Ozone trends and variability in a changing climate

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Universität Bremen

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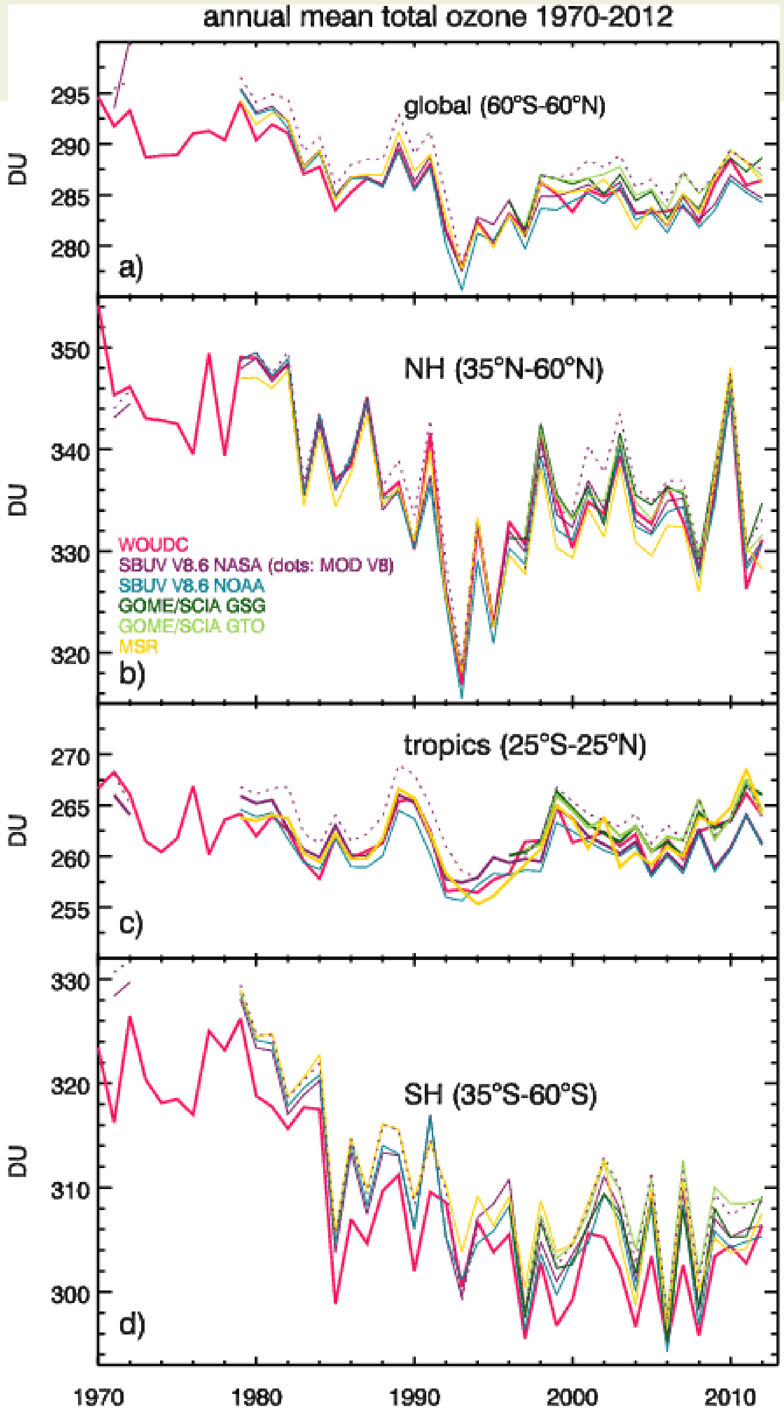
Motivation/Introduction

- Ozone recovers as a consequence of the Montreal Protocol 1986 and its amendments (e.g. Mäder et al. 2010, Kittipurath et al., 2013, Newchurch et al., 2003)

- Long-term changes (& variability) in total ozone (lower stratospheric ozone) are also governed by atmospheric dynamics (and BDC) in a changing climate

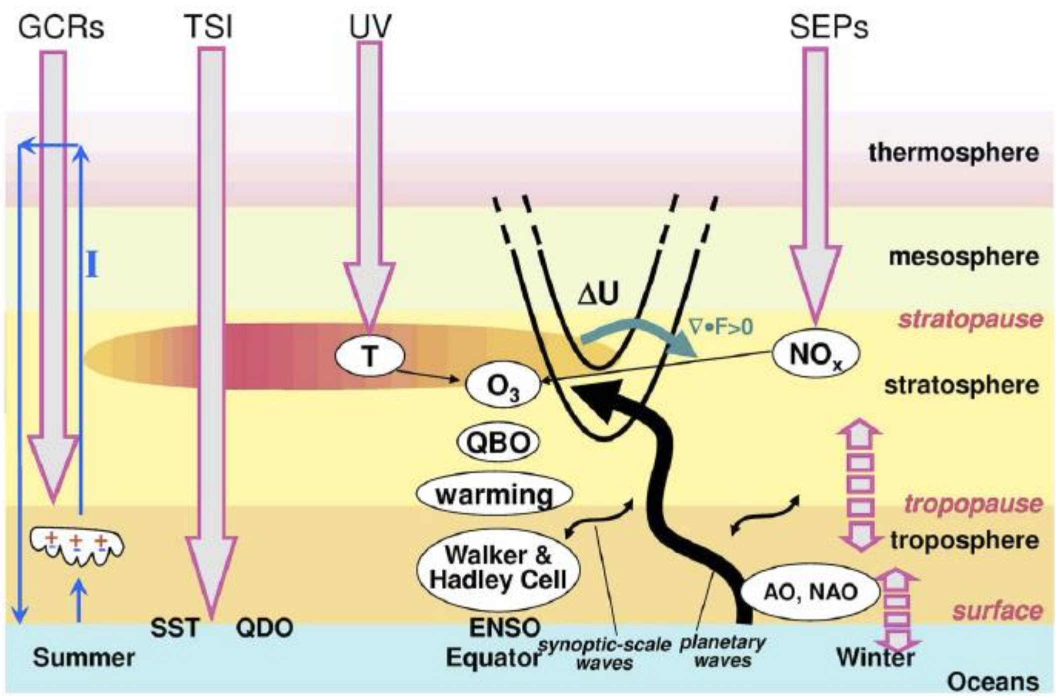
    - How do variability/long-term changes in atmospheric dynamics (e.g. BDC) impact ozone recovery? What does observation tell us? Can we sperate ODS from climate related trends?



Weber et al., 2013

Motivation/Introduction

- „Bottom-up“ (troposphere, SST) and „top down“ (e.g. UV solar activity, PP) processes
  - ozone climate feedback
- Close links between BD ciculation and other processes, e.g. AO/AAO (NAO/SAO,NAM/SAM), QBO, solar activity
- AO/AAO, QBO, ENSO, solar activity link to ozone
  - all used as factors in ozone trend regressions (normally assumed to be independent factors)



Gray et al., 2010

Outline

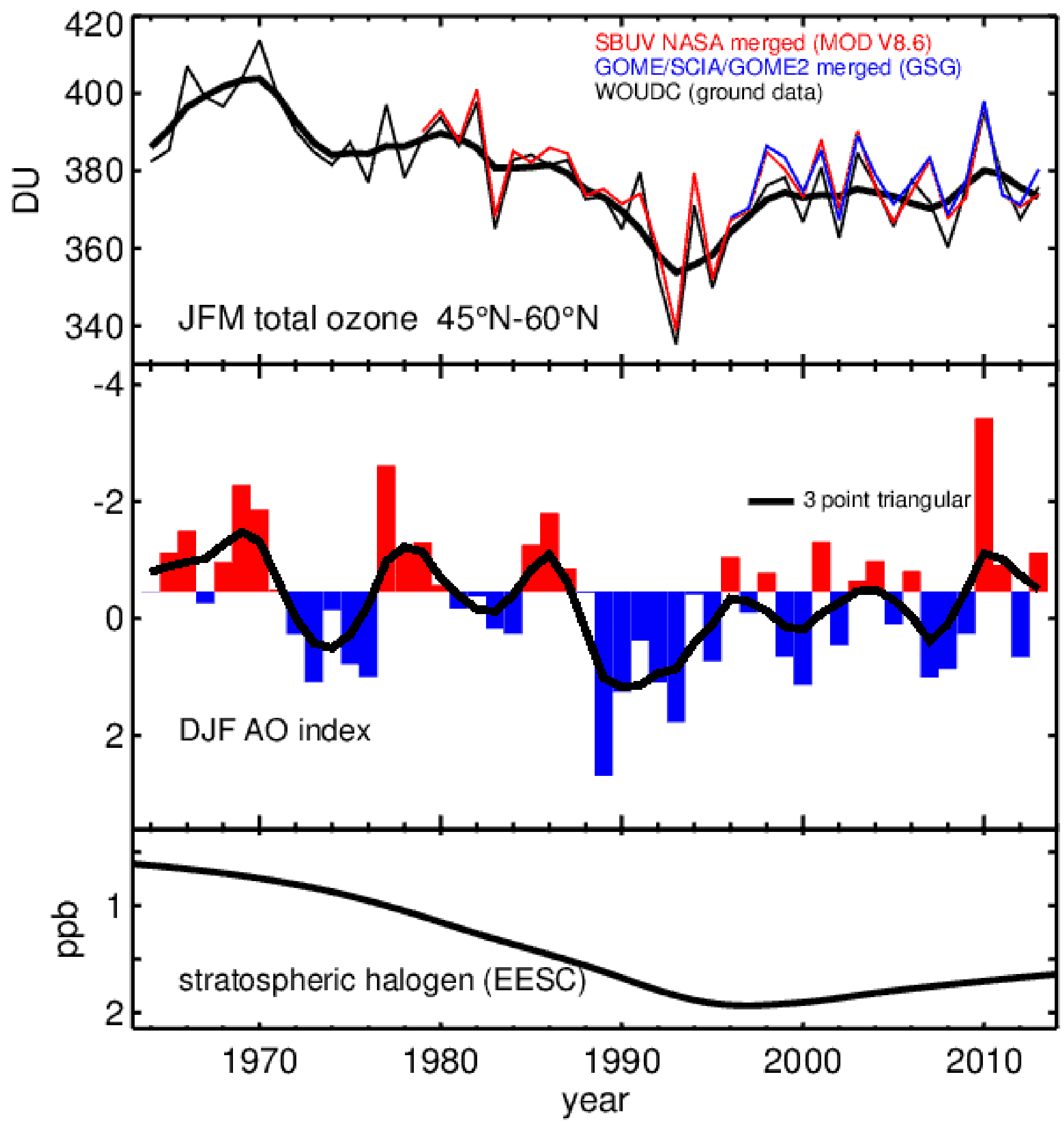
- (Some aspects on) dynamical and chemical coupling in ozone changes
- Total (lower stratosphere) ozone trends
- Ozone profile trends

