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School on "Exploring the Atmosphere by Remote Sensing Techniques"
18 October - 5 November 1999

1151-16

"Ground-Based Measurements of Stratospheric Trace Gases in the Perspective of Climate & Environment"

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Brussels
Belgium

Please note: These are preliminary notes intended for internal distribution only.

Ground-based measurements of stratospheric trace gases in the perspective of climate and environment

☑ Ground-based remote sensing techniques, and O_3 sondes

- ! Complementarity with space- and airborne techniques !
- ! Complementarity with in-situ sampling methods !

☑ observed atmospheric changes: variabilities, trends

☑ assessments, related policies and perspectives

Ground-based techniques (1/4)

☑ O_3 sonde

- based on a chemical redox reaction in an electrochemical cell
- balloon-borne, in-situ measurement of the O_3 vertical profile, from ground up to < 35 km

Ground-based techniques (2/4)

☑ GB techniques are mostly based on extinction of light in the atmosphere

- extinction ⇒ absorption and scattering by atmospheric constituents (gaseous, particles)
  - ← laboratory data!
- in various regions of the spectrum:
  - UV/Vis
    - DOAS
    - LIDAR (DIAL)
  - infrared
    - FTIR or Fourier-Transform Infrared Spectroscopy
  - microwave
- remote sensing

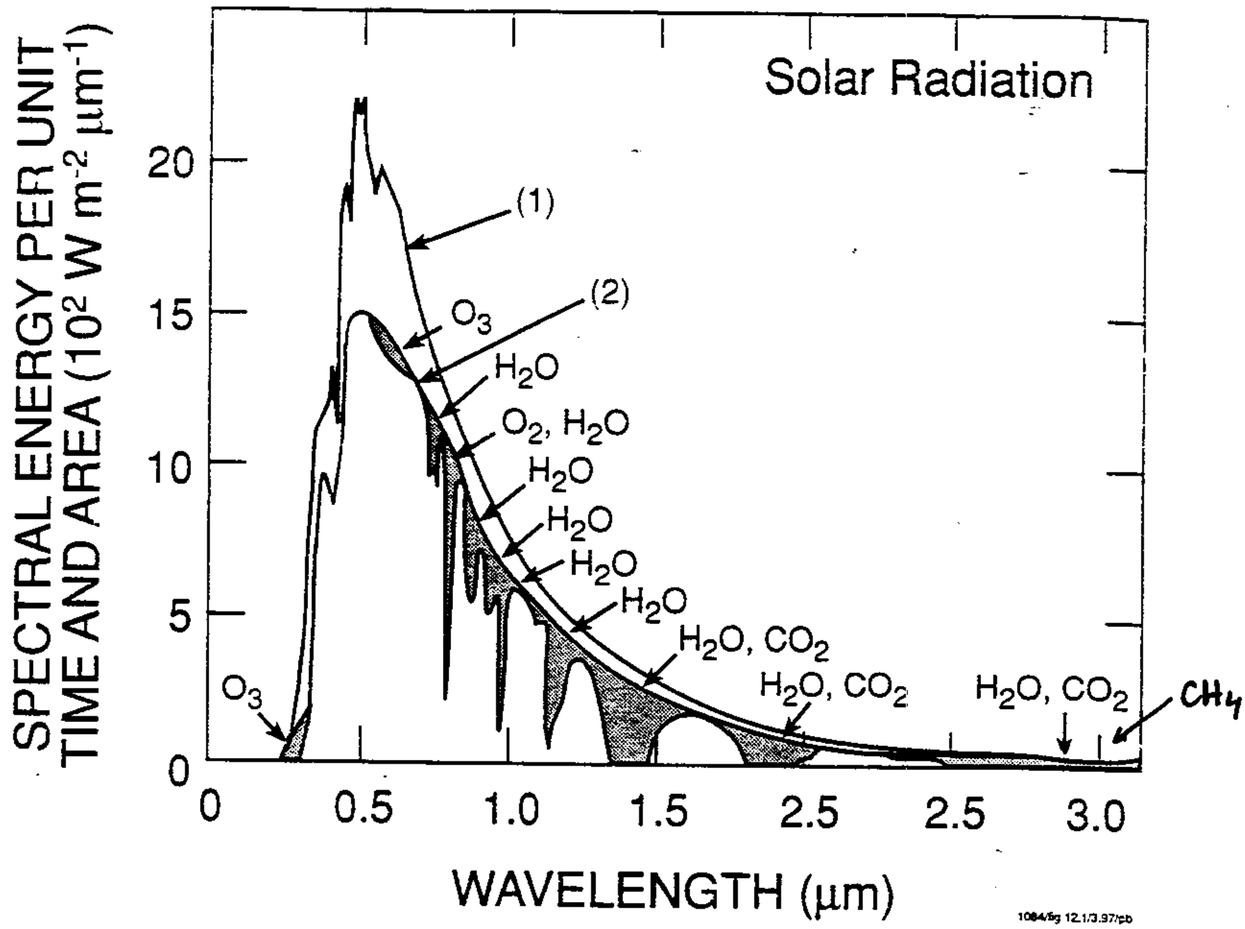


Figure 15.1. *Spectrum of solar radiation (1) outside the Earth's atmosphere and (2) at sea level for clear sky conditions (from Gast, 1961). The shaded area represents the energy absorbed by various gases in a clear atmosphere.*

Ground-based techniques (3/4)

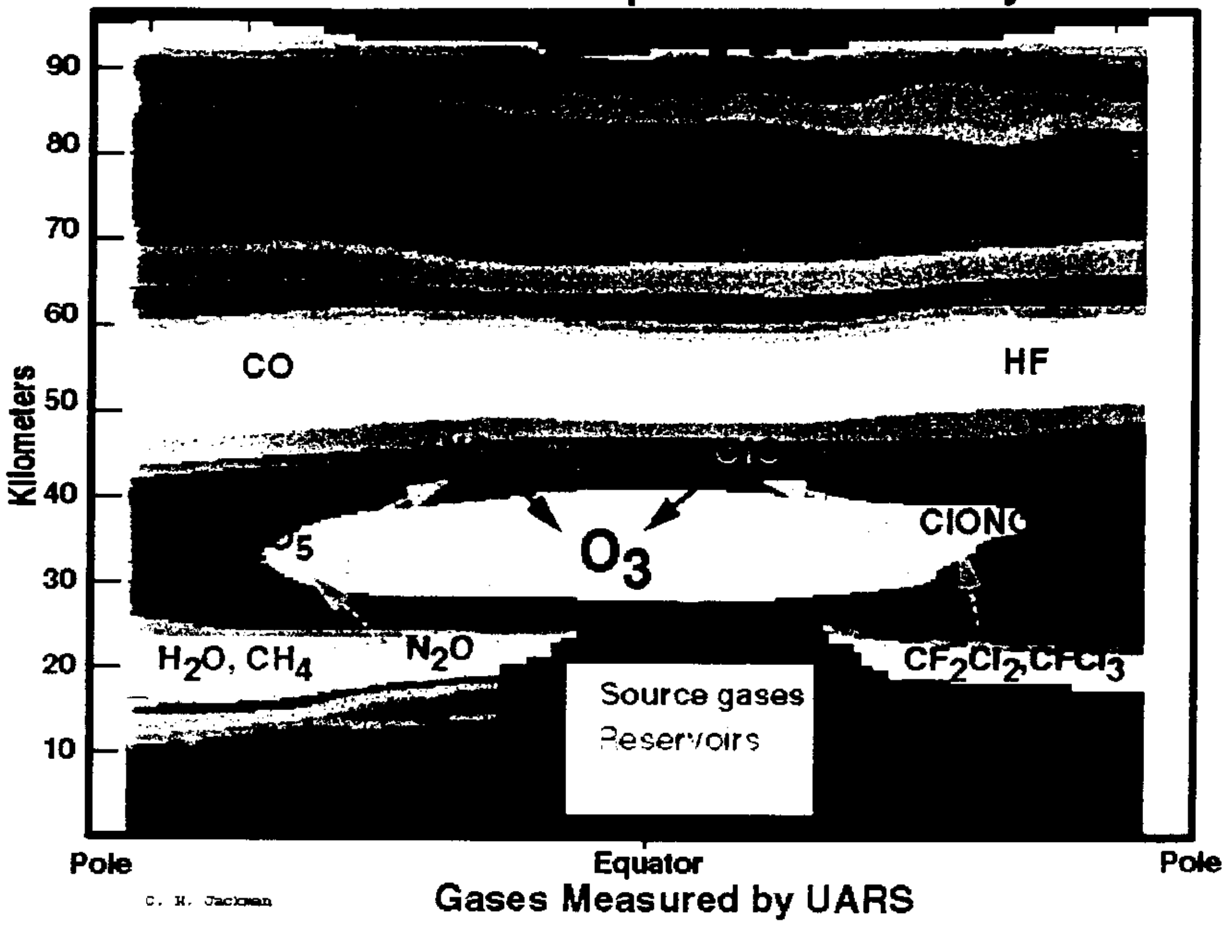
Atmospheric data products

GB	UV/Vis	LIDAR	FTIR	Mwave
O_3	C	P	C	stratP/C
NO_2	C		C	
BrO	C			
OClO	C			
ClO			(C)	stratP/C
Cl_y			C	
NO_y			C	
H_2O	(C)	P	C	stratP/C
tracers			C	
sources			C	
CO, CO_2			C	

(Strat)P = (stratospheric) profile; C = column;

tracers = N_2O, CH_4, HF, O_3, … ; sources = N_2O, CFC, HCFC, CO_2, ...

Middle Atmosphere Chemistry



Gases Measured by UARS

Ground-based techniques (4/4)

Atmospheric data products: interest ?

- ☑ Stratospheric O_3 depletion ⇔ increase of UV at Earth surface
  - O_3, Cl_y, Br_y, halocarbons (CFC, HCFC,…) NO_y, aerosol/PSC, ...
- ☑ Changes in tropospheric and PBL O_3 ⇔ biological health
  - H_2O (→ OH, HO_2), CH_4, CO, RC, NO_x, …
- ☑ Climate and surface warming
  - Greenhouse Gases: H_2O, CO_2, CH_4, N_2O, O_3, halocarbons, aerosol, clouds,…

! Other factors are playing a role: dynamics, solar cycle,...

! Effects are coupled

Observed atmospheric changes: variabilities, trends

☑ diurnal, seasonal cycles and daily variabilities

☑ inter-annual variabilities

☑ long-term trends (> 1 decade)

- possibly as a function of altitude

⇒ interest in long-term, regular monitoring,

e.g., from ground-based monitoring networks.

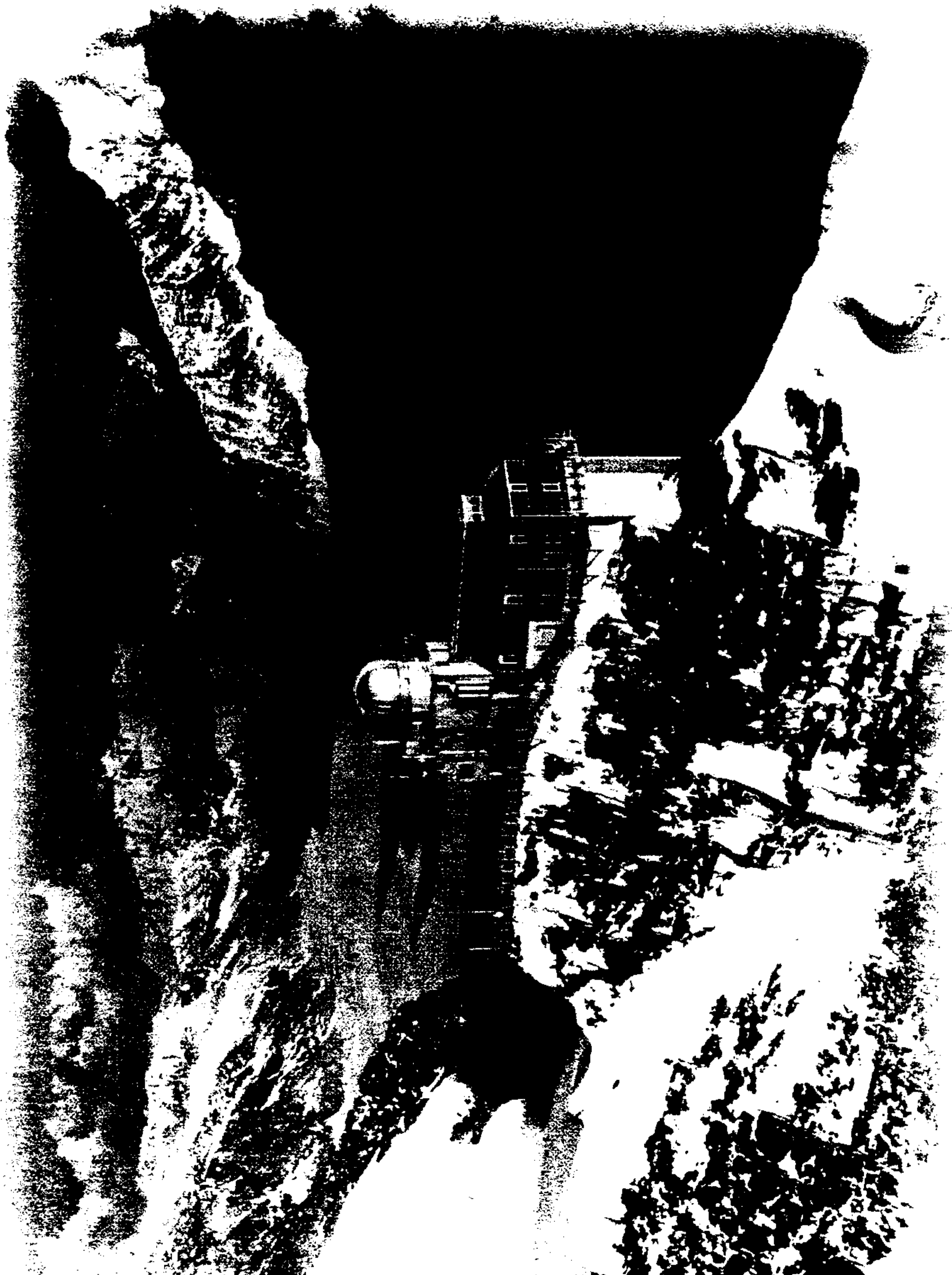
Example:

Jungfraujoch Observatory in the Swiss Alps,

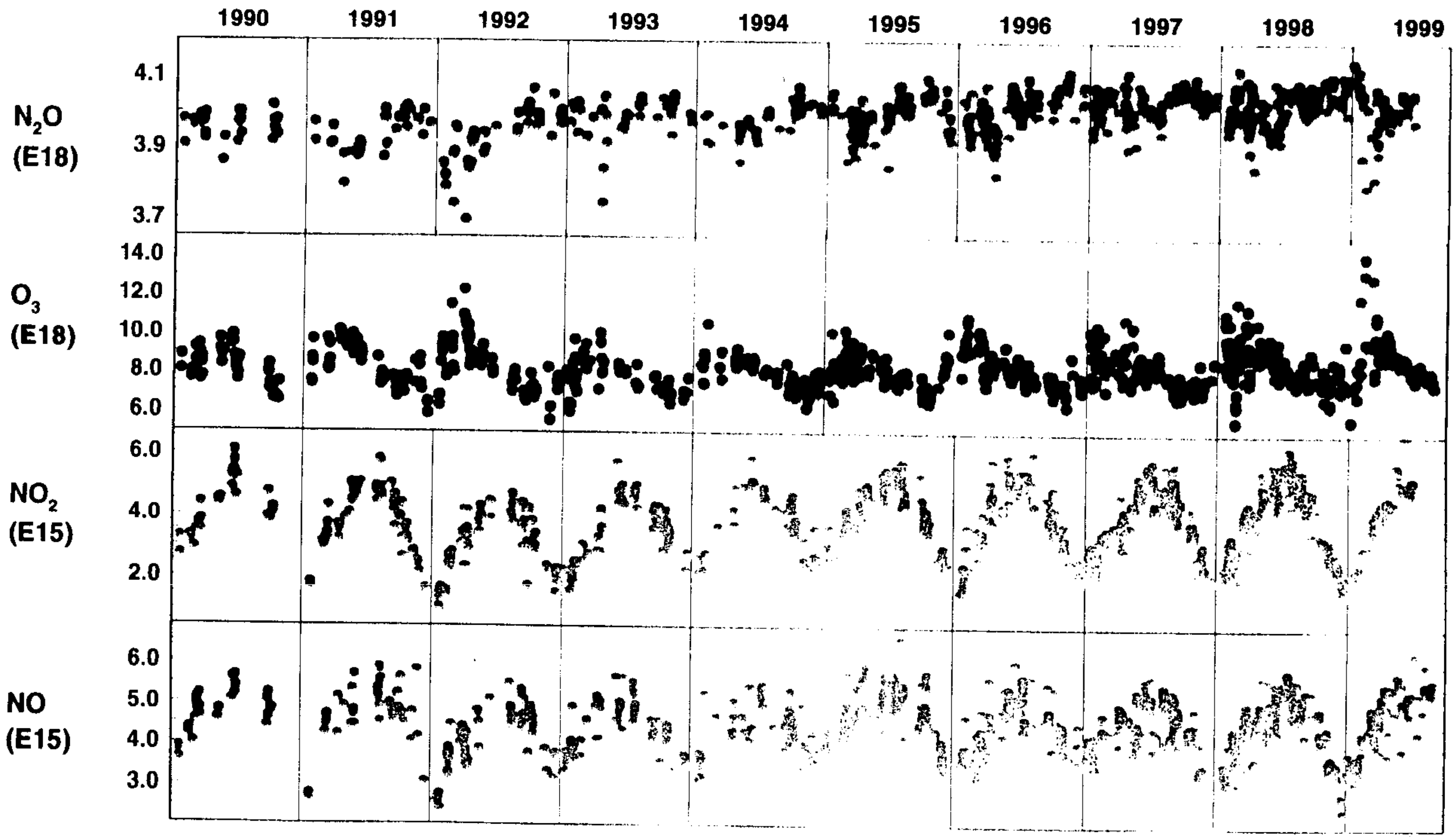
primary alpine NDSC station, at 3580 m asl, 44.6°N, 8.0°E,

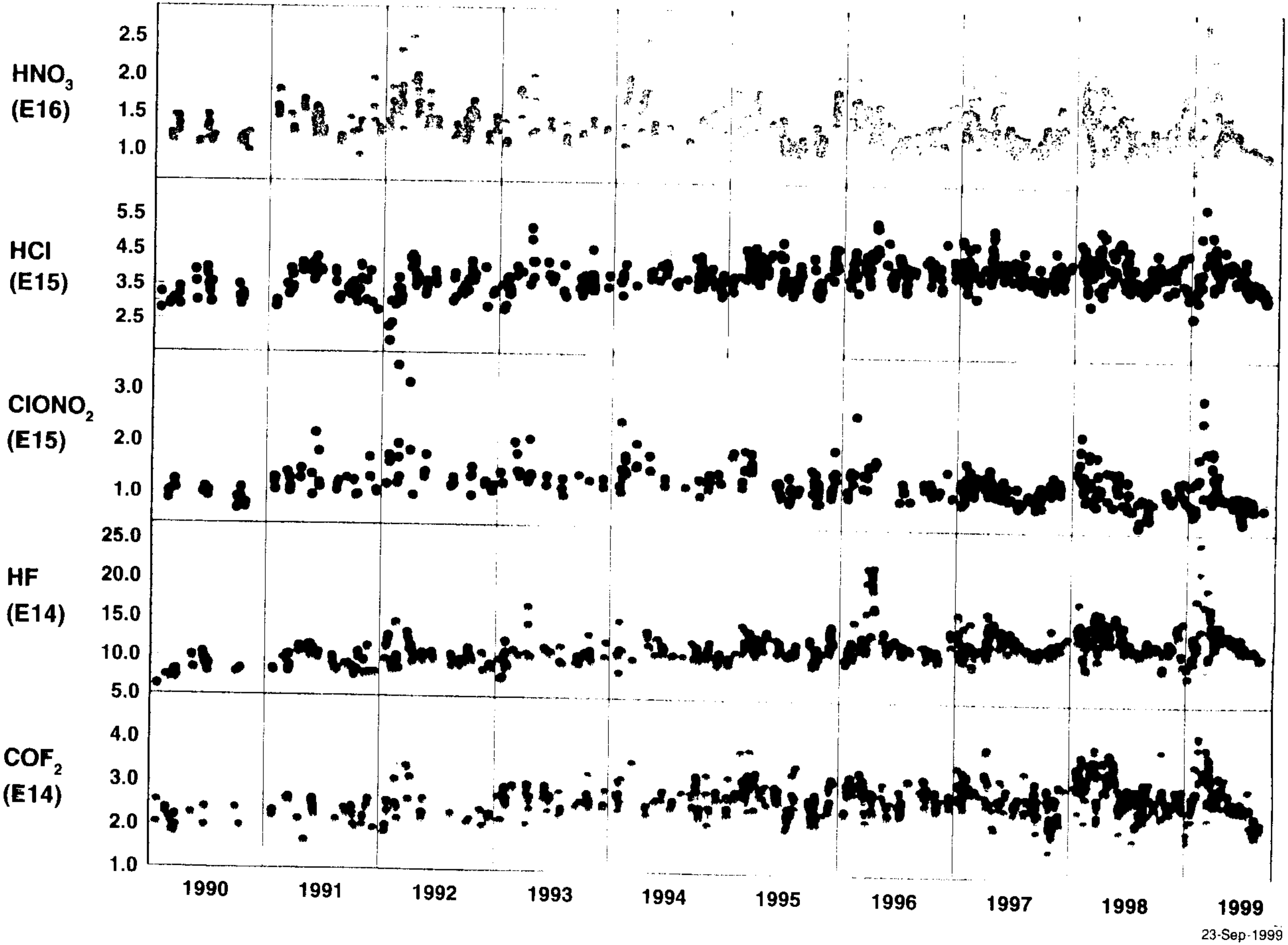
operating on a regular basis since 1985,

some measurements already in the 50s



Daily mean vertical column abundances of 8 stratospheric constituents above ISSJ



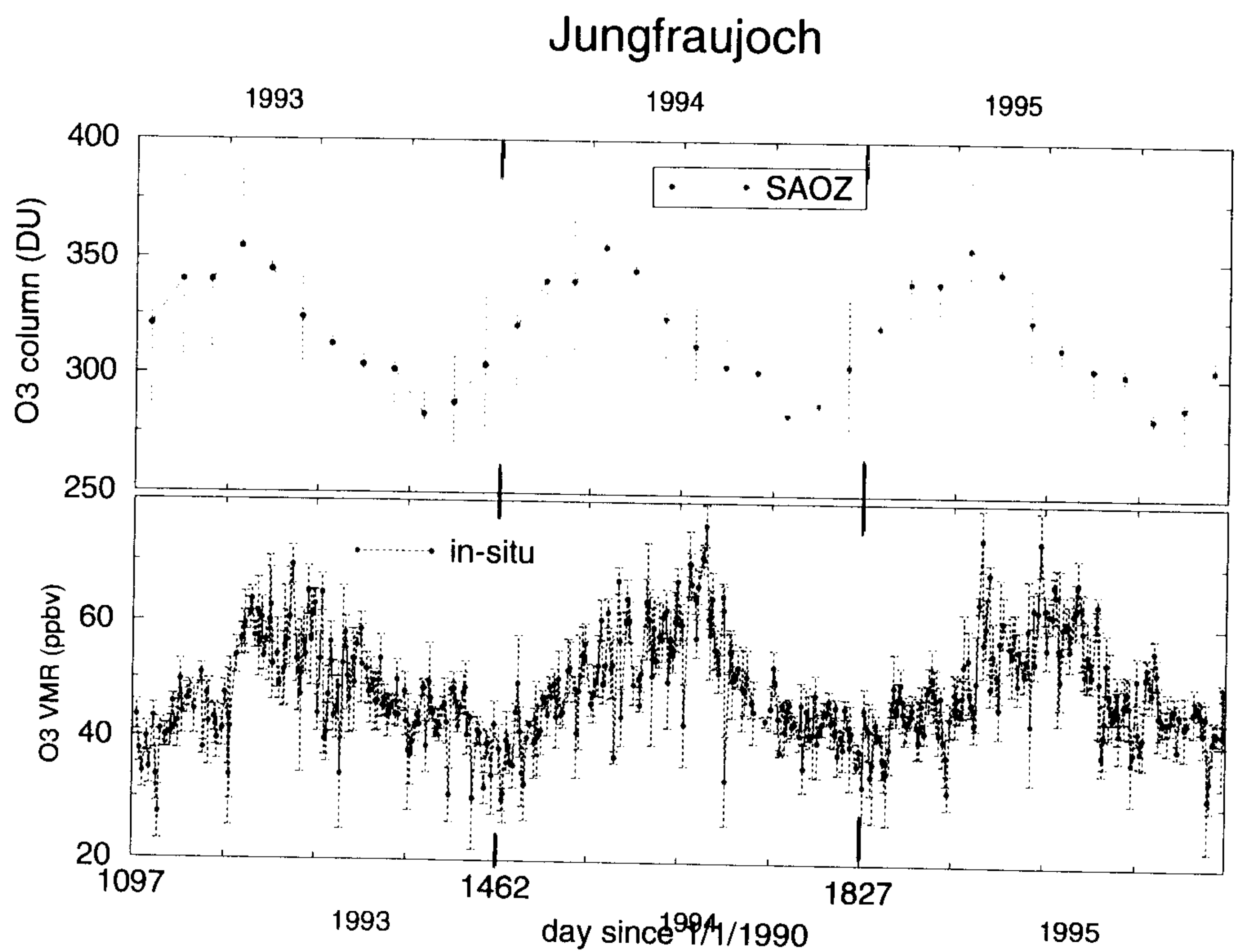

HNO3
(E16)
2.5
2.0
1.5
1.0
HCl
(E15)
5.5
4.5
3.5
2.5
ClONO2
(E15)
3.0
2.0
1.0
HF
(E14)
25.0
20.0
15.0
10.0
5.0
COF2
(E14)
4.0
3.0
2.0
1.0
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
23-Sep-1999

