MLS-based detection and "attribution" of the recovery of ozone in the Antarctic ozone hole

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Recovery of ozone in the Antarctic Ozone Hole

New method/different approach:

- **changes in probability distribution**

- **occurrence of extremely low ozone concentrations**

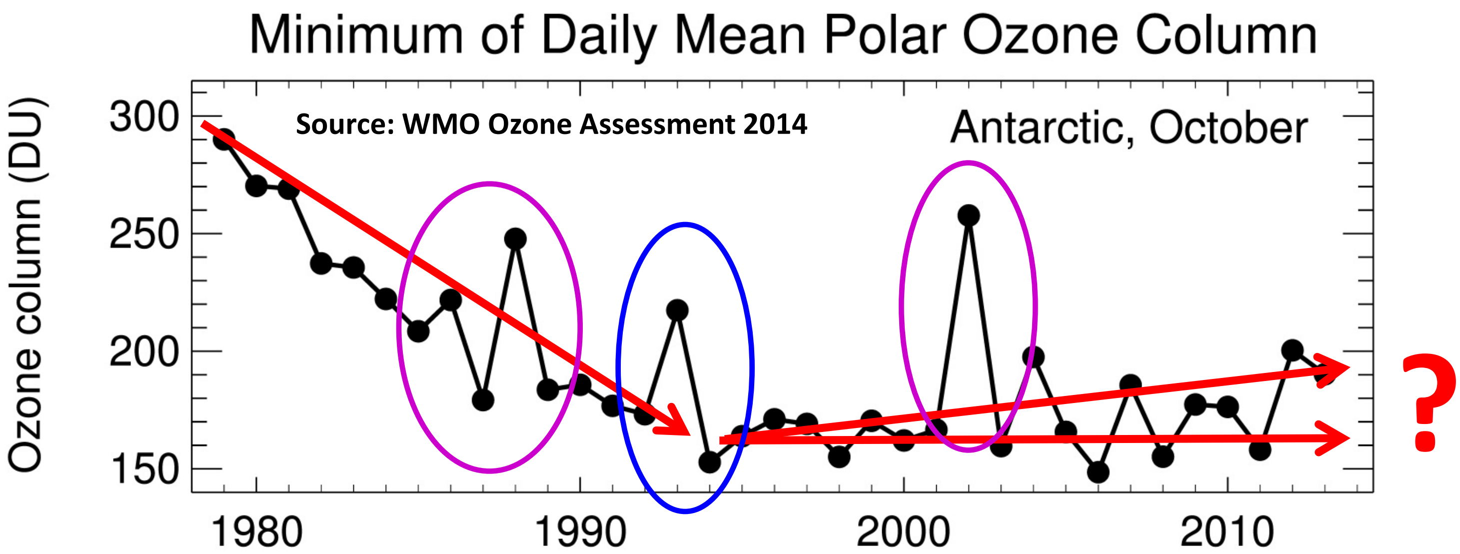


Figure ADM 4-1. High-latitude time series of the minimum daily average total column ozone amount in Dobson units (DU) with October Antarctic values in the bottom panel. Values are those poleward of the 63° equivalent latitude contour. For further details see Figure 3-5 of Chapter 3.

Antarctica

- **Ozone decreased during 1980s – 1990s**
- **Ozone stabilized since mid 1990s**
- **Has there been an post-2000 increase in Antarctic ozone or are we just looking at noise?**
- **Considerable year-to-year variability**
- **… warm winters, volcano …**

***NOTE: common methods look at vortex average springtime* ozone**

Recovery detection: methods [1]

Total ozone and/or ozone profiles

- Typically use of (seasonal) averages and area averages
- Multivariate regression to account for effects of:
  - QBO
  - Solar
  - ENSO
  - Eliassen-Palm flux (heat flux)
  - Volcanoes
  - Halogens (EESC) or linear trend (PWLT)

➔ post – "late 1990s" statistically significant positive trends in Antarctic springtime ozone attributed to decreasing halogens
[Salby et al., 2011, 2012; Kuttippurath et al., 2013; Knibbe et al., 2014]

➔ statistical significance of positive trends is not very high (2-3 σ)

Recovery detection: methods [2]

Many uncertainties are not accounted for:

- Uncertainties in dependent variables in regression (QBO, Solar, ENSO, EP flux, volcanoes etc.)
- Fitting complete EESC curve prescribes trends in ozone (no flexibility to change trends)
- Time period for averaging ozone?
- Area for averaging ozone?
- Metric (average ozone, minimum ozone)?

