Global Ground-based UT/LS Ozone Trends from TOAR II/HEGIFTOM (2000-2022) and SHADOZ (1998-2023): Regional and Seasonal Variability

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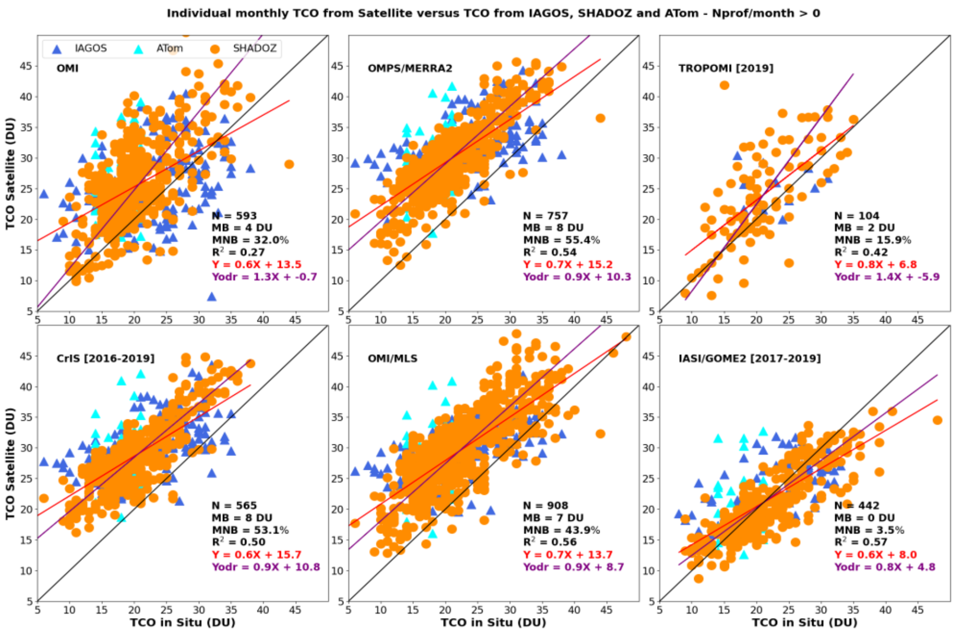
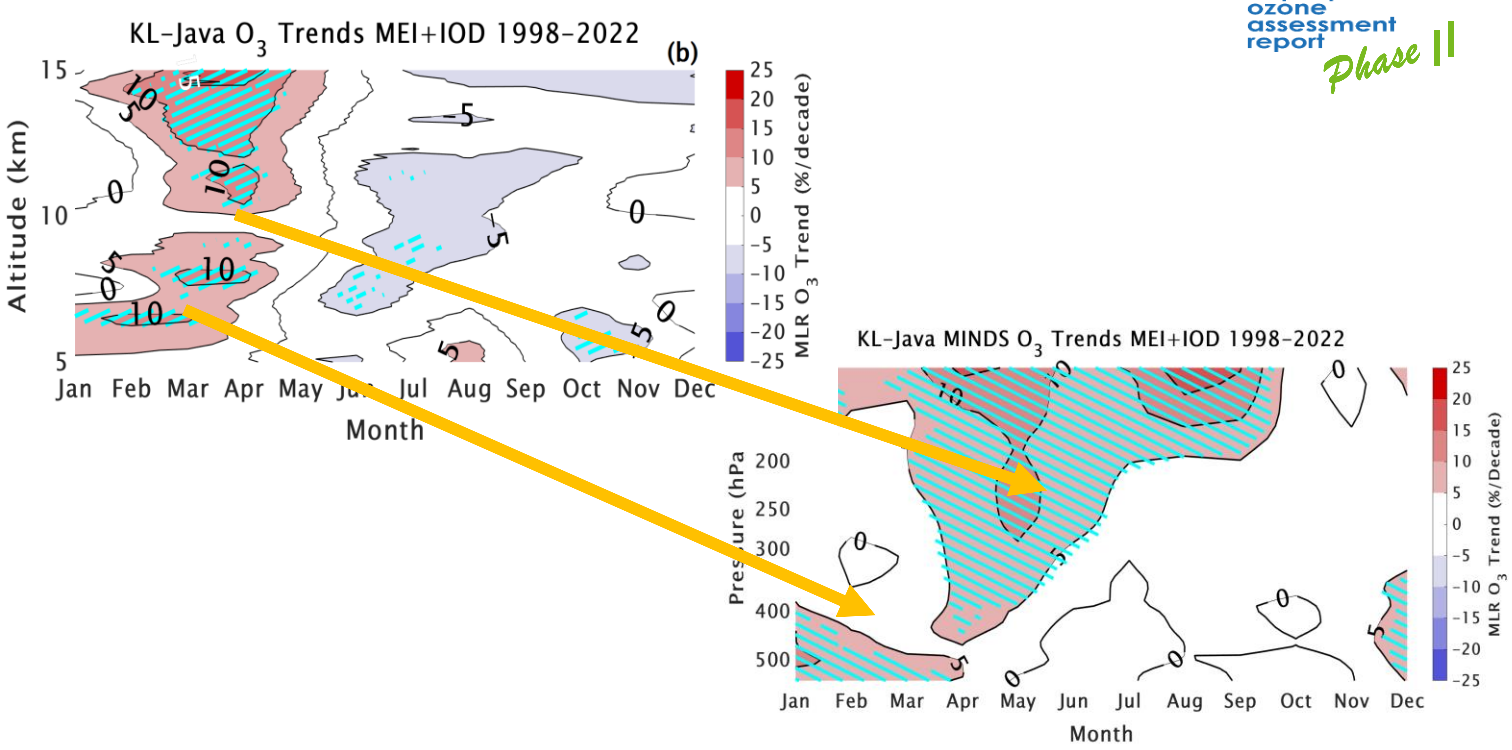
NOTE: Talk based on 4 TOAR II *ACP* Papers, 2 published, 2 submitted

Outline

- **WHY and WHAT is HEGIFTOM** (Harmonization and Evaluation of Ground-based Instruments for Free Tropospheric Ozone Measurements). **Importance in Tropospheric Ozone Assessment Report** (TOAR II)
- **Present "Total tropospheric ozone column" (TrOC, surface to 300 hPa) trends, annually averaged, emphasizing *regional variability***
  - **Focus on 55 HEGIFTOM station from 2000-2022; data from 5 instruments**
  - **Trends and uncertainties are examined latitudinally/longitudinally**
- **Present FT and Lowermost Stratosphere (LMS) *seasonal* trends from SHADOZ (Southern Hemisphere Additional Ozonesondes, 1998-2023)**
- ***Summary:***
  - ***All sites within ± 3 ppbv/dec → equivalent to ±(1-8)%/dec, for TrOC, depending on location, but independent of statistical method***
  - ***Seasonal SHADOZ FT and LMS ozone trends display dynamical signatures***
  - ***HEGIFTOM & SHADOZ data = *the* reference for satellite, model evaluation***

Why Does IGAC/TOAR II Need HEGIFTOM?





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

WHAT & HOW: HEGIFTOM Data to the Rescue!

TOAR
tropospheric ozone assessment report
Phase II

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

- **Ozone from 5 ground-based instrument types: in-service aircraft [IAGOS], ozonesondes, FTIR, 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. Each measurement is delivered with *uncertainty* and a *quality flag.***
- **Contributing networks** →