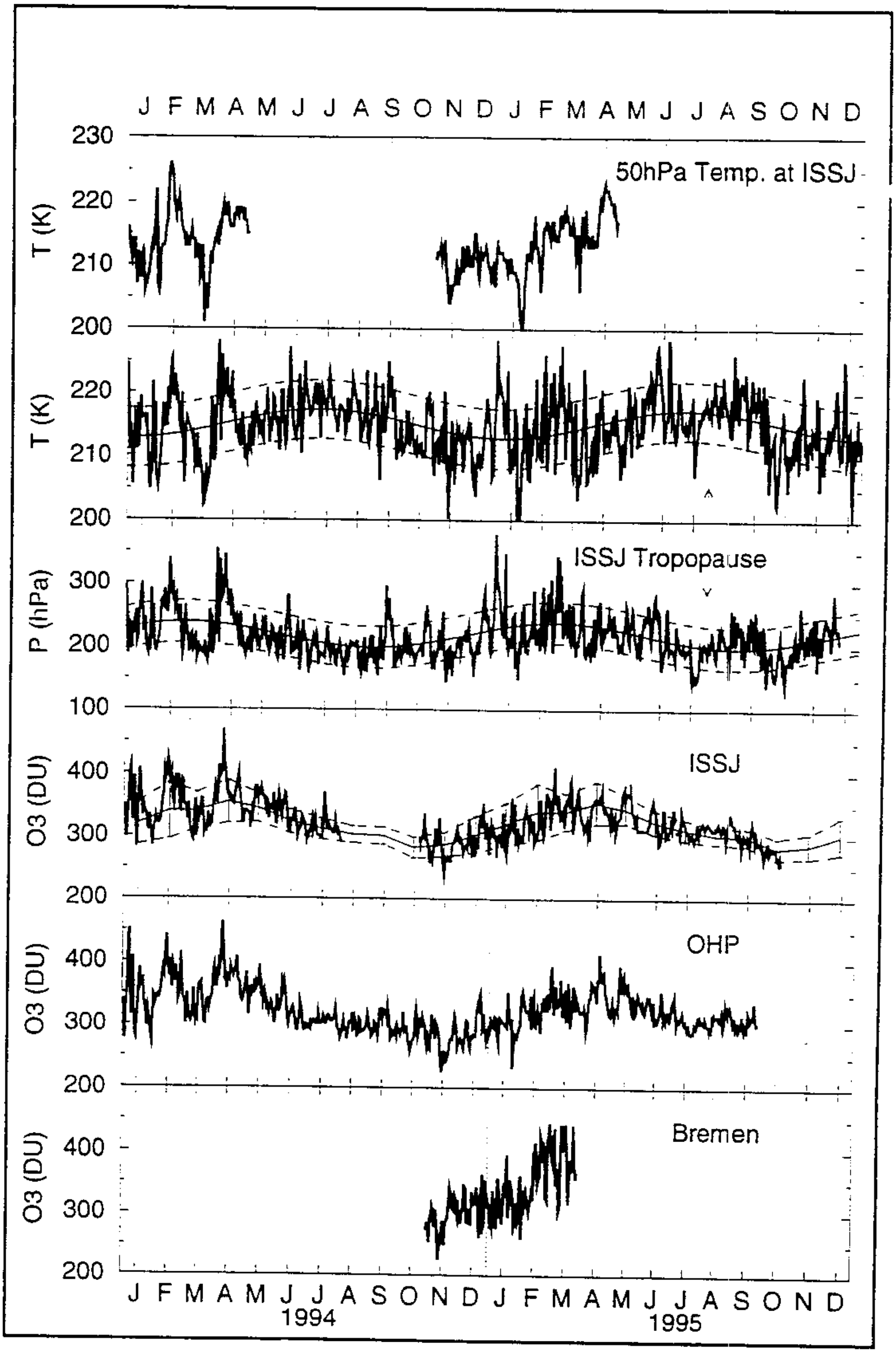
Atmospheric variabilities:

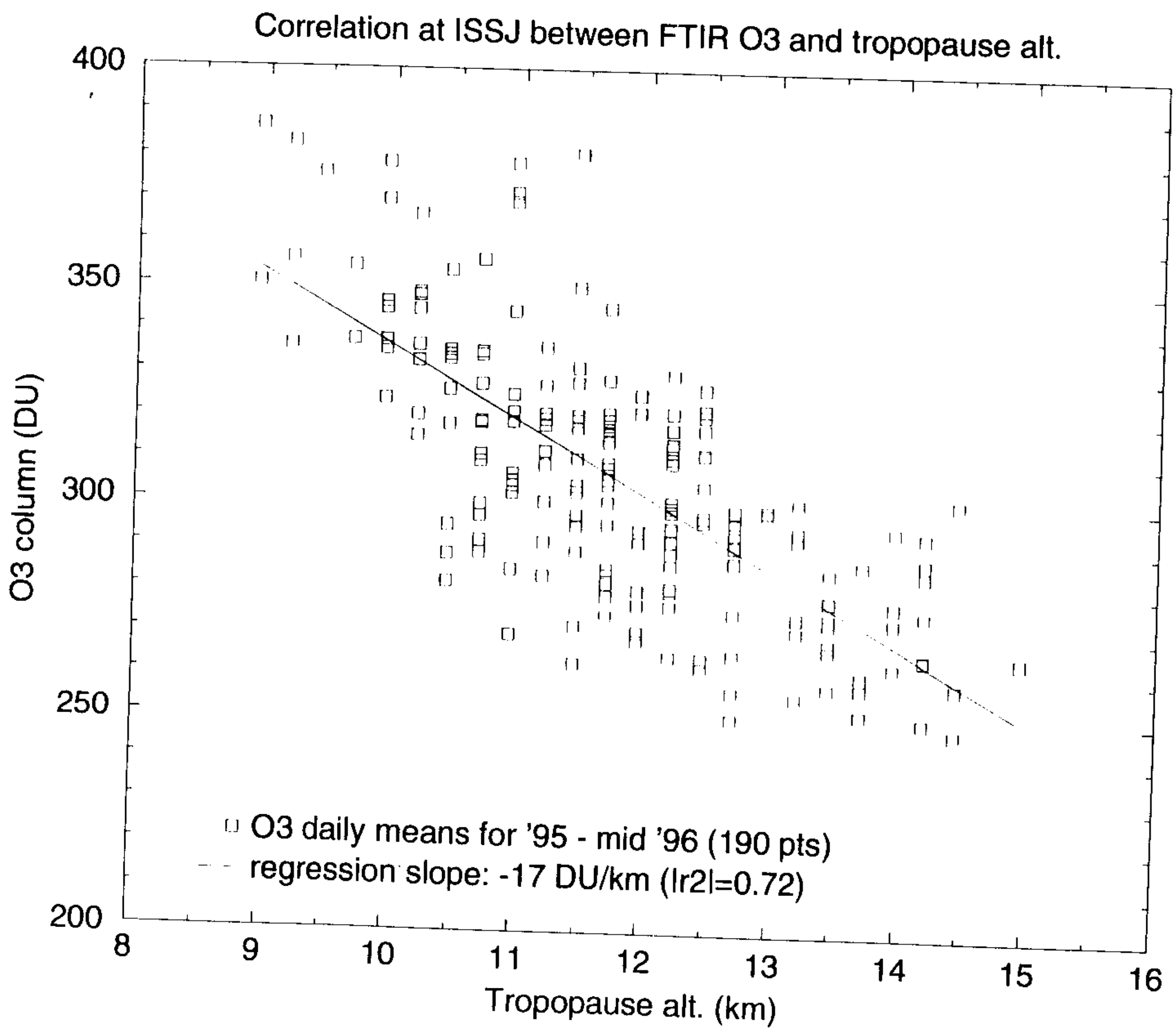
Examples of O_3 + tracers, ClO & OClO, and NO_2

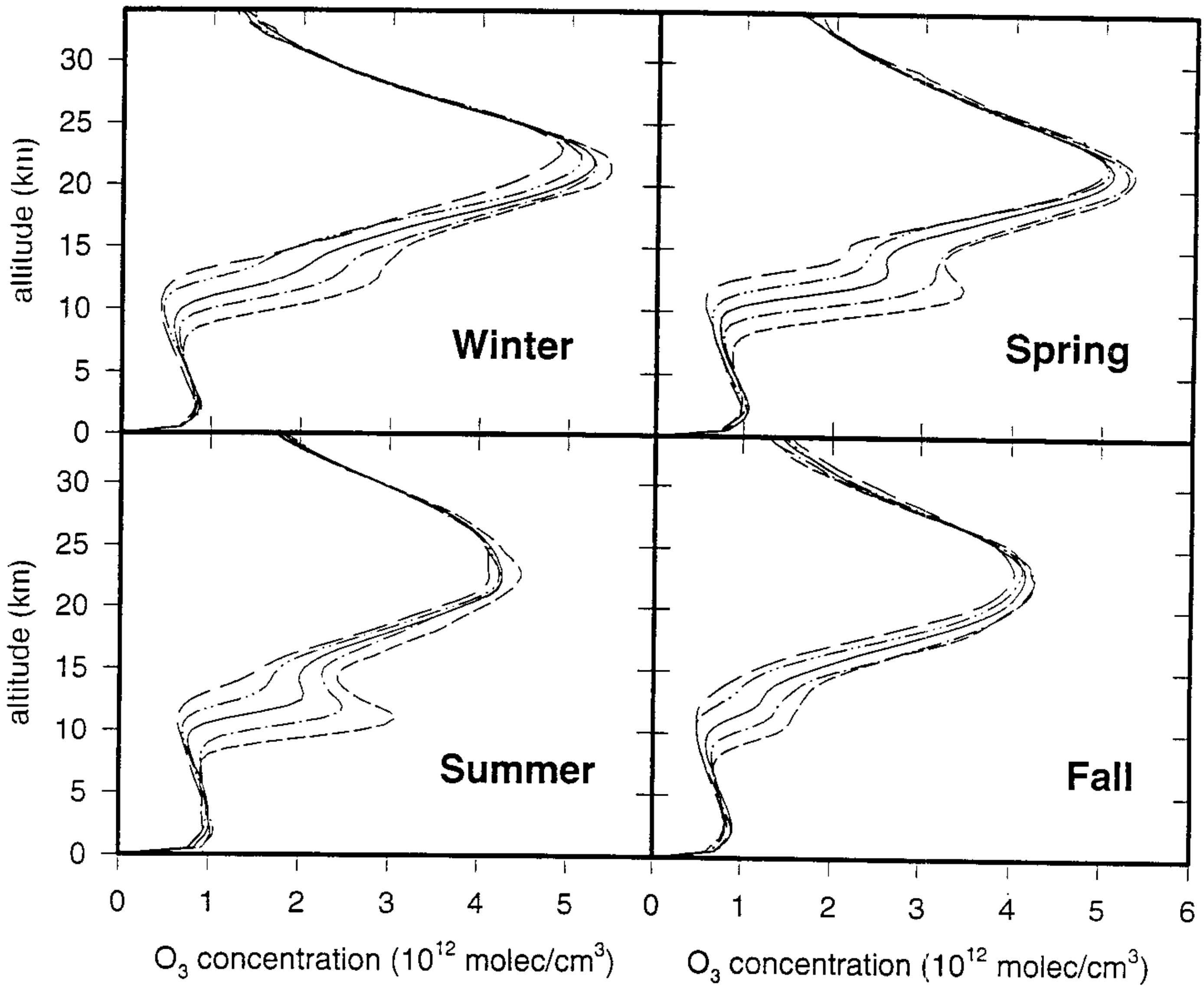
O_3

- diurnal variation in the mesosphere, related to solar photolysis
- pronounced seasonal variation, altitude and site-dependent
  - difference as to dominant photochemical processes
- high day-to-day variation
  - to a large extent related to dynamics - cf. tropopause height variations
- O_3 destruction events
  - to a large extent related to 'activation' of catalytic O_3 destruction catalyzers (e.g., ClO, BrO, ...), T, hν


Jungfraujoch
1993
1994
1995
400
350
300
250
O3 column (DU)
SAOZ
in-situ
60
40
20
O3 VMR (ppbv)
1097
1462
1827
1993
1994
1995
day since 1/1/1990

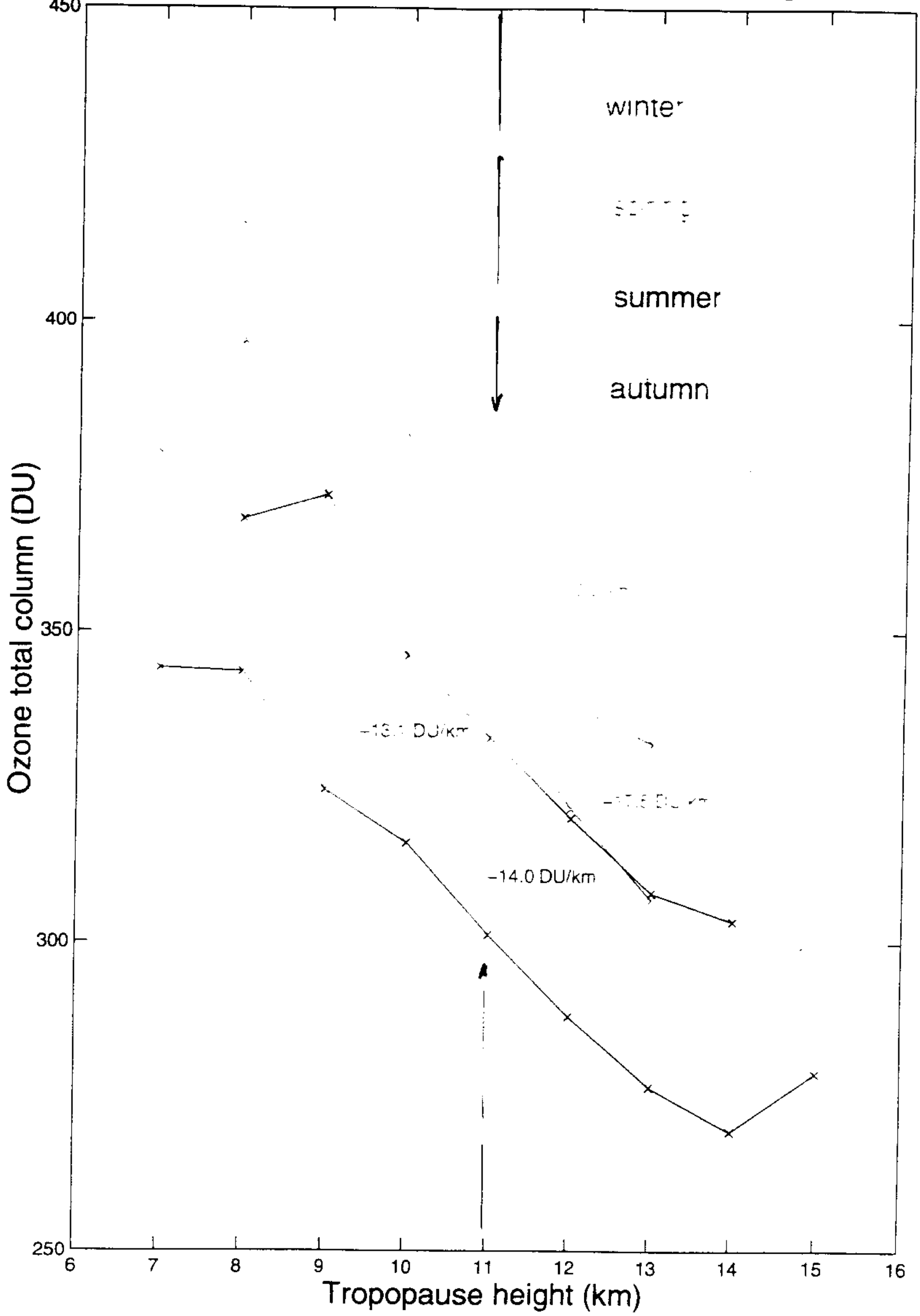

J F M A M J J A S O N D J F M A M J J A S O N D
230
50hPa Temp. at ISSJ
T (K)
220
210
200
T (K)
220
210
200
ISSJ Tropopause
P (hPa)
300
200
100
ISSJ
O3 (DU)
400
300
200
OHP
O3 (DU)
400
300
200
Bremen
O3 (DU)
400
300
200
J F M A M J J A S O N D J F M A M J J A S O N D
1994
1995


Correlation at ISSJ between FTIR O3 and tropopause alt.
400
350
300
250
200
O3 column (DU)
8
9
10
11
12
13
14
15
16
Tropopause alt. (km)
O3 daily means for '95 - mid '96 (190 pts)
regression slope: -17 DU/km (|r2|=0.72)



Tropopause height : 13 km → 9 km

Mid latitude Ozone dependence on tropopause height

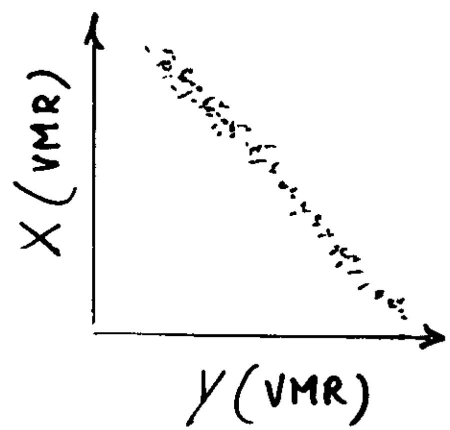


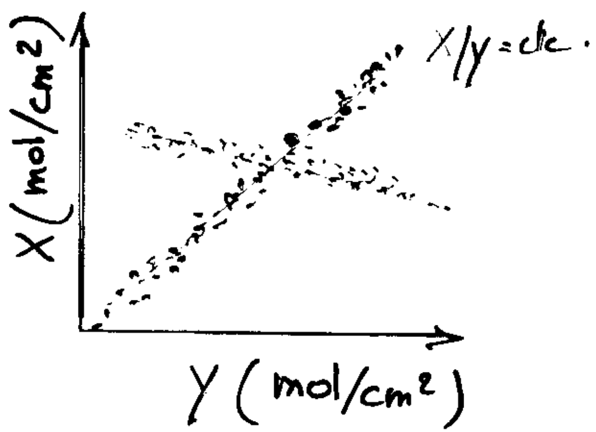
Atmospheric variabilities:
Examples of O_3 + tracers, ClO & OClO, and NO_2

Tracers of dynamics

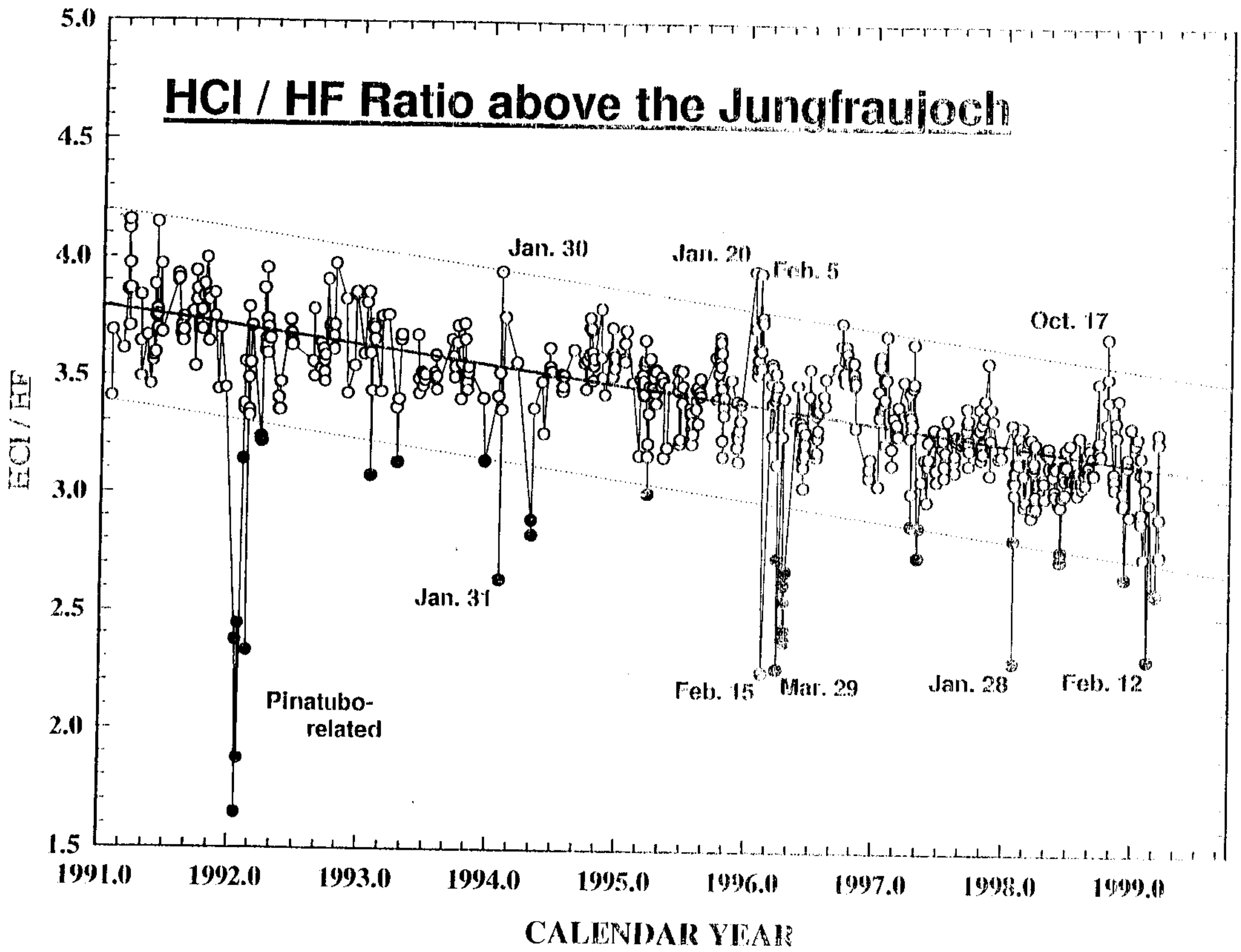
e.g., O_3, HF, N_2O, ...