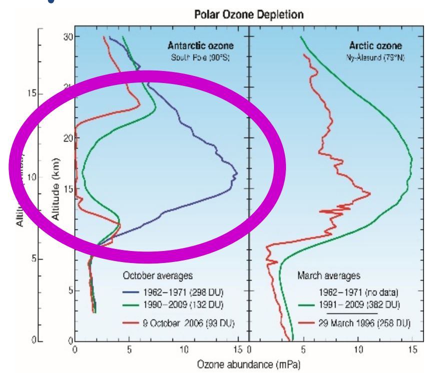
Be careful !!!
[Kramarova et al., 2014; de Laat and van Weele, 2014; Kuttippurath et al., 2015; Varai et al., 2015]

➔ Also the reason why the WMO 2014 Ozone Assessment was careful in its wording (but concluded everything is nonetheless moving in the right direction)

de Laat and van Weele [2014]:
- √ Multivariate regressions help in reducing trend uncertainties
- × Uncertainties in assumptions and fit parameters increase trend uncertainties
- Trend uncertainties also strongly depend on record length

The last one appears more important, i.e. just be patient

Different approach: occurrence of extremely low ozone



Long term changes probability distribution of ozone as a function of height

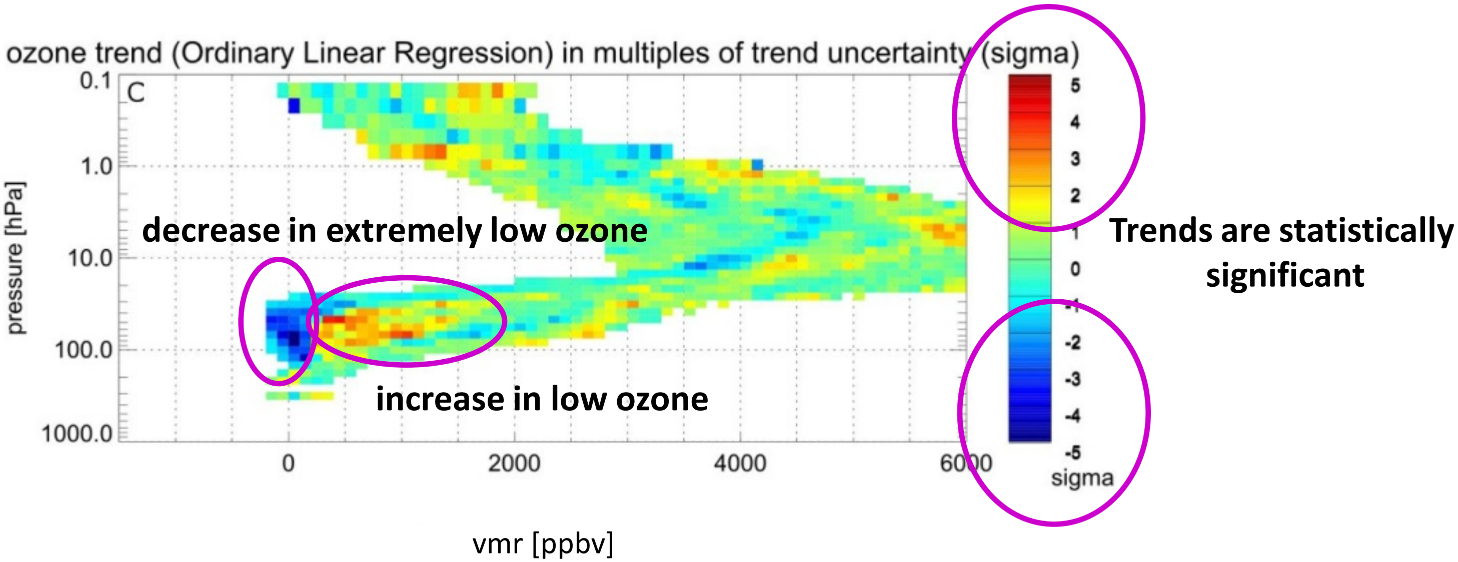
- Why?
    - Currently, Antarctic ozone gets completely destroyed at 15-20 km
    - expectations are that recovery is to occur in 50-70 years time
    - at some point **complete** ozone destruction thus **SHOULD** cease
    - With 50-70 years, one can expect that in 10-15 years "100% ozone destruction" should become "80-90% ozone destruction"
    - Change from 100% destruction to 80-90% destruction should be detectable if:
        - Measurements can resolve the ozone profile
        - Measurements are sufficiently accurate
        - Measurements sufficiently cover the Antarctic Ozone Hole
            - Spatially
            - Temporarily

MLS instrument on EOS-AURA satellite provides ozone profiles meeting these requirements since 2005 (now 10 year record)

Occurrence of extremely low ozone [1]

Method:

- MLS ozone profile measurements (= correct height for Antarctic Ozone Hole)
- Ozone profiles south of 80°S
- Count each year how often a certain ozone concentration occurs (100 ppbv bins)
- Calculate height dependent 2005-2014 trend in occurrence of ozone concentrations



