Is stratospheric ozone recovering as we expect? Results of the SPARC/WMO LOTUS analyses.

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LONG-TERM OZONE TRENDS AND UNCERTAINTIES IN THE STRATOSPHERE
LOTUS

The LOTUS-2 project goals:

(a) Update and extend stratospheric ozone observations to recent years

(b) Improve our understanding of crucial yet poorly known sources of uncertainties in trend retrieval

(c) Investigate how uncertainties interact and propagate through the different stages of analysis chain

(d) Re-evaluate current best practices and possibly establish more suitable alternatives.

SPARC website :
http://www.sparc-climate.org/activities/ozone-trends/

LOTUS 2020 workshop website
https://events.spacepole.be/event/81/

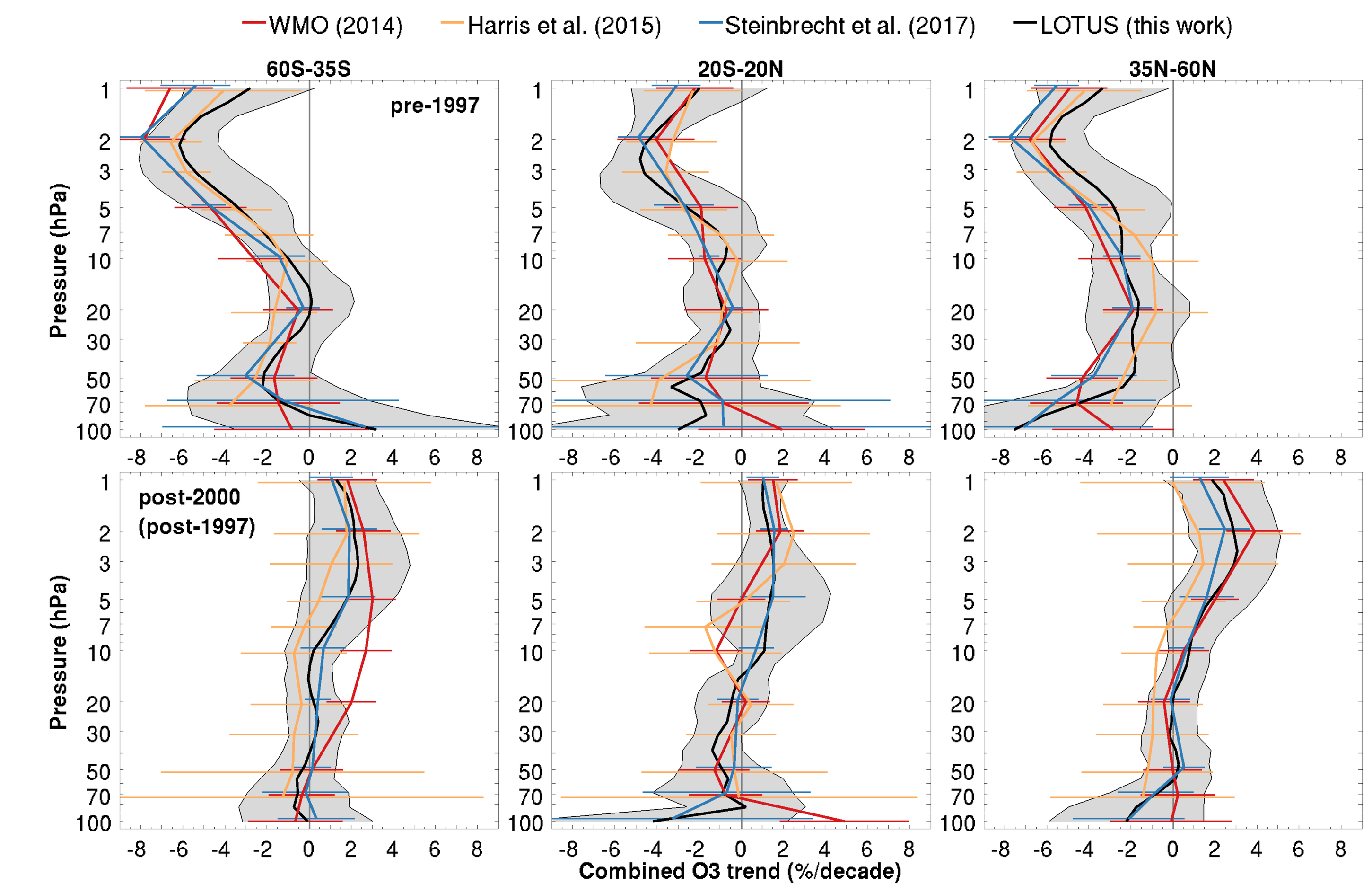


Figure 1: Trends from SPARC/WMO LOTUS Report 41 compared to WMO/UNEP 2014 Ozone Assessment, SI2N initiative (Harris et al, 2014) and W. Steinbrecht et al (2017). Upper panel: trends from 1985-1996, Lower panel: trends for 2000-2016 period. Satellite trends are combined in three latitude bands.

