Stratospheric Ozone Vertical Distribution at Select NOAA Global Monitoring Laboratory Dobson Monitoring Stations and Updated Trends of the Based on the LOTUS Regression Model

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NOAA Dobson 065 at Boulder, CO

Introduction

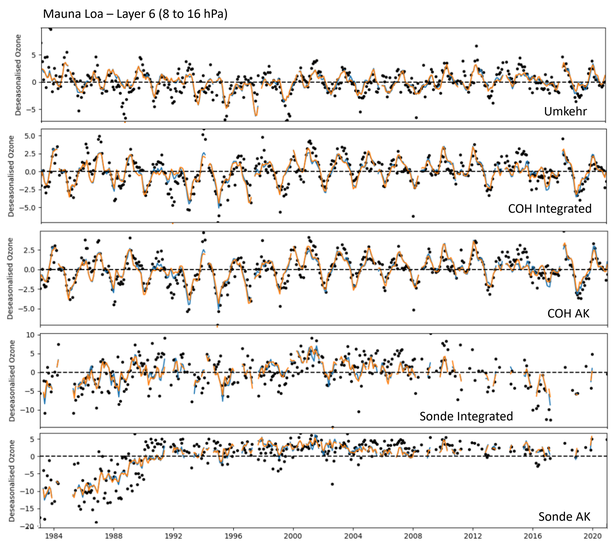
- Ozone recovery is governed by the reduction in Ozone Depleting Substances (ODSs) after the Montreal Protocol. Depending on latitude, the ODS peaked sometime in the late 1990s or early 2000s, and the 'recovery' period is here defined as post-2000.
- Assessing trends in ozone are complicated by natural variability in the global circulation.
- Multi-linear regression with the LOTUS model is used to find the linear trend in ozone by using several natural explanatory variables to predict the ozone concentrations.
- The goal of this study is to 1) quantify the trends and uncertainties in the NOAA Dobson Umkehr vertical profile record by comparing it to the trends in the Ozonesonde record and the "COH" Satellite Overpass record and 2) To improve the model fit by testing additional natural variability proxies.

Data Description

- Dobson Umkehr: Uses the ratio of intensities of the 'C' wavelength pair from zenith sky observations taken daily between 90 and 60 solar zenith angle, sunrise and sunset. Profiles are optimized (Petropavlovskikh, 2022) for long-term trend analysis by removing inhomogeneities and discontinuities in the monthly mean record. Archived at NOAA GML.[5]
- Ozonesondes: ECC ozonesondes Homogenized (Smit, 2021) and downloaded from the HEGIFTOM archive.[4] Umkehr Averaging Kernels have been applied.
- COH satellite overpass: Overpass data homogenized from OMPS S-NPP (NOAA/NESDIS version v3r2) and SBUV/2 (NASA version v8.6) nadir profiler instruments. Data archived at NOAA.[6] Umkehr Averaging Kernels have been applied.

Averaging Kernel smoothing

Averaging Kernels (AK) are applied to the ozonesonde and COH satellite data so that the vertical characteristics/resolution is similar to Umkehr for ease of comparison. It is important to monitor the impact of this averaging on the data. The figure compares the time series of the datasets with AK applied, or with COH and ozonesonde profiles integrated along the Umkehr layer.



- Using AK or integrating to Umkehr layer has little impact on COH values.
- Using AK dramatically changes the ozonesonde data in the beginning of the record. Likely balloon burst is lower, and AK curves extend above the sonde data max height.

Links

1) LOTUS model: https://arg.usask.ca/docs/lotus_regression/
2) LOTUS Activity homepage: https://www.sparc-climate.org/activities/ozone-trends/
3) AC4: https://cpo.noaa.gov/Meet-the-Divisions/Earth-System-Science-and-Modeling/AC4
4) HEGIFTOM database: https://hegiftom.meteo.be/datasets/ozonesondes
5) Optimized Umkehr data: GML OZWV FTP: https://gml.noaa.gov/aftp/data/ozwv/Dobson/AC4/Umkehr/Optimized/
6) COH (SBUV&OMPS) Overpass: https://ftp.cpc.ncep.noaa.gov/SBUV_CDR/overpass/

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Petropavlovskikh, I., et al., SPARC/IO3C/GAW, SPARC Report No. 9, WCRP- 17/2018, GAW Report No. 241, https://doi.org/10.17874/f899e57a20b, 2019.
Petropavlovskikh, I., et al., AMT, 15, 1849-1870, https://doi.org/10.5194/amt-15-1849-2022, 2022.
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LOTUS Model Overview

