Tropospheric ozone trends from harmonized ground-based measurements in TOAR-II & implications for stratospheric ozone trends assessment

Roeland Van Malderen

Royal Meteorological Institute of Belgium, Brussels, Belgium

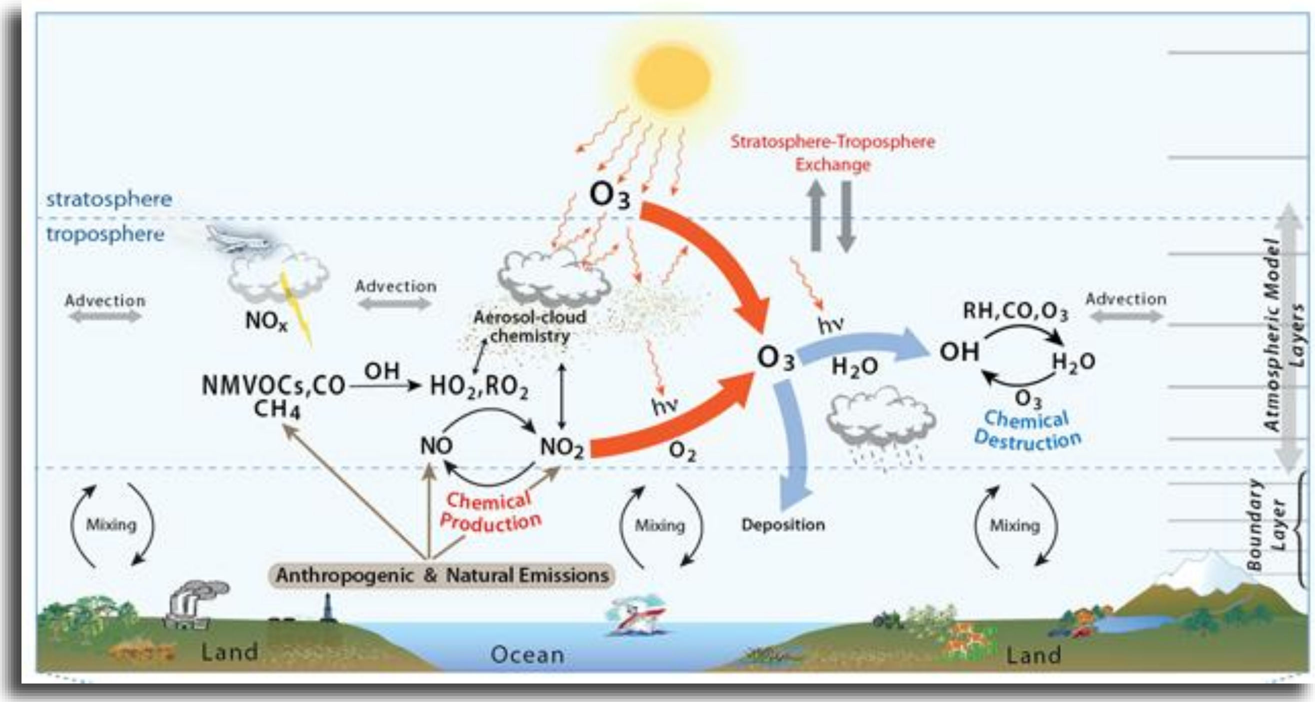
… but with contributions from many, many colleagues

Outline

- **Introduction: (tropospheric) ozone**
- **From TOAR-I to TOAR-II**
- **Harmonized ground-based measurements (HEGIFTOM)**
- **Tropospheric ozone column distribution**
  (+ impact of COVID-19)
- **Tropospheric ozone column trends**
  - ✓ Individual site trends
  - ✓ Regionalized trends
  (+ impact of COVID-19)
- **Conclusions and outlook**
  - ✓ Tropospheric ozone trends
  - ✓ Implications for stratospheric ozone trends assessment

Tropospheric Ozone

- **10% of atmospheric ozone**
- **harmful impact: toxic effects on humans (health), ecosystems and crops**
- **greenhouse gas (→ climate)**
- **formation/destruction of tropospheric ozone by**
  - ✓ stratosphere-troposphere exchange
  - ✓ photochemical formation: sun + precursors (NO_x, CO, CH_4 and VOC) coming from vehicule exhaust and industrial emissions
  - ✓ photochemical destruction in low NO_x conditions (OH-HO_2 cycle)
  - ✓ dry deposition on the ground



From Young et al., *Elementa*, 2018

TOAR-I 2014-2019

Tropospheric Ozone Assessment Report

co-chairs: Owen Cooper (NOAA) & Martin Schultz (FZJ)

Mission:
To provide the research community with an up-to-date scientific assessment of tropospheric ozone's global distribution and trends from the surface to the tropopause.

Deliverables:

1) The first tropospheric ozone assessment report based on all available surface observations, the peer-reviewed literature and new analyses.

Stakeholders:

WMO GAW World Health Organization NOAA LRTAP Long-range Transboundary Air Pollution Task Force on Hemispheric Transport of Air Pollution

IGAC — International Global Atmospheric Chemistry

TOAR-I Publications

https://collections.elementascience.org/toar

TOAR — tropospheric ozone assessment report — Phase II

ELEMENTA Science of the Anthropocene

Young, PJ, et al. 2018 Tropospheric Ozone Assessment Report: Assessment of global-scale model performance for global and regional ozone distributions, variability, and trends. *Elem Sci Anth*, 6: 10. DOI: https://doi.org/10.1525/elementa.265

REVIEW

Tropospheric Ozone Assessment Report: Assessment of global-scale model performance for global and regional ozone distributions, variability, and trends

P. J. Young[§,†,‡], V. Naik[§], A. M. Fiore[‖,¶], A. Gaudel[**,††], J. Guo[‖], M. Y. Lin[§,‡‡], J. L. Neu[§§], D. D. Parrish[**,††], H. E. Rieder[¶¶,‖‖], J. L. Schnell[¶¶], S. Tilmes[***], O. Wild[*], L. Zhang[†††], J. Ziemke[‡‡‡,§§§], J. Brandt[‖‖‖], A. Delcloo[¶¶¶], R. M. Doherty[****], C. Geels[‖‖‖], M. I. Hegglin[††††], L. Hu[‡‡‡‡], U. Im[‖‖‖], R. Kumar[§§§§], A. Luhar[‖‖‖‖], L. Murray[¶¶¶¶], D. Plummer[*****], J. Rodriguez[‡‡‡], A. Saiz-Lopez[†††††], M. G. Schultz[‡‡‡‡‡], M. T. Woodhouse[‖‖‖‖] and G. Zeng[§§§§§]

ELEMENTA Science of the Anthropocene

Schultz, MG, et al 2017 Tropospheric Ozone Assessment Report: Database and metrics data of global surface ozone observations. *Elem Sci Anth*, 5: 58, DOI: https://doi.org/10.1525/elementa.244

RESEARCH ARTICLE

Tropospheric Ozone Assessment Report: Database and metrics data of global surface ozone observations

Martin G. Schultz[1,82], Sabine Schröder[1], Olga Lyapina[1], Owen R. Cooper[2,3], Ian Galbally[4], Irina Petropavlovskikh[2,3], Erika von Schneidemesser[5], Hiroshi Tanimoto[6], Yasin Elshorbany[7,8], Manish Naja[9], Rodrigo J. Seguel[10], Ute Dauert[11], Paul Eckhardt[12], Stefan Feigenspan[11], Markus Fiebig[12], Anne-Gunn Hjellbrekke[12], You-Deog Hong[13], Peter Christian Kjeld[14], Hiroshi Koide[15], Gary Lear[16], David Tarasick[17], Mikio Ueno[15], Markus Wallasch[18], Darrel Baumgardner[19], Ming-Tung Chuang[20], Robert Gillett[4], Meehye Lee[21], Suzie Molloy[4], Raeesa Moolla[22], Tao Wang[23], Katrina Sharps[24], Jose A. Adame[25], Gerard Ancellet[26], Francesco Apadula[27], Paulo Artaxo[28], Maria E. Barlasina[29], Magdalena Bogucka[30], Paolo Bonasoni[31], Limseok Chang[32], Aurelio Colomb[33], Emilio Cuevas-Agulló[34], Manuel Cupeiro[35], Anna Degorska[36]

ELEMENTA Science of the Anthropocene

Archibald, A. T., et al. 2020. Tropospheric Ozone Assessment Report: A critical review of changes in the tropospheric ozone burden and budget from 1850 to 2100. *Elem Sci Anth*, 8: 1. DOI: https://doi.org/10.1525/elementa.2020.034

RESEARCH ARTICLE

Tropospheric Ozone Assessment Report: A critical review of changes in the tropospheric ozone burden and budget from 1850 to 2100

A. T. Archibald[1,2,*], J. L. Neu[3], Y. F. Elshorbany[4], O. R. Cooper[5,6], P. J. Young[7,8,9], H. Akiyoshi[10], R. A. Cox[1], M. Coyle[11,12], R. G. Derwent[13], M. Deushi[14], A. Finco[15], G. J. Frost[6], I. E. Galbally[16,17], G. Gerosa[15], C. Granier[5,6,18], P. T. Griffiths[1,2], R. Hossaini[7,8], L. Hu[19], P. Jöckel[20], B. Josse[21], M. Y. Lin[22], M. Mertens[20], O. Morgenstern[23], M. Naja[24], V. Naik[25], S. Oltmans[26], D. A. Plummer[27], L. E. Revell[28], A. Saiz-Lopez[29], P. Saxena[30], Y. M. Shin[1], I. Shahid[31], D. Shallcross[32], S. Tilmes[33], T. Trickl[34], T. J. Wallington[35], T. Wang[36], H. M. Worden[33], and G. Zeng[23]

ELEMENTA Science of the Anthropocene

Lefohn, AS, et al. 2018 Tropospheric ozone assessment report: Global ozone metrics for climate change, human health, and crop/ecosystem research. *Elem Sci Anth*, 6: 28. DOI: https://doi.org/10.1525/elementa.279

RESEARCH ARTICLE

Tropospheric ozone assessment report: Global ozone metrics for climate change, human health, and crop/ecosystem research

Allen S. Lefohn[*], Christopher S. Malley[†,‡,§], Luther Smith[‖], Benjamin Wells[¶], Milan Hazucha[**], Heather Simon[¶], Vaishali Naik[††], Gina Mills[‡‡], Martin G. Schultz[§§], Elena Paoletti[‖‖], Alessandra De Marco[¶¶], Xiaobin Xu[***], Li Zhang[†††], Tao Wang[‡‡‡], Howard S. Neufeld[‡‡‡], Robert C. Musselman[§§§], David Tarasick[‖‖‖], Michael Brauer[¶¶¶], Zhaozhong Feng[****], Haoye Tang[††††], Kazuhiko Kobayashi[‡‡‡‡], Pierre Sicard[§§§§], Sverre Solberg[‖‖‖‖] and Giacomo Gerosa[¶¶¶¶]

ELEMENTA Science of the Anthropocene

Gaudel, A, et al. 2018. Tropospheric Ozone Assessment Report: Present-day distribution and trends of tropospheric ozone relevant to climate and global atmospheric chemistry model evaluation. *Elem Sci Anth*, 6: 39. DOI: https://doi.org/10.1525/elementa.291

RESEARCH ARTICLE

Tropospheric Ozone Assessment Report: Present-day distribution and trends of tropospheric ozone relevant to climate and global atmospheric chemistry model evaluation

A. Gaudel[1,2], O. R. Cooper[1,2], G. Ancellet[3], B. Barret[4], A. Boynard[3,5], J. P. Burrows[6], C. Clerbaux[3], P.-F. Coheur[7], J. Cuesta[8], E. Cuevas[9], S. Doniki[7], G. Dufour[8], F. Ebojie[10], G. Foret[8], O. Garcia[11], M. J. Granados-Muñoz[12,13], J. W. Hannigan[14], F. Hase[15], B. Hassler[1,2,16], G. Huang[17], D. Hurtmans[7], D. Jaffe[18,19], N. Jones[20], P. Kalabokas[21], B. Kerridge[22], S. Kulawik[23,24], B. Latter[22], T. Leblanc[12], E. Le Flochmoën[4], W. Lin[25], J. Liu[26,27], X. Liu[17], E. Mahieu[27], A. McClure-Begley[1,2], J. L. Neu[23], M. Osman[29], M. Palm[6], H. Petetin[4], I. Petropavlovskikh[1,2], R. Querel[28], N. Rahpoe[23], A. Rozanov[23], M. G. Schultz[31,32], J. Schwab[33], R. Siddans[22], D. Smale[20], M. Steinbacher[34], H. Tanimoto[35], D. W. Tarasick[36], V. Thouret[4], A. M. Thompson[37], T. Trickl[38], E. Weatherhead[1,2], C. Wespes[39], H. M. Worden[40], C. Vigouroux[40], X. Xu[41], G. Zeng[30], J. Ziemke[42]

ELEMENTA Science of the Anthropocene

Tarasick, D, et al. 2019. Tropospheric Ozone Assessment Report: Tropospheric ozone from 1877 to 2016, observed levels, trends and uncertainties. *Elem Sci Anth*, 7: 39. DOI: https://doi.org/10.1525/elementa.376

REVIEW

Tropospheric Ozone Assessment Report: Tropospheric ozone from 1877 to 2016, observed levels, trends and uncertainties

David Tarasick[*], Ian E. Galbally[†,‡], Owen R. Cooper[§,‖], Martin G. Schultz[¶], Gerard Ancellet[**], Thierry Leblanc[††], Timothy J. Wallington[‡‡], Jerry Ziemke[§§], Xiong L… Martin Steinbacher[¶¶], Johannes Staehelin[***], Corinne Vigouroux[†††], James W. Hanniga… Omaira García[§§§], Gilles Foret[‖‖‖], Prodromos Zanis[¶¶¶], Elizabeth Weatherhead[§,‖], Irina Petropavlovskikh[§,‖], Helen Worden[‡‡‡], Mohammed Osman[****,†††††,‡‡‡‡], Jane Liu[§§§§,‖‖‖‖], Kai-Lan Chang[§,‖], Audrey Gaudel[§,‖], Meiyun Lin[¶¶¶¶,*****], Maria Granados-Muñoz[†††††], Anne M. Thompson[§§], Samuel J. Oltmans[‡‡‡‡], Juan Cuesta[‖‖‖], Gaelle Dufour[‖‖‖], Valerie Thouret[§§§§§], Birgit Hassler[‖‖‖‖‖], Thomas Trickl[¶¶¶¶¶] and Jessica L. Neu[******]

ELEMENTA Science of the Anthropocene

Fleming, ZL, et al. 2018 Tropospheric Ozone Assessment Report: Present-day ozone distribution and trends relevant to human health. *Elem Sci Anth*, 6: 12. DOI: https://doi.org/10.1525/elementa.273

RESEARCH ARTICLE

Tropospheric Ozone Assessment Report: Present-day ozone distribution and trends relevant to human health

Zoë L. Fleming[*], Ruth M. Doherty[†], Erika von Schneidemesser[‡], Christopher S. Malley[§,**,††,‡‡‡], Owen R. Cooper[‖,‖‖‖], Joseph P. Pinto[¶], Augustin Colette[**], Xiaobin Xu[††], David Simpson[‡‡,¶¶¶], Martin G. Schultz[§§,‖‖], Allen S. Lefohn[¶¶], Samera Hamad[***], Raeesa Moolla[†††], Sverre Solberg[‡‡‡] and Zhaozhong Feng[§§§]

ELEMENTA Science of the Anthropocene

Mills, G, et al. 2018. Tropospheric Ozone Assessment Report: Present-day tropospheric ozone distribution and trends relevant to vegetation. *Elem Sci Anth*, 6: 47. DOI: https://doi.org/10.1525/elementa.302

RESEARCH ARTICLE

Tropospheric Ozone Assessment Report: Present-day tropospheric ozone distribution and trends relevant to vegetation

Gina Mills[*,†], Håkan Pleijel[†], Christopher S. Malley[‡,§,‖], Baerbel Sinha[¶], Owen R. Cooper[**], Martin G. Schultz[††], Howard S. Neufeld[‡‡], David Simpson[§§,‖‖], Katrina Sharps[*], Zhaozhong Feng[¶¶], Giacomo Gerosa[***], Harry Harmens[*], Kazuhiko Kobayashi[†††], Pallavi Saxena[‡‡‡], Elena Paoletti[§§§], Vinayak Sinha[¶] and Xiaobin Xu[‖‖‖]

ELEMENTA Science of the Anthropocene

Chang, K-L, et al 2017 Regional trend analysis of surface ozone observations from monitoring networks in eastern North America, Europe and East Asia. *Elem Sci Anth*, 5: 50, DOI: https://doi.org/10.1525/elementa.243

RESEARCH ARTICLE

Regional trend analysis of surface ozone observations from monitoring networks in eastern North America, Europe and East Asia

Kai-Lan Chang[*], Irina Petropavlovskikh[*,†], Owen R. Cooper[*,†], Martin G. Schultz[‡] and Tao Wang[§]

Surface ozone is a greenhouse gas and pollutant detrimental to human health and crop and ecosystem productivity. The Tropospheric Ozone Assessment Report (TOAR) is designed to provide the research community with an up-to-date observation-based overview of tropospheric ozone's global distribution and trends. The TOAR Surface Ozone Database contains ozone metrics at thousands of monitoring sites

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ELEMENTA Science of the Anthropocene

Xu, X, et al. 2020. Long-term changes of regional ozone in China: implications for human health and ecosystem impacts. *Elem Sci Anth*, 8: 13. DOI: https://doi.org/10.1525/elementa.409

RESEARCH ARTICLE

Long-term changes of regional ozone in China: implications for human health and ecosystem impacts

Xiaobin Xu[*], Weili Lin[†,‡], Wanyun Xu[*], Junli Jin[†], Ying Wang[*], Gen Zhang[*], Xiaochun Zhang[†], Zhiqiang Ma[§], Yuanzhen Dong[‖], Qianli Ma[¶], Dajiang Yu[**], Zou Li[††], Dingding Wang[‡‡] and Huarong Zhao[§§]

TOAR-I 2014-2019

Tropospheric Ozone Assessment Report

co-chairs: Owen Cooper (NOAA) & Martin Schultz (FZJ)

Mission:
To provide the research community with an up-to-date scientific assessment of tropospheric ozone's global distribution and trends from the surface to the tropopause.

Deliverables:

1) The first tropospheric ozone assessment report based on all available surface observations, the peer-reviewed literature and new analyses.
2) A database containing ozone exposure metrics at thousands of measurement sites around the world, freely accessible for research on the global-scale impact of ozone on climate, human health and crop/ecosystem productivity:
   https://toar-data.org/ → **hosted by Jülich Supercomputing Center at FZJ!**

Stakeholders:

TOAR-I Database key results

TOAR tropospheric ozone assessment report Phase II

The first global-scale view of all available surface ozone observations

98th percentile

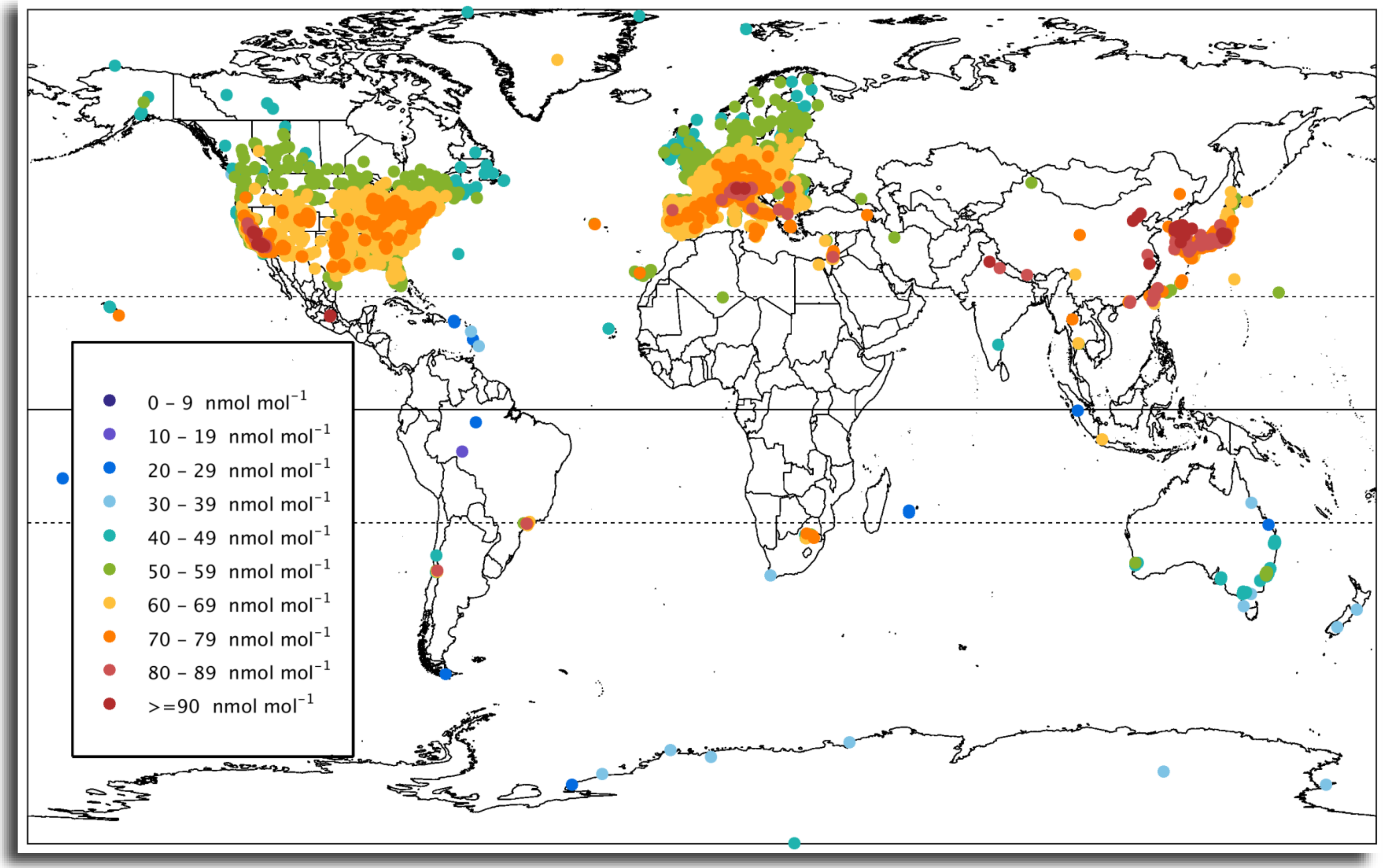
5-year average (2010-2014)

Summertime months

➔ surface O_3 data harmonization: world's largest database of surface ozone observations, with ozone metrics and trends calculated consistently for all time series

https://toar-data.org/

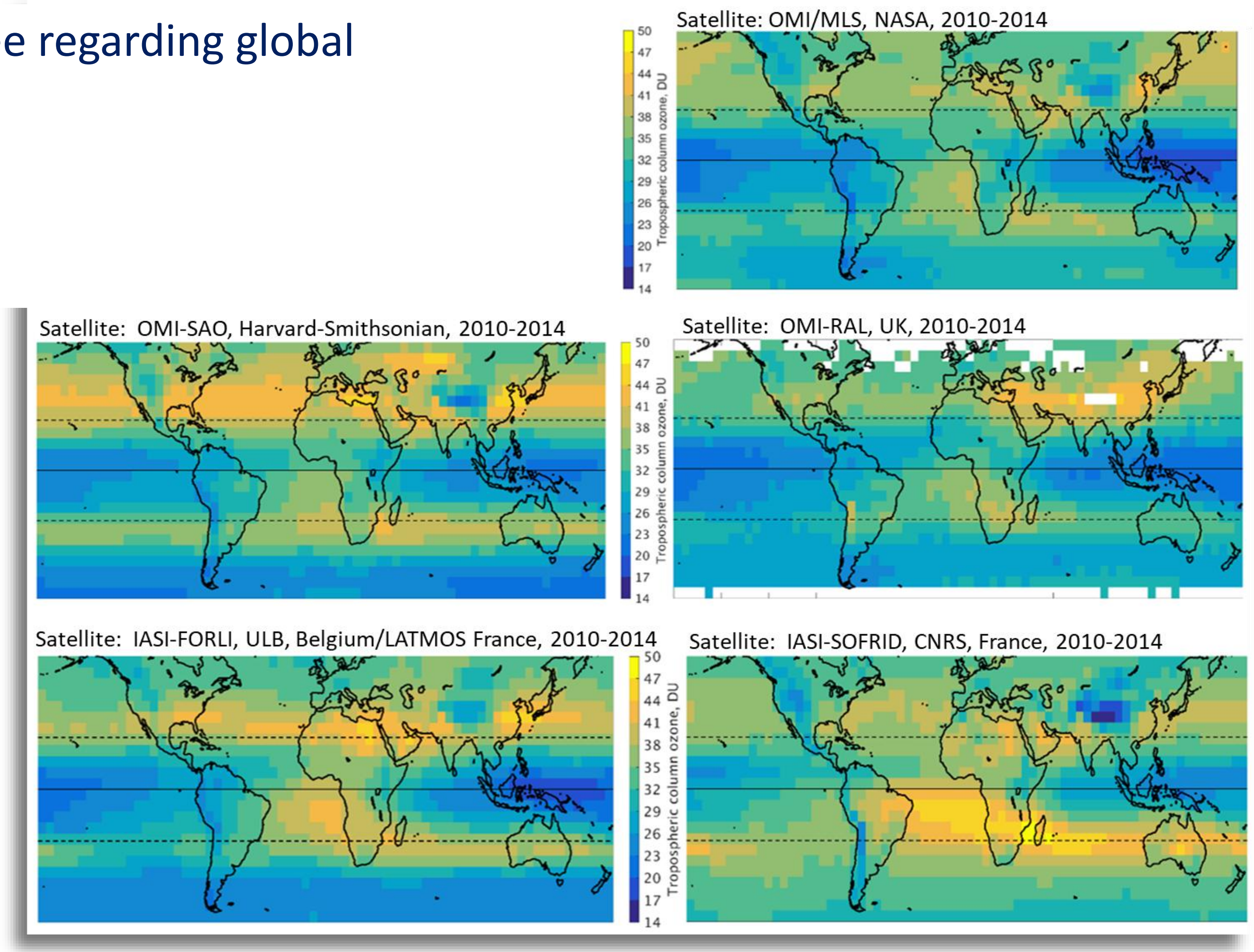
https://toar-data.fz-juelich.de/



TOAR-I key results

The first intercomparison of satellite ozone products

Satellite products generally agree regarding global tropospheric ozone hotspots.



TOAR-I key results

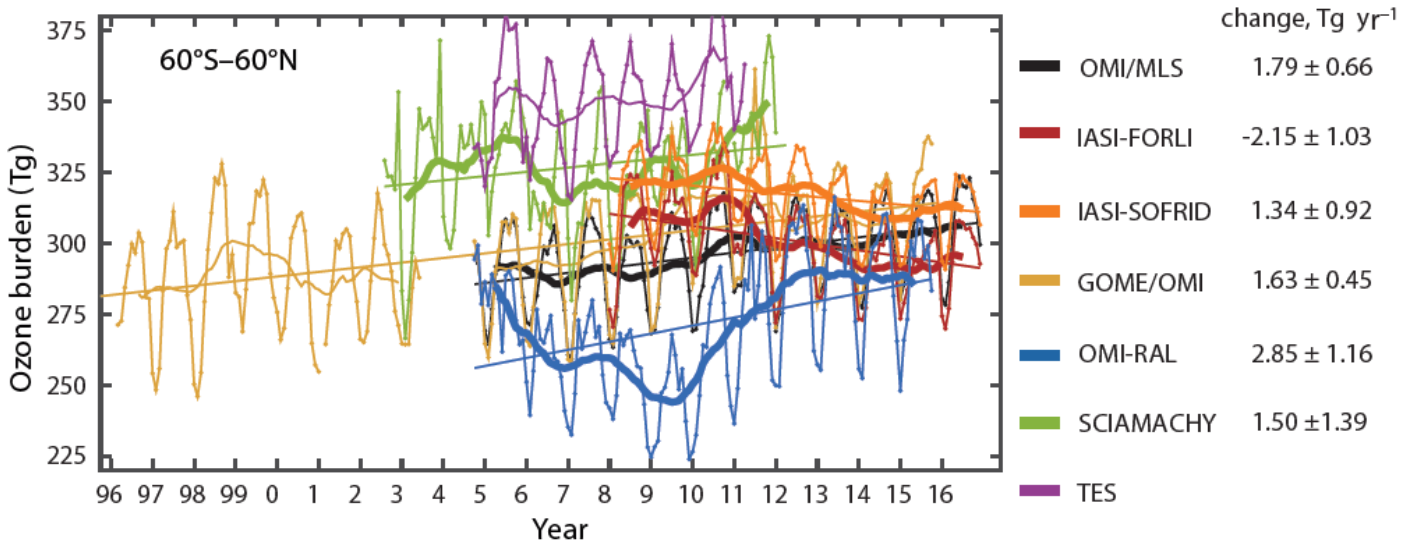
The first intercomparison of satellite ozone products

Satellite products generally agree regarding global tropospheric ozone hotspots.

Satellites and IPCC models report similar values for the tropospheric ozone burden.

However, the satellites disagree regarding trends over the past decade (2008-2016).

➔ TOAR-I identified major discrepancies among the ozone trends reported by different satellite products: TOAR-II Satellite Ozone working group.



➔ Tropospheric ozone trends from ground-based and in-situ techniques? TOAR-II GB working group

TOAR-II 2020-2026: Primary goals

Tropospheric Ozone Assessment Report, Phase II

co-chairs: Helen Worden (NCAR) & Martin Schultz (FZJ)

TOAR Database: Updated with all recent ozone observations worldwide; add ozone precursors and meteorological data.