•SPARC LOTUS activity phase 1 results:

- •delivered and intercompared several state-of-the-art satellite and ground-based ozone profile data sets, complemented with CCMI model data
- •developed a common multiple linear regression test-bench written in Python
- •defined a baseline regression model after review of methods and auxiliary datasets used for ozone trend analyses
- •assessed trend and trend significance of individual data sets
- •suggested a new and reviewed previous methods to combine trends and trend uncertainties
- •assessed ozone profile trends in the stratosphere based on satellite, ground-based, and model records

Satellite datasets per measurement principle

Group 1. Ozone profiles from nadir sensors (partial columns on pressure grid)
SBUV NASA MOD (Release 6)
NOAA COH

Group 2. Ozone profiles from limb instruments in mixing ratio on pressure grid
HALOE – MLS

Group 3. Ozone profiles from limb instruments in number density on altitude grid
corrSAGE II (by Damadeo)–OSIRIS–OMPS (Usask 2D v1.02)
SAGE II – OSIRIS – OMPS (Usask 2D v1.02)
SAGE II – Ozone_cci – OMPS (Usask 2D v1.02)
SAGE-II – MIPAS – OMPS (NASA v2.2)

The dataset with converted ozone representation
Mixed coordinates converted to mixing ratio on pressure
GOZCARDS v2.2, SWOOSH v 2.6

Ground-based Instrument s	Station, period since
Lidar	OHP (1986), Hohenpeißenberg (1987), Table Mountain (1988), Mauna Loa (1993), Lauder (1994)
Microwave	Bern (1994), Payerne (2000), Mauna Loa(1995), Lauder (1992)
FTIR	Izana (1999), Lauder (2001), Jungfraujoch (1995), Wollongong (1996)
Umkehr	Mauna Loa (1984), Lauder (1987), Arosa (1956), OHP(1984), Boulder(1984), Perth (1984)
Ozonesond es	NOAA and SHADOZ datasets, zonal averages

***Q:** How stable are the new satellite combined ozone records relative the to the ground-based data?*
***A:** Insignificant drifts are found in most combined limb-satellites. SBUV NASA MOD and NOAA COH merged datasets show different drifts relative to MLS.*

