Ozone tropospheric and stratospheric trends (1995-2011) at six ground-based FTIR stations (28°N to 79°N)

Corinne Vigouroux, M. De Mazière (BIRA-IASB, Brussels); P. Demoulin, C. Servais (Univ. of Liège); T. Blumenstock, F. Hase, R. Kohlhepp, S. Barthlott (IMK-ASF, Karlsruhe); O. García, M. Schneider (AEMET, Spain), J. Mellqvist, G. Personn (Univ. of Chalmers); M. Palm, J. Notholt (Univ. of Bremen); J. Hannigan, M. Coffey (NCAR, Boulder).

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Introduction

Why adding G-b FTIR to the many other ozone measurements?

- **Tropospheric** ozone trends depend on:
  - Local pollution; long range transport of pollution
  - Lower stratospheric trends (Stratosphere-Troposphere Exchange; STE)

- **Stratospheric** ozone trends depend not only on leveling-off of Equivalent Effective Stratospheric Chlorine (EESC), but also
  - Dynamical changes (Brewer-Dobson circulation)
  - Solar cycle (11-year), volcanic eruptions,…
  - Temperature variability at polar latitude (dynamics)
  - Climate change due to GHG increase,…

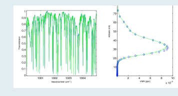
  To understand the causes and predict the time of ozone recovery we need:
  1) Long-time series: present work: **1995-mid 2011**; and of course **on-going measurements.** (Vigouroux et al., ACP, 2008: Ozone trends for the 1995-2004 period; WMO/UNEP Scientific Assessment of Ozone Depletion 2010: update 1995-2009).
  2) Latitudinal information: present work: stations from **28°N to 79°N**; can be extended to the NDACC network. (Vigouroux et al., ACP, 2008: only Europe; this work extended to Thule; in a near future Wollongong, 34°S and Mauna Loa, 20°N)
  3) Altitude: FTIR provide total column ozone, but also **4 partial columns** at different altitudes (one in the troposphere; 3 in the stratosphere).

→ FTIR measurements are part of the SI²N Initiative (SPARC/IO3C/IGACO-O3/NDACC) on past changes in the vertical distribution of ozone; together with satellite, and other ground-based instruments. The main objective of SI²N is to assess and extend the current knowledge and understanding about measurements of the vertical distribution of ozone, with the aim of providing input to the next WMO Scientific Assessment of Ozone Depletion anticipated for 2014. See http://igaco-o3.fmi.fi/VDO/index.html

FTIR total and partial columns

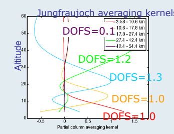
- FTIR solar absorption spectra: we retrieved ozone in the 1000-1005 cm^{-1} micro-window.
- Solar absorption along the line of sight: **total columns** of absorbers are given by the area of absorption lines.
- **Vertical information** from p, T dependence of the lines shape.

The problem is ill-posed: Optimal Estimation Method (Rodgers):

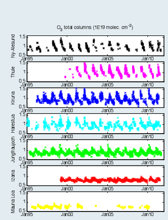


$$x_{retrieved} = x_{apriori} + A\,[x_{true} - x_{apriori}] + \text{errors terms}$$

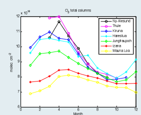
→ the retrieved profile is a combination of a priori and measurement.
→ rows of A: averaging kernels; Degrees of Freedom for Signal **DOFS = trace(A) = 4.7** we have 4 independent layers: Ground-10 km; ~ 10-18 km; ~ 18-27 km;~ 27-42 km.
→ Precision: TC:4%; Gd-10km: 10%; 10-18: 7%; 18-27: 9%; 27-42: 6%.