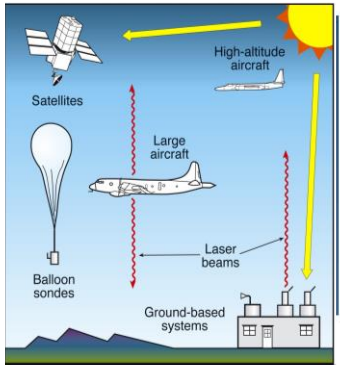
IAGOS


Ozonesondes


Brewer/Dobson Umkehr


FTIR


Lidar



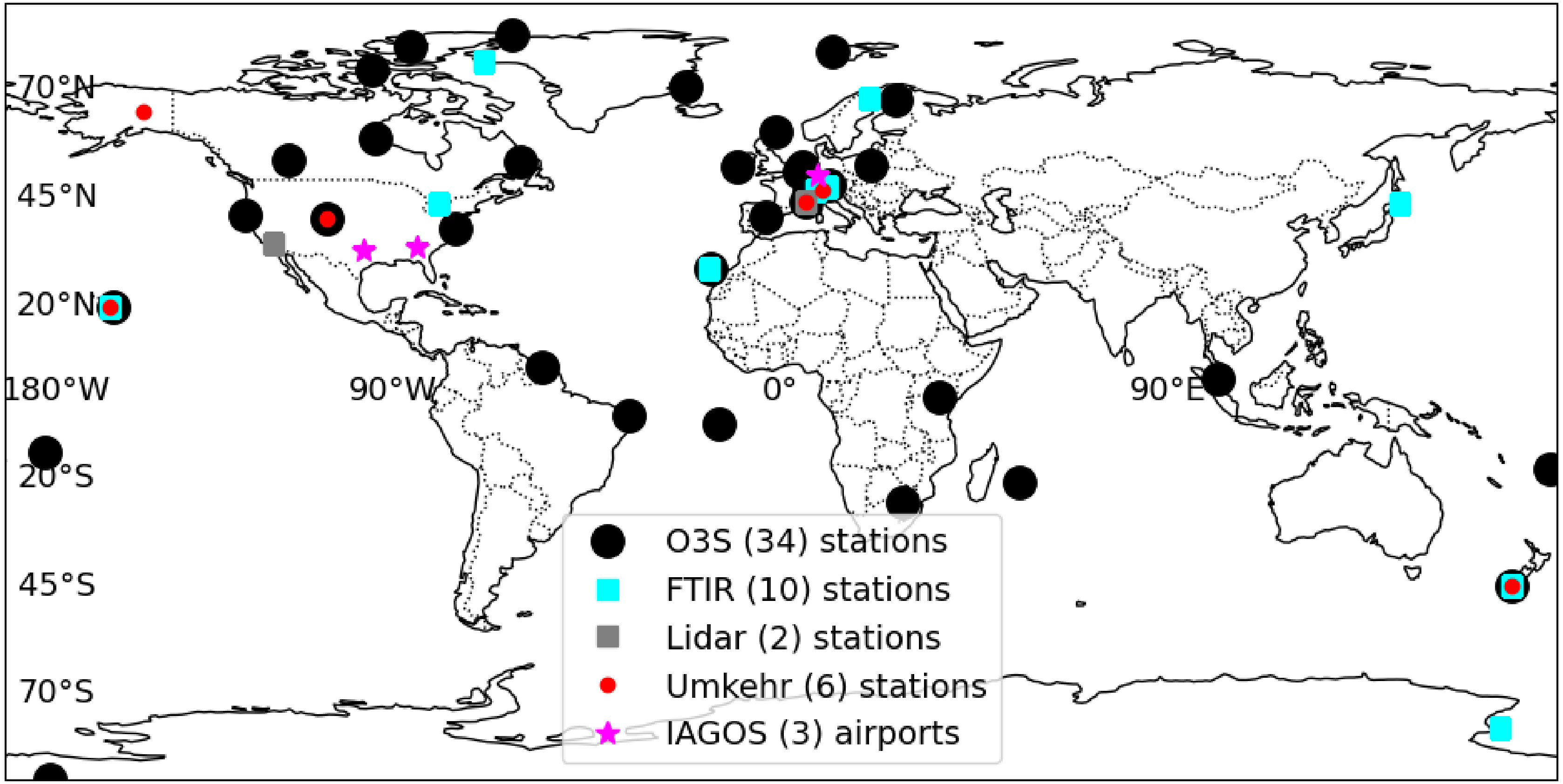
NDACC NOAA SHADOZ GAW

SHADOZ=So. Hemisphere Additional Ozonesondes
IAGOS = In-service Aircraft for a Global Observing System

http://hegiftom.meteo.be/datasets

HEGIFTOM Sites/Datasets for 2000-2022 Trends

Global Sites Contributing to HEGIFTOM (55 L1 Data) Trends



Partial Tropospheric Ozone Column datasets used:

TrOC: surface to 300 hPa

FT OC: 700 hPa > P > 300 hPa

https://hegiftom.meteo.be/datasets/tropospheric-ozone-columns-trocs

Sample locations (55 of > 300 HEGIFTOM sites) meet TOAR II protocol on minimal sample size, start/end years. QR (Quantile Regression) L1 "all data" trends, only 50%-ile results displayed. NOTE: QR and MLR (multiple linear regression) trends with monthly mean HEGIFTOM data (L3) are nearly identical (not shown)

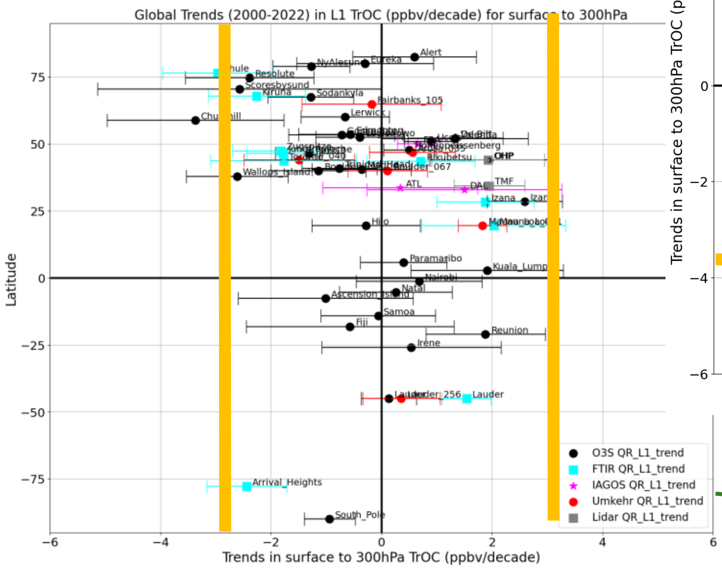
Trends Questions Addressed with HEGIFTOM Data

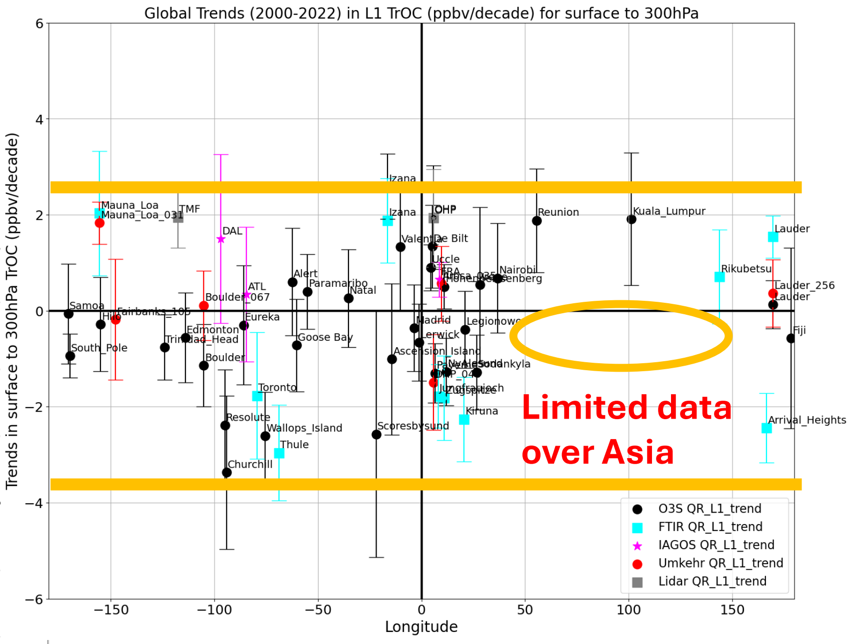
1. What do TrOC trends for 2000-2022 look like? How do TrOC trends from 5 instrument types differ? *Examine median QR trends at 55 sites – Regional Variability Focus*
2. How do TrOC trends vary by region? *Examine trends on map*

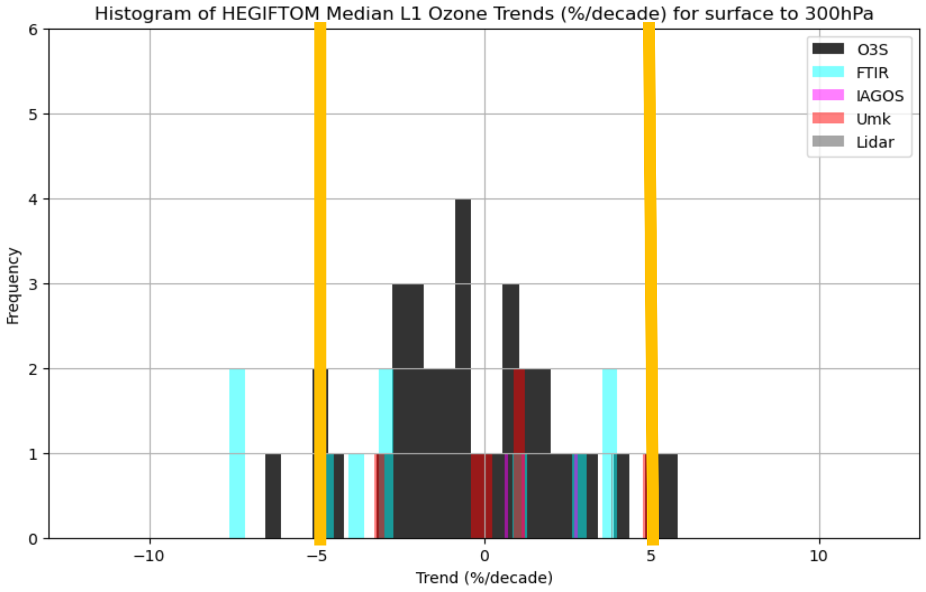
Trends in SHADOZ Tropical Sondes (surface to ~50 hPa)

1. What do FT & lowermost stratosphere (LMS) ozone trends (1998-2023) look like? *Examine data from 5 SHADOZ sites with MLR – Seasonal Variability Focus*
2. What role do dynamic factors play in FT & LMS ozone trends?

