ACP 2026:

Detecting Ozone Recovery in the Arctic

FTIR annual meeting - Göteborg 2026

Caroline Jonas
Corinne Vigouroux

Collaborators: B. Langerock, R. Björklund, A. Boynard, T. Carlund, M. De Mazière, P. Effertz, Q. Errera, M. Frey, J. Granville, J.W. Hannigan, N. Jepsen, A. Keppens, R. Kivi, N. Lyall, G. McConville, M. Palm, M. Prignon, V. Sofieva, K. Strong, T. Svendby, D. Tarasick, L. Thölix, R. Van Malderen, Y. Virolainen, S. von Löwis, and X. Zhao

Context of the project

Montreal Protocol and Amendments (since 1987)

↓

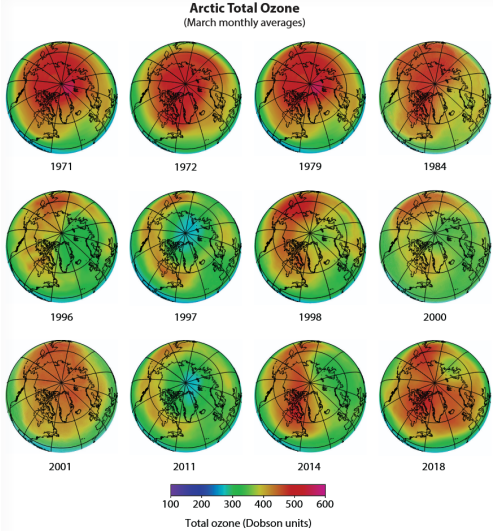
Diminution of **Ozone Depleting Substances (ODS):** CFCs, HCFCs, ...

↓

Predicted recovery of stratospheric ozone

↙ ↘

Observed in the Antarctic | Not yet detected in the Arctic



Difficulties detecting recovery in the Arctic:

- ⋆ **smallness of trends** (few % per decade)
- ⋆ **large uncertainties** (natural variability)

Ross J. Salawitch et al., WMO 2019.

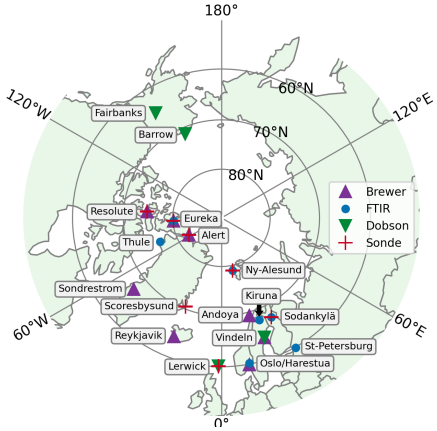
1. Ground-based detectors of Ozone

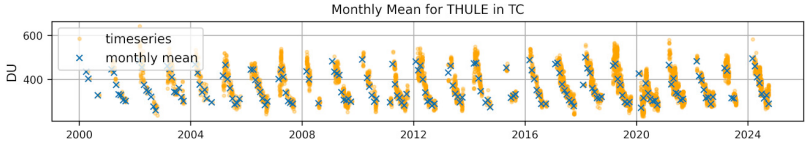
Using 3 types of O_3 ground-based detectors:

1. Fourier Transform Infrared spectrometer: **IRWG2023** FTIR
2. Ozonesondes in Balloons
3. Dobson and Brewer spectrophotometers

Network summary

- ⋆ 17 stations in the Arctic (60°N – 90°N)
- ⋆ 2000 - 2024 timeseries
- ⋆ **GB ozone profiles + total column ozone**
  - FTIR Total column + 3 stratospheric partial columns: 8 – 17 km, 17 – 26 km, 26 – 48 km + 1 tropospheric column 0 – 8 km
  - Ozonesondes Profile but only up to 26 km
  - Brewer and Dobson spectrophotometers Total Column only





2. Comparison of satellites vs GB time series

1) **Validate quality of individual ground-based time series**

2) **Evaluate satellites drifts in the 60°N – 90°N region**

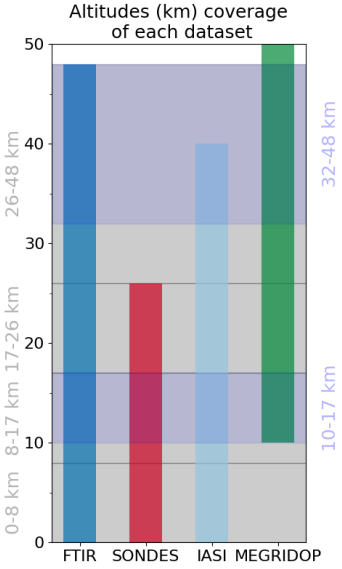
Satellite datasets used:

IASI:

- IR interferometer, 2008 – 2024, monthly gridded
- Total column: IASI-A+B
- Partial columns: IASI-AB profiles 0 – 40km

MEGRIDOP:

- 6 limb satellite instruments merged
- 2001 – 2024, monthly gridded 10 – 50km



Method of comparison: Compare monthly deseasonalized anomalies time series

$$\text{anom}^{\text{month}_i,\,\text{year}_j} = \frac{O_3^{\text{month}_i,\,\text{year}_j} - O_3^{\text{month}_i}}{O_3^{\text{month}_i}} \quad \text{where} \quad O_3^{\text{month}_i} = \frac{1}{n+1} \sum_{j=\text{start year}}^{\text{start year}+n} O_3^{\text{month}_i,\,\text{year}_j}\,.$$

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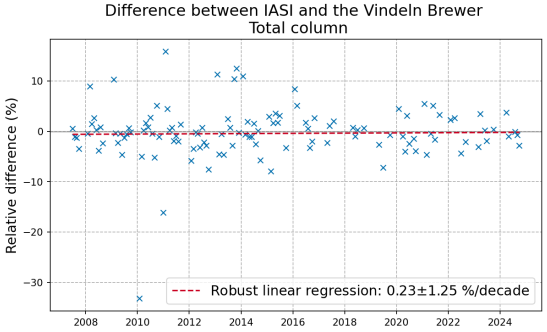
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Drift = Trend of the difference

|b| satellite & GB anomalies:

$$\left(\text{anom}^{i}_{\text{sat}} - \text{anom}^{i}_{\text{GB}}\right) \cdot 100\%$$

