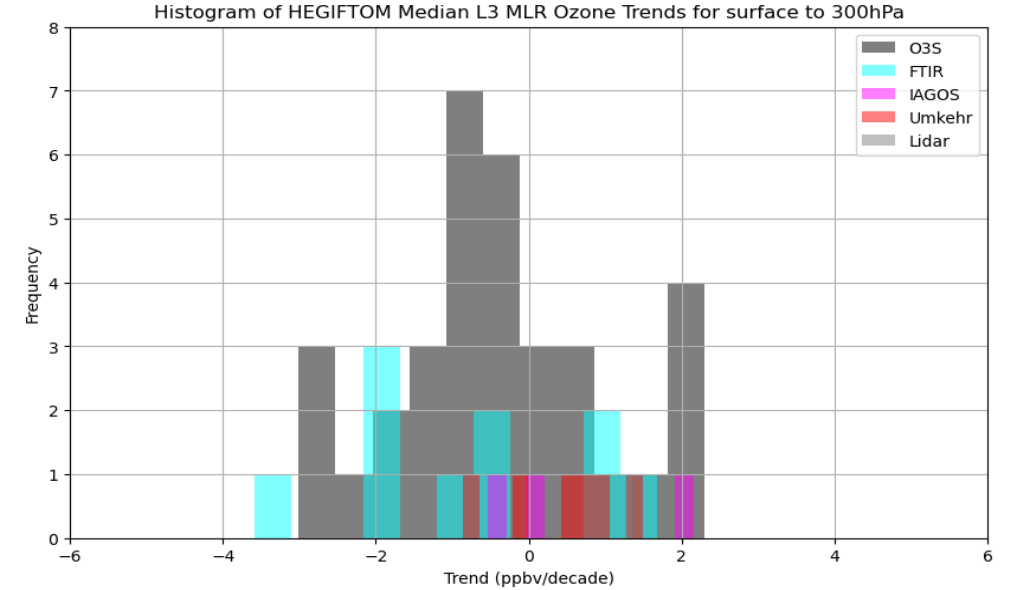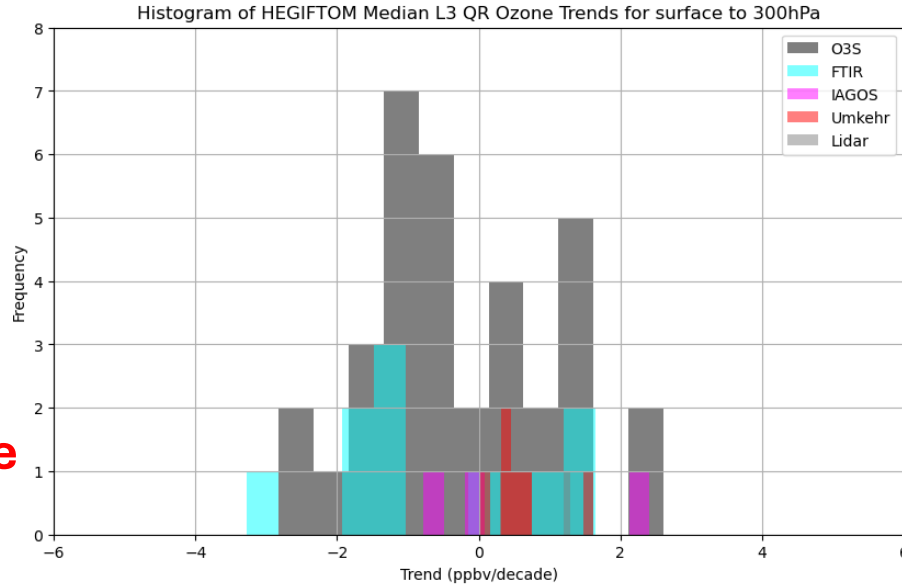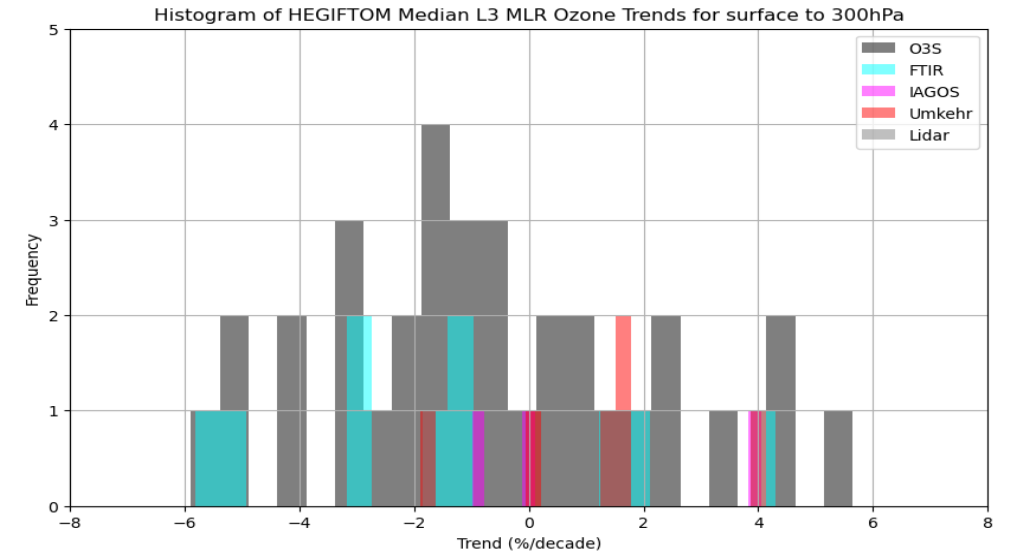
- **Left:** L1 QR trends, 4 of 6 sites with > 1 instrument show large offsets: MLO/Hilo, Boulder, Izaña, Lauder (Zeng et al., 2024; Björklund et al., 2024)
- **Right:** Pronounced offsets observed at same sites (MLO/Hilo, Boulder, Lauder) with both statistical methods. Causes unclear – different sampling frequency, protocols, diurnal, seasonal effects investigated