Coupling of chemistry & dynamics

- Longterm changes (low frequency variability) in winter AO similar to stratospheric halogen trends

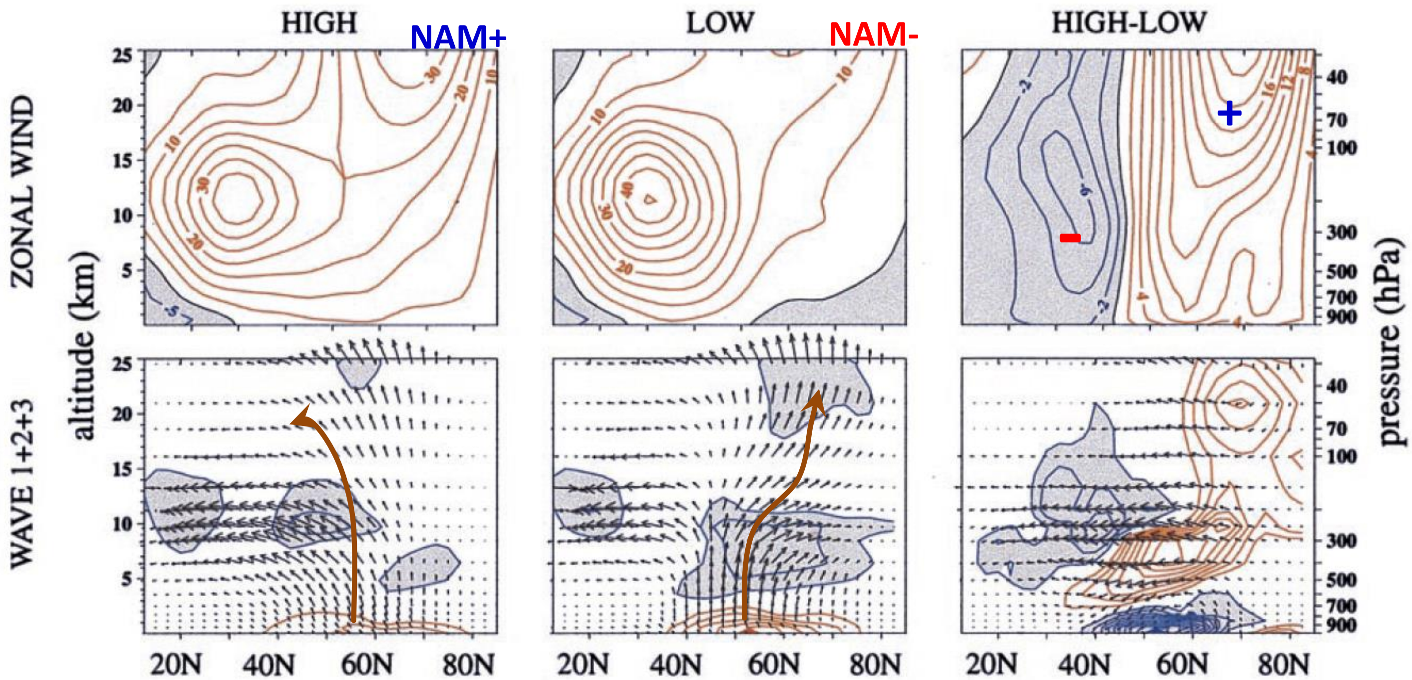
- Ozone-climate feedback

relationship between AO/NAO and NH ozone, see e.g. Appenzeller et al., 2001.



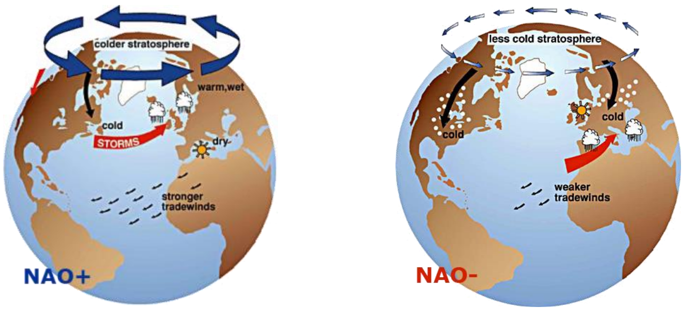
Update from Weber et al. (2011)

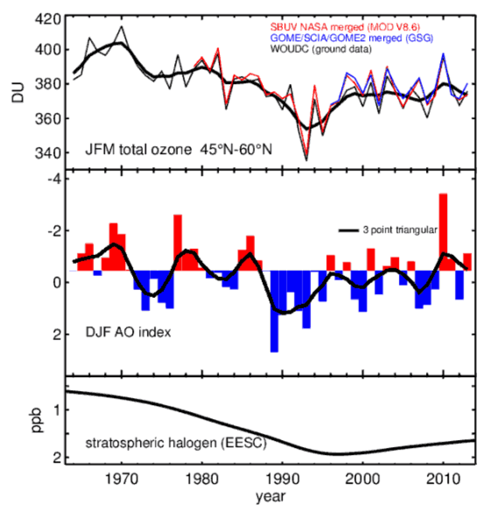
BDC (extratropical wavedriving) and AO



DJFM

Hartmann et al. (2000)

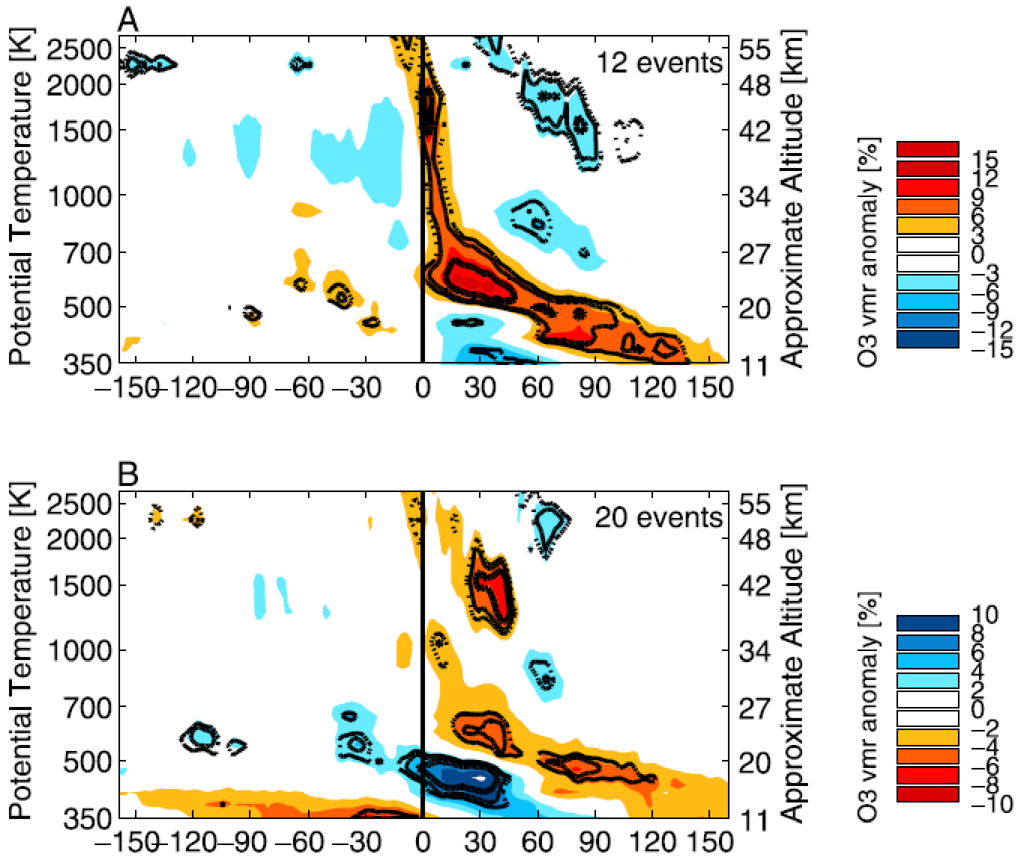




- QBO and solar cycle modulate propagation of waves, thus wind, T, SSW occurences (e.g. Baldwin et al., 2001, Kudera and Kuroda, 2002, Gray et al. 2003, Camp and Tung, 2007, Salby 2008)

Polar ozone and NAM

- SBUV assimilated ozone (1979-2008)
- NH: 20 strong vortex events (NAM > 1.5 @ 10hpa) and 12 weak vortex events (NAM <-3)
- Immiediate ozone response in upper and middle stratosphere
- Ozone anomalies (positive and negative) descend over 4-5 months into the lowermost stratosphere

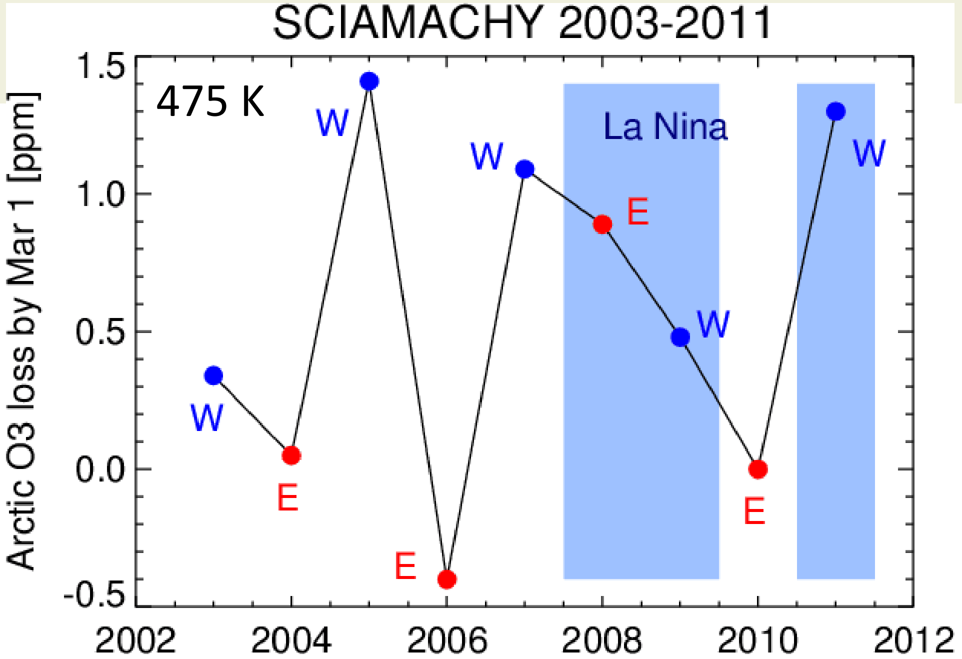


Kiesewetter et al. (2010)