Robust linear regression (Theil-Sen)
+ bootstrap for autocorrelation

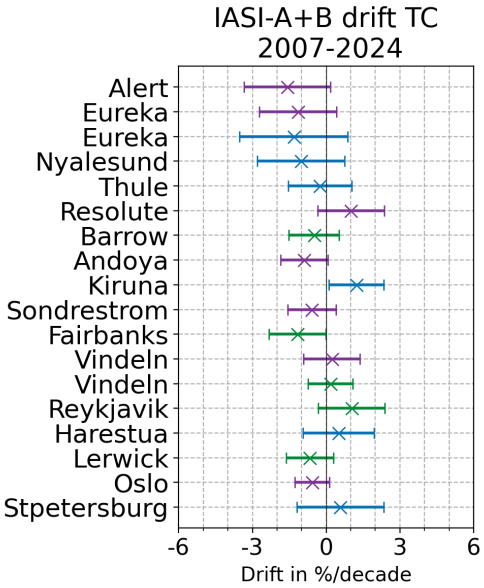


1) Validate individual GB time series

Total column:

FTIR, Brewer and Dobson vs. IASI-A+B

- All drifts $<$ |1.6% per decade|



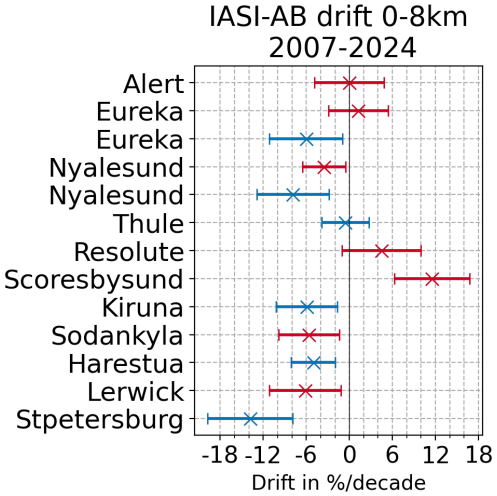
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Tropospheric column:

FTIR and Ozonesondes vs. IASI-AB

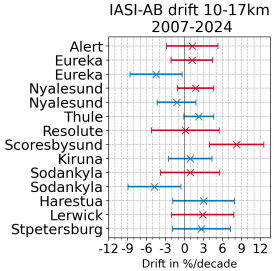
- **Significant negative drift in 8 GB stations**
  Degrading FTIR and sondes profiles to IASI sensitivity (DOFS<0.4) worsen negative drifts! (Boynard, 2025)

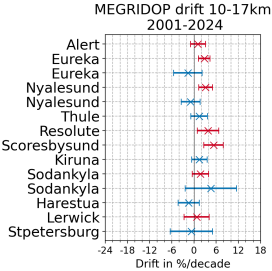
- **Scoresbysund sonde:** outlier

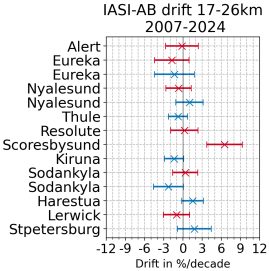


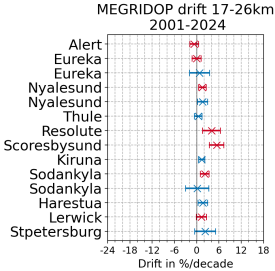
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Lower and Mid Strato: FTIR and Sondes vs. IASI and MEGRIDOP



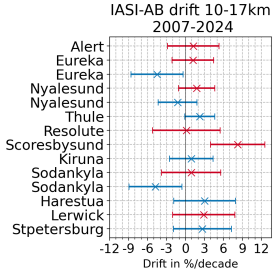


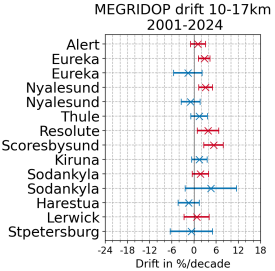


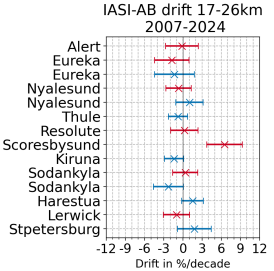


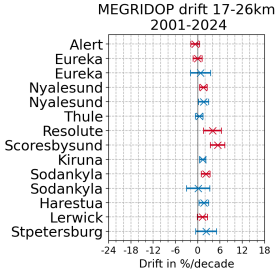
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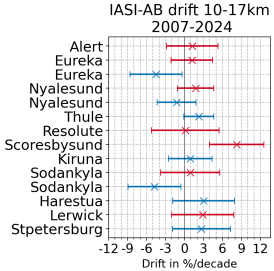


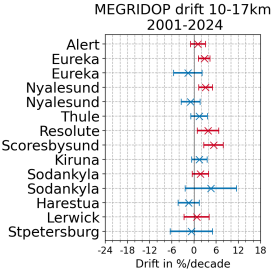


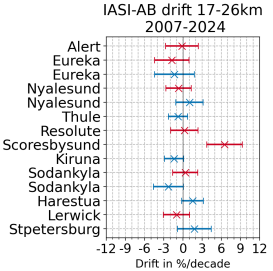
- **Scoresbysund sonde:** identified pump temperature issue starting 2016
  → **Scoresbysund time series excluded**

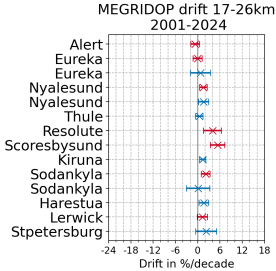
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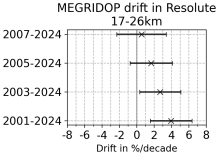






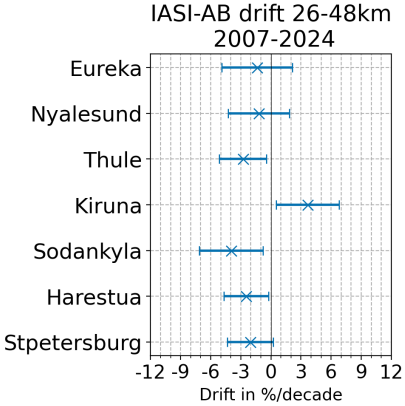
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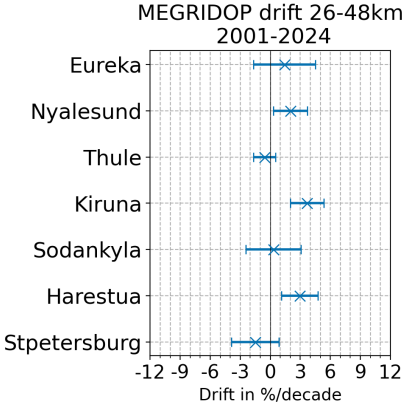
- **Resolute sonde:** Period issue, drift disappears starting from 2005: jump? → **Resolute time series restricted to 2005 – 2024**