Final Product: An observation-based assessment of tropospheric ozone's distribution and trends on regional, hemispheric and global scales

(modelled after IPCC Working Group I)

New

Impact studies: will quantify the ***impacts*** of ozone on human health, vegetation and climate

(modelled after IPCC Working Group II)

TOAR-II Focus Working Groups

New research is organized in independent **Focus Working Groups**:

- **Africa** Focus Working Group
- **Chemical Reanalysis** Focus Working Group
- **East Asia** Focus Working Group
- **Global and Regional Models** Focus Working Group
- **HEGIFTOM** Focus Working Group
- **Human Health Impacts of Ozone** Focus Working Group
- **Machine Learning for Tropospheric Ozone**
- **Ozone over the Oceans** Focus Working Group
- **Ozone and Precursors in the Tropics (OPT)** Focus Working Group
- **Ozone Deposition** Focus Working Group
- **Radiative Forcing** Focus Working Group
- **ROSTEES** Focus Working Group
- **Satellite Ozone** Focus Working Group
- **South Asia** Focus Working Group
- **Statistics** Focus Working Group
- **Tropospheric Ozone Precursors (TOP)** Focus Working Group
- **Urban Ozone** Focus Working Group

TOAR-II Community Special Issue

- Focus Working Group findings submitted to the **Community Special Issue** before 30 Nov 2024 = inter-journal special issue hosted by **Copernicus** https://acp.copernicus.org/articles/special_issue1256.html
- Papers from this community SI (and others) will feed the TOAR-II Assessment Papers:

Health, Climate, Vegetation, STE,

Satellite, S. America, Africa,

Oceans

TOAR-II Focus Working Groups

New research is organized in 17 independent **Focus Working Groups**:

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TOAR-II Focus Working Group HEGIFTOM

Harmonization and Evaluation of Ground-based Instruments for Free Tropospheric Ozone Measurements, *chairs: Herman Smit & Roeland Van Malderen*

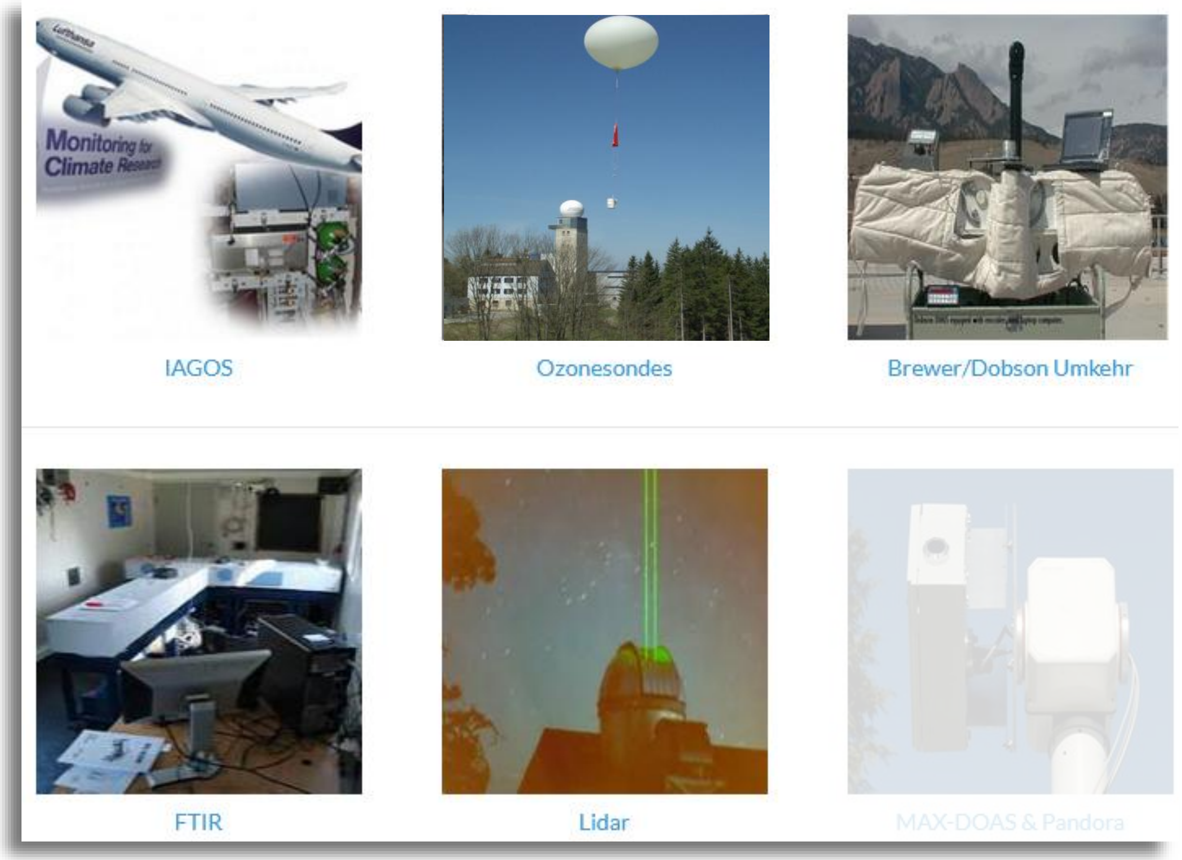
Key Objective:

Evaluation and harmonization of the different free tropospheric ozone profiling datasets of the established measuring platforms (in-service aircraft, ozonesondes, Brewer/Dobson Umkehr, FTIR, Lidar).

Major Deliverables:

- ***Quality assessed*** ozone data sets, whereby each measurement gets also an ***uncertainty*** and a ***quality flag***.
- Thereby, ***representativeness*** and ***instrumental drifts*** will be characterized and evaluated.
- Assessment of tropospheric ozone trends.

- ~~Testing ozone retrievals from new remote sensing techniques (MAX-DOAS, Pandora) against the established techniques.~~



http://hegiftom.meteo.be/datasets

HEGIFTOM: Homogenized datasets - internal consistency

Achievements and updates:

- **IAGOS**:
  - internal consistency paper published in AMT (Blot et al., https://doi.org/10.5194/amt-14-3935-2021),
  - simulation chamber comparison of IAGOS-CORE UV-photometer and reference photometer for ozonesondes (Smit et al., 2025, *AMT*, TOAR-II SI, https://doi.org/10.5194/egusphere-2024-3760)
- **Lidar**: TMF data has been updated with new data processor, OHP will follow
- **FTIR:** flagging applied to the NDACC data
- **Brewer/Dobson Umkehr**:
  - 6 Dobson Umkehr sites have been homogenized (Petropavlovskikh et al., https://doi.org/10.5194/amt-15-1849-2022)
  - Updated uncertainty estimation of the retrievals.
- **ozonesondes**:
  - 12 more sites homogenized, e.g. OHP, Lauder, Arctic sites (10-15/55 remaining)
  - homogenized data available on ftp-server

HEGIFTOM: Homogenized datasets

Deliverable: Homogenized free tropospheric ozone profile data, described at HEGIFTOM website, with same template for each dataset:

Availability

location (ftp, data archive, website, doi, e-mail address contact person, etc.).

Data field description

Measured data fields (and their units), incl. auxiliary data fields, available metadata. Data format

Description of homogenization procedure

short description of the steps taken to make the dataset (more) homogeneous within the network.

Data management

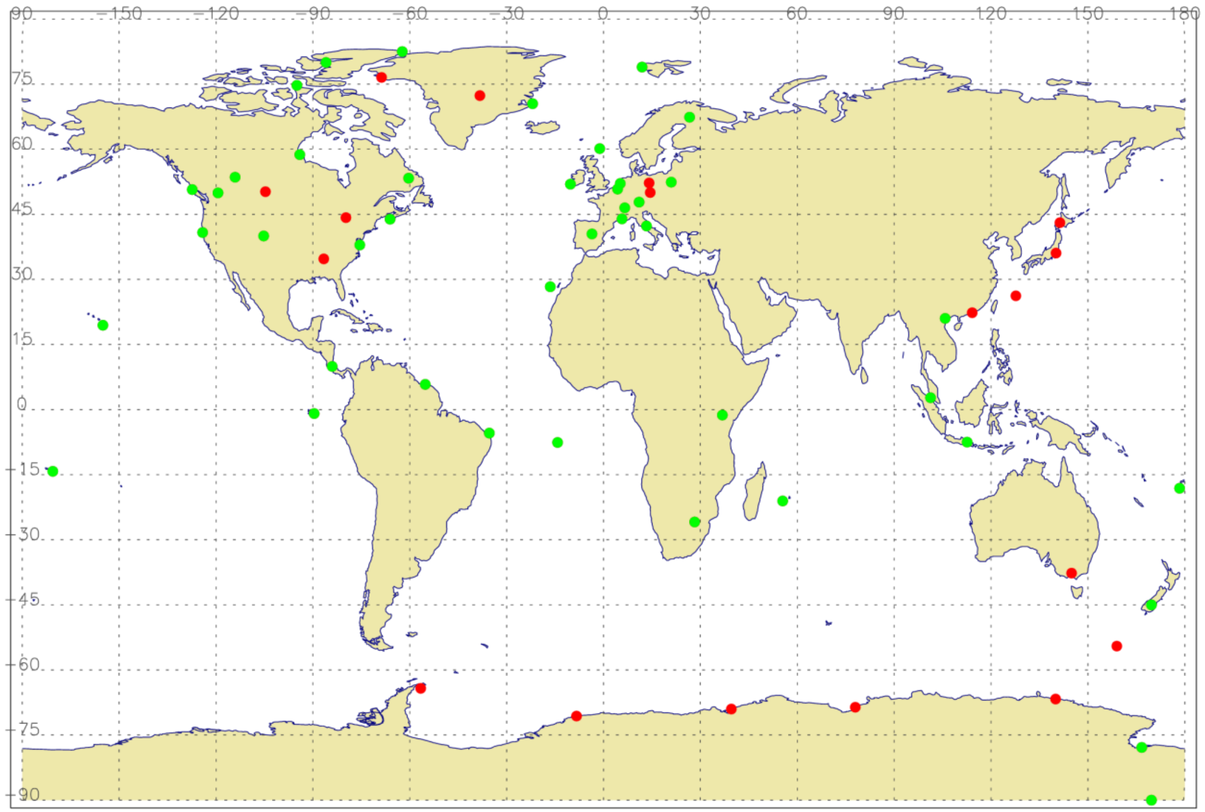
- *Flagging*
- *Uncertainties*
- *Traceability*
- *Internal consistency*
- *External consistency*
- *Data quality indicators*
- *List of homogenized sites (name, geographical location, period of observations)*

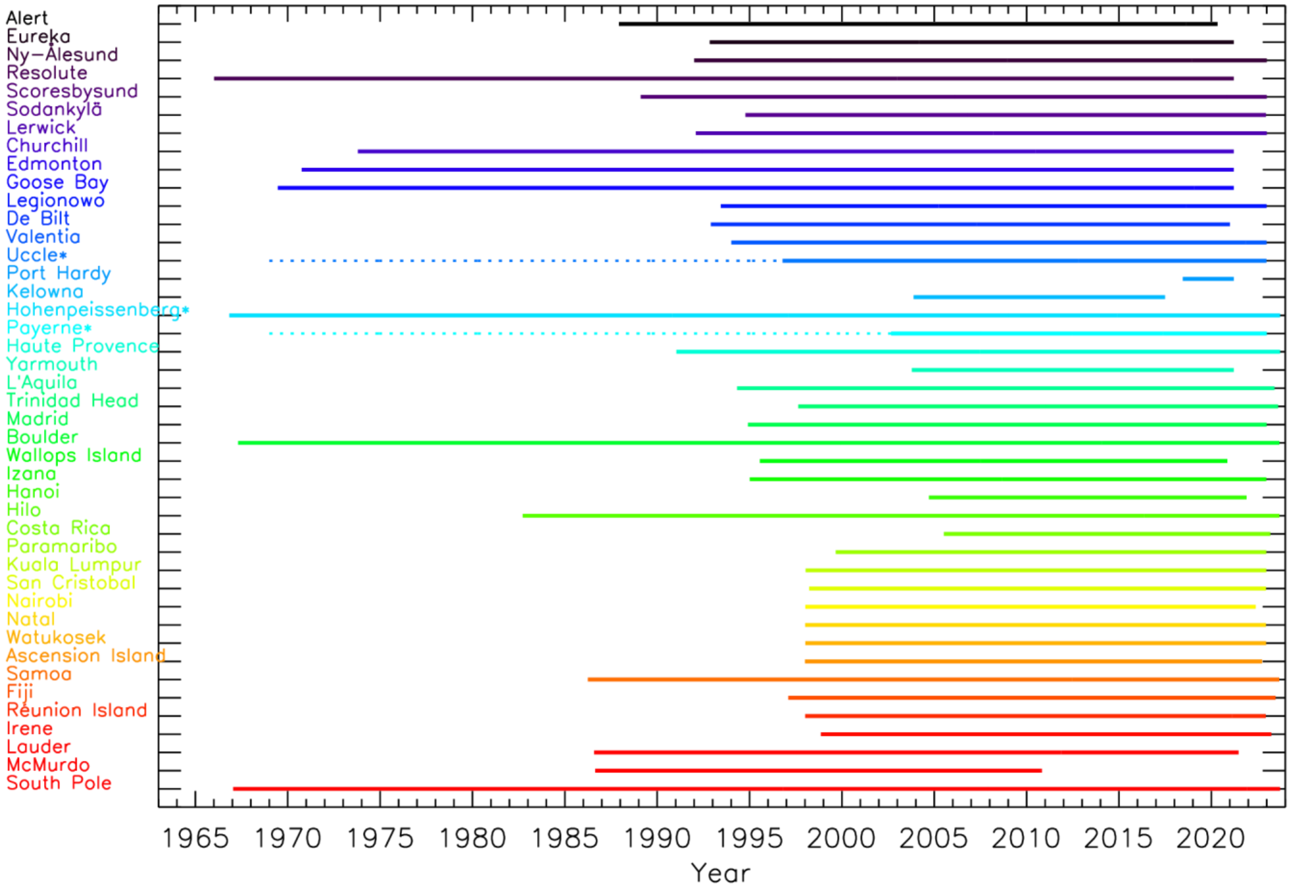
https://hegiftom.meteo.be/datasets

HEGIFTOM: Homogenized datasets

TOAR tropospheric ozone assessment report Phase II

Ozonesondes





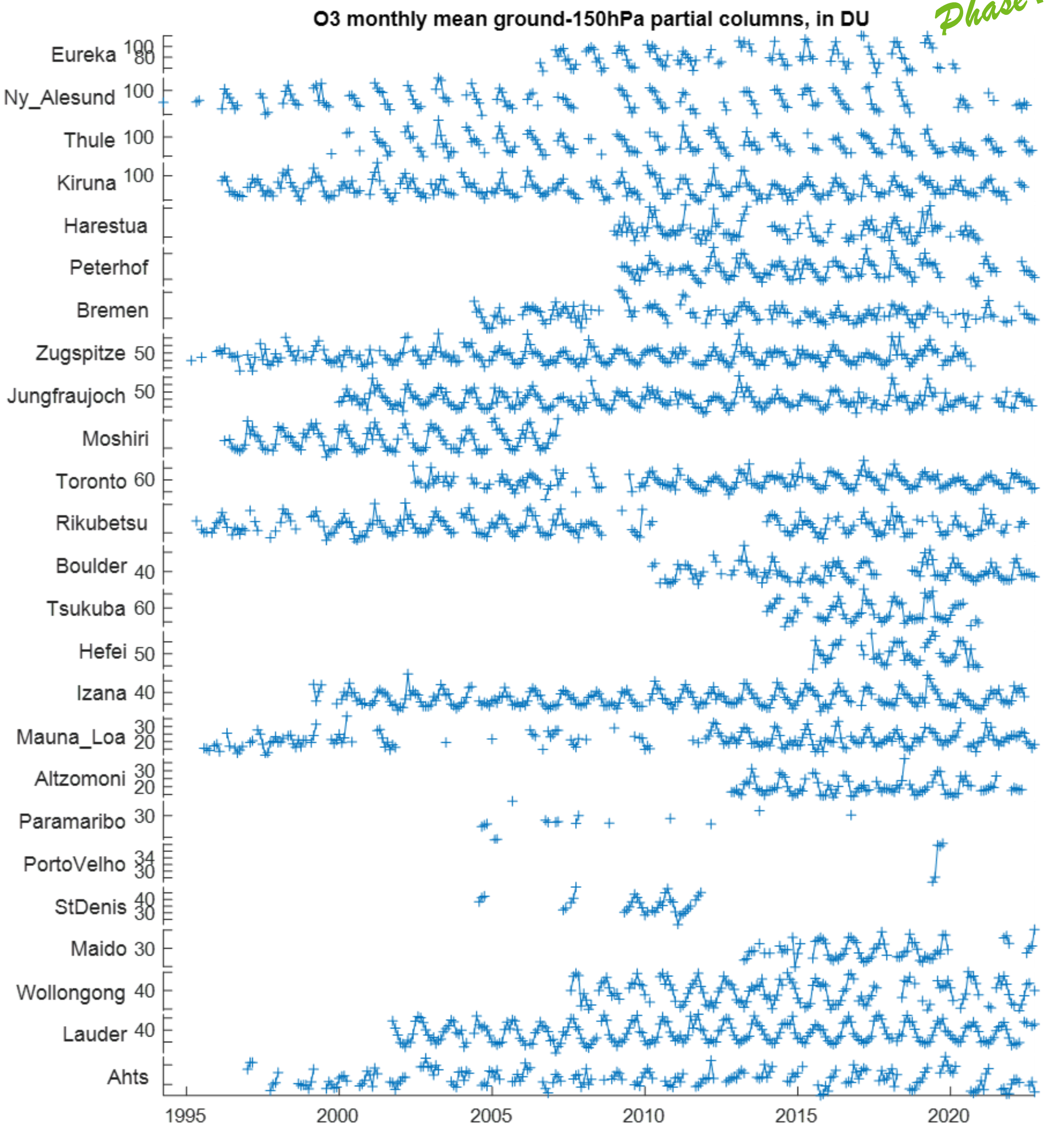
- 43 sites (green dots) with homogenized ozone profile data
- Profile data available at ftp-server

https://hegiftom.meteo.be/datasets/ozonesondes

HEGIFTOM: Homogenized datasets

TOAR
tropospheric ozone assessment report
Phase II

FTIR

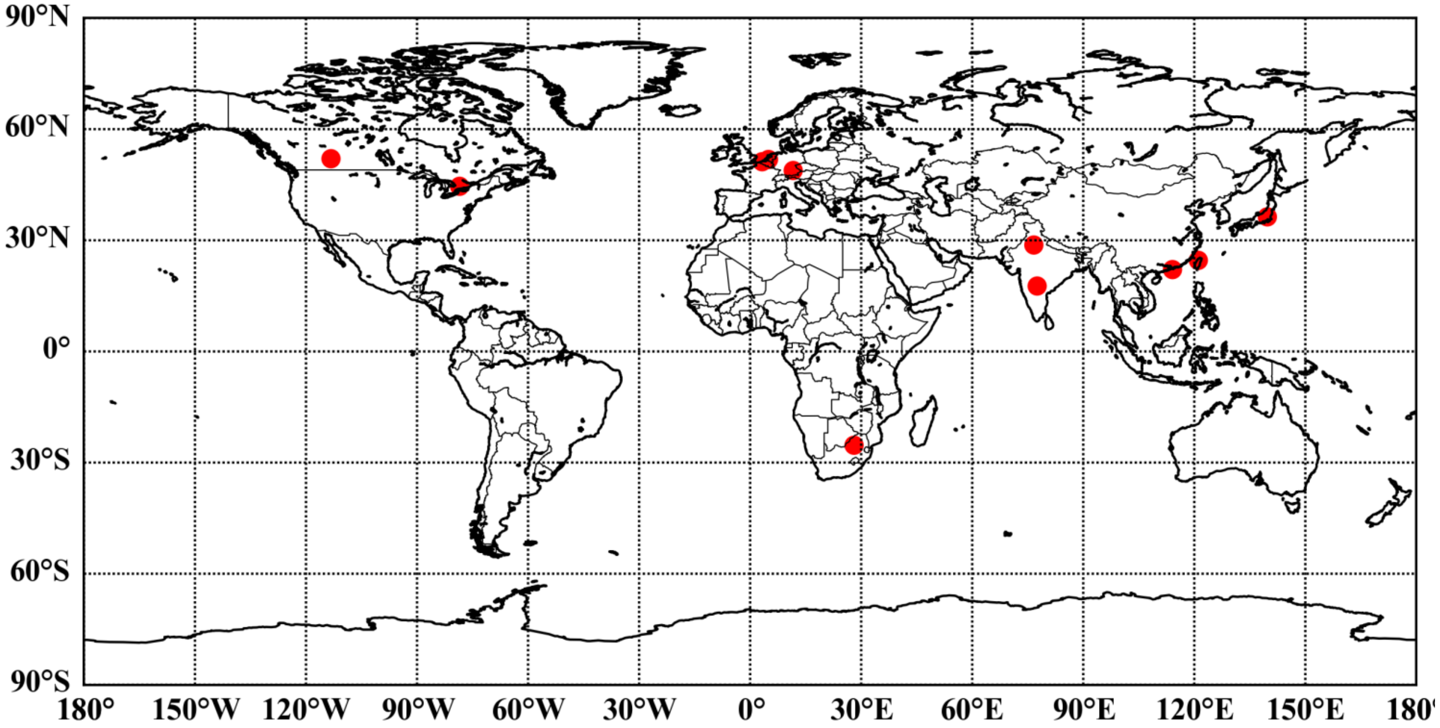


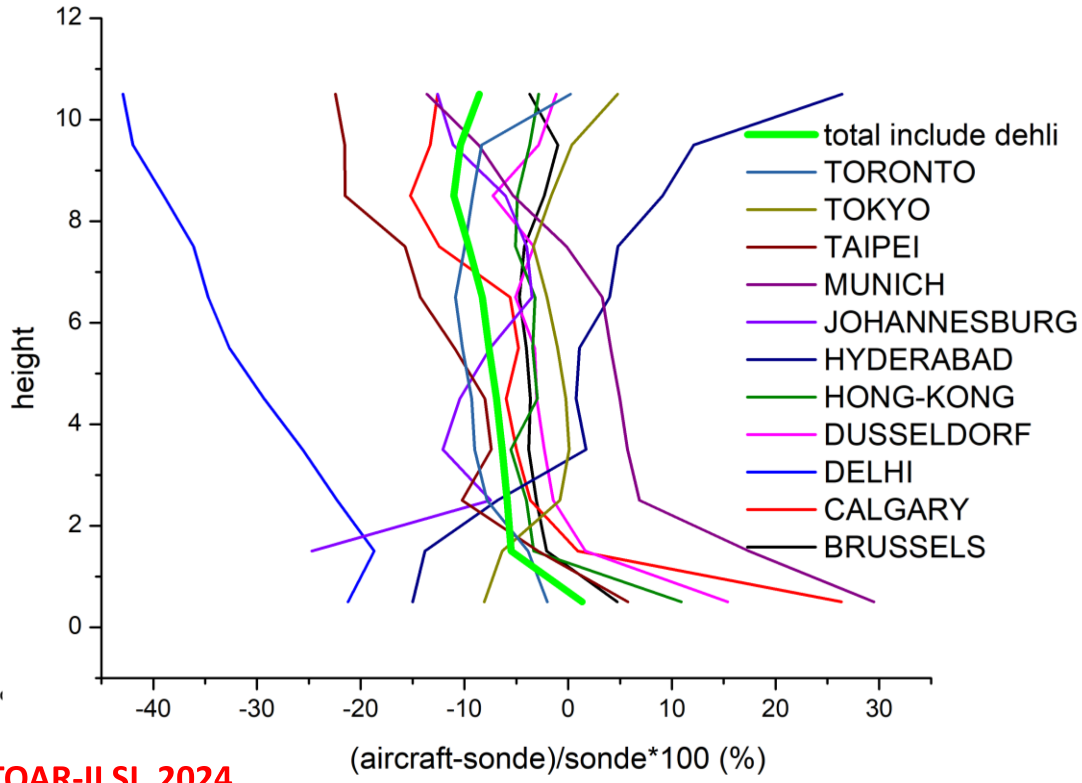
https://hegiftom.meteo.be/datasets/ftir

- 25 sites (22 active in O_3) providing O_3 data. See NDACC Infrared WG: https://www2.acom.ucar.edu/irwg
- Oldest date back to the mid 90s, most since mid 2000s
- Those sites also provide CO/HCHO

HEGIFTOM: Intercomparisons (external consistency)

- **Deliverable:** TOAR-II Intercomparison Guidelines for Observations of Tropospheric Column Ozone and Tropospheric Ozone Profiles (https://igacproject.org/sites/default/files/2022-03/TOAR-II_Guidelines_for_TCO_and_Profile_Intercomparisons.pdf)
- **IAGOS aircraft vs. ozonesonde profiles** at 11 stations





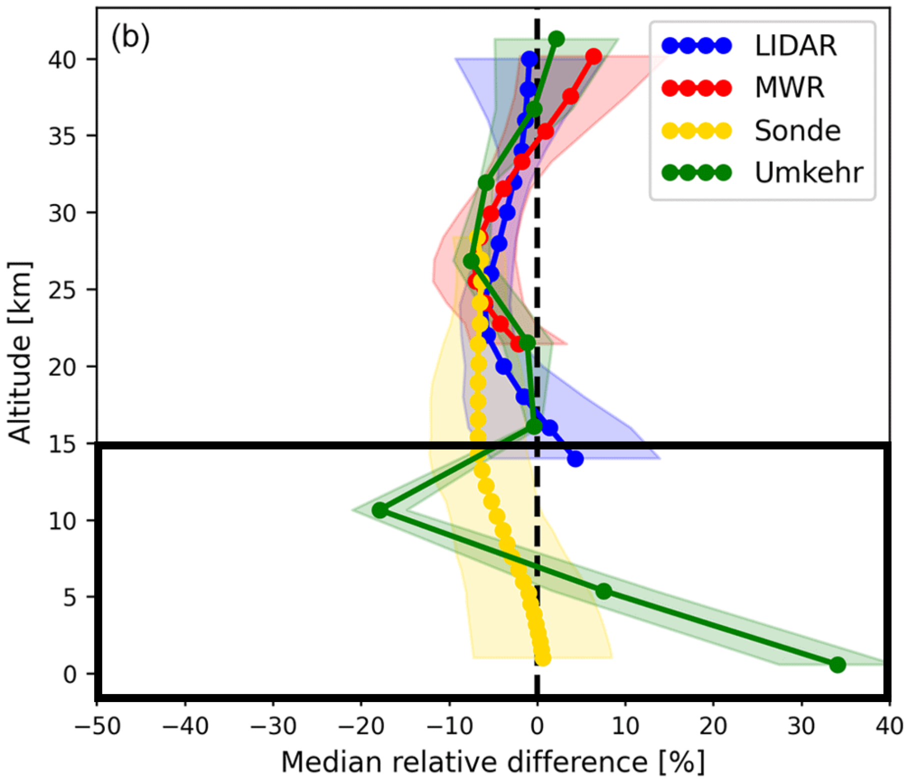
Wang et al., *ACP*, TOAR-II SI, 2024

HEGIFTOM: Intercomparisons (external consistency)

Intercomparisons: comparison of (tropospheric) ozone retrievals from different ground-based instruments at dedicated sites

Lauder (New Zealand)

Reference: FTIR



Björklund et al., *AMT*, TOAR-II SI, 2024

HEGIFTOM: Tropospheric ozone columns (TrOC)

Deliverable: time series of different (partial) tropospheric ozone column amounts

1. P > P_TP (WMO)
2. P > P (lat) (e.g. 150 hPa @ tropics, 400 hPa in polar regions)
3. P > 300 hPa
4. FT: 4 < h < 8 km AND 700 hPa > P > 300 hPa
5. LT: h < 4 km AND P > 700 hPa
6. BL: h < 2 km

the 2 recommended TOAR-II tropospheric ozone column definitions

- for all sites/techniques, if feasible
- provided for all measurements (**L1**), together with daily means (**L2**) and monthly means (**L3**)
- available in DU or ppb
- uncertainties included (random, systematic, total, statistical)
- simple csv files, with readme files per technique

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

HEGIFTOM: Tropospheric ozone columns (TrOC)

TOAR tropospheric ozone assessment report Phase II

Deliverable: time series of different (partial) tropospheric ozone column amounts

1. P > P_TP (WMO)
2. P > P (lat) (e.g. 150 hPa @ tropics, 400 hPa in polar regions)
3. P > 300 hPa ← **HERE!**
4. FT: 4 < h < 8 km AND 700 hPa > P > 300 hPa
5. LT: h < 4 km AND P > 700 hPa
6. BL: h < 2 km

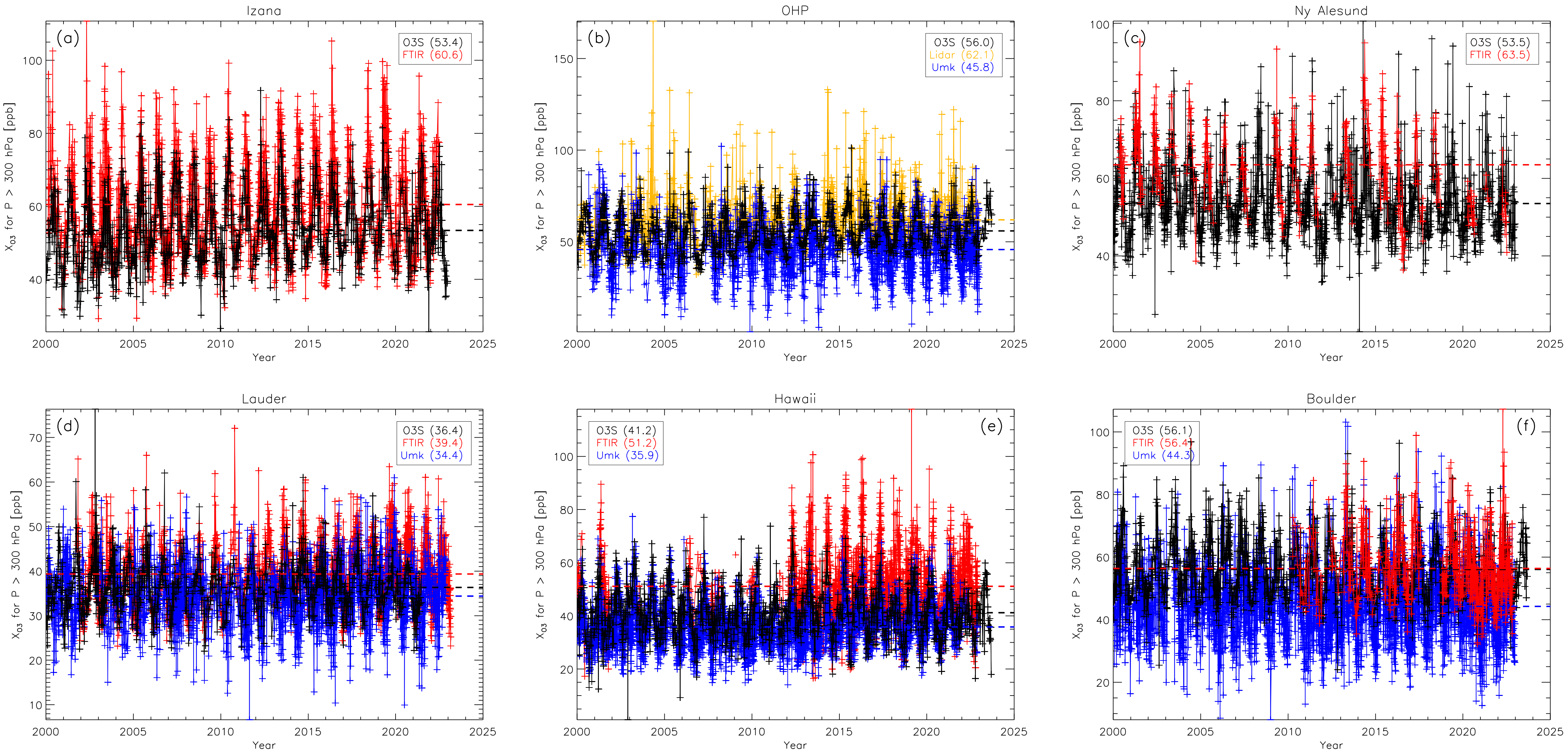
(1–2:) the 2 recommended TOAR-II tropospheric ozone column definitions