- LOTUS: Long-term Ozone Trends and Uncertainties in the Stratosphere (Godin-Beekmann, 2022 & Petropavlovskikh, 2019) v 0.8.0[1,2]
- General multi-linear regression (MLR) model with two independent linear trends (pre-1997, post 2000), constrained to be continuous across gap.
- Predictors or proxies included in the LOTUS model are
  - ENSO
  - 11-year solar cycle
  - QBO with **two** orthogonal components
  - AOD is not used in this study

$$O_3 predicted\,(t) = \beta_1 QBO_1(t) + \beta_2 QBO_2(t) + \beta_3 ENSO(t) + \beta_4 Solar(t)$$
$$+\beta_5 Linear_{pre}(t) + \beta_6 Linear_{post}(t) + \beta_7 Const_{pre} + \beta_7 Const_{post} + \beta_6 Const_{gap} + residuals$$

- Seasonal variation is modeled using seasonal (Fourier) components.

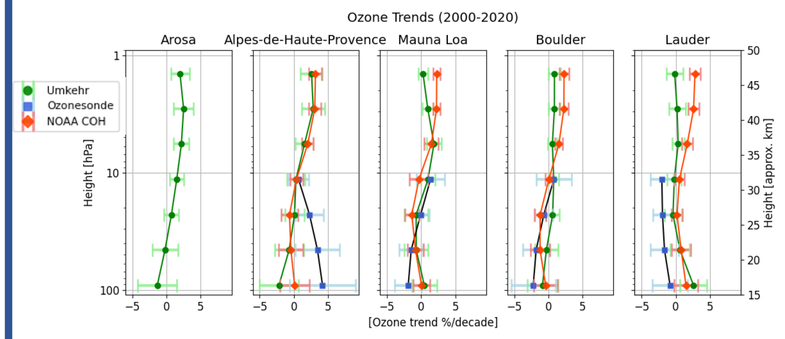
$$\beta_n(t) = \beta_{n_0}(t) \sum_{i=1}^{4} \beta_{n_i}(t) \sin\left(\frac{2\pi i t}{12}\right) + \sum_{i=1}^{4} \beta_{n_i}(t) \cos\left(\frac{2\pi i t}{12}\right)$$

Trends:

Upper Stratosphere (~6-1 hPa):
- Umkehr and COH trends are generally positive and statistically significant confirming recovery of the ozone layer.
- At OHP trends from Umkehr and COH are similar at 2-4% per decade.
- At Mauna Loa, Boulder & especially Lauder, Umkehr trends are smaller than COH nearing 0.

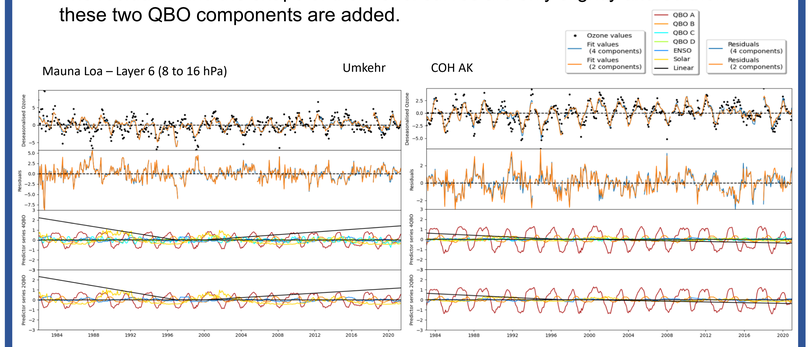
Mid-Stratosphere (~30-6 hPa):
- Trends are in general not significantly different from zero in this range.

Lower Stratosphere(~100-30 hPa):
- Larger Uncertainties lead to non-significant results. However there are a few trends that are:
  - Mauna Loa COH: -3%/Decade at ~25 hPa
  - Lauder Ozonesonde:-2% to -3%/decade at ~25-45 hPa
- Ozonesonde trends differ significantly from Umkehr and COH at Lauder, OHP



Proxy impact on model – QBO example

- In both the COH and Umkehr cases the two additional components of the QBO make a smaller contribution to the modeled time series than the first two components.
- The residuals and the shape of the model curves are only slightly altered then these two QBO components are added.



Test with Additional Proxies in the LOTUS Model.

Questions of interest:
- Are additional proxies of value for the trend analysis of localized station data?
- Are residuals and trend errors reduced when the proxies are added?

