Combining recent satellite time-series for analyses of trends in stratospheric trace gases: methodology, results, possibilities

J. Urban (1), A. Jones (1,2), S. Brohede (1), D. Murtagh (1), K. Walker (2), H. Vömel (5), S. Oltmans (4), M. Fujiwara(6), M. Shiotani (7), M. Weber (3), C. von Savigny (3), A. Rozanov(3), J. Burrows (3), G. Stiller (8), M. Santee (9), L. Froideveaux (9), and other (data) contributors ...

(1) Chalmers University of Technology, Göteborg, Sweden

(2) University of Toronto, Canada

(3) University of Bremen, Germany

(4) Boulder, USA

(5) Lindenbergh, Germany

(6) Hokkaido University, Sapporo, Japan

(7) Kyoto University, Japan

(8) Forschungszentrum Karlsruhe, Germany

(9) Jet Propulsion Laboratory, Pasadena, USA

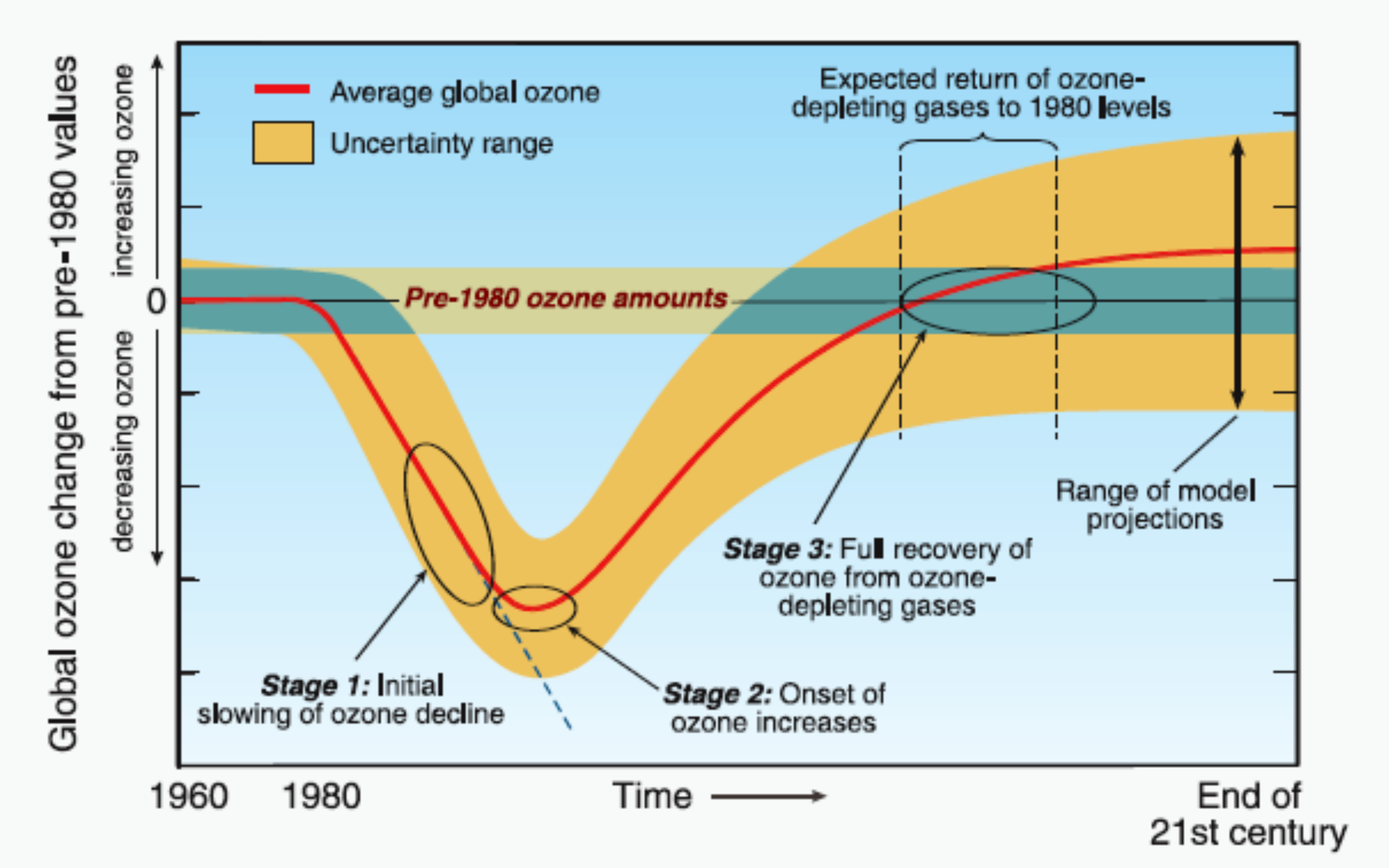
Objectives

- Extension of "historical" stratospheric satellite time-series (SAGE, HALOE, ...) with data from "new generation" of satellites, launched from 2001 onward: Odin, Envisat, ACE, Aura, ...

- Ozone recovery?
- Stratospheric chlorine (Cly, ClOx)?
- Nitrogen family (NOy)?
- Water vapour evolution?

Ozone

Recovery stages of stratospheric ozone



Ozone depletion from satellites

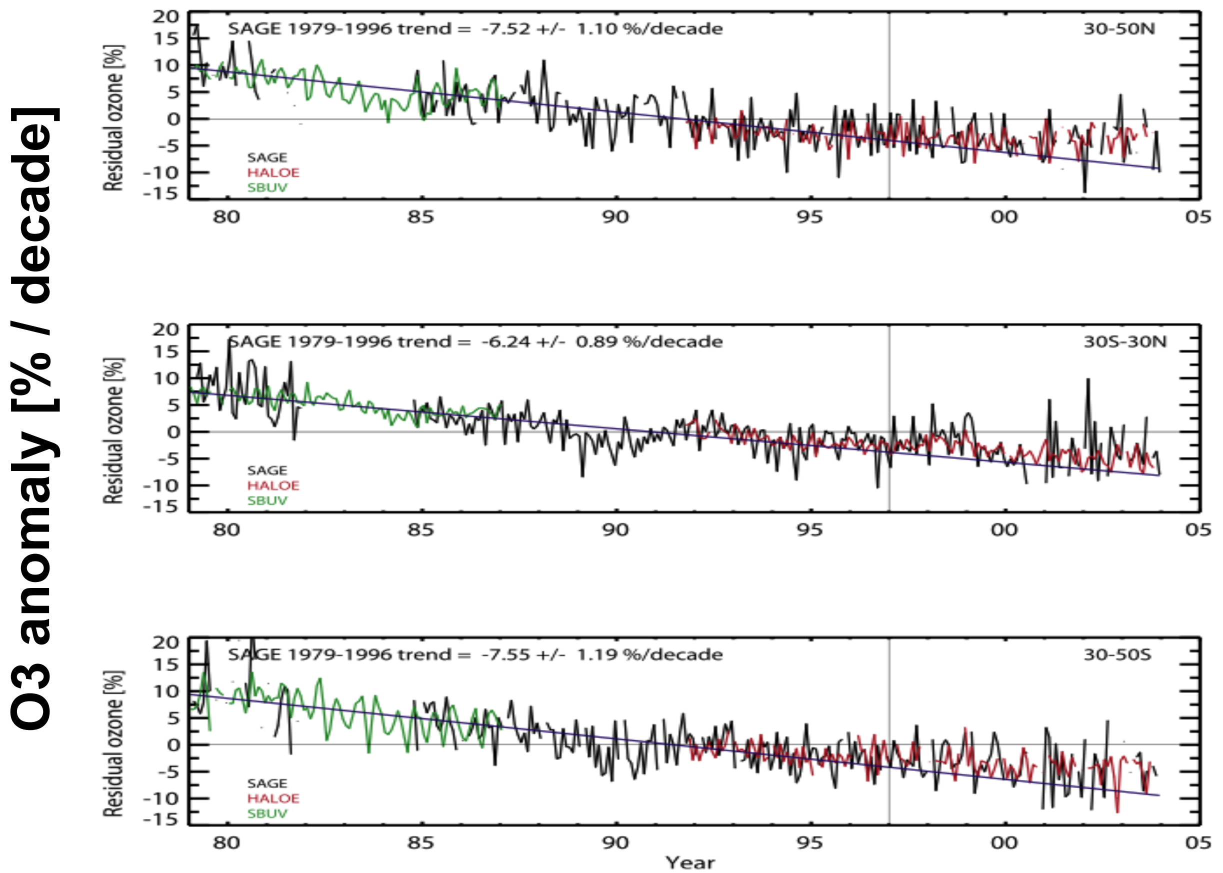


Figure 3. Residuals of the SBUV Nimbus 7 ozone series (green lines) at 35–45 km, (top) 30°–50°N, (middle) 30°S to 30°N, and (bottom) 30°–50°S, respectively. The trend lines are derived from the SAGE residuals (black lines) for 1979–1996. The HALOE residuals are shown by the red lines. These residuals were all obtained using the F10.7cm flux proxy for the removal of the solar cycle effect (as given by N3).