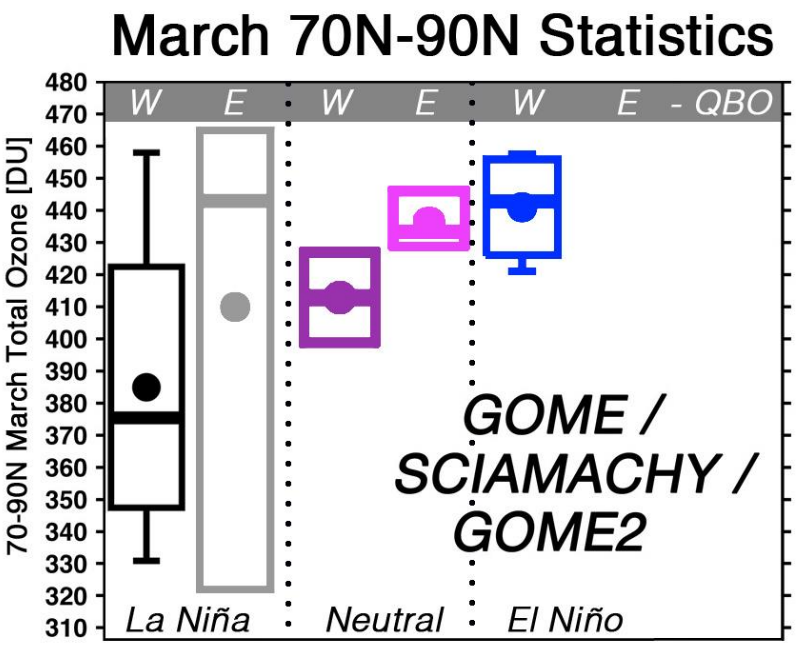
QBO, ENSO and ozone

- QBO-W and/or La Nina favor severe Arctic ozone losses and lower March polar cap total (as expected from Holton & Tan, 1980, Garfinkel and Hartmann, 2008)

- also North-Pacific SST may play a role (see Hurwitz et al., 2011, 2012)

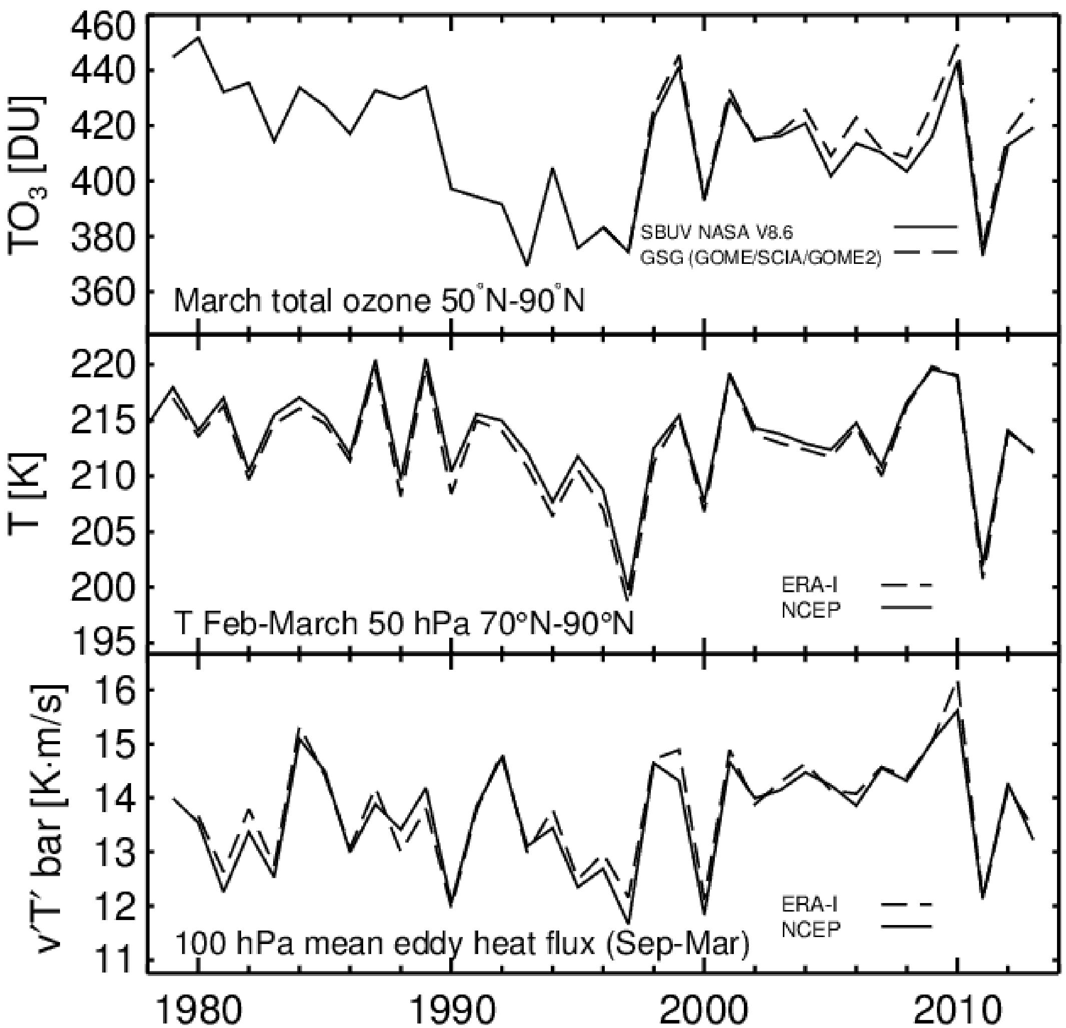


Update from Sonkaew et al., 2013 and Hommel et al., 2013



Hommel et al., in preparation

Interannual variability in BD circulation: polar O3 and T



- Polar ozone in spring correlates with
  - polar stratospheric temperatures (Newmann et al., 2001)
  - Planetary wave activity during winter (e.g. Fusco & Salby 1999, Randel et al., 2002, Weber et al. 2003)

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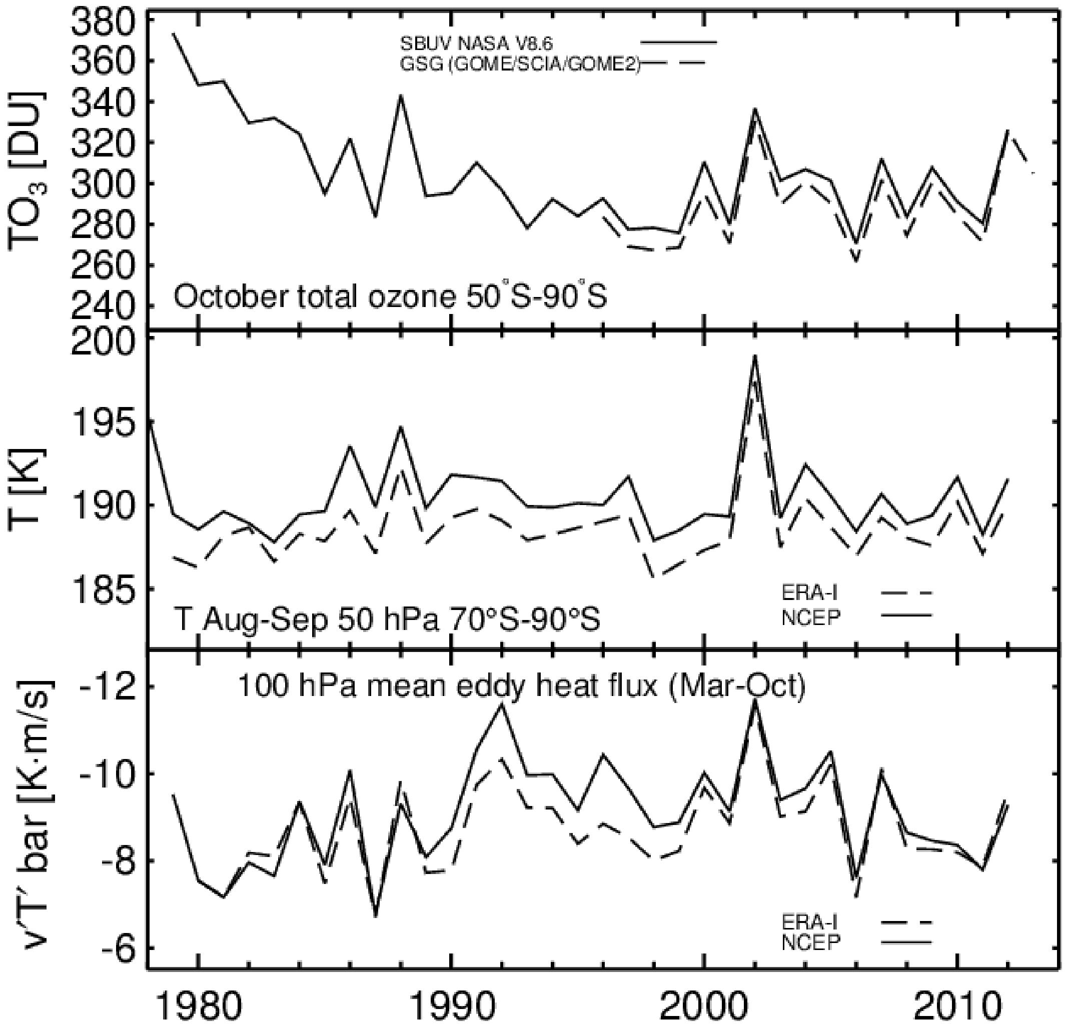