- for all sites/techniques, if feasible
- provided for all measurements (**L1**), together with daily means (**L2**) and monthly means (**L3**)
- available in DU or ppb
- uncertainties included (random, systematic, total, statistical)
- simple csv files, with readme files per technique

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

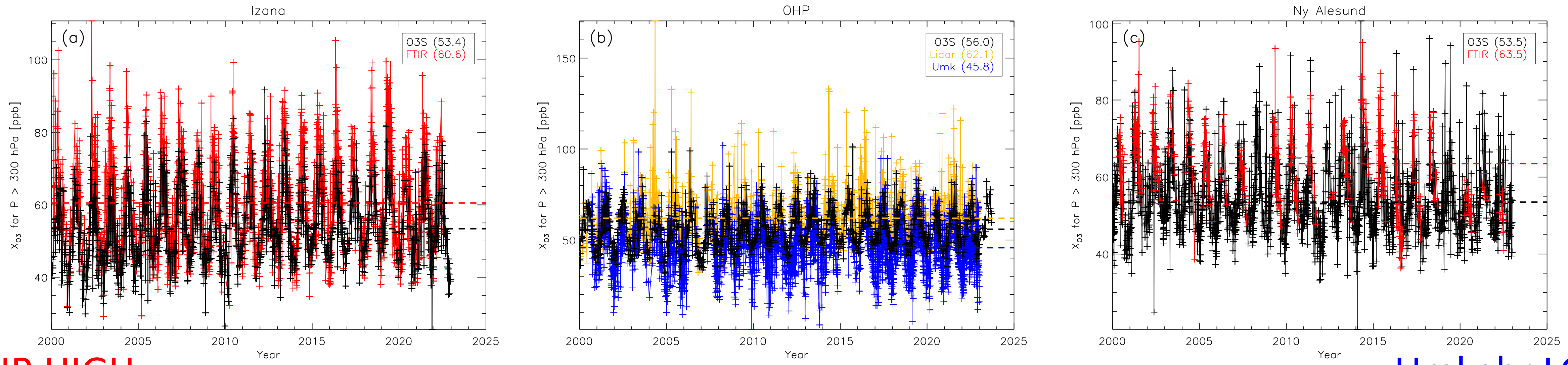
HEGIFTOM: TrOC intercomparisons at collocated sites

Daily means



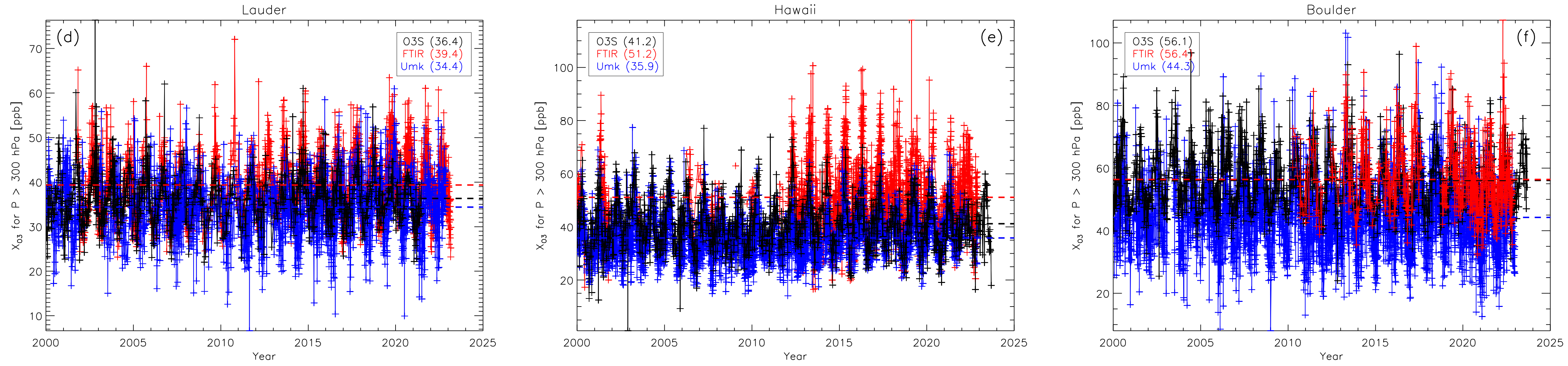
HEGIFTOM: TrOC intercomparisons at collocated sites

Daily means



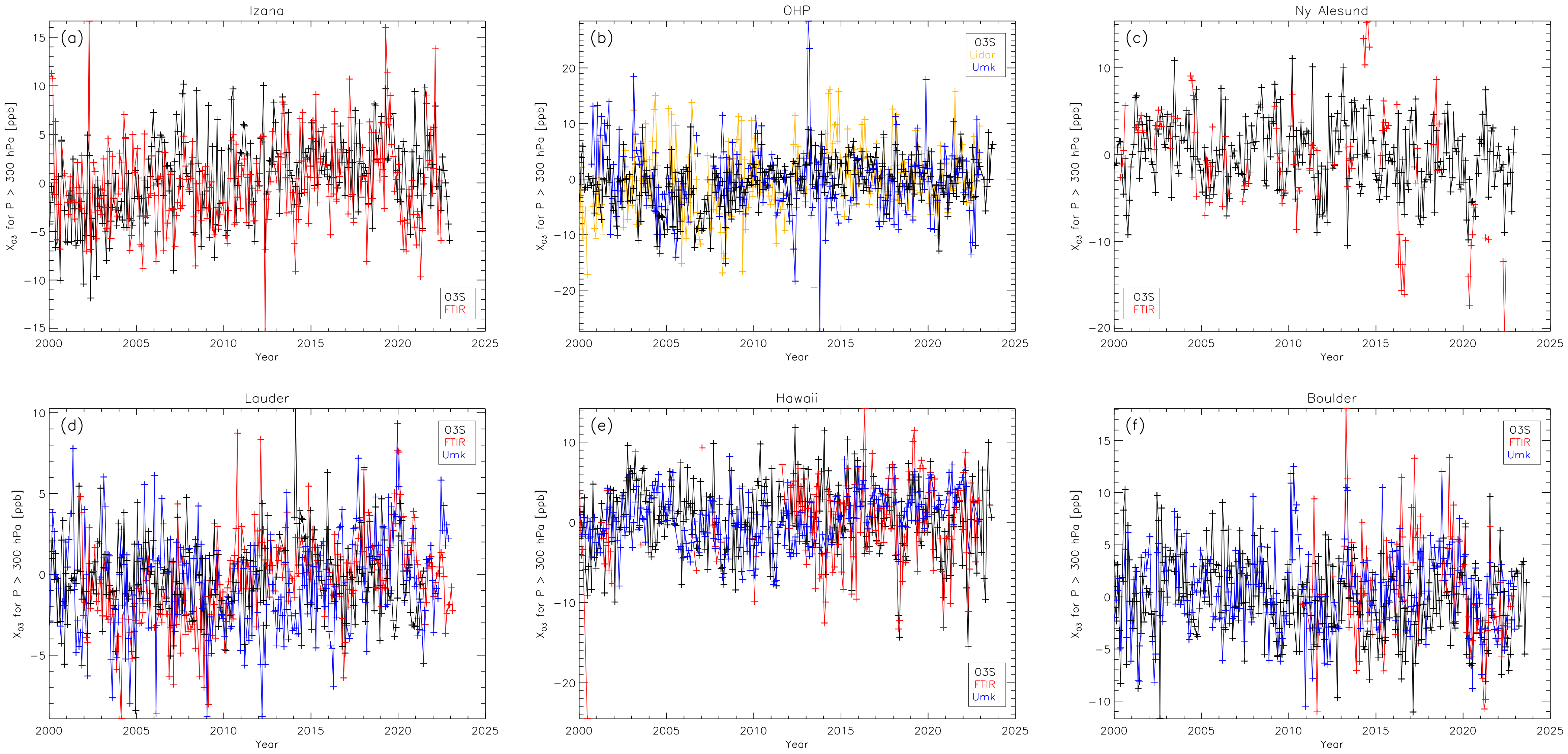
FTIR HIGH

Umkehr LOW



HEGIFTOM: TrOC intercomparisons at collocated sites

Monthly anomalies ➔ TRENDS

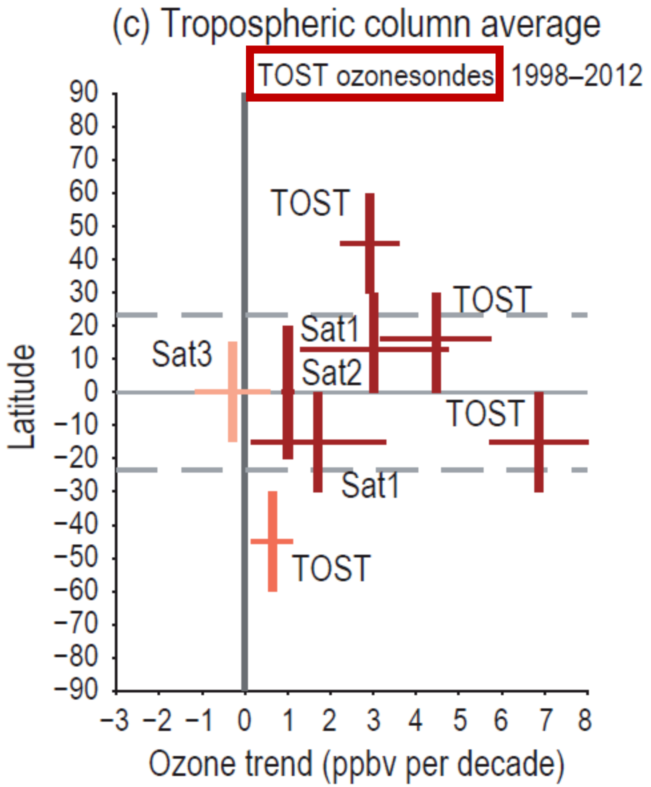


HEGIFTOM: Tropospheric ozone column trends

- TOAR-II: tropospheric ozone **trends** assessment
- In literature:

TOST = Trajectory-mapped Ozonesonde dataset for the Stratosphere and Troposphere

(Wang et al., ACP, TOAR-II SI, 2024)



Satellite products:
Sat1 1979–2016 (TOMS, OMI/MLS)
Sat2 1995–2015 (GOME, SCIAMACHY, OMI, GOME-2A, GOME-2B)
Sat3 1995–2015 (GOME, SCIAMACHY, GOME-II)

Fig. 2.8 of IPCC AR6, 2021.

✓ **Here**: focus on high-quality **ground-based** and **in-situ** measurements (individual sites + "merged")

✓ Consistency in tropospheric ozone column metric (**here**: surface to 300 hPa)

✓ Consistency in used trend estimation tools (QR vs. MLR)

✓ Consistency in time ranges (here: 2000-2002 till 2019-2022)

✓ Consistency in units (ppbv/dec)

✓ Not only as function of latitude!

HEGIFTOM: Tropospheric ozone column trends

- TOAR-II: tropospheric ozone **trends** assessment
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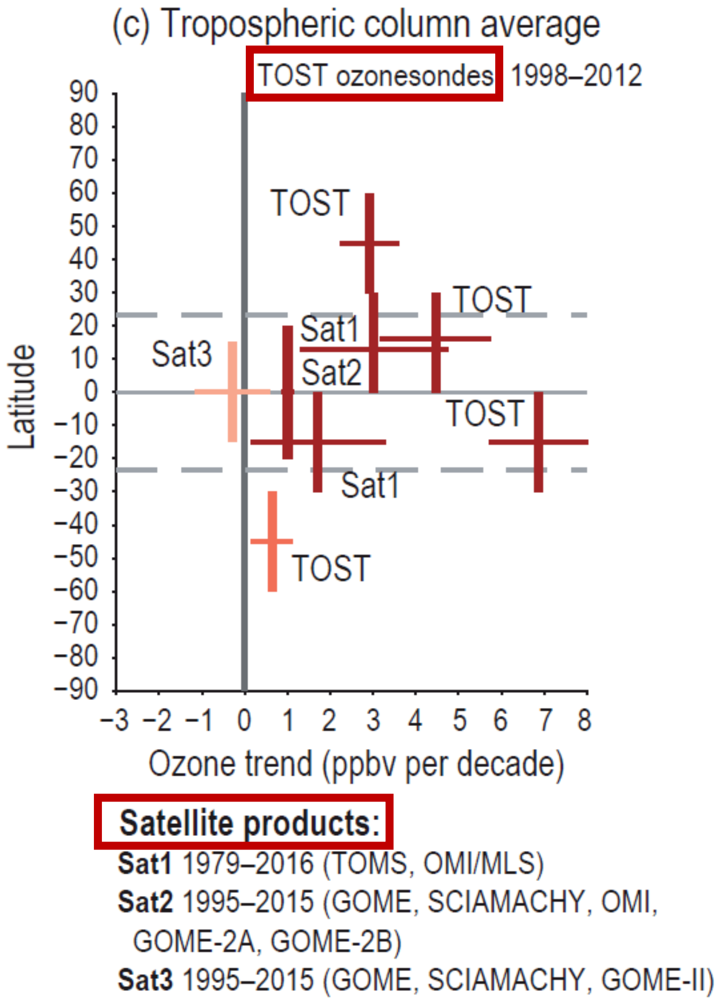

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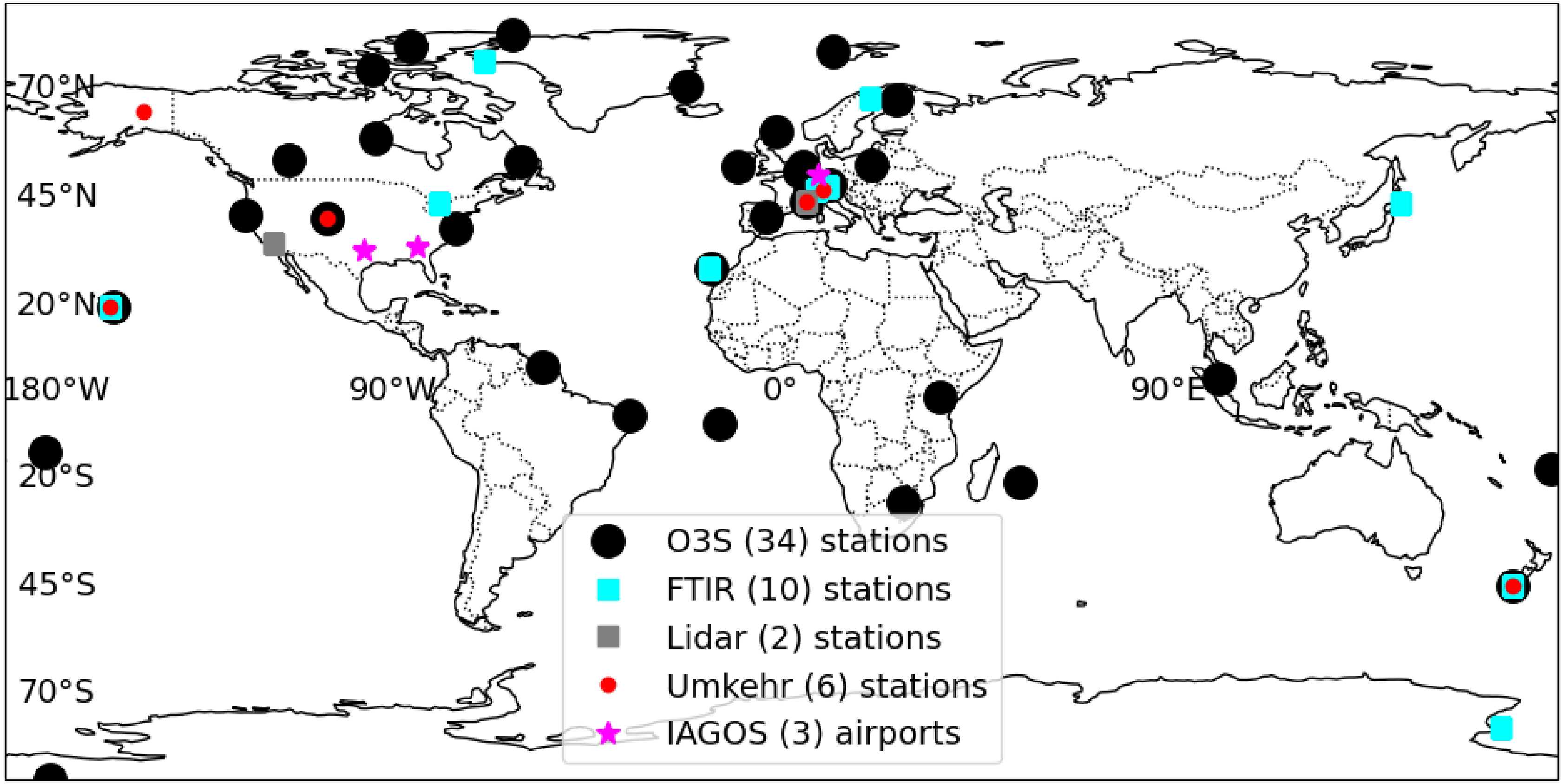
✓Not only as function of latitude!

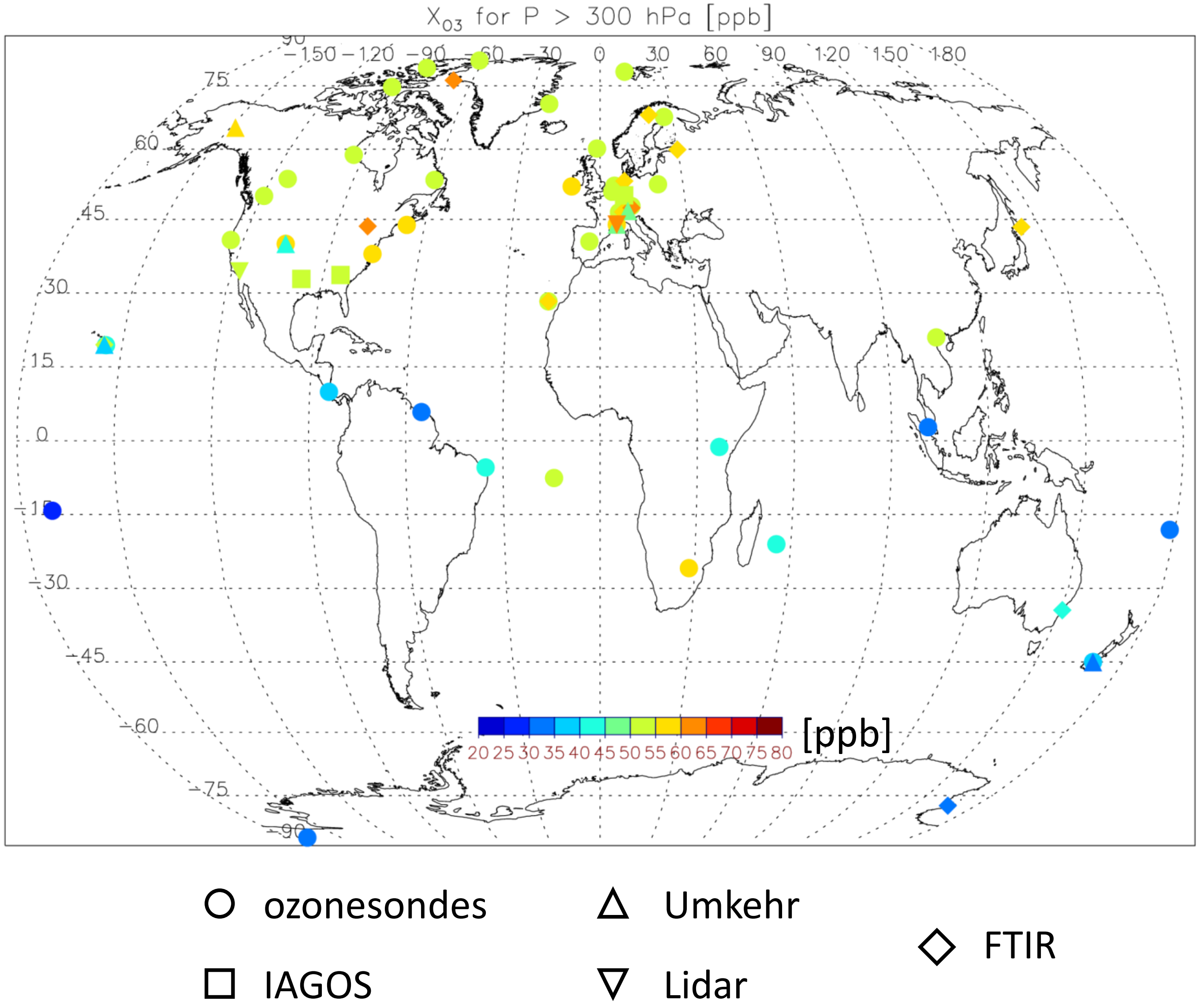
Individual site trends sample

Global Sites Contributing to HEGIFTOM (55 L1 Data) Trends



- Sampling (> 120 months of data) and gaps (2000+) put constraints
- 55 sites
- Some sites with different techniques (Boulder, Hawaii, Lauder, OHP, Ny Ålesund, Izaña, …) ➔ intercomparisons

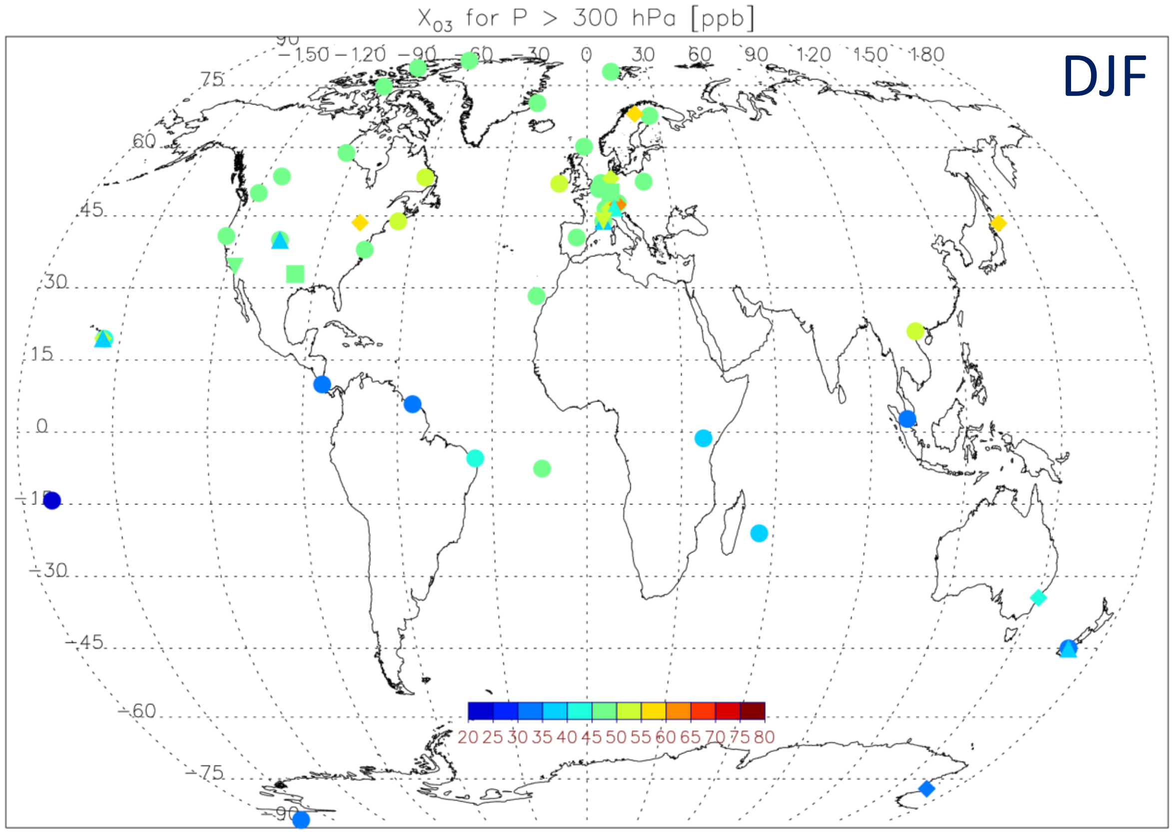
Tropospheric ozone column distribution

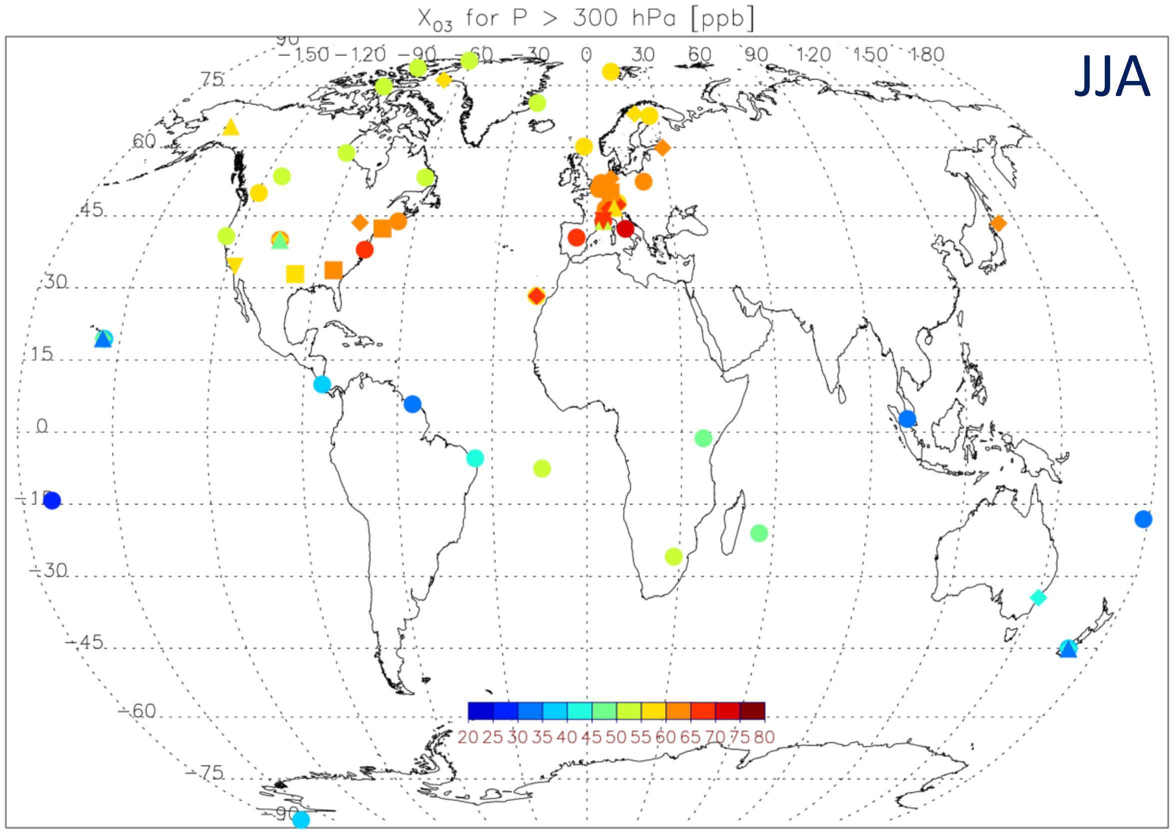


- Mean column-averaged tropospheric ozone distribution (TrOC) from **surface – 300 hPa** for **2000-2022**
- **Lowest**: tropics (< ±15°) and SH; **Highest**: NH (spring & summer!)
- **Reason**: ozone production from enhanced anthropogenic emissions in the NH and higher rates of stratospheric downwelling

Tropospheric ozone column distribution

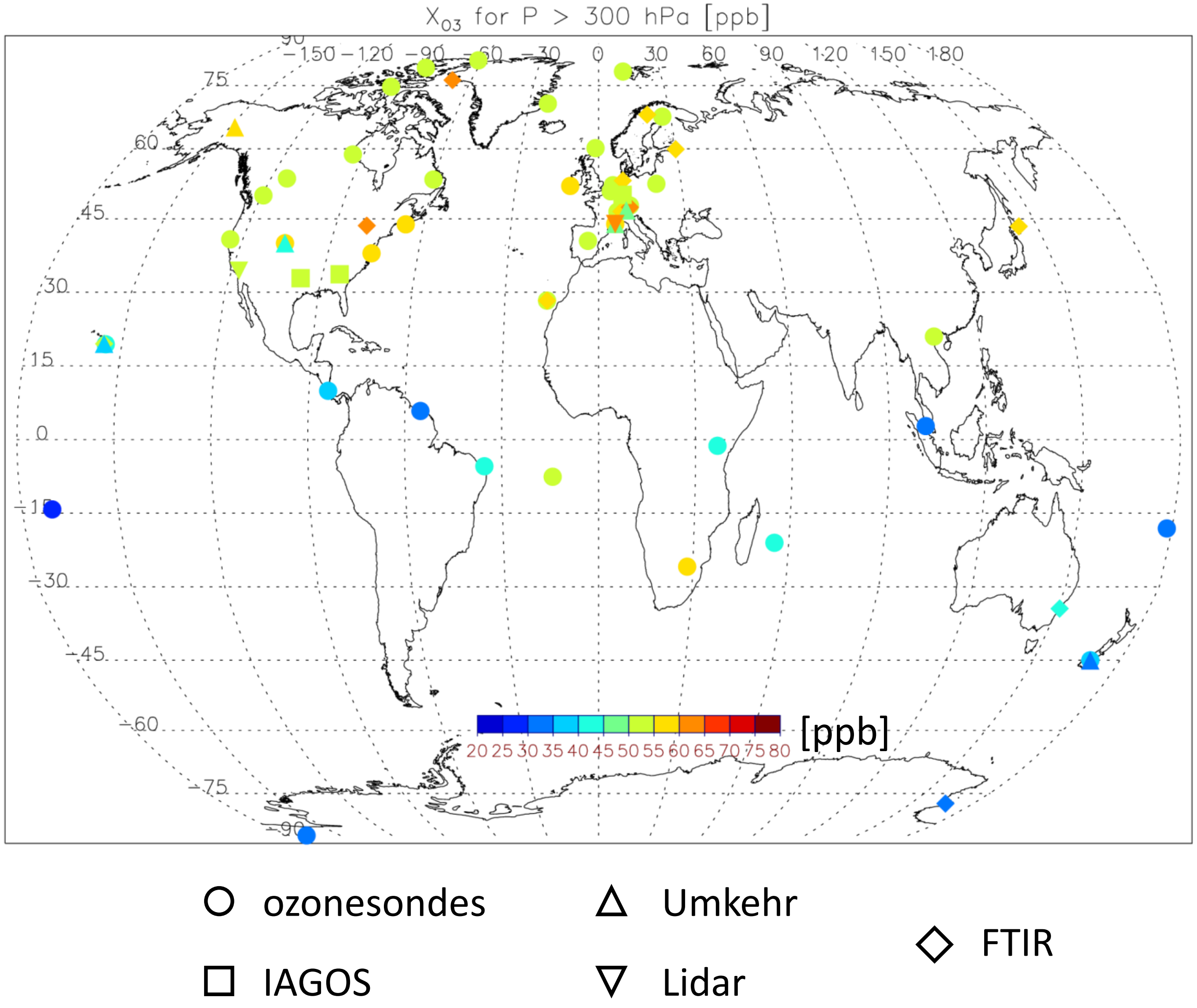
(mean) Tropospheric ozone column distribution: DJF vs. JJA