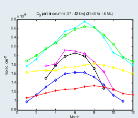
Total column Time-series



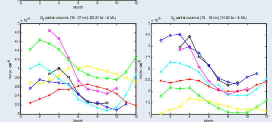
Total and partial columns seasonal cycle

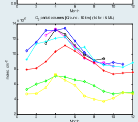


Maximum in **spring** for **total** columns (mid-high latitude): due to **lower-middle stratosphere** maximum in spring: **Brewer-Dobson circulation**



Maximum in **summer in upper stratosphere** (mid-high latitude): **chemistry** dominates





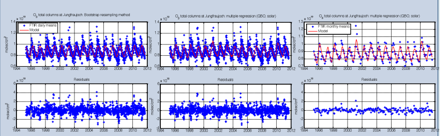
Troposphere:
-Max. in spring at high latitude: STE.
-Broad max. spring-summer in mid-lat.: Pollution in summer STE in spring

Results: 1995 – 2011 ozone trends (28°N – 79°N)

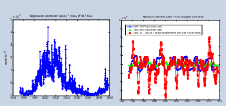
Trend estimation methods

We compare 2 different methods:

- **The bootstrap resampling method** (used in Vigouroux et al., ACP, 2008; and the WMO 2010 report) applied on daily means.
- **A multiple regression model, using QBO** (Singapore zonal winds at 30 and 10 hPa) and **solar cycle** (F10.7 radio flux) as explanatory variables. For QBO, a seasonal dependence is allowed by the use of a 2[nd] order Fourier series. We applied this model on daily and on monthly means for comparison.
- In both models, the ozone annual cycle is represented by a 3[rd] order Fourier series.
- Example in plots below: total columns at Jungfraujoch:



- **Effect of using the multiple regression model (QBO, solar):** a decrease of about 5% is generally observed in the residuals; the main part is due to QBO (mainly proxy at 10hPa for Jungfraujoch and 30hPa for other stations).



Total columns trends

In %/decade			Bootstrap daily means	Regression QBO, solar daily means	Regression QBO, solar monthly means
Ny-Alesund **March-Sept.**	1995-2011	79°N	-1.8±2.1	-1.0±2.4 (±4.3)	+1.5±4.1(±4.6)
	1999-2011		-6.7±2.8	-11.4±4.4 (±6.9)	-7.2±7.5 (±7.7)
Thule **March-Sept.**	**1999**-2011	77°N	-7.3±2.6	-6.3±3.8 (±7.5)	-1.9±8.0 (±10.3)
Kiruna **Jan.-Nov.**	1996-2011	68°N	+1.5±1.8	+4.6±1.9 (±3.6)	+3.0±3.1 (±3.2)
Harestua	1995-2011	60°N	+0.6±2.2	+3.3±2.3 (±3.4)	+2.3±3.4 (±3.5)
Jungfraujoch	1995-2011	47°N	+0.7±0.9	+1.5±1.0 (±1.6)	+1.6±1.7 (±1.7)
Izaña	**1999**-2011	28°N	+0.3±0.9	+0.1±1.4 (±2.1)	-0.7±2.3 (±2.8)

High latitude stations (& bootstrap method):
-1995-2011: non significant trends
-1999-2011: agreement Thule and Ny-Alesund trends (significantly <0)
The high ozone variability in Arctic (warm/cold winters) induces big changes in observed trends depending on the observation period: important to keep on measuring.

Mid-latitude station (& bootstrap method):
-1995-2011: non significant trend
- In agreement with many observations: leveling off of the decreasing trends at Northern mid-latitudes since 1995-1996 (WMO 2006).
- Difficult to quantify the causes: EESC, Brewer-Dobson circulation, transport from Arctic, GHG increase… : **trend vs altitude helps !**

Sub-tropic station:
-non significant trend (in agreement with WMO 2010; satellite)

- **Effect of using the multiple regression model (QBO, solar):** The total column trends are increased at all the stations with a long period of measurement. For Ny-Alesund and the short time-series stations (Thule and Izaña) the solar regression coefficient is not significant; and its inclusion in the model increases significantly the error on the trends for the two latters.
- **Note on daily vs monthly means:** The trends at Kiruna, Harestua and Jungfraujoch appear significantly positive with daily means and non significant with monthly means. This is due to the fact that we did not take into account auto-correlation in the residuals up to now. We give in (±black) the errors when corrected for auto-correlation (time-lag of 1 day and 1 month for daily and monthly means respectively): the increase of the uncertainties for daily means is larger than for monthly means. Also, we did not correct yet the monthly means taking into account the possible big gaps in time-series, which could explain the present differences between the daily and monthly trend values, especially at high latitude stations.