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10

Global Median L1 (55 sites) QR Trends (2000-2022) in TrOC (%/decade) for surface to 300hPa
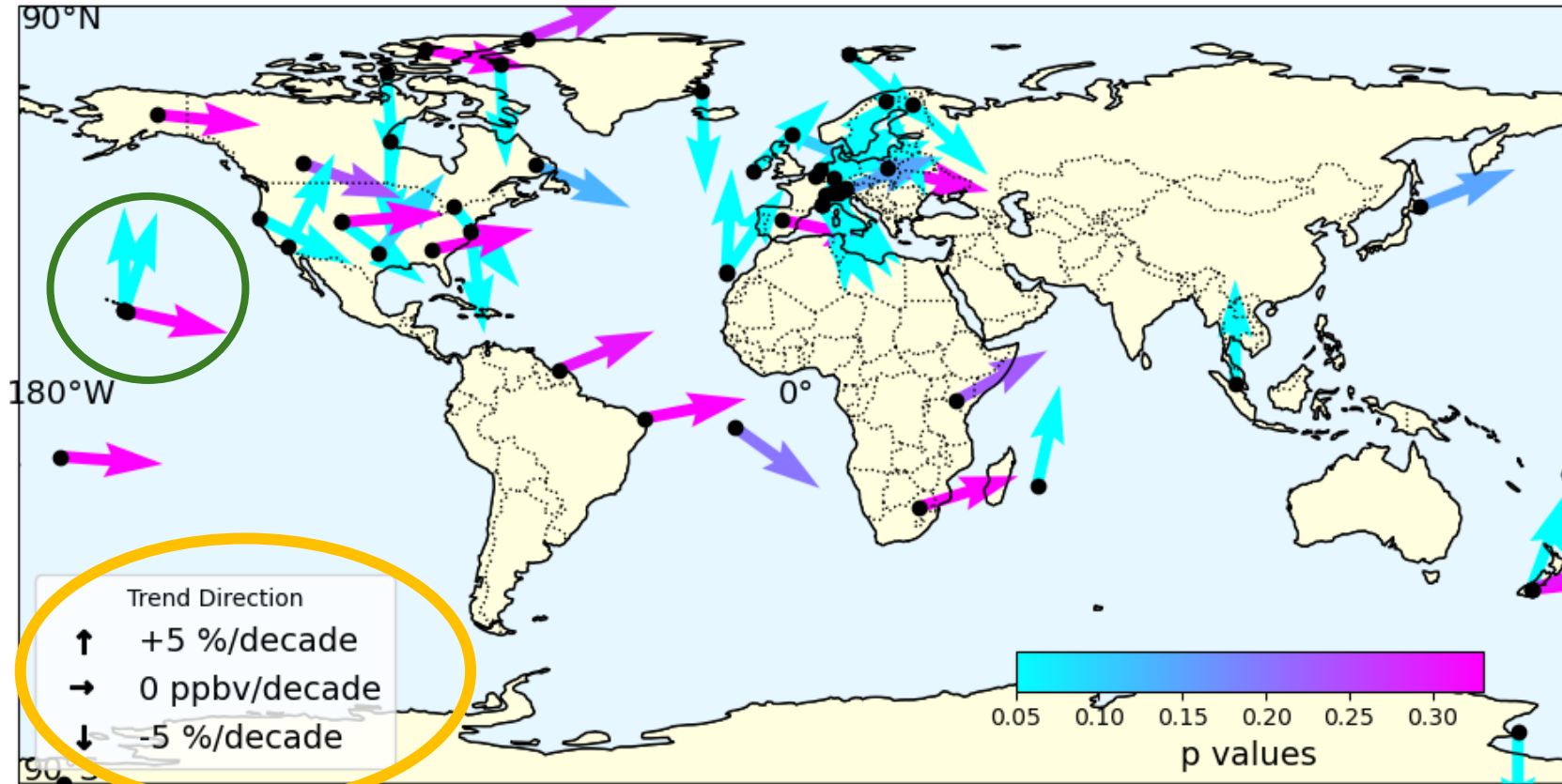
Summarizes: 55 station Trends, moderately positive to negative trends with more confidence (lower p-value) in no. hemisphere (NH). More negative trends in NH. Large divergences at multi-instrument stations. Lack of SH and Asian data in HEGIFTOM limits "global" assessment