Ques 1. TrOC QR L1 Trends, 5 Instrument Types







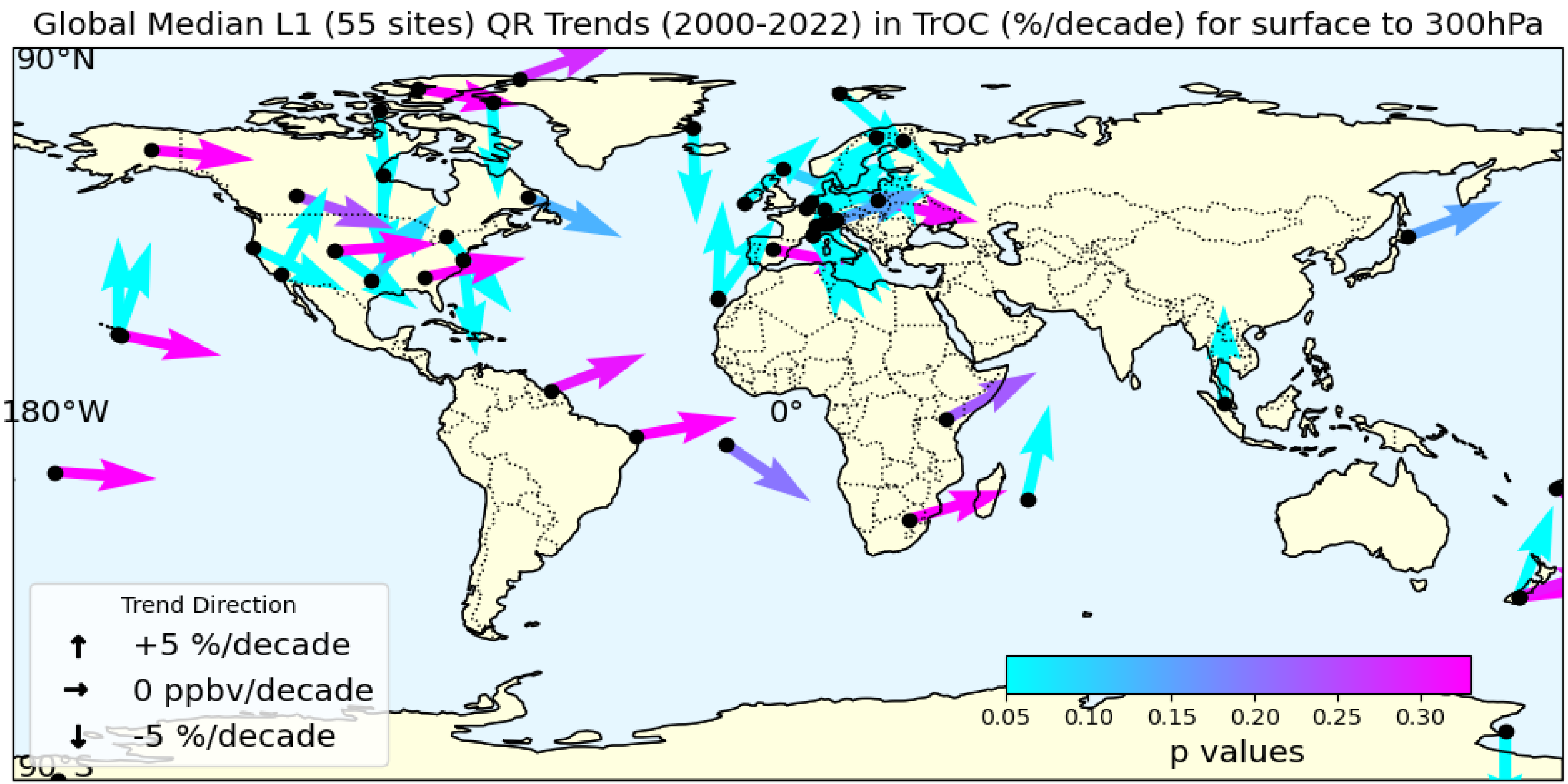
5 instruments, color-coded

Arrival Hts
Zugspitze
-7.5%/dec

Kuala
Lumpur
+6%/dec

- **Left:** Quantile Regression, all data (QR L1) trends for TrOC in **TOAR-preferred ppbv/decade (2σ)** versus latitude. **Median trends nearly all +/- *3 ppbv*/decade. Right: 90% lie within +/- *5* *%/decade*, regardless of instrument type. Extremes are within <u>+ 8</u>%/decade**
- **Center: Positive <u>and</u> negative trends at all longitudes.** ***~42% of trends are ~zero***

Ques 2. TrOC Trends – Global Map View



Moderately positive to negative trends, with more confidence (lower p-value) are in Northern Hemisphere (NH). Divergences at some multi-instrument stations (e.g., Hawaii). Sparse SH and Asian data limit a HEGIFTOM "global" assessment

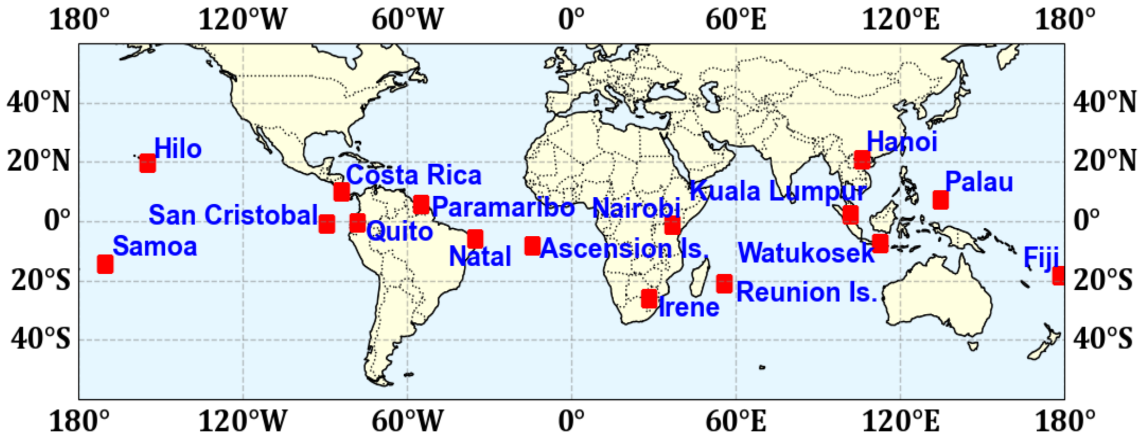
Background for SHADOZ Trends Questions

Most SHADOZ sites are part of HEGIFTOM but SHADOZ profiles cover 50% more troposphere (~300-100 hPa) and the LMS, (~100-50 hPa) which are not in HEGIFTOM

1. Earlier study (Thompson et al. 2021 = "T21") displayed strong **seasonality and regional variability** in FT, LMS trends, 1998-2019
2. FT ozone increased most Feb.-April/May => declining convection in those months
3. LMS ozone decreased in July-Sept. when tropopause height (TH) from radiosondes increased => trend = artifact of TH change

Two new papers (Stauffer et al. 2024; Thompson et al., 2024) are T21 updates.

SHADOZ covers latitude band equal to ~35% of Earth's surface



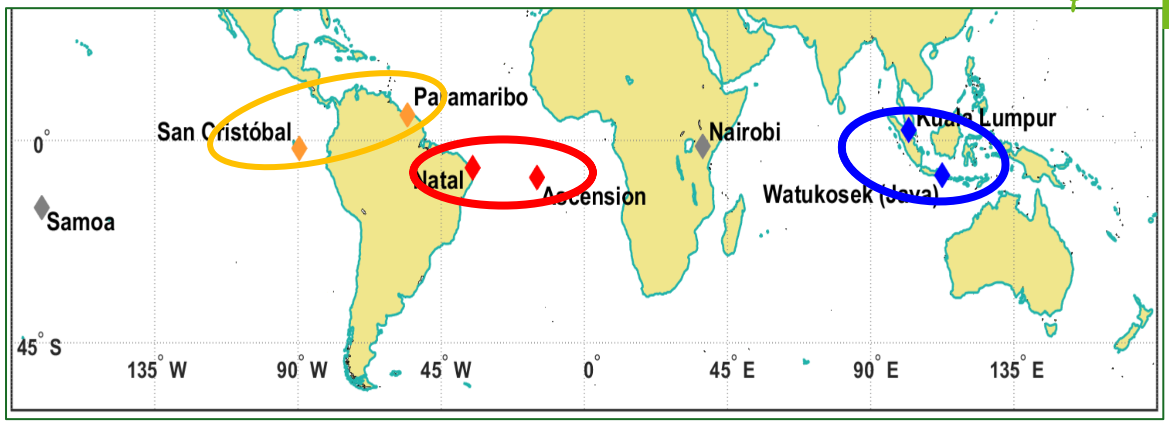
https://tropo.gsfc.nasa.gov/shadoz

SHADOZ stations – now 16! 15 stations have 15 or more years of data

- 10,500 ozone & P-T-U profiles
- Sustainability of SHADOZ for 26 years depends on 20+ International partners
- Stations empowered by participating in Quality Assurance exercises, training

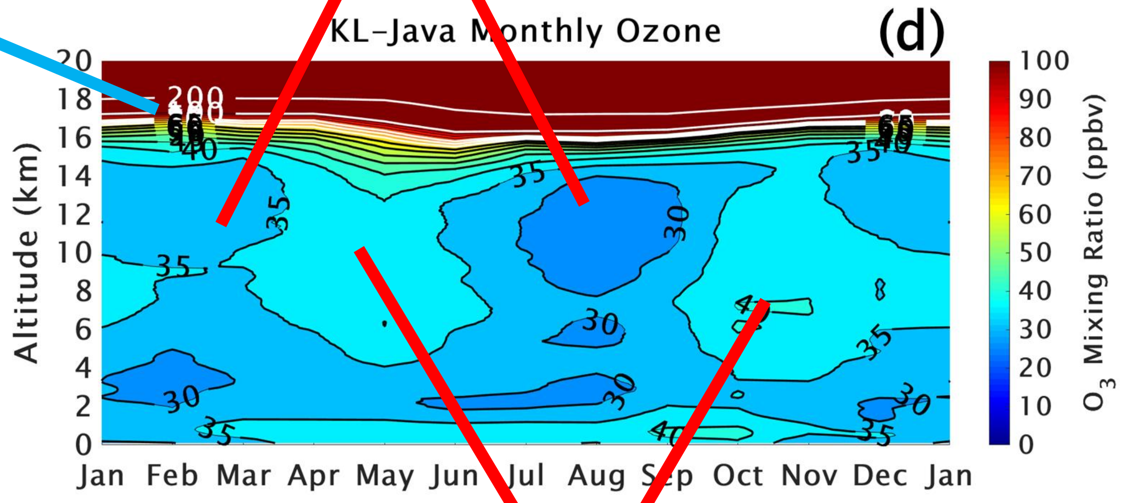
SHADOZ Equatorial Ozone Climatology & Trends

- **Analyses use "5-sites" data, with 3 "combo" sites** for better statistics; > 6000 total profiles **(Upper).** Only equatorial data used to avoid extra-tropical influences
- **Seasonal FT O_3 (Below)** derives from alternating influences of convection and fire pollution, often transported from afar. Radiosondes display **TH cycle, white**