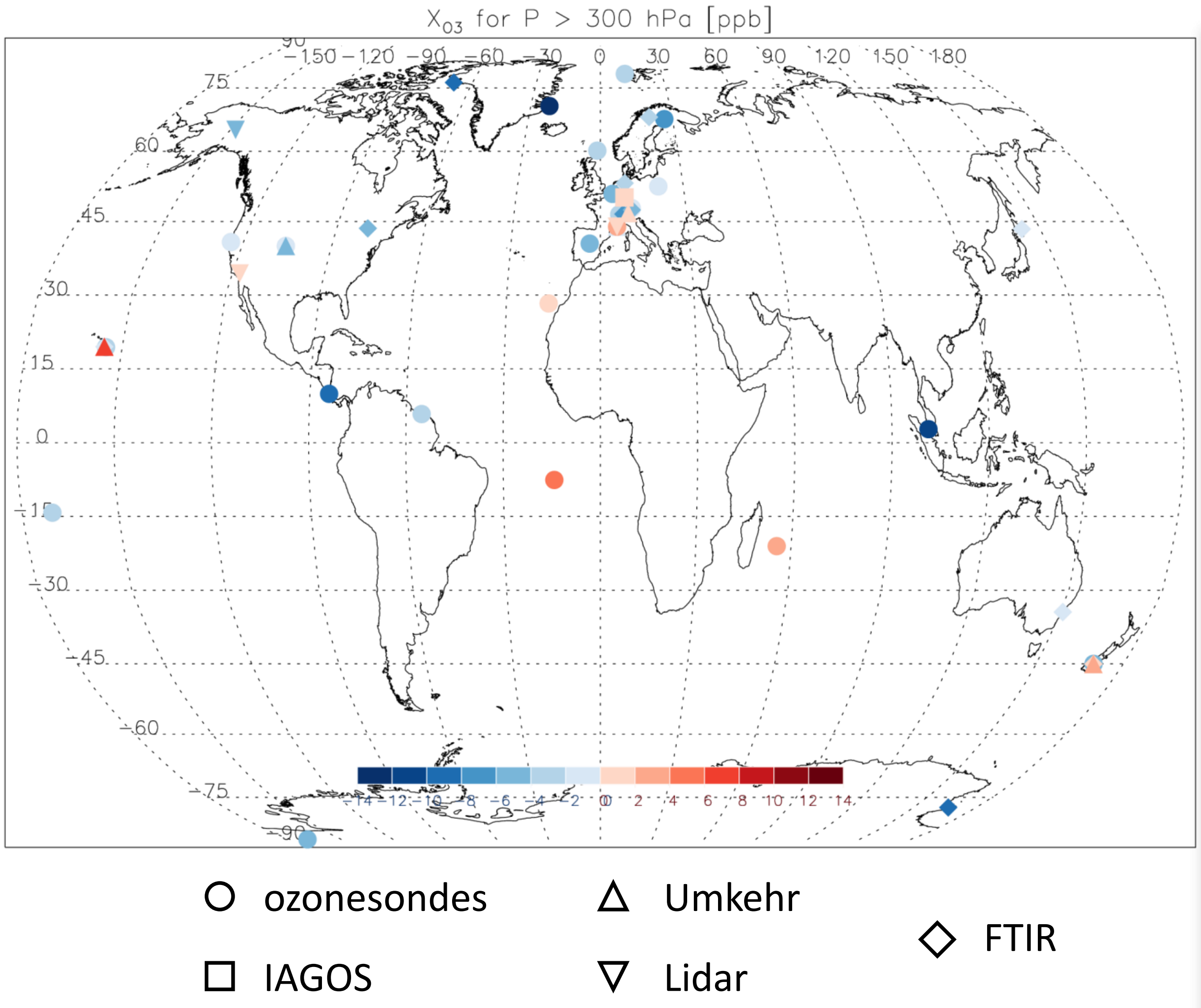
- Highest values in JJA in **NH**: peak photochemical production & summertime emission max of biogenic VOC ozone precursors
- >< **SH** (SON): STE & biomass burning

Tropospheric ozone column distribution



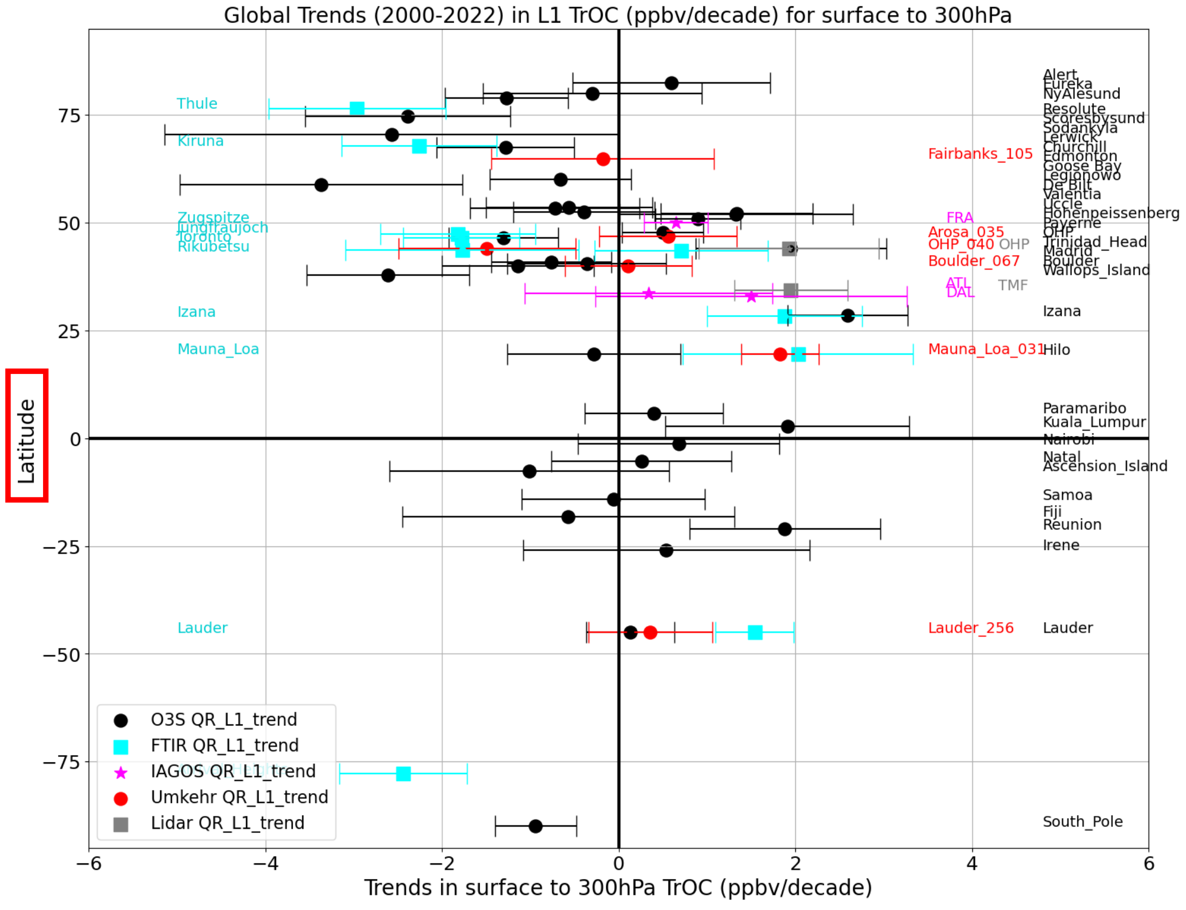
- Mean column-averaged tropospheric ozone distribution (TrOC) from **surface – 300 hPa** for **2000-2022**
- Now compare mean TrOC values for 2000 – 2019 vs. 2020 – 2022 (COVID-19 period)

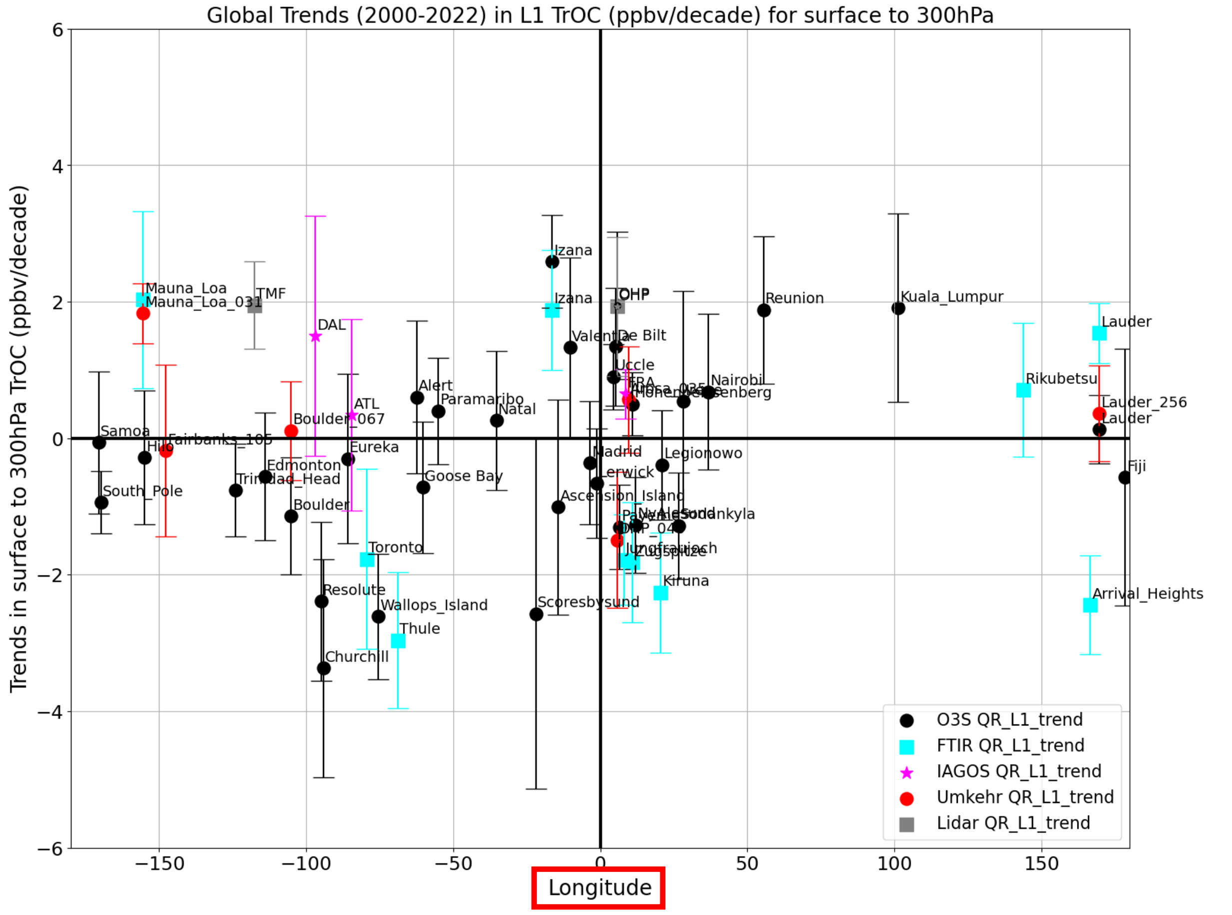
Tropospheric ozone column distribution: COVID impact



- **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)
- **Reason**: decreased emissions of ozone precursors (e.g. NO_2) due to COVID-19 lockdown restrictions
- Impact on trends!

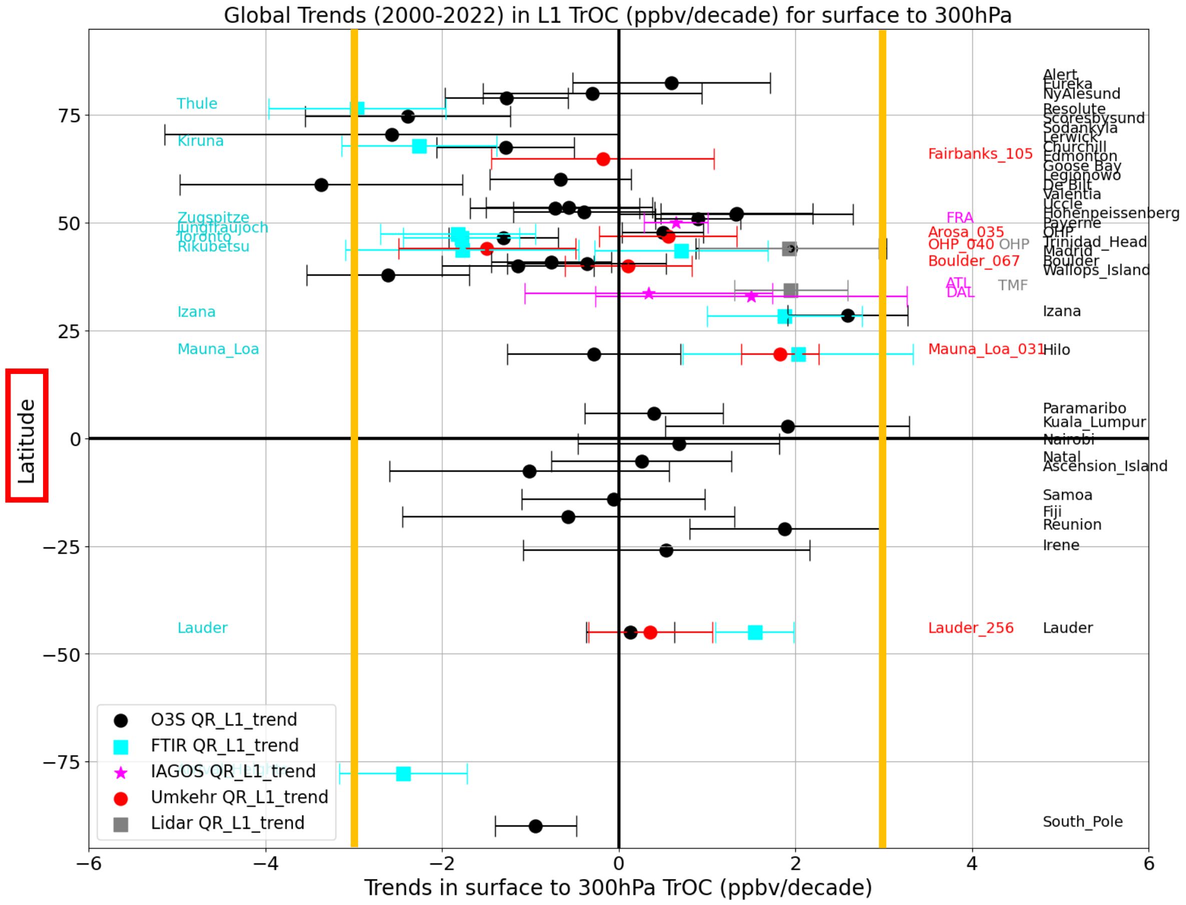
Individual site trends: QR median trends

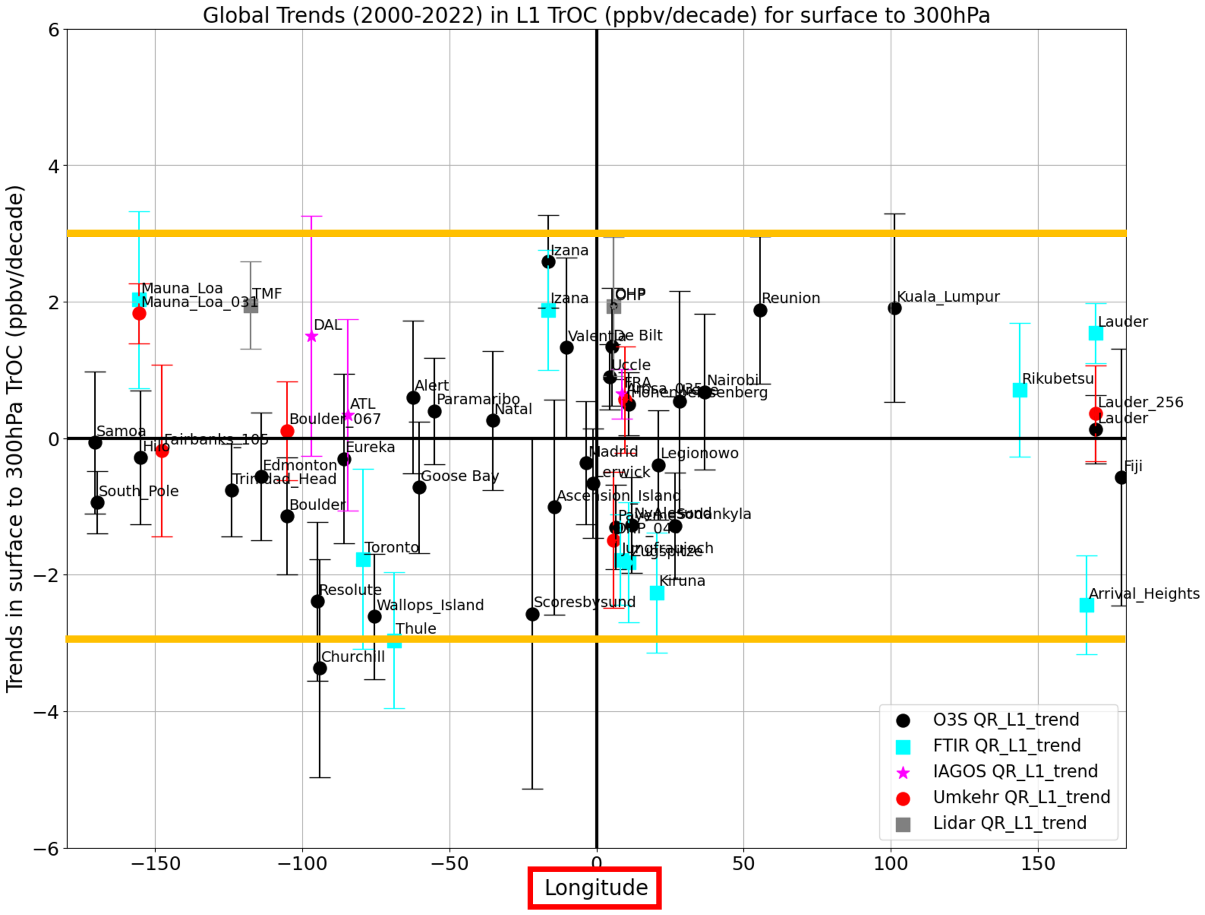




- same number of positive and negative trends, **42%** of the sites with **non-significant trends**
- mostly within **± 3 ppbv/decade** → constraints for satellite and model products

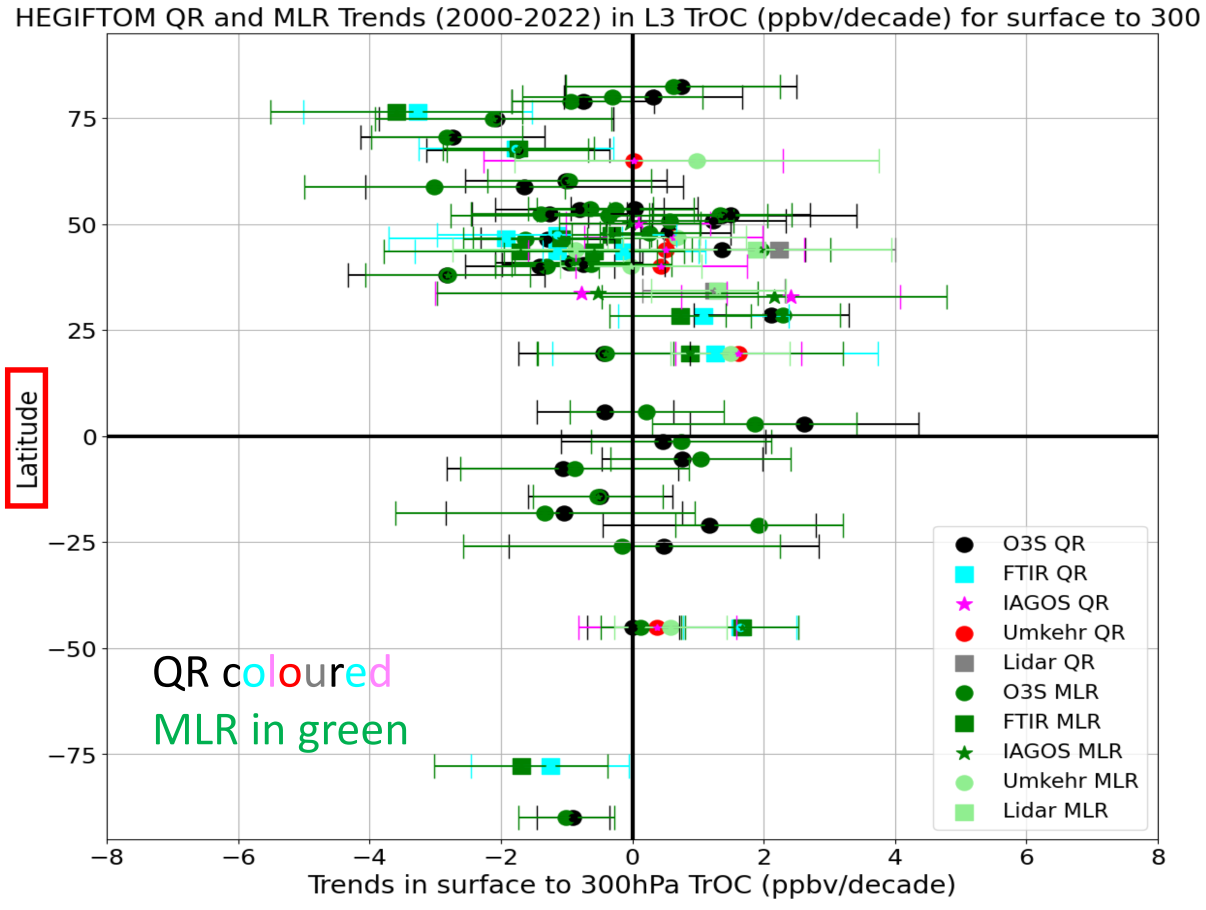
Individual site trends: QR median trends

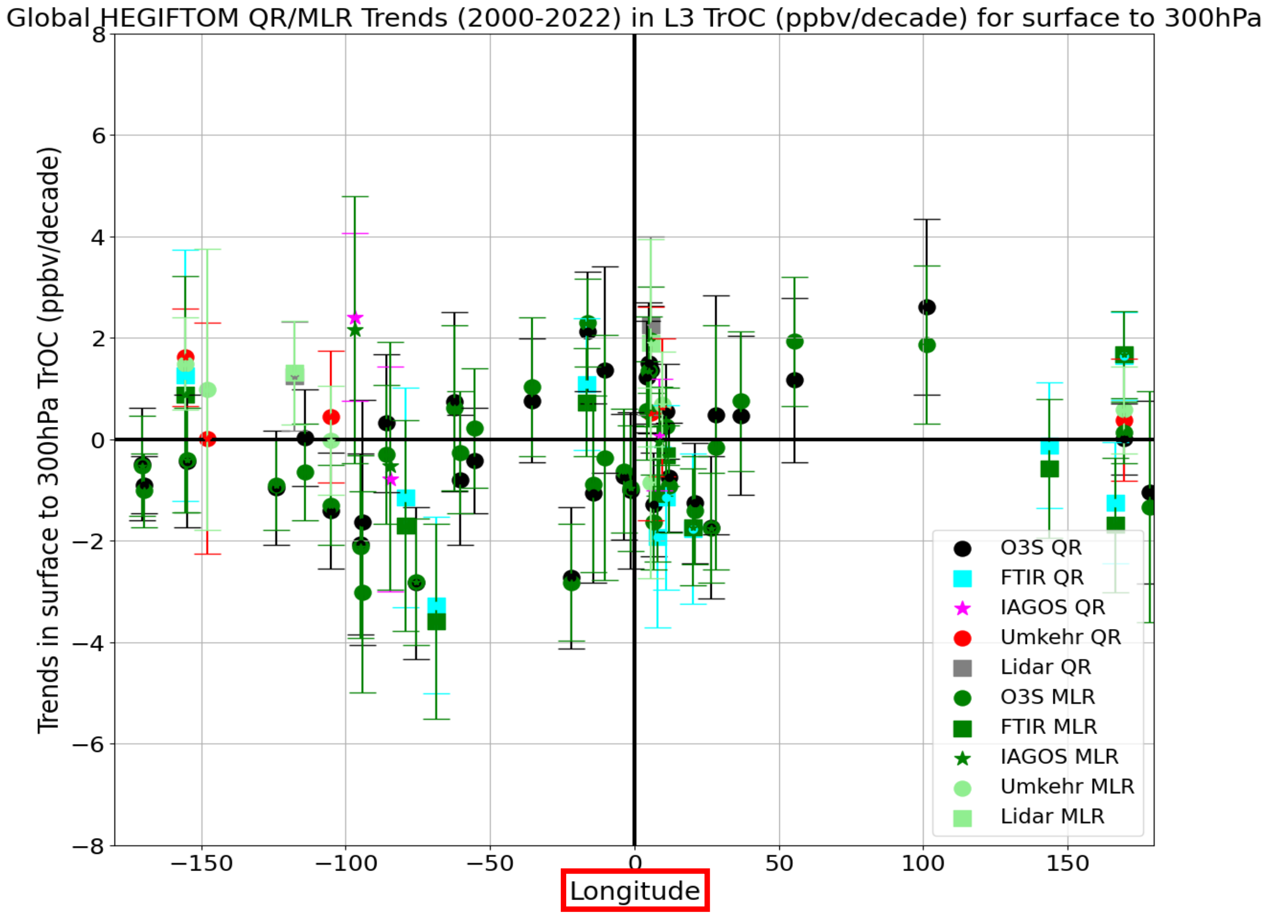




- same number of positive and negative trends, **42%** of the sites with **non-significant trends**
- mostly within **± 3 ppbv/decade** → constraints for satellite and model products

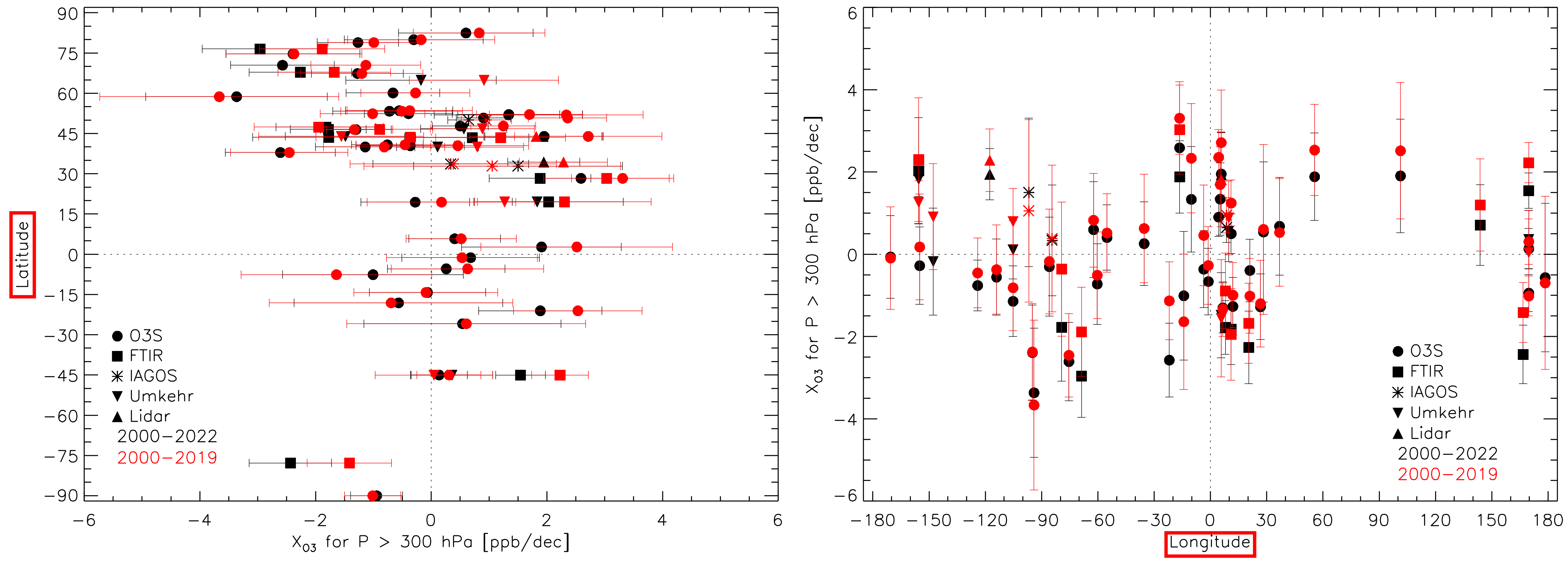
Individual site trends: QR median + MLR trends





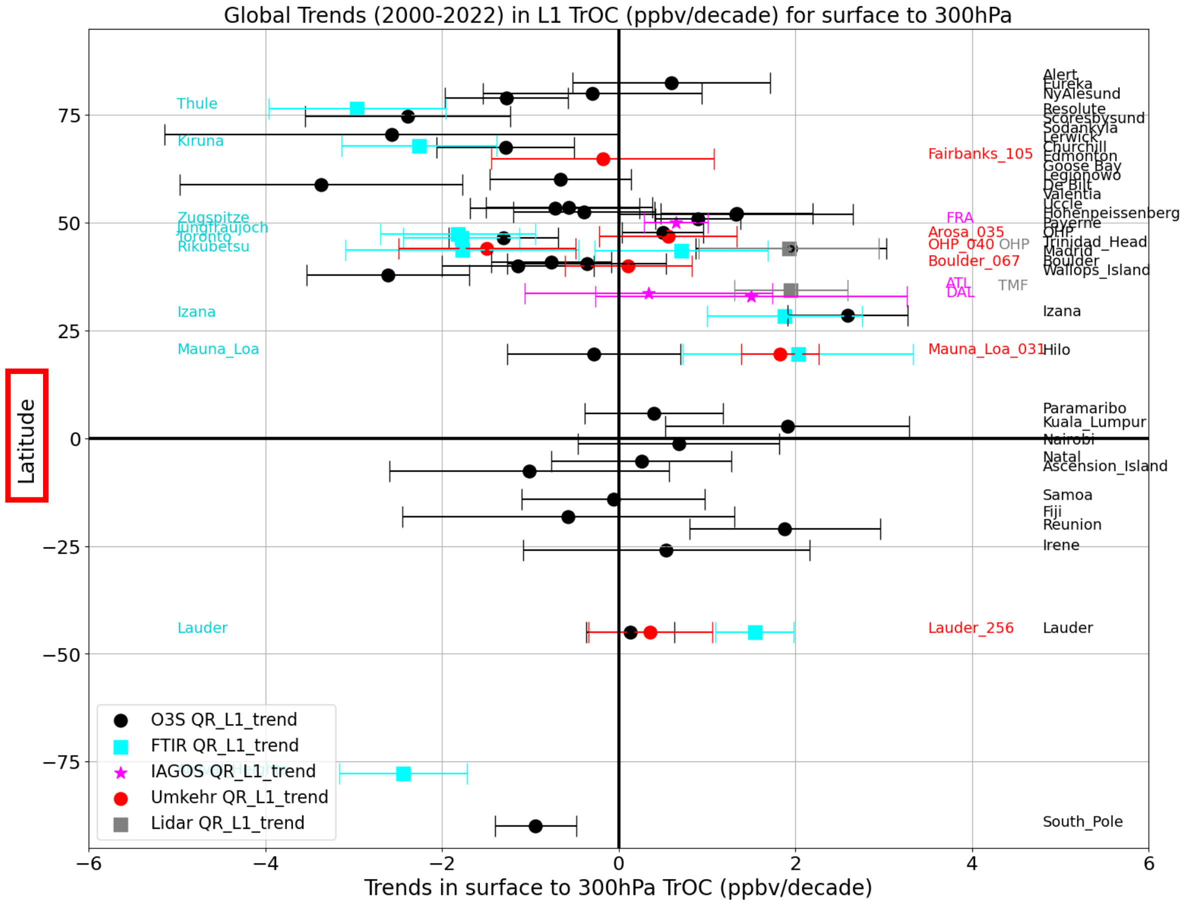
➔ Estimates and conclusions fairly **independent** of used statistical **trend estimation** tool