SAGE I+II
1979 - 1997 trend:

-7.5 ± 1.1 %/decade 30-50N

-6.2 ± 0.9 %/decade 30S-30N

-7.6 ± 1.2 %/decade 30-50S

upper stratosphere 35-45km

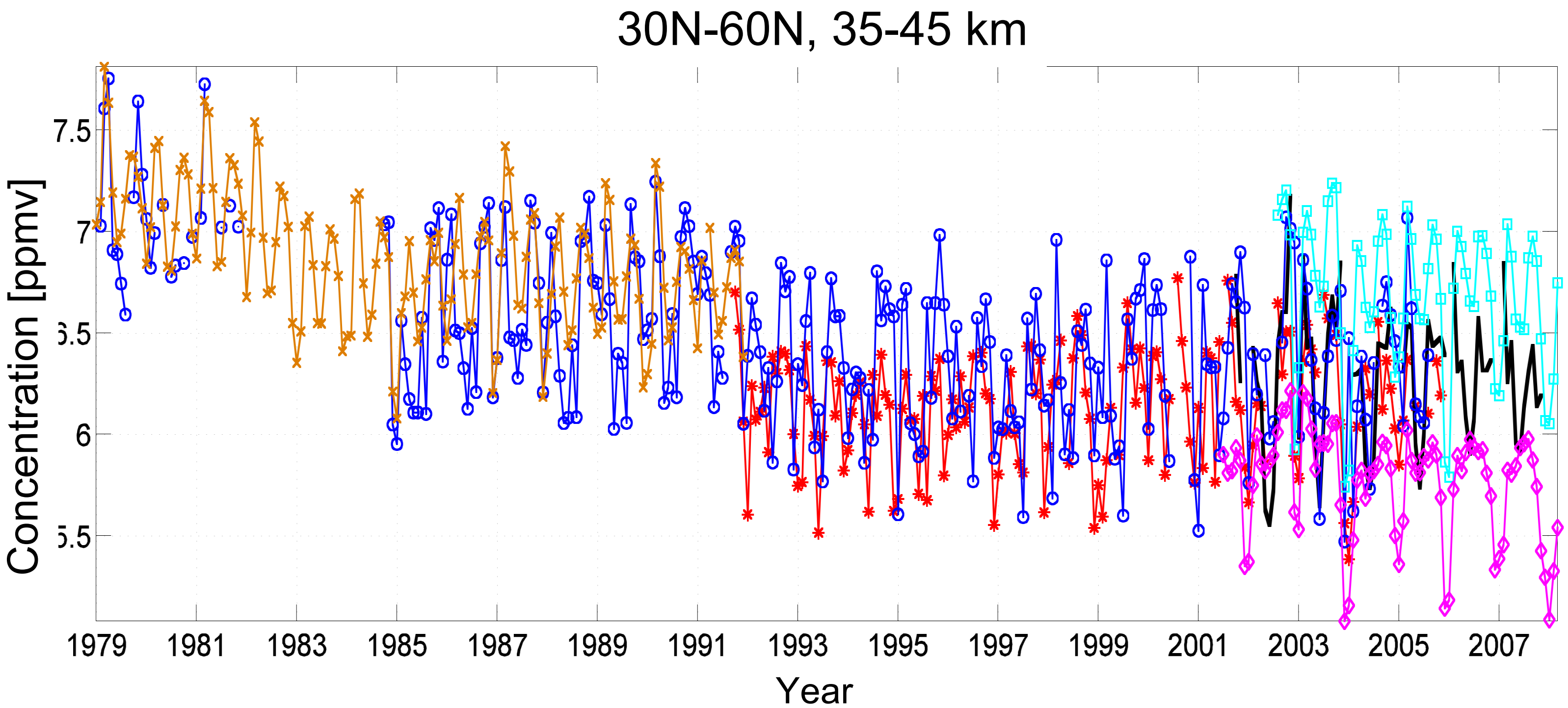
(Cunnold et al, 2004) **HALOE SAGE SBUV/2**

Satellite ozone profile data sets

- **SBUV**	(v8.0)	**1979-1992**	UV/VIS - nadir
- **SAGE I + II**	(v6.2)	**1979-2005**	UV/VIS - limb
- **HALOE**	(v19.0)	**1991-2005**	thermal IR - limb
- **OSIRIS**	(v3.0)	**2001-present**	UV/VIS - limb
- **SMR**	(v2.1)	**2001-present**	microwave - limb
- **SCIAMACHY**	(v2.0)	**2002-present**	UV/VIS -limb

Ozone trend from satellites

Monthly zonal mean ozone - 30N-60N - 35-45km



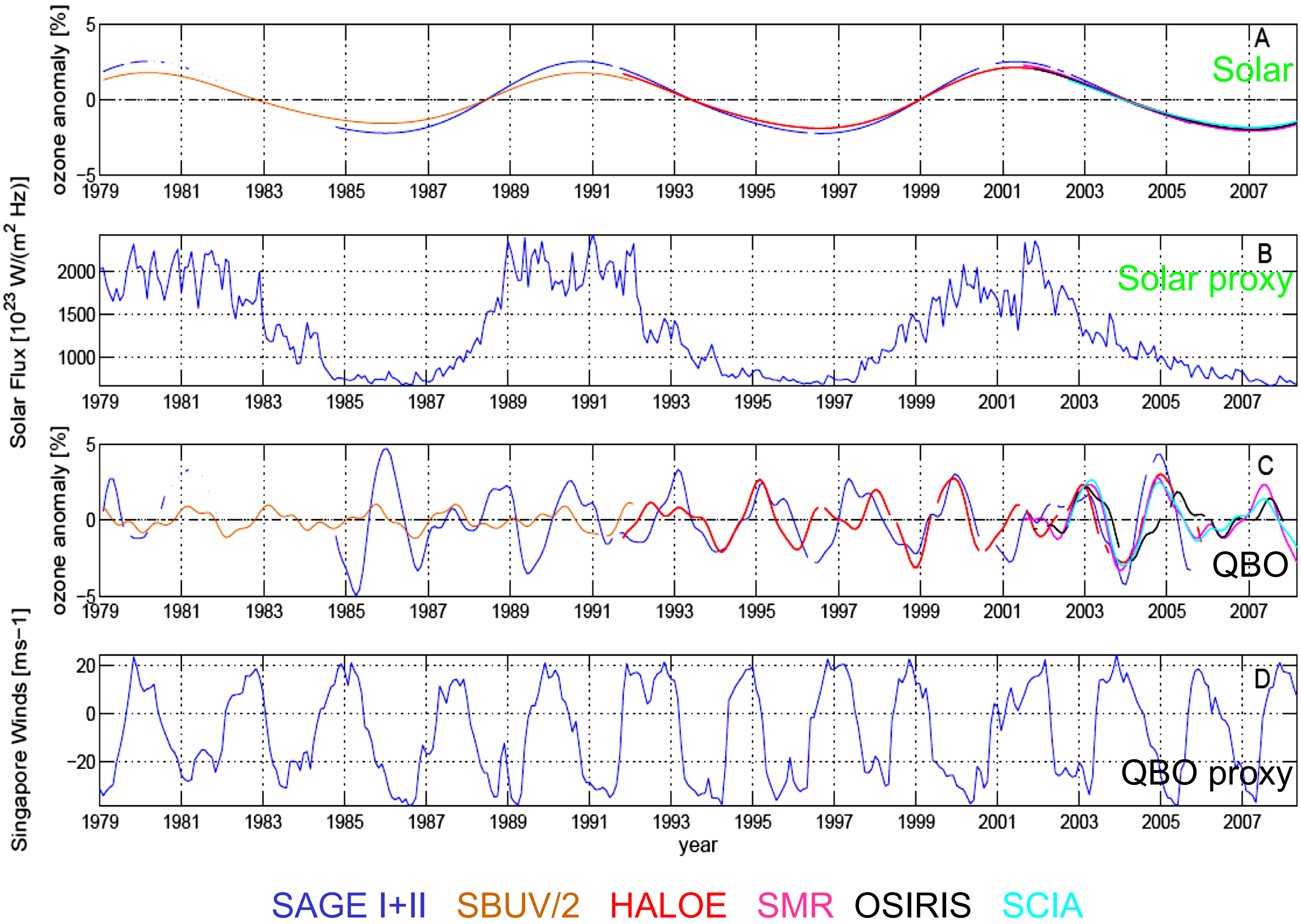
SAGE I+II HALOE SBUV SMR OSIRIS SCIAMACHY

Linear regression model

$$O_3(t) = a + b\,t + [\text{Seasonal terms}]$$
$$+ [\text{QBO periodic terms}]$$
$$+ [\text{Solar terms}]$$
$$+ N_t$$

a	**= constant offset**
b	**= linear slope**
Seasonal terms	**= 12 and 6 months**
QBO terms	**= periods between 3 and 30 months (examined using a FFT model)**
Solar terms	**= 63 and 127 months (as suggested by Cunnold et al., 2004)**
N_t	**= auto-correlated error term (i.e. remaining residual)**