SC-Para Nat-Asc KL-Java

Convective seasons – KL-Java/Eq. SE Asia



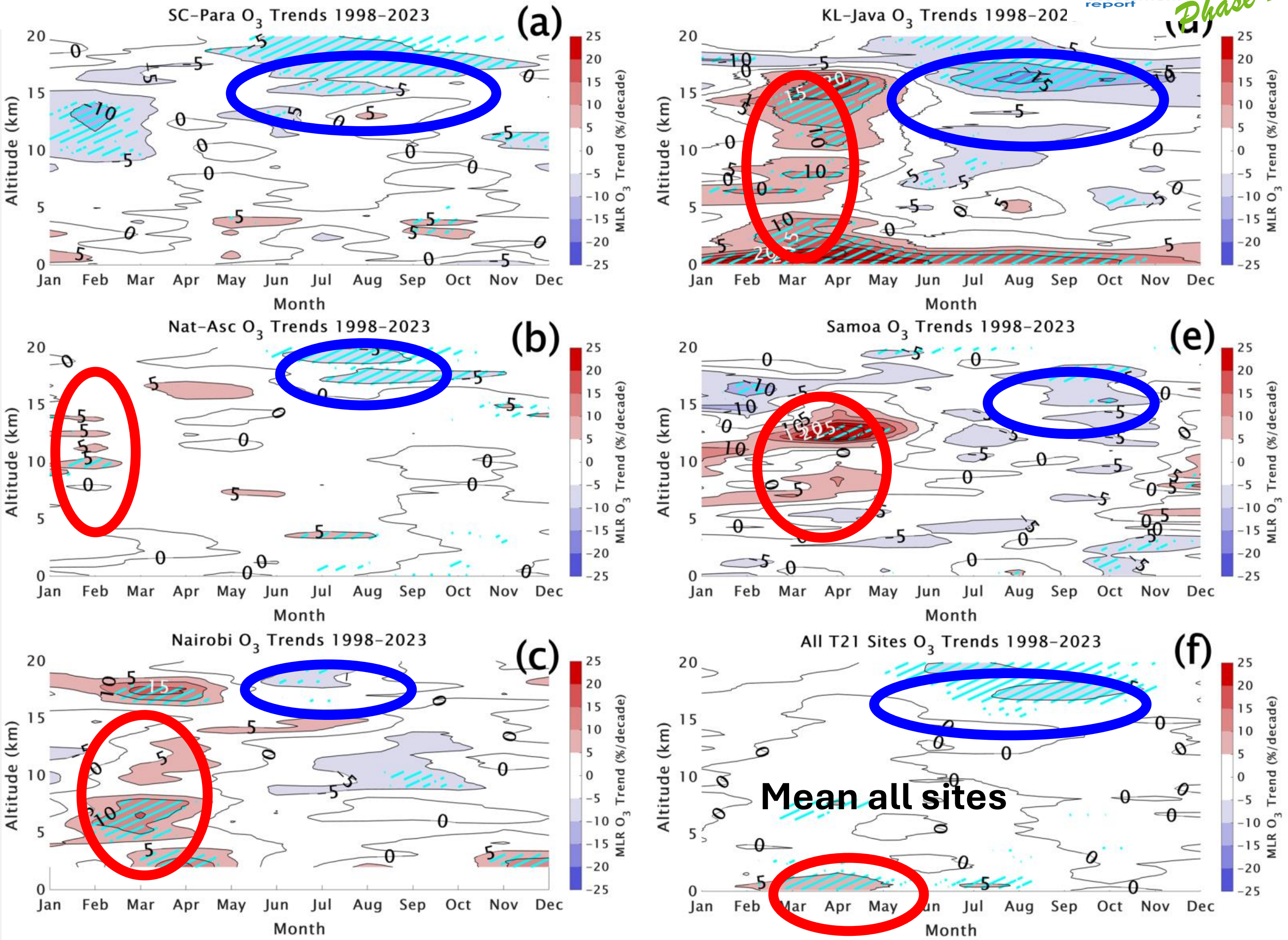
Biomass Fires

- Trends in ozone & TH (altitude at 380K θ) computed by Goddard MLR model with ENSO as MEI, IOD terms, seasonal, annual cycles, computed at 100-m resolution, based on monthly means appear on **Next Slide**:

What Do Trends Look Like? (1) Generally Similar Seasonality with (2) Distinct Regional Differences

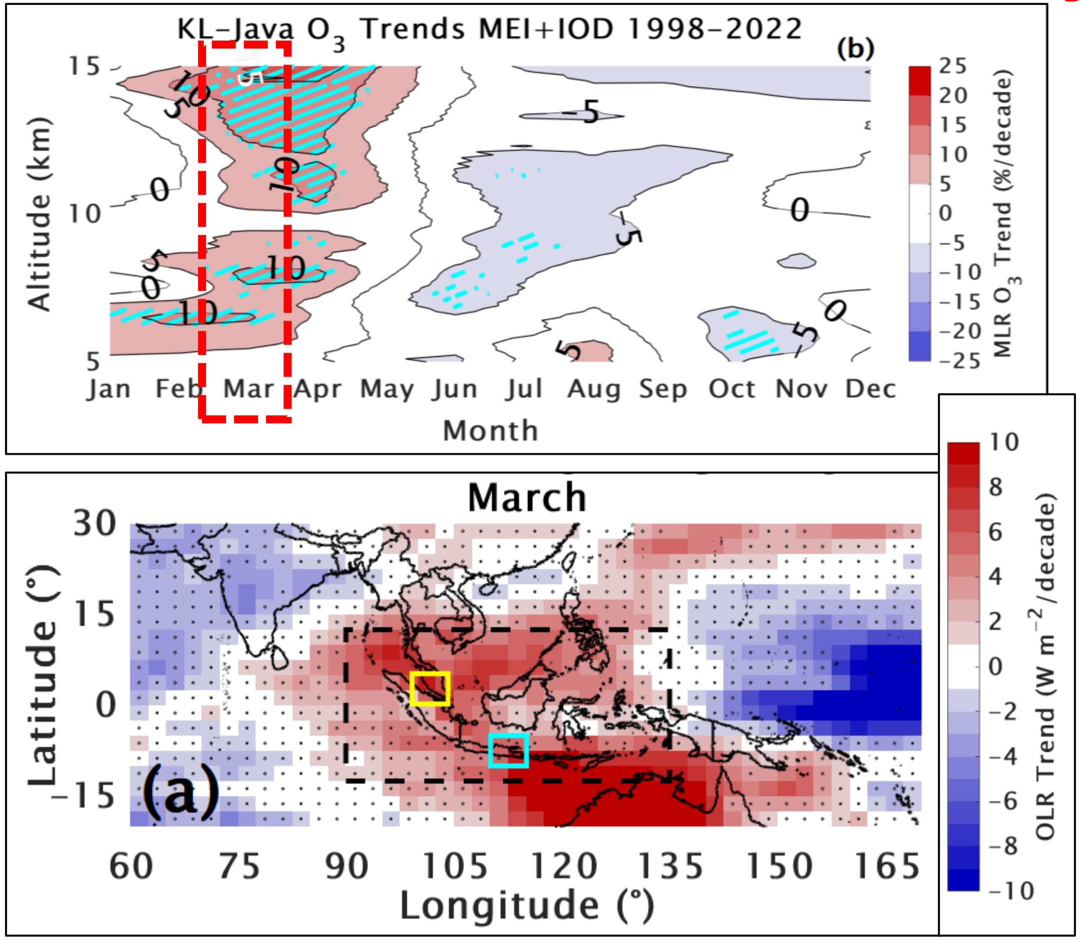
- **Monthly Mean Trends***: **Reds = ozone increase. Blues = ozone loss. Cyan significant at 95% CI**
- **LMS** ozone losses greatest after June,~5-10%/dec over all sites
- Early year **FT** ozone increases (5-10)%/dec except SC-Para
- **Mean** (**f, *lower right***) LMS loss; tropospheric increases only occur below 3 km

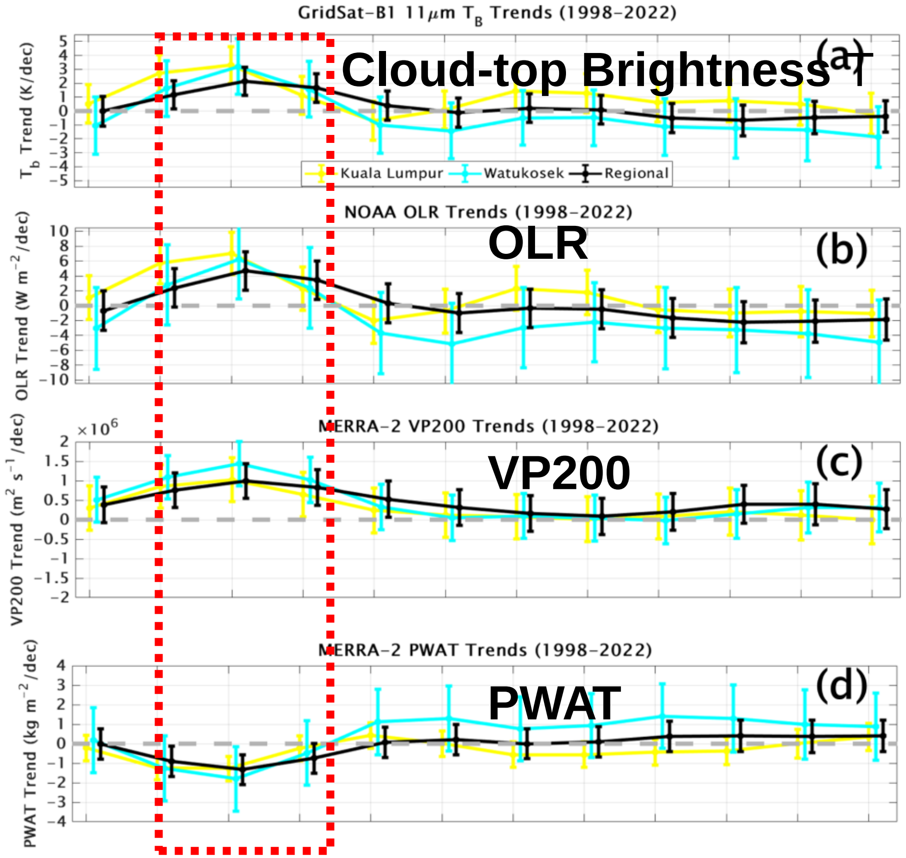
* Similar to T21, except SC-Para (COVID impacts?)