- empirical correlation plot of a chemically active species versus an 'inert' tracer represent situation dominated by transport

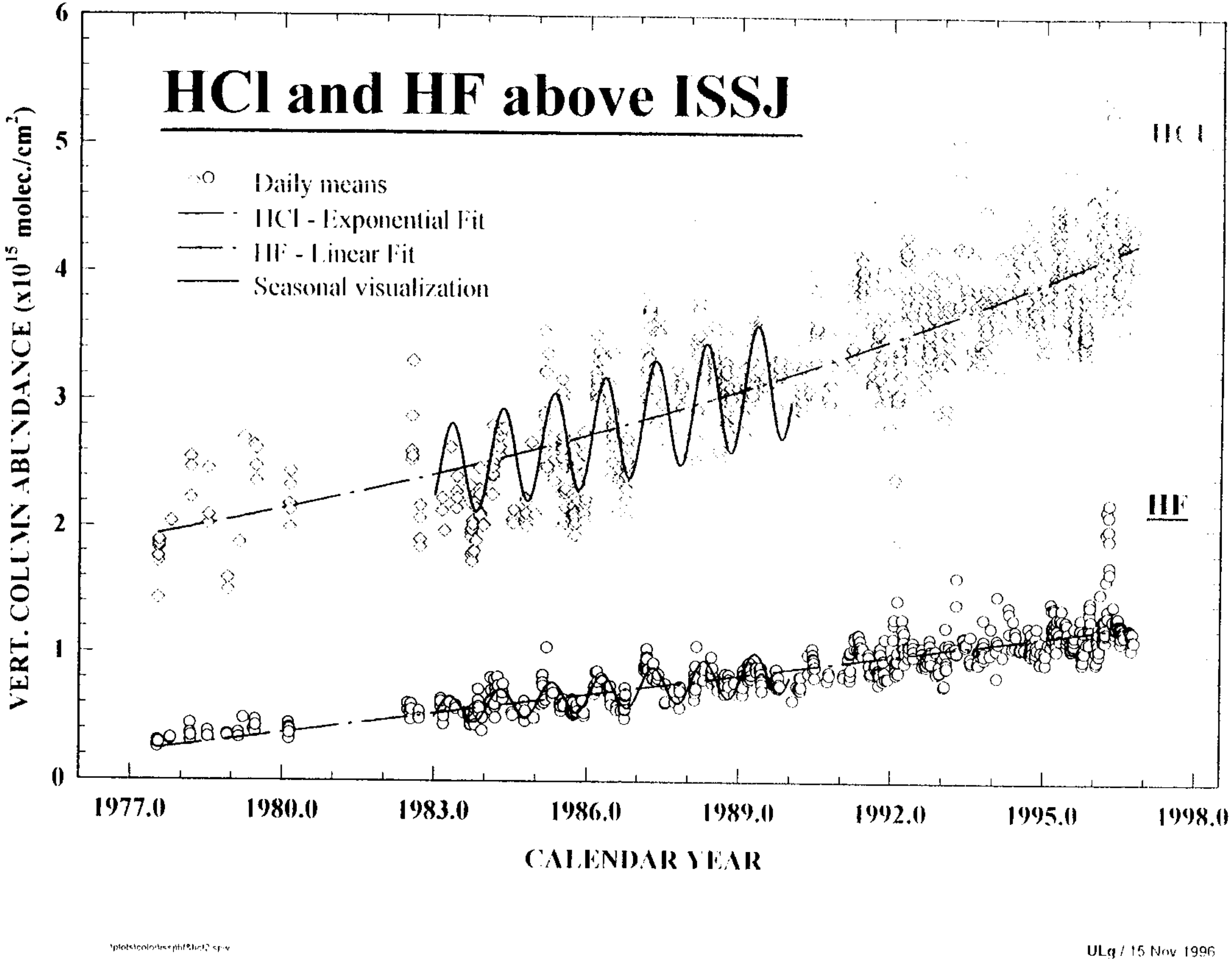




- deviations from normal correlation indicate chemical processing, e.g., HCl versus HF, HNO_3 versus N_2O



R. Zander et al.



HCl and HF above ISSJ
Daily means
HCl - Exponential Fit
HF - Linear Fit
Seasonal visualization
HCl
HF
VERT. COLUMN ABUNDANCE (x10^15 molec./cm^2)
0
1
2
3
4
5
6
1977.0
1980.0
1983.0
1986.0
1989.0
1992.0
1995.0
1998.0
CALENDAR YEAR
ULg / 15 Nov 1996

Atmospheric variabilities:

Examples of O_3 + tracers, ClO & OClO, and NO_2

ClO, OClO

- ClO, BrO are catalysts for O_3 destruction;
- chlorine activation, i.e., increased abundance of ClO, in case of low T, activation of heterogeneous chemistry

  ⇒ typically in polar vortex conditions, in presence of PSC, or under high aerosol load
- OClO short-lived component, formed in case of chlorine activation, i.e., high amounts of ClO, possibly with presence of BrO:
  - » ClOOCl + hν → OClO + Cl
  - » ClO + BrO → OClO + Br

➪ Distinction of a long-term trend in activated chlorine ??

Stratospheric O_3 production / loss

Chapman atmosphere

$O_2 + h\nu\ (< 242\ nm) \rightarrow O + O$

$O_2 + O + M \rightarrow O_3 + M$

production

$O_3 + O \rightarrow O_2 + O_2$

$O_3 + h\nu \rightarrow O_2 + O^*$

loss

Catalytic cycles (X = Cl, Br, NO, OH, H, …)

$\underline{XO} + O \rightarrow X + O_2$

$X + O_3 \rightarrow \underline{XO} + O_2$

netto: $O + O_3 \rightarrow 2\ O_2$

Polar Stratospheric Clouds

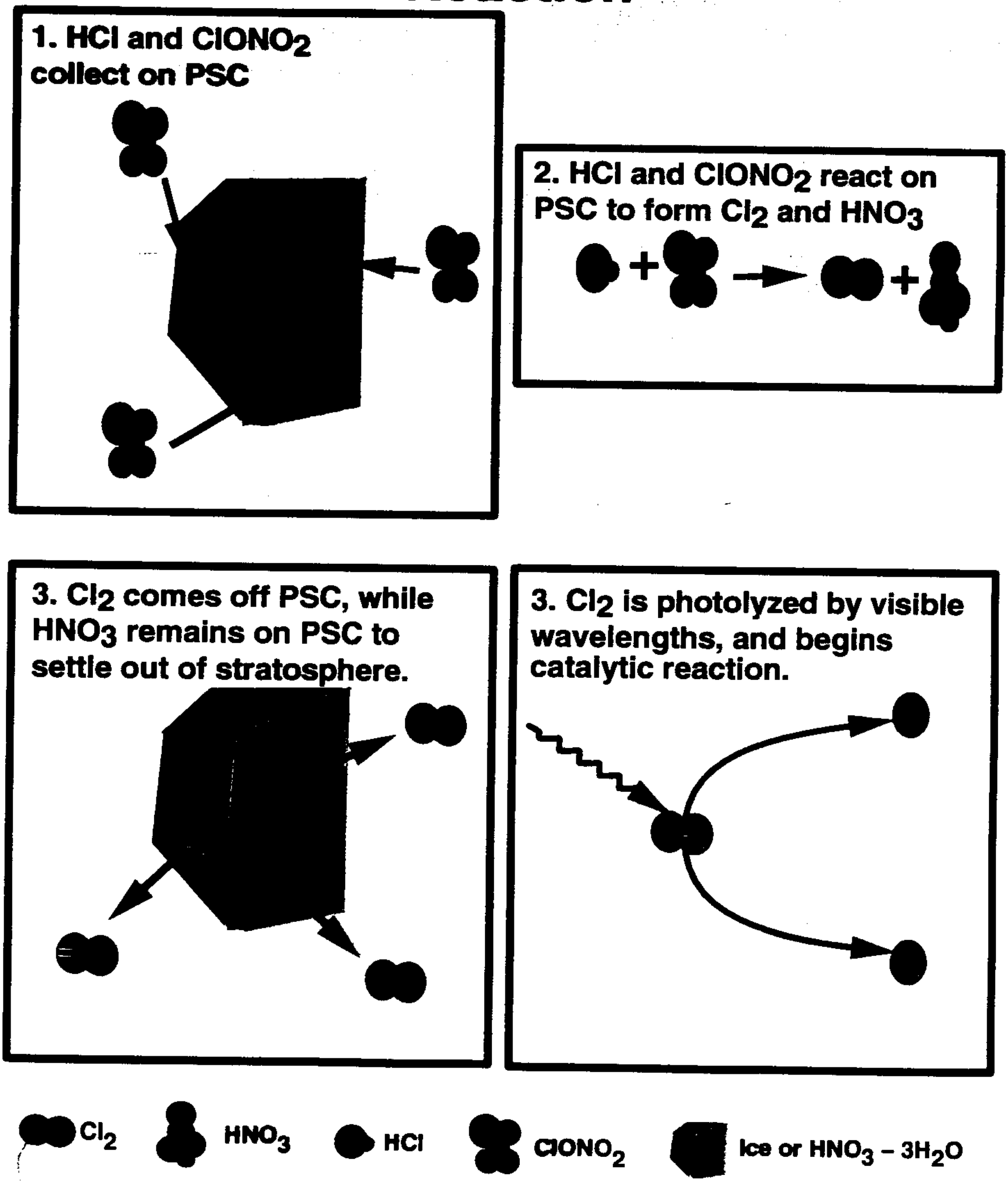
Type I PSC:	Nitric acid trihydrate (HNO_3–3•H_2O) Ternary solution (H_2O, H_2SO_4, HNO_3)
Formation Temp:	195 K
Particle diameter:	1μm
Altitudes:	10–24 km
Settling rates:	1km/30 days
Type II PSC:	Water Ice
Formation Temp:	188 K
Particle diameter:	> 10 μm
Altitudes:	10–24 km
Settling rates:	> 1.5 km/day

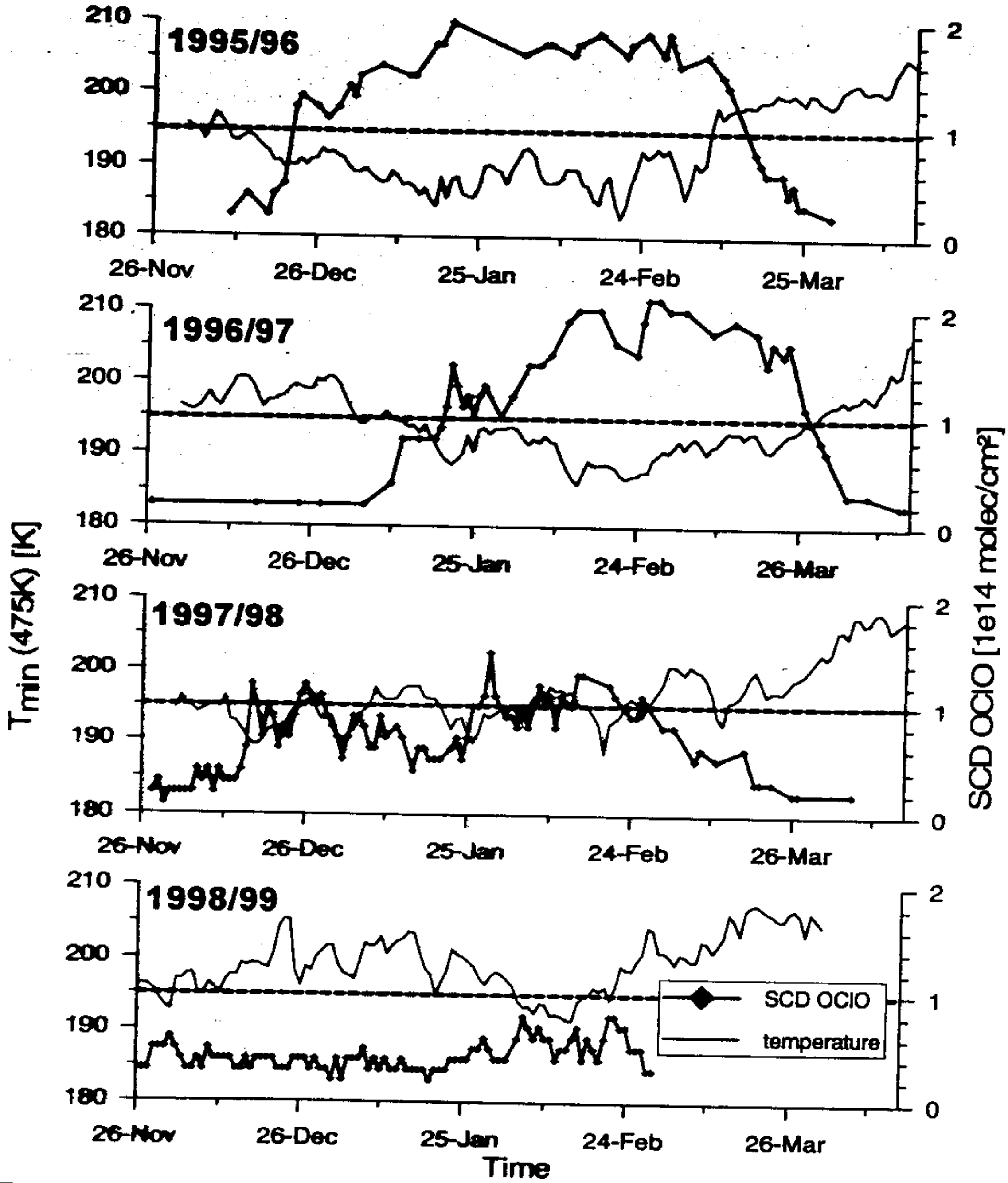
PSC

Heterogeneous reactions take place on PSCs, releasing chlorine from reservoir species (HCl and $ClONO_2$) into reactive forms (ClO) that can rapidly destroy ozone.

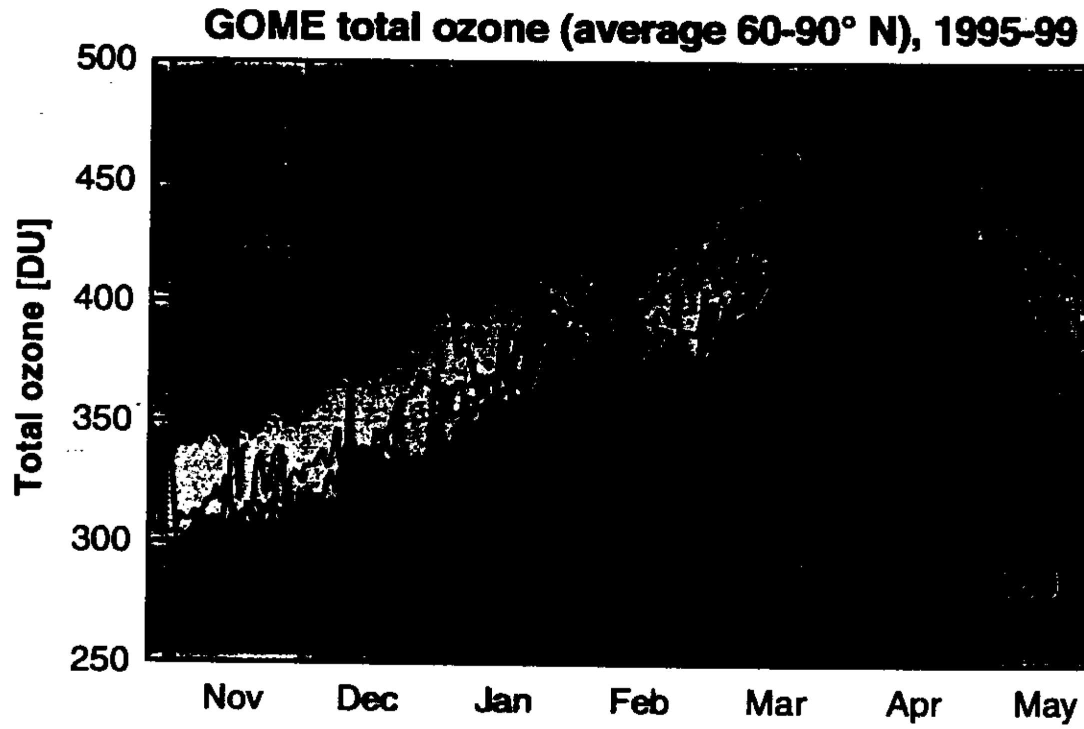
PSC over North Atlantic, January 1989, taken from the NASA DC-8 by O. B. Toon

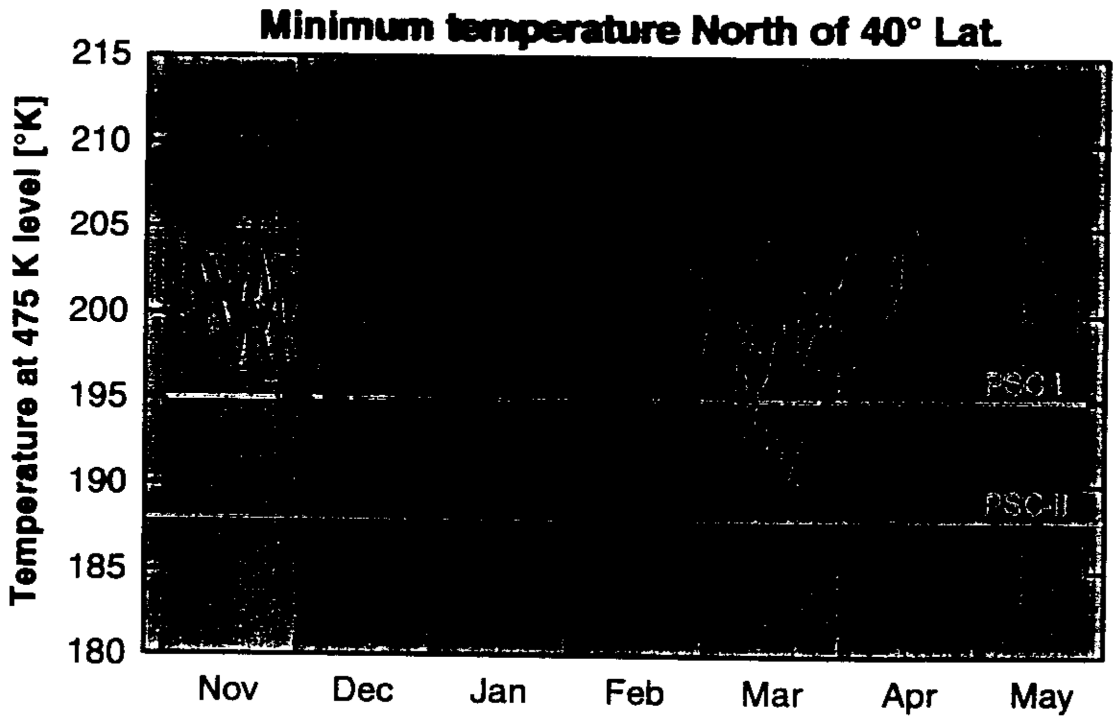
Polar Stratospheric Cloud Surface Reaction





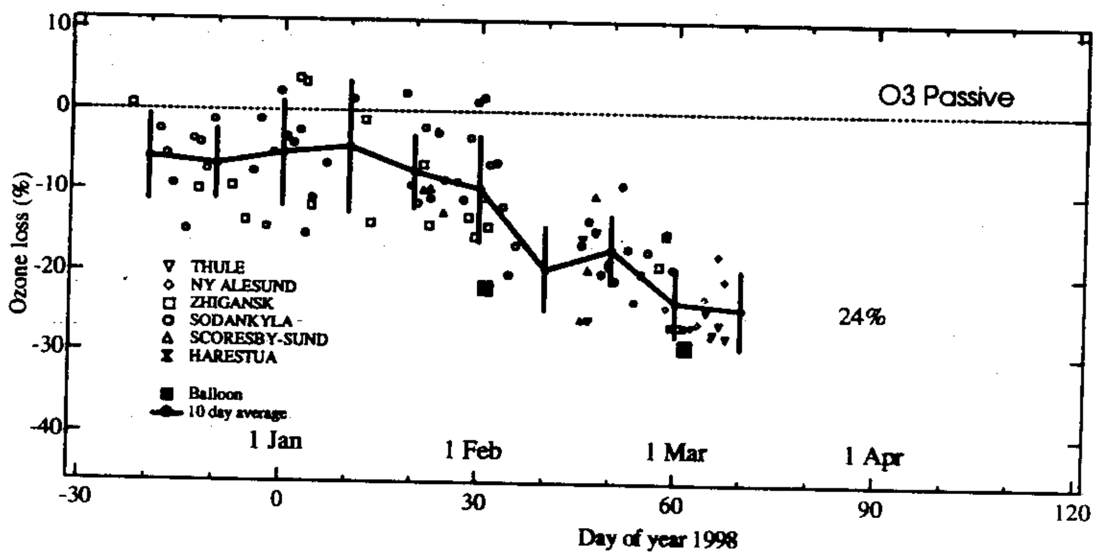
Time series of the daily maximum OClO SCDs (at a SZA of 90°) observed by GOME and the minimum stratospheric temperatures at the 475 K level (from ECMWF data) for the four Arctic winters after the launch in 1995. The formation threshold for PSCs is indicated by the dashed line.