- Polar ozone in spring correlates with
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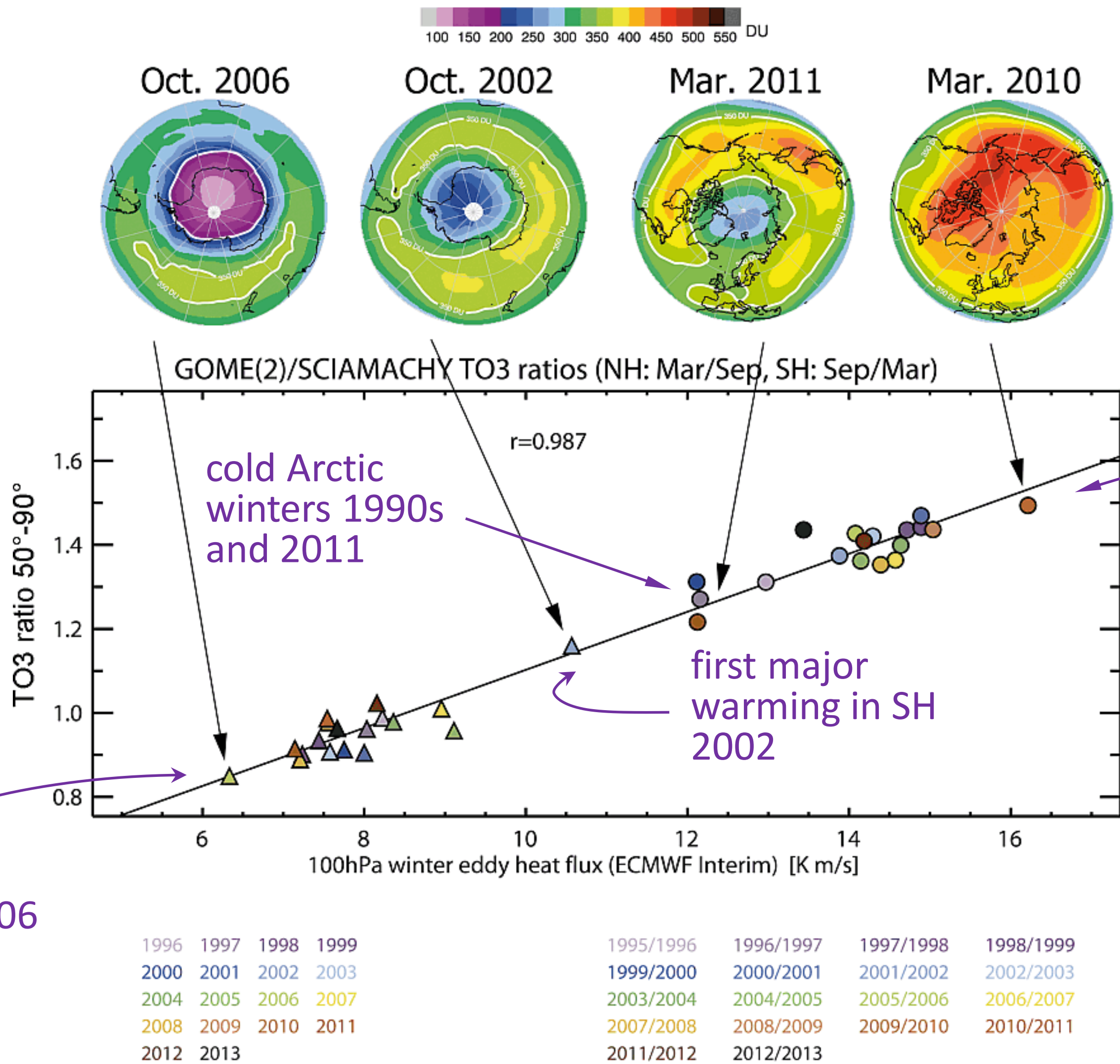
  - Planetary wave activity during winter (e.g. Fusco & Salby 1999, Randel et al., 2002, Weber et al. 2003)
- Correlation between eddy heat flux and ozone is higher after 1990 and in NH
  - Data quality issue with met analyses?

Coupling of transport and chemistry („LEO“)

LEO=Linear eddy heat flux - ozone relationship



very high ozone in 20120

transport

polar ozone loss

record size ozone hole 2006

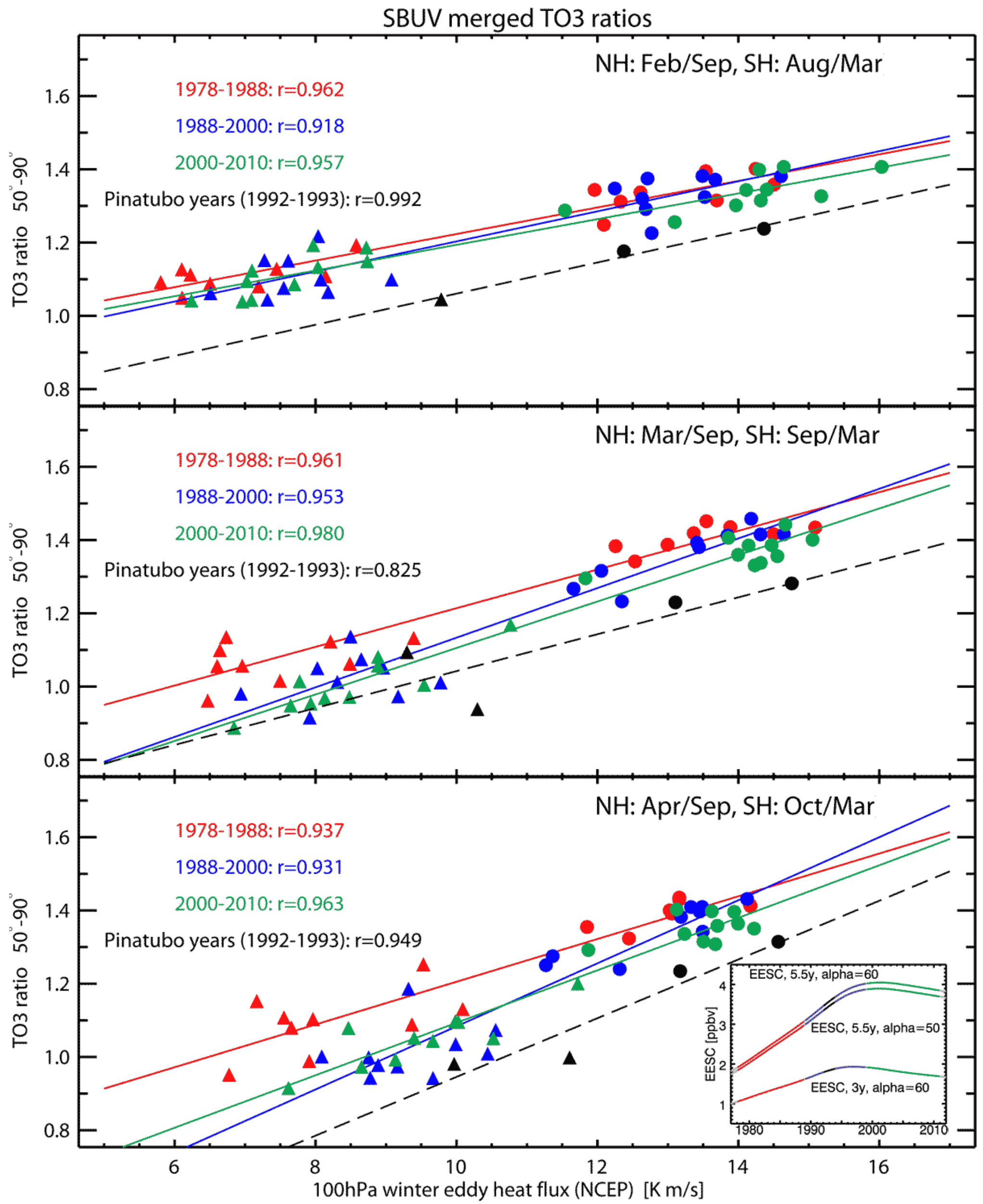
Update from Weber et al. (2011)

-weak Brewer-Dobson circulation
-low T/strong polar vortex
-high polar ozone loss

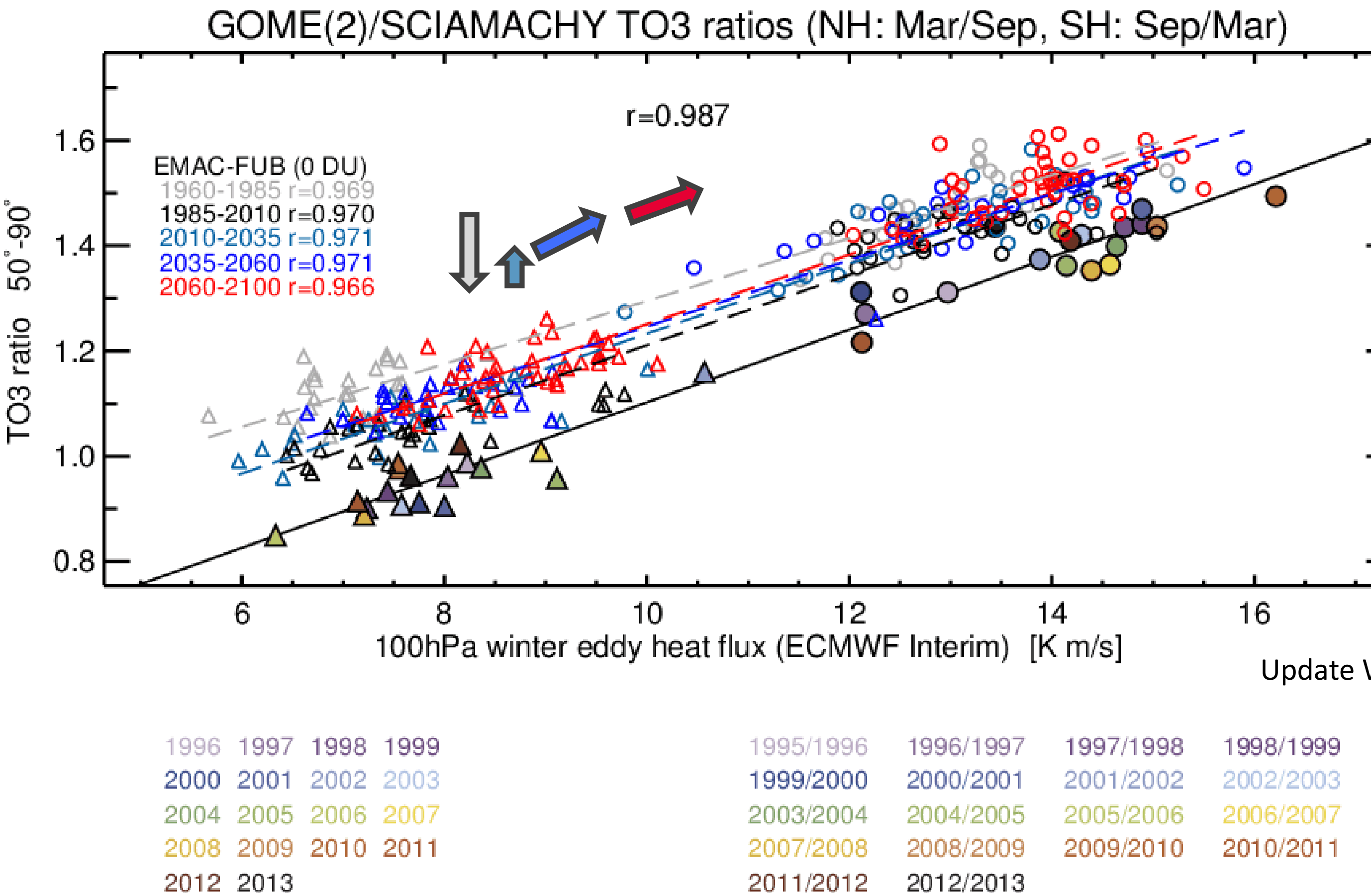
-strong Brewer-Dobson circulation
-high T/weak polar vortex
-enhanced ozone transport