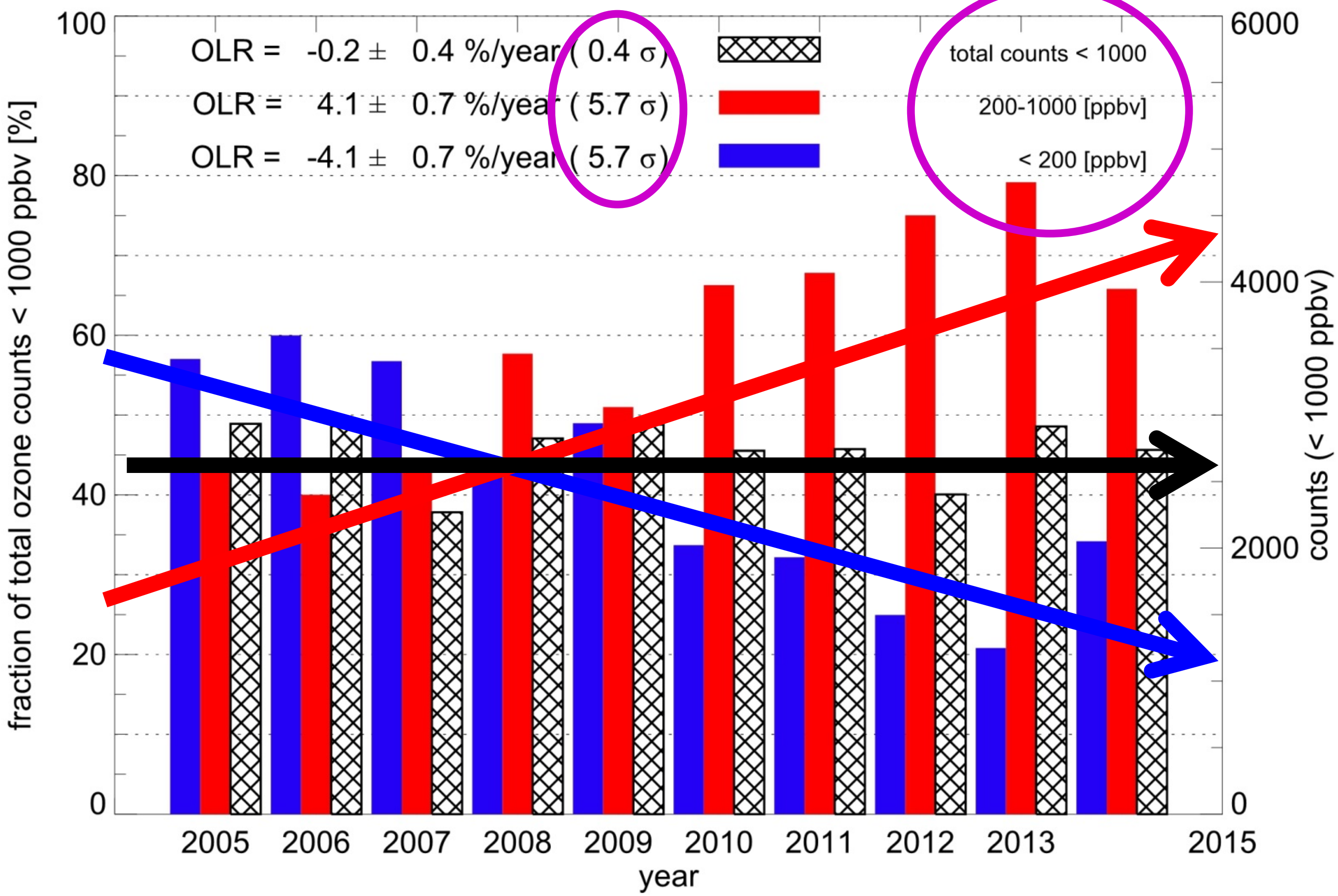
Occurrence of extremely low ozone [2]

At 68 hPa
DOY 220-280

< 200 ppbv

vs

200-1000 ppbv



Occurrence of extremely low ozone: discussion

MLS Antarctic ozone hole 2005-2014: statistically significant decrease in "*extremely low ozone*" (< 200 ppbv), increase in "*low but not extremely low ozone*" (200-1000 ppbv)

Results turn out NOT to depend on:

- Choice of area (south of 80°S, 70°S, 60°S)
- Choice of time period (DOY 220-280, Sep, Oct, Sep-Oct, Jun-Oct)

What about mixing (vertically, horizontally)???