Estimates of QBO and sun related ozone variation, 30–60N, 35-45km



Statistical methods for detection of milestones

(a) "Change in linear trends" method

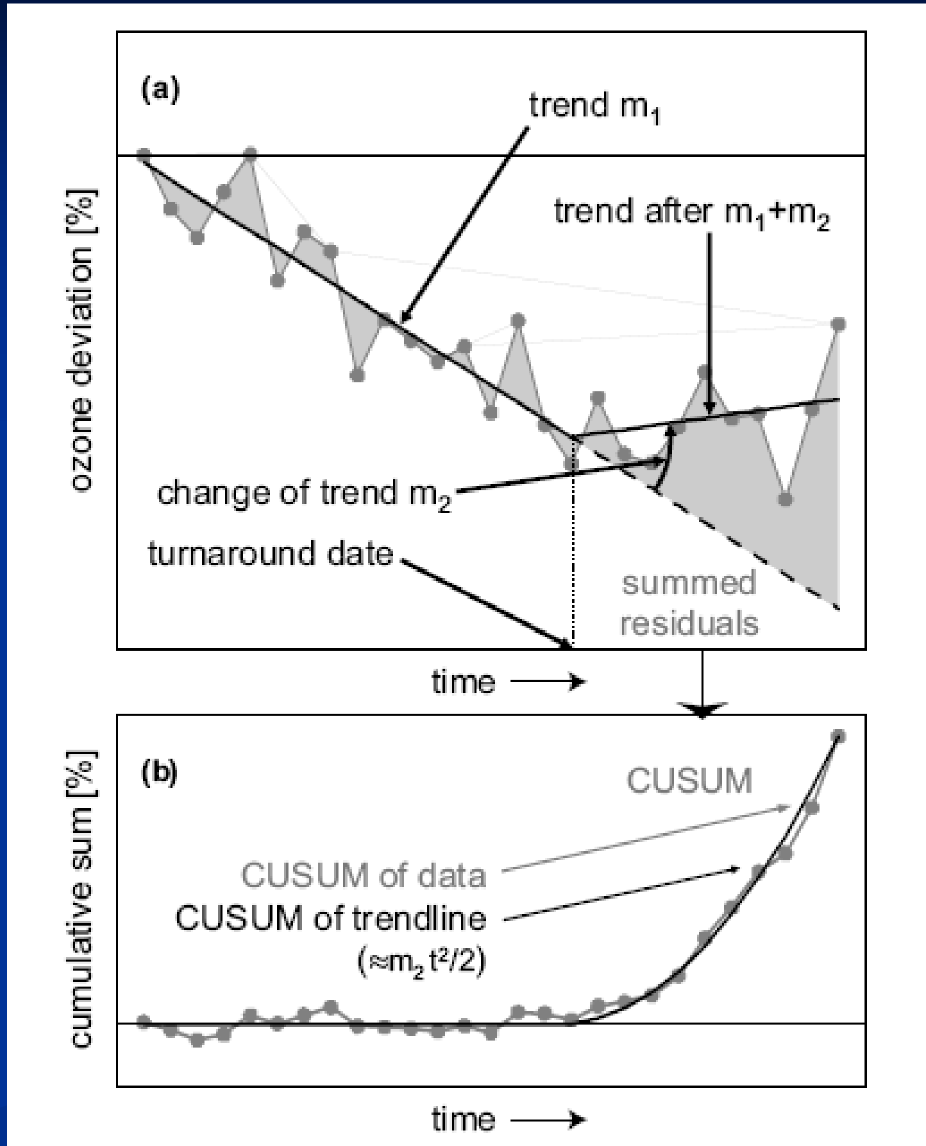
linear trends before and after selected turn-around date

[Reinsel et al., JGR 2002]

(b) "Cumulative sum of residuals" (CUSUM) method

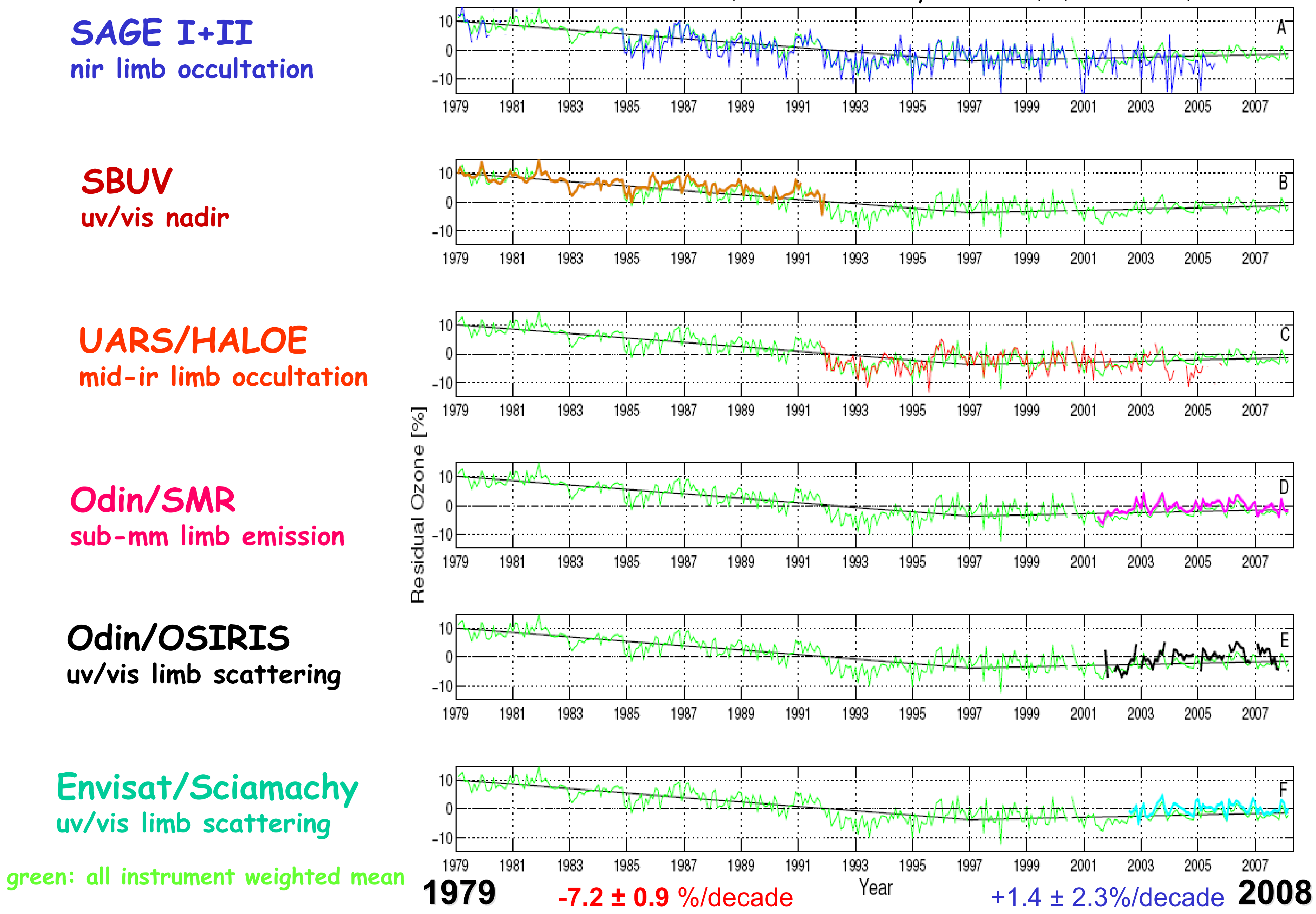
deviation from extrapolated linear trend after selected turn-around date by cumulated sum over residuals

[Reinsel et al., JGR 2002; Newchurch, JGR 2003]



Stratospheric ozone changes: Northern mid-latitudes 30-60N, 35-45km

A. Jones et al., Atmos. Chem. Phys. Discuss., 9, 1157–1209, 2009



Ozone: linear trend estimates

in [% / decade], 2-sigma uncertainties (95% confidence),
assumed "turn-around": 1-Jan-1997

altitude	trend period	SH: 60S-30S	EQ: 30S-30N	NH: 30N-60N
35-45km upper strat.	pre-1997	**-7.1 ± 0.9**	**-4.1 ± 0.6**	**-7.2 ± 0.9**
	1997 - 2008	0.8 ± 2.1	-0.5 ± 1.5	1.4 ± 2.3
25-35km	pre-1997	**-1.5 ± 0.6**	**0.7 ± 0.5**	**-3.3 ± 0.7**
	1997 - 2008	**-2.1 ± 1.3**	**-2.7 ± 1.2**	0.8 ± 1.5
20-25km lower strat.	pre-1997	**-4.4 ± 0.9**	0.5 ± 1.0	**-3.8 ± 0.8**
	1997 - 2008	-1.0 ± 2.0	0.5 ± 2.3	0.2 ± 1.9

=> Upper stratospheric ozone: Statistical significant change of trend, but small "recovery" after 1997 not yet significant at 95% confidence level!

Turn-around year ?