Observed changes in "LEO" with time

- Change in LEO with time (1979-2010)
  - SBUV MOD V8 ozone data
  - "recovery" most evident in SH (but somewhat noisy)
  - Large shift in "LEO" due to Pinatubo



Comparison: CCM model with observations



Update Weber et al., 2011a

- EMAC CCM („high top model“) with IPCC A1B and halogen A1 scenarios
  - among the models with the fastest ozone recovery (Austin et al., 2010)
- until ~2035: vertical shift in LEO → ODS dominated changes
- until 2100: shift towards higher eddy heat flux → GHG dominated changes

Total ozone trends: multiple linear regression (MLR)

- Trend analysis of annual mean total ozone
- Regression model:

$$OZ(yr) = OZ° + \alpha^{EESC} \cdot EESC(yr)$$
$$+ \alpha^{qbo10} \cdot qbo10(yr) \quad + \alpha^{qbo30} \cdot qbo30(yr)$$
$$+ \alpha^{enso3,4} \cdot enso3,4$$
$$+ \alpha^{ehf} \cdot ehf(yr)$$
$$+ \alpha^{solar} \cdot solar(yr)$$
$$+ \alpha^{aerosols} \cdot EESC(yr) \cdot aerosols(yr)$$
$$+ \varepsilon(yr)$$

dynamics
chemistry
mixed

Sample regression

- SBUV/OMI/TOMS Mod V8
  - 1979-2012 (Stolarski and Frith, 2006, update)
- 60°N-65°N

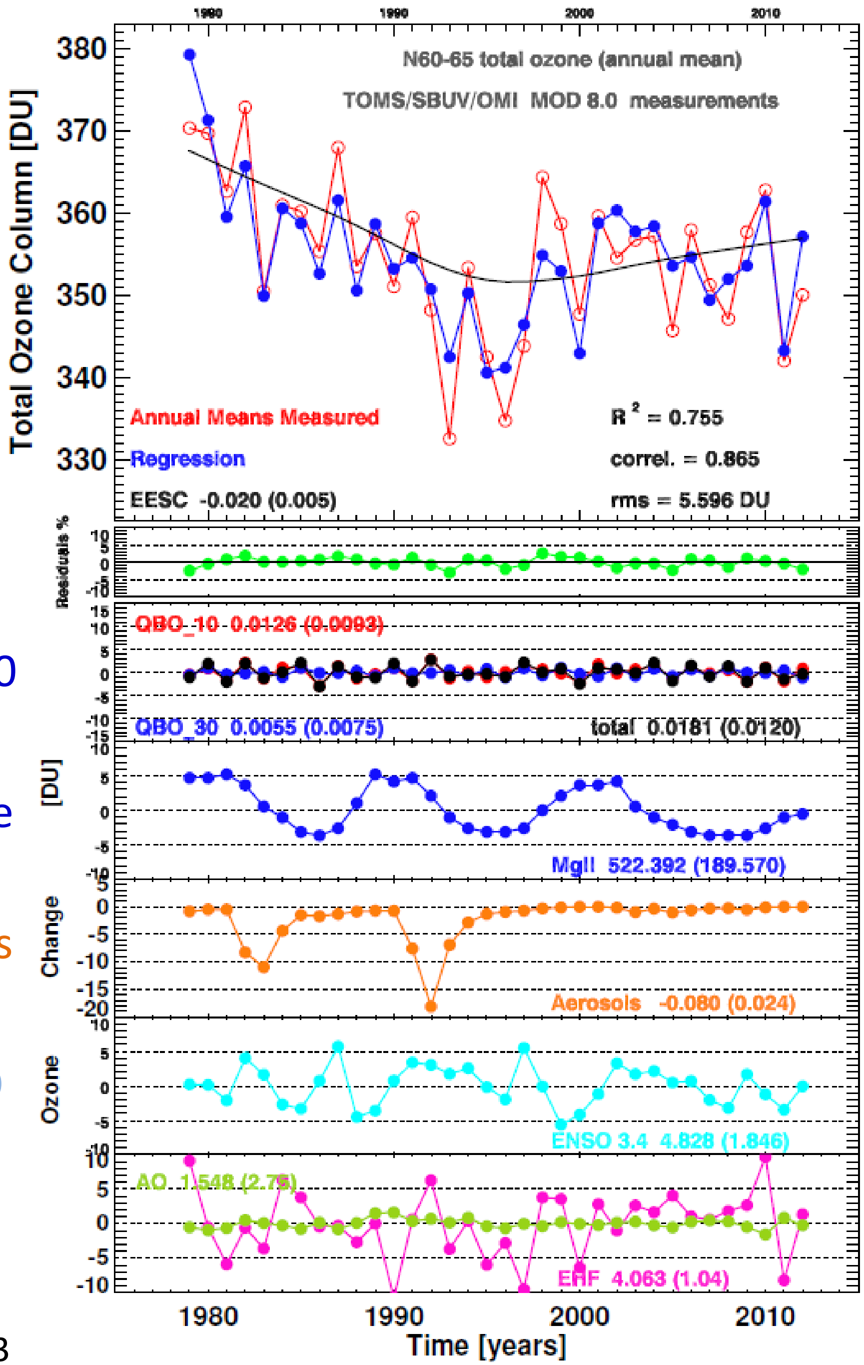
QBO 10, QBO 20

Solar cycle

aerosols

ENSO

EHF, AO



Chehade et al. 2013

MLR results

- SBUV/OMI/TOMS Mod V8 1979-2012
- Regression coefficients as a function of latitude (w/ 2σ uncertainties)
  - EESC trends statistically significant in extratropics (>25°)
  - Aerosols only significant at NH latitudes (see Schnadt-Proberaj et al., 2011, Aquila et al., 2013)