1) Validate individual GB time series

Upper Strato: FTIR only vs. IASI and MEGRIDOP



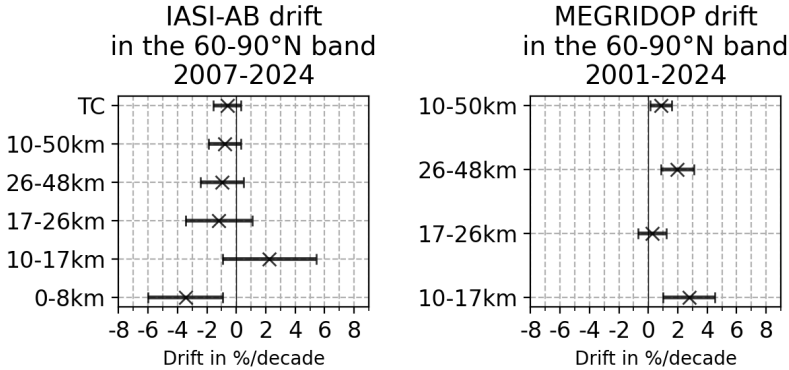


Kiruna FTIR:
outlier for IASI but not for MEGRIDOP

(clear outlier for both on 2007-2022!) satellites

2) Evaluate the satellite drifts in the Arctic

Drifts of IASI and MEGRIDOP after removing problematic GB timeseries:



- **IASI:** only significant drift in **troposphere**
- **MEGRIDOP:** small drifts in **lower strato**, **upper strato** and **total strato**

3. Representativeness of Ozone Variability

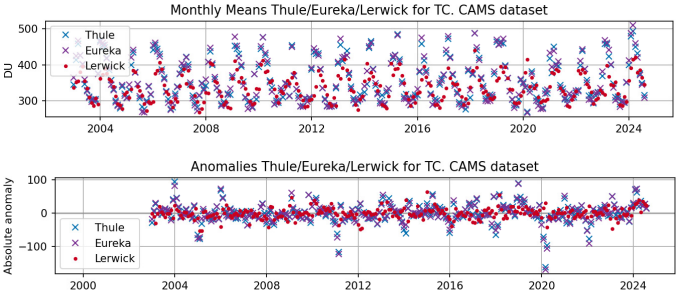
- For which **spatial extent** is each ground-based ozone detector representative of the ozone variability?

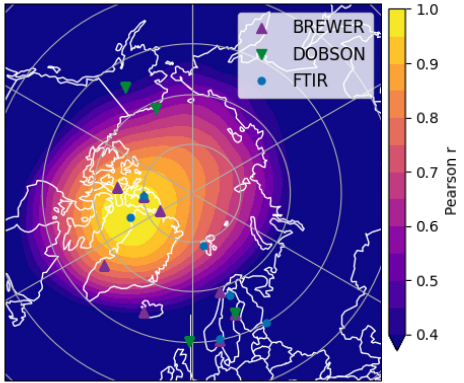
  → Which datasets can be merged together to help reduce uncertainties?

Representativeness of Ozone Variability

- ⋆ Based on CAMS datasets: **monthly ozone profiles 2003-2024**
- ⋆ Pearson coefficient of correlations r |b| monthly deseasonalized absolute anomalies:

$$\mathrm{a}^{\mathrm{month}_j,\,\mathrm{year}_i} = \mathrm{O}_3^{\mathrm{month}_j,\,\mathrm{year}_i} - \mathrm{O}_3^{\mathrm{mean\ month}_j}$$

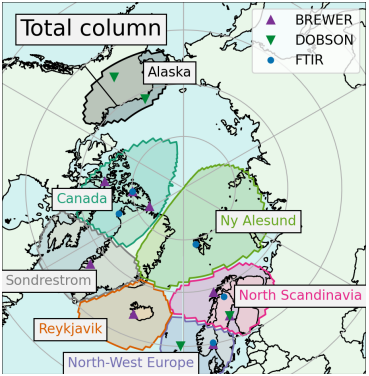




Correlation map for Thule (total column)

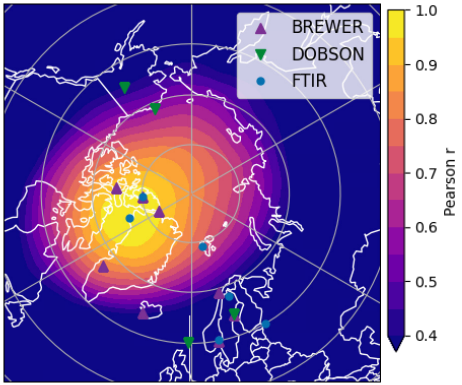
Representativeness of Ozone Variability

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- Pearson coefficient of correlations r |b| monthly deseasonalized absolute anomalies:



Representative regions for $r > 0.8$

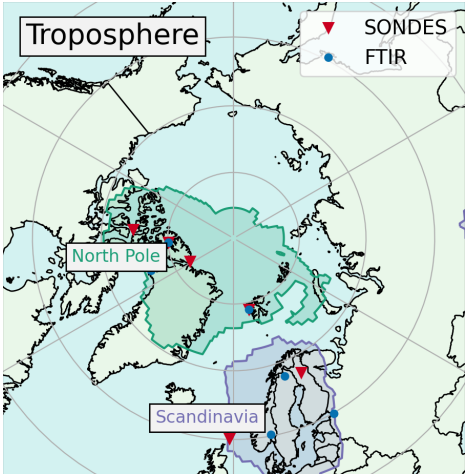
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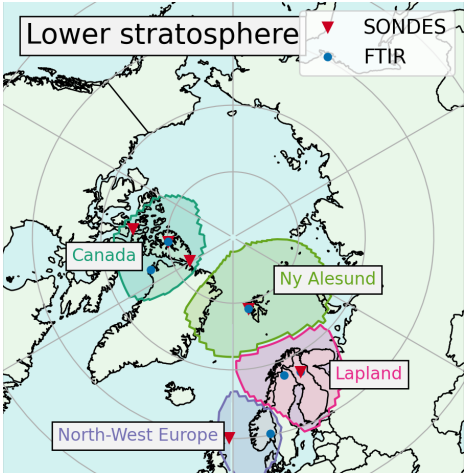