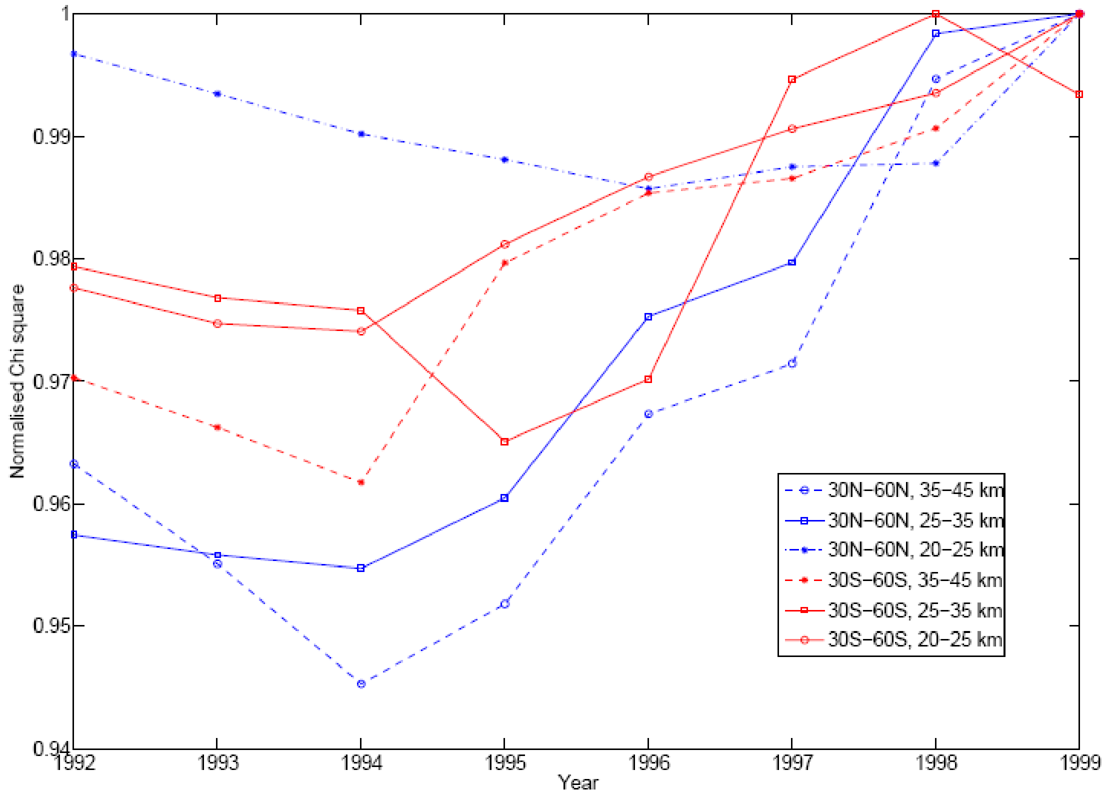


Table 3. Turn around years for each altitude/bin based on minimum χ^2 values rounded to the nearest year. Also shown in brackets are the corresponding trend values up to each turn around date and after. Bold values indicate where the trend value is statistically significant at the two sigma level.

	60 S–30 S	30 N–60 N
20–25 km	1994 (**−5.2±0.9/0.7±1.6)**	1996 (**−3.8±0.9/−0.5±1.8)**
25–35 km	1995 (**−2.0±0.6/−2.0±1.1)**	1994 (**−4.3±0.6/0.4±1.2)**
35–45 km	1994 (**−8.1±0.9 /−0.8±1.6)**	1994 (**−8.3±1.0/−0.5±1.8)**