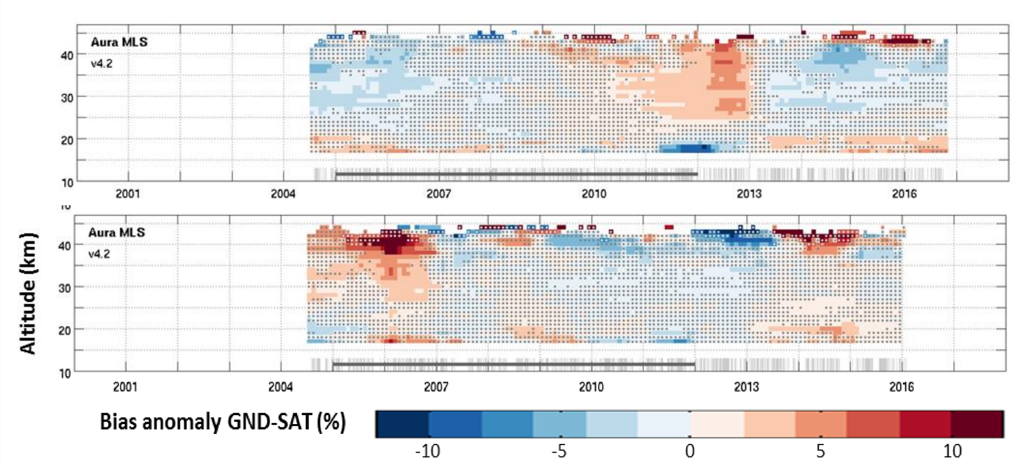


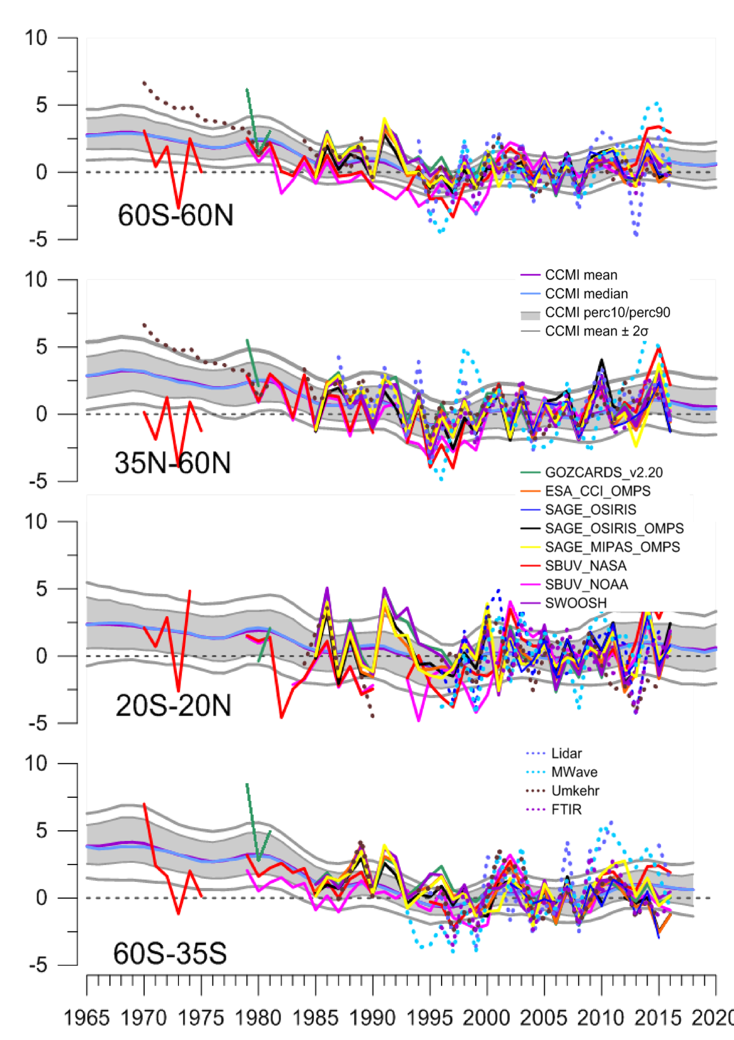
***Figure 3.** Time series of the time-smoothed relative difference of Hohenpeissenberg (top) and Observatoire Haute Province (Bottom) lidar and Aura MLS satellite ozone profile data, offset to the median value in the reference period. Thin grey vertical lines at the bottom show the sampling of the co-located profile data records. Adapted from Hubert et al. (in preparation, 2020).*

Q: Are there sampling issues that can impact on the derived trends?

Approach 1: Create sampling-bias corrected monthly zonal mean data set (**corrSAGE**) **Simultaneous temporal and spatial (STS) regression** can separate and characterize sampling effects (with limitations)

Approach 2: Bayesian Integrated and Consolidated (**BASIC**) composite method merges multiple ozone composites within a probabilistic framework to form the most likely ozone time-series given the data.