Thompson et al., ACPD, 2024

FT Ozone-Convection Links and Value of High-Resolution Monthly Data are Confirmed!





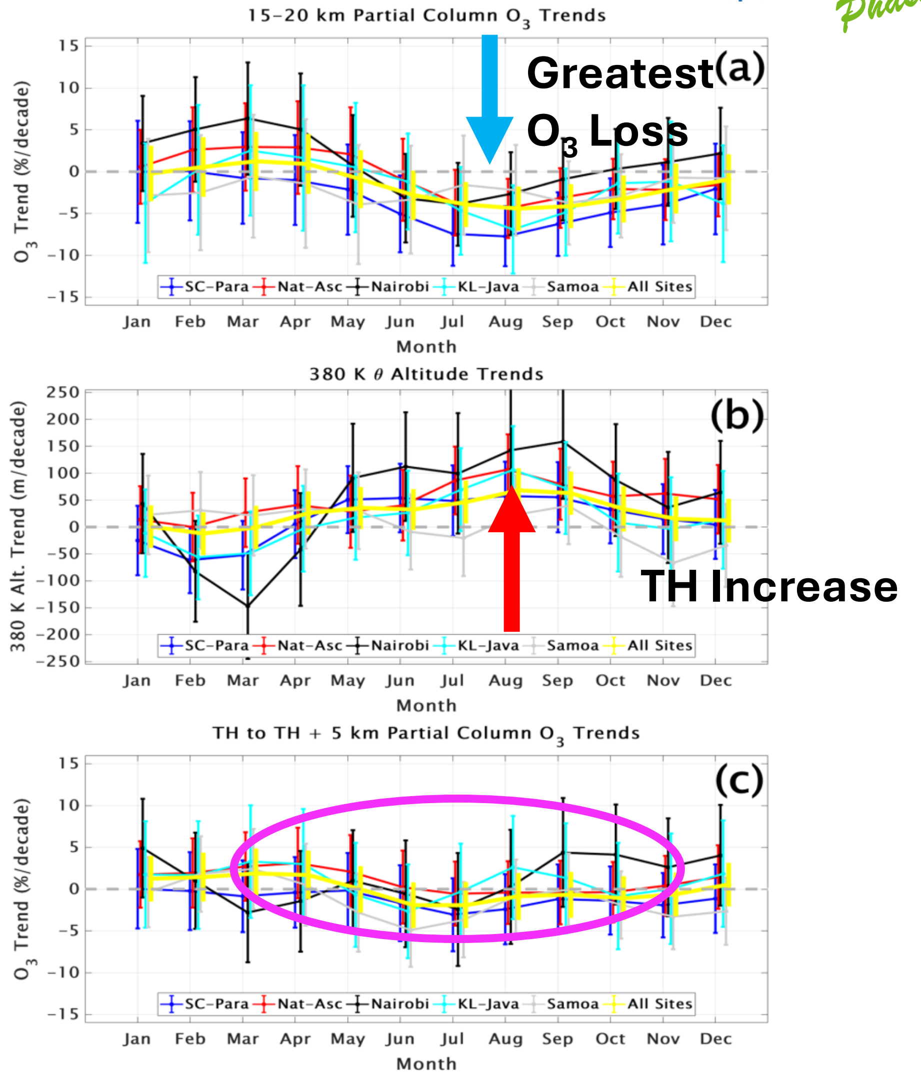
Same result: 3 other proxies for convection imply less activity *only* In Feb.-April

- *Stauffer et al.,* (2024) tested T21 hypothesis that **Feb-Apr increased FT ozone (1998-2022)** (**Top left),** @ KL-Java, is associated with convection loss in the equatorial SE Asia **(ESEA)** region
- **Bottom left**: OLR as convective proxy confirms the loss over ESEA (dashed line) and stations **Yellow = KL, Cyan = Java.** Less convection reduces lofting, dilution of near-surface ozone; FT ozone piles up

LMS Ozone Trends – Artifact of Higher Tropopause?

- **SHADOZ ozone 15-20 km trends updated from T21. 1998-2023 trends calculated with MLR model at five color-coded stations *and* all site-mean monthly trend in yellow**
- **In the 15-20 km layer, negative trends of -5 to -7 %/decade occur ~July-September (top). This coincides with positive trends in tropopause height (TH) (middle)**
- **As for T21 referencing LMS column to the TH and re-calculating shows trends "disappear"! (bottom). A "climate signal?"**

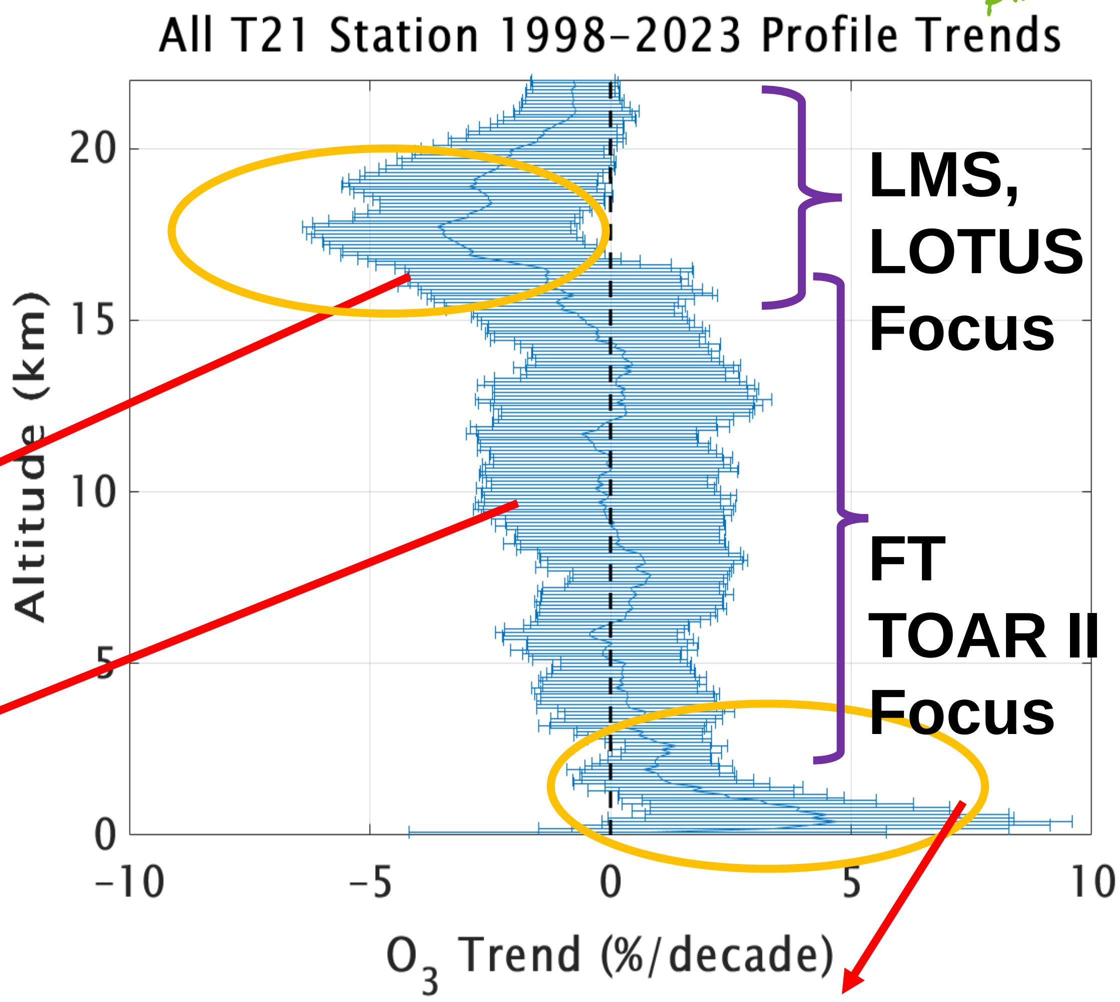
- **Trends output from *Thompson et al., (2021; JGR)* at: https://tropo.gsfc.nasa.gov/shadoz/SHADOZ_PubsList.html - Constraint for model comparisons**



T21 update in Thompson et al. (2024)

HEGIFTOM & SHADOZ for TOAR II Trends

- Given the uncertainty in evolving tropospheric ozone satellite data for 23-25-yr periods of HEGIFTOM & SHADOZ trends, these ground-based results are the *most reliable information* for the TOAR II "Climate Assessment"
- SHADOZ trends in LMS & FT ozone "Set the Bar" for satellite data & models to reproduce in the tropics
    - LMS O_3 ***negative*** trends, July-Sept., are negligible given TH changes
    - FT trends: zero on average; ***early-year increase*** ➔ declining convection
- TOAR II & LOTUS challenges – why/how do dynamic/climate changes perturb UT/LS ozone?



Only below 5 km is tropospheric O_3 increasing, mostly over SE Asia

Thank You for Attention!