CIO and HCI

Tropospheric abundance of organic chlorine

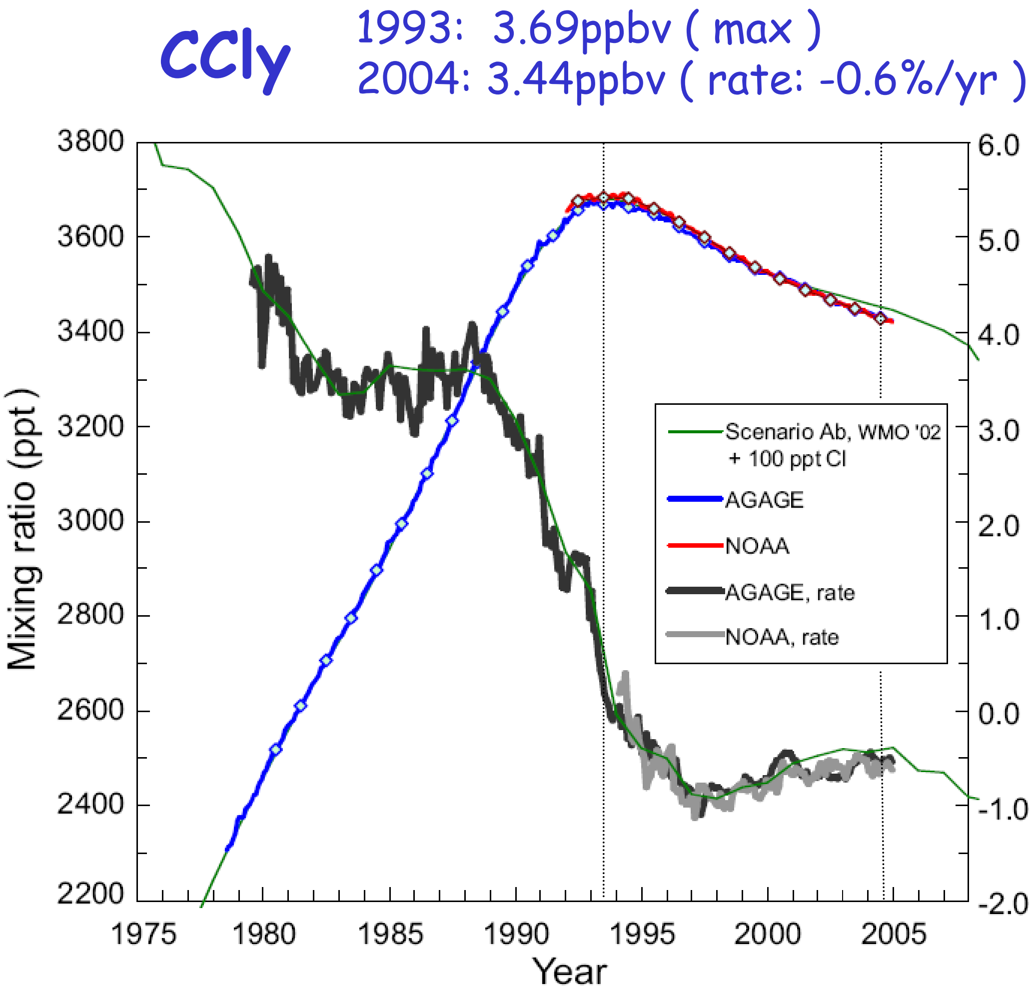


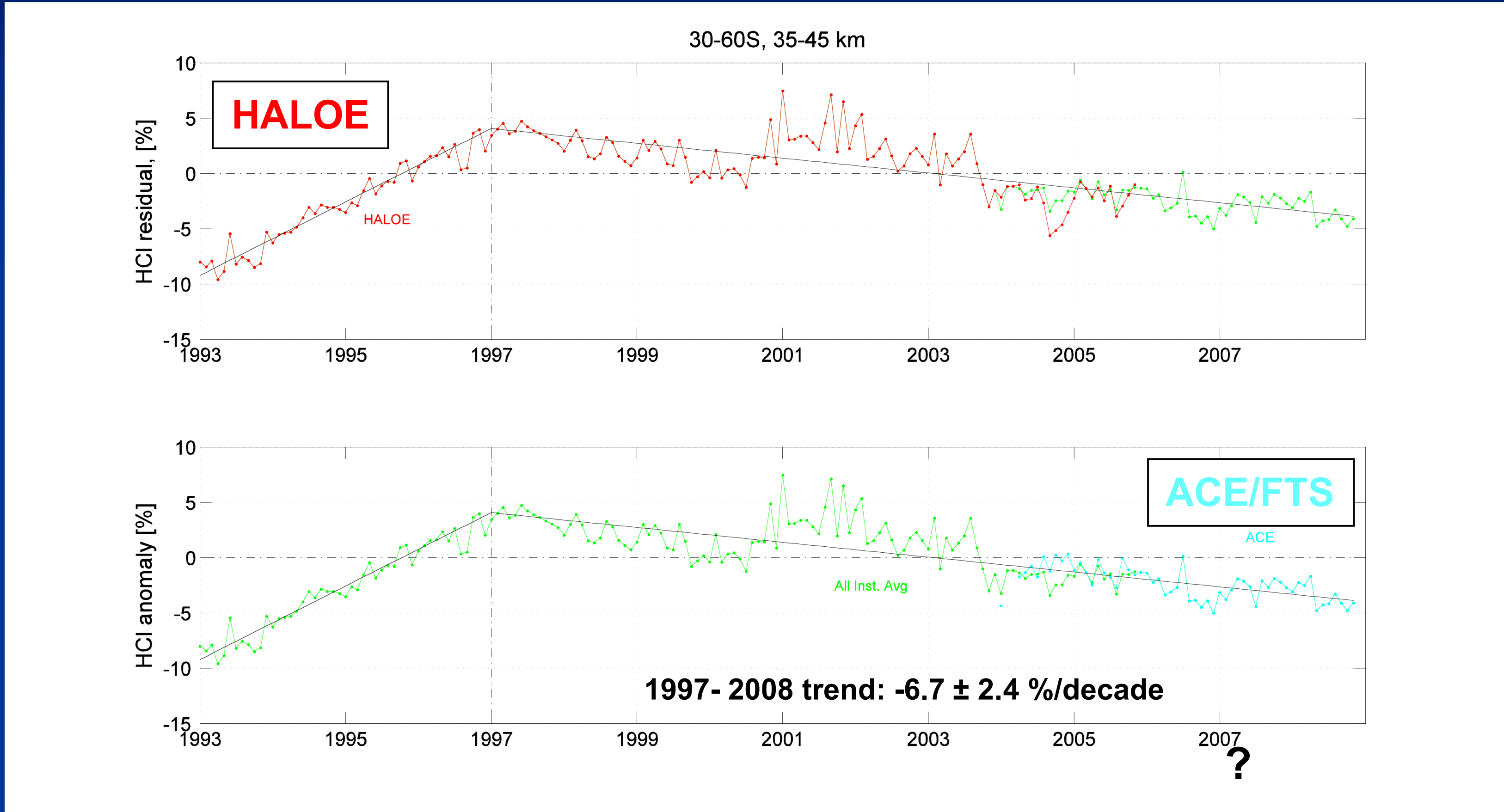
Figure 1-9. The tropospheric abundance of organic chlorine (CCl_y) from the NOAA/ESRL and AGAGE global measurement networks (updates of Montzka et al., 1999, and O'Doherty et al., 2004) and its rate of change over time. Quantities are based upon independently measured mixing ratios of CFC-11, CFC-12, CFC-113, HCFC-22, HCFC-141b, HCFC-142b, methyl chloroform, and carbon tetrachloride. Results for CFC-114 and CFC-115 from Prinn et al. (2000) are used in both compilations. An additional constant 550 ppt was added for CH_3Cl and 100 ppt was added for short-lived gases such as CH_2Cl_2, $CHCl_3$, C_2Cl_4, and $COCl_2$. Rates of change are determined from 12-month differences and are plotted with respect to the right-hand axis. Observations are compared with the projections from *WMO 2002* (green line).

CFC's 62%, CH3Cl: 16%, CCl4: 11%, HCFC's: 6%, others: 5%

[WMO-2006]

HCl trend: HALOE and ACE/FTS

SH 30-60S - 35-45km



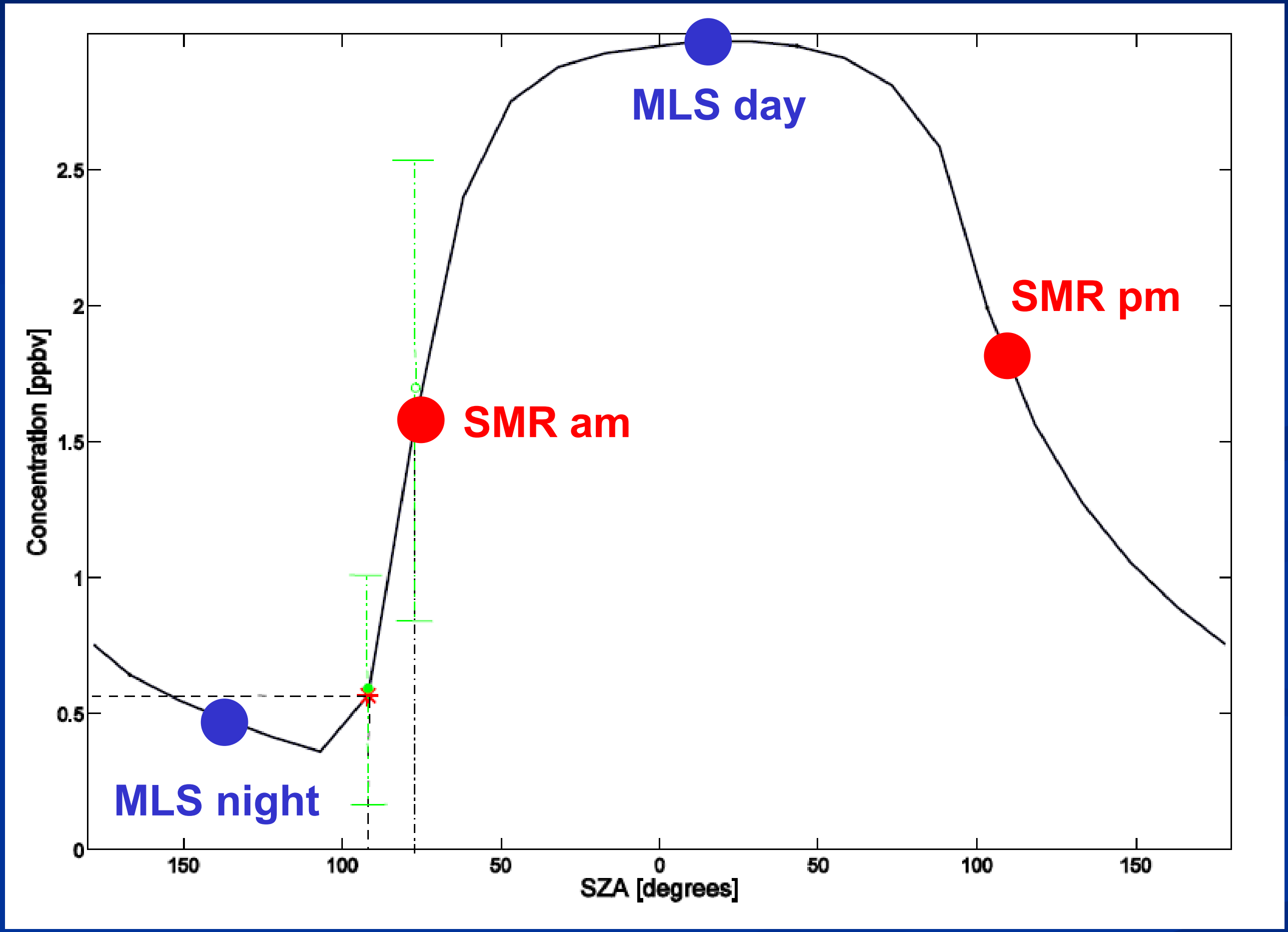
+33.7 ± 1.8 %/decade

-6-7 %/decade

[Jones et al., manuscript in preparation]

ClO: diurnal variation

Sun-synchronous orbits: equator crossing MLS ~1:30am/pm, SMR ~6:00am/pm



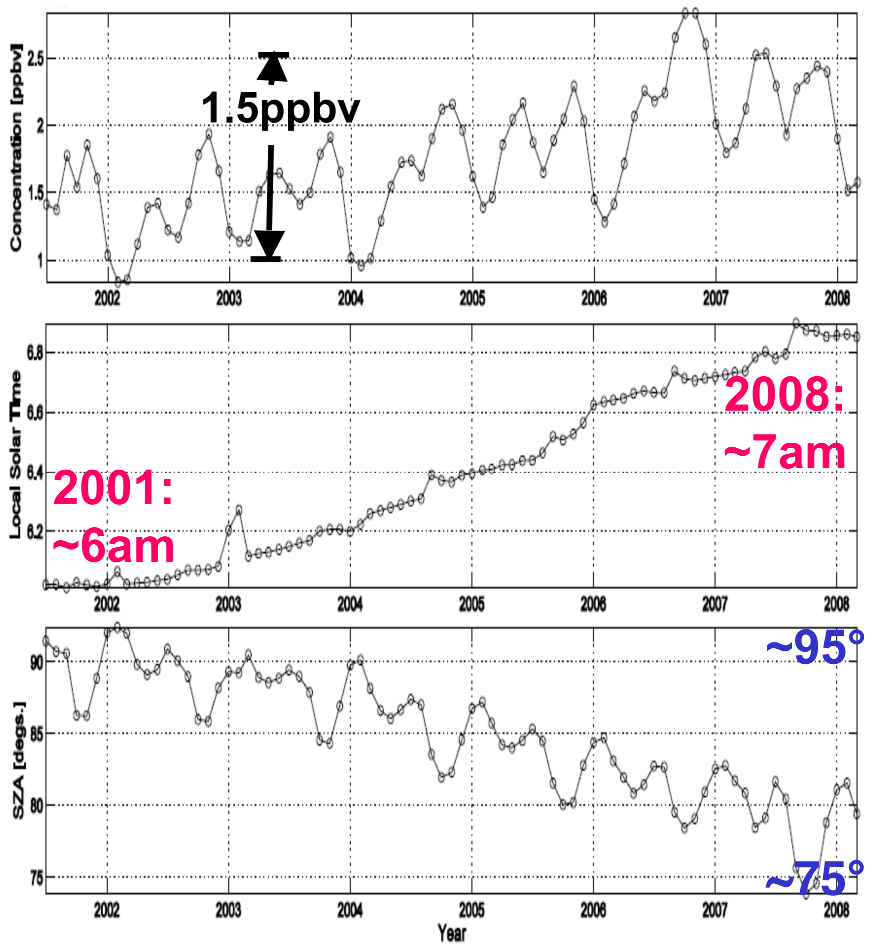
Scaling factors for local time correction from 1-d model