Conclusions – HEGIFTOM TOAR II Trends

Phase II

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

Chang, K-L. et al. (2024) Challenges of detecting free tropospheric ozone …https://doi.org/10.5194/egusphere-2023-2739

Gaudel, A., et al. (2018) Tropospheric Ozone Assessment Report: Present-day distribution and trends…
https://doi.org/10.1525/elementa.291

Gaudel, A., et al. (2024) Tropical tropospheric ozone distribution and trends from in situ…, *ACP,
https://doi.org/10.5194/egusphere-2023-3095*

Kollonige, D. E., et al. (2024) SHADOZ ozonesonde network – Overview and updates, This Meeting, Talk Today

Stauffer, R. M., et al. (2019) The effects of a changing observing system on MERRA-2-based ozone …
https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2018JD030090

Stauffer, R, M., et al. (2024) Dynamical drivers of free-tropospheric ozone… *ACP* https://doi.org/10.5194/egusphere-2023-2618

Smit, H. G. J., A. M. Thompson et al. (2021) WMO/GAW ASOPOS Report 268 https://library. wmo.int/records/item/57720-ozonesonde-measurement-principles-and-best-operational-practices

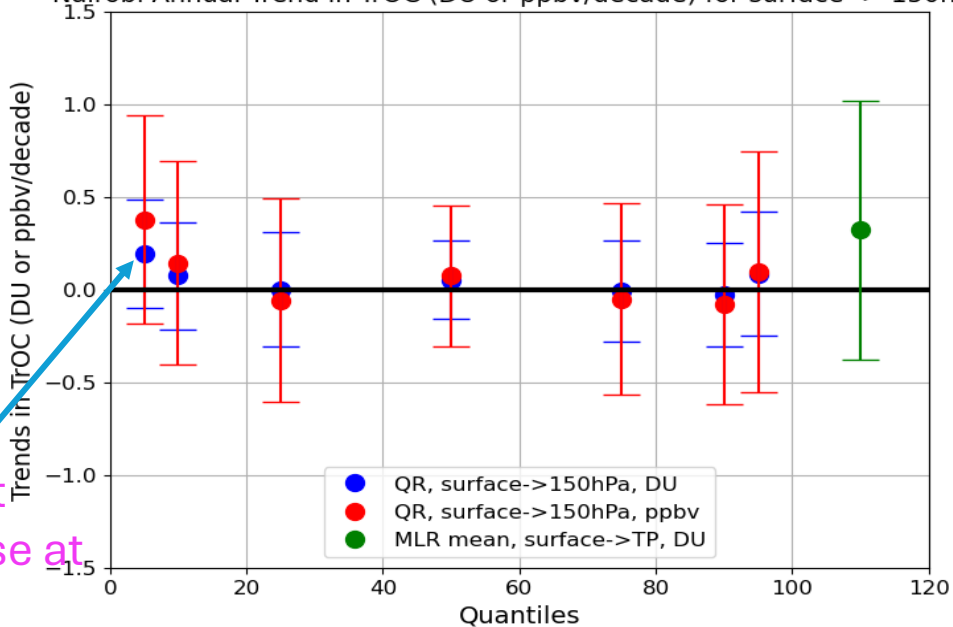Smit, H. G. J. et al. (2024) New insights from the Juelich OzoneSonde … https://doi.org/10.5194/amt-17-73-2024

Thompson, A. M., et al. (2021) Regional and seasonal trends in tropical ozone from SHADOZ profiles…
https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2021JD034691

Phase II

Nairobi Annual Trend in TrOC (DU or ppbv/decade) for surface -> 150hPa

Largest Increase at Low O_3

- QR, surface->150hPa, DU
- QR, surface->150hPa, ppbv
- MLR mean, surface->TP, DU

Nairobi Tropospheric Column MLR Trends (1998–2021)
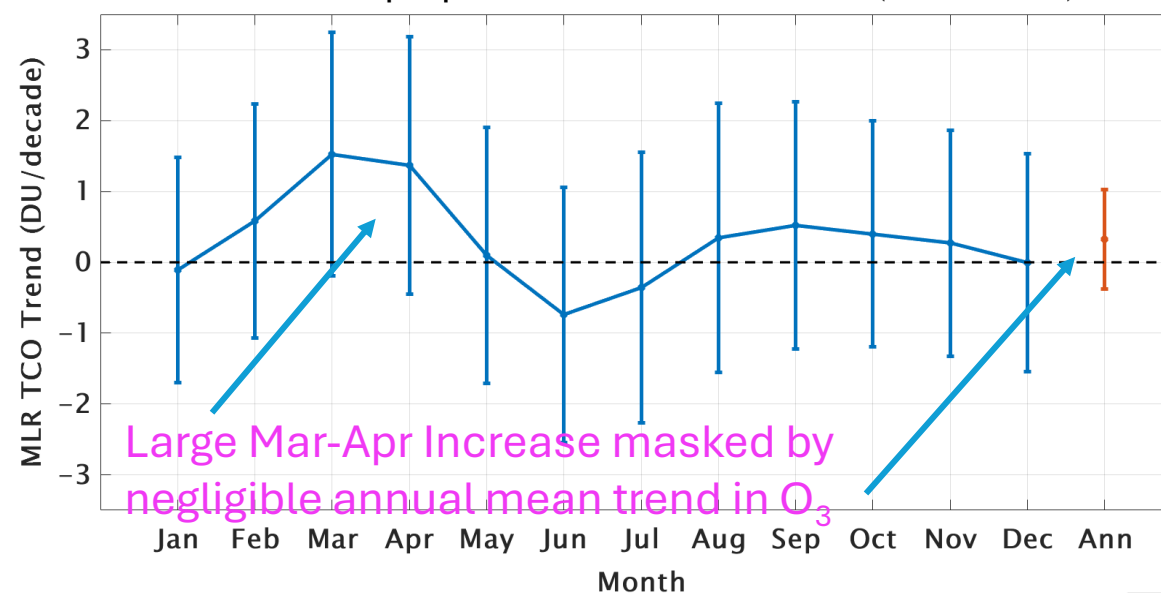
Large Mar-Apr Increase masked by negligible annual mean trend in O_3