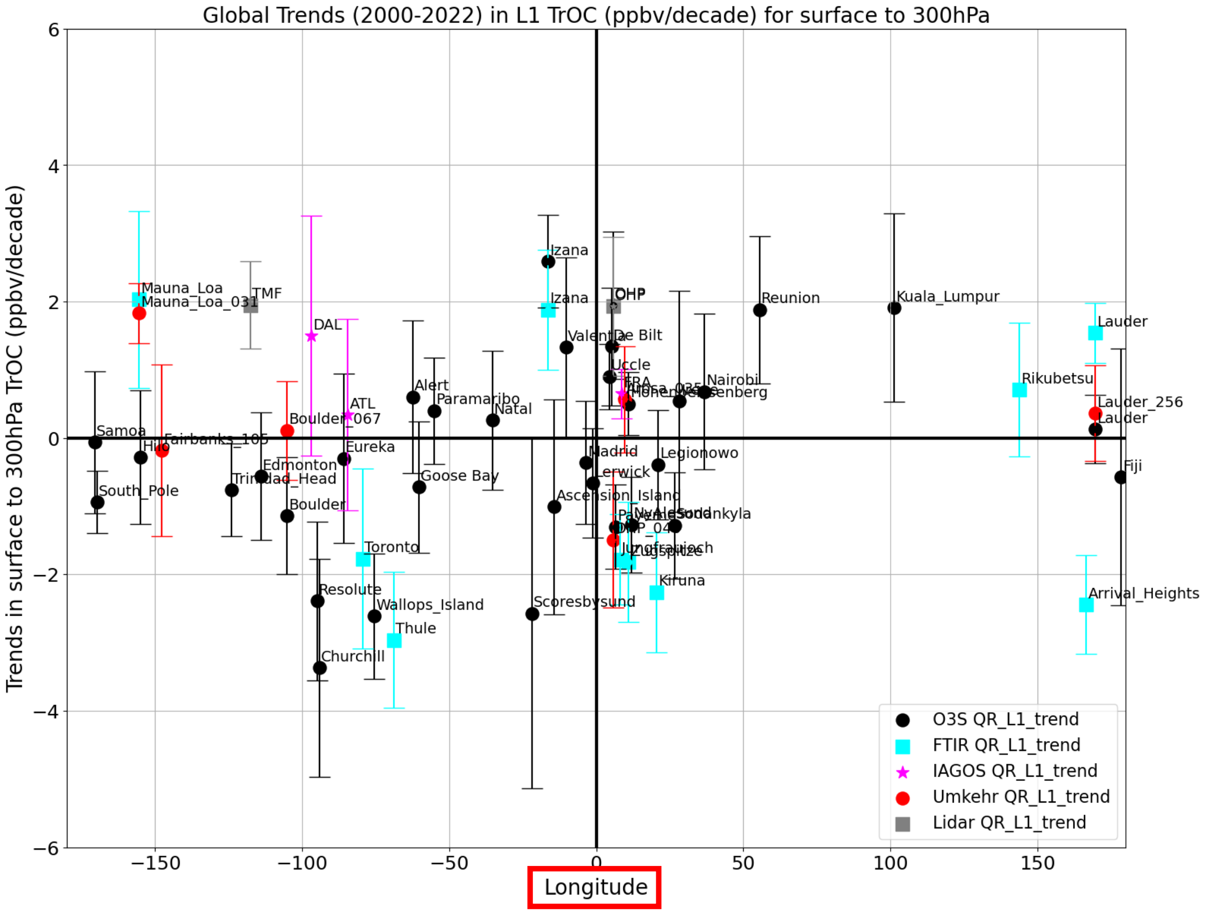
Individual site trends: post-COVID impact



For 75% of sites: **trend reduction** in 2000-2022 w.r.t. 2000-2019 period!
(-0.34 ppbv/dec for entire sample)

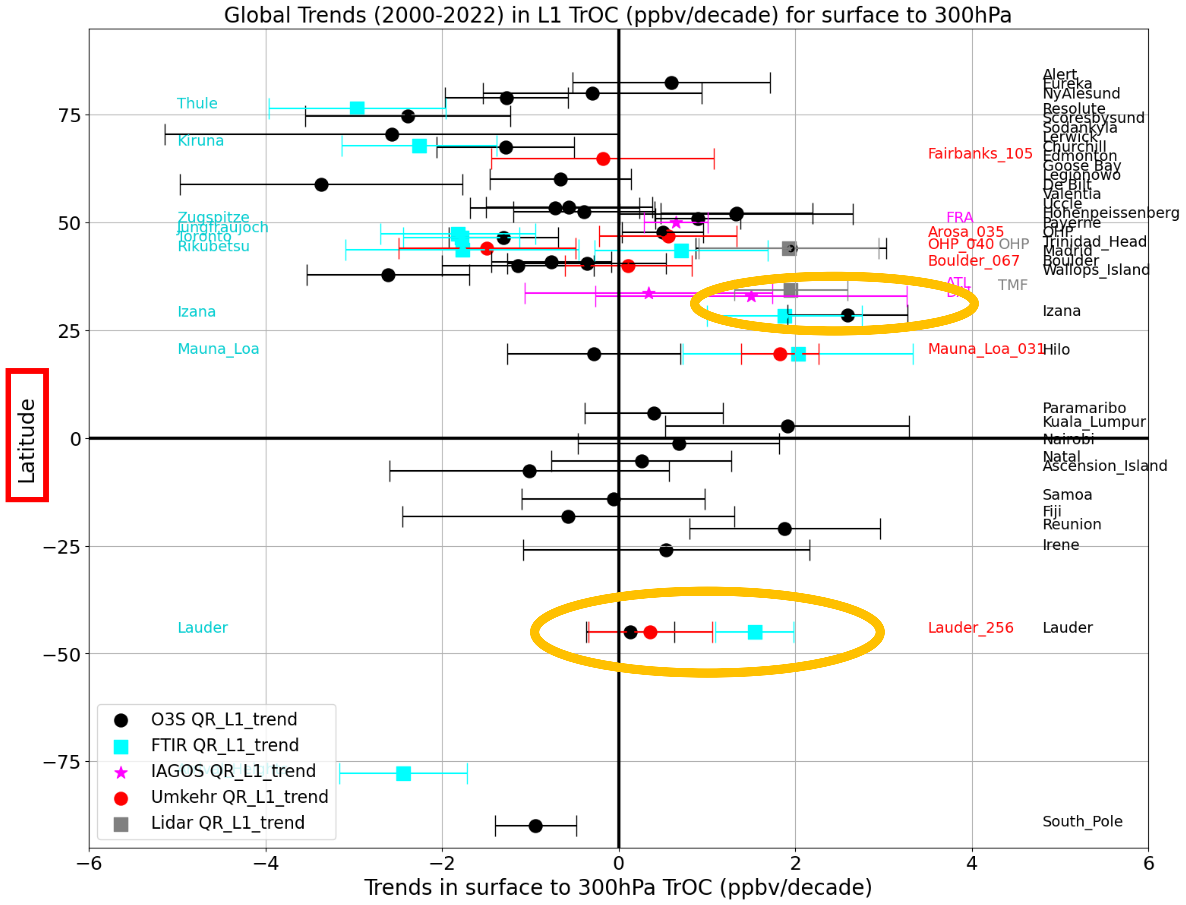
Individual site trends: QR median trends

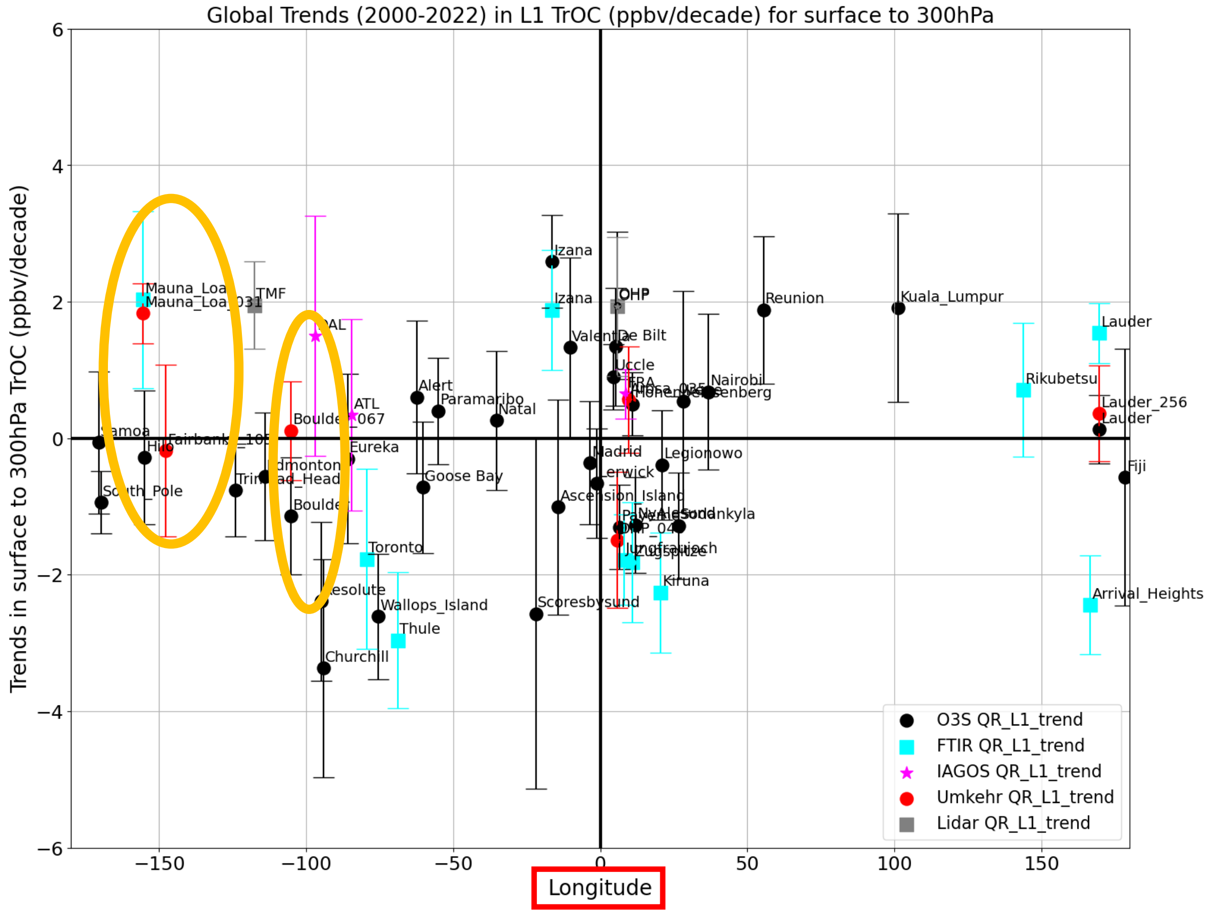




- Trend differences at multi-instrument sites?
- Negative trends at high (polar) latitudes?

Individual site trends: QR median trends





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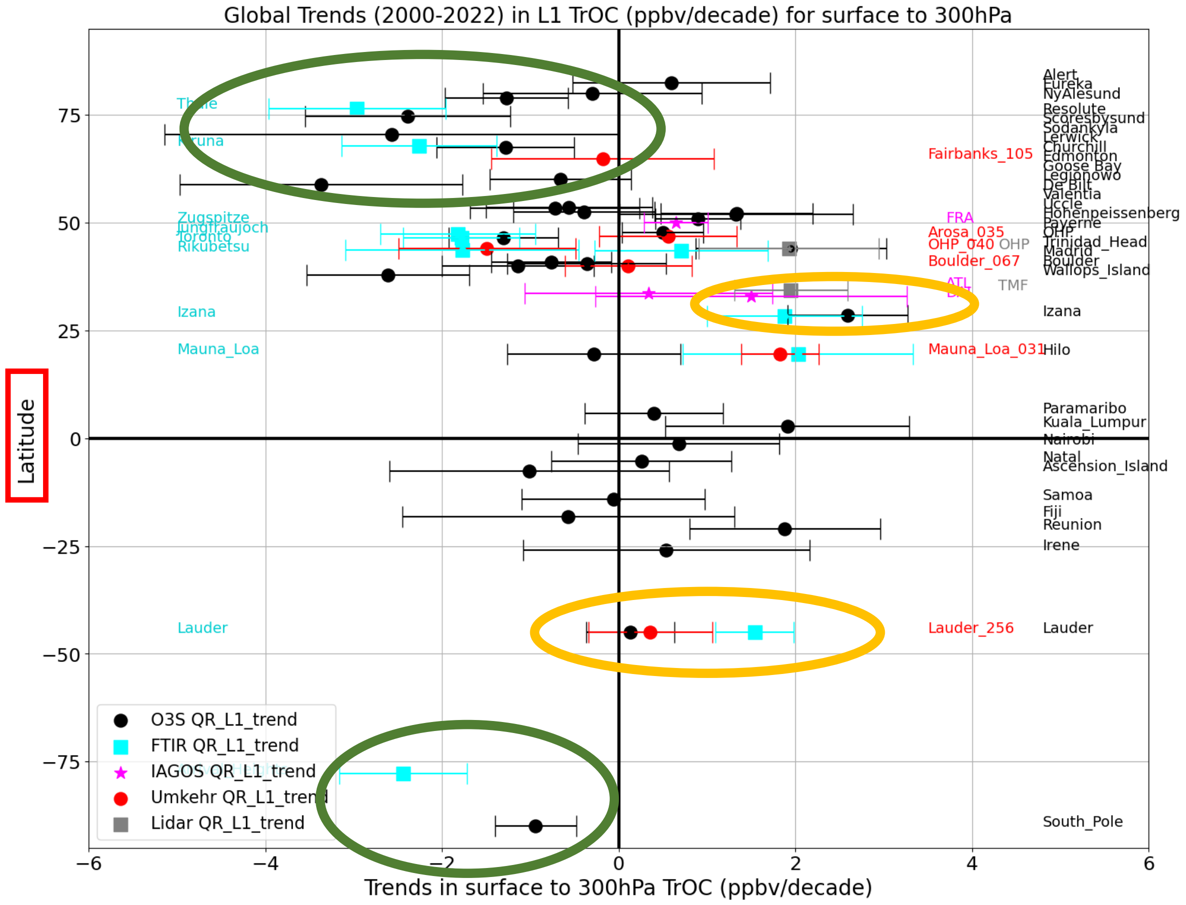

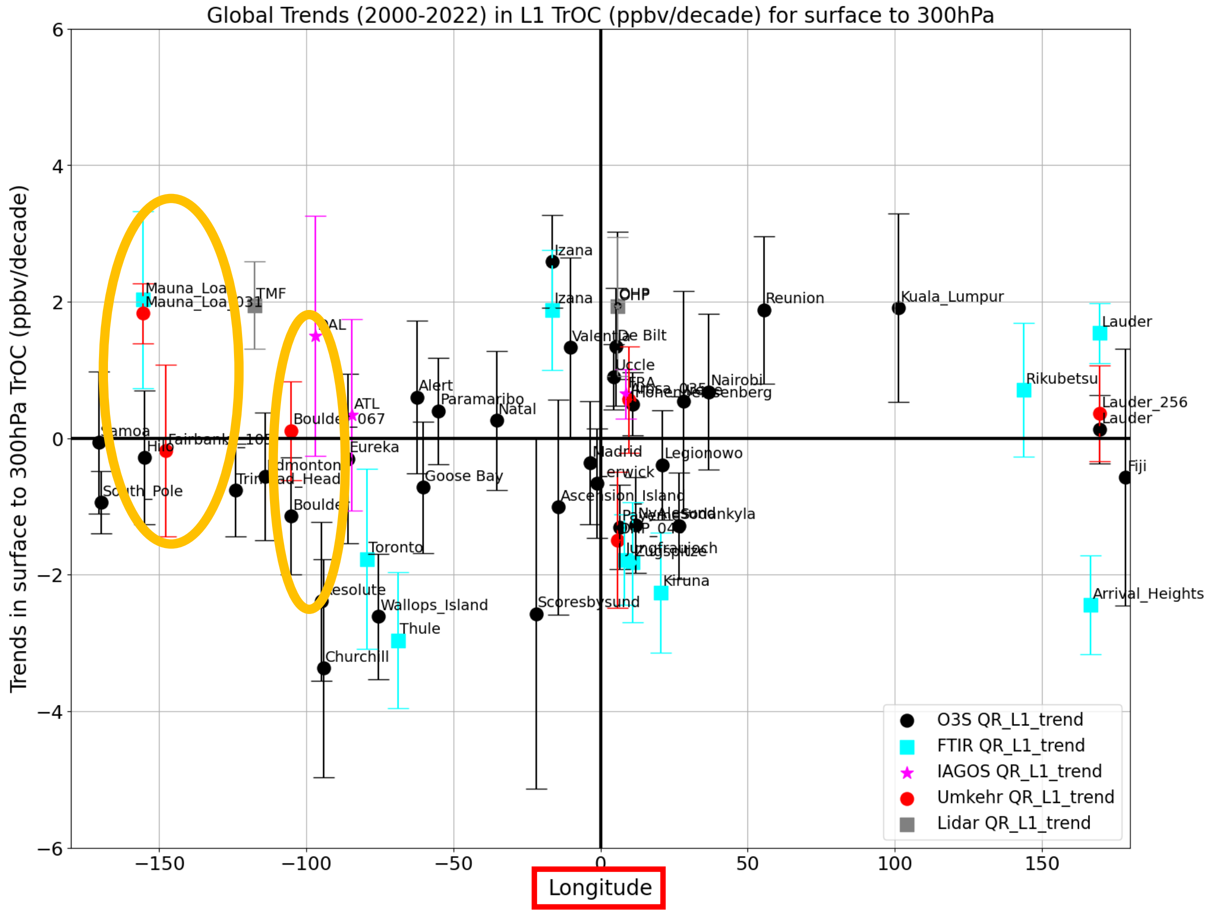

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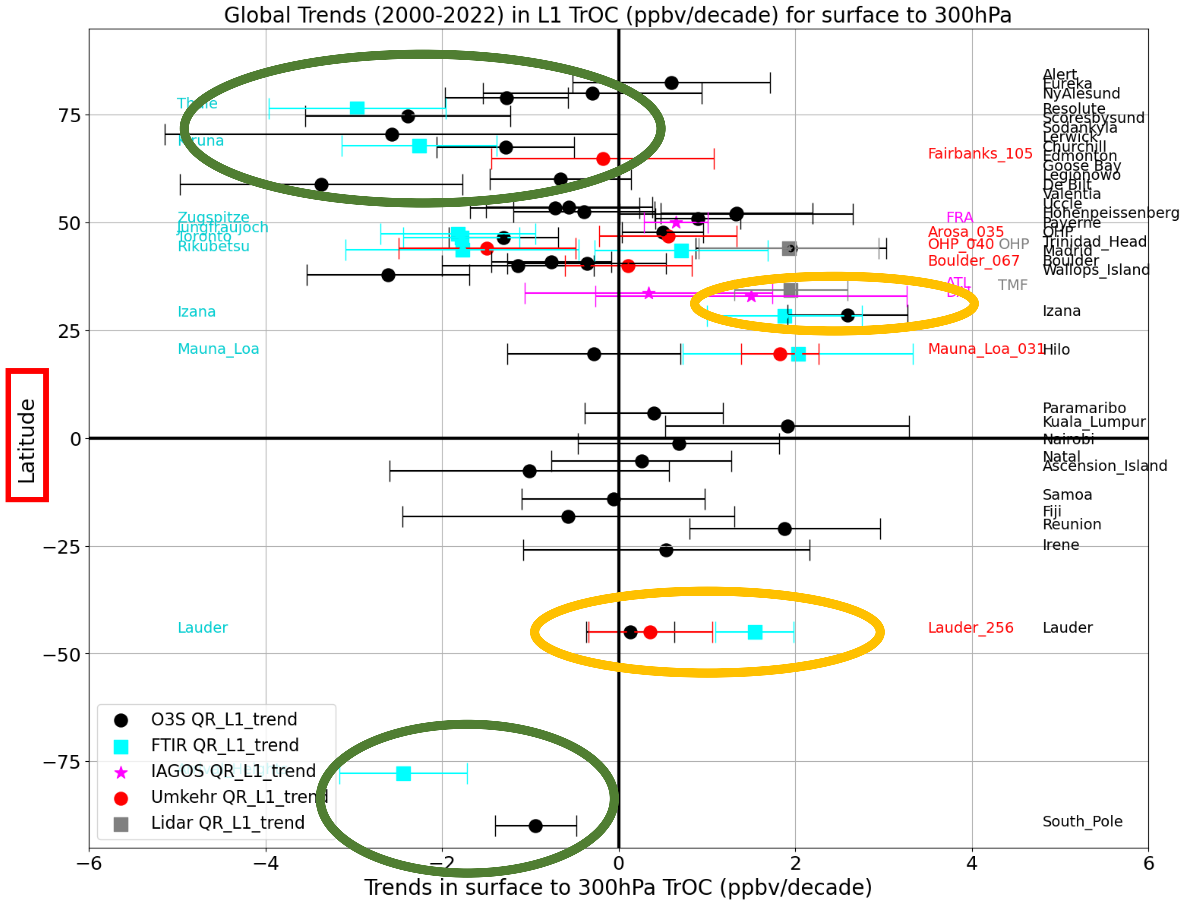
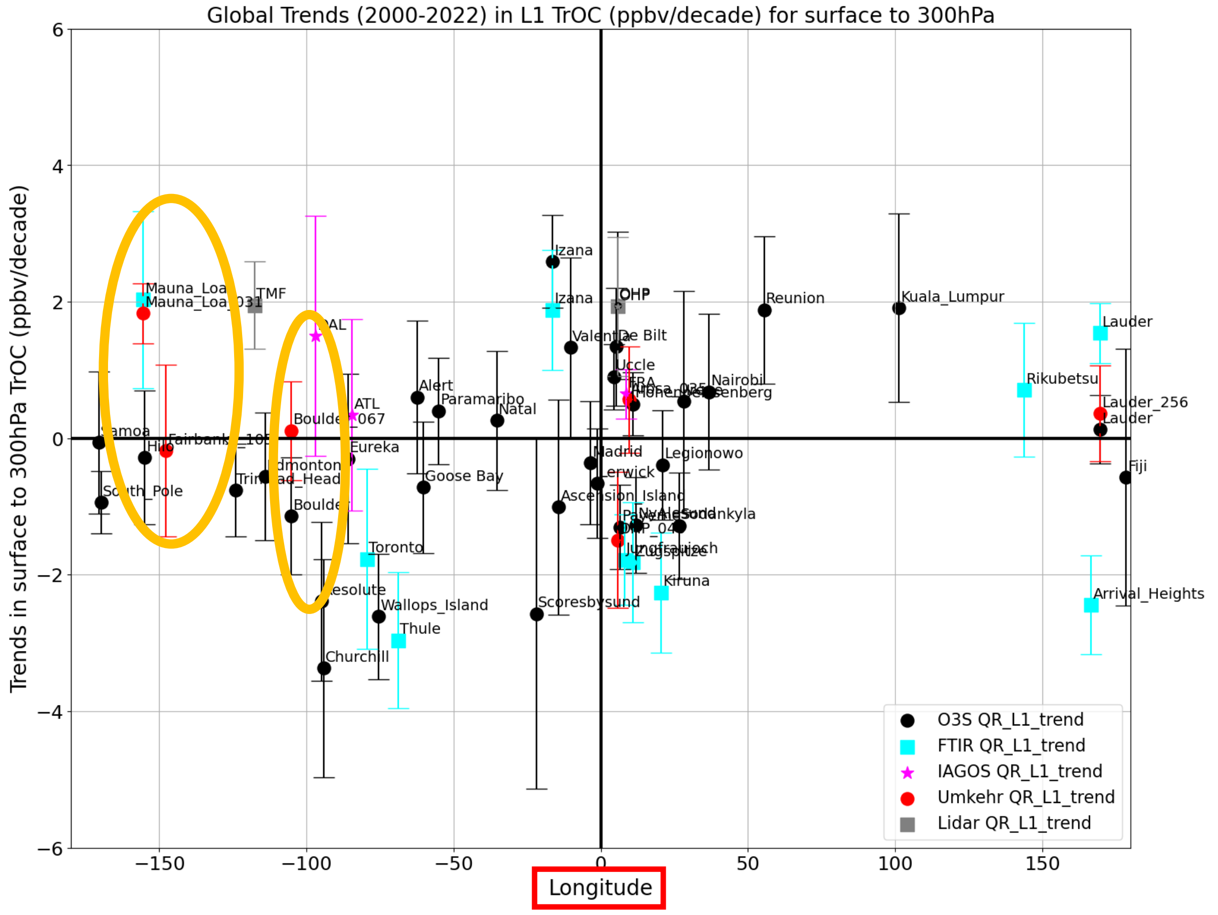


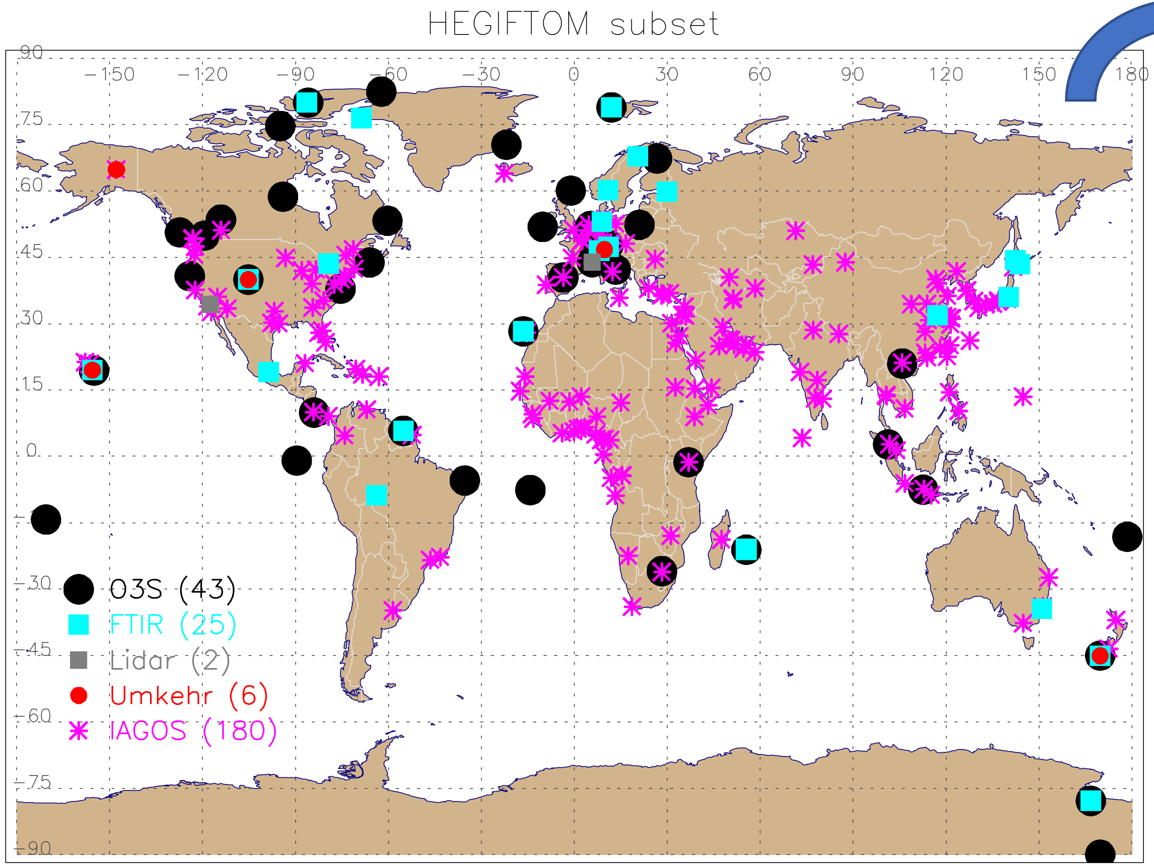


- Trend differences at multi-instrument sites?
- Negative trends at high (polar) latitudes?

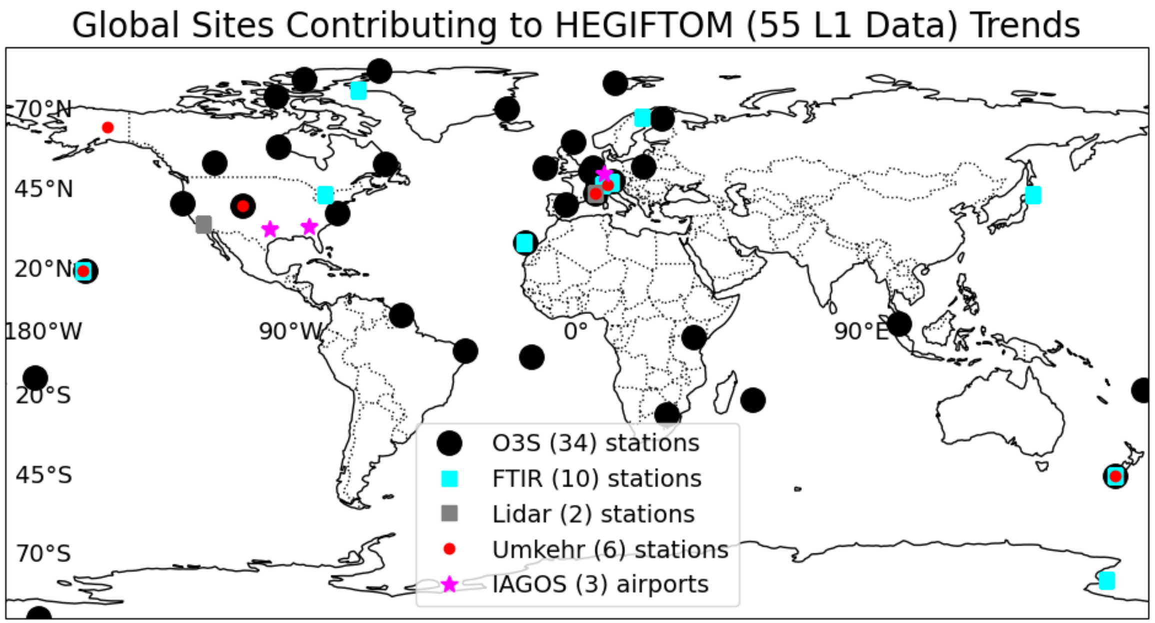
Regional trend consistency? Merging? Spatial Gap filling?