adapted from Jones et al., Ph.D., Chalmers 2009

Effect of drifting Odin orbit on local time, SZA, and ClO: 2001-2008

Eq: 20S-20N - 35-45km

am

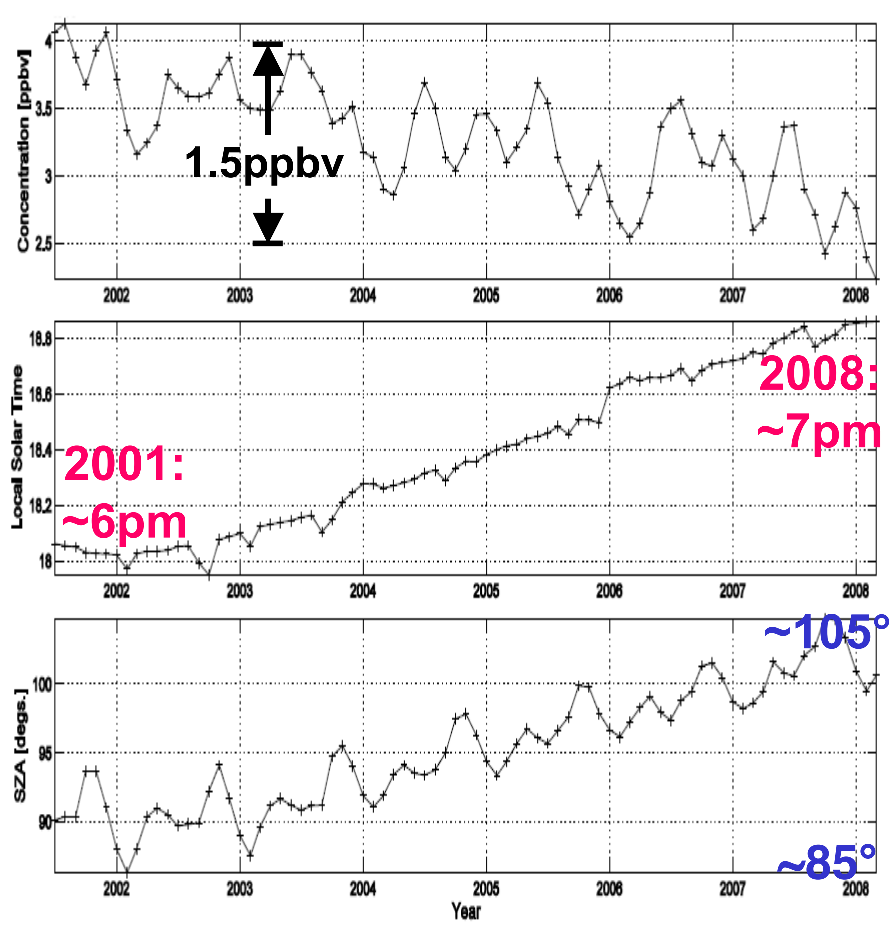


ClO

LST

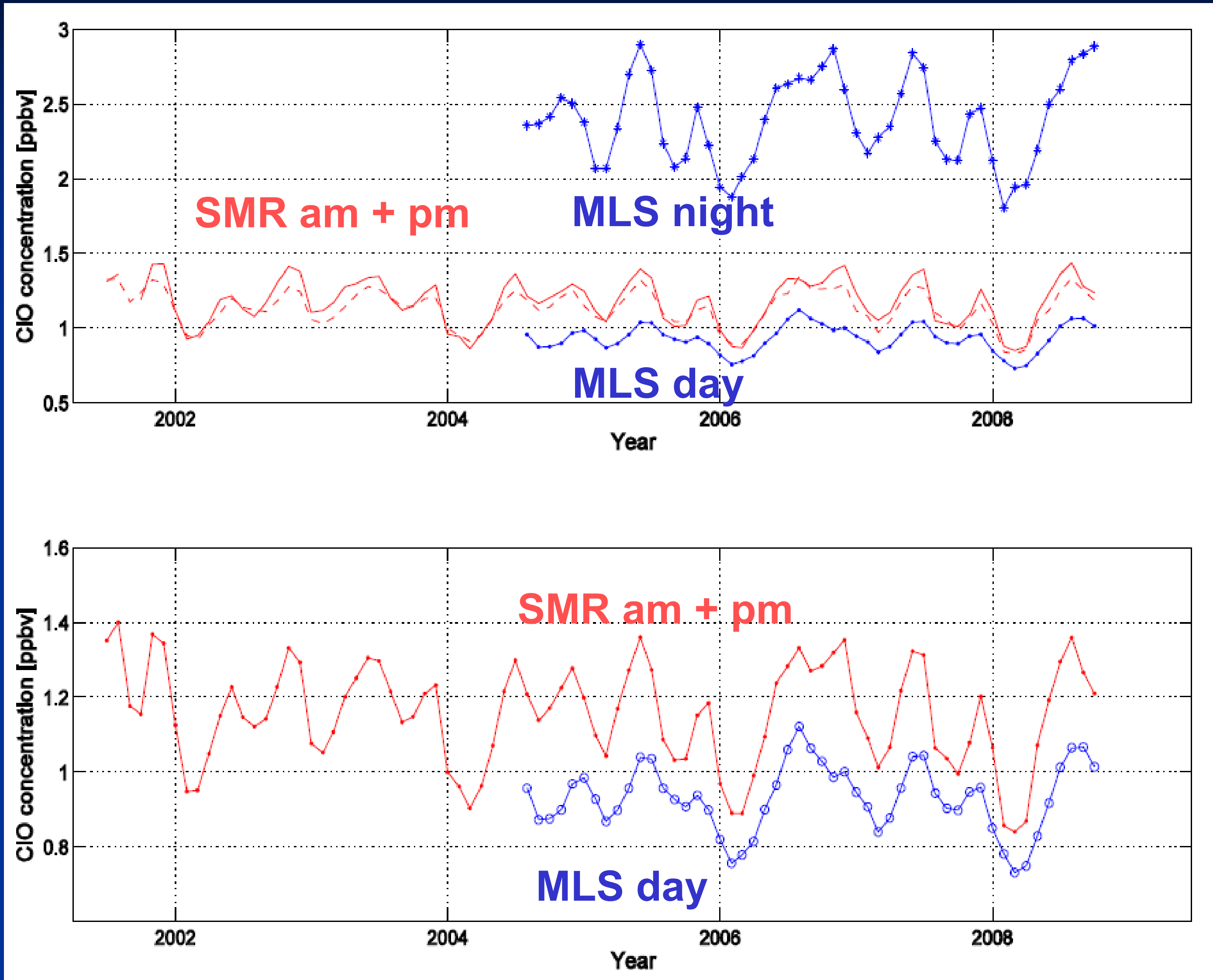
SZA

pm



from Jones et al., Ph.D., Chalmers 2009

ClO: Odin/SMR and Aura/MLS / 35-45km



Eq: 20S-20N

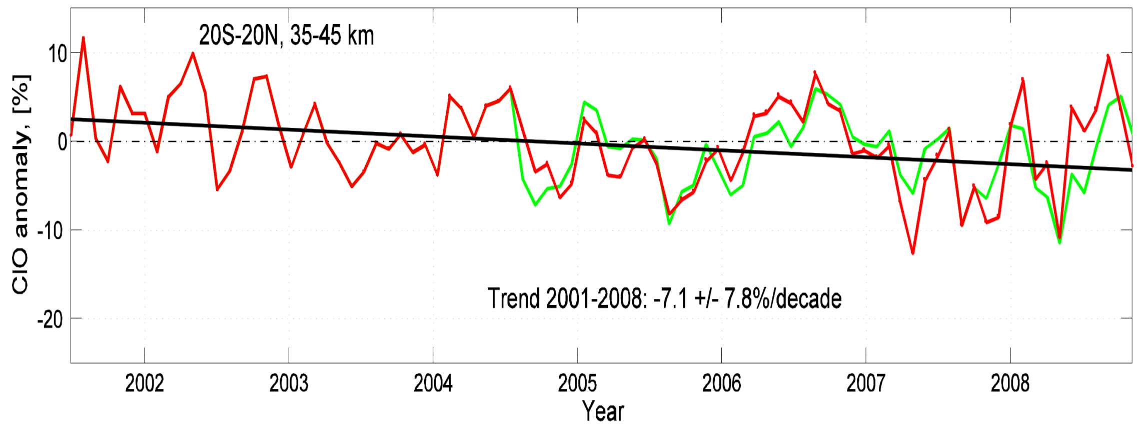
Scaled to sza=90° (am) using 1-d model!