- **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

X_{O3} for P > 300 hPa [ppb]
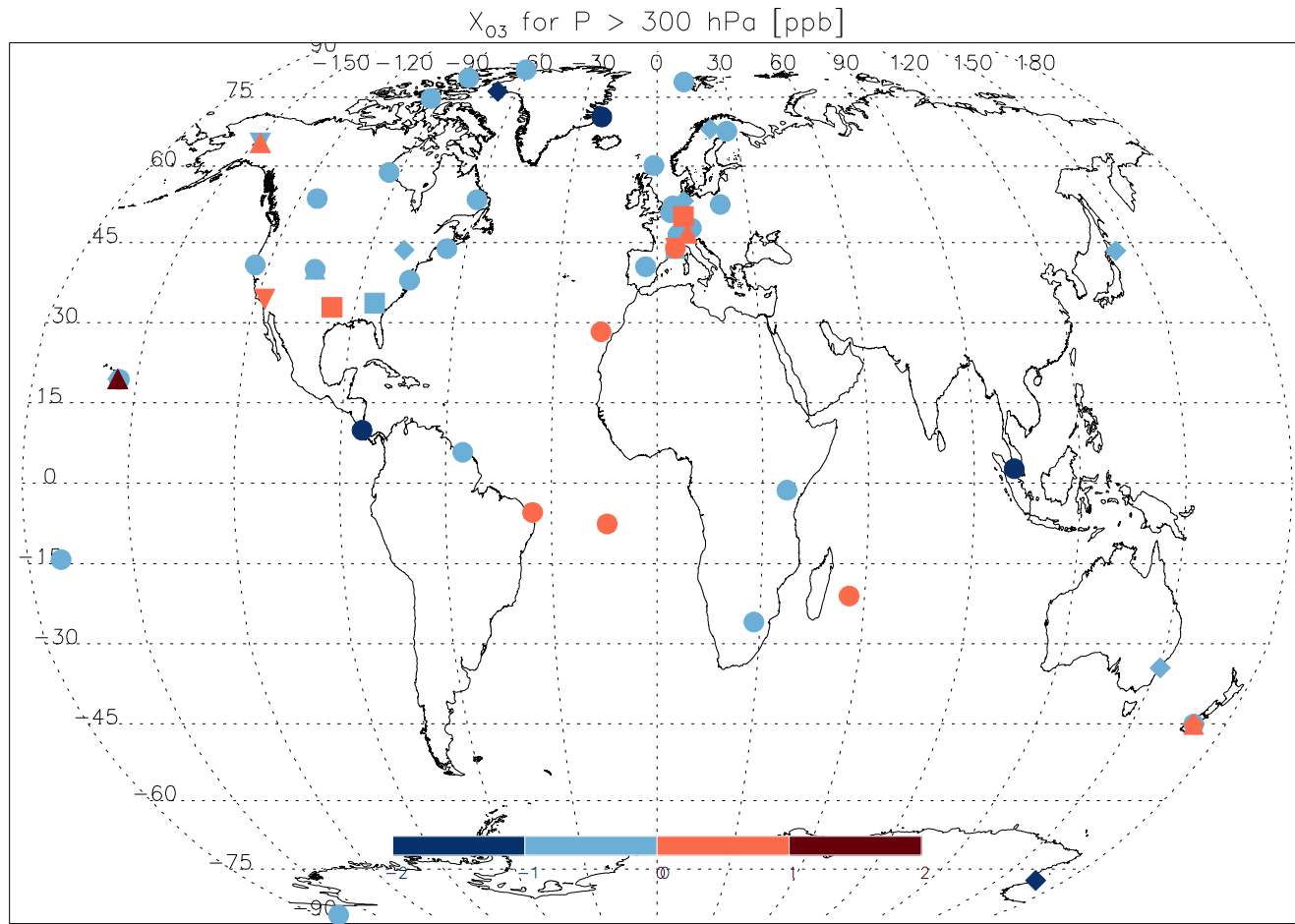
○ ozonesondes △ Umkehr ◇ FTIR
□ IAGOS ▽ Lidar

- 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!

- **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)

Global Trends (2000-2022) in L1 TrOC (ppbv/decade) for FT (300hPa<p<700hPa)

Histogram of HEGIFTOM Median L1 Ozone Trends for FT (300hPa<p<700hPa)

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16