“Regionalized” trends

Gap filling?



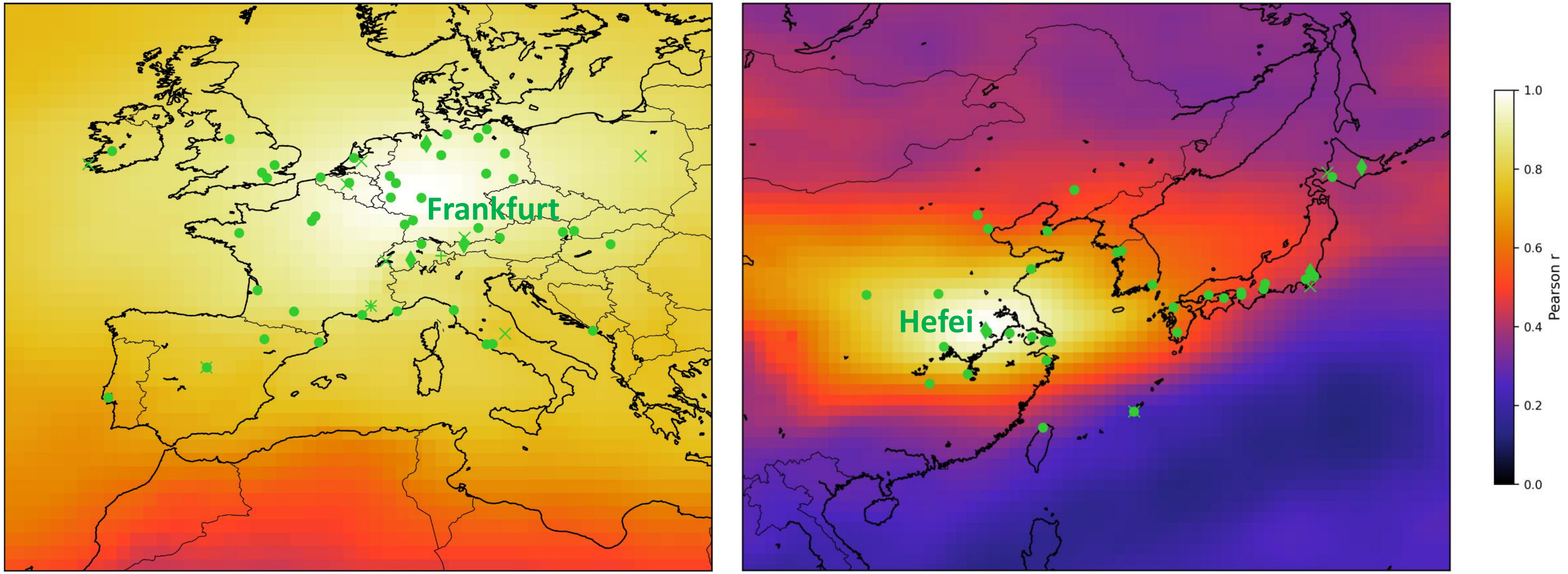
Sites with data in 2000-2022 period



Sites used for trend calculation for 2000-2022 period

Strategy for regionalized trends

Which regions/sites?

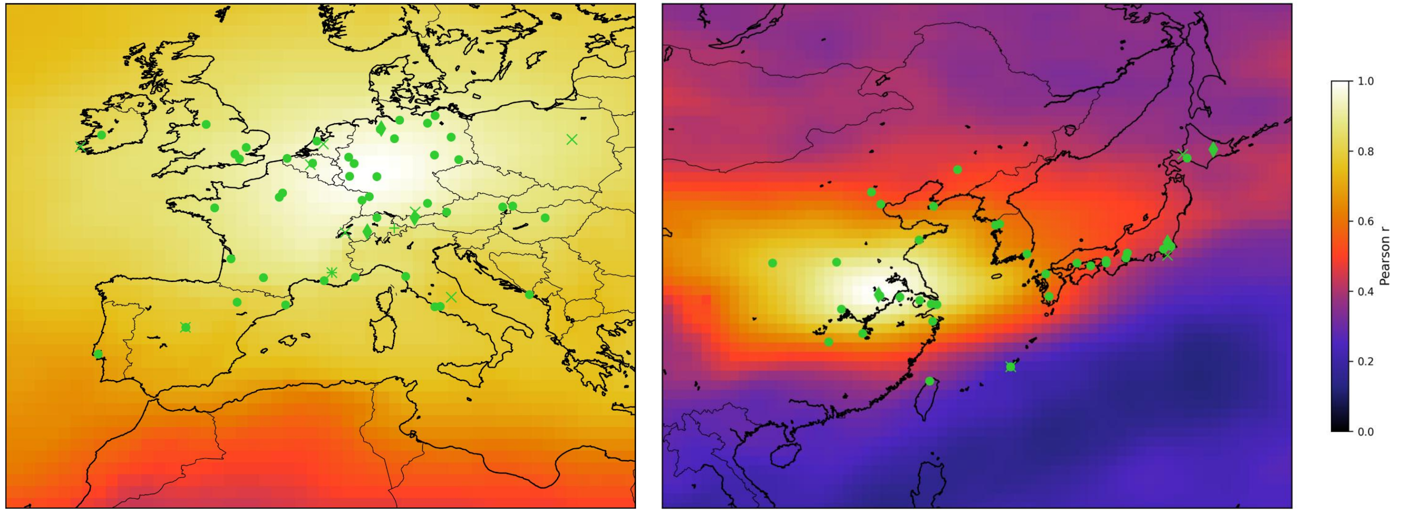


- Correlation maps between CAMS TrOC (sfc – 300 hPa) monthly anomalies at HEGIFTOM sites (here: Frankfurt, IAGOS & Hefei, FTIR)
- r > 0.7!

2 strategies for regionalized trends

TOST

LMM



1. regions

2. sites

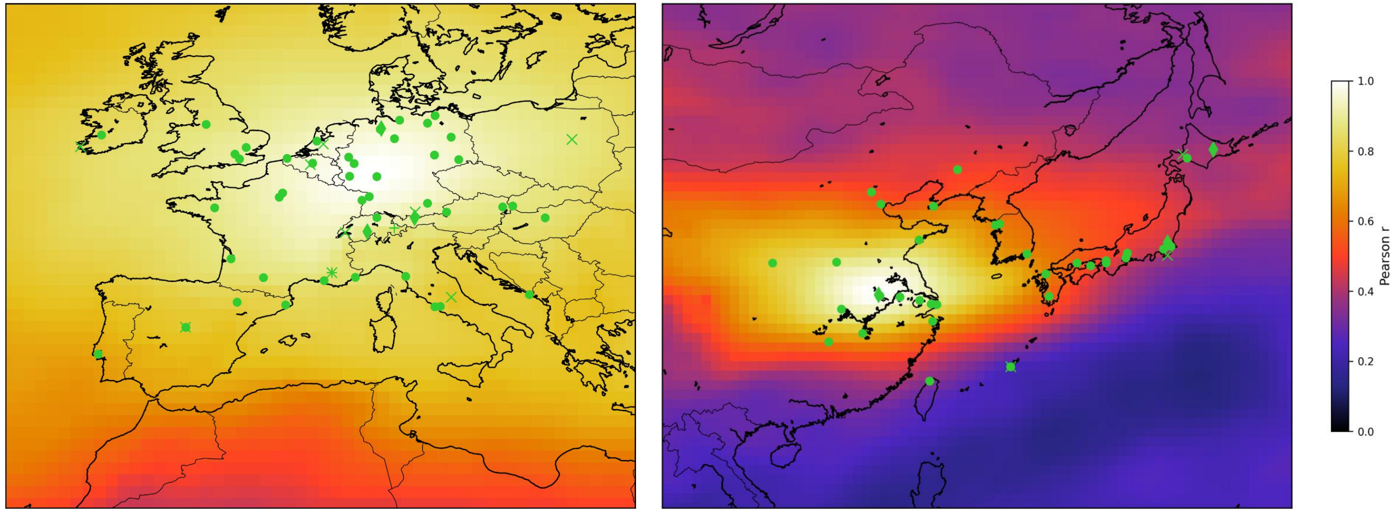
Trends in defined regions with TOST (Trajectory-mapped Ozonesonde dataset for the Stratosphere and Troposphere): **ozonesondes only**!

Statistical method (linear mixed-effects modelling, LMM) for calculating synthetized trends from **well-correlated individual time series** for **all instruments**, allowing an intercept and a slope to adjust the difference from each individual trend against the overall trends.

2 strategies for regionalized trends: 1. TOST

TOST

1.
regions

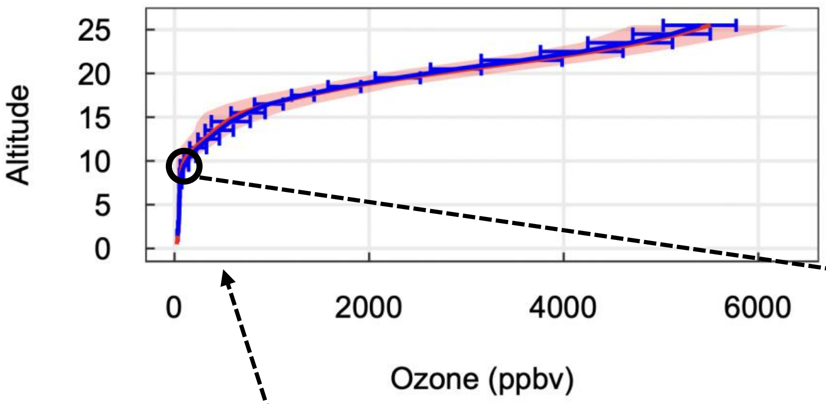


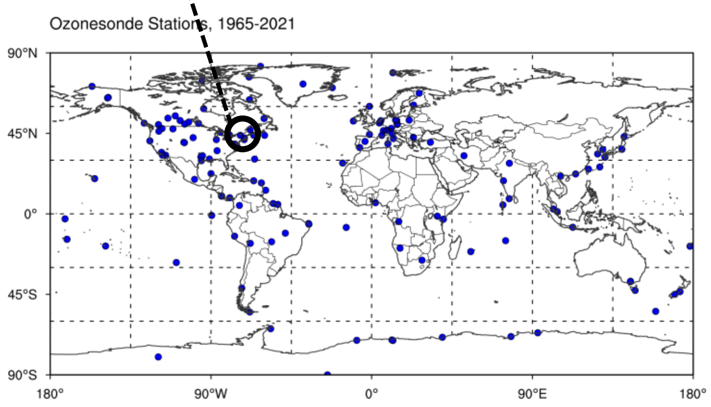
Trends in defined regions with TOST (Trajectory-mapped Ozonesonde dataset for the Stratosphere and Troposphere): **<u>ozonesondes only</u>**!

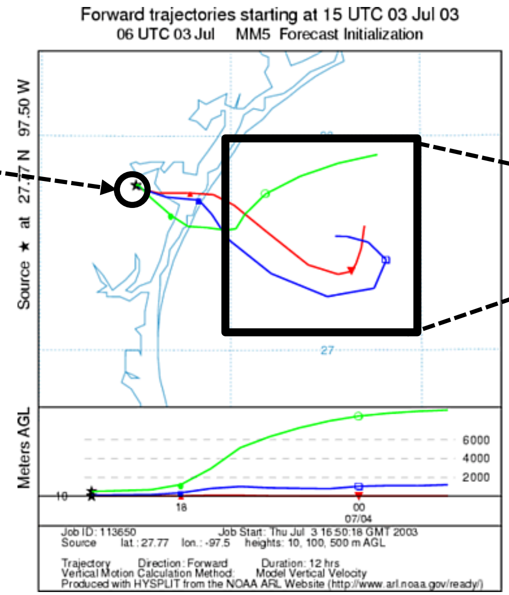
2 strategies for regionalized trends: 1. TOST

TOST

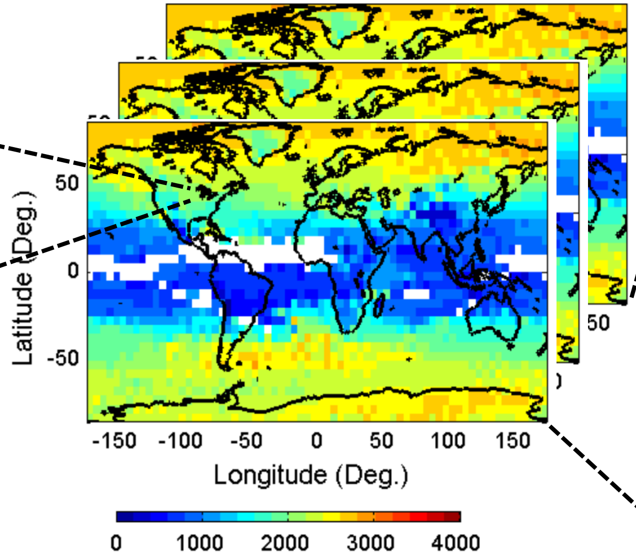
Ozonesonde raw data → Interpolate into 1km vertical ozone profile → HYSPLIT trajectory calculation for each site and each level → Bin the trajectories into grids at each level → Calculating TrOC

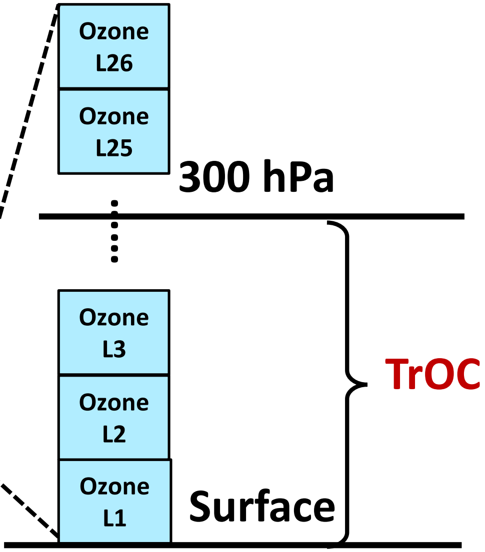






5°× 5° × 1 km (latitude, longitude, and altitude), monthly





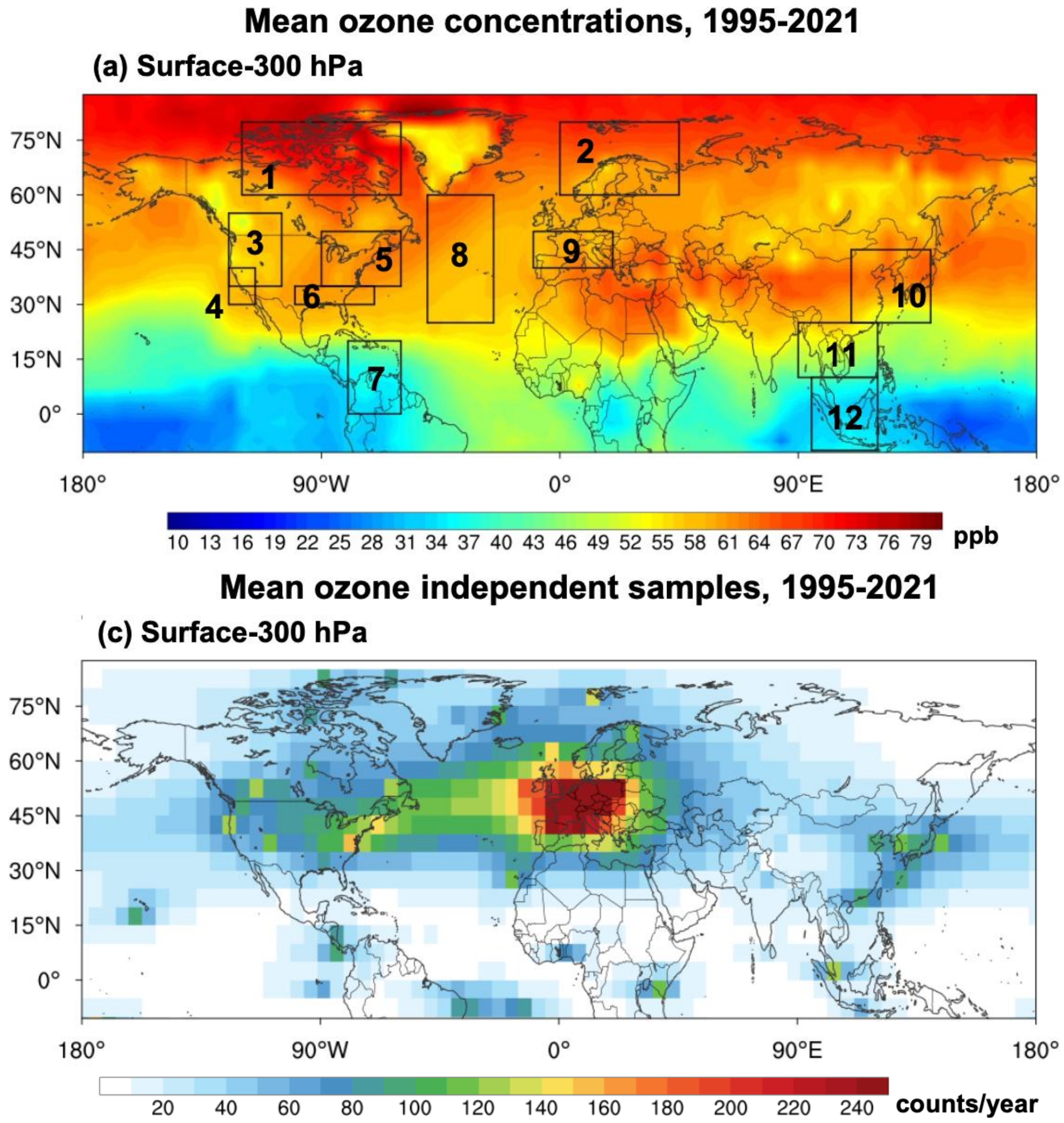
2 strategies for regionalized trends: 1. TOST

Regions

TOST

1\. regions

- 12 regions, mainly NH *(highest TrOC amounts)*
- Based on the density of **ozonesonde** observations in well-correlated regions
- 2 periods: 1995-2021, 2000-2021

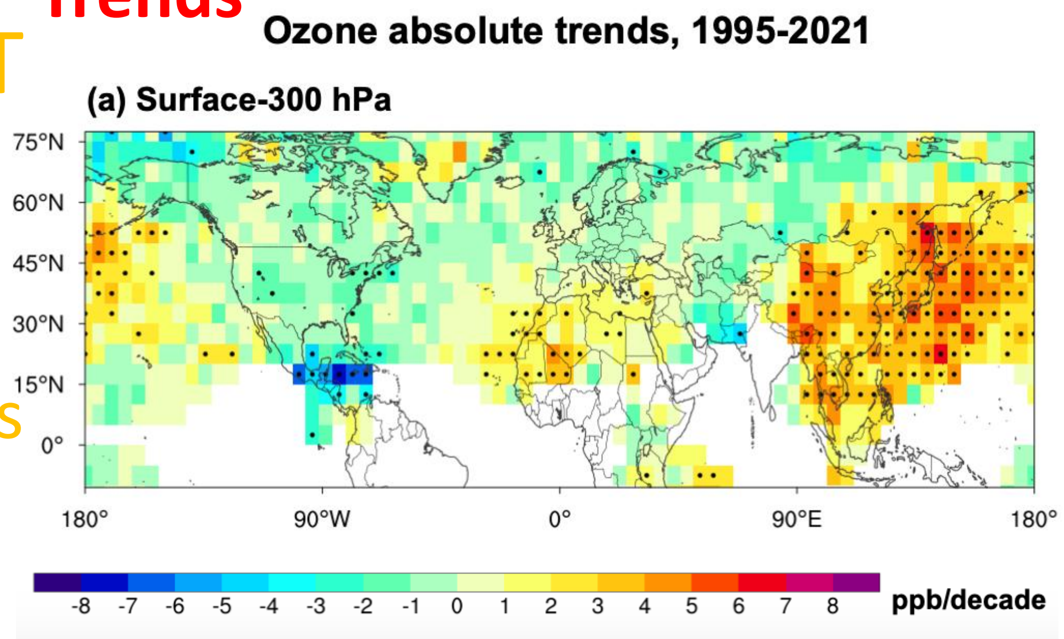


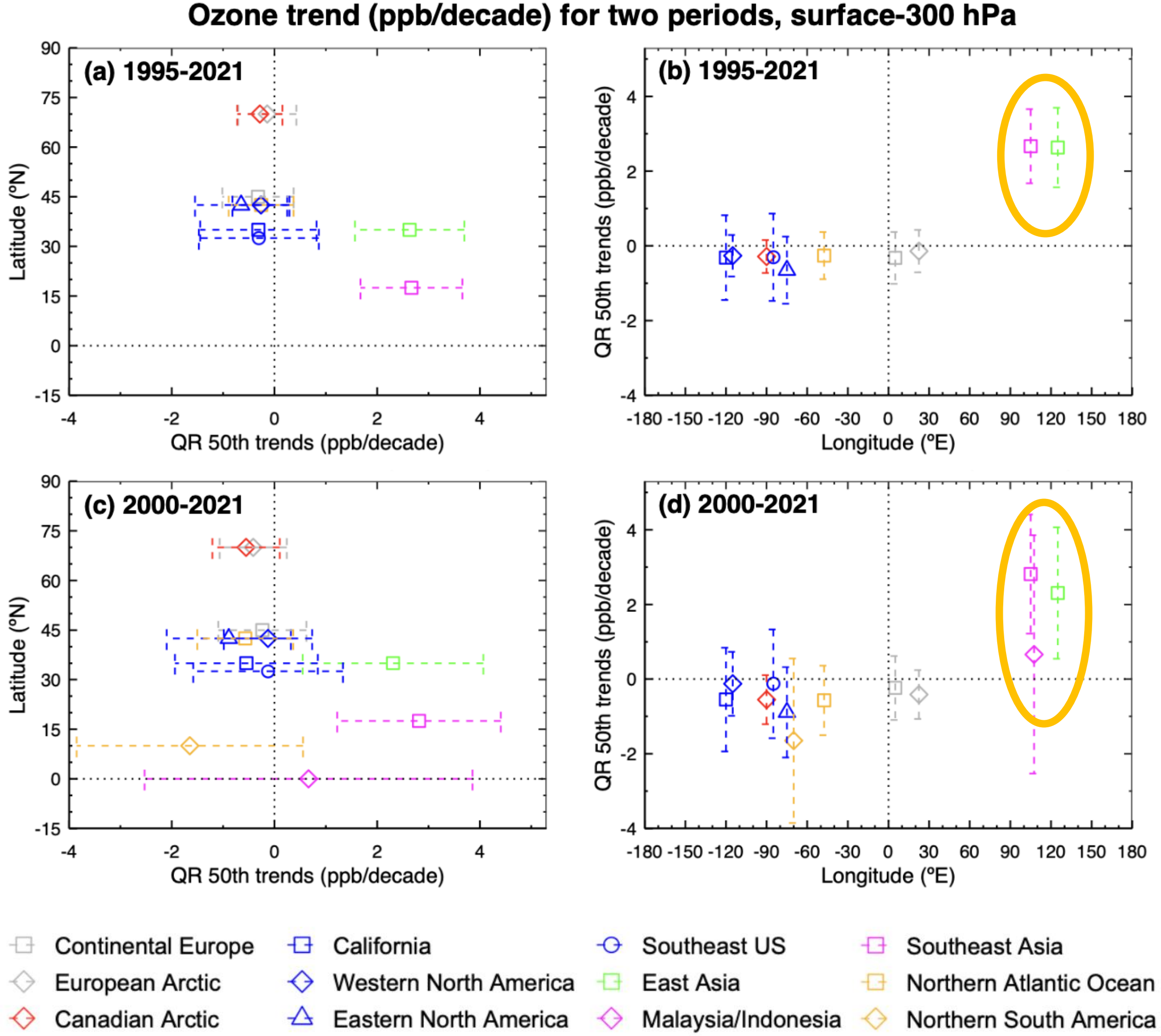
2 strategies for regionalized trends: 1. TOST

TOST

Trends

1. regions





- **positive trends** in (**South)East Asia**, negative elsewhere (*except around some individual sites in Africa*)
- **trend differences** between two different periods (1995+ vs. 2000+) **insignificant**

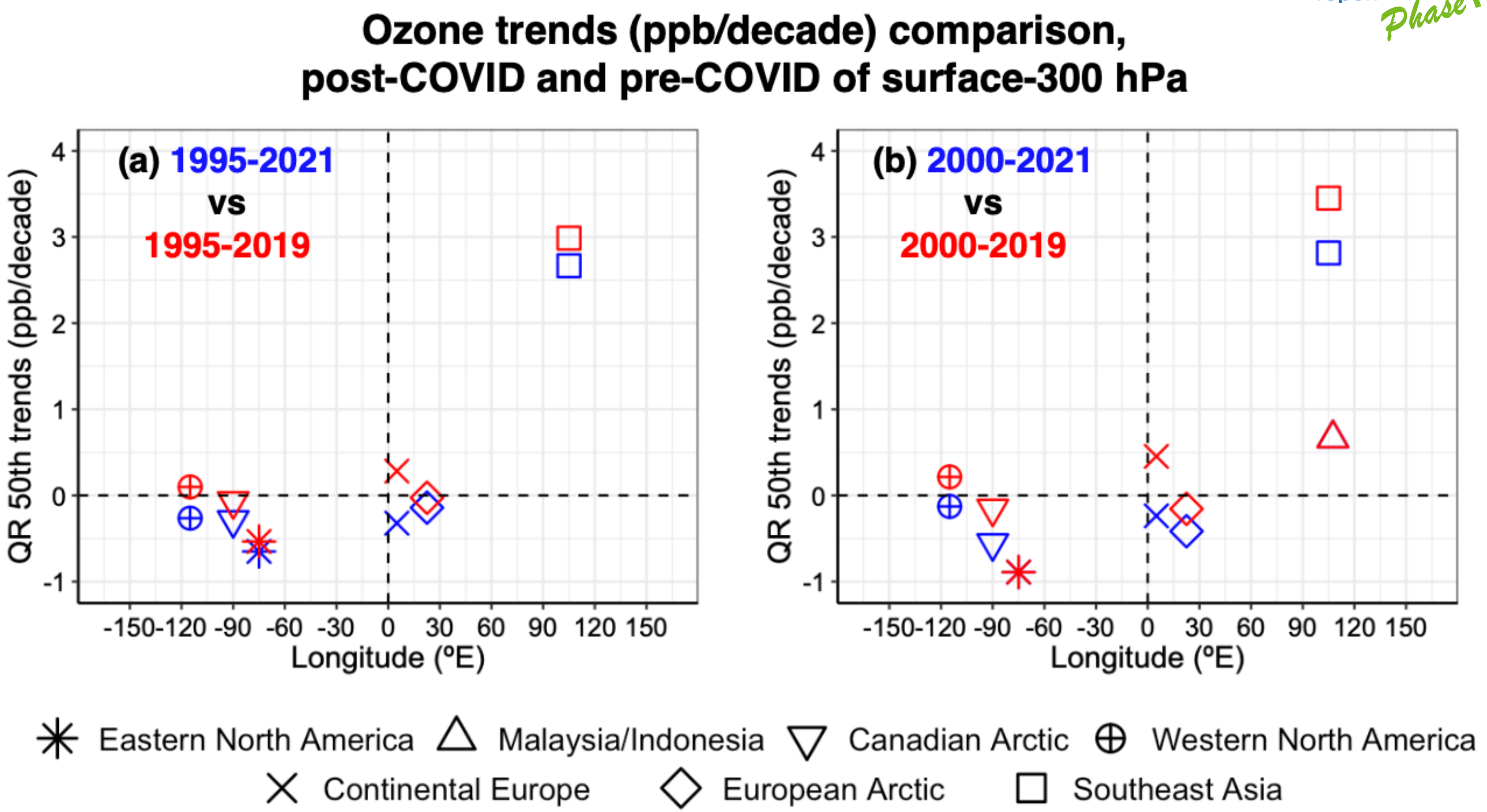
2 strategies for regionalized trends: 1. TOST

COVID impact?