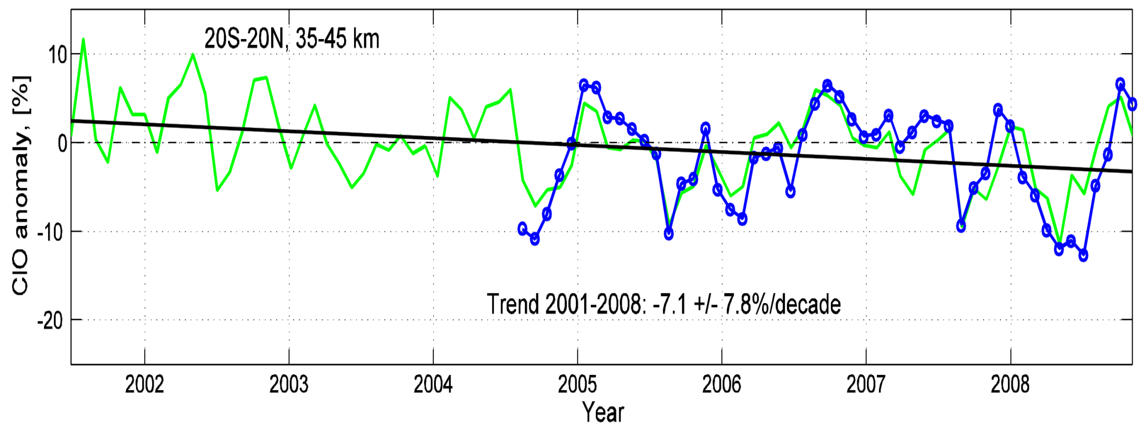
from Jones et al., Ph.D., Chalmers 2009

ClO trend: Odin/SMR and Aura/MLS

equator 20S-20N, upper stratosphere 35-45km,
de-seasonalized and QBO removed, sza corrected to 90°(am)

-7 ± 8% / decade
(not significant at 2-σ)





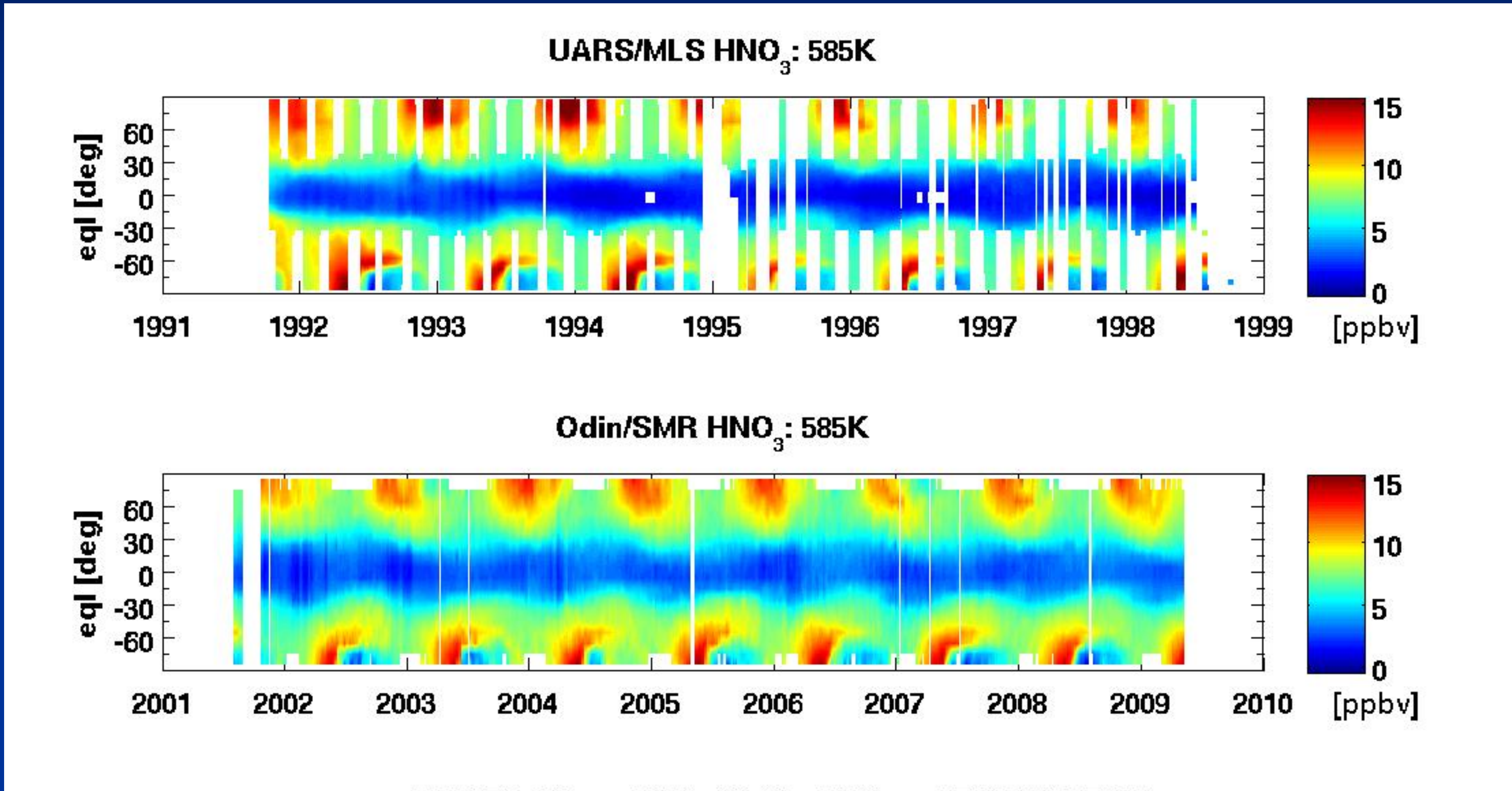
green: all instrument mean

from Jones et al., Ph.D., Chalmers 2009

HNO3

HNO3 - UARS/MLS and Odin/SMR

UARS/MLS: 1991-1998 **Odin/SMR: 2001-2009**

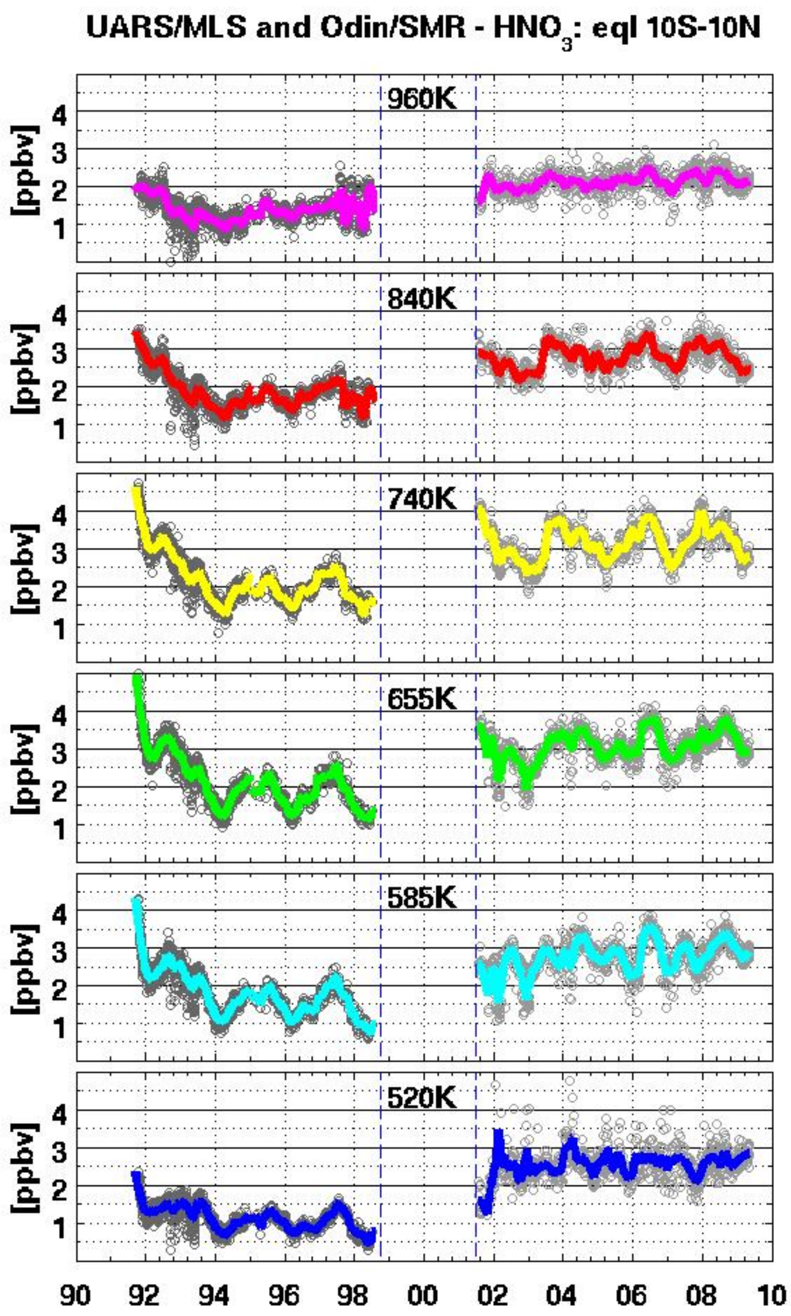


HNO3 evolution: UARS/MLS and Odin/SMR

tropics:
10S-10N
equivalent latitude

UARS/MLS: 1991-1998
Odin/SMR: 2001-2009

Urban et al., ACP-2009 (in press)