PI (1998-2021)

PI (2021-)

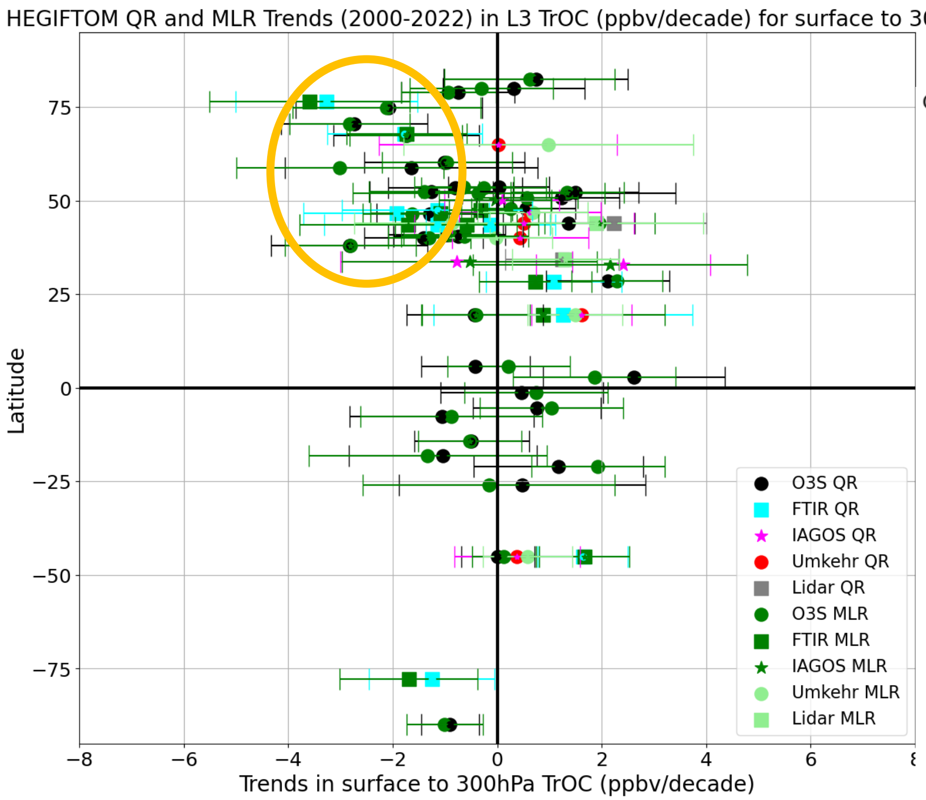
Archiver, Webmaster (2019-)

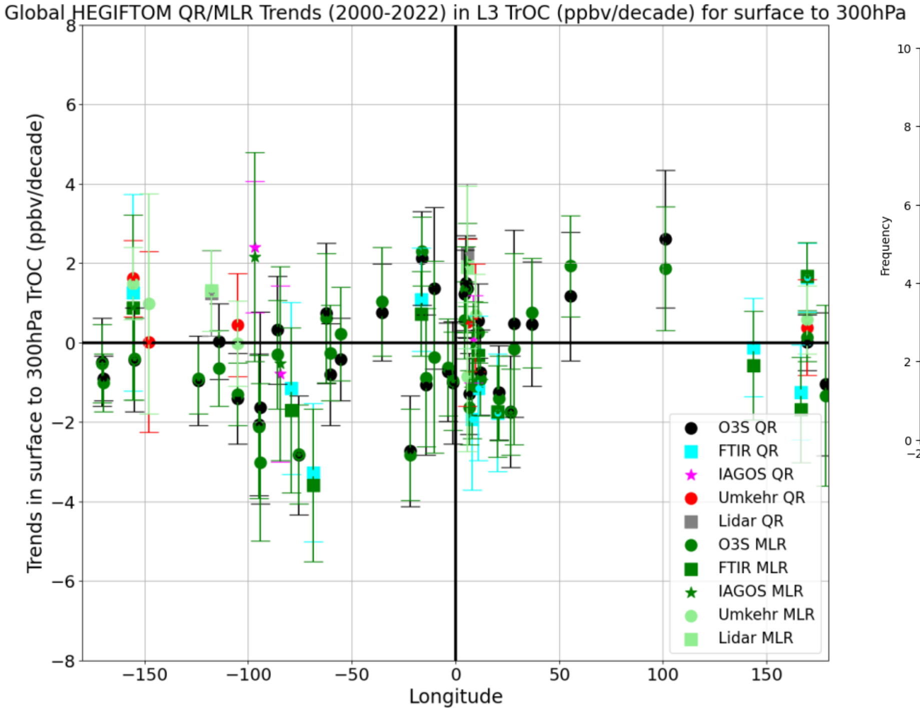
Dr. Anne M. Thompson   Dr. Ryan M. Stauffer   Dr. Debra E. Kollonige

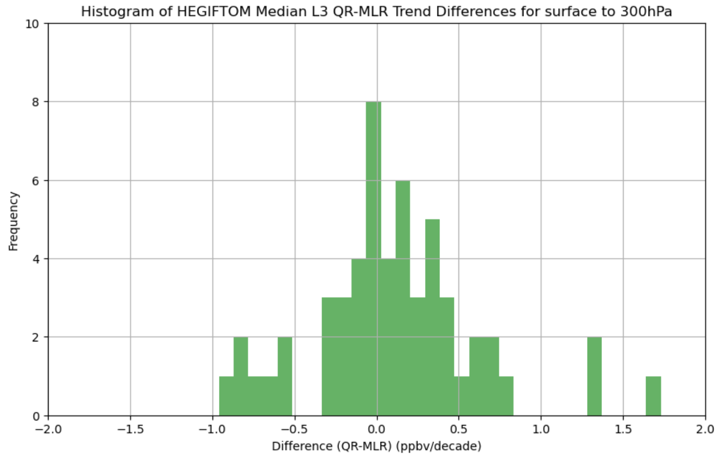
Funding: NASA HQ (UACO, K. Jucks; SAGE III, R. Eckman). **Relevant TOAR II References in Bold**

Gaudel, A., et al. (2024) Tropical tropospheric ozone distribution and trends from in situ..., *ACP*, *https://doi.org/10.5194/egusphere-2023-3095*
Thompson, A. M., et al., *J. Geophys. Res* ,126, https://doi.org/10.1029/2021JD034691, 2021 (= T21 SHADOZ Trends)
Stauffer, R. M., et al., *J. Geophys. Res.,* 123, doi: 10.1002/2017JD028465, 2018 (SHADOZ, Sonde Clusters)
Stauffer, R. M., et al., *Geophys. Res. Lett.,* doi: 10.1029/2019/GL086791, 2020
Stauffer, R. M., et al., *Earth Space Sci.,* https://doi.org/10.1029/2022EA002459, 2022 (Stability of Global Sonde Network)
Stauffer, R. M., et al., *Atmos. Chem. Phys.,* https://acp.copernicus.org/articles/24/5221/2024 (Dynamical Drivers…)
Smit, H. G. J., et al., https://doi.org/10.5194/egusphere-2024-3760 (Intercomparison of IAGOS....(Profile QA)
Thompson, A. M., et al., *J. Geophys. Res.,* 122, 13000-13025, doi: 10.1002/2017JD027406, 2017   (SHADOZ Reprocessing)
Thompson, A. M., et al., *Bull. Am. Meteor. Society,* doi.org/10.1175/BAMS-17-0311, 2019   (JOSIE-2017-SHADOZ)
Thompson, A. M., Stauffer, R. M., Kollonige, D. E., et al., *Atmos. Chem. Phys,* egusphere-2024-3761 (SHADOZ Trends)
Van Malderen, R., Thompson, A. M., Kollonige, D. E., et al. *Atmos. Chem. Phys,* egusphere-2024-3736 (Global Trends)
Witte, J. C., et al., *J. Geophys. Res.,* 122, 6611-6636, doi: 10.1002/2016JD026403, 2017   (SHADOZ Reprocessing)