GOME total ozone (average 60-90° N), 1995-99
Total ozone [DU]
500
450
400
350
300
250
Nov
Dec
Jan
Feb
Mar
Apr
May

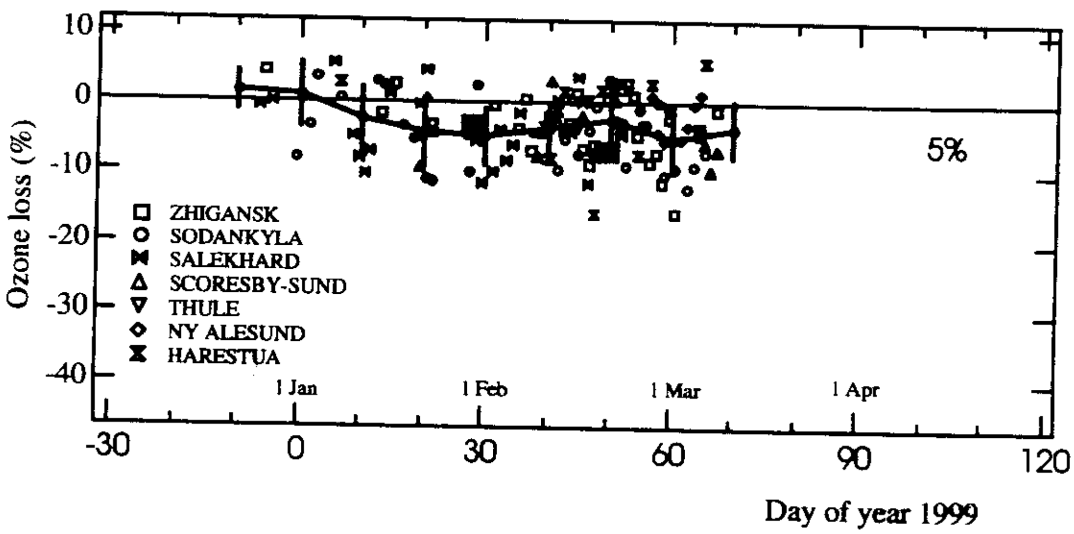

Minimum temperature North of 40° Lat.
Temperature at 475 K level [°K]
215
210
205
200
195
190
185
180
PSC I
PSC-II
Nov
Dec
Jan
Feb
Mar
Apr
May

Ozone loss studies

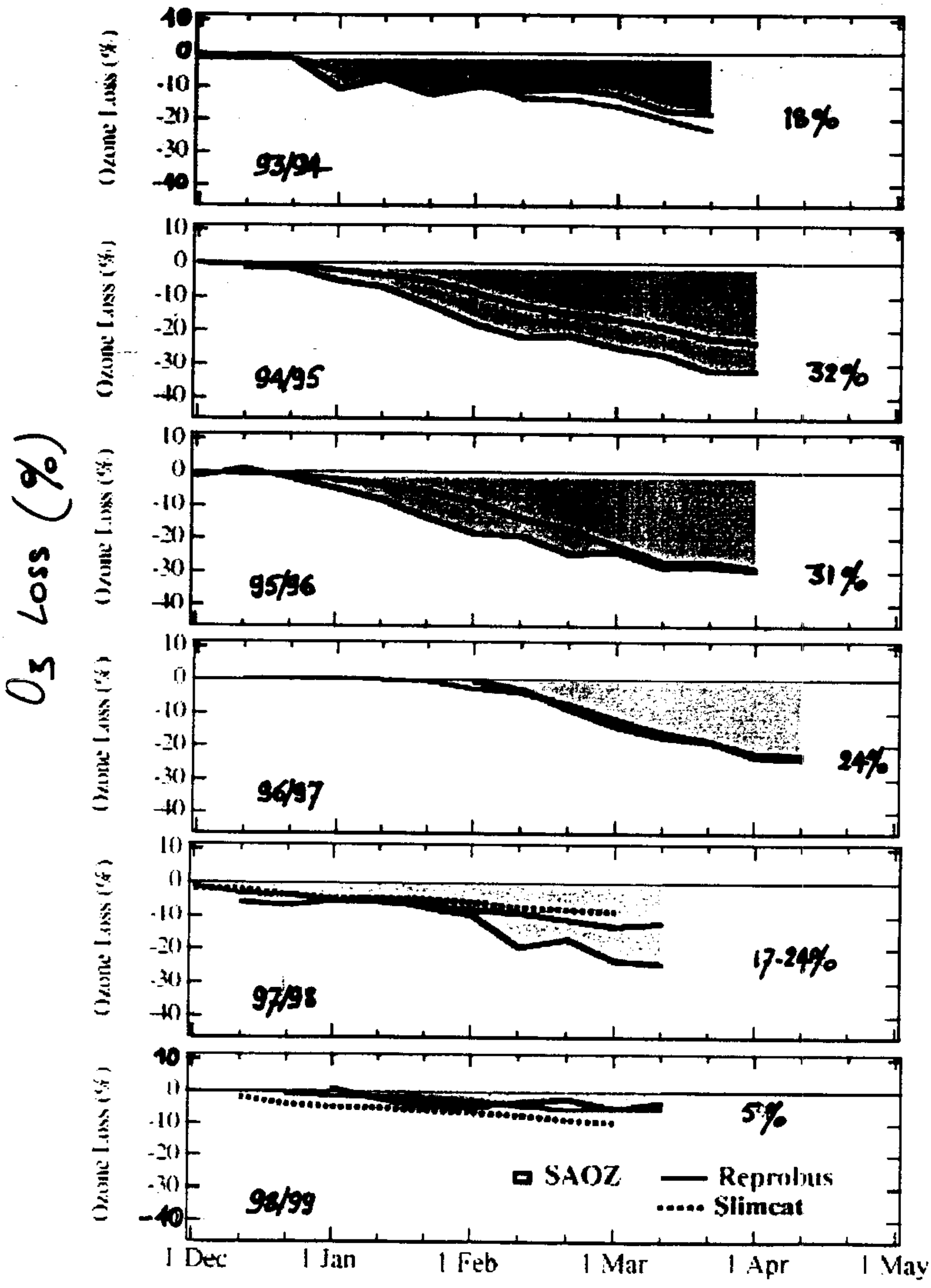
Winter 1997/98



Winter 1998/99



F. Goutail, et al.
CNRS-SA


O3 Loss (%)
Ozone Loss (%)
93/94
18%
94/95
32%
95/96
31%
96/97
24%
97/98
17-24%
98/99
5%
SAOZ
Reprobus
Slimcat
1 Dec
1 Jan
1 Feb
1 Mar
1 Apr
1 May

Atmospheric variabilities:

Examples of O_3 + tracers, ClO & OClO, and NO_2

NO_2

- pronounced diurnal variation
  - related to day-night photochemistry
    - simplified scheme:
      - (R1) $NO_2 + O_3 \rightarrow NO_3 + O_2$
      - (R2) $NO_2 + NO_3 + M \leftarrow\rightarrow N_2O_5 + M$
      - (R3) $NO_3 + h\nu \rightarrow NO + O_2$

        $\rightarrow NO_2 + O$
      - (R4) $NO_2 + h\nu \rightarrow NO + O$
      - (R5) $N_2O_5 + h\nu \rightarrow NO_2 + NO_3$

$\Rightarrow$ am/pm ratio (z) = $\exp(-2k_1(z)\ \underline{[O_3(z)]}\ \Delta T_{night}$

with $k_1(z) = 1.2 \cdot 10^{-13} \exp(-2450K/\underline{T(z)})$

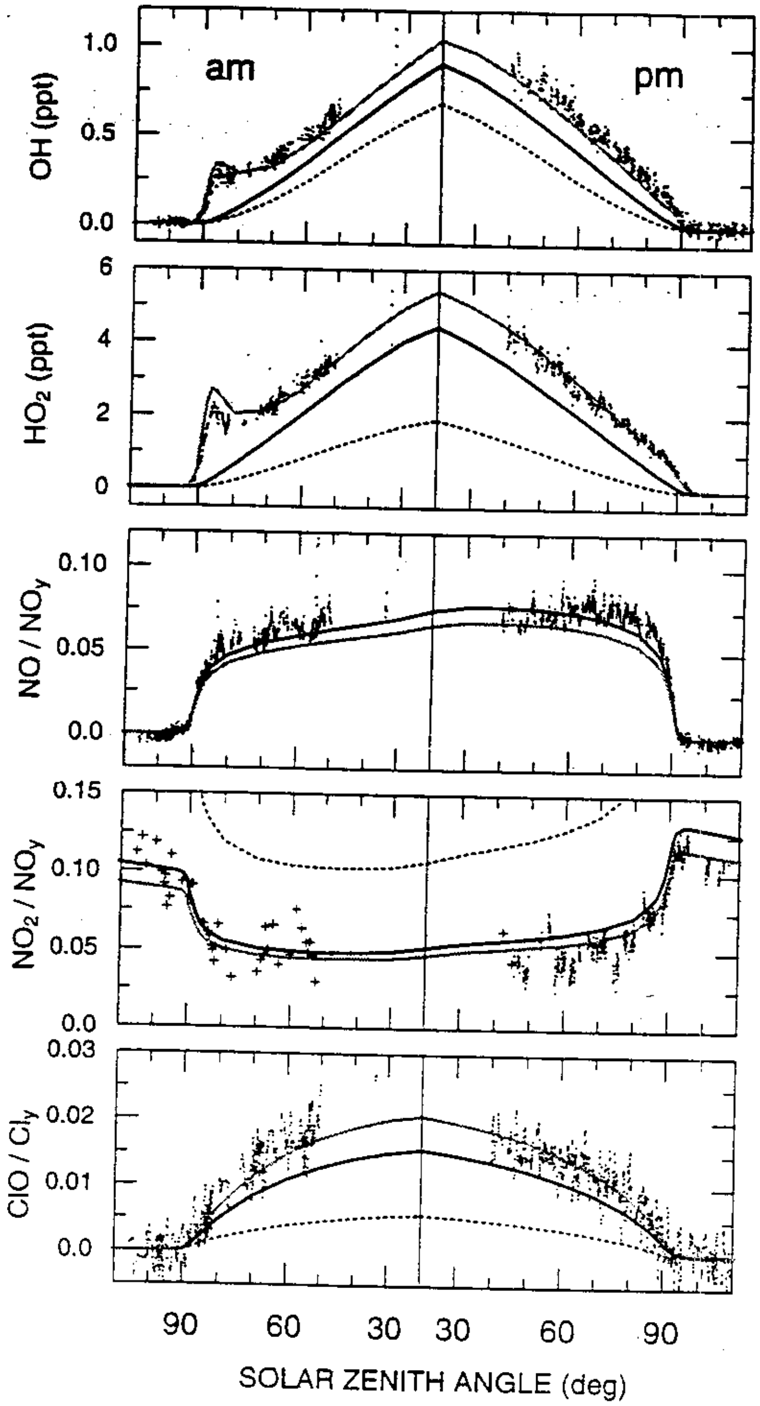
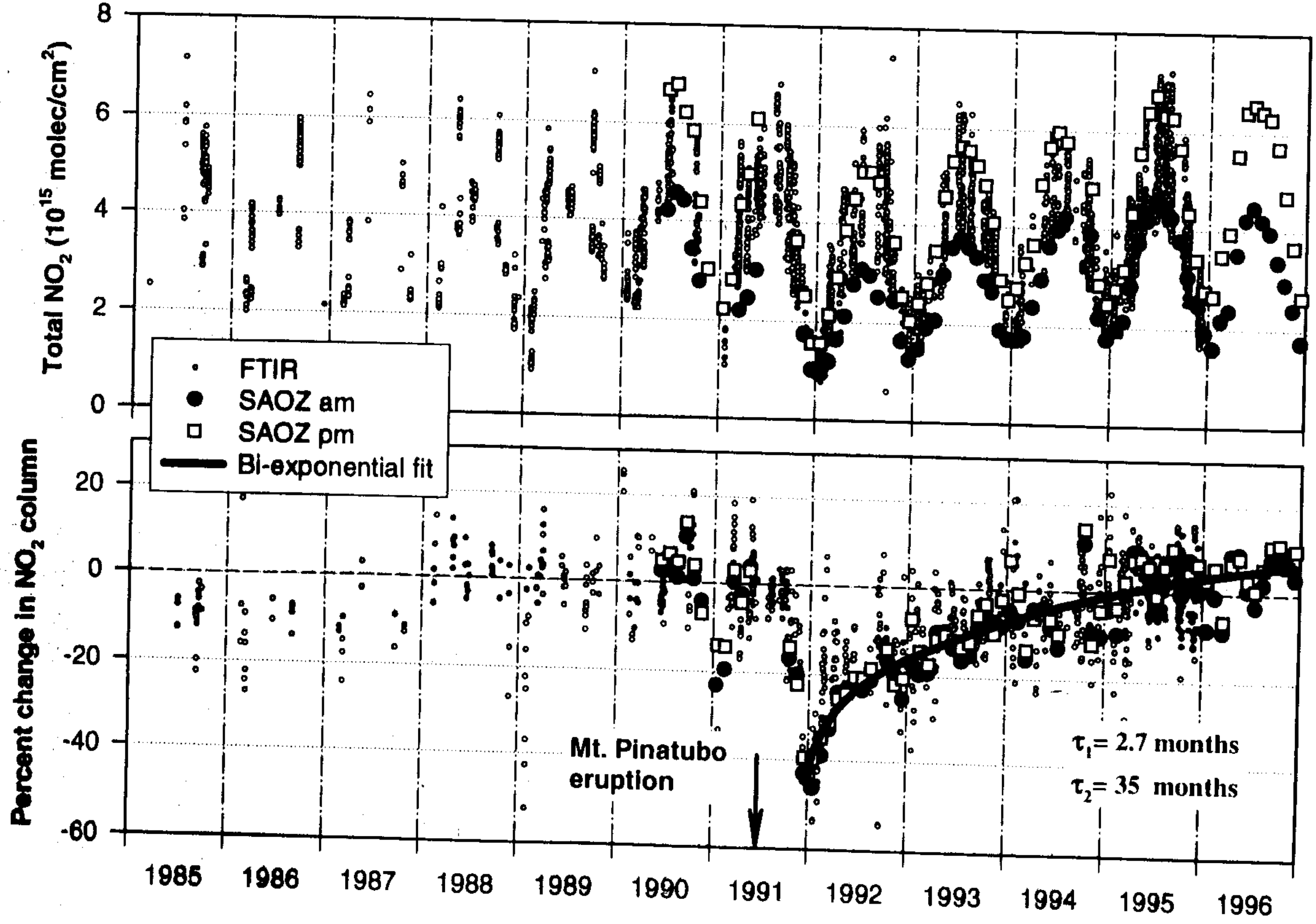


Figure 4-5. Measurements (dots) of the diurnal variations of stratospheric free radicals NO_2, NO, HO_2, OH (crosses and dots represent data from the JPL and NOAA instruments, respectively), and ClO from two ER-2 flights of May 11 (sunrise) and May 12 (sunset), both near 37°N and 63 hPa and [N_2O] between 240 and 260 ppbv, plotted as a function of solar zenith angle. Also shown are results from a constrained data assimilation model (Salawitch *et al.*, 1994a). Three calculations are shown. Dark dotted curve: gas phase reactions only, using rate constants and cross sections of DeMore *et al.* (1992). Curve 1, dark solid line: as for above, except including also the heterogeneous hydrolysis of N_2O_5 and $ClONO_2$. Curve 2, gray line: as for curve 1, except including the heterogeneous decomposition of HNO_4 to form HONO, the $O(^1D)$ quantum yield of Michelsen *et al.* (1994), and the temperature-dependent cross sections of HNO_3 from Burkholder *et al.* (1993). (From Salawitch *et al.*, 1994a.)

Total NO_2 reduction at the Jungfraujoch after Mt. Pinatubo eruption



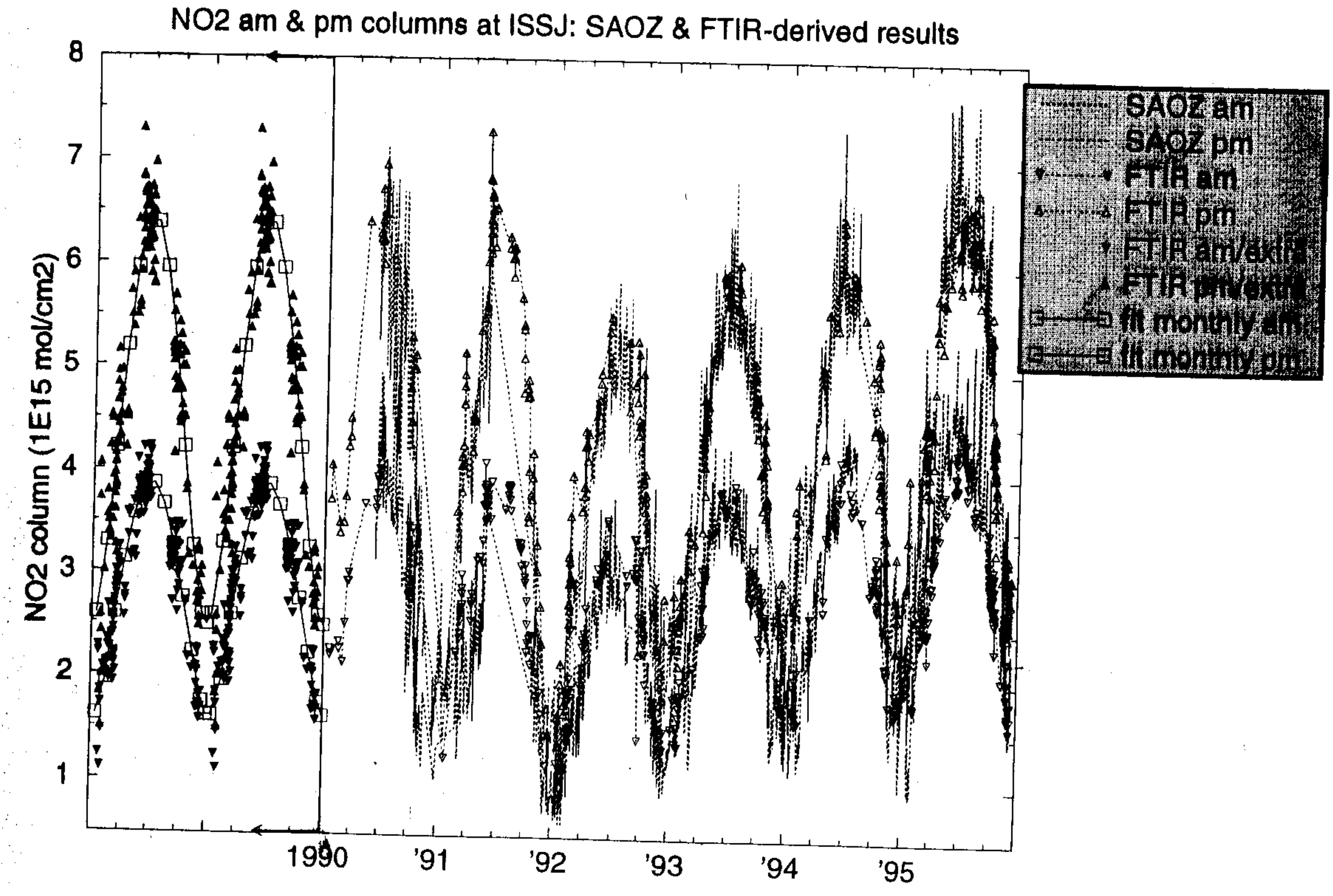
Atmospheric variabilities:

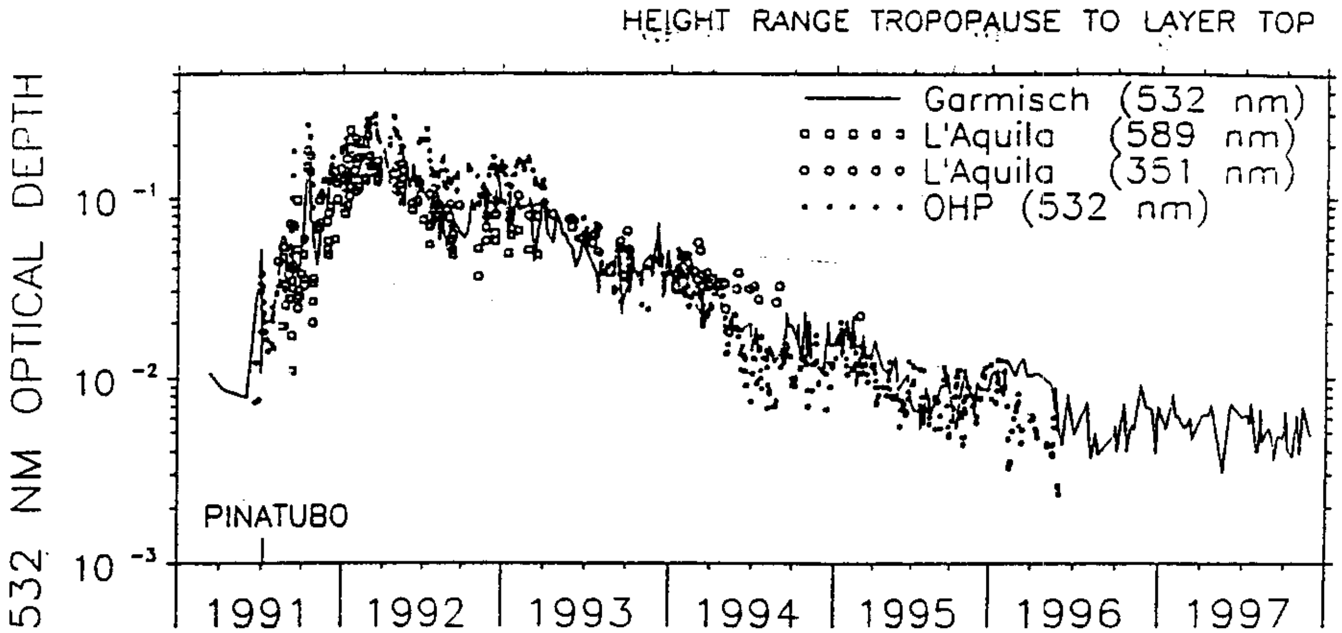
Examples of O_3 + tracers, ClO & OClO, and NO_2

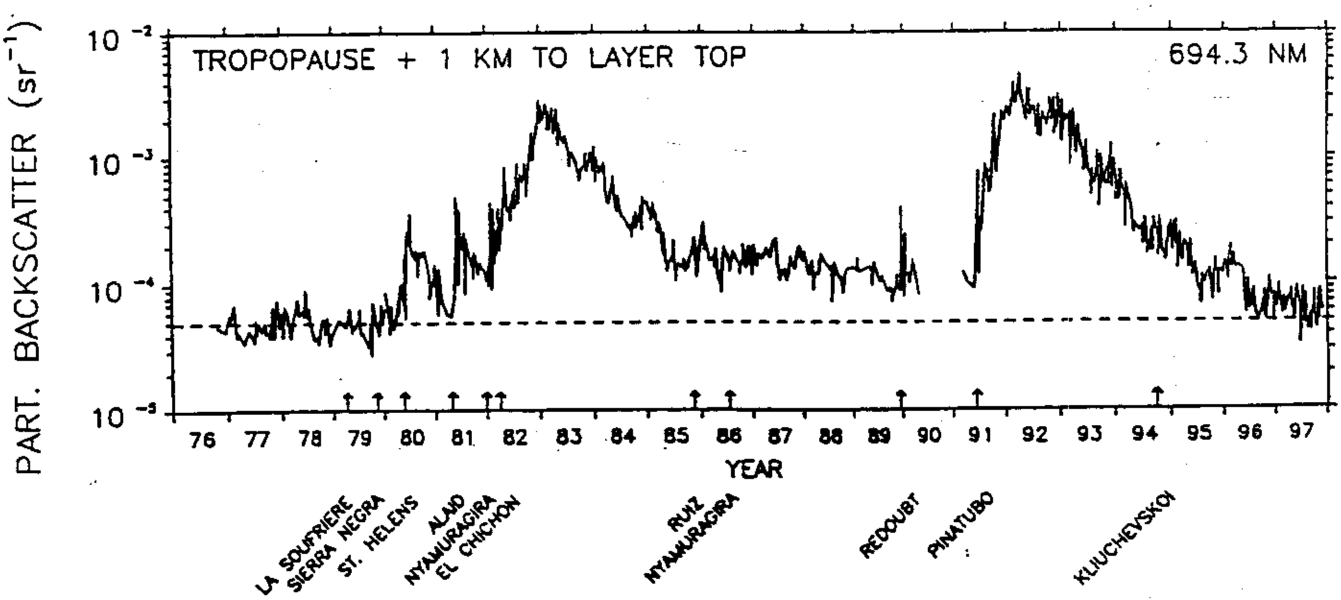
NO_2 (cont'd)

- interannual variations
  - example 1: impact of Mt. Pinatubo eruption
    - dominant mechanism behind:
      - » $NO_2 + NO_3 + M \rightarrow N_2O_5 + M$
      - $\rightarrow \rightarrow N_2O_5 + H_2O \rightarrow 2\ HNO_3$ saturated !