CHALMERS
Radio and Space Science

Water vapour

Boulder balloon time-series / 17-22km

middle latitudes

Boulder
40N / 105 W

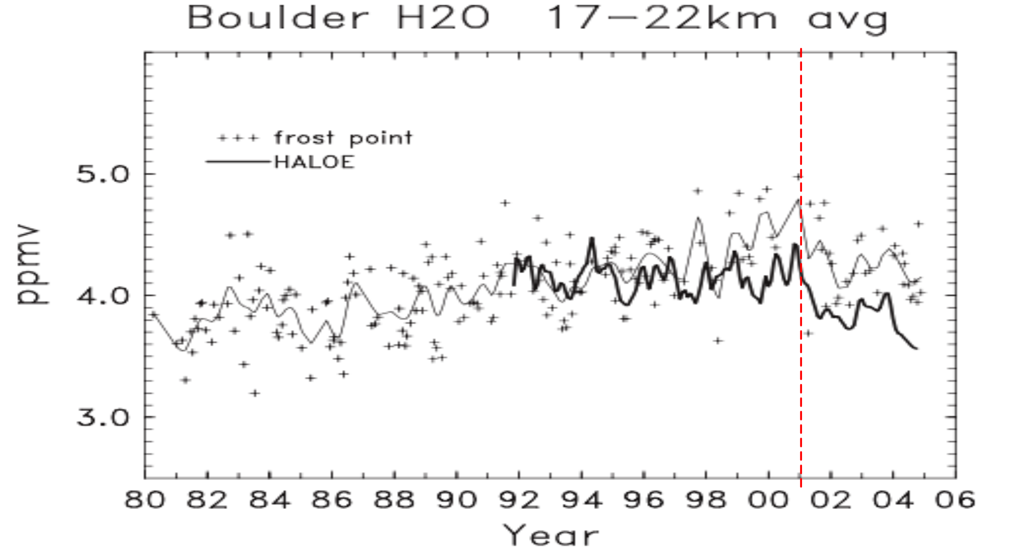


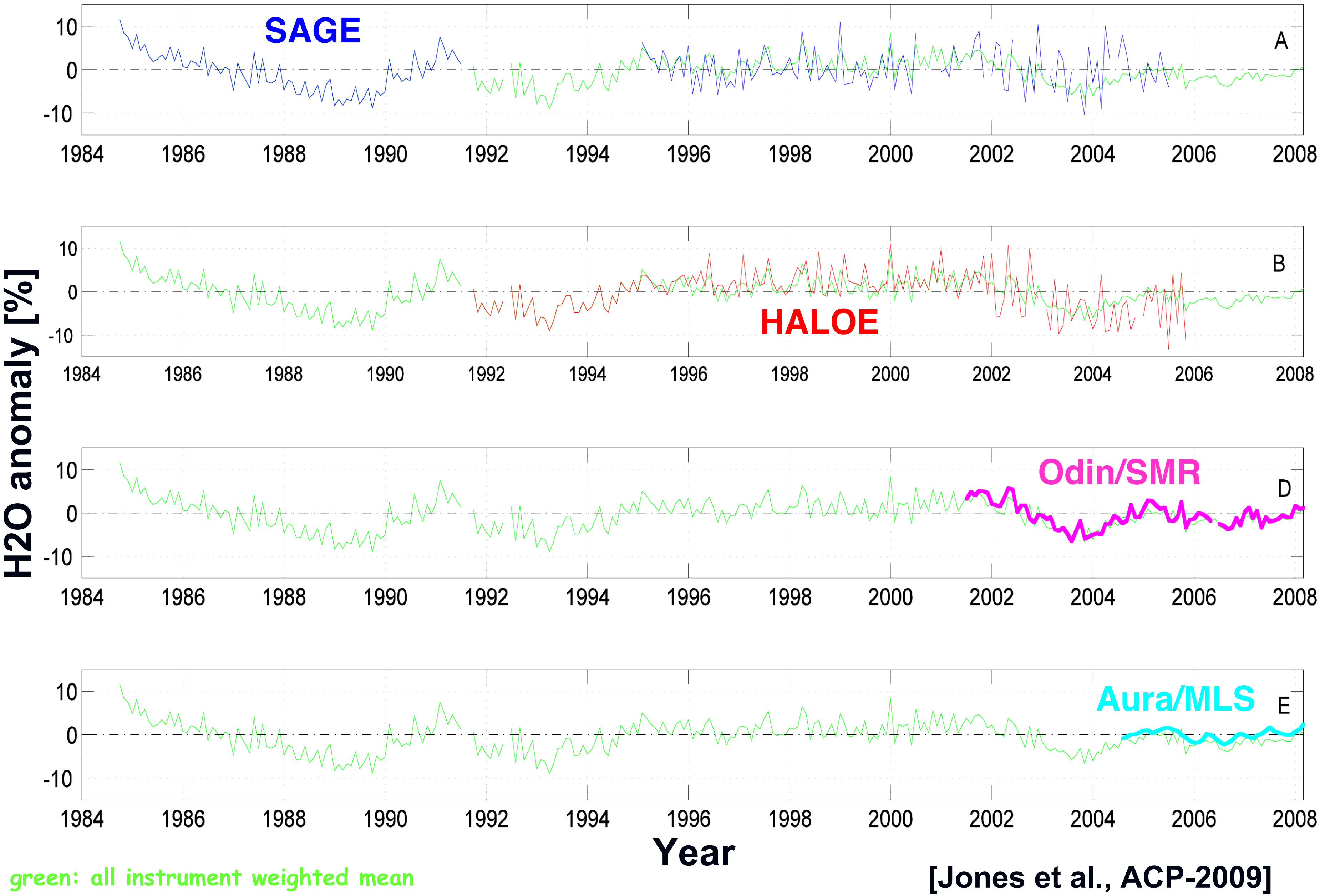
Figure 5-4. Evolution of stratospheric water vapor mixing ratio (in ppmv, averaged over 17-22 km) at Boulder, Colorado (40°N, 105°W), derived from balloonborne frost point hygrometer measurements covering 1980-2005. The thin line shows a smooth fit through the data points, using a running Gaussian window with a half-width of three months. The heavy line shows HALOE satellite water vapor data during 1992-2005 for the same altitude region, using measurements near Boulder (over latitudes 35°N-45°N, and longitudes 80°W-130°W). Note the difference between the two datasets after about 1997. Updated from Randel et al., 2004a.

from [Randel et al, 2004]

H2O evolution / tropics

Water vapour / 30°S to 30°N / 25-35 km

1984-2008 - deseasonalized and combined data sets

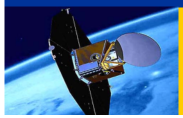


[Jones et al., ACP-2009]

Summary (1)

- **Satellite data sets:** "historical" - HALOE, SAGE, SBUV, ...
  "new" - Odin, Envisat, ACE, Aura, ...

- **Combination of satellite time-series:**
  - Required overlap period at least ~1 year (better longer!) for bias correction (→ analysis of "anomaly" or weighted mean).
  - Use of multiple overlapping time-series allows to detect drifts in individual data sets and during specific periods.
  - 11yr solar cycle correction requires long data set (→SAGE-I/II 1979-2005).
  - Low noise in zonal means from thermal emission and limb scattering techniques due to better spatio-temporal sampling characteristics compared to solar occultation.
  - Aerosol sensitivity of short-wave techniques is critical (Pinatubo period).
  - Correction required for diurnally variable species.
  - Gaps between satellite time-series make combined trend analysis difficult, due to systematic errors in individual time-series (→ NDACC, balloons ...).



Summary (2)

- **Satellite data sets**: "historical" - HALOE, SAGE, SBUV, ...
  "new" - Odin, Envisat, ACE, Aura, ...

- **O_3 depletion**: largest decline of ~7%/decade until 1997 in upper stratosphere at mid-latitudes. Slowdown thereafter, recovery not (yet?) significant with 95% confidence (in 2008).
- **HCl**: HCl increase in upper stratosphere of 25-33% until 1997. Decline thereafter, rate ~6-7%/decade at mid-latitudes.
- **ClO** : -7% for 2001-2008 period (not significant).
- **HNO_3**: positive trend 1991-2009 or bias of satellite sensors?
- **H_2O**: increase until ~2000 (balloon, HALOE), then sudden drop in ~2001 which can be seen in tropical upper stratosphere and at mid-latitudes ~1-2 years later. Increase after 2004 in tropics and from ~2005 at NH mid-latitudes (Boulder).

Thank you!