Ozone tropospheric and stratospheric trends (1995-2012) 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).

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: **1995-2012**; 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; Lauder, 45°S;…)
  3) Altitude: FTIR provide total column ozone, but also **4 partial columns** at different altitudes (one in the troposphere; 3 in the stratosphere).

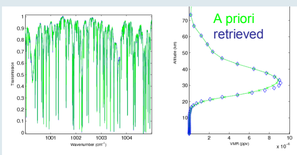
→ FTIR measurements are part of the SI²N Initiative (SPARC/IO3C/IGACO-O3/NDACC) on past changes in the vertical distribution of ozone; together with satellite, and other ground-based instruments. The main objective of SI²N is to assess and extend the current knowledge and understanding about measurements 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

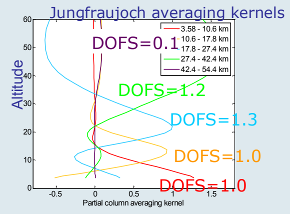
- FTIR solar absorption spectra: we retrieved ozone in the 1000-1005 cm⁻¹ micro-window.
- Solar absorption along the line of sight: **total columns** of absorbers are given by the area of absorption lines.
- **Vertical information** from p, T dependence of the lines shape.
  The problem is ill-posed: Optimal Estimation Method (Rodgers):

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

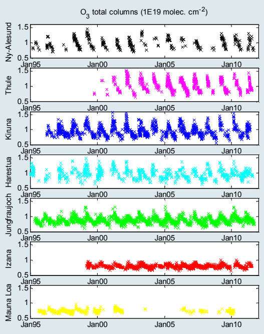
→ the retrieved profile is a combination of a priori and measurement.
→ rows of A: averaging kernels; Degrees of Freedom for Signal **DOFS = trace(A) = 4.7**
we have at least 4 independent layers.
We define 4 layers where we have 1 DOFS, and avoiding the 2-4 km band where the tropopause height is varying the most, so where our smoothing error is the largest.



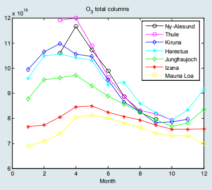
Jungfraujoch averaging kernels



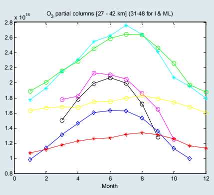
Total column Time-series



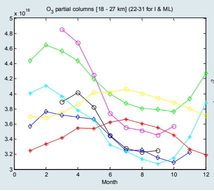
Total and partial columns seasonal cycle

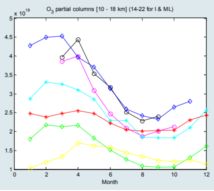


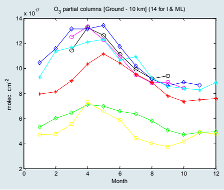
Maximum in **spring** for **total** columns (mid-high latitude): due to **lower-middle stratosphere** maximum in spring: **Brewer-Dobson circulation**



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

Trend estimation using a multiple regression model

Description of the method

- First, a 3rd order Fourier series is applied to the daily means of the total and partial columns time-series, to represent the ozone annual cycle. This is used to generate monthly means that are corrected for possible gaps, bad sampling, in the data (G. Bodeker http://how-to-do-mlr.wikidot.com/correcting-sampling-bias).
- Then we deseasonalized the monthly means corrected time-series, by subtracting to them the monthly means calculated for the whole period.
- **A multiple regression model is applied to the deseasonalized monthly means time-series** *Y(t)*.

$$Y(t) = A_1 + A_2 \cdot t + \sum_{k=3}^{n} A_k \cdot X_k + \varepsilon$$

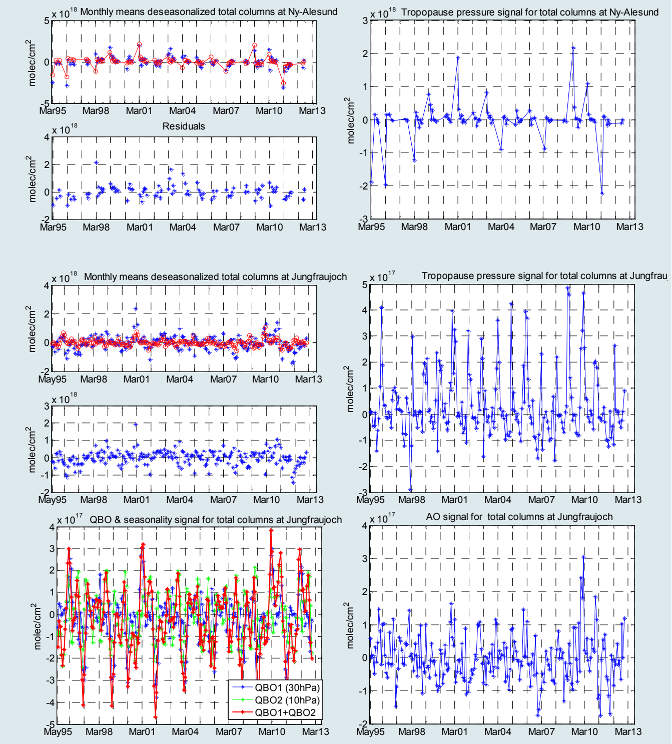
X_k are the explanatory variables and A_k their respective coefficients; Ɛ represents the residuals; A_2 is the annual trend.