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Representativeness of Ozone Variability

Partial columns: $\neq$ groups and regions $\propto$ altitude ($\neq$ dynamics and homogeneity)

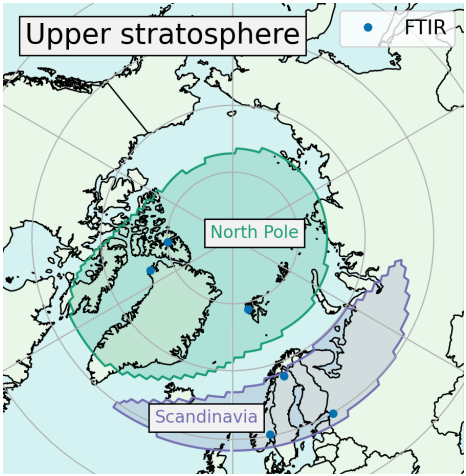




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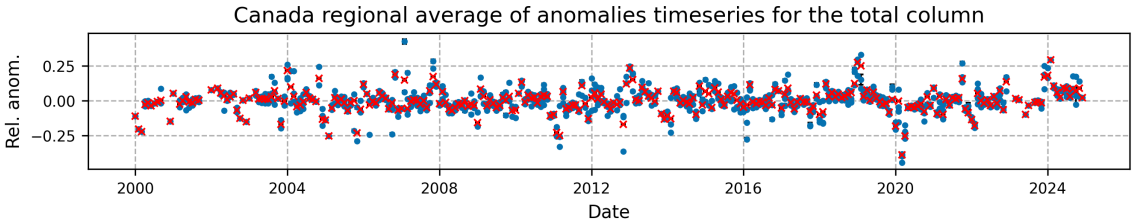


4. Merged ground-based datasets

⋆ **Weighted merging** of all datasets within each representative regions:

For N anomalies datasets anom_α,

$$\mathrm{anom}_{\text{w-m}} = \frac{\sum_{\alpha=1}^{N} \omega_\alpha \, \mathrm{anom}_\alpha}{\sum_{\alpha=1}^{N} \omega_\alpha} \qquad \text{with weight } \omega_\alpha = 1/(\Delta\mathrm{anom}_\alpha)^2.$$



5. Trends

- Multiple linear regression (MLR) and proxies relevant in the trends
- Analysis of trend results

Multiple Linear Regression

Ozone trends are small $><$ **Ozone variability is large**

↓

Need MLR to reduce uncertainty and explain variability

Multiple Linear Regression

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Need MLR to reduce uncertainty and explain variability

Regression Model: $a(t) = A_1 + A_2 \cdot t + \sum_{n=3}^{m} A_n \cdot X_n(t) + \varepsilon(t)$

$X_n(t)$= proxies; A_2= trend; $\varepsilon(t)$= residual. Error on trend: $2\sigma \times$ factor for autocorrelation

Process	Proxy used
11-year solar cycle	Bremen composite Mg II index
QBO30,10	Singapore wind speed at 30 and 10hPa
ENSO	Multivariate ENSO Index (MEI)
AO	Arctic Oscillation Index
BDC	Accumulated eddy heat flux (ERA5) at 100 hPa, 45°-75°
VPSC	Volume of Polar Stratospheric Clouds
TP	Tropopause Pressure at each station location (ERA5)
EL (LS,MS,US)	Local Equivalent Latitude averaged over each stratospheric column (ERA5)
T (LS,MS,US)	Local Temperature averaged over each stratospheric column (ERA5)

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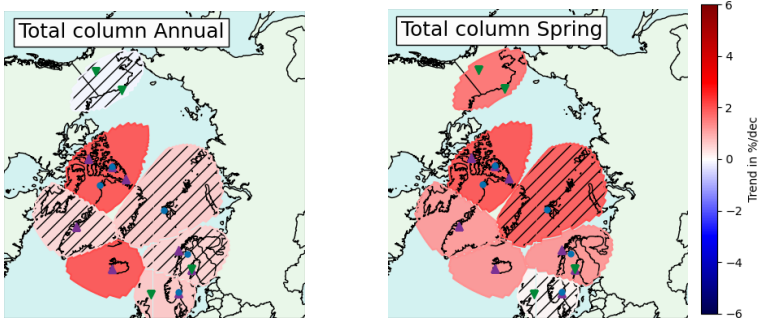
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Stepwise regression procedure: make sure only relevant proxies are included + avoid overfitting

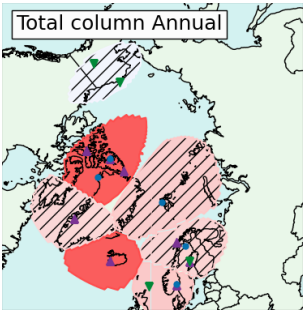
Trends results Total column: FTIR, Brewer and Dobson

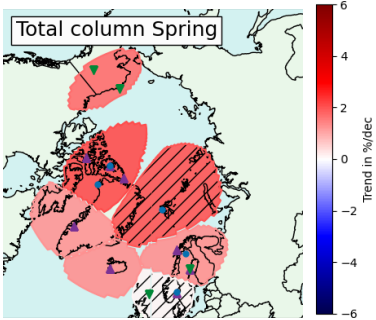
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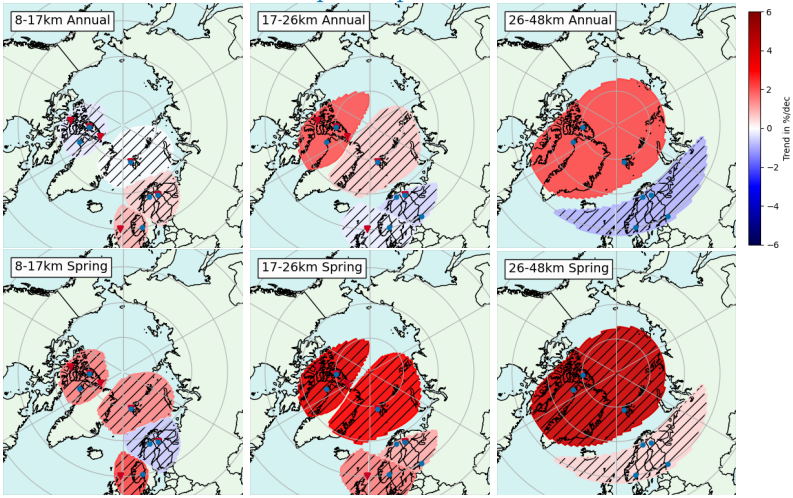