Upper stratospheric trends (27-42 km)

% / decade		Bootstrap daily means	Regression QBO, solar daily means	Regression QBO, solar monthly means
Ny-Alesund **March-Sept.**	1995-	+5.9±2.1	+8.1±1.9	+9.3±3.7
	1999-	+2.8±2.6	+3.6±3.3	+5.0±7.7
Thule **March-Sept.**	1999-	+3.3±3.7	+1.4±5.4	+2.5±11.3
Kiruna Jan-Nov.	1996-	+10.0±2.1	+12.1±2.4	+8.3±4.6
Harestua	1995-	+9.5±2.2	+10.3±2.4	+9.2±3.6
Jungfraujoch	1995-	+1.4±0.8	+1.4±0.8	+1.7±1.4
Izaña	1999-	+0.9±0.9	-0.7±1.4	-1.3±3.3

High latitude stations (Bootstrap):
-1995-2011 & 1999-2011: the trends in the upper stratosphere remain significantly positive, whatever the period is. Could be the signature of the decreasing EESC, but the magnitude of the trends is still varying a lot.

Mid-latitude station:
- significant positive trends.
- in agreement with Umkehr (WMO 2010)
- signature of the decreasing EESC.

Lower stratospheric trends (10-18 km)

Bootstrap daily means	Regression QBO, solar daily means	Regression QBO, solar monthly means
-3.5±4.2	-1.5±4.7	+0.2±7.3
-13.3±5.7	-20.2±9.1	-22.1±13.7
-16.9±5.8	-8.3±8.5	-3.3±17.4
-2.6±3.0	+1.6±3.3	+1.6±5.1
-4.0±4.8	-0.1±5.3	-1.0±7.6
+0.8±3.1	+4.1±3.3 (±5.1)	+3.9±5.6
-1.3±3.6	-3.4±5.9	-6.1±9.2

High latitude stations:
- More variability on the trends depending on the period / stations.
- Lower stratospheric trends highly variable (warm/cold winter) and impact the total columns trends.
- Temperature / dynamics variability do not allow to detect long-term trends yet.

Mid-latitude station:
- non significant positive trends
- In agreement with satellite (WMO2010)
- leveling off the past negative trend in the lower stratosphere: contribution of dynamics

Tropospheric trends (Ground-10 km)

Bootstrap daily means	Regression QBO, solar daily means	Regression QBO, solar monthly means
-6.7±2.6	-5.8±2.8	-4.5±4.7
-12.2±3.4	-12.2±5.5	-9.0±8.5
-7.7±3.8	-5.9±5.9	-6.3±9.2
-1.0±2.3	+1.6±2.6	+2.1±3.3
-8.3±3.7	-5.4±4.0	-7.6±5.0

High latitude stations:
- significant negative trends (except Kiruna): seems to correlate well with the observed lower stratosph. trends.

	Bootst. daily means	Regr. daily means	Regr. monthly means
Jungfrauj.	-2.0±2.2	+0.3±2.3	+0.6±3.3
winter	-0.0±5.8	+0.7±6.6	+1.1±6.4
spring	-2.1±4.0	+1.2±5.4	+3.7±7.4
autumn	+0.9±4.0	+0.8±4.5	-2.4±6.8
summer	-3.8±2.9	-1.9±3.2	-2.3±5.3
Izaña	-0.8±2.8	-1.4±4.0	-0.3±6.9

Mid-latitude station:
- non significant annual trends
- summer: negative trend in agreement with the decreasing emissions of ozone precursors.
- win/aut: Jungfraujoch measures "background O_3" (Cui et al., JGR, 2011): long range transport & STE (Hess and Zbinden, ACPD, 2011).

Conclusions

- Effect of the EESC decline is visible in the upper stratosphere.
- Mid-latitude: leveling off the past negative trend in the lower stratosphere: contribution of dynamics.
- Correlation observed between lower stratospheric and tropospheric trends at high latitude stations.
- Mid-latitude troposphere: non significant annual trend & negative in winter: decreasing emissions of O_3 precursors.
- Bootstrap vs multiple regression (QBO, solar): the residuals are improved by 5% (mainly due to QBO), the trends are increased with the QBO,solar inclusion. The solar cycle proxy should may not be included yet, at least for the short (99-2011) time-series.
- On-going discussion with SI²N partners to use an homogenized regression model (EESC,…).