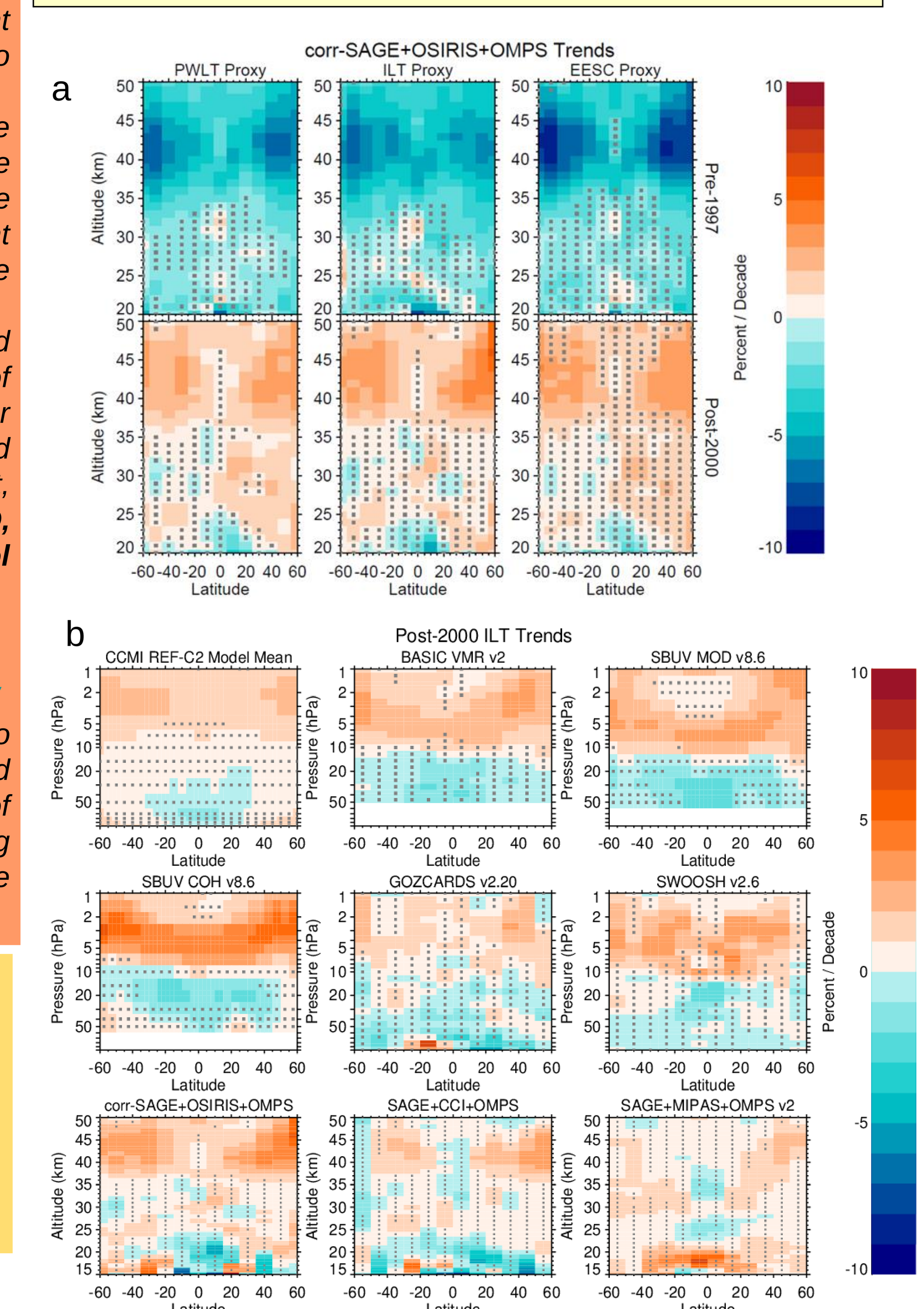
Q: Do CCMI models agree with observations?
A: Yes, in long-term, but models (REF-C2) cannot fully capture the natural (i.e. volcanic/QBO) variability that is seen in observations.



LOTUS models for trend analyses:
***PWLT** – piece wise linear trend*
***ILT** – independent linear trends for two periods*
***EESC (1,2)** – single and two EOFs as the long-term proxy for the Effective Equivalent Stratospheric Chlorine in the atmosphere*
*The **LOTUS MLR** trend model is comprised of the trend (linear or EESC based) and seasonal component, **Solar cycle, QBO, ENSO and aerosol proxies.***
***LOTUS trend model:** https://arg.usask.ca/docs/LOTUS_regression/*
Special thanks to Daniel Zawada and Doug Degenstein of USASK for developing and maintaining the LOTUS trend code.

Figure 6. The evolution of ozone changes as annual mean anomalies at the 10 hPa/31 km level. Four different latitude bands are shown. Satellite data are based on zonal means, and ground-based stations are averaged over the latitude bands. The grey "envelope" gives the **CCMI (RefC2)** model results, based on the models 10th and 90th percentile. The model mean, the median and the ± 2 standard deviation range of the mean are also plotted. All anomalies are calculated over the base period 1998-2008, and the CCMI models are shown as 5-year weighted averages

Q: How will trends change if three different trend methods are applied?
A: All three methods capture very similar patterns in stratospheric ozone trends.
Q: If one regression method (ILT) is used what do different datasets tell us about stratospheric trends?
A: Similar patterns are found in all tested satellite records, i.e. statistically significant ozone recovery at ~ 40-50 km (1-5 hPa) altitude. Although magnitude of the trends vary they are all comparable within individual trend uncertainties.