Ques 3. TrOC QR, MLR L3 Trends Similar



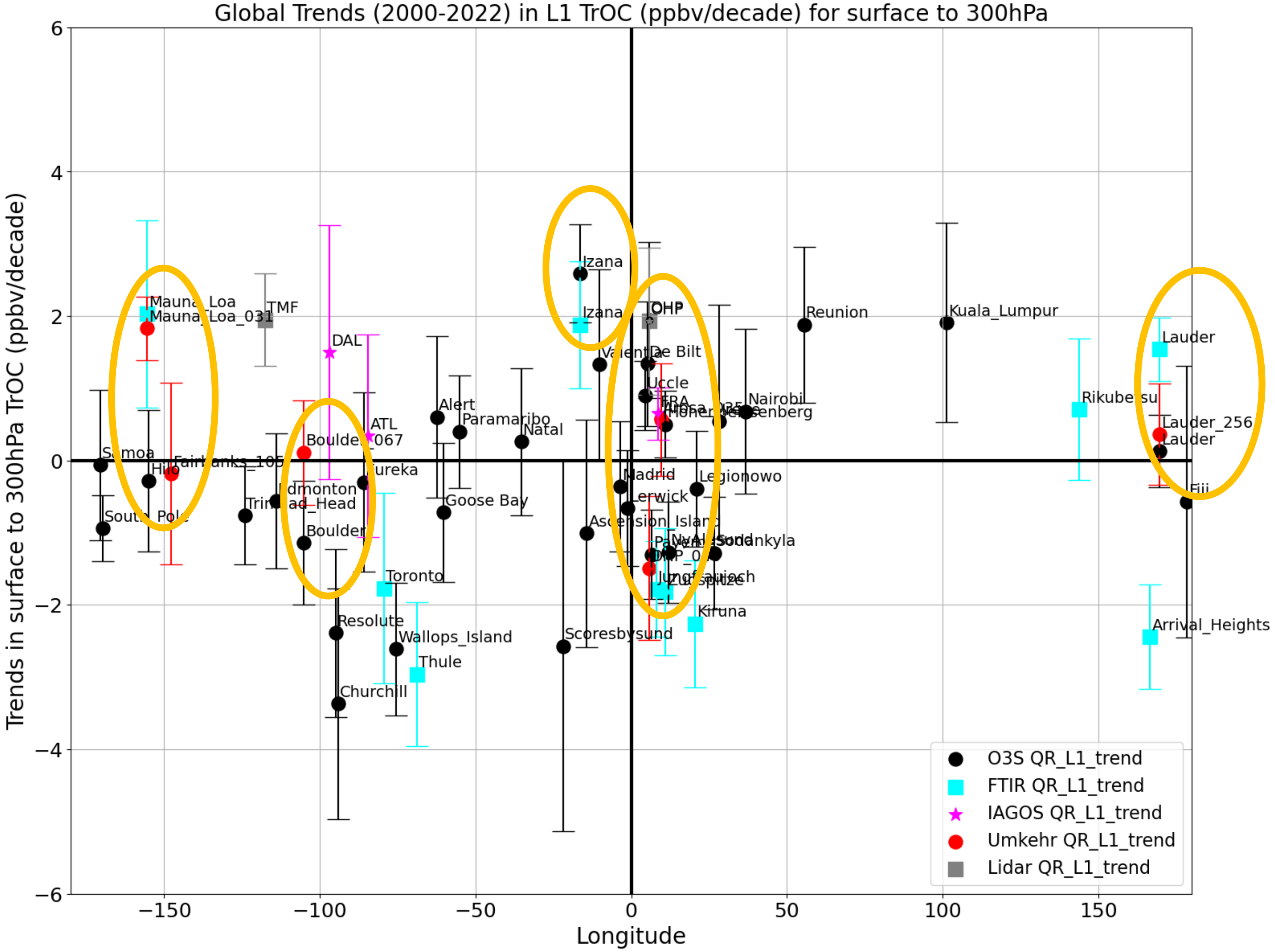




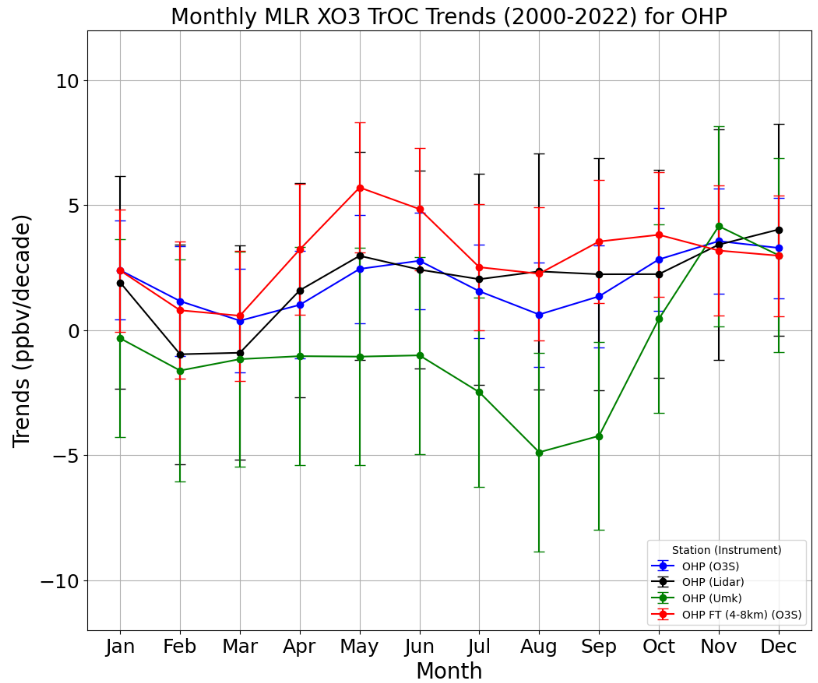
QR-MLR trends, ppbv/dec

- **Left & Center: TrOC QR trends, color-coded for above, compared to green-shaded MLR trends are mostly identical within their uncertainties.**
- **Right:** QR-MLR differences fairly small; QR trends slightly higher than MLR

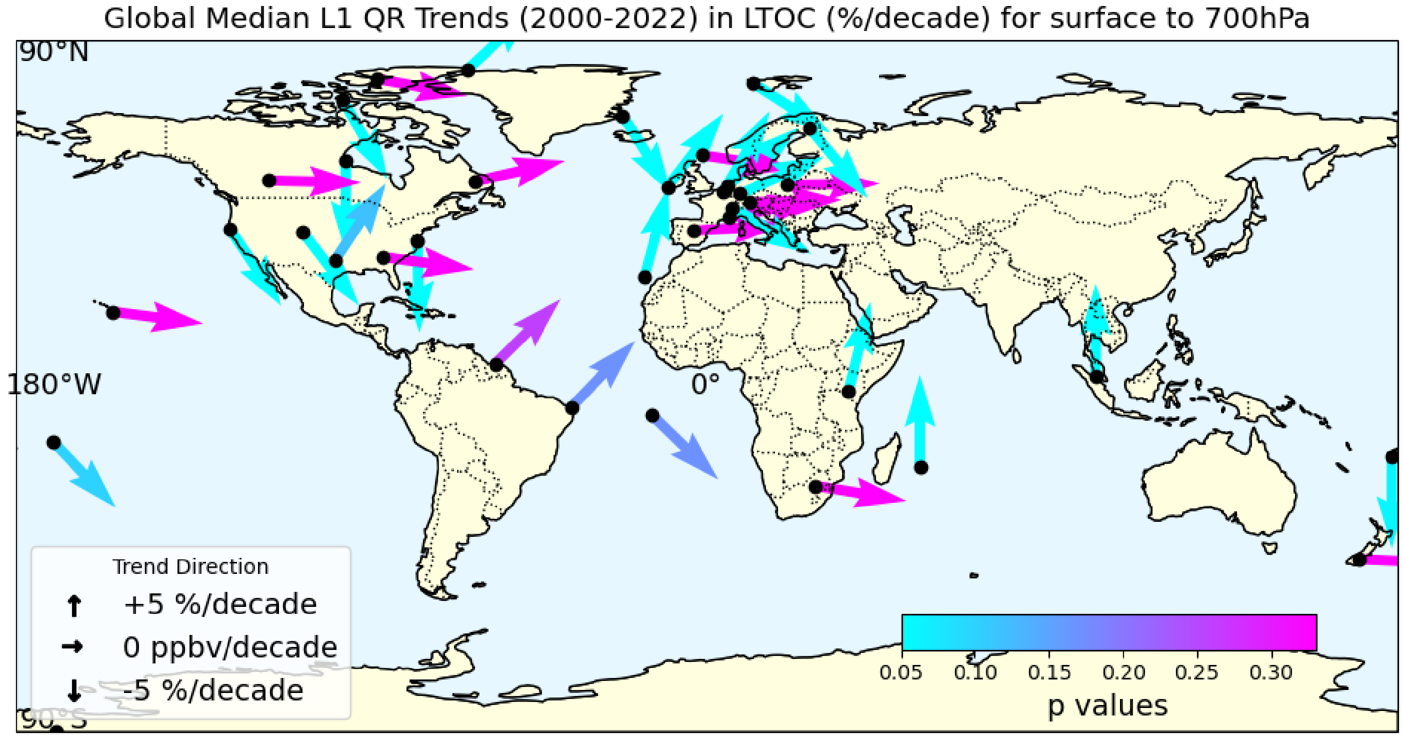
Ques 4. TrOC Trends from 5 Instruments Compared

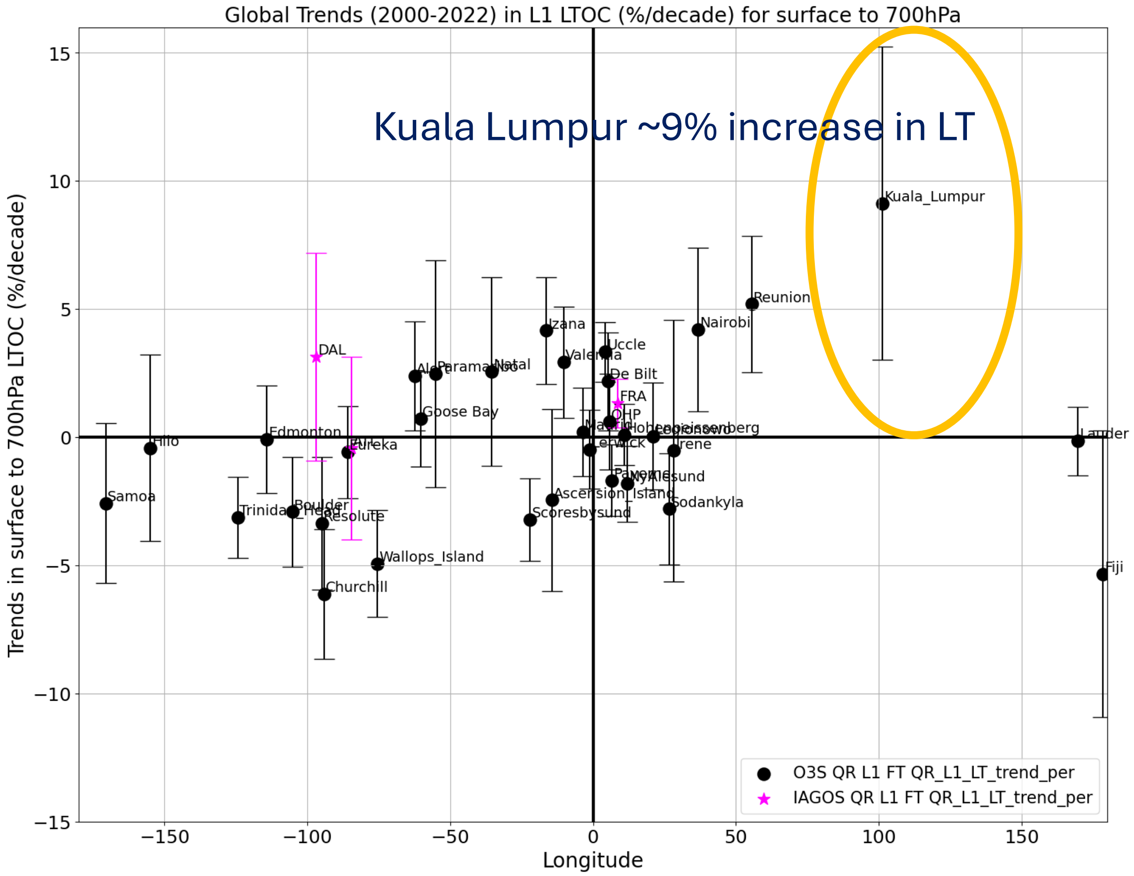


L1 QR trends sites with > 1 instrument show offsets (Left): MLO/Hilo, Boulder, Izaña, Lauder & OHP. (Eg. OHP Lidar & O3S show positive trends, but Umkehr shows negative.) Causes unclear – different sampling frequency, protocols, diurnal & seasonal effects (Below).