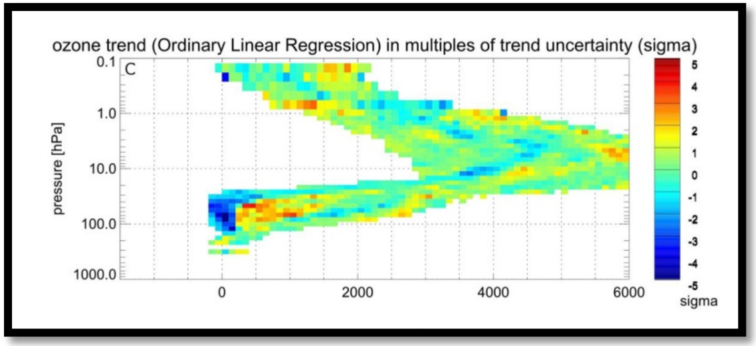
- It is is known how mixing within the Antarctic Ozone Hole manifests itself (via N_2O and temperature)
    - Final warming
    - Fingerprint of "warm winters"

- No indications found of systematic changes in mixing playing a role.

Statistical significance of trend is considerably higher than with "traditional" methods

Occurrence of extremely low ozone: conclusions

- According to MLS, the occurence of extremely low ozone (< 200 ppbv) within the Antarctic Ozone Hole has significantly decreased over the time period 2005-2014 (more than -50%, trend significance up to 6σ).



- Decrease in occurence of extremely low ozone (< 200 ppbv) is accompanied by increase in low ozone (200-1000 ppbv) ➔ shift in probability distribution

- Signal is robust to choice of area and time period

- No indications found of systematic changes in vortex mixing playing a role

- Consistent with expections (”this should occur …”) ➔ “attribution”

- **Conclusion: recovery of ozone in the Antarctic Ozone Hole is also underway**
- … but it is not a more formal attribution as is often done in our field

That's all

Questions?

Definition of Antarctic Ozone Hole recovery

WMO Ozone Assessment 2007: three phases of recovery

(1) Slowing of ozone depletion	√	**1997-2000**
(2) Onset of ozone increase (turnaround)	**?**	**now ???**
(3) Ozone recovery to 1970s levels	×	**not until after 2050**

Add (2): “*the occurrence of statistically significant increases in ozone - above a previous minimum value - that can be attributed to declining stratospheric halogens*.”

Four criteria must be met:

(1) Ozone must have reached a minimum	**√**
(2) Ozone must be increasing after the minimum	**√**
(3) Increase must be statistically significant	**√** or **×**
(4) Increase must be attributable to decreasing halogens	**√** or **×**

Recovery detection methods: problems

Slow decrease in halogens = slow increase in ozone (small year-to-year changes)

Total columns: variability of AOH + layers above (large year-to-year changes)

Lots of varia … van Weele, 2011]

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- Dyna … M, heat flux)

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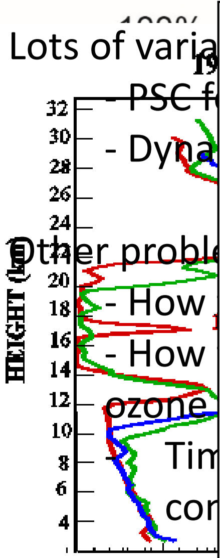