TOST

1.

regions



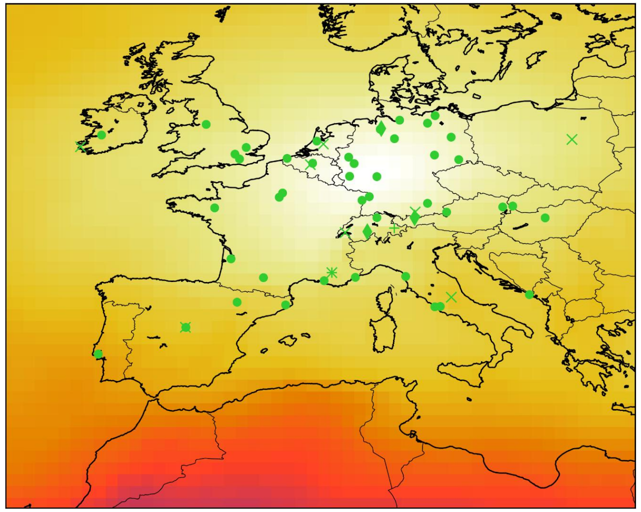
for all regions and two periods (1995+, 2000+):

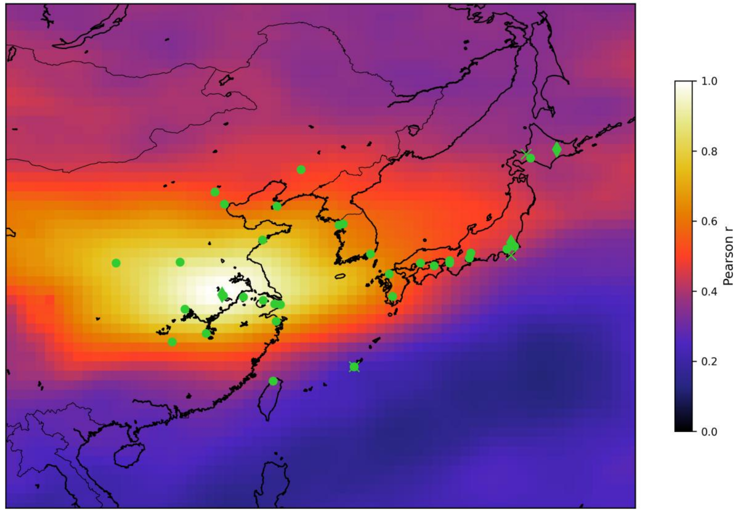
pre-COVID trends > post-COVID trends

2 strategies for regionalized trends

TOST

LMM





1. regions

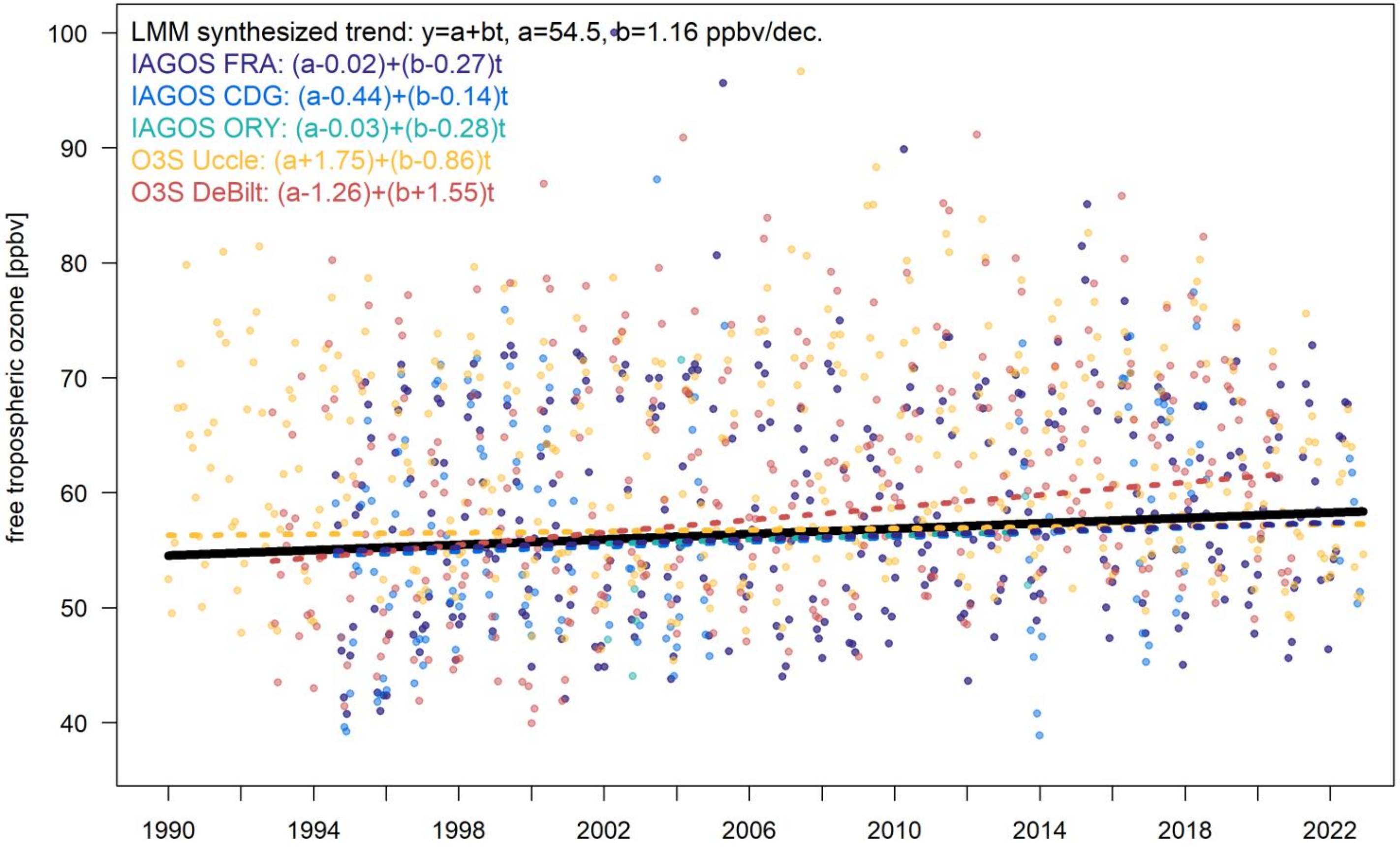
2. sites

Trends in defined regions with TOST (Trajectory-mapped Ozonesonde dataset for the Stratosphere and Troposphere): **ozonesondes only**!

Statistical method (linear mixed-effects modelling, LMM) for calculating synthetized trends from **well-correlated individual time series** for **all instruments**, allowing an intercept and a slope to adjust the difference from each individual trend against the overall trends.

2 strategies for regionalized trends: 2. LMM

- the **individual trends** are **adjusted** to calculate a synthetized trend for the combined time series
- example: monthly means, in practice: **all measurements!**
- different **weights** for different techniques (uncertainties) to counterbalance weight given to higher number of measurements



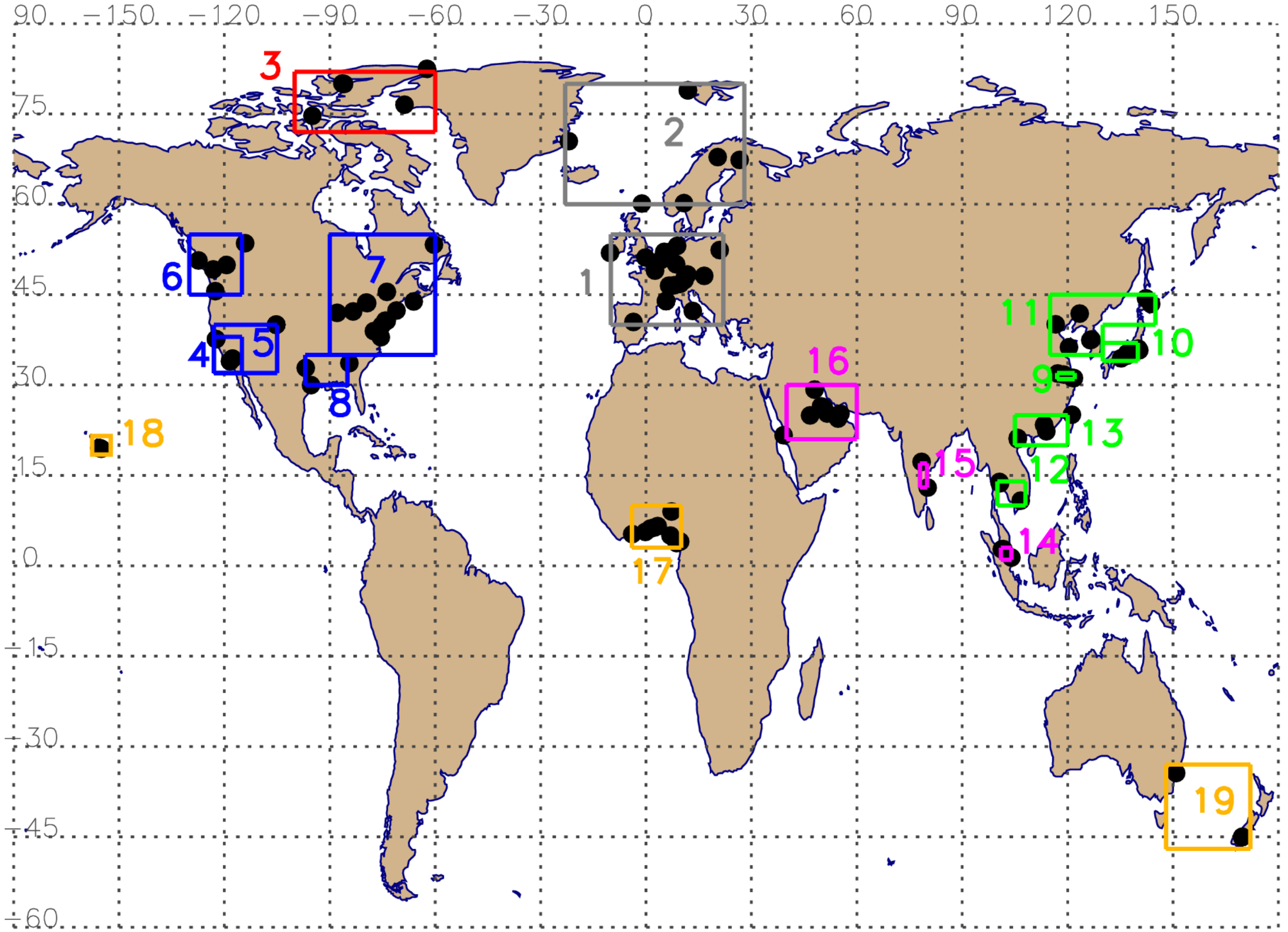
LMM

2.

sites

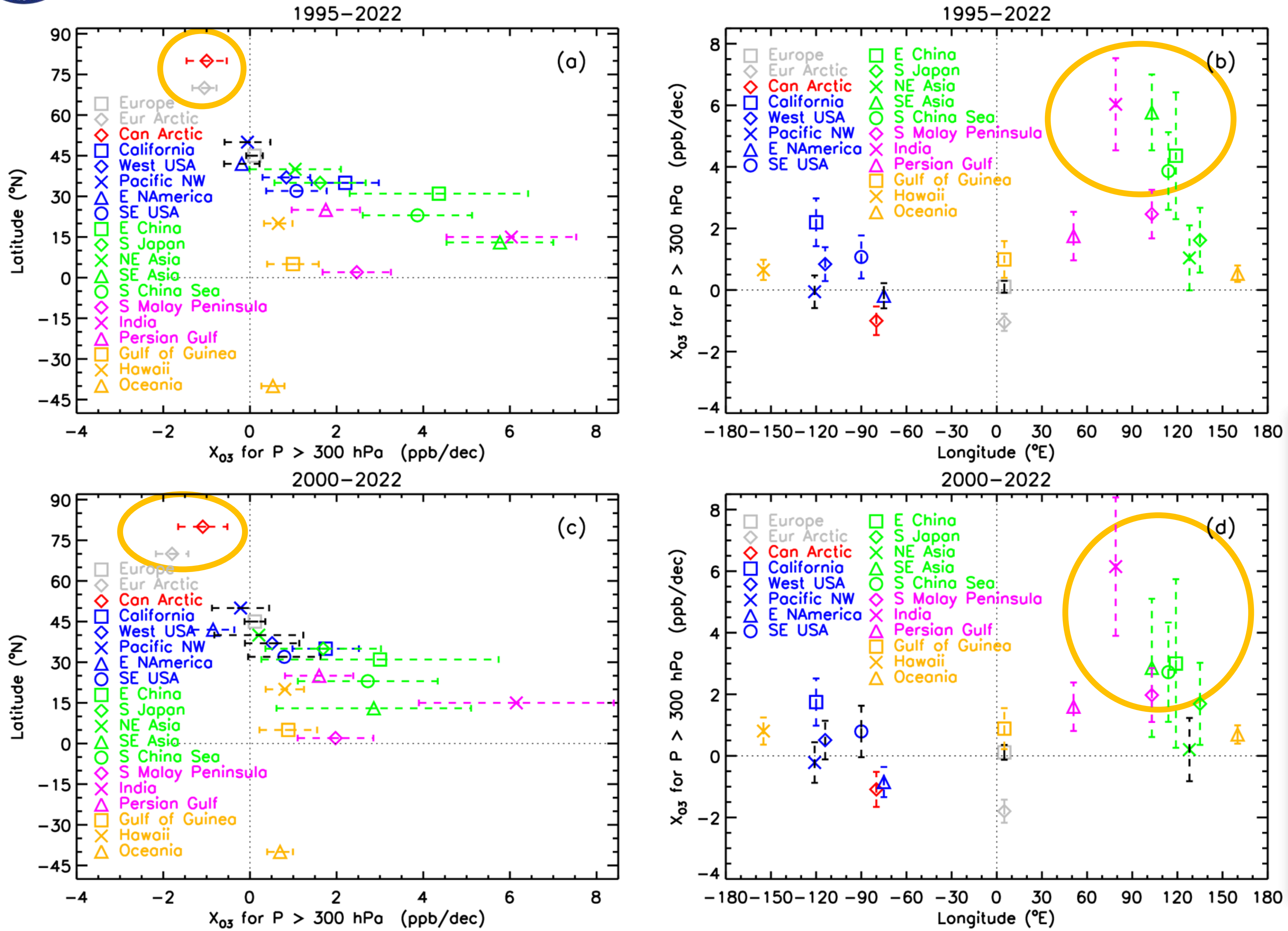
2 strategies for regionalized trends: 2. LMM

TOAR tropospheric ozone assessment report Phase II



- 19 regions! Mostly NH.
- at least two sites/techniques (Hawaii)
- only time series which are long enough (>60 months of data) are included
- 2 periods:
  1995-2022 & 2000-2022

2 strategies for regionalized trends: 2. LMM



Trends

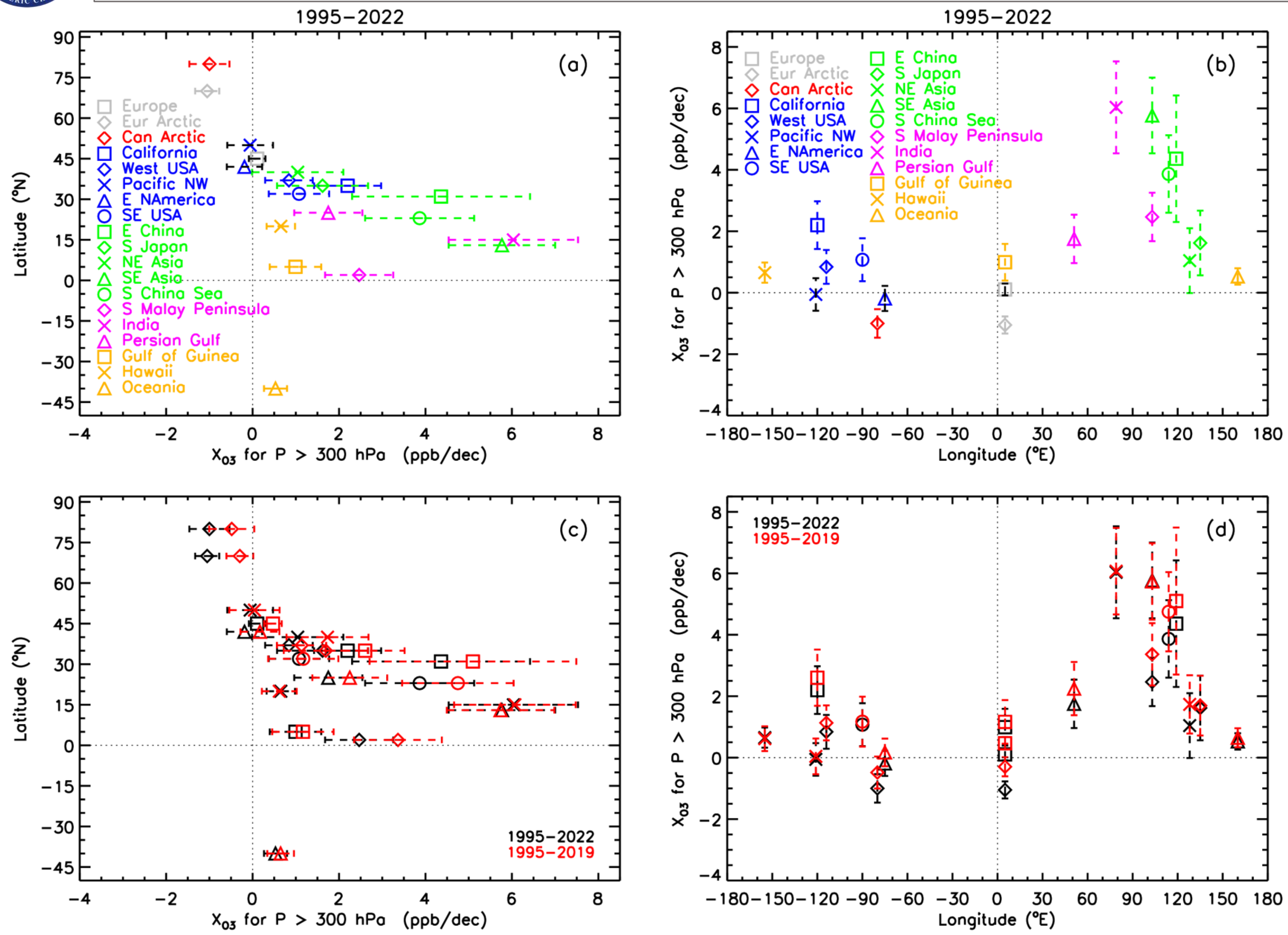
LMM

2.

sites

- mostly pos. trends (**Asia**!), except in Arctic regions
- trend diff. between two different periods (1995+ vs. 2000+) mostly insignificant (! East China + SE Asia)

2 strategies for regionalized trends: 2. LMM



COVID Impact

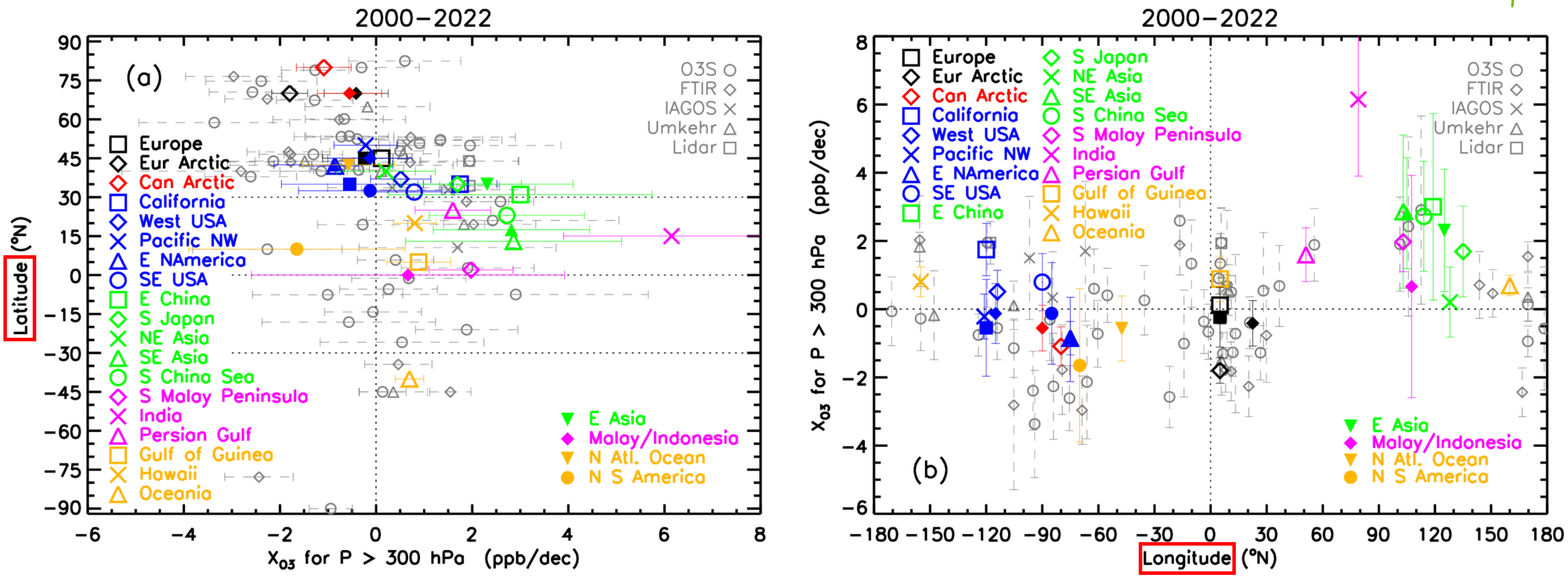
LMM

2. sites

for all regions and two periods (1995+, 2000+):

pre-COVID trends >
post-COVID trends

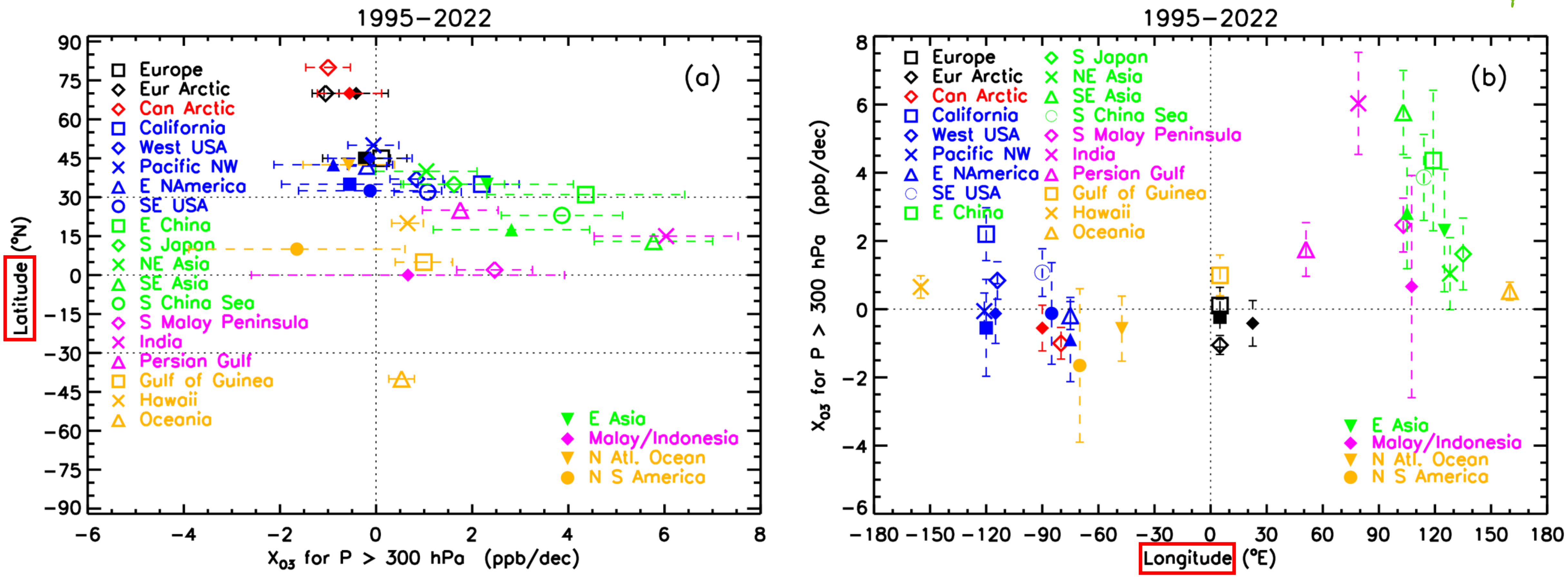
All trends: 2000-2022



background grey = individual site trends
different colors = different regions
open symbols = synthesized LMM trends
filled symbols = TOST regional trends

- Regional trends "summarize" individual trend estimates
- No large trend diff. between similar regions for 2 approaches

All trends: 1995-2022

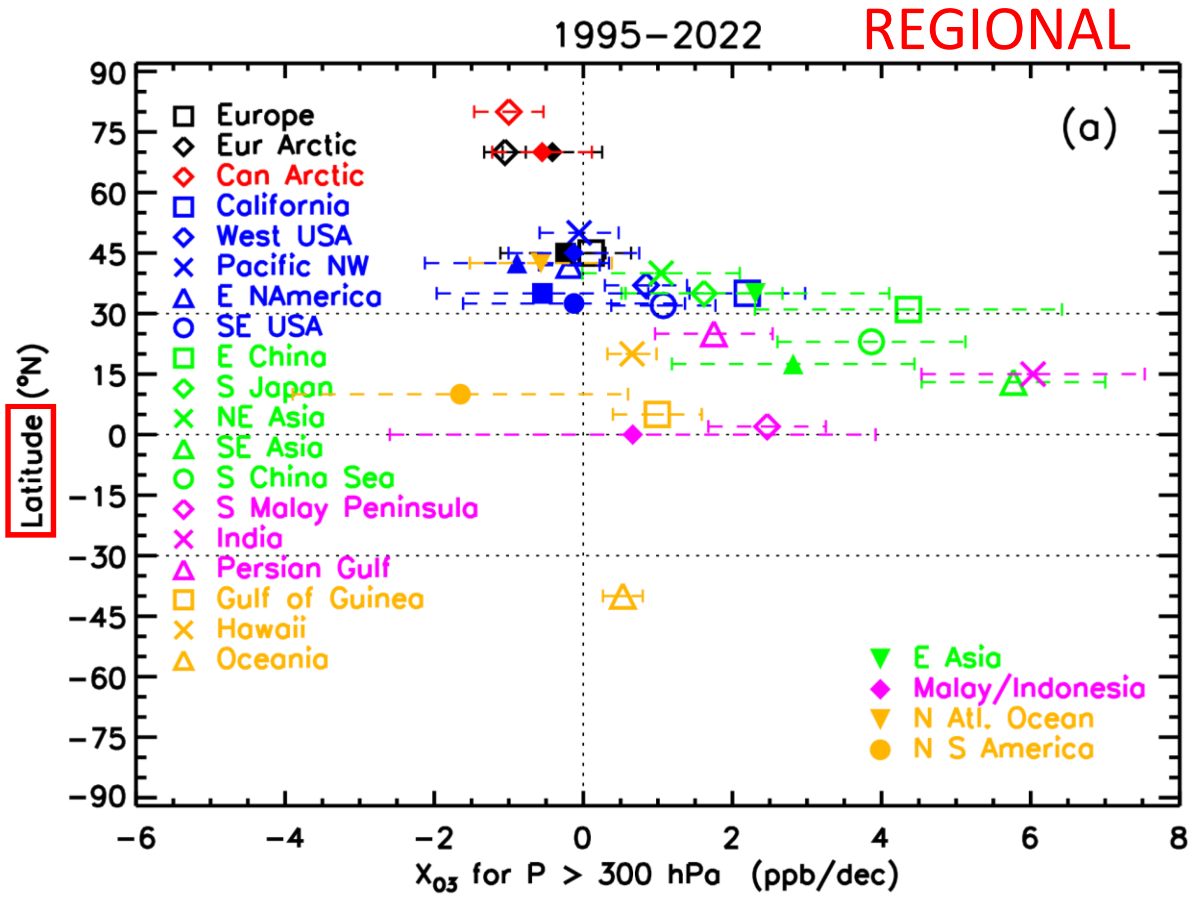


different colors = different regions
open symbols = synthesized LMM trends
filled symbols = TOST regional trends

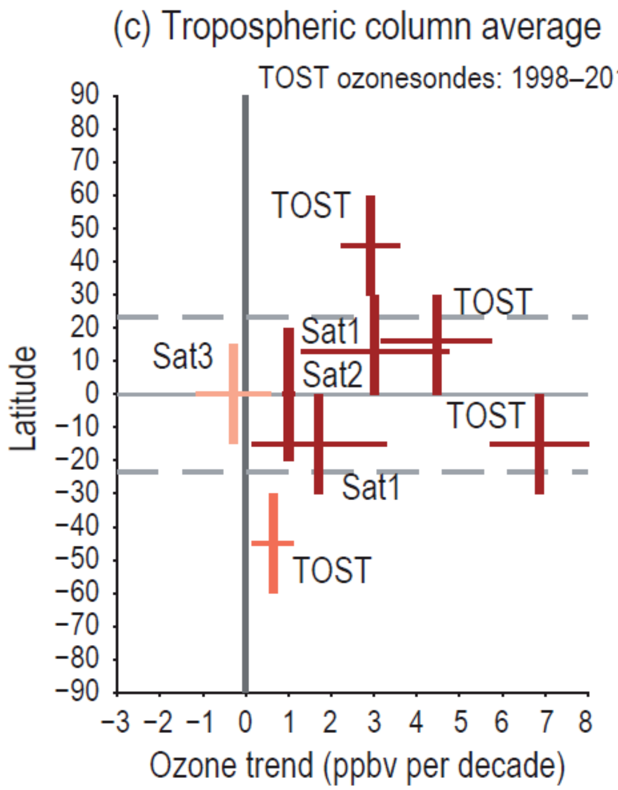
- No large trend diff. between similar regions for 2 approaches
- TOST trends closer to zero than LMM trends

All trends

REGIONAL



LATITUDINAL



Satellite products:

Sat1 1979–2016 (TOMS, OMI/MLS)

Sat2 1995–2015 (GOME, SCIAMACHY, OMI, GOME-2A, GOME-2B)

Sat3 1995–2015 (GOME, SCIAMACHY, GOME-II)