- Bernet et al. 2023:
  Norway GB stations **B2023**

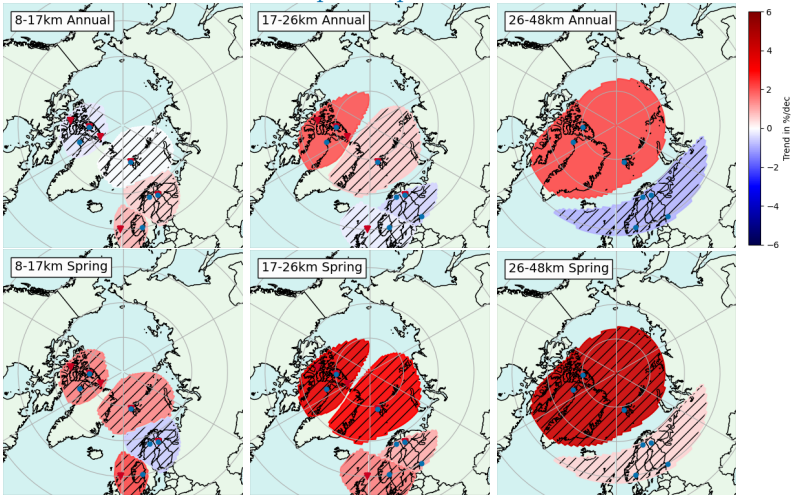
- Anjali, Kuttippurath 2025:
  Zonal mean (merged stations 59°N-90°N) **AK2025**

	B2023	**AK2025**	**Us**
% per dec.	Andoya		Lapland
Annual	0.9 ± 0.7		0.53 ± 0.84
% per dec.	Oslo		NW EU
Annual	0.1±0.5		0.70 ± 0.68
% per dec.	Ny Alesund		Ny Alesund
Annual	1.5 ± 0.1		0.63±1.49
DU per dec.		59-90°N	60-90°N
Annual		6.5 ± 4.0	5.56 ± 2.69
Spring		7.5 ± 6.1	5.89 ± 7.50

Trends results Stratospheric partial columns: FTIR and Ozonesondes

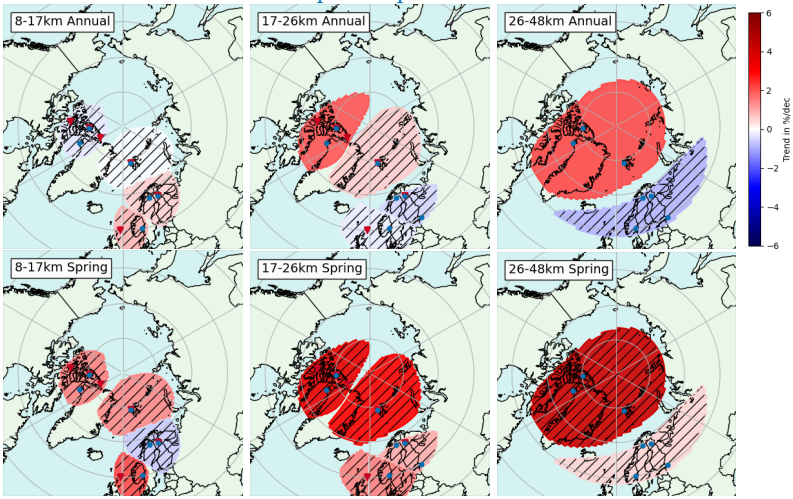


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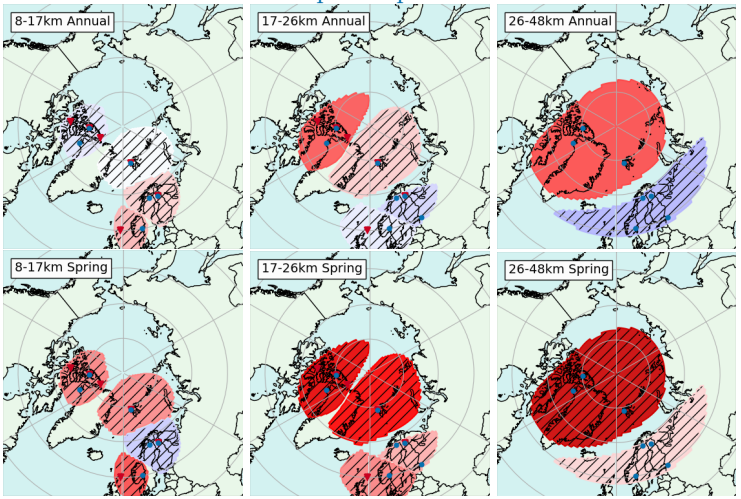
- Lower strato: only non-significant trends

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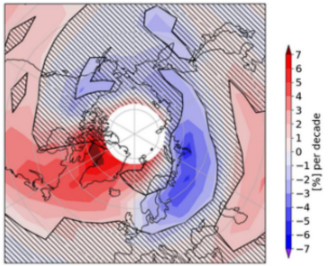


- Lower strato: only non-significant trends
- Mid strato: non significant but coherent increase in Spring + positive significant annual trend in Canada ⇒ **hint of ozone recovery!**

Trends results Stratospheric partial columns: FTIR and Ozonesondes



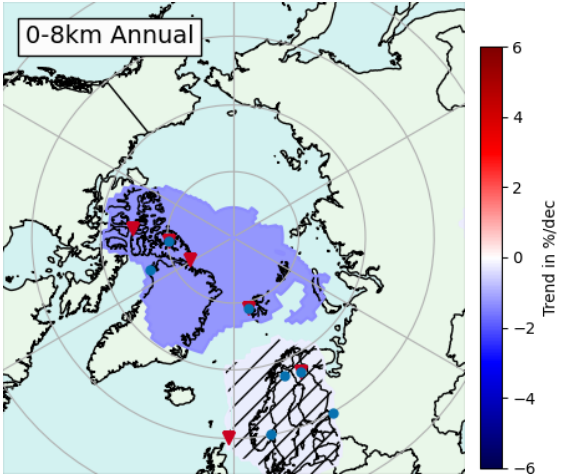
- Mid and upper strato: **zonal asymmetry** already observed with satellites and attributed to decadal changes in the Polar Vortex position in Arosio et al., 2024