Values reported in the table below are the percent difference in the standard error (SE) of the trend term of the model. $\frac{\sigma_{ref} - \sigma_{proxy}}{\sigma_{ref}} * 100\%$

Proxies tested:

a) **Equivalent Latitude**: EqLat is the constant Potential Vorticity (PV) contour enclosing an area equivalent to the associated latitude band and is a proxy for dynamical variability. EqLat/PV data used from MERRA 2 reanalysis from pressure level nearest the Umkehr layer pressure at each site.

b) **Tropopause Pressure**: Derived from daily NCEP reanalysis at each site.

c) **Quasi-Biennial Oscillation (QBO):** QBO is an index representing variations in magnitude and direction of tropical zonal winds. This study explores the impact of adding two additional QBO components.

Results from the LOTUS Trend Model: Change in The Standard Error [%]

	Height (hPa)	Arosa	Obs. Haute Provence			Mauna Loa			Boulder			Lauder		
		UMK	UMK	SND	COH	UMK	SND	COH	UMK	SND	COH	UMK	SND	COH
Eq Lat a)	1-2	0.0	0.0	N/A	5.4	0.0	N/A	0.0	6.4	N/A	0.0	9.5	N/A	7.5
	2-4	1.4	1.2		1.9	0.0		0.0	-2.3		0.0	-3.2		-2.6
	4-8	15.8	1.6		15.7	3.7		2.0	2.9		7.1	-8.7		-7.9
	8-16	16.0	4.7	4.1	18.9	0.0	-2.8	-2.9	5.3	-1.5	14.3	-1.9	6.3	5.7
	16-32	11.3	-1.4	-2.0	4.5	1.2	-1.6	2.0	-4.3	0.0	2.5	6.2	-3.0	9.8
	32-63	0.0	1.0	-0.6	-2.0	0.0	0.0	1.8	0.0	0.0	2.9	-1.4	-1.0	-1.5
	63-127	7.7	-1.4	-3.7	-1.6	4.4	-2.1	0.0	-0.8	-2.6	1.1	-1.0	0.0	-1.1
TP b)	1-2	0.0	0.0	N/A	0.0	0.0	N/A	0.0	0.0	N/A	0.0	0.0	N/A	0.0
	2-4	0.0	0.0		0.0	0.0		3.8	-2.3		0.0	-3.2		0.0
	4-8	0.0	0.0		0.0	0.0		0.0	0.0		0.0	2.2		0.0
	8-16	0.0	0.0	-1.4	0.0	-1.9	-0.9	1.5	0.0	-0.8	0.0	1.9	1.3	0.0
	16-32	1.9	0.0	1.0	4.5	4.8	3.2	7.8	0.0	0.0	2.5	-1.5	0.0	2.4
	32-63	7.4	5.8	6.7	11.0	4.7	4.7	8.8	1.2	1.1	5.8	5.6	3.0	8.8
	63-127	13.3	11.3	7.4	12.6	1.1	2.1	5.1	4.2	0.6	5.7	11.0	3.9	8.0
QBO c)	1-2	-4.6	0.0	N/A	0.0	-8.3	N/A	0.0	6.4	N/A	0.0	-3.2	N/A	0.0
	2-4	-2.8	3.6		0.0	-2.4		3.8	0.0		0.0	-9.7		0.0
	4-8	-3.5	0.0		0.0	-3.7		0.0	0.0		0.0	-2.2		0.0
	8-16	-6.0	-3.1	-1.4	0.0	-5.7	-0.9	1.5	-2.6	-0.8	0.0	-1.9	1.3	0.0
	16-32	-5.7	-4.3	1.0	4.5	3.6	3.2	7.8	-4.3	0.0	2.5	-6.2	0.0	2.4
	32-63	7.4	7.7	6.7	11.0	4.7	4.7	8.8	1.2	1.1	5.8	4.2	3.0	8.8
	63-127	14.0	13.4	7.4	12.6	-1.1	2.1	5.1	2.5	0.6	5.7	14.0	3.9	8.0

Proxy Testing Results:

Trend values *were not significantly changed with the addition of the proxies.*

Tropopause Pressure
- The addition of the TP proxy consistently reduces SE at all sites with all datasets for the lowest stratospheric levels. Little to moderate reduction of SE is seen at mid to upper stratosphere.

Equivalent Latitude
- The addition of Eq Lat proxy yielded inconsistent results. At Arosa, the Eq Lat proxy reduced the SE in the middle atmosphere (16-4 hPa). At OHP and Boulder, COH was improved more than the Umkehr and Sonde records. At OHP, Boulder, and Lauder, the highest layer analyzed (1-2hPa) showed some improvement as well. Mauna Loa saw weak, no, or negative improvement. Mauna Loa does not see the large scale variability in the airmass that the higher latitude stations see.

4 components of QBO
- As with Tropopause Pressure the greatest reduction of SE occurred in the lower stratosphere at all stations, esp. Arosa, OHP and Lauder. The SE of Umkehr trends increased in mid and upper stratosphere.

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