***Q:** Do different regression models have impact on trends?*
***A:** Trend results agree within ~1%/decade. Larger differences noted for other regressed terms, e.g. Solar & QBO. Tests were used to identify importance of different explanatory variables for the LOTUS regression models.*

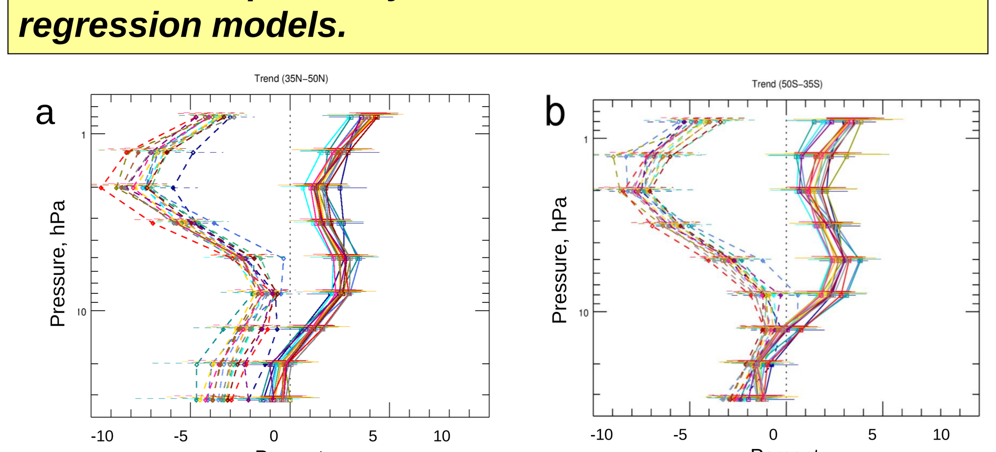


***Figure 2 (to the right).** Common dataset (SBUV NASA MOD) test was used in 8 multiple linear regression (MLR) models. Results for Trends (dashed lines for pre-1998 and solid lines for post 2000) and associated uncertainties are shown for **a)** 35N-50N and b) 35S-50S.*

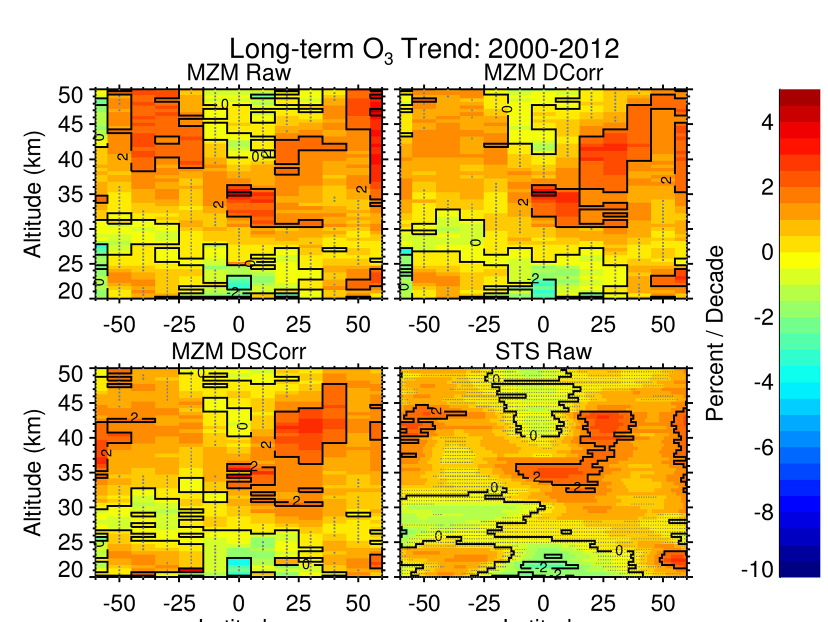


***Figure 4** Trends derived from MZM using different corrections (raw=top left, diurnal correction =top right, diurnal & seasonal corrections =bottom left) and STS (raw=bottom right) regressions*