Seasonal ozone trends in Spring 2004-2021, 32 km SCIA+OMPS

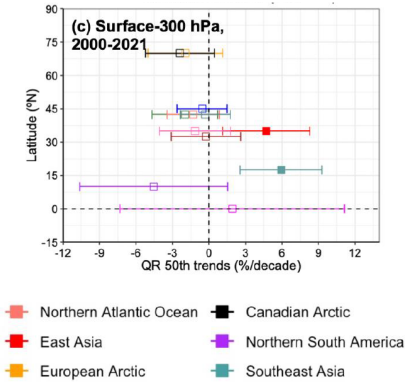
- Lower strato: only non-significant trends
- Mid strato: non significant but coherent increase in Spring + positive significant annual trend in Canada ⇒ **hint of ozone recovery!**

Trends results Tropospheric column: FTIR and Ozonesondes



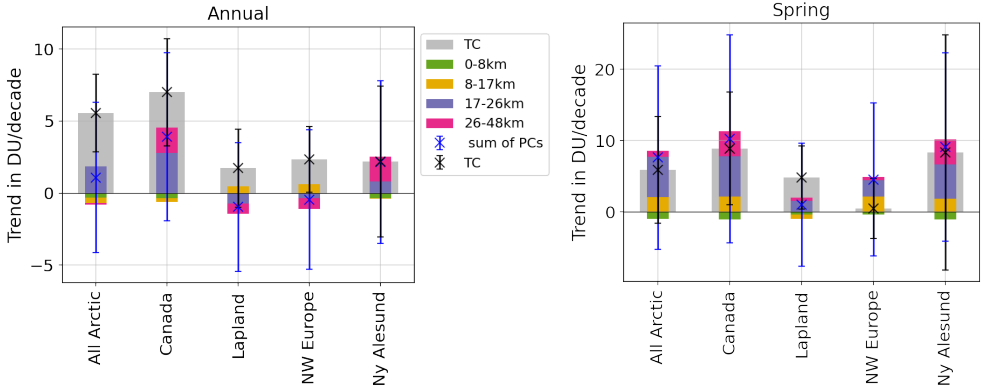
- Significant negative 2000-2024 annual trends in Canada

Comparison with TOAR (Tropospheric Ozone Assessment Report) **results:**



Van Malderen et al. 2025

Trends results Comparison of the sum of partial columns to the total column



- Overall agreement despite ≠ instruments in PCs and TC

Conclusions

1. Cross-comparison of all GB O_3 time series with satellites (IASI, MEGRIDOP) data in the Arctic: problems in some GB time series + evaluation of satellites drifts

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   - **Decline of tropospheric O_3** but not affecting the TCO!

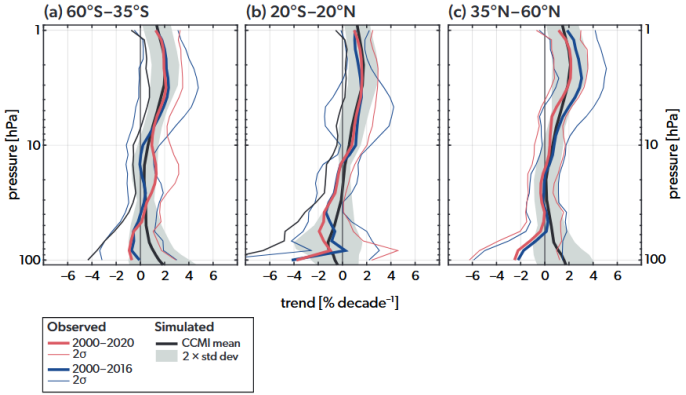
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Aim: Understand the mid latitude lower strato. O_3 trend discrepancy:
observations ($-$) vs. models ($+$)

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Hassler B., Young P. et al, WMO 2022, Figure 3-12

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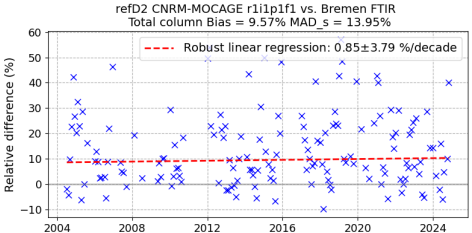
How:

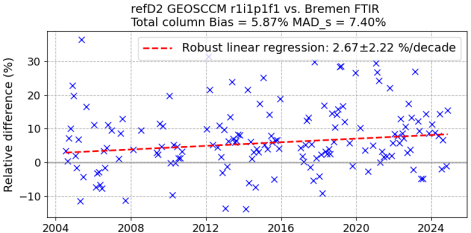
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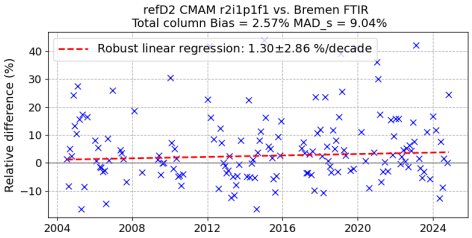
⇒ Better understand chemical & dynamical factors influencing O_3 trends

Future prospects: New funded 4-year project on O_3 (**OZOMATIC**)

Evaluation of CCMI-2022 models:







Examples of O_3 total column comparison between models and FTIR at Bremen.

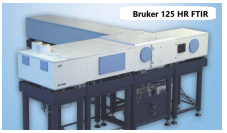
Thank you for your attention!

ACP 2026:



https://acp.copernicus.org/articles/26/8089/2026/

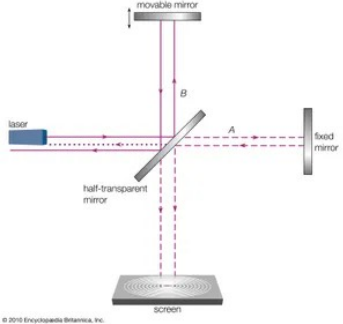
1. FTIR spectrometers

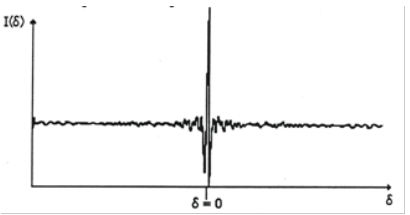


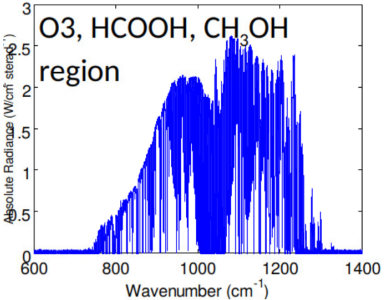
Measures the solar absorption Spectrum (O_3, CH_4, CO_2, CH_2O, ...)
$\Rightarrow$ need clear-sky, no measurement in polar night