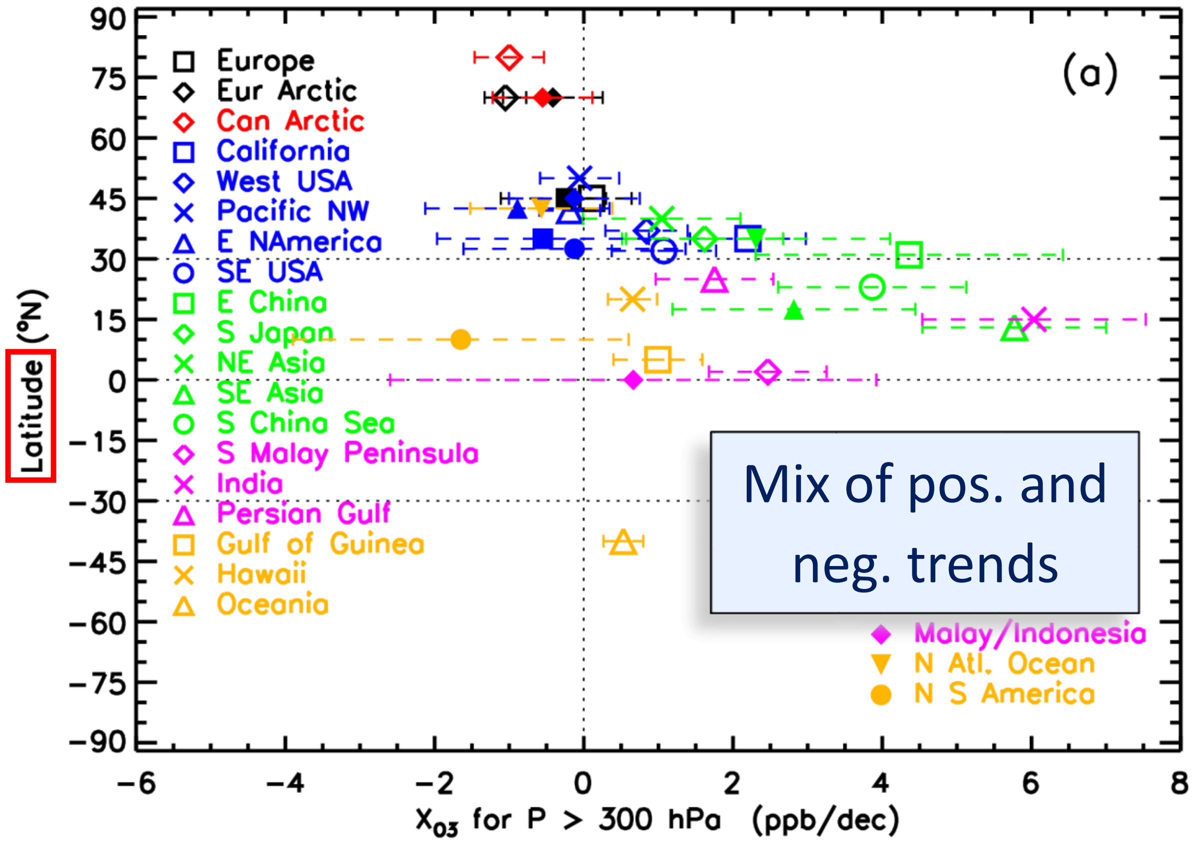
different colors = different regions

open symbols = synthesized trends

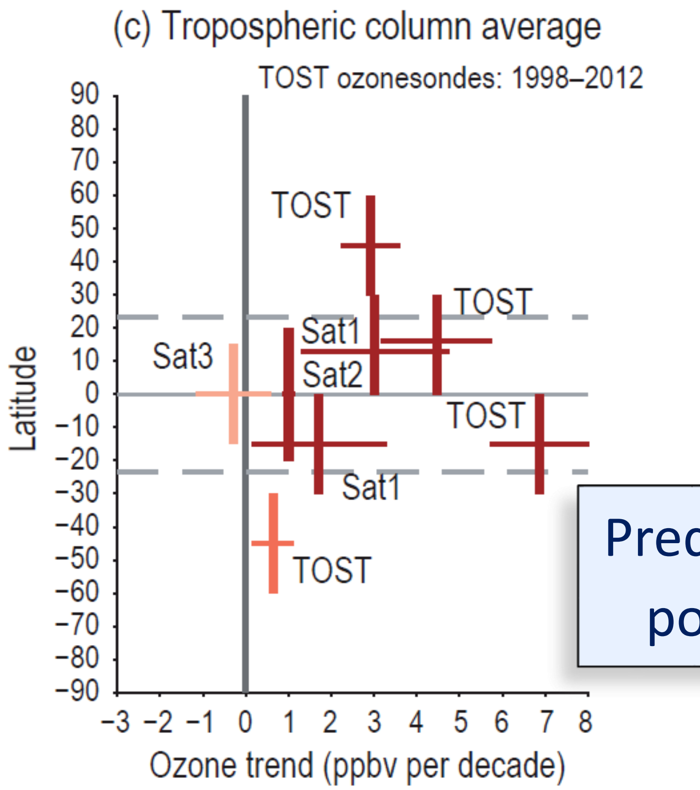
filled symbols = TOST regional trends

All trends

REGIONAL



Mix of pos. and neg. trends



Satellite products:
Sat1 1979–2016 (TOMS, OMI/MLS)
Sat2 1995–2015 (GOME, SCIAMACHY, OMI, GOME-2A, GOME-2B)
Sat3 1995–2015 (GOME, SCIAMACHY, GOME-II)

LATITUDINAL

Predominantly pos. trends

different colors = different regions
open symbols = synthesized trends
filled symbols = TOST regional trends

Conclusions and outlook

- Homogenized ground-based measurements provide TrOC (sfc- 300 hPa) trend estimates **within ± 3 ppb/dec**, for TrOC ranging between 20 (SH, DJF) and 80 ppb (NH, MAM & JJA, especially East USA, South EU, East Asia)
- Mixture of **positive and negative trends** worldwide, but consistently **negative in Arctic** (?) and **positive in East Asia** (continuing increase of ozone precursor emissions)
- **COVID-19 restrictions** led to less ozone precursor emissions and **decreasing TrOC amounts**, impacting present-day (i.e. post-COVID) trends

Further reading and outlook

Atmos. Chem. Phys., 25, 7187–7225, 2025
https://doi.org/10.5194/acp-25-7187-2025

Atmospheric Chemistry and Physics
Open Access
EGU

https://doi.org/10.5194/acp-25-7187-2025

Global ground-based tropospheric ozone measurements: reference data and individual site trends (2000–2022) from the TOAR-II/HEGIFTOM project

Roeland Van Malderen[1], Anne M. Thompson[2,3], Debra E. Kollonige[2,4], Ryan M. Stauffer[2], Herman G. J. Smit[5], Eliane Maillard Barras[6], Corinne Vigouroux[7], Irina Petropavlovskikh[8,9], Thierry Leblanc[10], Valérie Thouret[11], Pawel Wolff[12], Peter Effertz[8,9], David W. Tarasick[13], Deniz Poyraz[1], Gérard Ancellet[14], Marie-Renée De Backer[15], Stéphanie Evan[16], Victoria Flood[17], Matthias M. Frey[18], James W. Hannigan[19], José L. Hernandez[20], Marco Iarlori[21], Bryan J. Johnson[9], Nicholas Jones[22], Rigel Kivi[23], Emmanuel Mahieu[24], Glen McConville[9], Katrin Müller[25], Tomoo Nagahama[26], Justus Notholt[27], Ankie Piters[28], Natalia Prats[29], Richard Querel[30], Dan Smale[30], Wolfgang Steinbrecht[31], Kimberly Strong[17], and Ralf Sussmann[32]

Atmos. Chem. Phys., 25, 9905–9935, 2025
https://doi.org/10.5194/acp-25-9905-2025

Atmospheric Chemistry and Physics
Open Access
EGU

https://doi.org/10.5194/acp-25-9905-2025

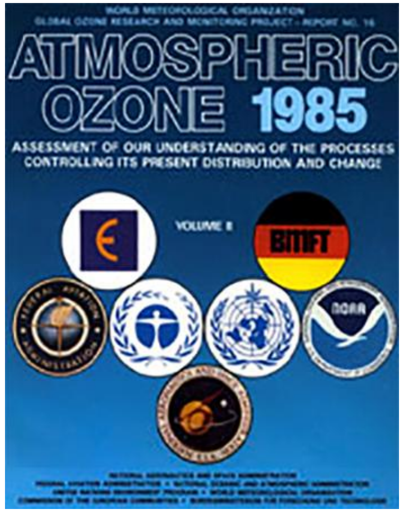
Ground-based tropospheric ozone measurements: regional tropospheric ozone column trends from the TOAR-II/HEGIFTOM homogenized datasets

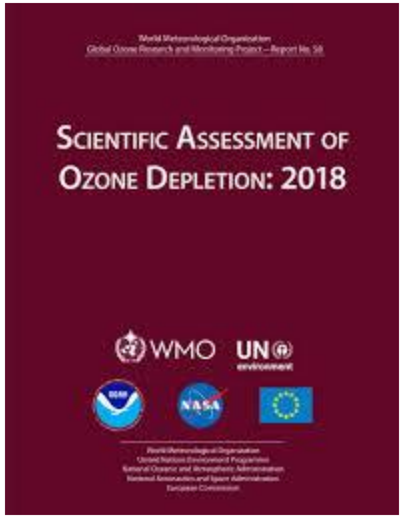
Roeland Van Malderen[1], Zhou Zang[2], Kai-Lan Chang[3,4], Robin Björklund[5], Owen R. Cooper[4], Jane Liu[2], Eliane Maillard Barras[6], Corinne Vigouroux[5], Irina Petropavlovskikh[3,7], Thierry Leblanc[8], Valérie Thouret[9], Pawel Wolff[10], Peter Effertz[3,7], Audrey Gaudel[3,4], David W. Tarasick[11], Herman G. J. Smit[12], Anne M. Thompson[13,14], Ryan M. Stauffer[13], Debra E. Kollonige[13,15], Deniz Poyraz[1], Gérard Ancellet[16], Marie-Renée De Backer[17], Matthias M. Frey[18], James W. Hannigan[19], José L. Hernandez[20], Bryan J. Johnson[7], Nicholas Jones[21], Rigel Kivi[22], Emmanuel Mahieu[23], Isamu Morino[24], Glen McConville[7], Katrin Müller[25], Isao Murata[26], Justus Notholt[27], Ankie Piters[28], Maxime Prignon[29], Richard Querel[30], Vincenzo Rizi[31], Dan Smale[30], Wolfgang Steinbrecht[32], Kimberly Strong[33], and Ralf Sussmann[34]

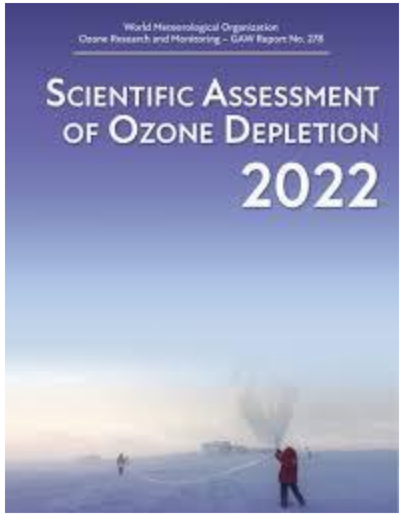
- Those contain additionally detailed TrOC **intercomparisons** at nearby/collocated sites, **1990/1995/2000** – 2022 trend comparisons, relative contribution of **lower+free-tropospheric ozone column trends** to entire tropospheric ozone column trends, TrOC **seasonal cycle change**, etc.
- Those do not contain: variation of **seasonal or low/high percentile trends**!

Outlook: implications for stratospheric ozone assessment

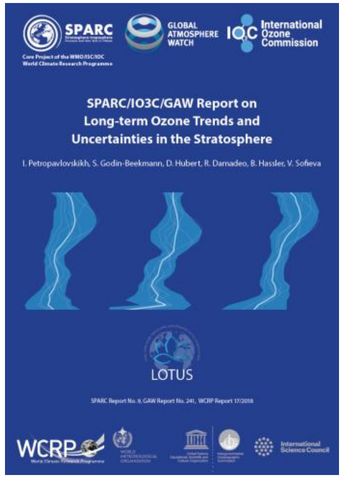
- Stratospheric ozone trends in "**Scientific Assessment of Ozone Depletion**" (every 4 years)





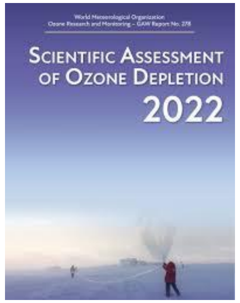


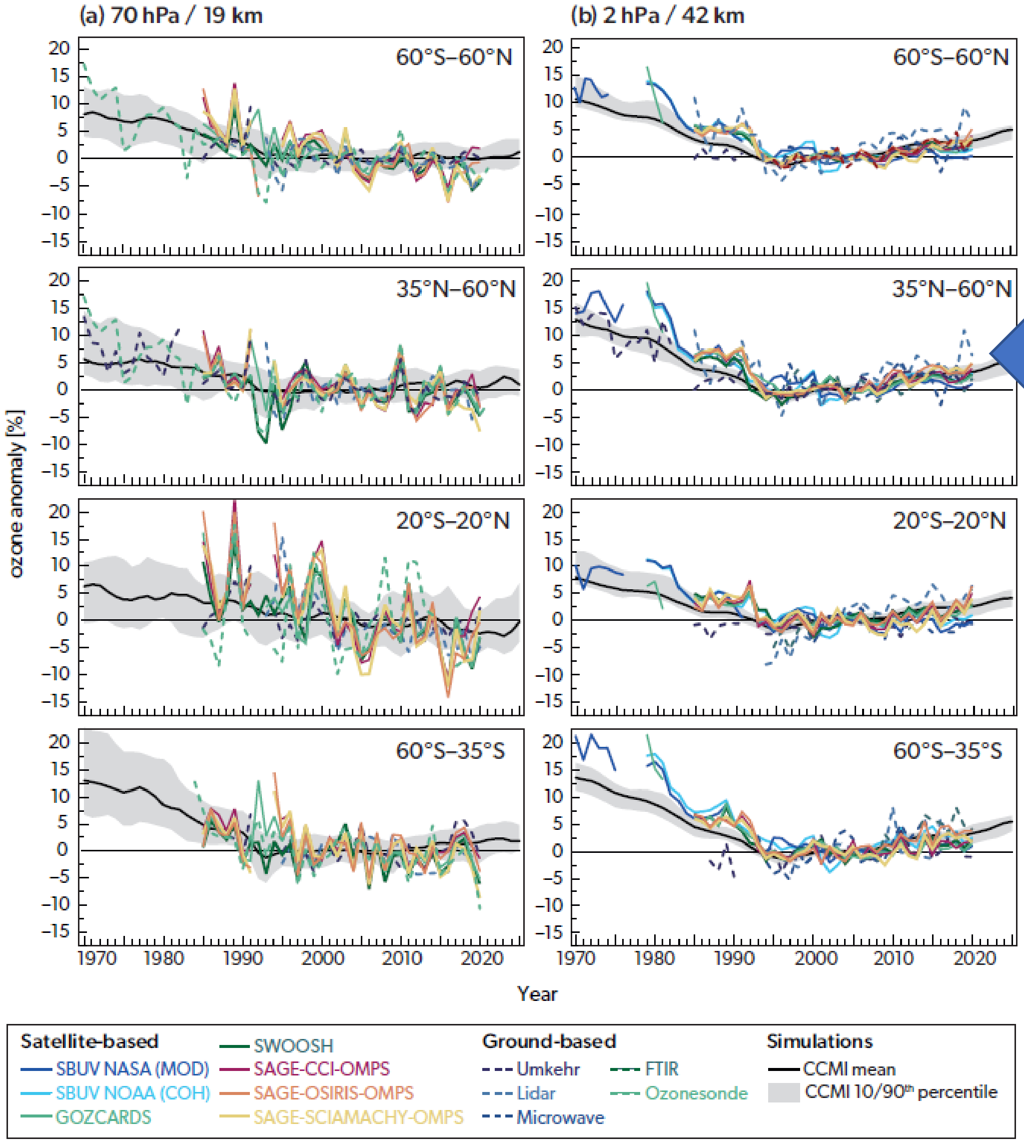
- For last two assessments: **APARC LOTUS** (Long-term Ozone Trends and Uncertainties in the Stratosphere)



Outlook: implications for stratospheric ozone assessment

- **"Limited" role of ground-based profile data in assessments**



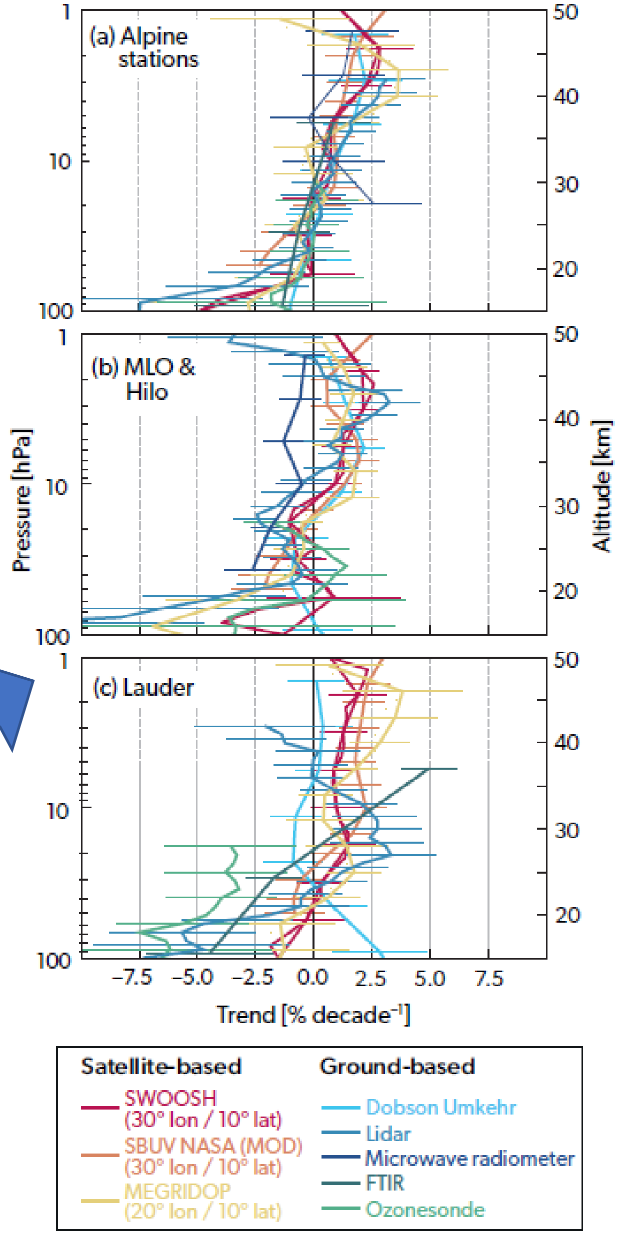


variations in

latitude bands

individual

collocated sites



Outlook: implications for stratospheric ozone assessment

- For next assessment, within LOTUS, **“mimic” HEGIFTOM regional trends** approach

different partial stratospheric ozone columns for different techniques (~~IAGOS~~ → MWR)

→

correlation analysis between CAMS partial ozone columns @ site locations

→

merge the partial ozone column time series within regions with BASIC

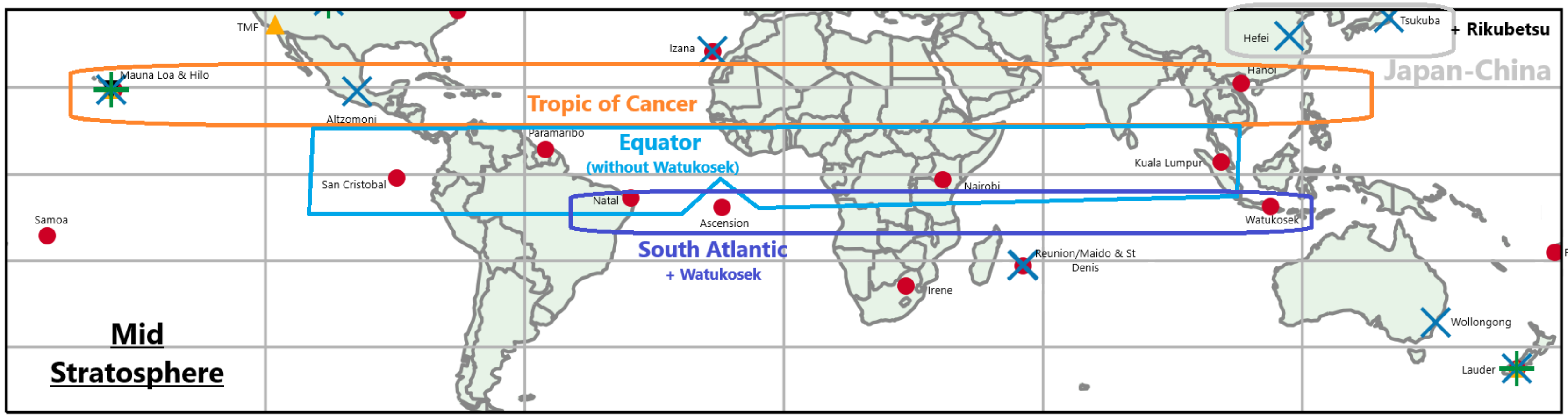
→

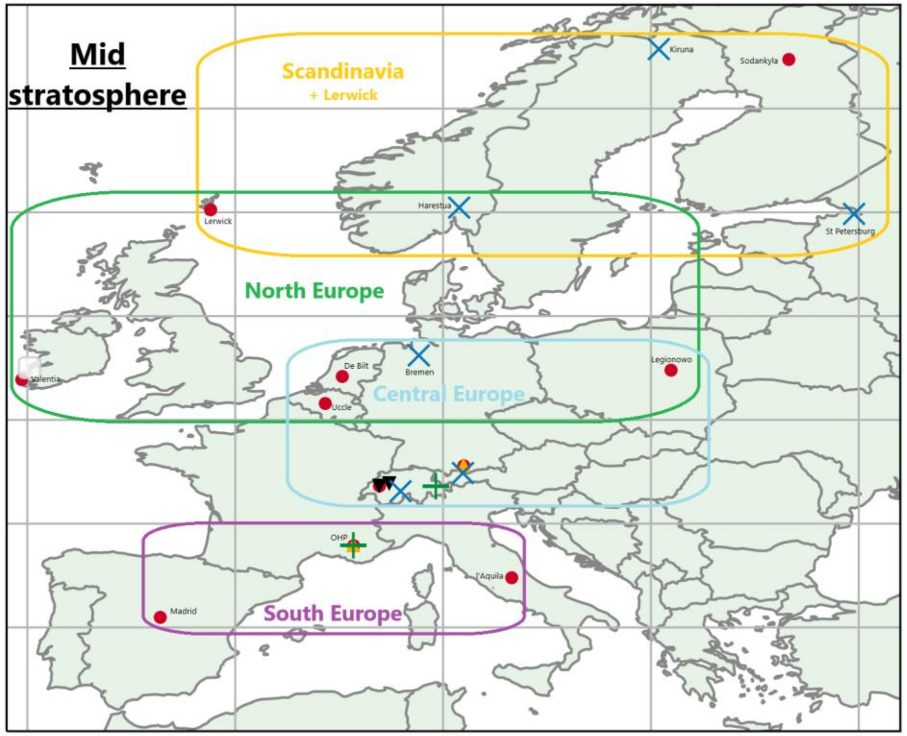
regional trend estimation for different partial ozone columns

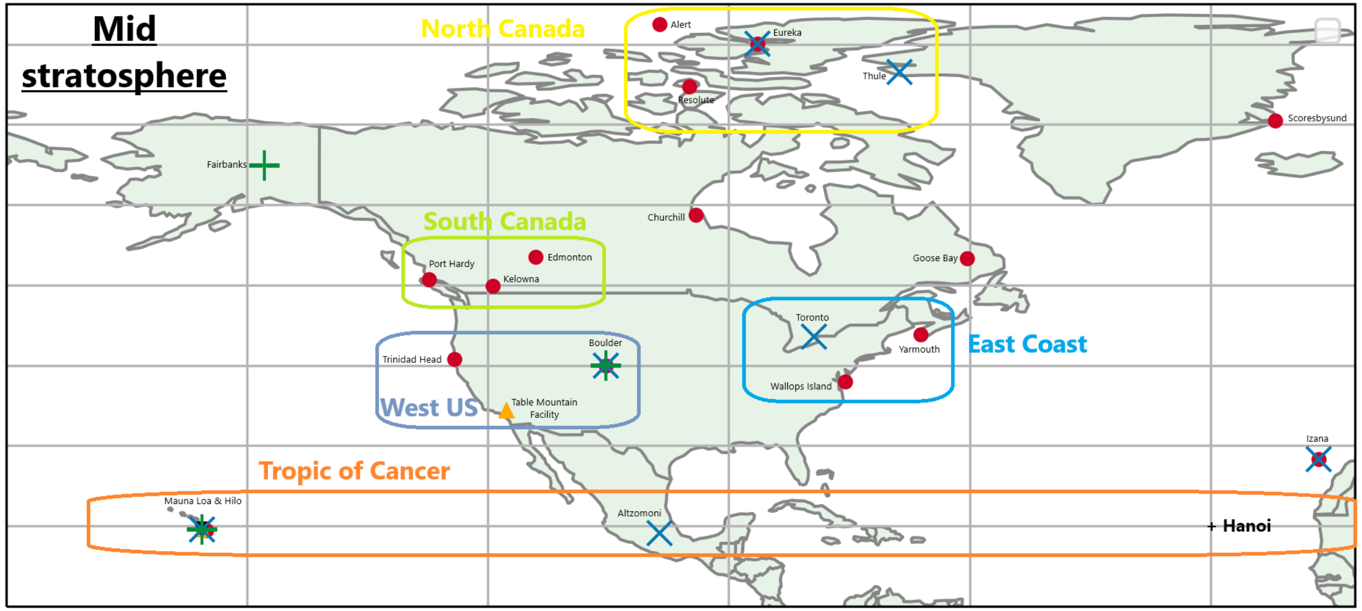
Outlook: implications for stratospheric ozone assessment

TOAR tropospheric ozone assessment report Phase II

correlation analysis between CAMS partial ozone columns @ site locations







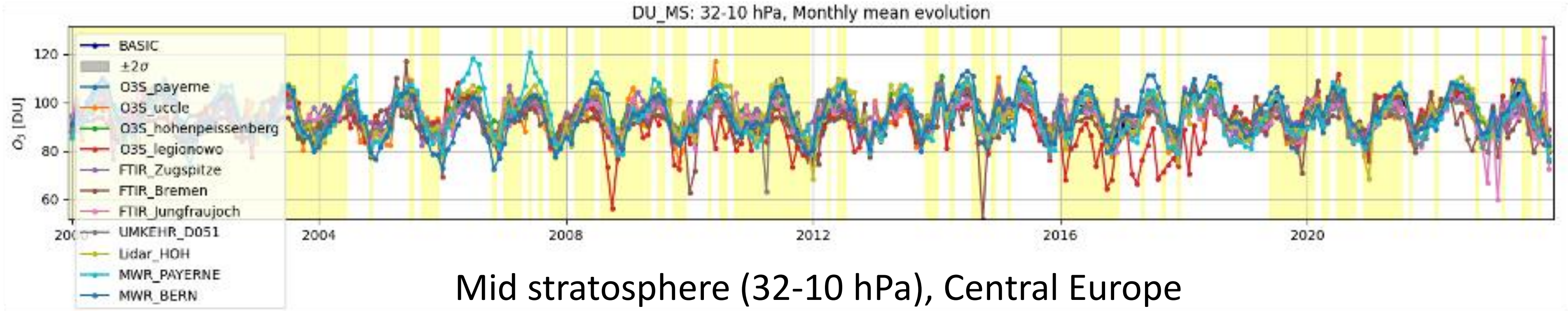
Courtesy Caroline Jonas & Corinne Vigouroux (BIRA)

Outlook: implications for stratospheric ozone assessment

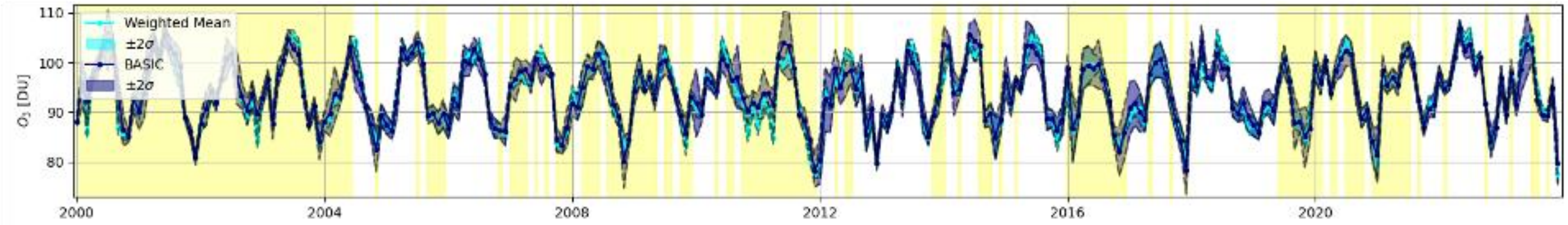
merge the partial ozone column time series within regions with BASIC

Use Bayesian method to "automatically correct" the ozone composites:

1. Construct uncertainty estimates (on each monthly mean) and include all additional prior information that we have available
2. Form a Gaussian-mixture likelihood (Probabilistic model of the data)
3. Develop transition priors to estimate how ozone is expected to vary on monthly timescales (month-to-month climatology)
4. Multiply the transition prior with the likelihood and obtain the posterior distribution.



Mid stratosphere (32-10 hPa), Central Europe

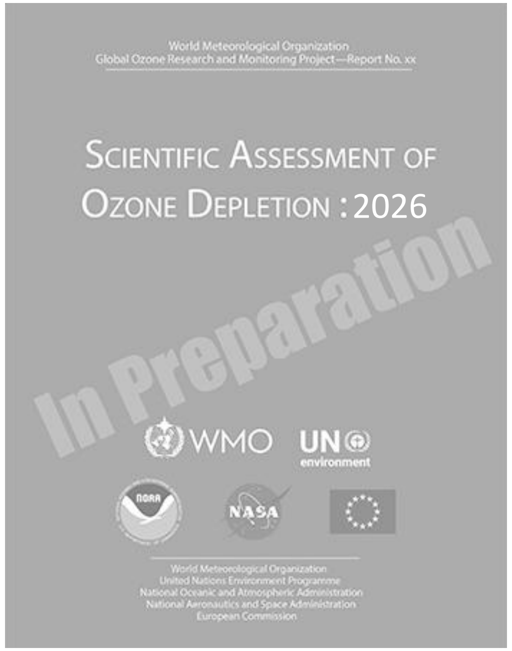


Courtesy Louis Miralle & Eliane Maillard Barras (MeteoSwiss)

This talk:

TOAR
tropospheric
ozone
assessment
report

TOAR
tropospheric
ozone
assessment
report
Phase II


World Meteorological Organization
Global Ozone Research and Monitoring Project—Report No. xx

SCIENTIFIC ASSESSMENT OF OZONE DEPLETION : 2026

In Preparation

WMO UN environment

NOAA NASA

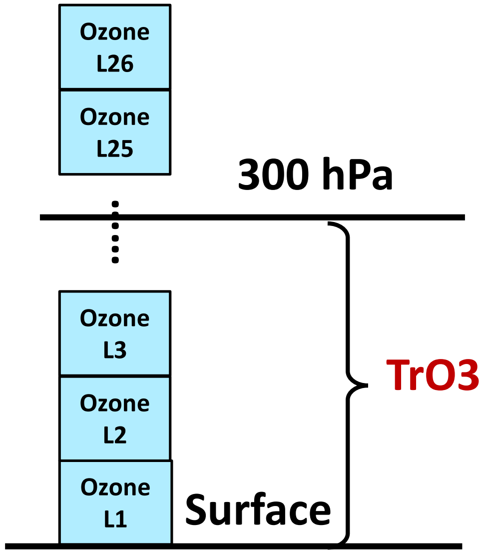
World Meteorological Organization
United Nations Environment Programme
National Oceanic and Atmospheric Administration
National Aeronautics and Space Administration
European Commission

… with focus on ground-based measurements!

Thank you for your attention!

Questions?

2 strategies for regionalized trends: 1. TOST



1. Convert TOST **from altitude level to pressure level:** using the MERRA-2 geopotential height at each pressure level.

2. Monthly TOST **gap filling vertically**: linearly interpolate the profile when there are >80% available data between the selected altitude range (>300hPa/4-8km)

3. Monthly TOST **gap filling horizontally**: if there's a gap, averaging the closest surrounding (<1000km) gridpoints with available data, weighted by distance [details see Liu et al. (2022)].

4. Calculate **seasonal mean TOST** in each year: at least one available value for each season.

5. Calculate **seasonal mean TrO3** in each year.

6. Calculate **the annual mean TrO3**: at least one available value for each season.

7. Calculate **the regional mean TrO3**: average the TrO3 over the selected region weighted by grid area [*cosine(lat)].

8. Calculate the **Quantile Regression trend** using the annual and regional mean TrO3

BASIC

Use Bayesian method to "automatically correct" the ozone composites:
1. Construct uncertainty estimates (on each monthly mean) and include all additional prior information that we have available
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