        on aerosol/PSC surface
      - » $ClONO_2 + H_2O \rightarrow HNO_3 + HOCl$
      - » $BrONO_2 + H_2O \rightarrow HNO_3 + HOBr$
      - » … (+ HCl)
  - example 2: denoxification / denitrification in winter
    - » similar reactions on PSC / settling out of HNO_3


NO2 am & pm columns at ISSJ: SAOZ & FTIR-derived results
NO2 column (1E15 mol/cm2)
8
7
6
5
4
3
2
1
1990
'91
'92
'93
'94
'95
SAOZ am
SAOZ pm
FTIR am
FTIR pm
FTIR am/extra
FTIR pm/extra
fit monthly am
fit monthly pm





H. Jaeger et al.

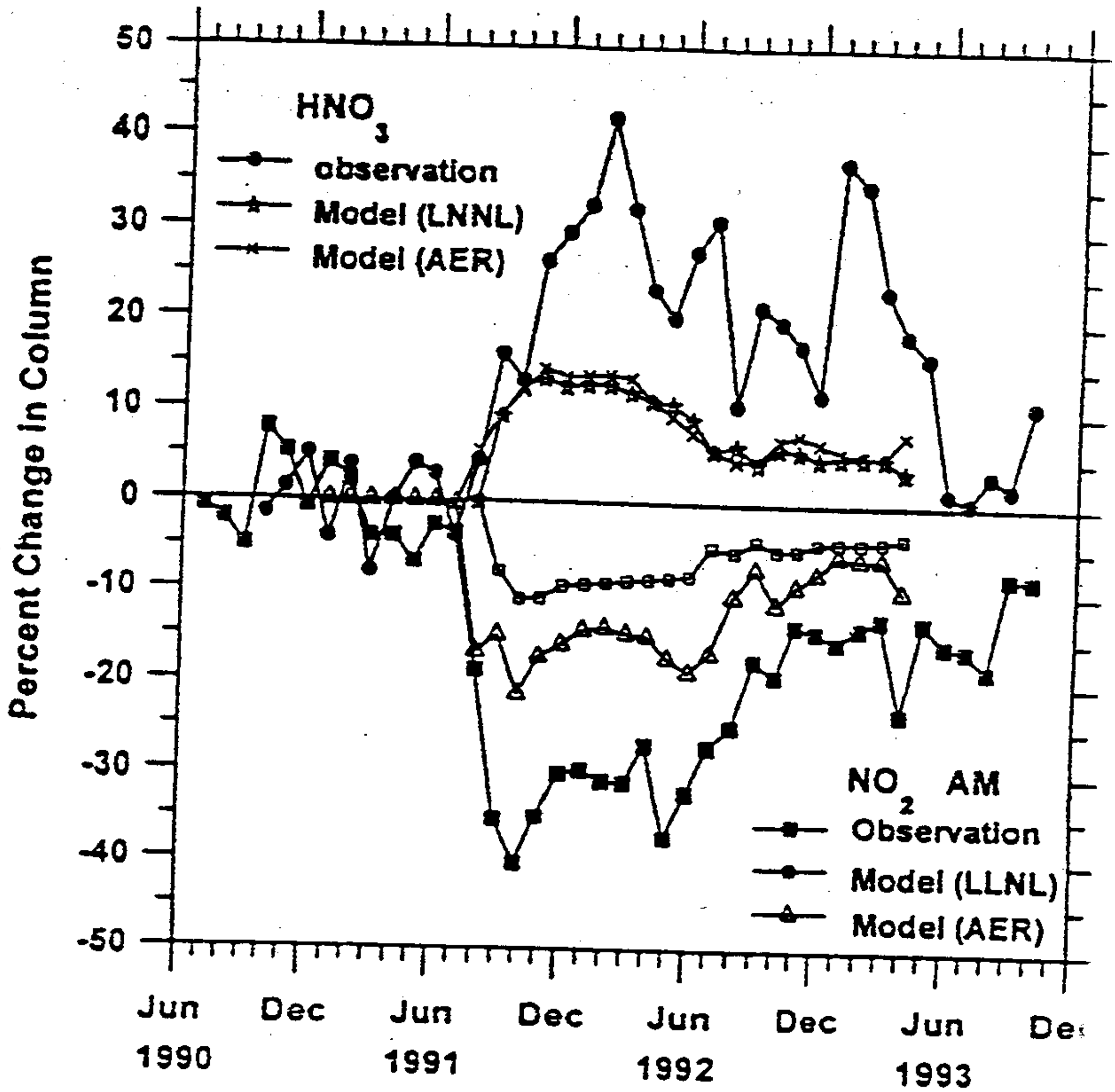


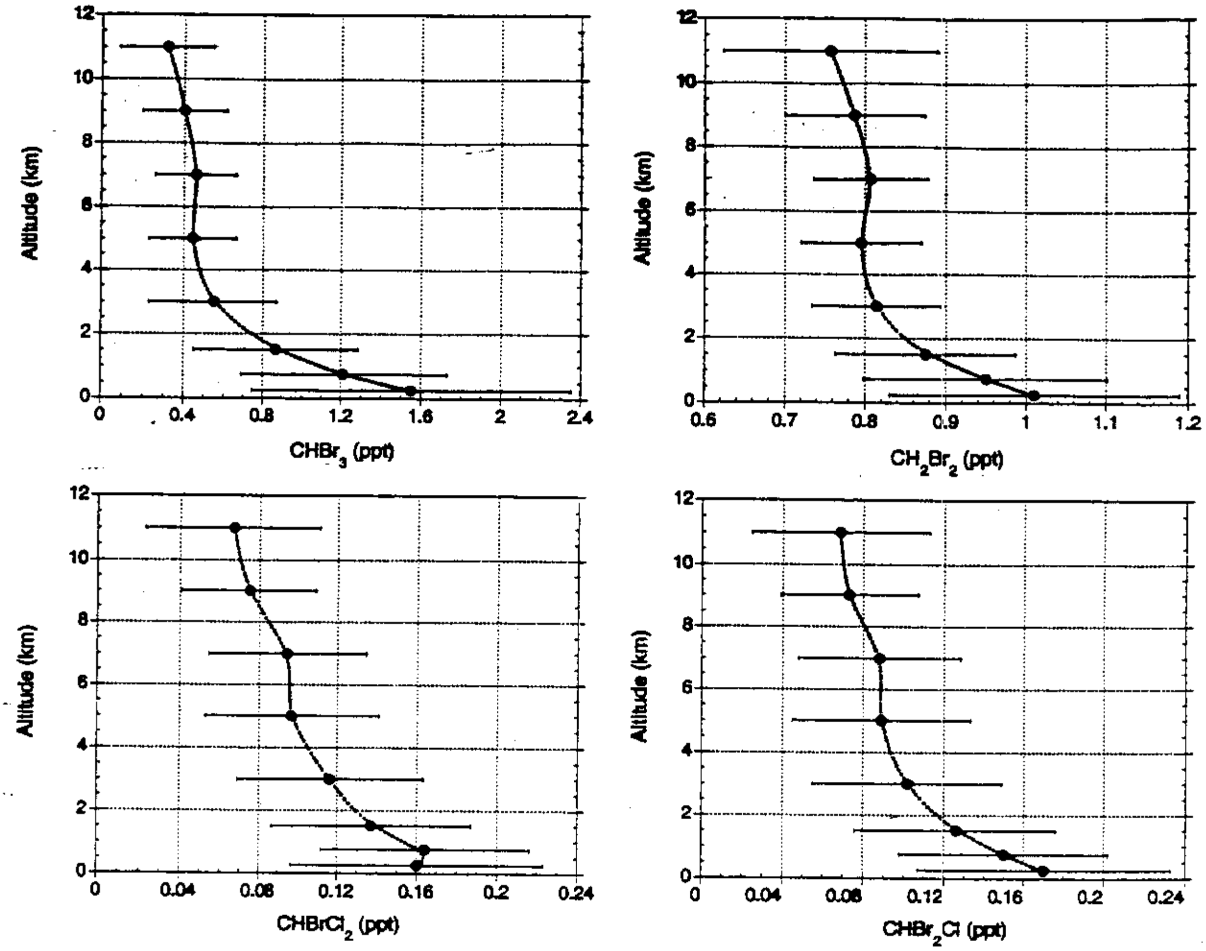
Figure 4-9. Percentage changes in HNO_3 and NO_2 column amounts above Lauder, New Zealand (45°S) following the arrival of the Mt. Pinatubo aerosol. The Lawrence Livermore National Laboratory (LLNL) results are for 42.5°S and the Atmospheric Environmental Research, Inc. (AER) results are for 47°S. Heterogeneous chemistry is included in the calculations based on the observed aerosol field from SAGE II. (From Koike *et al.*, 1994.)

Atmospheric long-term changes

- ☑ halogen compounds:
  - ➢ short-lived (< 1 yr) and long-lived (> 1 yr) constituents
    - lifetime determines vertical distribution profile, in particular survival into the stratosphere
    - degradation, essentially by
      - photolysis
      - reaction with OH
  - ➢ sources = halocarbons, incl. HCFC
- ☑ greenhouse gases (GHG)
- ☑ temperature, dynamics, aerosol/PSC, clouds, ...
- ☑ Ozone: tropo- and strato-

Industrial Name	Chemical Formula	Lifetime, WMO (1998) (years)	Actual Abundance / Source
Nitrous oxide	N_2O	120	
CFC-11	CCl_3F	45	③ ≈ 50% of [CH_3Cl]
CFC-12	CCl_2F_2	100	② ≈ [CH_3Cl]
CFC-113	CCl_2FCClF_2	85	
Carbon tetrachloride	CCl_4	35	④ ≈ 20% of [CH_3Cl]
H-1211	$CBrClF_2$	11	
H-1301	$CBrF_3$	65	
Methyl chloroform	CH_3CCl_3	4.8	
HCFC-22	$CHClF_2$	11.8	
HCFC-141b	CH_3CCl_2F	9.2	
HCFC-142b	CH_3CClF_2	18.5	
HFC-134a	CH_2FCF_3	13.6	
HFC-23	CHF_3	243	
Methane	CH_4	8.9	
Methyl chloride	CH_3Cl	~ 1.3	① Most abundant halocarbon **natural origin**: biomass burning, ocean, wood-rotting fungi
Methyl bromide	CH_3Br	0.7	**natural origin**: oceans, fumigation, biomass burning; 50% anthropogenic (automobile)!
methylene chloride	CH_2Cl_2	5 to 6 months	
chloroform	$CHCl_3$	~ 6 months	
trichloroethene	C_2HCl_3	~ 1 week	
tetrachloroethene	C_2Cl_4	3 to 4 months	
phosgene	$COCl_2$	70 days	
methyl iodide	CH_3I	4 days at surface 1.5 days (10 km)	
ethyl iodide	C_2H_5I	Similar to CH_3I	
chloroiodomethane	CH_2ClI	~ 100 minutes	
diiodomethane	CH_2I_2	2.5 minutes	
isopropyliodide	CH_3CHICH_3	~ 16 hours	
1-iodopropane	$CH_3CH_2CH_2I$	~ 1 day	
iodotrifluoromethane	CF_3I	1 day	
dibromochloromethane	$CHBr_2Cl$	≤ 120 days	
bromoform	$CHBr_3$	≤ 36 days	
methylene bromide	CH_2Br_2	≤ 130 days	
bromodichloromethane	$CHBrCl_2$	≤ 120 days	

Figure 2-11. Vertical profiles of individual reactive organic Br gases, total reactive organic Br, and fraction of reactive/total organic Br over the Pacific Ocean (adapted from Schauffler *et al.*, 1998b). Mean and standard deviation are plotted.



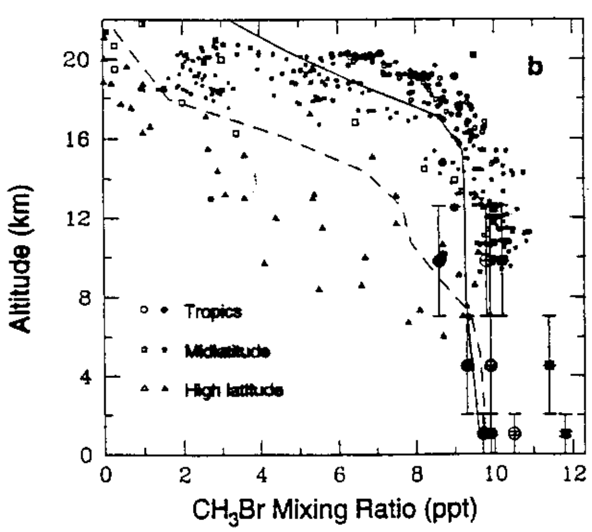
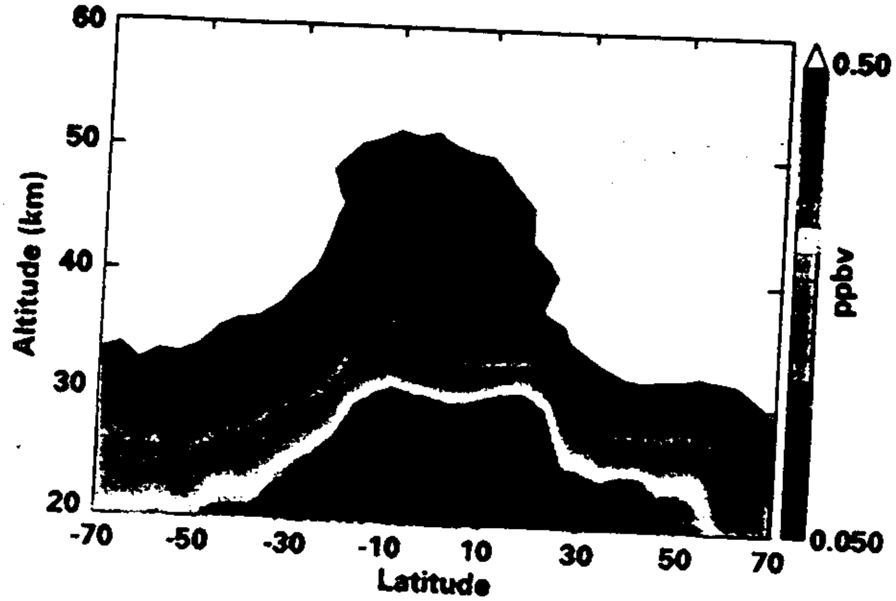


Figure 2-10. (a) Vertical profiles of CH_3Br measured at various latitudes during winter (filled symbols) and summer (open symbols) using different techniques (big symbols - Blake *et al.*, 1997; small symbols - Schauffler *et al.*, 1998a; medium symbols - Lal *et al.*, 1994, Kourtidis *et al.*, 1998). Some of the data are normalized to 10 ppt at the tropospheric level. Measurements are compared with the NASA Goddard Space Flight Center 2-D model (Jackman *et al.*, 1996) results; continuous line is for 15°N and dotted line is for 65°N. (b) Data shown on linear scale for greater clarity.

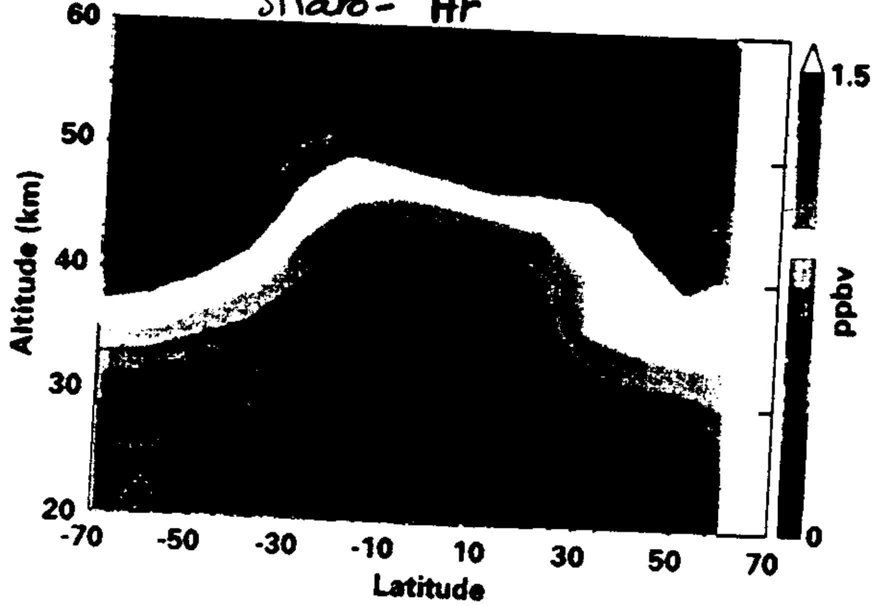
Strato - CFC's

CLAES/UARS



Strato - HF

HALOE/UARS



Atmospheric long-term changes:
halogens (2/2)

- Halogens: Cl, Br, F (I) -containing
- in the *stratosphere* :
  - 'aggressivity'/atom vis-à-vis O_3 or catalytic efficiency α:

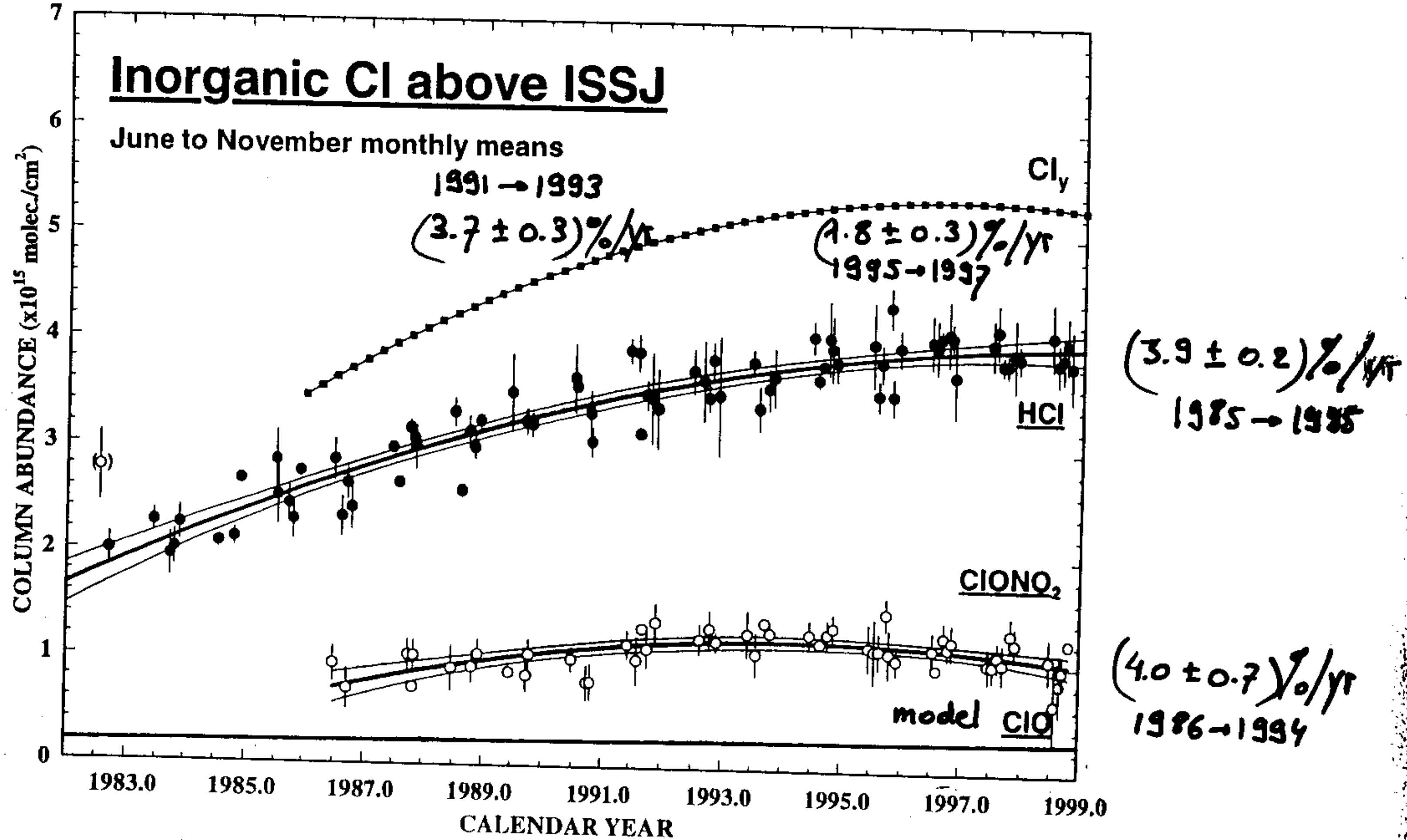
    $\alpha_{Br} \cong 40\text{-}60$ (100) $> \alpha_{Cl} \equiv 1 > \alpha_F \cong 0$ (10^{-4})

    cf. partitioning between reservoirs and active species depends on relative reaction rates;
    - Br mostly (>50%) in form of BrO

      cf. $HBr + OH \rightarrow BrO$ *fast*
    - Cl mostly in form of reservoirs: HCl, $ClONO_2$ (HOCl, Cl_2O_2)

      cf. $HCl + OH \rightarrow ClO$ slow
    - F almost only in form of HF

      cf. $HF + OH \rightarrow \ldots$ *too slow*
  - <u>but:</u> Cl-abundance ($\cong$ 3.5 ppb) >> Br-abundance ($\leq$ 20 ppt); I has not been detected yet (estimate: 0.2 ±0.3 pptv)



...\epw32\color\ias\inorg_Cl.jnb-G98bw

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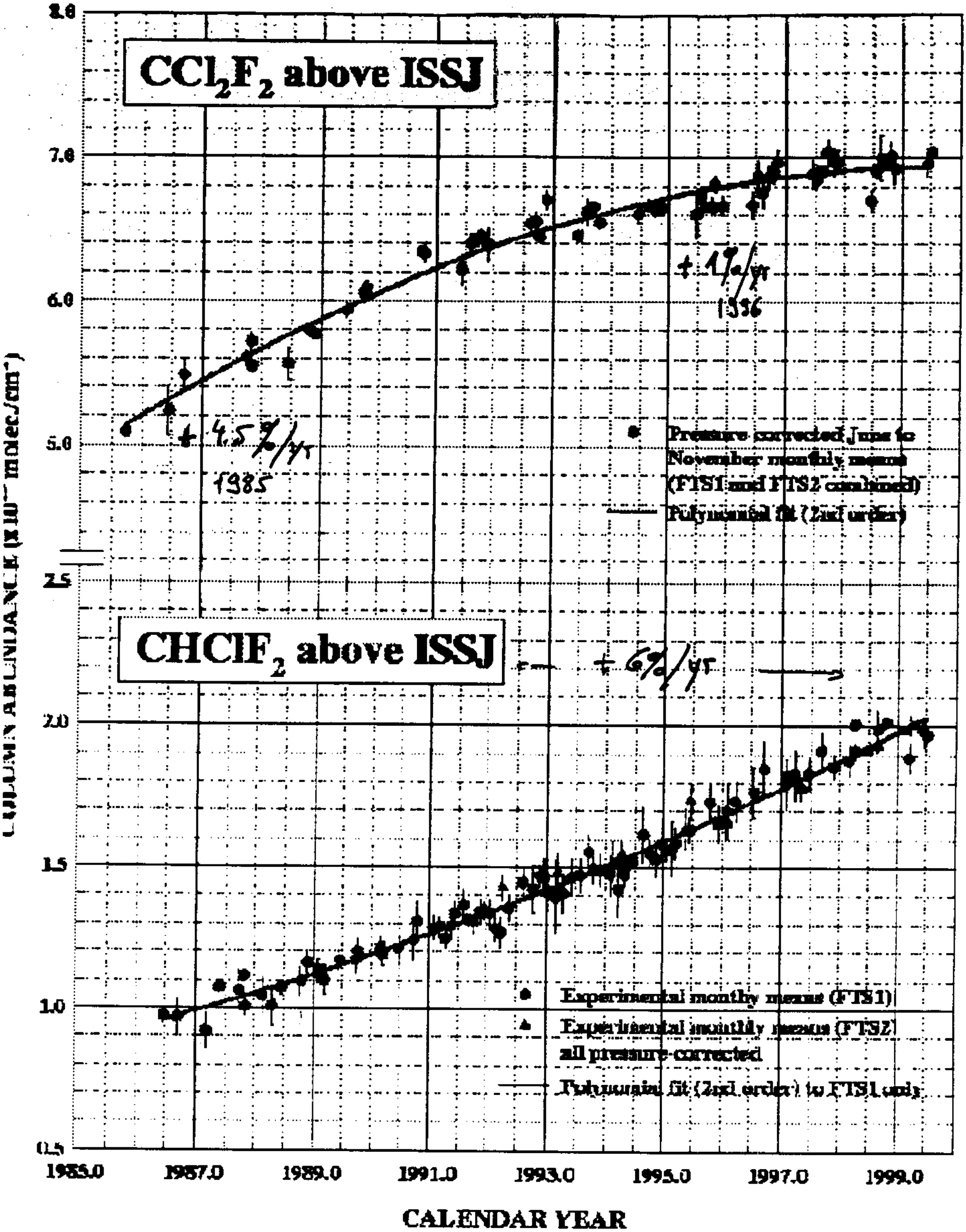