QBO 10, QBO 30

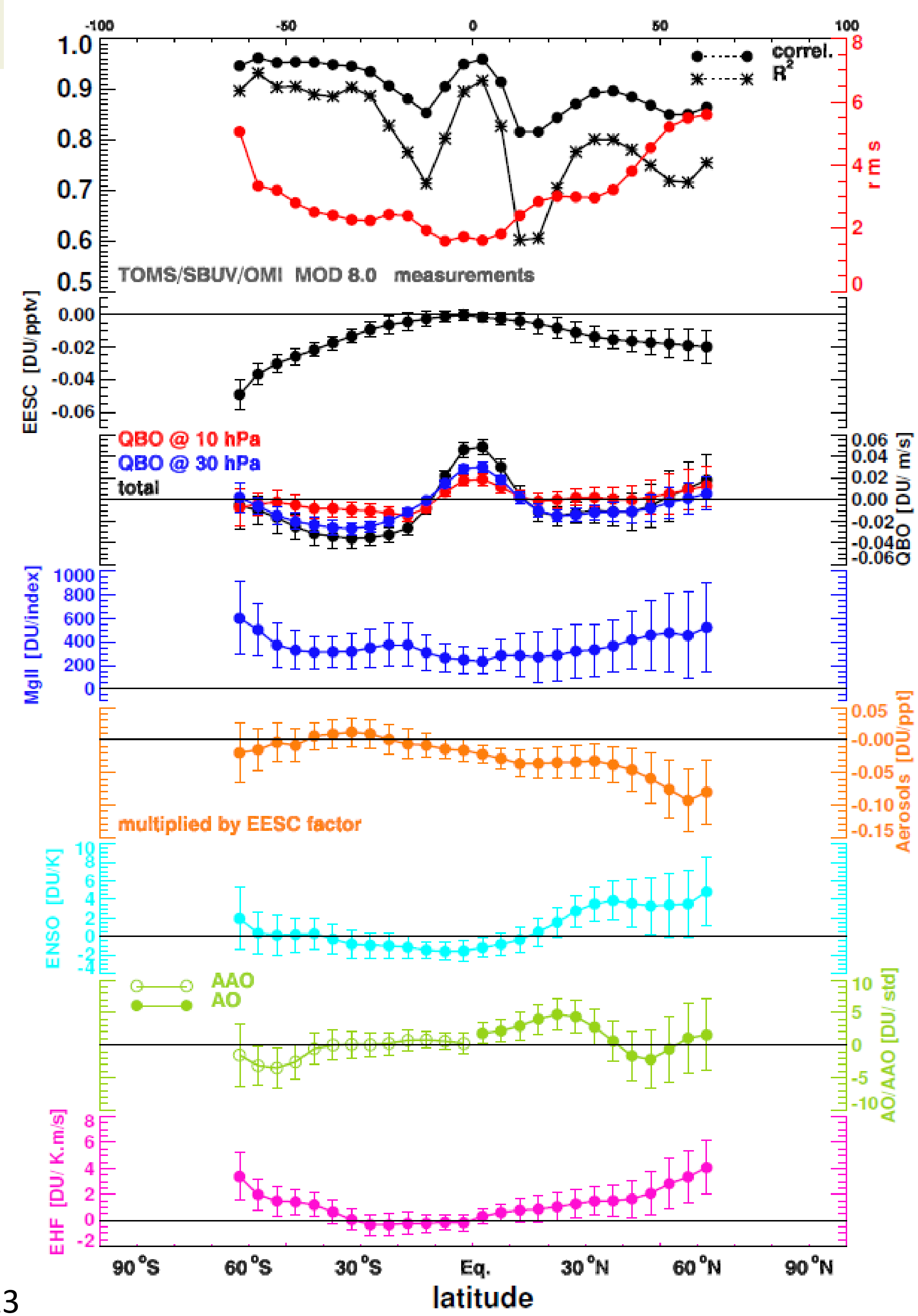
Solar cycle

aerosols

ENSO

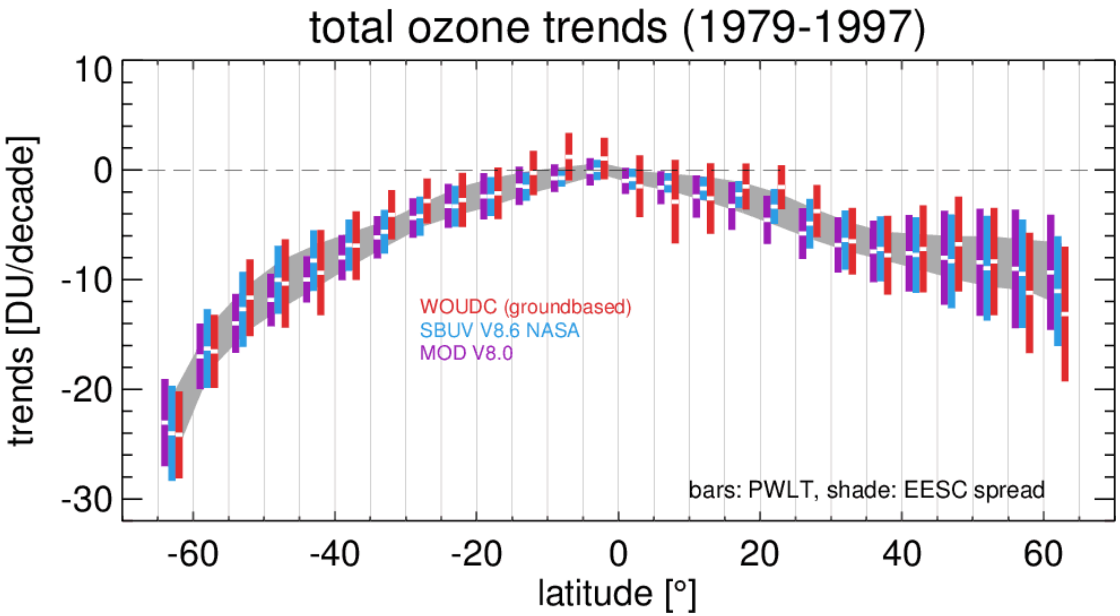
AAO/AO

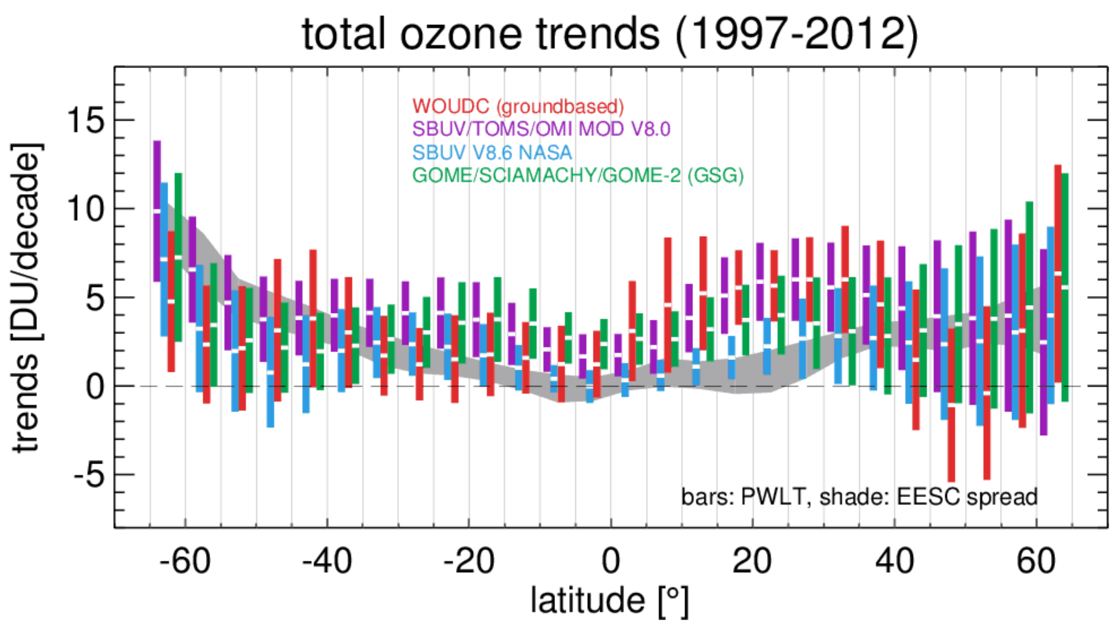
EHF



Chehade et al. 2013

Total ozone recovery



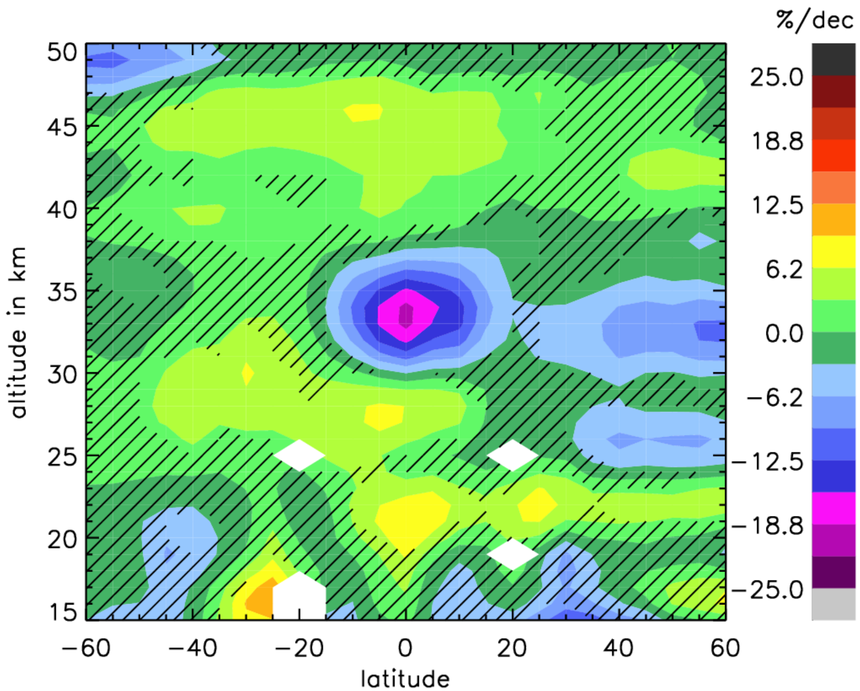


- EESC and „hockey stick 1997“ trends
  - WOUDC ground data (Fioletov et al., 2002 update)
  - Mod V8 (SBUVs/TOMS/OMI)
  - SBUV Mod V8.6
  - GOME/SCIA (GSG)
- Trend change after 1997 (statistically robust outside the tropics) → success of MP!
- Post-1997 linear trends differ for some latitudes from EESC trend (see also WMO 2011) → PWLT indicate addtional contribution from atmspheric dynamics