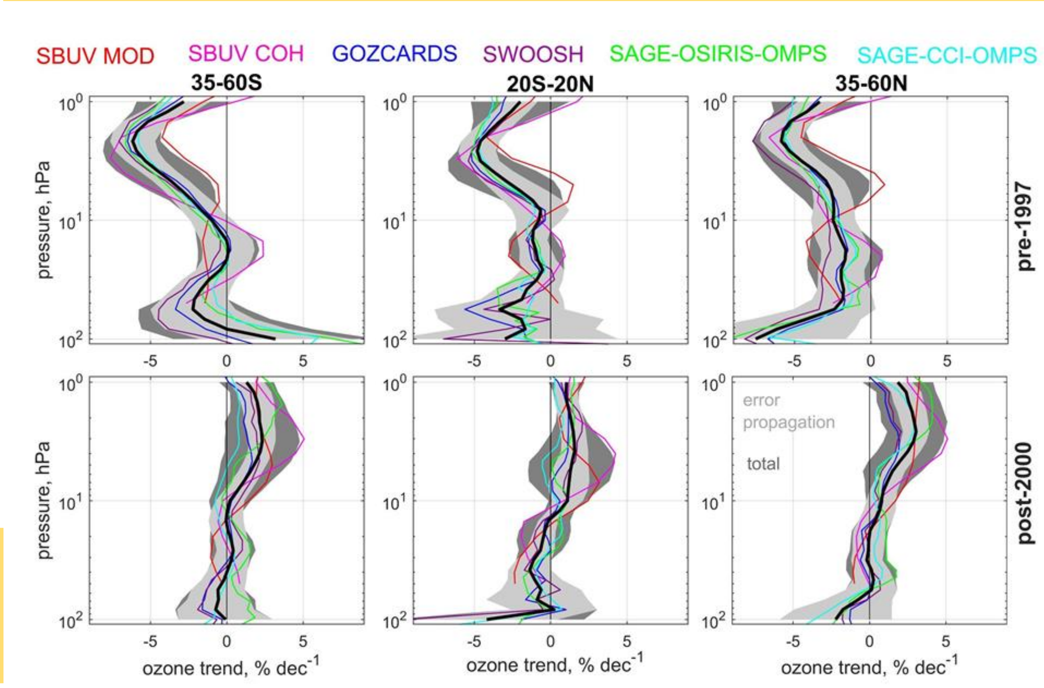


Figure 7 (above). a) Derived trends in ozone in percent per decade for the corrSAGE II-OSIRIS-OMPS data sets for both the pre-1997 (1985-1997, top row) and post-2000 (2000-2016, bottom row) time periods. Results are shown for each of the three trend proxies: the PWLT (left), ILT (middle), and EESC EOFs (right) proxies.
b) Derived trends in satellite ozone in percent per decade for the period 2000 to 2016 for each of the satellite data sets, using the ILT trend proxy in a regression analysis. Grey stippling denotes results that are not significant at the 2-sigma level.

Figure 8 (left). Combining pre-1997 (top) and post-2000 (bottom) trend estimates and uncertainties (2-sigma) from six limb profile data sets. Black solid line indicates the mean trend. The uncertainty component corresponding to error propagation (envelop in light grey shading), and total (dark grey shading) uncertainty are included. Dataset correlation correction is included.