CCl2F2 above ISSJ
CHClF2 above ISSJ
+4.5%/yr
1985
+1%/yr
1996
+6%/yr
Pressure corrected June to November monthly means (FTS1 and FTS2 combined)
Polynomial fit (2nd order)
Experimental monthly means (FTS1)
Experimental monthly means (FTS2)
all pressure-corrected
Polynomial fit (2nd order) to FTS1 only
CALENDAR YEAR
1985.0
1987.0
1989.0
1991.0
1993.0
1995.0
1997.0
1999.0

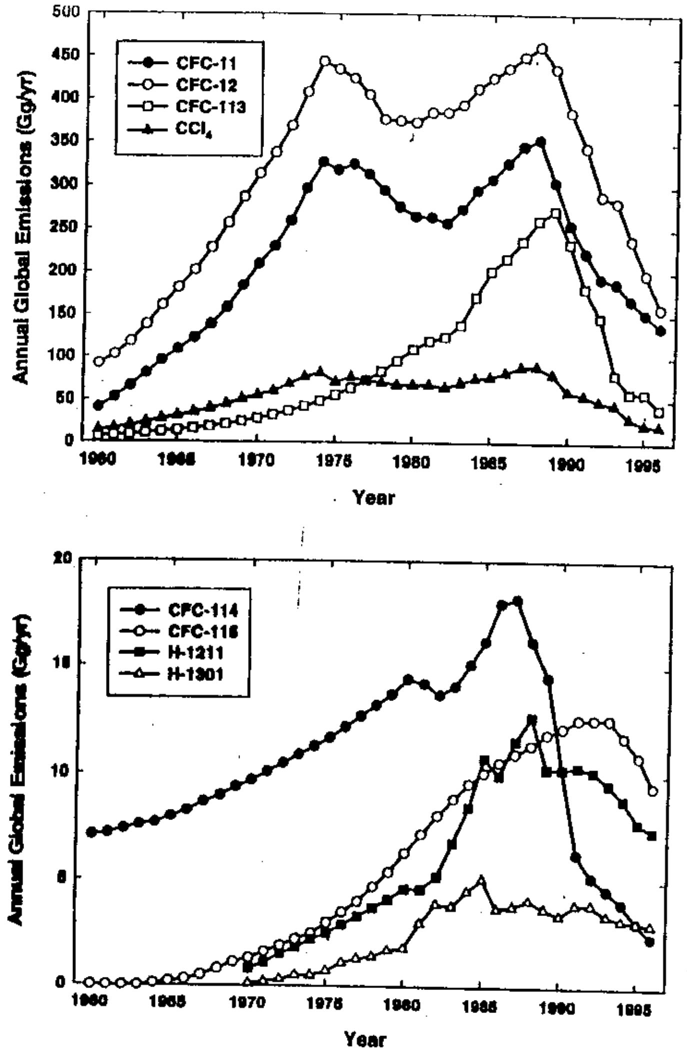


Figure 1-11. Annual global emissions (in Gg yr^{-1}) of long-lived halocarbons estimated by industry from audited production, sales, and other data (AFEAS, 1998; Fisher *et al.*, 1994; McCulloch, 1992; Fraser *et al.*, 1998; updated by P. Midgley, personal communication).

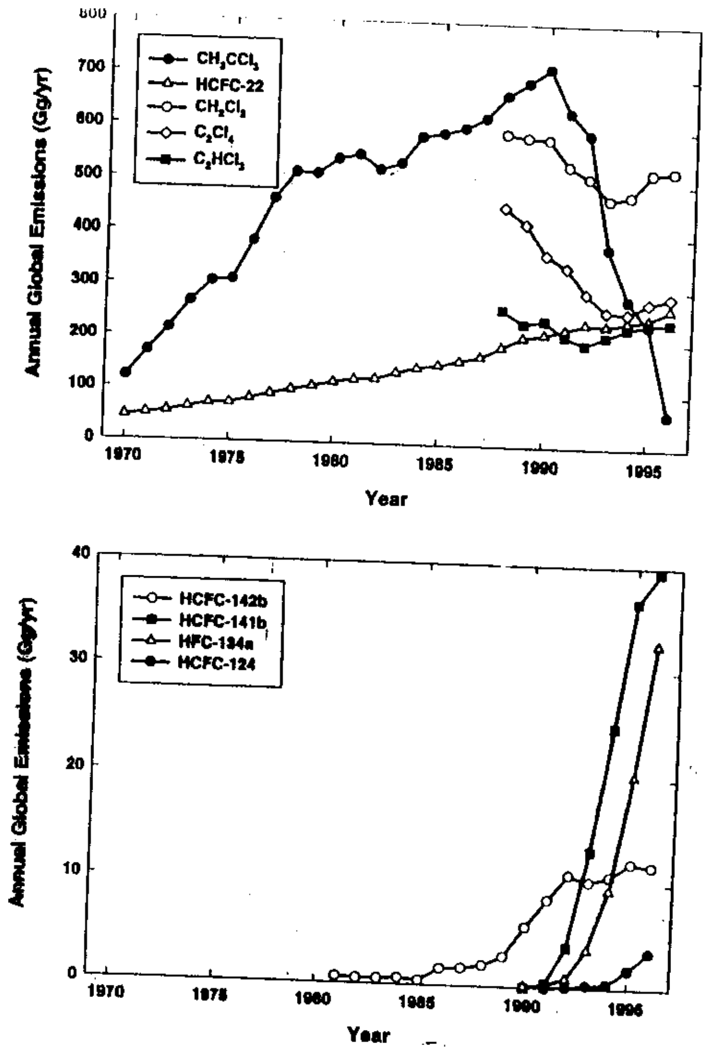
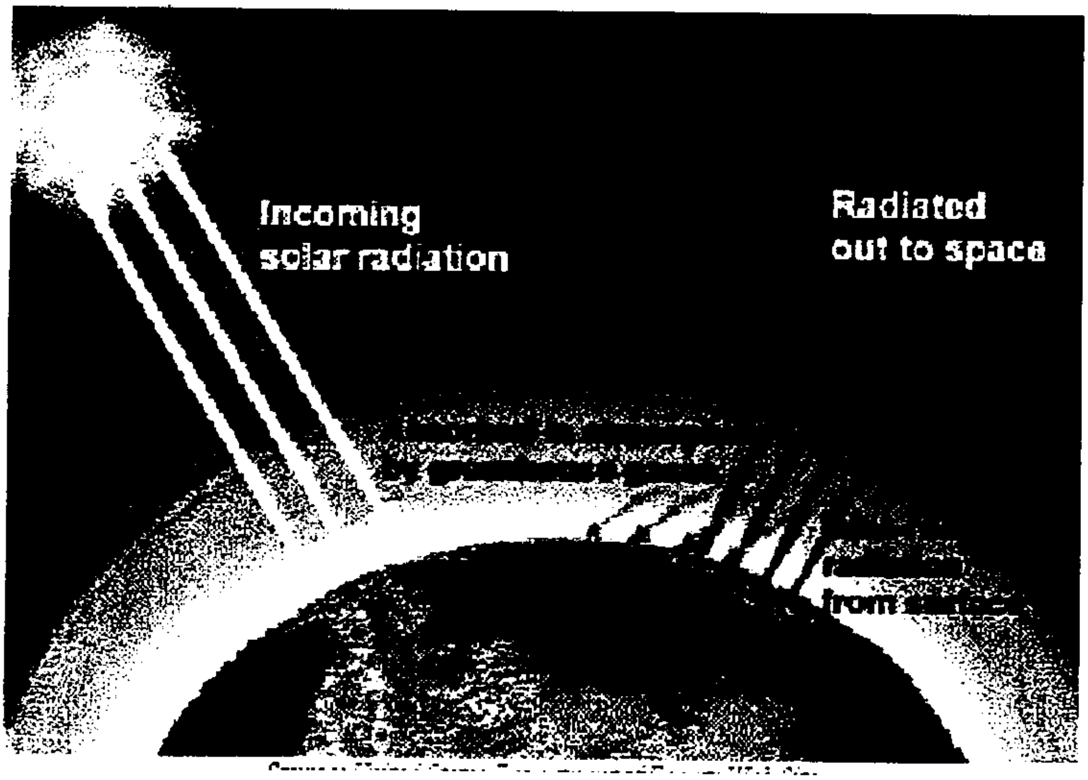


Figure 2-1. Annual global emissions of short-lived halocarbons (kt yr^{-1}, Gg yr^{-1}) estimated by industry from audited production, sales, and other data (AFEAS, 1998; Fisher *et al.*, 1994; Midgley and McCulloch, 1995; McCulloch and Midgley, 1996; and Midgley *et al.*, 1998). Note: There are no surveyed data for CH_2Cl_2, C_2Cl_4, and C_2HCl_3 prior to 1988.

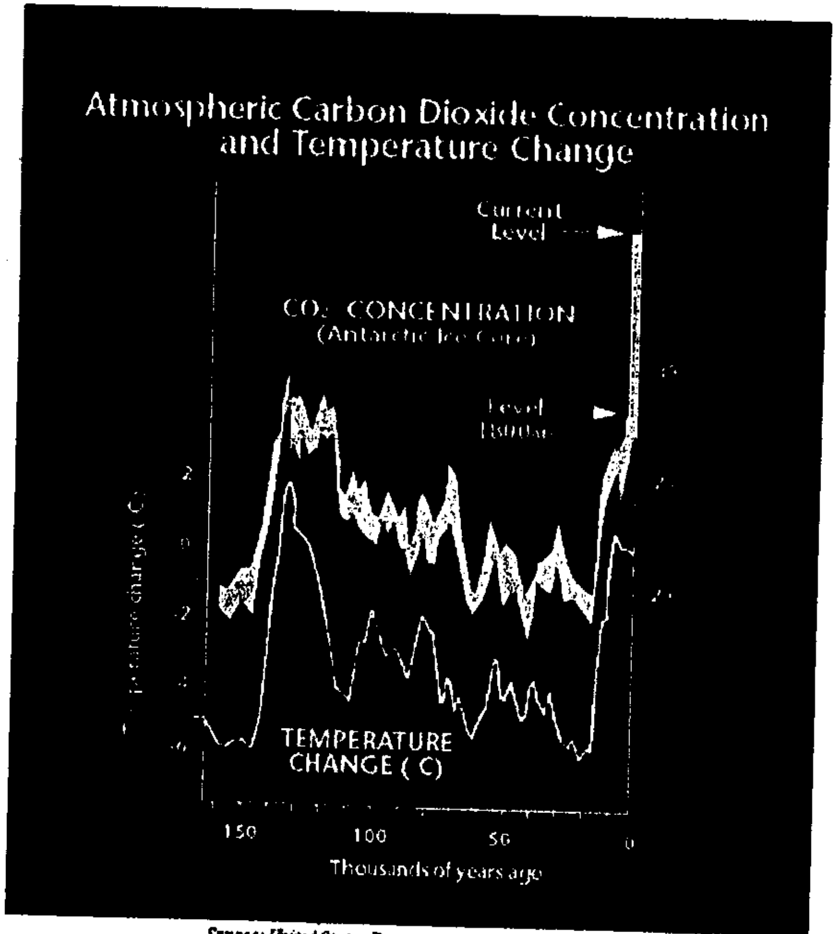
~~'Greenhouse effect'~~

↓

Atmospheric heating.



Atmospheric long-term changes:
'Greenhouse' gases, climate change (1/5)



Source: United States Department of Energy Web Site

Figure 1: Trends in CO2 Concentrations and Global Temperatures (past 160,000 years)
PPMV = parts per million by volume

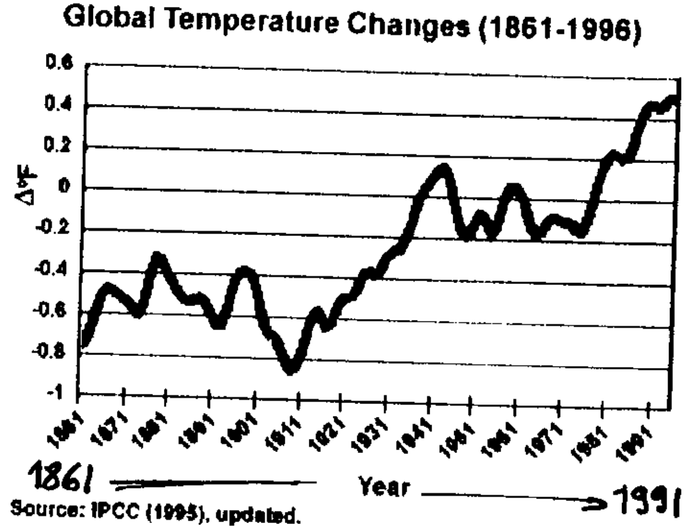
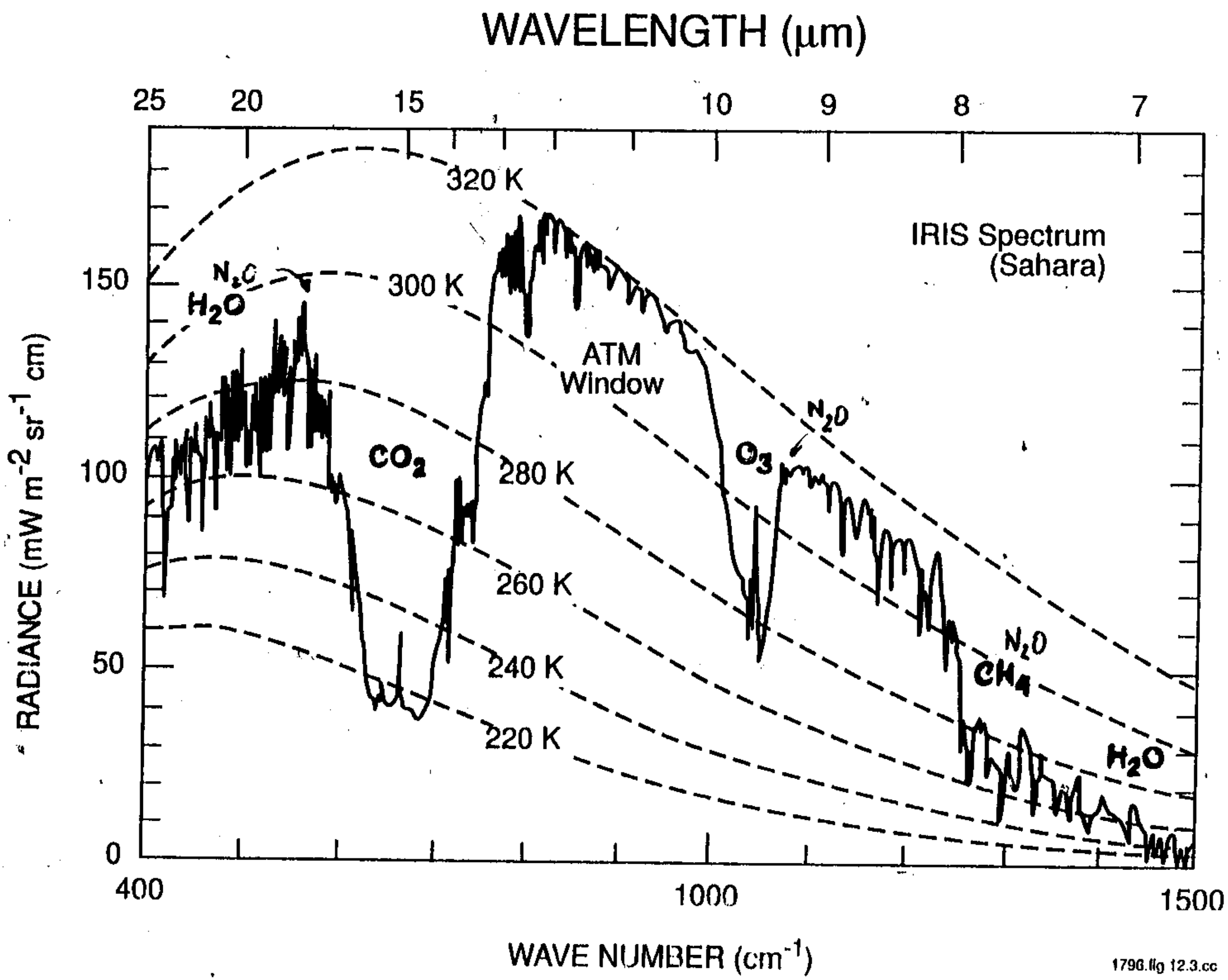


Figure 15.3. *Example of terrestrial radiation spectrum obtained by the Nimbus 3 IRIS instrument for clear sky conditions (from Hanel et al., 1972).*



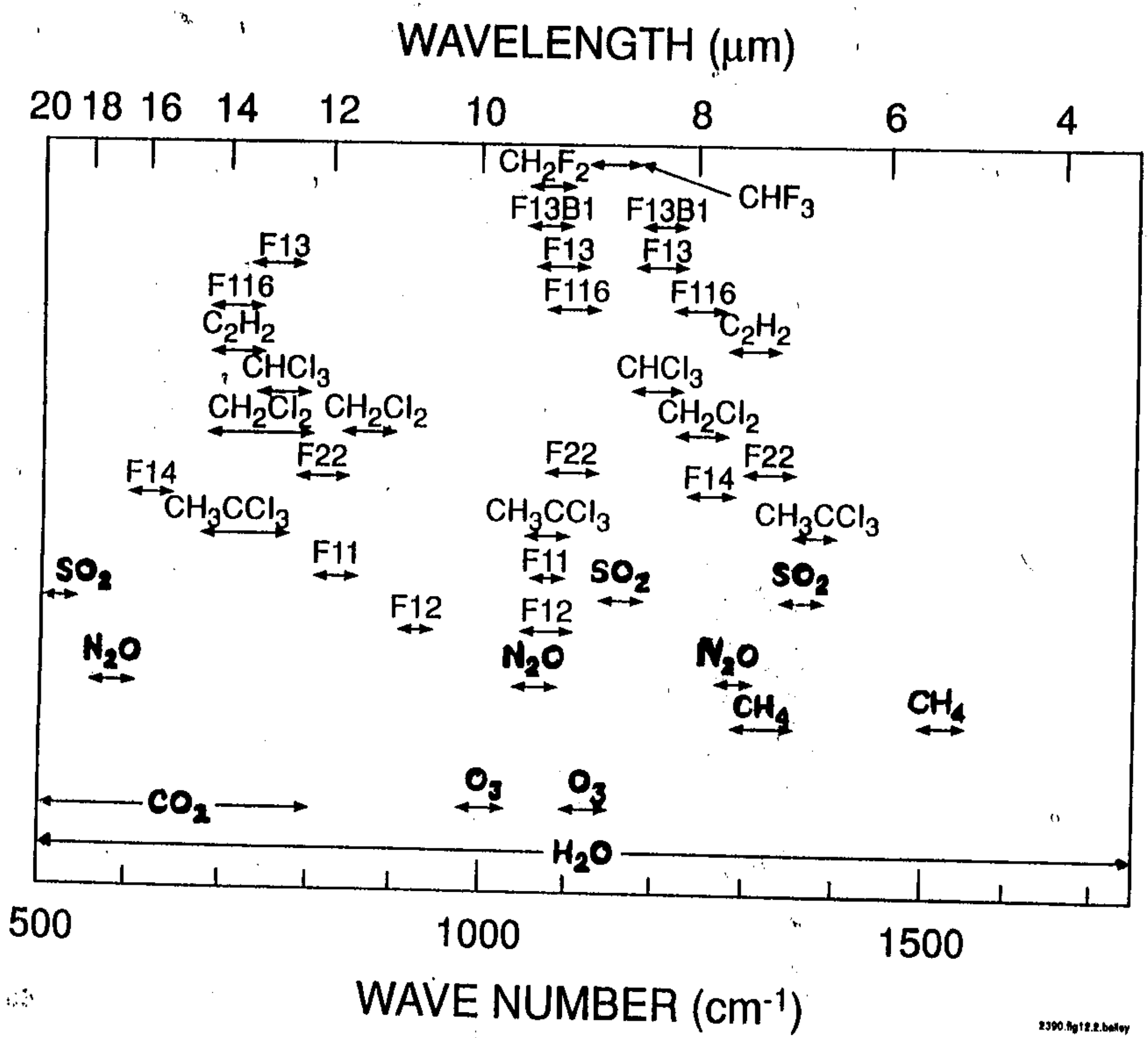
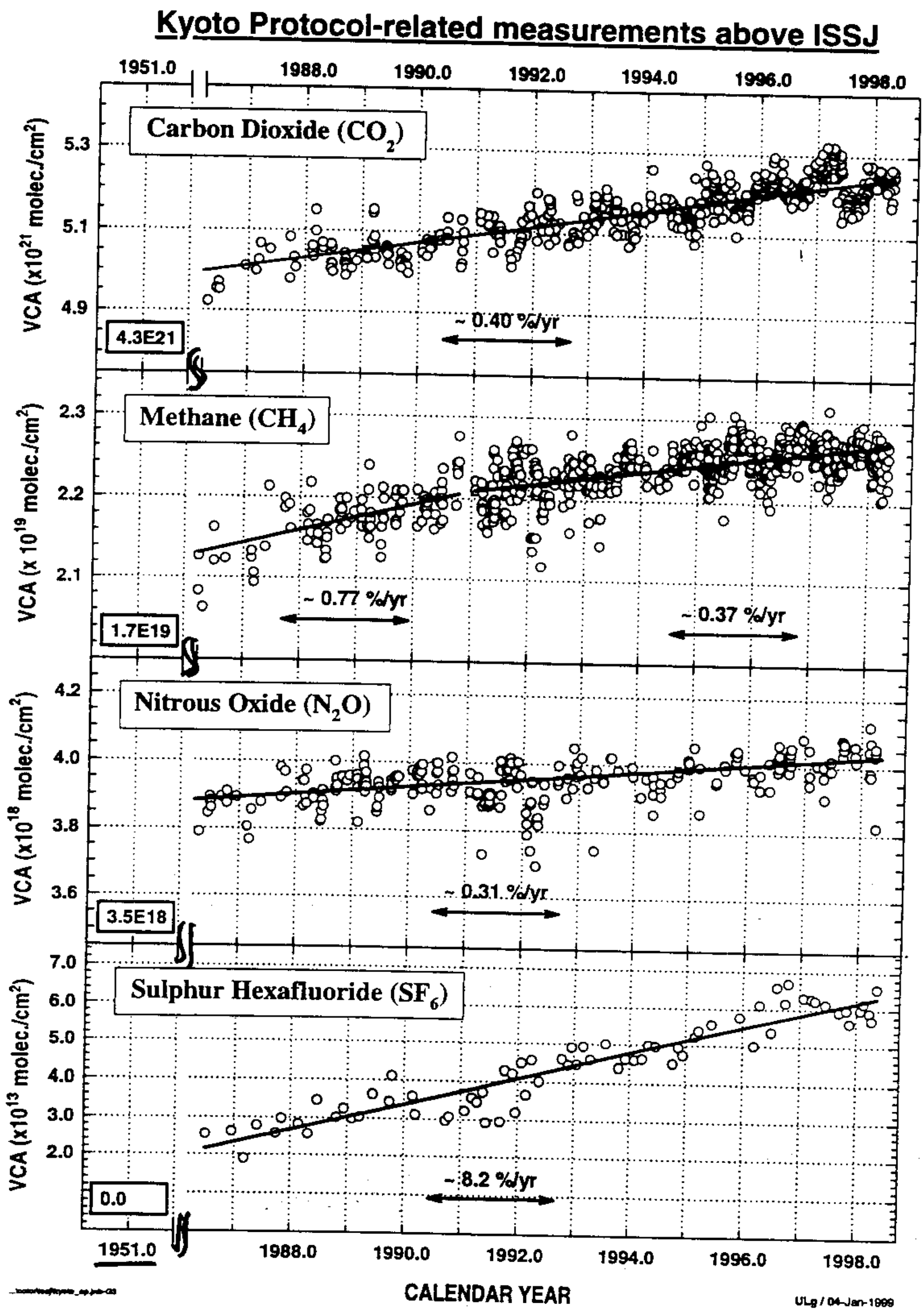