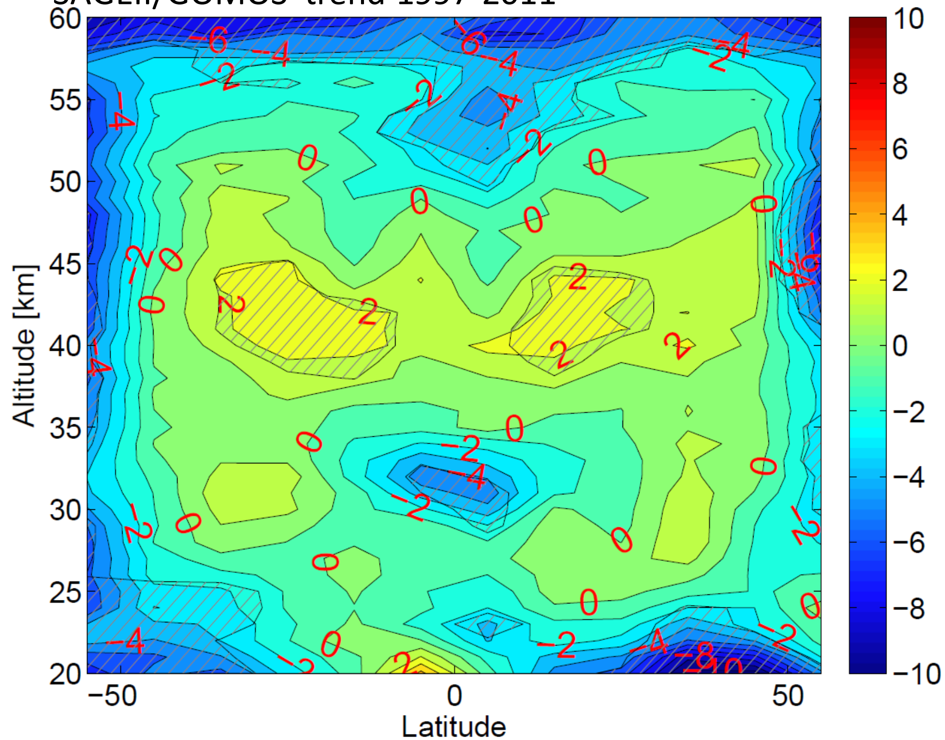
Post 1997-trends in O3

SCIAMACHY trend 2002-2011

Gebhardt et al., 2014



SAGEII/GOMOS trend 1997-2011

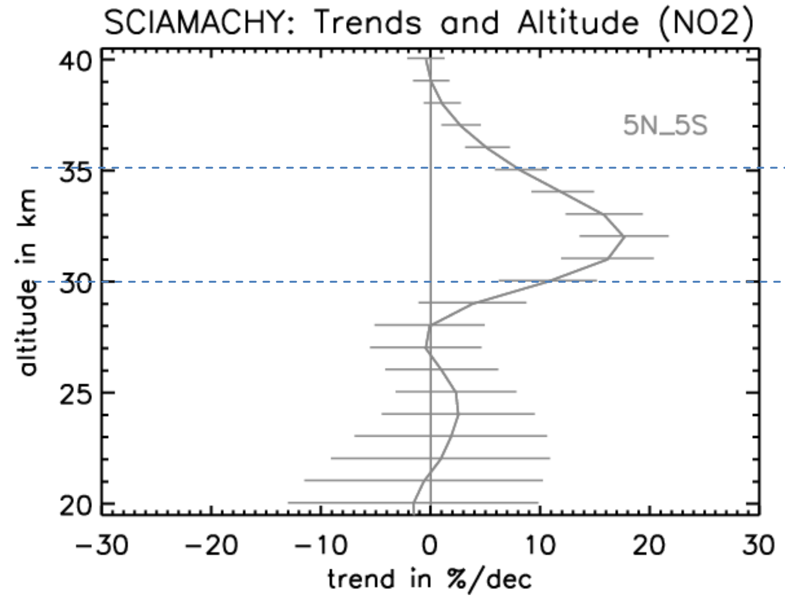


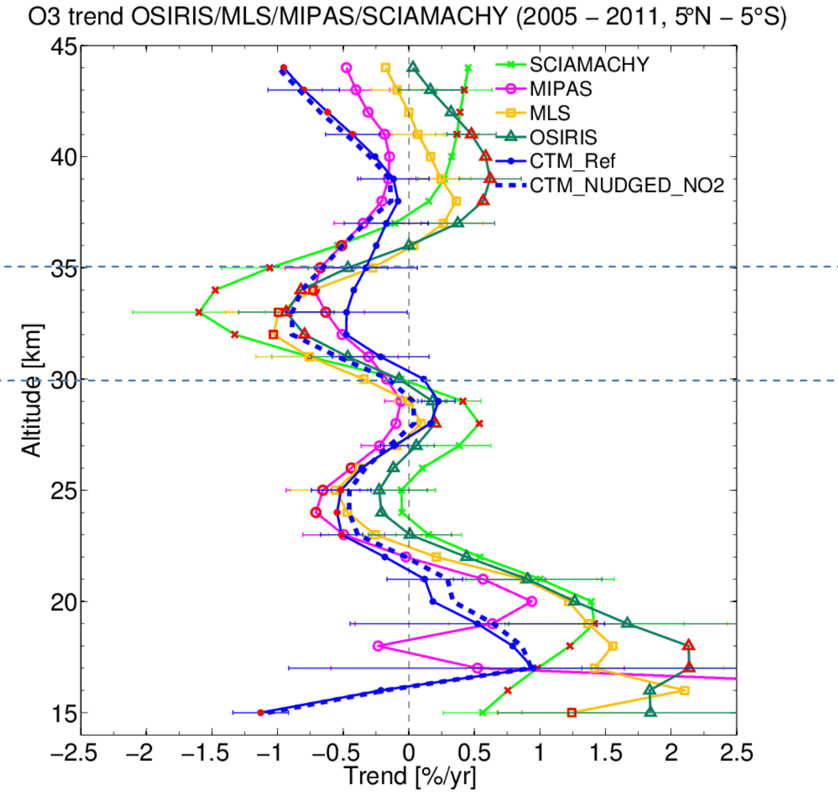
Kyröla et al. 2013

- +2-3% /decade @ 40-45 km → ODS changes (recovery!)
- Negative post-1997 trends in tropics @ 32 km(see also Eckert et al. 2013/MIPAS data → poster) → NOx related?

Possible role of NOx in the tropics @ 32 km?

2002-2011

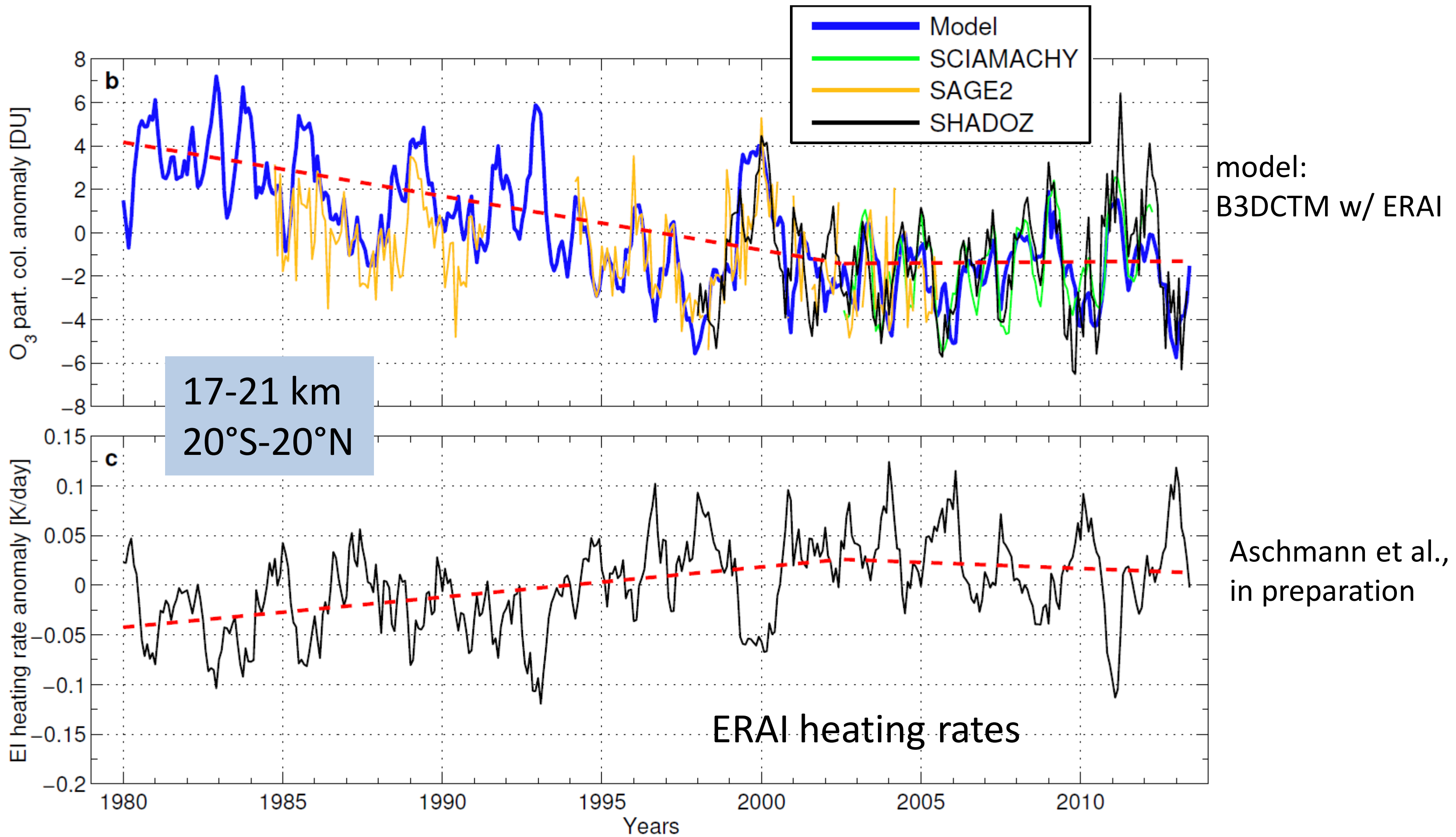




See Poster by Burrows et al.

- Strong positive trends in NO2 near 32km from SCIAMACHY
  - SCIA NO2 nudged B3DCTM shows larger O3 trends than CTM with background N2O, but still a factor of two smaller than SCIAMACHY, but in better agreement with MIPAS/OSIRIS/MLS

Tropical UTLS O3 trends



- Tropical UTLS ozone changes related to changes in tropical upwelling (Randel and Thompson, 2011, Sioris et al., 2013)
- trend changes in tropical upwelling and ozone after ~2002 → Global warming hiatus (East Pacific SST cooling after ~2000, Meehl et al., 2011, Kosaka and Xie 2013)

Summary and conclusion

- Total ozone show in the extratropics a significant trend change after 1997 consistent with stratospheric halogen (EESC)/ODS changes → anthropogenic ozone recovery due to MP

- Current total ozone trends, however. are also influenced by low-frequency (decadal) as well as short-term variability in atmospheric dynamics → can we clearly separate ODS and climate related trends in observed ozone?

- Upper stratospheric ozone (40-45 km) shows positive trends of about +2 to +3%/decade since 1997 → success due to MP!

- Negative ozone trends in tropical middle stratosphere (30-35 km) during the last decade → related to NOx chemistry?

- Tropical UTLS ozone (and tropical upwelling) has levelled off after 2000 → possible link to global warming hiatus (Kosaka & Xie, 2013, Meehl et al., 2013)

- Trends in profile ozone are qualitatively consistent between different satellites but differ in detail (see also, e.g., poster by Rahpoe, Eckert, Harris on drift/biases/trends in limb/occultation data)

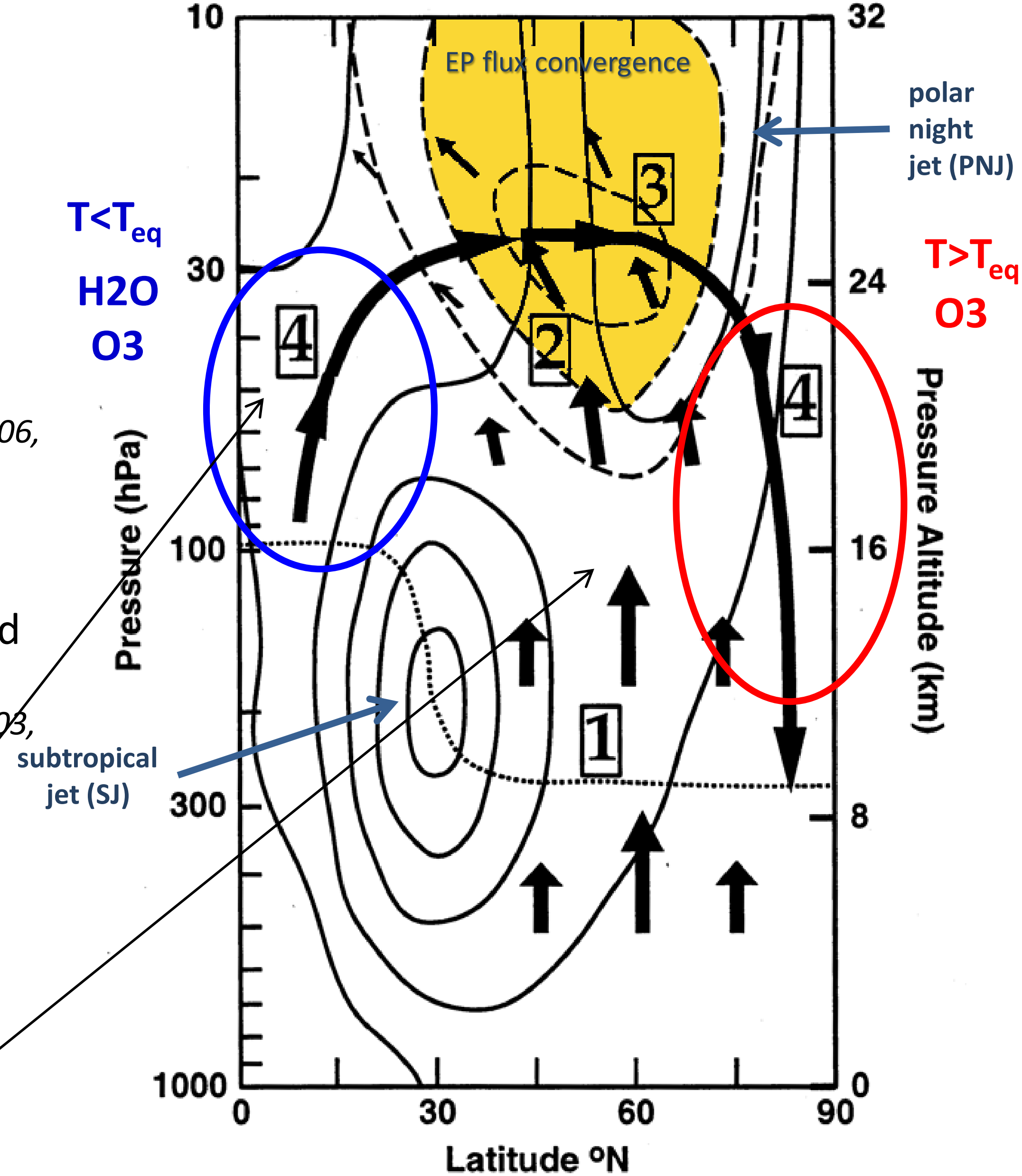
  → Need for improving & continuing satellite limb/occultation observations, the looming “limb data gap”