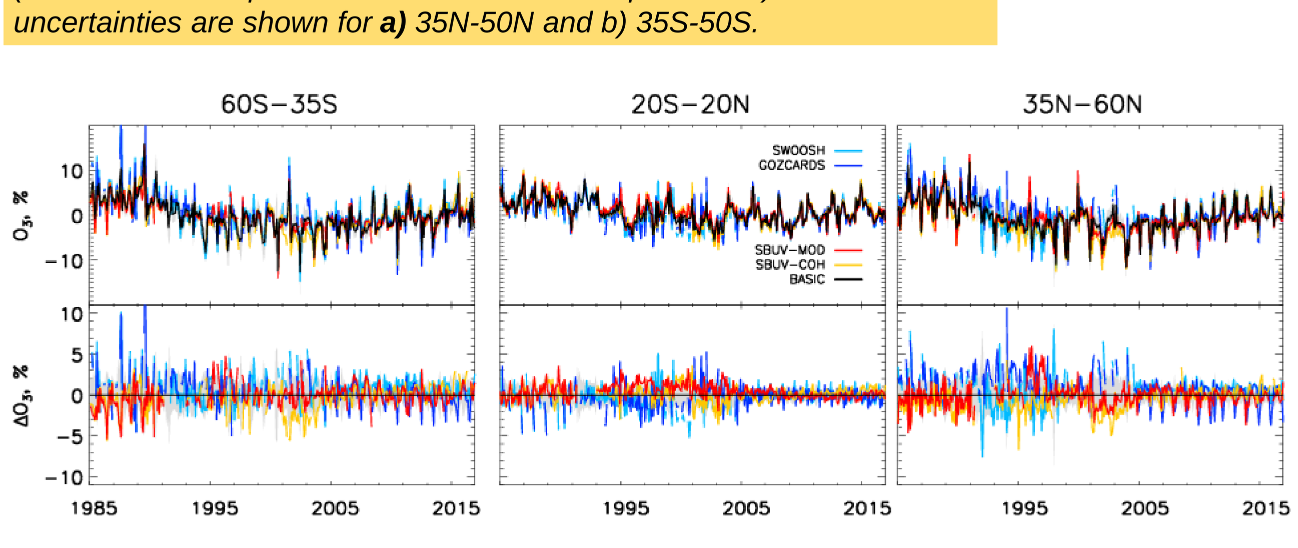


***Figure 5.** BASIC analyses: uses SWOOSH, GOZCARDS, SBUV NASA MOD (marked as SBUV-MOD in the legend) and NOAA COH (marked as SBUV-COH in the legend) ozone to identify instrumental drifts and then create the best record and derive trend.*

Recent accomplishments

➢Provided results of ozone trend analyses to Chapter 3 in the 2018 WMO/UNEP Ozone assessment.

➢SPARC/IO$_3$C/GAW, 2018: SPARC Report N°9 (2019) of The SPARC LOTUS Activity: SPARC/IO3C/GAW Report on Long-term Ozone Trends and Uncertainties in the Stratosphere. Edited by I. Petropavlovskikh, S. Godin-Beekmann, D. Hubert, R. Damadeo, B. Hassler, and V. Sofieva.
SPARC Report No. 9, WCRP Report 17/2018, GAW Report No. 241
doi: 10.17874/f899e57a20b, www.sparc-climate.org/publications/sparc-reports

➢ LOTUS multiple linear regression (MLR) trend model, download from https://arg.usask.ca/docs/LOTUS_regression

➢ Dynamical linear model (DLM; Laine et al., 2014; Alsing, 2019: github.com/justinalsing/dlmmc)

Open issues from the SPARC/WMO LOTUS report and NOAA OAR/AC4 project to homogenize NOAA COH and Umkehr ozone records for trends. Analyses

- Continue to monitor upper stratosphere ozone levels in tropics & mid SH latitudes. Do these continue to rise at mid NH latitudes?
- Are post-2000 LS ozone levels really declining? (Wargan et al., 2018; Chipperfield et al., 2018; Ball et al., 2018, 2019, 2020)
- Seasonal trends need to be evaluated (Szeląg, ACPD, 2020)
- Do O3 profile & column trends agree? (Weber et al, 2018 found semi-neutral TO trends)
- What is tropospheric ozone contribution to TO (IGAC TOAR questioned stability in some records, Ziemke et al, 2018, Gaudel et al, 2018).
- How consistent are GND (local) & SAT (zonal) data? (Zerefos et al, 2018, Bernet et al, 2019, **NOAA/OAR AC4 project**)

• **Data records**

- Ultimately, LOTUS analyses conclude that the most meaningful way to improve the uncertainties in future analyses would be to **reconcile the discrepancies between the data sets** themselves prior to the merging process (**NOAA/OAR AC4 project**)
- Satellites: new updates to L1, L2, L3, **i.e. JPSS S-NPP OMPS nadir and limb profiles in combined and homogenized records (NOAA OAR AC4 project); gridded data for trends (i.e. NOAA's SWOOSH)**
- Ground-based (Umkehr, ozonesonde, NDACC lidar and MW homogenization, combining station data for trends to improve sampling biases)

• **Regression**

- Investigate if LOTUS regression model (developed for satellite records) is also adequate for ground-based records.
- More systematic study of sensitivity to proxies on all data records is needed (**NOAA/OAR AC4 project**).
- Explore spatial structure of proxy coefficients in more detail.
- DLM vs. MLR trends