In practice:

1) a Michelson Interferometer measures an Interferogram (interference pattern of Solar light with different arm sizes)
2) Fourier transformation $\rightarrow$ solar absorption Spectrum (absorption lines vs frequencies)



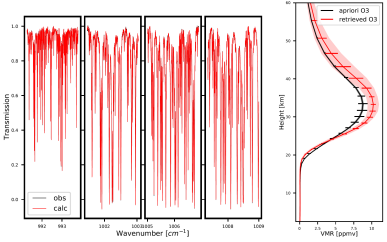




1. FTIR spectrometers

In practice:

3) Retrieval of nb of molecules/cm^2 over the **total column** of atmosphere
+low-resolution vertical profile: 4-5 **partial columns**



Line position: which gas is absorbing

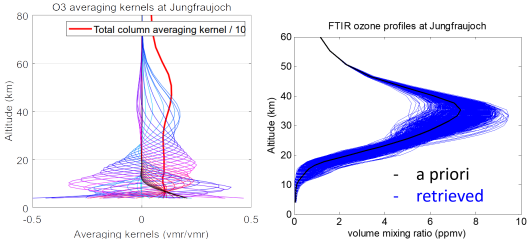
Line area: amount of gas (total column)

Line shape: vertical distribution (pressure and temperature broaden the lines)

1. FTIR spectrometers

In practice:

3) Retrieval of nb of molecules/cm^2 over the **total column** of atmosphere
+low-resolution vertical profile: 4-5 **partial columns**



Retrieval: Optimal Estimation (Rodgers 2000)

⋆ $x_{\text{retrieved}} = x_{\text{apriori}} + \mathbf{A}(x_{\text{true}} - x_{\text{apriori}}) + errors$

⋆ **A**: rows are the averaging kernels and trace gives the Degrees of Freedom for Signals (DOFS)

⇒ Retrieval settings: optimized to maximize DOFS & minimize uncertainties

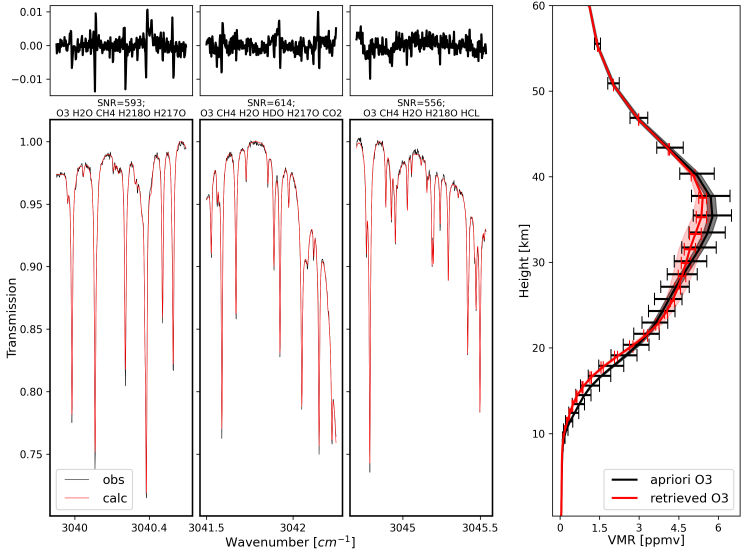
NDACC: in the mid IR ($600 - 4000\text{cm}^{-1}$)

• Harmonized strategy (InfraRed Working Group) Vigouroux et al. 2015, Björklund et al. 2024

• O_3 Settings updated: fitted spectral windows~1005cm^{-1} (reduced H_2O influence), spectroscopy database HITRAN2020 (reduced bias), a priori profiles and regularization matrix WACCMv7

1. FTIR spectrometers

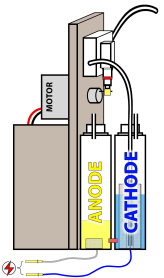
⋆ Sodankylä new O_3 time series retrieved from TCCON data (3040cm^{-1}): DOFS$\sim$ 2.5, 2012 – 2024

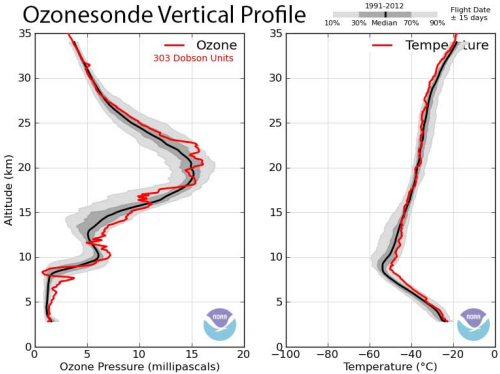


2. Ozone Sondes in Balloons

- ⋆ Electrochemical Concentration Cell (ECC) ozonesondes carried on balloon flights
- ⋆ Electrical current depends on ozone concentration → converted into **ozone partial pressure** (measurement done every 5 to 10 meters from 0 to 30/35km)
  ⇒ **High vertical resolution profile**







Pictures taken from NOOA `https://gml.noaa.gov/ozwv/ozsondes/`

3. Brewer and Dobson spectrophotometers

- ⋆ Compares solar intensity of wavelength pairs (one weakly absorbing and one strongly absorbing)
- ⋆ Uses UV light (about $300 - 350$ nm)
- ⋆ Direct Sun (DS) measurements (1% precision) but also moonlight (FM) and cloudy skys (ZS) ($5 - 10\%$ precision) $\Rightarrow$ measurements in polar night!
- ⋆ Only obtain total column of O_3
- ⋆ Alert Brewer: cloudy (ZS) measurements are not well calibrated $\rightarrow$ filtered out



Picture from KMI: Brewer spectrophotometers in Uccle



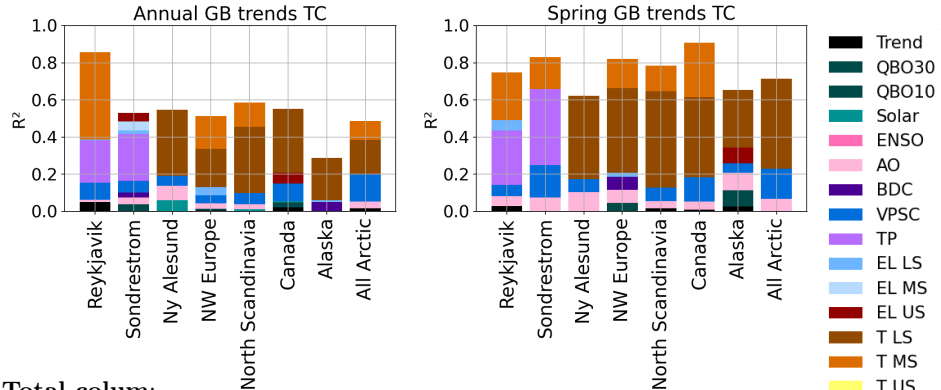
Picture from NOOA: Dobson spectrophotometer

Proxies analysis: Calculate the contribution to R^2 of each proxy

Coefficient of determination $R^2 \equiv$ "how well the model fits the data".