Figure 15.2. *Spectral locations of the absorption features of several atmospheric gases (WMO, 1986).*

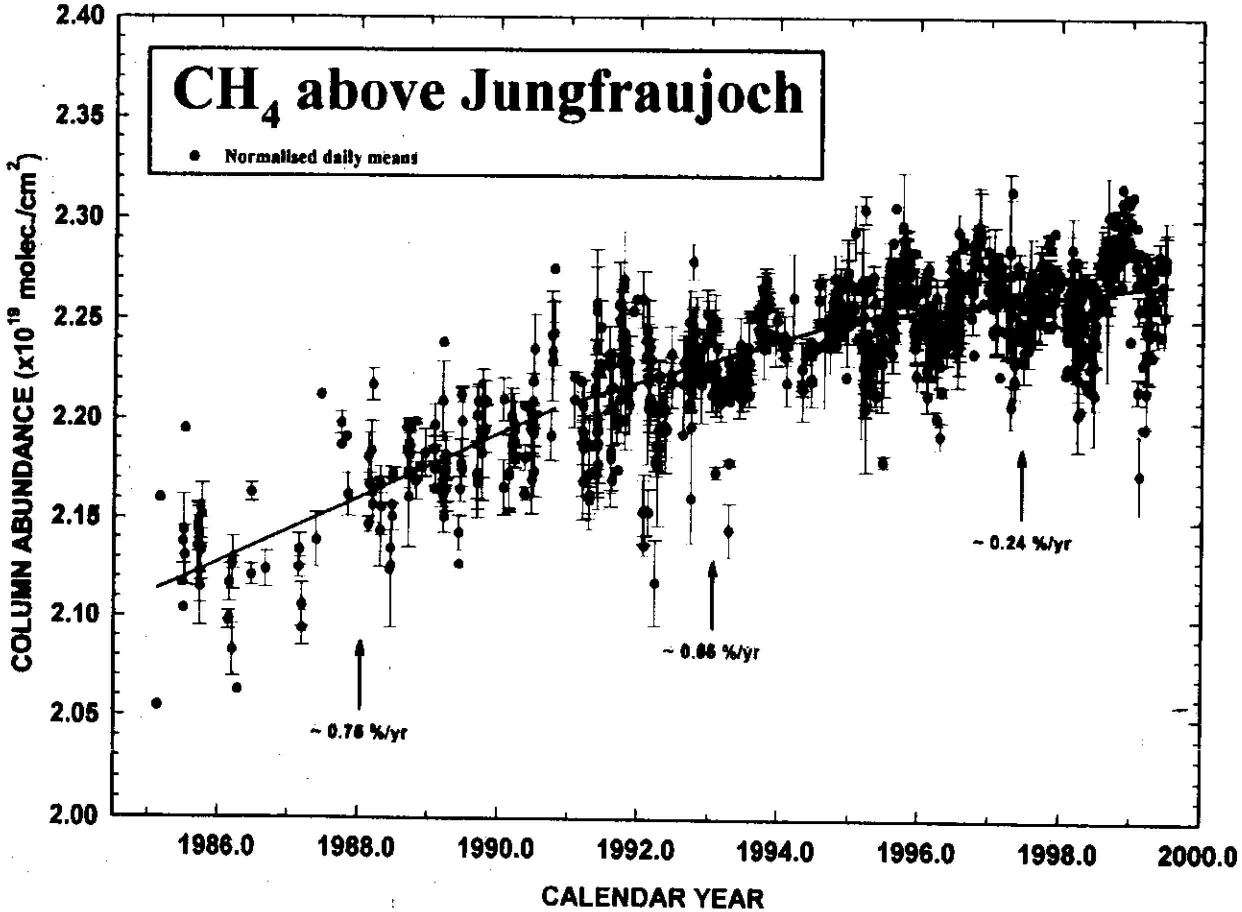
Atmospheric long-term changes:

'Greenhouse gases', climate change (2/5)

- <u>Direct</u> contribution to greenhouse forcing (heat trapping in tropo-, UT/LS region):
  - H_2O: largest forcing but little anthropogenic changes, badly known!
  - CO_2: ± saturated, well-mixed in tropo, well-characterized
  - CH_4: NRRF/mol≈ 25
  - N_2O: NRRF/mol≈ 225, well-mixed in tropo
  - O_3: tropo O_3 increase induces larger + forcing than - forcing from strato O_3 decrease
  - CFC, HCFC, HFC, ..: NRRF/mol ≈ 10000 - 20000
- Approximate contribution to <u>enhanced</u> heat trapping: 60% CO_2, 20% halocarbons, 15% CH_4, 5% N_2O (since mid-1800; IPCC, 1995)



Kyoto Protocol-related measurements above ISSJ
Carbon Dioxide (CO_2)
VCA (x10^{21} molec./cm^2)
4.3E21
~ 0.40 %/yr
Methane (CH_4)
VCA (x 10^{19} molec./cm^2)
1.7E19
~ 0.77 %/yr
~ 0.37 %/yr
Nitrous Oxide (N_2O)
VCA (x10^{18} molec./cm^2)
3.5E18
~ 0.31 %/yr
Sulphur Hexafluoride (SF_6)
VCA (x10^{13} molec./cm^2)
0.0
~ 8.2 %/yr
1951.0
1988.0
1990.0
1992.0
1994.0
1996.0
1998.0
CALENDAR YEAR
ULg / 04-Jan-1999



CH4 above Jungfraujoch
Normalised daily means
~ 0.76 %/yr
~ 0.66 %/yr
~ 0.24 %/yr
COLUMN ABUNDANCE (x10^19 molec./cm^2)
2.40
2.35
2.30
2.25
2.20
2.15
2.10
2.05
2.00
1986.0
1988.0
1990.0
1992.0
1994.0
1996.0
1998.0
2000.0
CALENDAR YEAR

Atmospheric long-term changes:

'Greenhouse gases', climate change (3/5)

- SF_6: actually very small abundance (≈ 1 ppt), but dramatic increase (8%/yr), very long lifetime (> 3000 yrs), NRRF/mol ≈ 25000
- clouds ? Positive or negative forcing ?
- negative radiative forcing impact on surface climate caused by *stratospheric* O_3 decrease & volcanic aerosol increases are smaller than positive forcing caused by increasing GHG (IPCC, 1996)

➢ **Indirect forcing: through coupling with chemical effects**

➢ Radiative cooling effect in the stratosphere ! *But: stratospheric T changes are mainly due to strato-O3 changes.*

» **LARGE UNCERTAINTIES, esp. as to H_2O !**

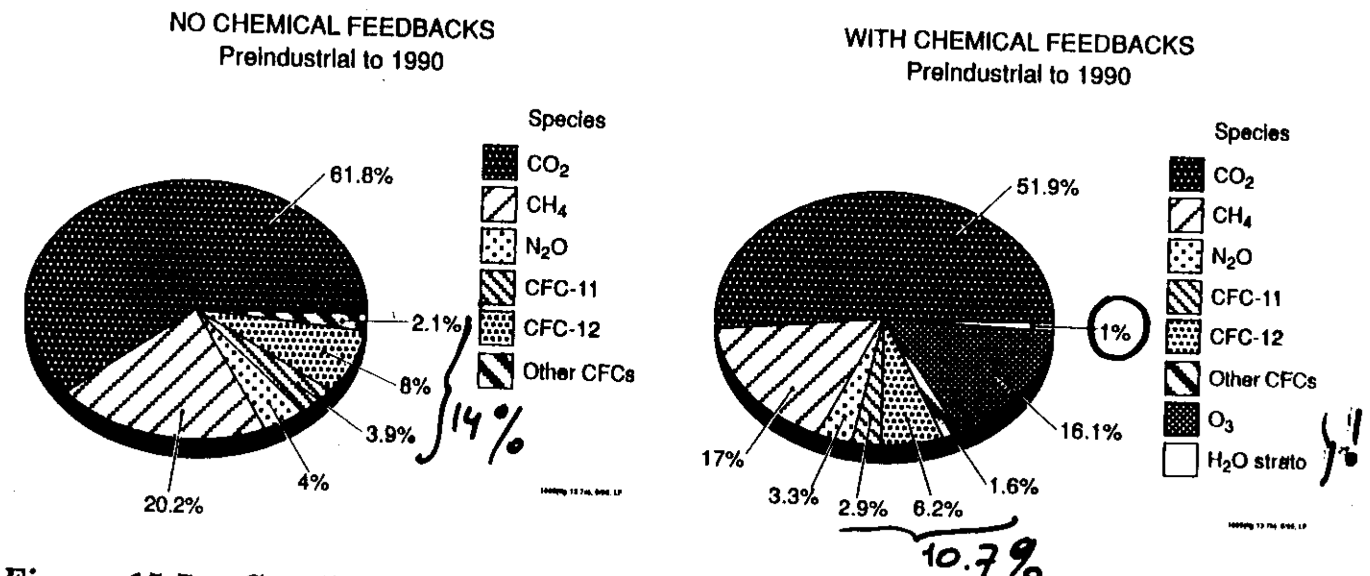


Figure 15.7. *Contribution to the radiative forcing due to increases in greenhouse gas concentrations for the period 1900-1990. Note that these values, especially those including chemical feedbacks, are rather uncertain because of the strong nonlinearities in the coupled chemical and climate systems.*

Atmospheric long-term changes:
'Greenhouse gases', climate change (4/5)

☑ Climate Index (Hansen et al., 1998)

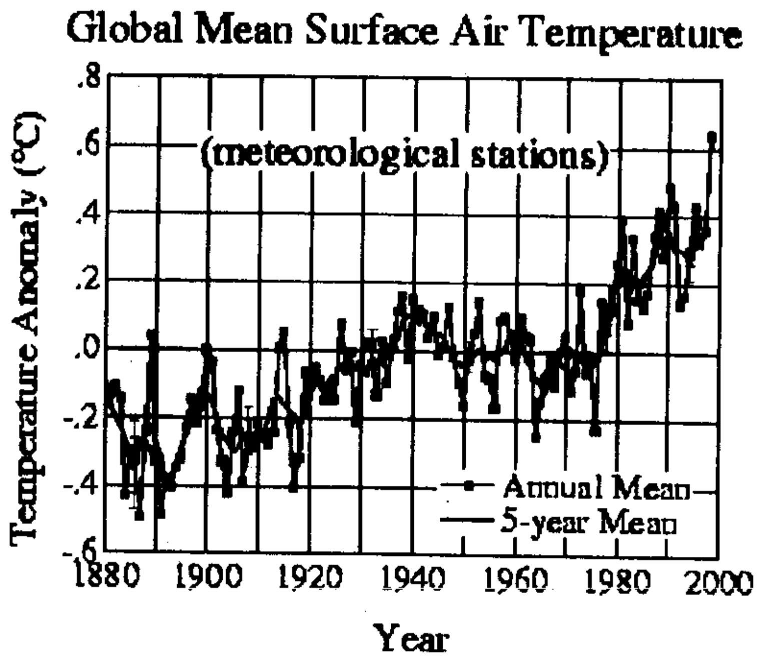
= mean of several climate change indicators, that tend to be noticed by people and have economic significance

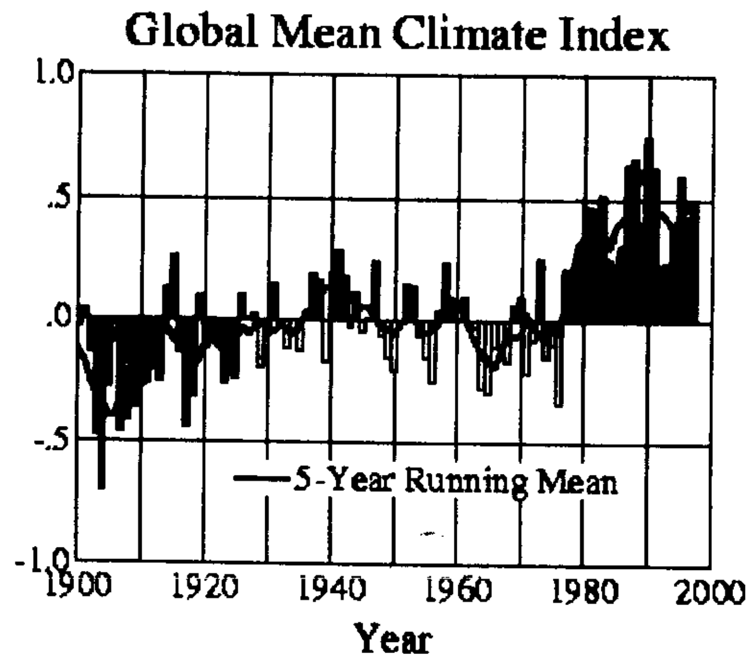
➢ climate change indicators:

- T indicators
  - seasonal mean temperatures (4 seasons)
  - degree days (heating season, cooling season)
  - frequency of extreme temperatures (hot summer days, cold winter days)
  - record daily temperatures (records high, records low)
- moisture indicators
  - precipitation frequency,....

Scale: $\pm 1 \Leftrightarrow \pm 1\ \sigma$ (interannual standard deviation) during 1951-1980

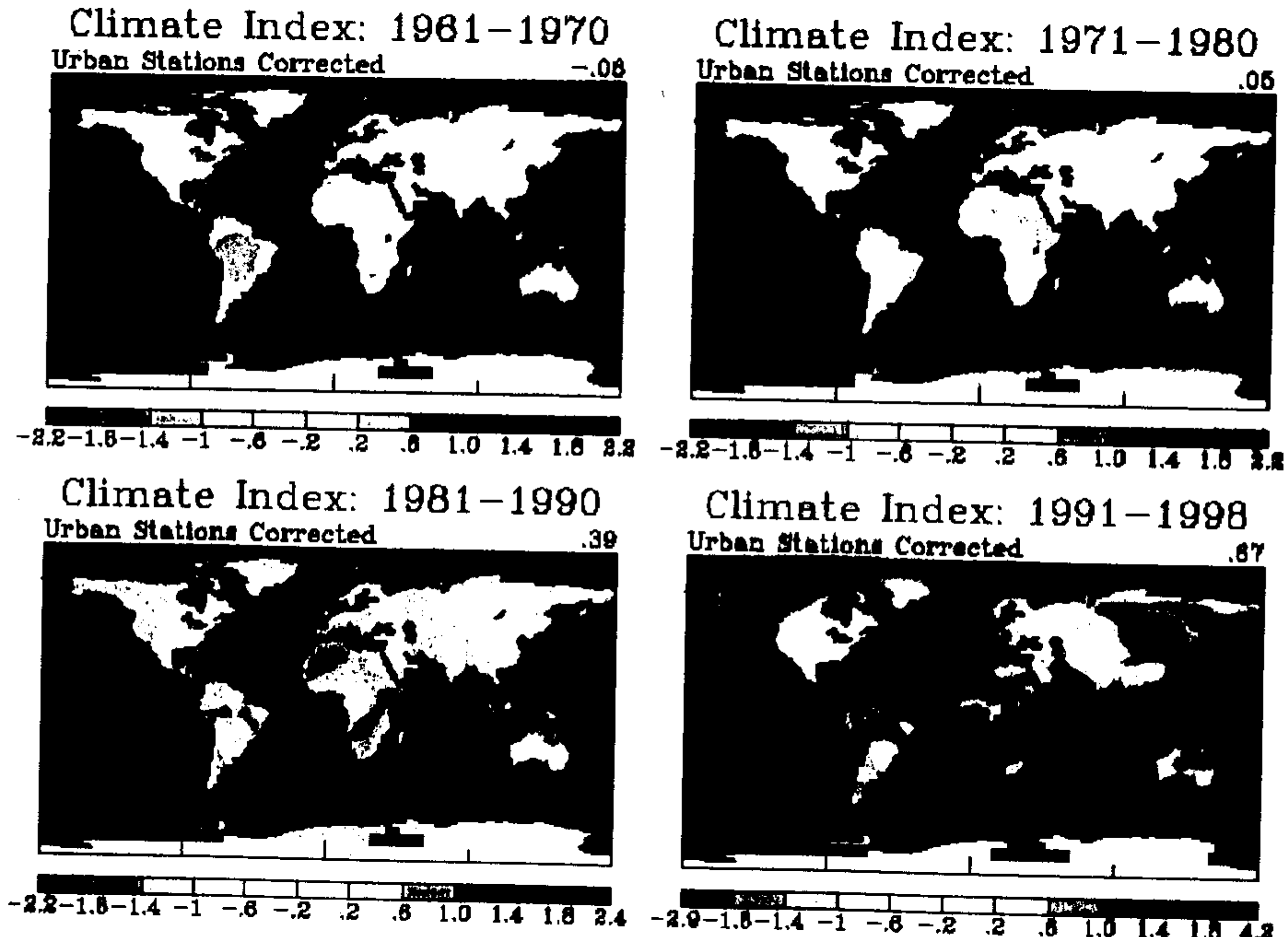
Atmospheric long-term changes:
'Greenhouse gases', climate change (5/5)





Atmospheric long-term changes:

'Greenhouse gases', climate change (5/5)



[redacted]

Year	Policy Process	Scientific Assessment
1981		*The Stratosphere 1981. Theory and Measurements.* WMO No. 11
1985	Vienna Convention	*Atmospheric Ozone 1985*. WMO No.16.
1987	Montreal Protocol	
1988		*International Ozone Trends Panel Report 1988.* Two volumes. MO No. 18
1989		*Scientific Assessment of Stratospheric Ozone: 1989.* Two volumes. WMO No. 20.
1990	London Adjustments and Amendment	
1990		*Climate Change, The IPCC first Scientific Assessment, Impacts Assessment and Response Strategies Reports*
1991		*Scientific Assessment of Ozone Depletion: 1991.* WMO No. 25.

1992 *Methyl Bromide: Its Atmospheric Science, Technology, and Economics* (Assessment Supplement). UNEP (1992).

1992 Copenhagen Adjustments and Amendment

1992 Rio de Janeiro Convention on Climate Change; ~~Kyoto~~ Protocol on Climate Change

IPCC Supplementary Report to the Scientific Assessment

1994 - *Scientific Assessment of Ozone Depletion: 1994.* WMO No. 37

- *Climate Change 1994, Radiative Forcing of Climate Change and an Evaluation of the IPCC IS92 Emission Scenarios*

1995 Vienna Adjustment

1995 *Climate Change 1995, The IPCC second Scientific Assessment, Impacts Assessment .... Reports*

1997 - Montreal Adjustments and Amendment

- Kyoto Protocol (UNFCCC third session, Kyoto, Dec. 1997)

1998 *Scientific Assessment of Ozone Depletion: 1998.* WMO. No. 44

1999 11th Meeting of the Parties (China)

2000 *The IPCC third Scientific Assessment, Impacts Assessment .... Reports*

Total Chlorine loading of the mid latitude stratosphere

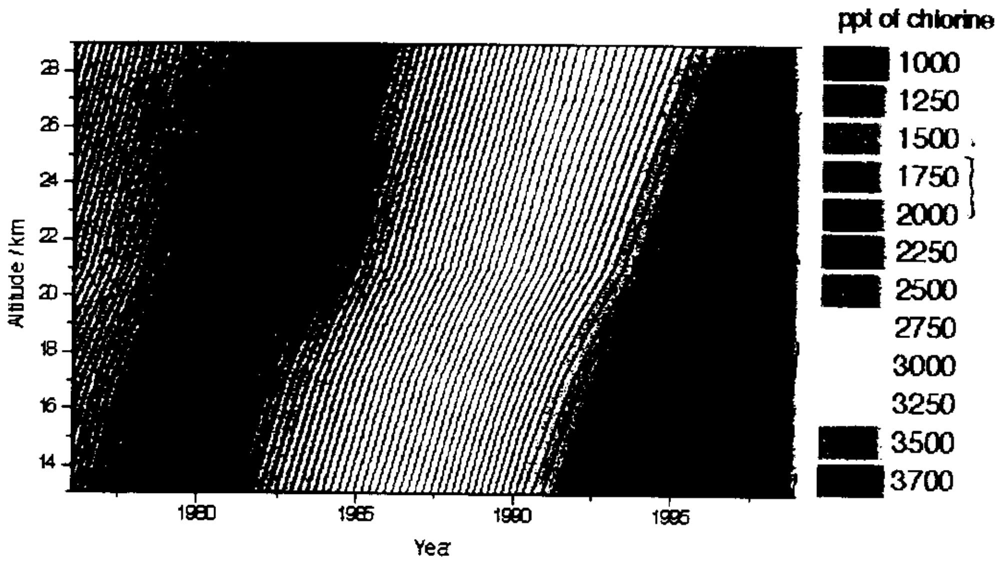


Figure 4. Reconstructed trend of Cl_{total} derived from the tropospheric trend of the mixing ratios of the 7 most important chlorine source gases (see text for detail). The calculation of the vertical propagation is based on the age profile determined from SF_6 measurements

Predicted Total Chlorine loading of the mid latitude stratosphere

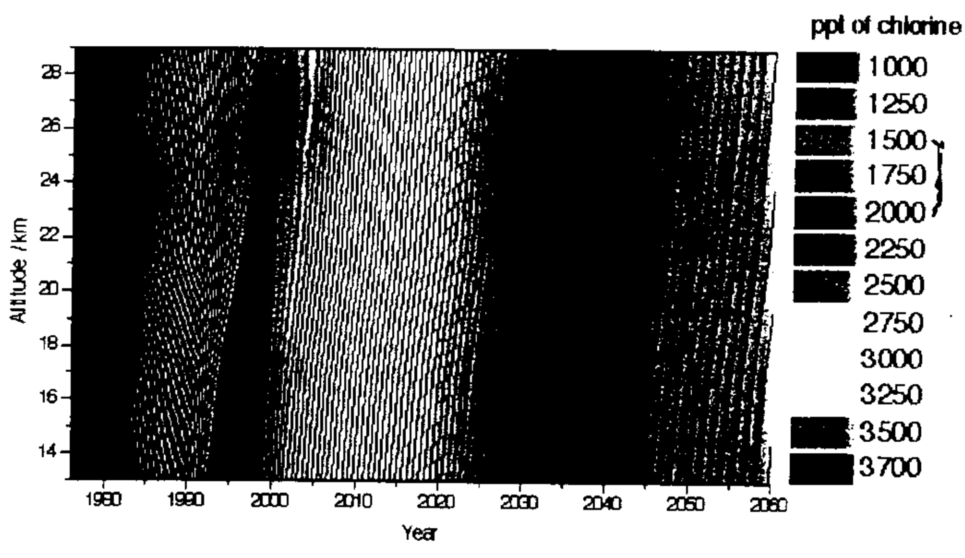


Figure 5. Same as Figure 4 but extended into the future based on the lifetimes of the chlorine compounds and assumptions about future emissions (see text). Pre-ozone hole values are expected to be reached again in about 60 years.