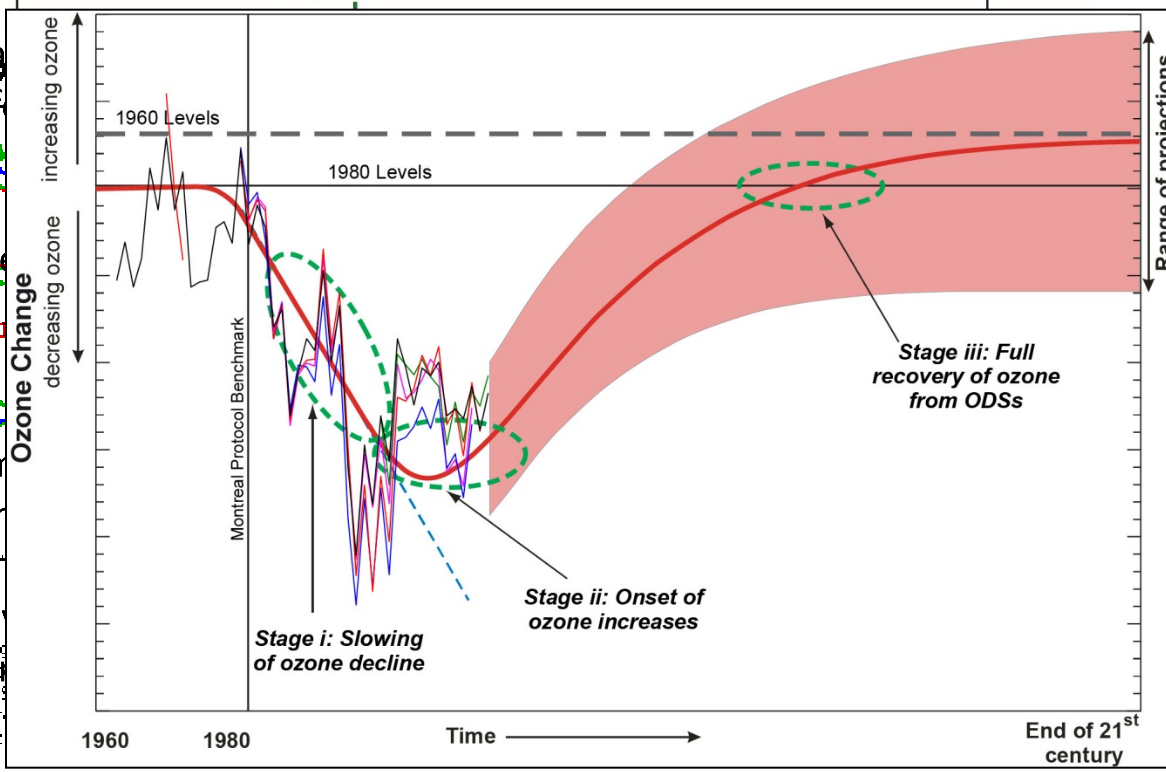

Recovery: multivariate regression

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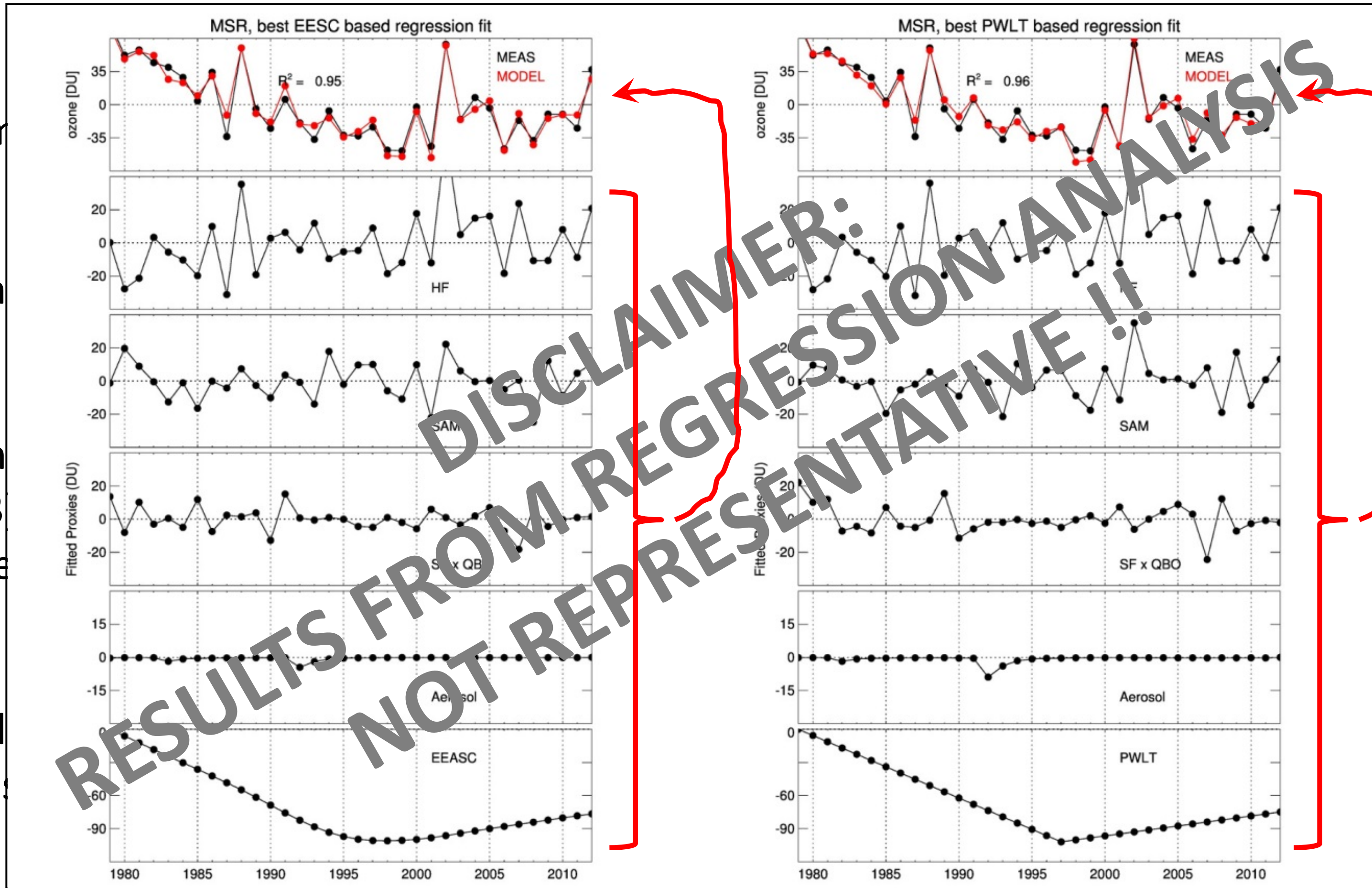
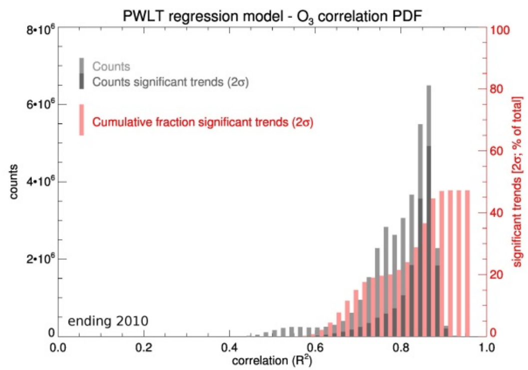
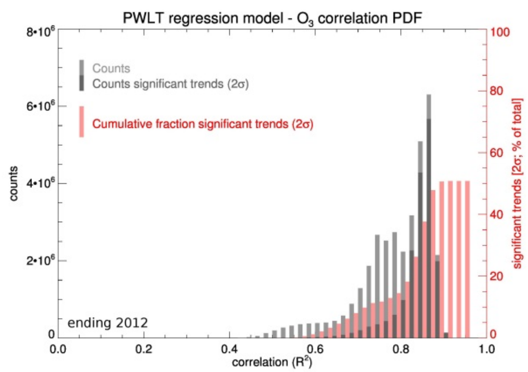