• **Uncertainties**

- Can / should we avoid combining trend profiles & uncertainties?
- How to estimate correlation between trend estimates? (NOAA/OAR AC4)

$$\sigma_{mean}^2 = \max\left(\frac{1}{N^2}\sum_{i,j} C_{ij}\sigma_i\sigma_j,\ \frac{1}{n_{eff}}\sum\frac{(x_i-\bar{x})^2}{N-1},\right)$$

$$n_{eff} = \frac{N^2}{\sum_{i,j=1}^{N} C_{ij}}$$

LOTUS Uncertainties.
The first term is the variance of the mean of correlated values, obtained through traditional propagation of errors. The second term is the unbiased estimator of the standard error of the mean, where n_{eff} independent measurements are assumed from the N=6 different trend estimates.

N is the number of independent observation records, C_{ij} are the correlation coefficients for the trend estimates x_i from data sets i and j , σ_i are the trend uncertainties estimated from the fit residuals for the individual data sets, and n_{eff} is the effective number of independent trend estimates.

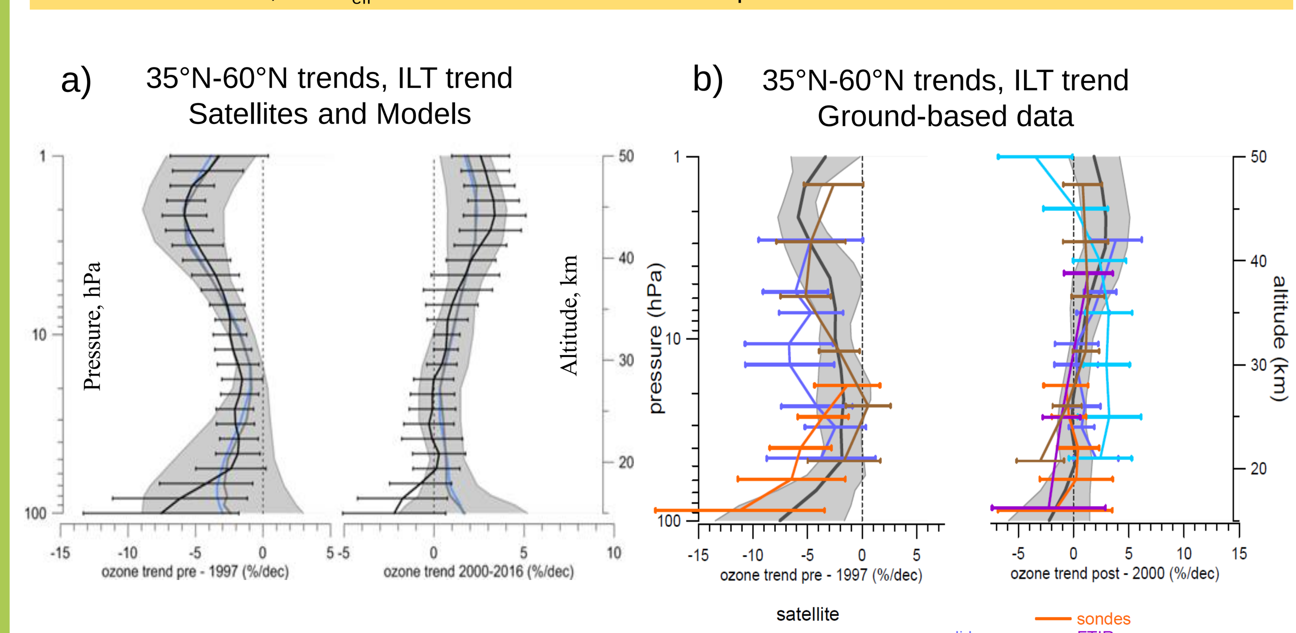


Figure 9. a) The combined satellite trends (black line) and uncertainties, calculated by the sequential averaging method: takes correlations between the individual trend estimates into account and considers systematic uncertainties as well. The CCMI model trends (grey – mean and blue – median) and variability is shown as grey envelops.
b) Derived trends from ground-based (GB) ozone records, in percent per decade, for the period 2000 to 2016, using the ILT trend proxy in a regression analysis. Ground-based trends are combined into zonal averages by weighted error means, but only in the upper stratosphere combined GB trends become representative of the broad-band zonal trends. Satellite combined trends are shown as mean with grey envelop.