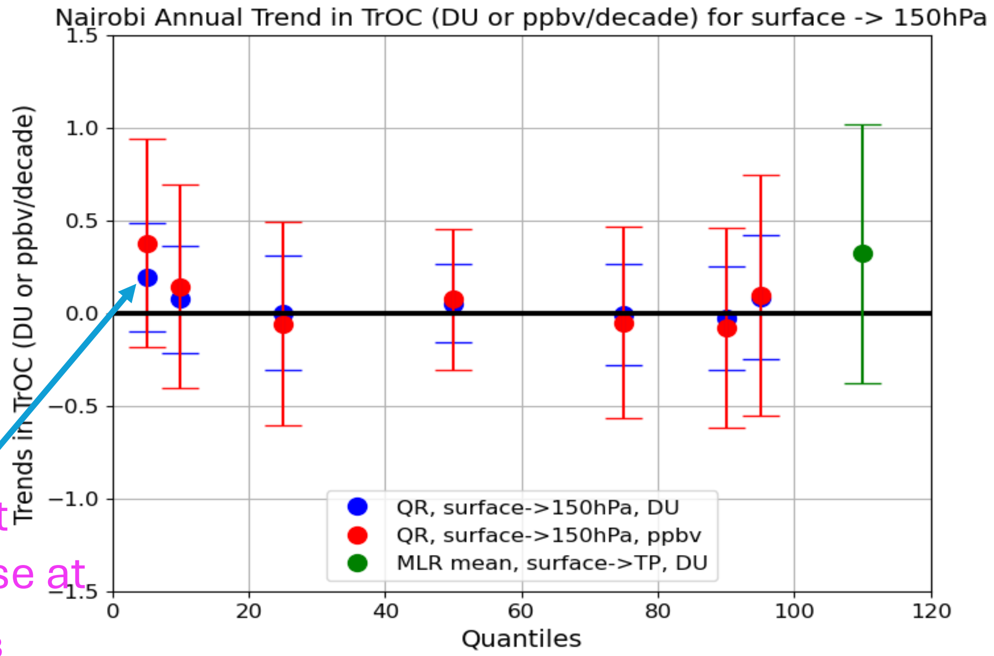
Ques 5. LT OC L1 QR Median Trend Variability



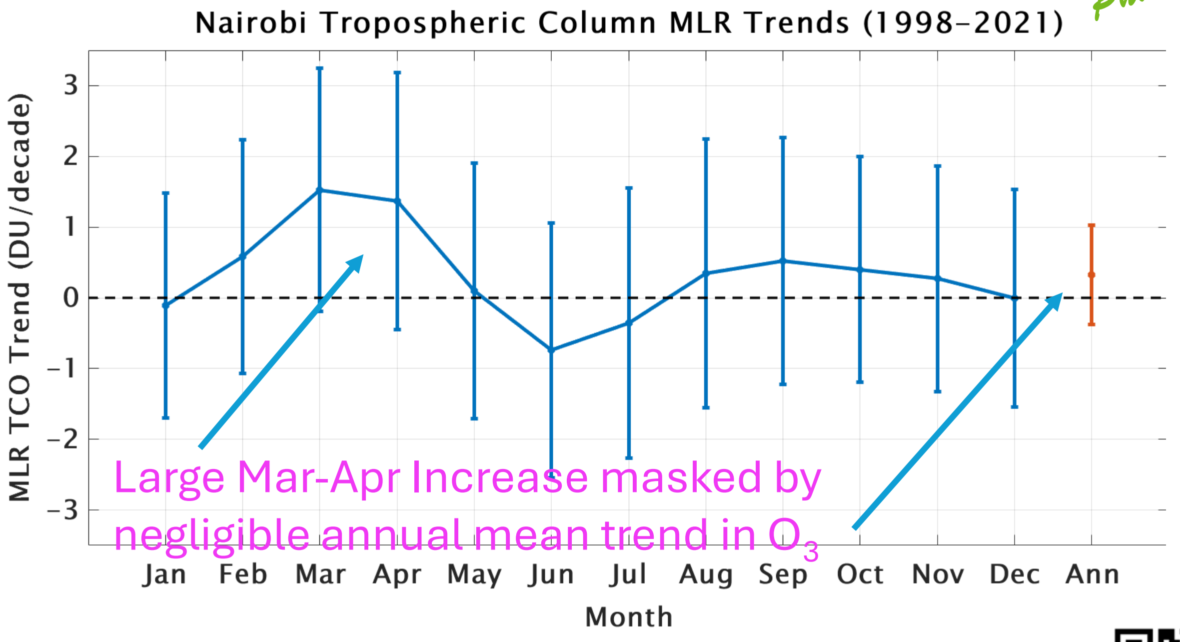


Left: L1 QR (sondes, IAGOS) **50-%ile median** 2000-2022 trends (in %/decade) in LT (p>700hPa).
Right: LT Trends versus longitude (mostly < 5%/dec, positive OR negative); in tropical and urban areas, high LTOC trends usually dominate the TROC increase.

HEGIFTOM Trends. Input & Guidelines

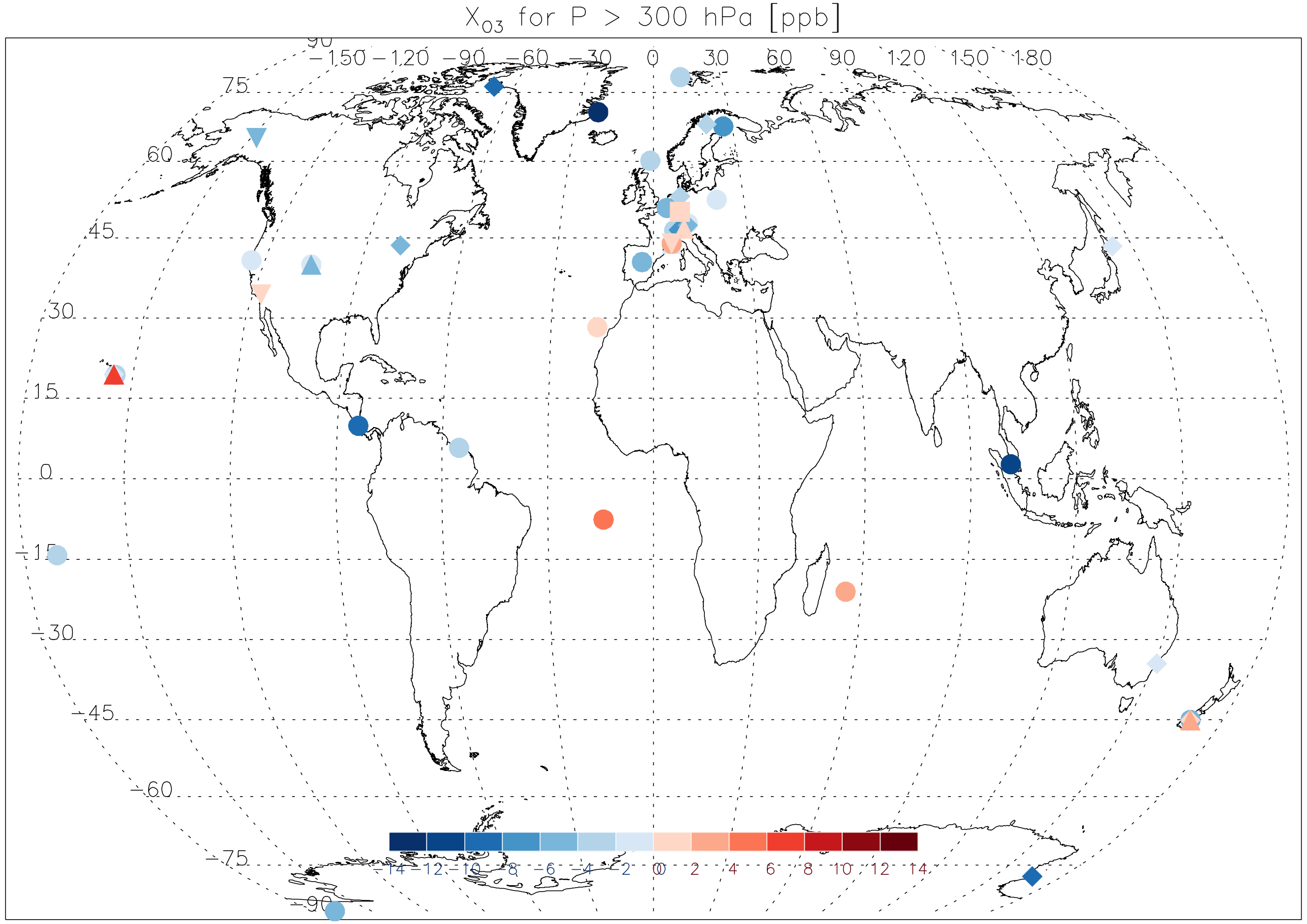


Largest Increase at Low O_3



- 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



- Relative change of mean TrOC for the time period 2020-2022 vs. 2000-2019
  Blue: 2020-2022 < 2000-2019
  Red: 2020-2022 > 2000-2019
- Decline in 75% of the sites, on average -2.5% prominent in NH (spring + summer), stronger in FT.
- Impact on trends!

○ ozonesondes △ Umkehr ◇ FTIR
□ IAGOS ▽ Lidar