Several explanatory variables have been tested: QBO (Singapore zonal winds at 30 and 10 hPa), **solar cycle** (F10.7 radio flux), **tropopause pressure** (from NCEP reanalysis), **Arctic Oscillation** (AO) and **El-Niño/Southern Oscillation (ENSO)**. Seasonal dependence of the parameters have been included when necessary, by using 2nd order Fourier series . Only the parameters that have been found significant are kept in the model.

- To account for the auto-correlation in the residuals, a Cochrane-Orcutt transformation is applied. This gives more reliable interval confidence for the regression parameters.

Significance of the regression model parameters

- The solar cycle parameters have been found non significant at all stations and all altitudes, except a few cases in the troposphere. Also, the correlation is high with the trend parameters. So, the **solar cycle is not included in the final model**. We think that our time-series are too short at present.
- The ENSO signal has also been found non significant at each station. **The ENSO influence might be too low** to be detected considering the FTIR error budget. We could test it again when using optimal FTIR datasets (García et al., AMT, 2012).
- The **QBO parameters have been found significant** at all the stations, except Ny-Alesund and Harestua.
- The **Arctic Oscillation has been found to have a significant influence** in ozone variability at Izaña (troposphere, lower stratosphere, and total columns), at Jungfraujoch (lower stratosphere), and at Ny-Alesund and Kiruna (upper stratosphere).
- The **tropopause pressure** parameters have been found significant in the regression model of total columns at all stations except at Izaña; and for some partial columns time-series as well, depending on the station.
- Some correlation exists between some of the parameters: the correlation coefficients are always below 0,21; except one case: Arctic Oscillation and Tropopause pressure at Jungfraujoch (max of 0,31 for total columns): event on March 2010 (see Figures).



Results: 1995 – 2012 ozone trends (28°N – 79°N)

Total columns trends

			Trends (in % / decade)
Ny-Alesund **March-Sept.**	1995-2012	79°N	-2.8±2.8
	1999-2012		-4.9±3.5
Thule **March-Sept.**	**1999**-2012	77°N	-1.5±3.1
Kiruna **Jan.-Nov.**	1996-2012	68°N	-0.1±1.7
Harestua	1995-2012	60°N	-0.1±2.3
Jungfraujoch	1995-2012	47°N	-0.6±1.7
Izaña	**1999**-2012	28°N	-0.1±1.2

High latitude stations :
-1995-2012: non significant total columns trends
-1999-2012: Thule and Ny-Alesund trends agree within the error bars, but significant at Ny-Alesund, and non significant at Thule. **The high ozone variability in Arctic induces big changes in observed trends depending on the observation period:** important to keep on measuring.

Mid-latitude station :
-1995-2012: non significant trend, **leveling off of the decreasing trends at Northern mid-latitudes since 1995-1996** (WMO 2006).
- To quantify the causes: EESC, Brewer-Dobson circulation, transport from Arctic, GHG increase… : **trend vs altitude helps; also more explanatory variables (EP flux, PSC Volume,…) can be used.**

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

Upper stratospheric trends (~29-48km)

		Trends (in % / decade)
Ny-Alesund **March-Sept.**	1995-	+6.9±5.0
	1999-	+3.6±5.1
Thule **March-Sept.**	1999-	-2.0±8.1
Kiruna **Jan-Nov.**	1996-	+4.8±3.6
Harestua	1995-	+9.5±3.5
Jungfraujoch	1995-	+1.2±1.2
Izaña	1999-	+0.5±4.5

High latitude stations:
-1995-2012: the trends in the upper stratosphere are significantly positive, at all the stations. Could be the signature of the decreasing EESC, but the errors are large, and trends are still varying a lot with the period.

Mid-latitude station:
Non significant positive trend, but close to be significant and error very small. Signature of the decreasing EESC

Sub-tropic station:
Non significant trend; large error due to auto-correlation in the residuals (error 2.0% when auto-corr not taken into account): probably due to the alignment of the instrument (García et al., AMT, 2012).

Lower stratospheric trends (13-20 km), except Izaña 16-23 km

Trends (in % / decade
-3.5±4.4
-7.1±6.4
-4.1±6.5
-2.5±3.0
+0.5±4.5
-1.0±3.9
-0.8±2.3

High latitude stations:
- the non significant trends are in agreement with sondes at Sodankylä for the 1998-2009 period (-5.7±7.0%/dec; R. Kivi, poster at QOS 2012).
- tests for the same period give same results (non significant negative trends)

Tropospheric trends (Ground-10 km), except Izaña gd-14km

Trends (in % / decade
-5.7±3.7
-9.0±4.0
-3.8±4.6
-0.8±2.4
-6.9±2.8
-2.6±3.0
+1.6±3.5

High latitude stations:
- significant negative trends (except Kiruna)
-This is not observed by sondes in the Arctic ! (R. Kivi, poster at QOS 2012: significant positive trends 1998-2009).

Mid-latitude station:
- Non significant annual trends;
- Summer – not shown: negative trend in agreement with the decreasing emissions of ozone precursors.

Conclusions

- Trends:
  - Effect of the EESC decline is visible in the upper stratosphere.
  - High-latitude troposphere: why disagreement with R. Kivi (sondes measurements at Sodankylä) ?
  - High-latitude lower stratosphere: good agreement with R. Kivi.
- Multiple regression parameters:
  - Solar influence: need more 11-cycles, at present parameter non significant and correlation with the trends.
  - ENSO non significant: random error too large ? Check when FTIR ozone random errors reduced.
  - Tropopause pressure, QBO, and Arctic Oscillation help to explain the ozone variability, so to reduce the trends errors.
- Future:
  - Check the influence of EP flux, volume of Polar Stratospheric Clouds. But correlation with tropopause pressure ?