$R^2 \sim 1 \Leftrightarrow \varepsilon(t) \sim 0$: most of the variability is explained

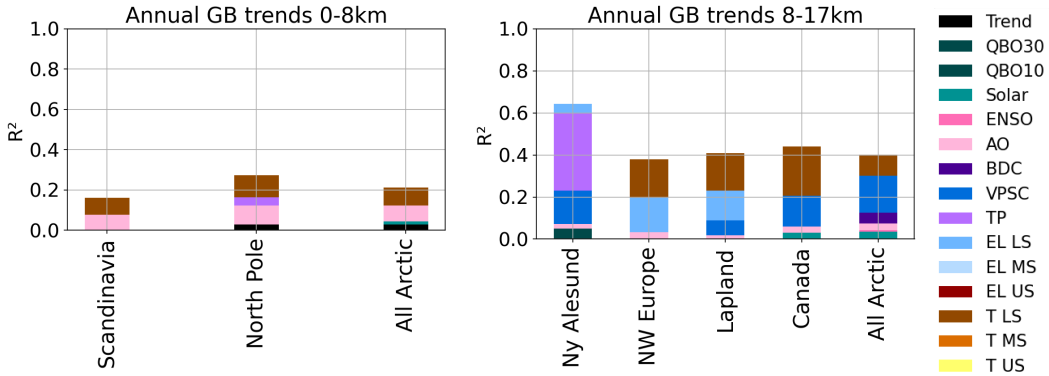
$R^2 \sim 0 \Leftrightarrow \varepsilon(t) \sim a(t)$: none of the variability is explained



Total colum:

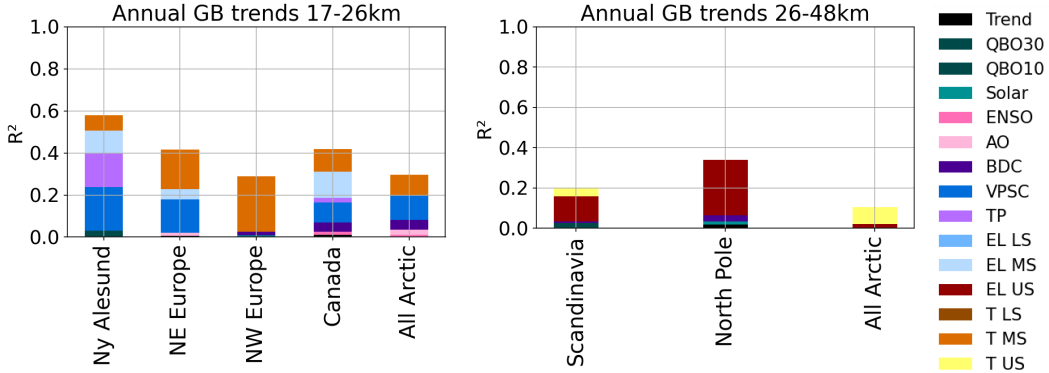
- averaged temperature T_{LS}, averaged temperature T_{MS}, VPSC and arctic oscillation AO
- TP only important at individual sites: well known (important for individual GB & not for satellites)

Proxies analysis



- **Troposphere**: trend, averaged temperature over $8-17$km (T_{LS}), arctic oscillation (AO) and solar cycle (Solar). **Much lower** R^2 (our dynamical proxies don't capture the variability there)
- **Lower stratosphere**: averaged temperature over $8-17$km (T_{LS}), VPSC and averaged equivalent latitude over $8-17$km EL_{LS}.

Proxies analysis

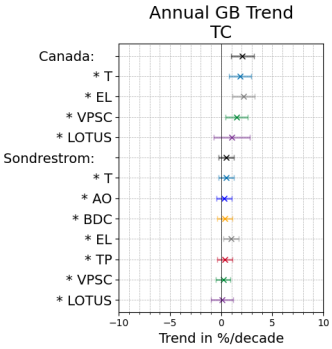


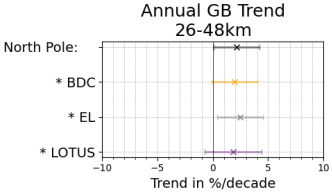
- **Mid stratosphere**: exactly the same as lower stratosphere: temperature, VPSC and equivalent latitude
- **Upper stratosphere**: averaged equivalent latitude over $26-48$km ($\mathrm{EL_{US}}$), averaged temperature over $26-48$km ($\mathrm{T_{US}}$), VPSC) and Brewer-Dobson circulation (BDC).

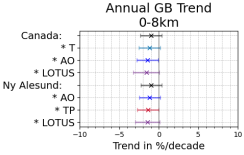
Conclusions

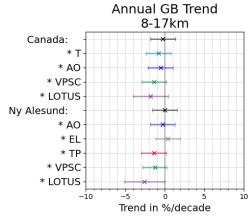
- ⋆ Trend plays a small role → large natural variability of O_3.
- ⋆ Overall good fits for anomalies + proxies homogeneous & sensible: trustworthy regression.
- ⋆ Some proxies correlate (T_{US}, EL_{US}) but simultaneous use improves R^2 while leading to smaller trends uncertainties (no overfitting detected)

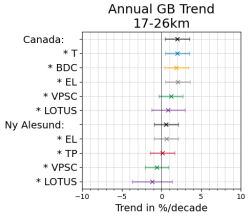
Trend results Comparison with LOTUS proxies and effect of detrending











- ⋆ **Compared to LOTUS:** additional proxies improve trends uncertainties (+ larger R^2)
- ⋆ Proxies detrending leads to non-significant differences within errors but can have impact on small trends
- ⋆ VPSC: -0.8%/dec: lower & mid strato trends become $\ominus$ / non-sign.
- ⋆ Other proxies: $< |0.5\%/\text{dec.}|$