However ...
- Trends “barely”statistically significant (~2 sigma)

multivariate regression: remarks & issues





De Laat et al. [2014; ACPD]

- Uncertainties in ozone record
- Uncertainties in regressors
- Issues with use of pre-defined EESC (no room to maneuver), PWLT preferred instead

- Trend significance depends on length of time period (which it should using OLR trend estimates)
- Approaching general statistical significance of post-EESC peak trend by 2012 …

… nevertheless, significance is fairly weak (generally 2-3 sigma)

Recovery detection with ozone profiles : issues

Sondes:

- spatial coverage is not good (South Pole plus dozen of Antarctic coastal stations)
- temporal coverage is not good (~ one profile/week)

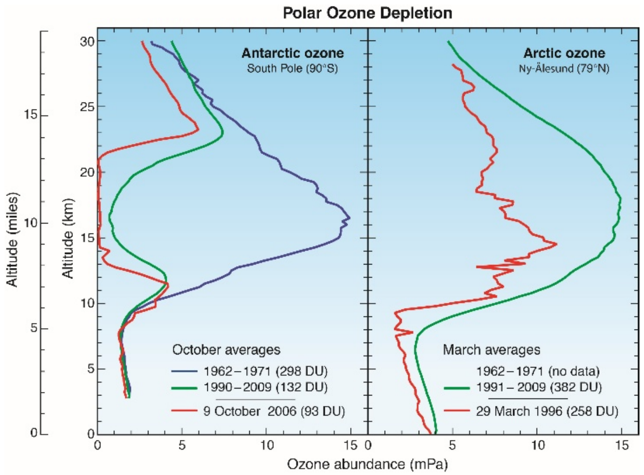
➔ No detection of recovery yet (also limited by general ozone recovery detection issues)

Satellite limb:

- Fair (limb) to poor (nadir) vertical resolution
- Data quality in nadir is unclear
- Period for which data is available is short (early 2000s onwards)

➔ Not used for recovery detection so far

Involvment WMO Ozone Assessment 2014



“Are we missing something?”

“So much data, something is hiding in there ...”

An idea: look at **<u>lowest ozone concentrations</u>** (additional trigger via WMO ozone assessment and the draft of the Solomon [2014] PNAS paper …)

Why? Decrease in halogens must at some point result in not all ozone being destroyed anymore. Maybe a lot (80-90%), but not everything (100%).

Antarctic ozone destruction and recovery are gradually occurring processes.

This must occur …

Occurrence of extremely low ozone: MLS

Why MLS:

- Best quality stratopsheric ozone profiles from satellites

- Just about the right time period (2005-2013)

- Vertically resolved AOH

- Not used before

- Good spatio-temporal coverage
    - ~**500-1000 profiles/day** throughout the Antarctic vortex, compared to **one** South Pole ozone sonde **profile a week**, the only location always providing inner-vortex ozone sonde profile measurements …

Why haven't we thought of that before?