Mechanism of the Brewer-Dobson circulation

- Variation in BD circulation
  - changes in transport
  - changes in temperatures

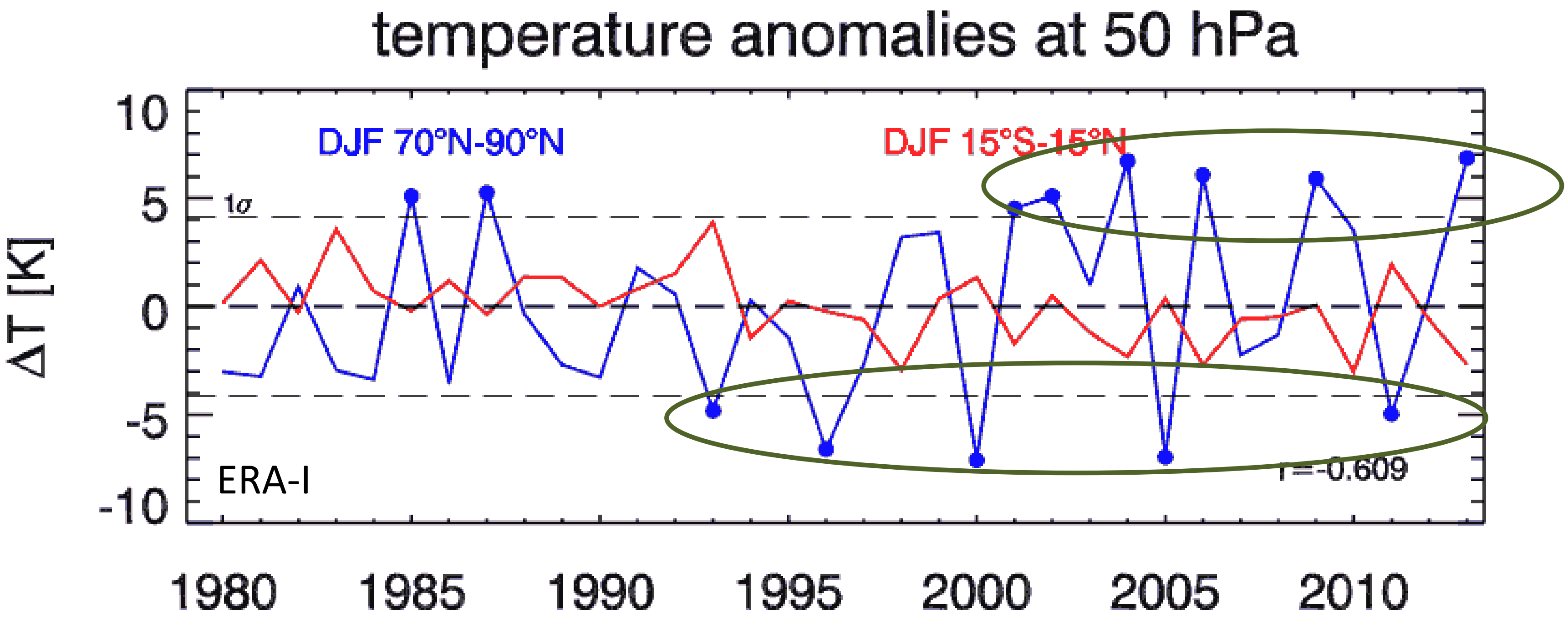
- stronger BD circulation means
  - cooling in tropics (affects H2O vapor and ozone, *e.g. Randel et al 2006, Dhomse et al., 2008, Rosenlof et al., 2008, Randel & Thompson, 2011*)
  - warming in polar region (e.g. ´major warmings´, (affects O3 and polar ozone loss, e. g. *Fusco & Salby 1999, Randel et al., 2002, Weber et al., 2003, 2011, Salby & Callaghan 2004*)

- measure of BD circulation strength/driving
  - EP flux convergence
  - tropical upwelling
  - extratropical eddy heat flux
  - age-of-air



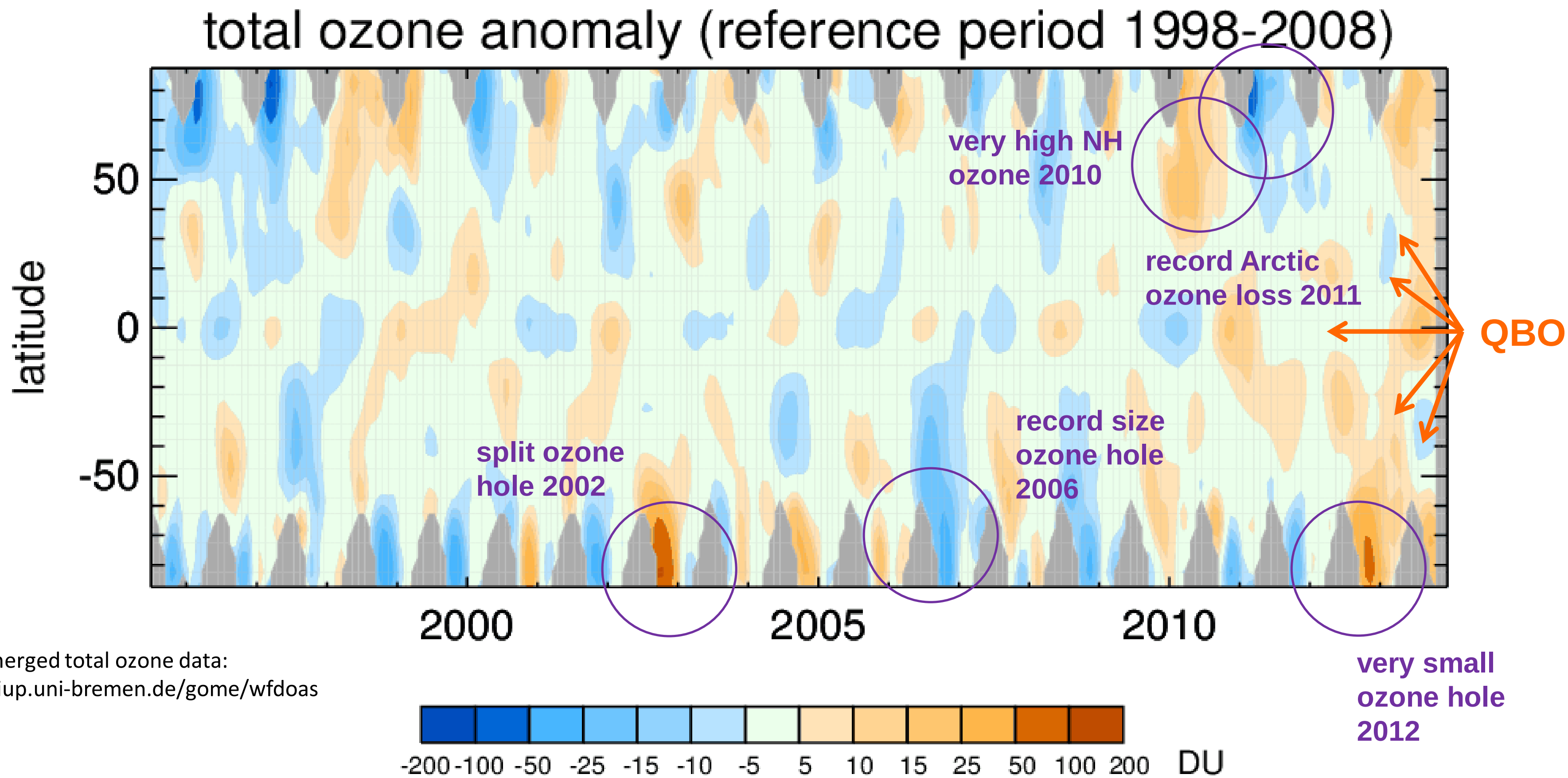
Newman et al. (2001)

BDC and stratospheric temperatures



- Increases in BDC driving:
  - Positive trend in polar T , negative trend in tropical T
  - Predicted by many models (see WMO 2010)
- cold Arctic winters are getting colder/increasing Vpsc trend (Rex et al. 2004, WMO 2010, Sinnhuber et al., 2011) or just decadal-scale variability (Rieder and Polvani, 2013)

Global ozone anomalies (1995-2012)



GSG merged total ozone data:
www.iup.uni-bremen.de/gome/wfdoas

- extreme conditions within last decade (climate related?):
  - split ozone hole in 2002 (WMO 2007), record size ozone hole in 2006, very high NH ozone in 2010 (Steinbrecht et al., 2011), record Arctic ozone loss in 2011 (e.g. Manney et al., 2011, Sinnuber et al., 2011), small Antarctic ozone hole in 2012 (Kramarova et al., 2013)