Don't know? (really, I don't …)

- Focus on total ozone (best/longest record), on understanding interannual variability
- In situ ozone profiles are not suitable for applying this method
- Satellite limb (MLS) only recently long enough record and mature enough (quality)
- Scientists are unfamiliar with the limb measurements
- Scientists are unfamiliar with the nadir ozone profiles (quality still being an issue)
- Not high on priority list: without multivariate regressions detection not expected before 2020.
- "it will come, it is a slow process …"
- requires stepping out of traditional thinking pattern ("outside of the box")

Occurrence of extremely low ozone: future

- Trying to publish in NGEO

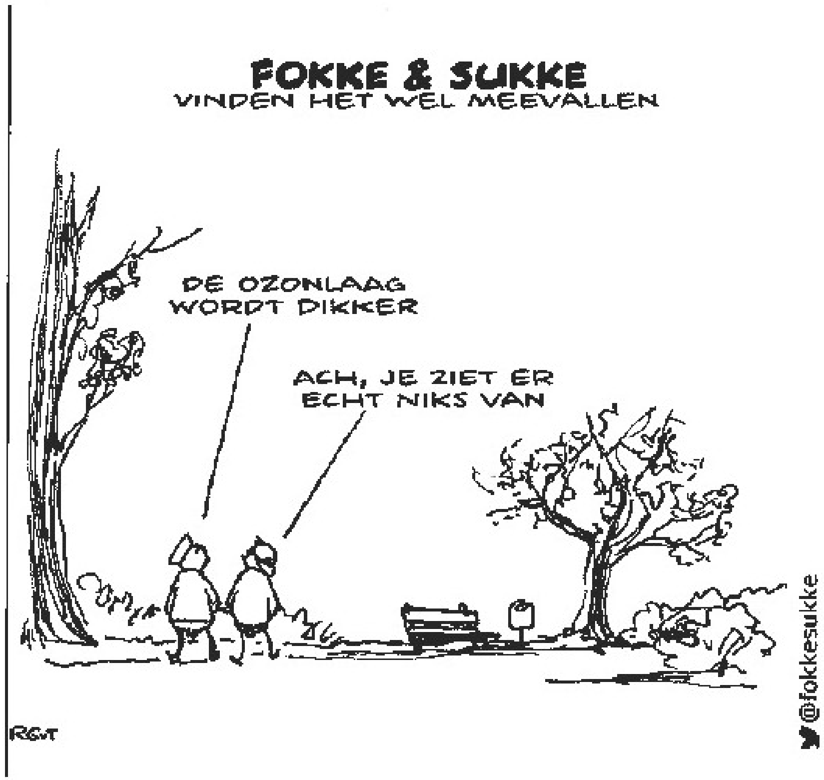
- Project proposal

Apply methodology to other satellite ozone profile measurements (MLS does not have eternal life), important for future monitoring of changes in ozone probability distribution in AOH

UV/VS (OMI, GOME2, OMPS and future TROPOMI)
IR (IASI)
LIMB (MIPAS, OMPS)

CCM-VAL chemistry-transport model results: do they agree???

That's all …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VINDEN HET WEL MEEVALLEN
DE OZONLAAG WORDT DIKKER
ACH, JE ZIET ER ECHT NIKS VAN
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out of the box: science at work

this story appears logical when presented like this, but …
… in reality it was not logical: here is a rough time-line:

- Initial thought: current recovery detection methods do not really work that well
- Are we missing something? There is so much data …
- A hunch: maybe we should look at low(est) ozone …
- accidentally could have a peek at the Solomon et al. PNAS paper …
- OK, let's use MLS and have a quick look at occurrence of low(est) ozone …
- hey, this looks interesting …
- why does this work?

In order of occurring in my mind while making preparations for the NGEO paper …

- realized the lowest ozone = cumulative effect of ozone destruction …
- back-of-the envelope calculation …
- realized that the method automatically selects AOH profiles …
- realized the method is insensitive of the time period chosen …
- checked temperatures and found no evidence of dynamical effects …
- back to the profile frequency of ozone sondes compared to MLS …
- checked the sensitivity to the area chosen …
- while checking all this I got a clear understanding of the "problems" with - - the multivariate regression on total ozone …
    - total ozone ≠ AOH
    - no properly defined time period
    - no properly defined vortex
    - lag-response relations
    - uncertainties in regressors

- PDF analysis almost completely avoids these problems (either implicitly – height, begin of time period, area, lag-relations, regressor uncertainties - or explicitly – end of time period is fairly well defined).

lessons learned

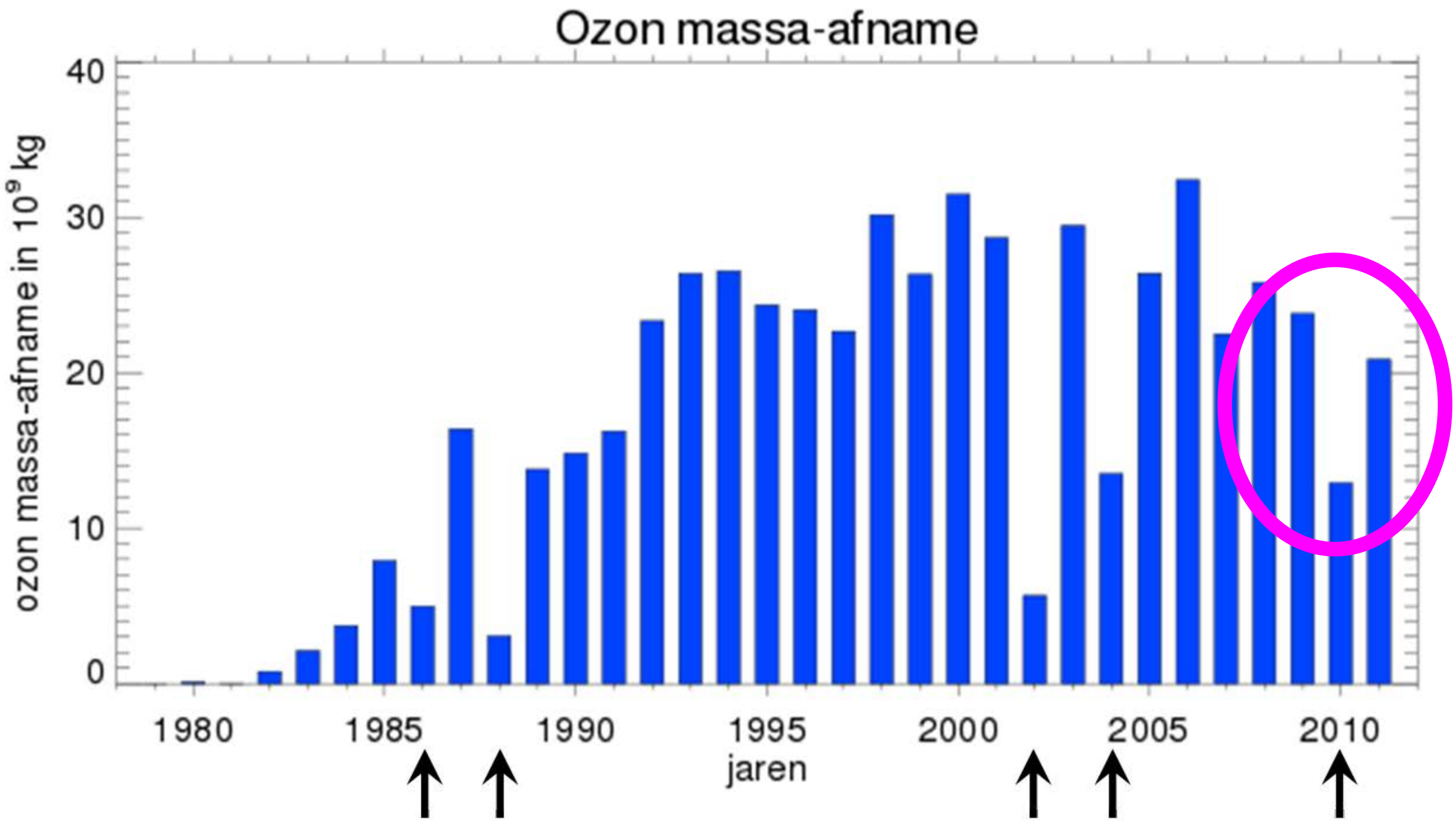
Lesson learned: science does not always progress linearly, intuition, gut feeling, being creative, daring to look at things differently, and the right circumstances, all matter. For example, the right circumstances:

- being at KNMI
- being of the opinion that we could do more science with our own data
- acting on that and KNMI allowing me to do this
- resulting in some papers and development of understanding relevant for this new idea)
- having to be smart as I have no funding for work on ozone (= being clever: optimizing output by minimizing effort and looking for topics that with limited effort still provide interesting papers)
- having the MSR and looking into regressions (developing understanding)
- the WMO involvement (= recognition of KNMI expertise)
- MLS “becoming of age”
- familiarity with MLS as I had used the data before

that’s all coincidental and definitely not planned. Who know what lies around the corner?

Figure is in Dutch, sorry …

2010



- Typical reduction in ozone destruction of 25-50% during ‘active’ years
- Vortex area size in 2010 was well above average (not shown)