A. Engel and U. Schmidt,

Atmospheric long-term changes:
Ozone (1/2)

☑ The Montreal Protocol is working, + Amendments !

but:

☑ The Ozone layer actually is in its most vulnerable state

- we are approx. at the peak of chlorine (ODS) loading
- the Antarctic O_3 hole is still at its highest level
- Arctic O_3 loss has been observed in most years since 1990
- mid-latitude O_3 changes are not as large as projected by early 1990
- if any volcanic eruption ...?

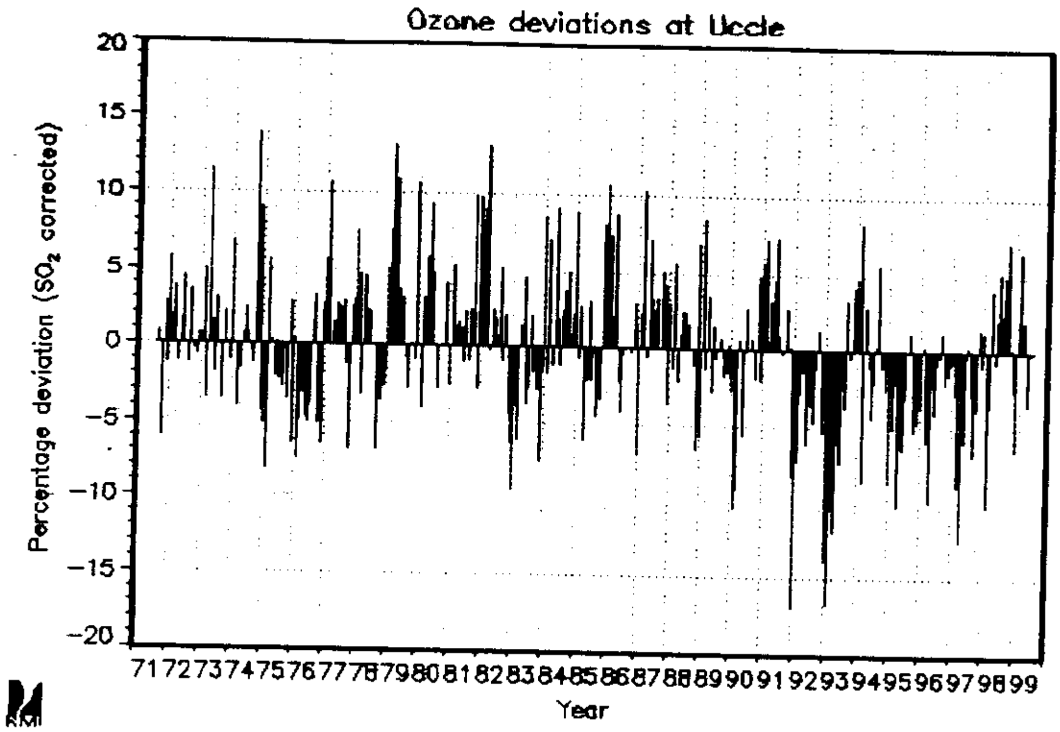
Atmospheric long-term changes:
Ozone (2/2)

- Current O_3 losses, since 1970,
  - about 6% at N midlatitudes in winter/spring
  - about 3% at N midlatitudes in summer/fall
  - about 5% at S midlatitudes all year round
  - about 50% in Antarctic spring
  - about 15% in the Arctic spring
  - none in the tropics

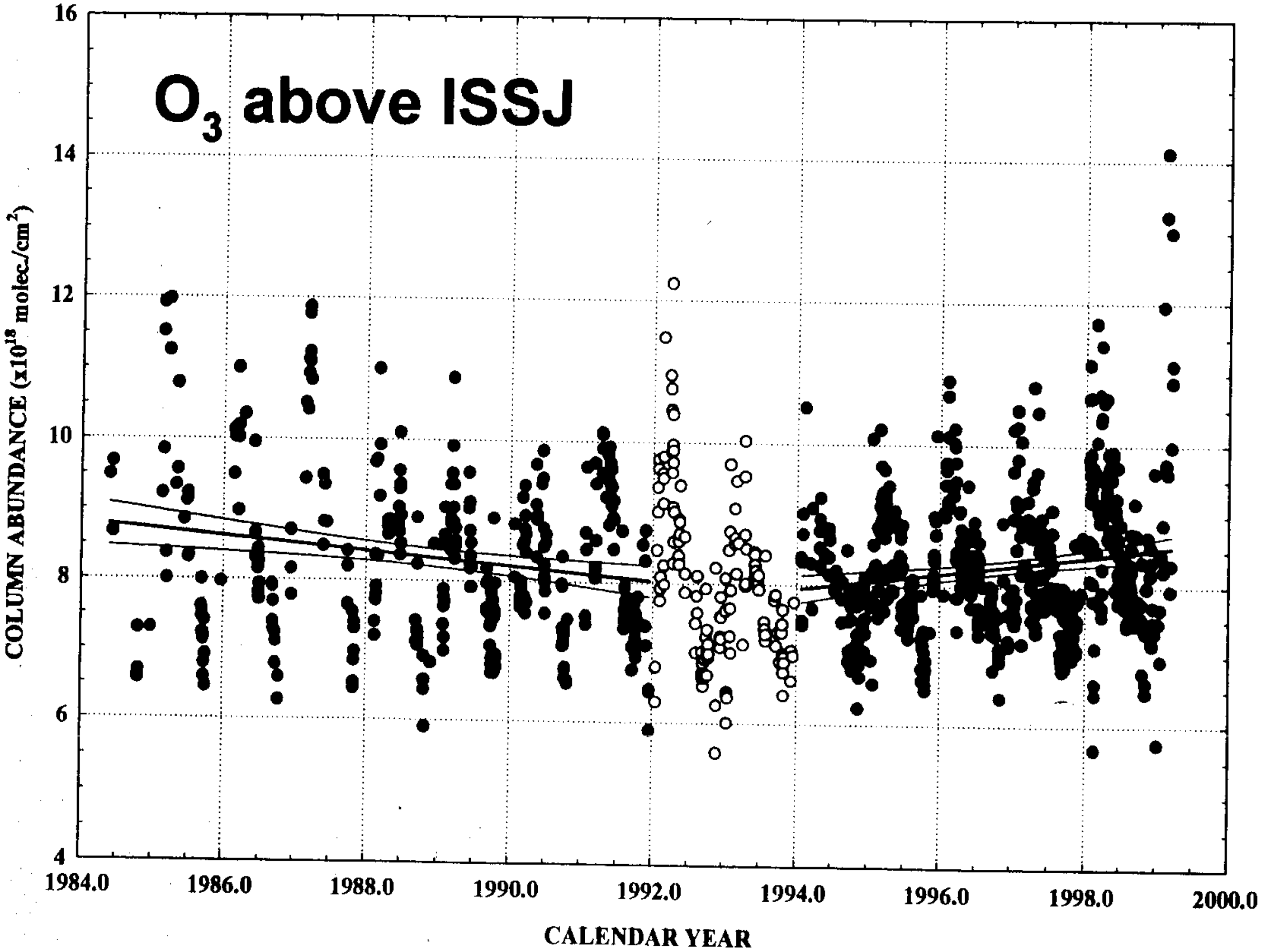
  close to maximum ?

☑ recovery is expected during next decades

- return to pre-industrial levels of chlorine (2 ppbv) are expected by 2050
- but O_3 recovery depends also on other changes: GHG, T, dynamics, etc...



monthly means ; relative to long-term means



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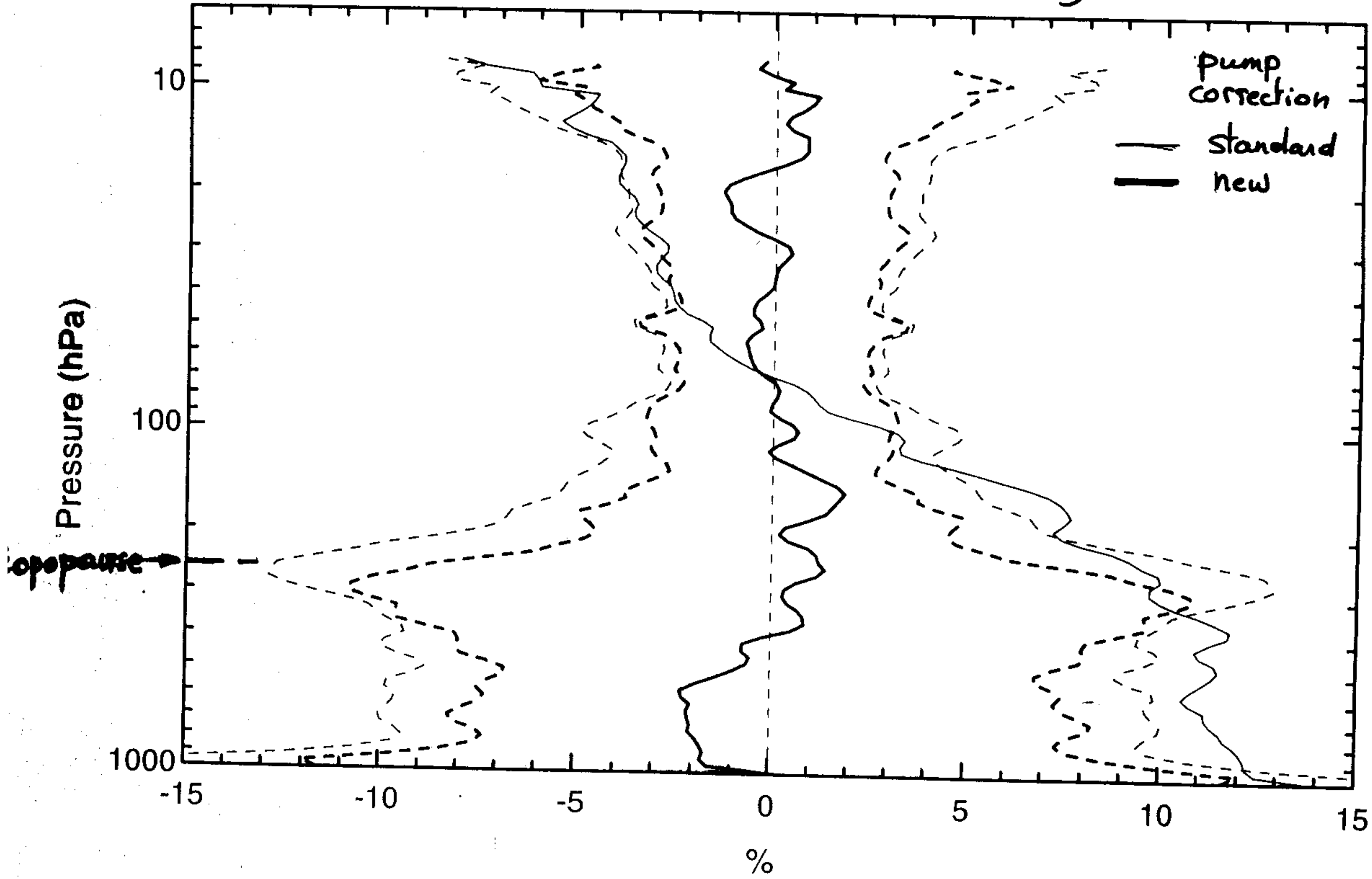
ULg / 03-May-1999

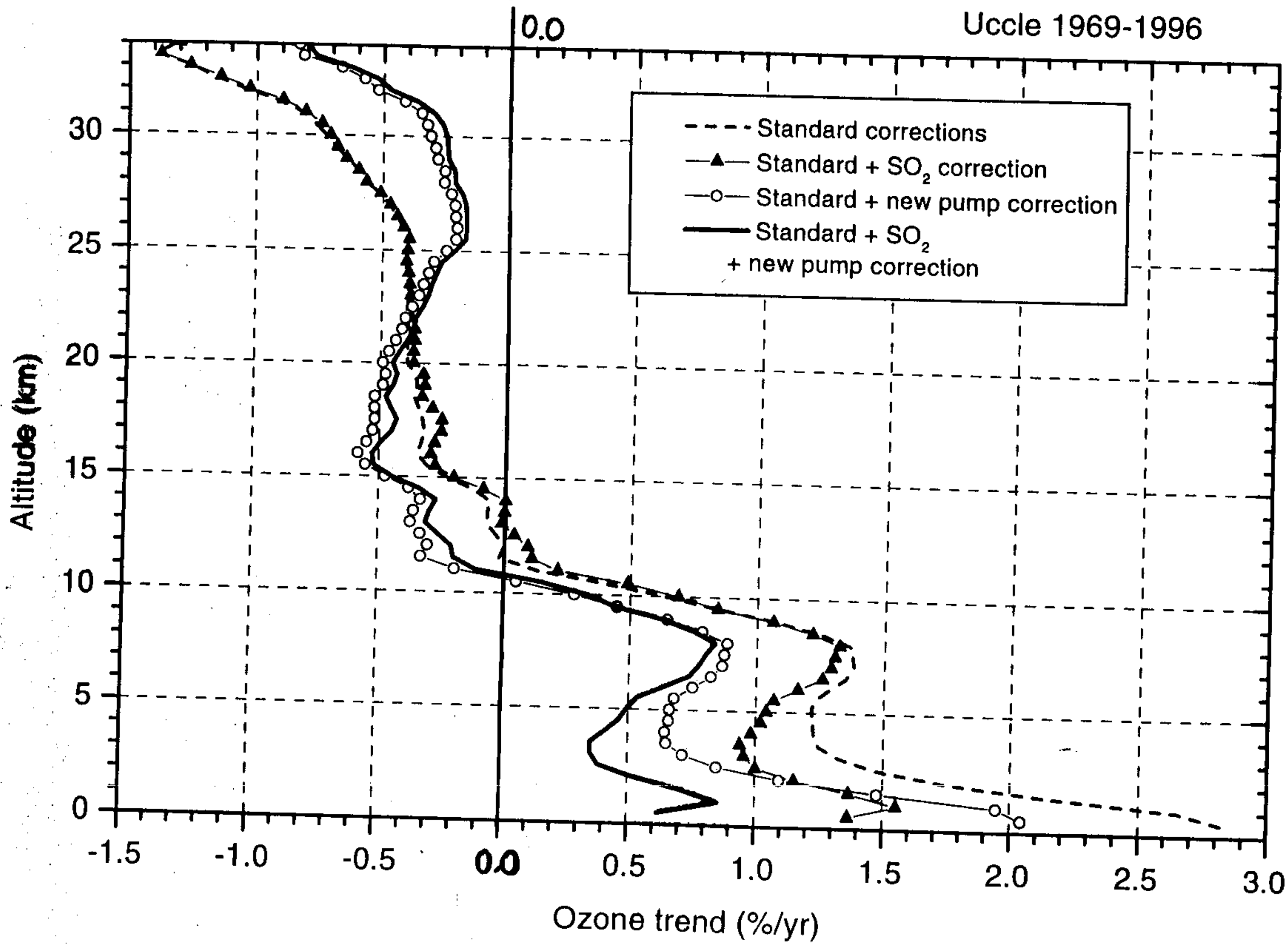
R. Zander et al.

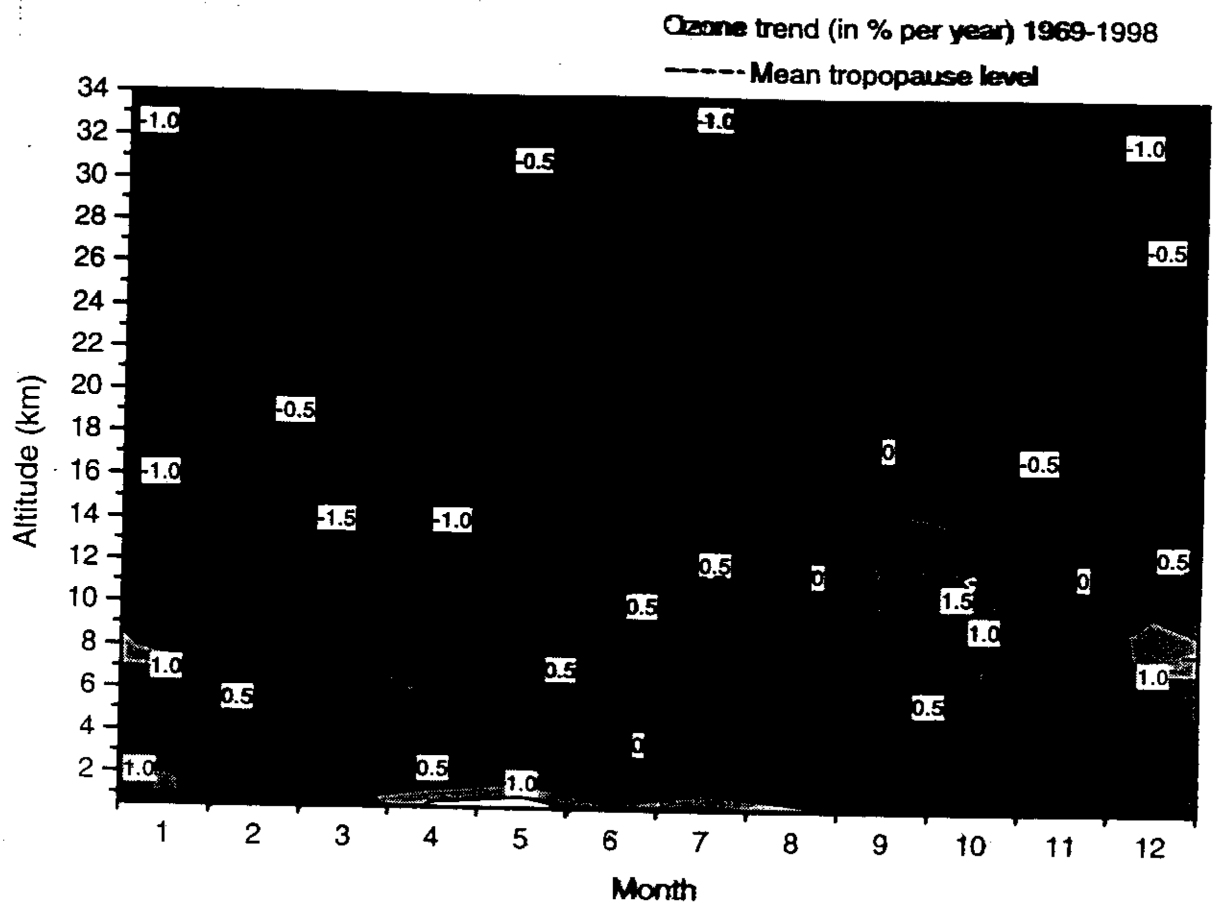
ΔO_3 (Brewer. Mast – 2-ECC sondes)



– Uccle –

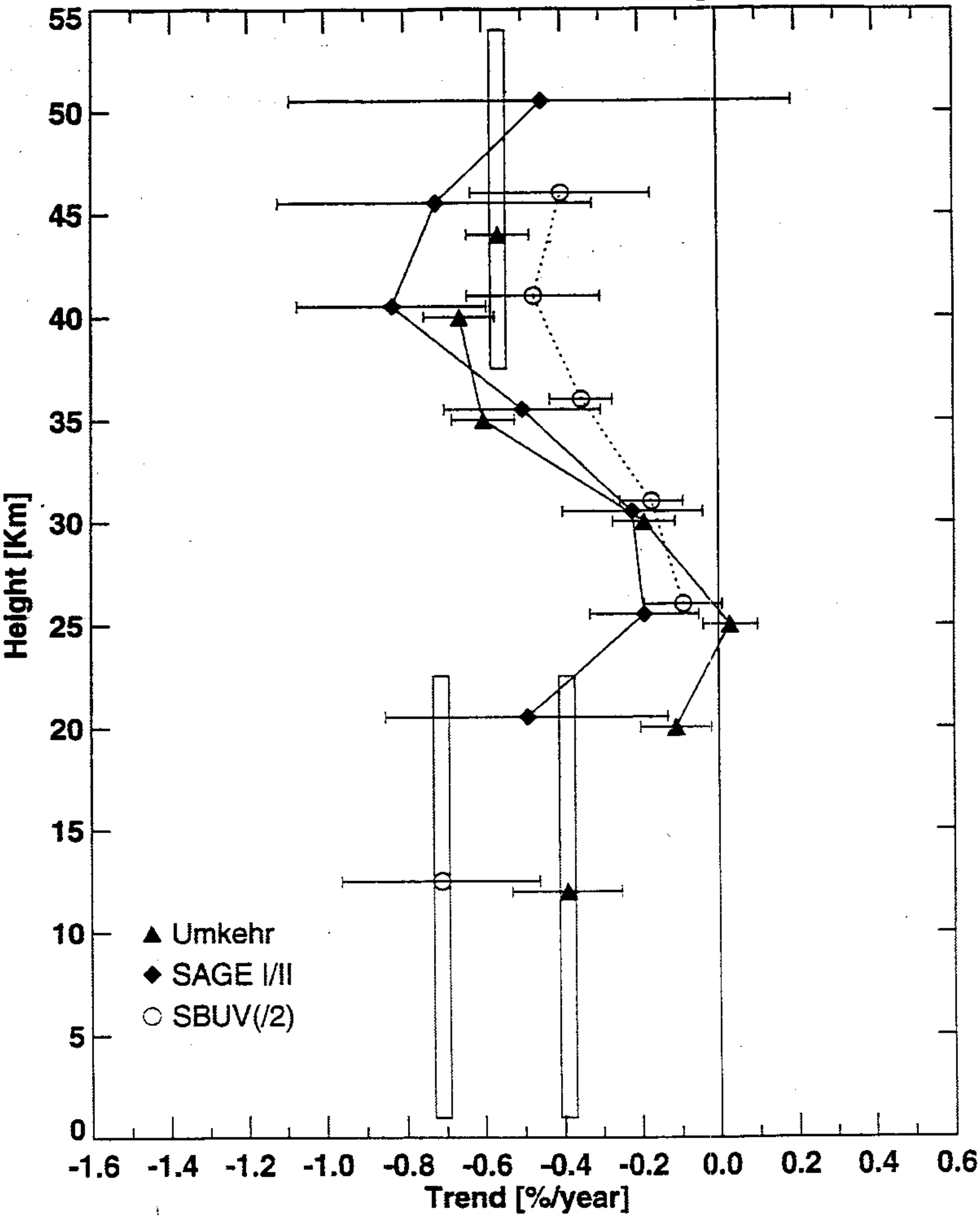
Tropo- + Low Strato-




Ozone trend (in % per year) 1969-1998
Mean tropopause level
Altitude (km)
Month
34
32
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
1
2
3
4
5
6
7
8
9
10
11
12
-1.0
-0.5
-1.0
-1.0
-0.5
-0.5
-1.0
-0.5
-1.5
-1.0
0
0.5
0
0
1.5
1.0
0.5
0.5
0.5
0.5
1.0
1.0
0.5
1.0
1.0
0.5
0

– Uccle –

1979-1996 Annual Trends, 40-50 N [%/Yr +/- 2σ]



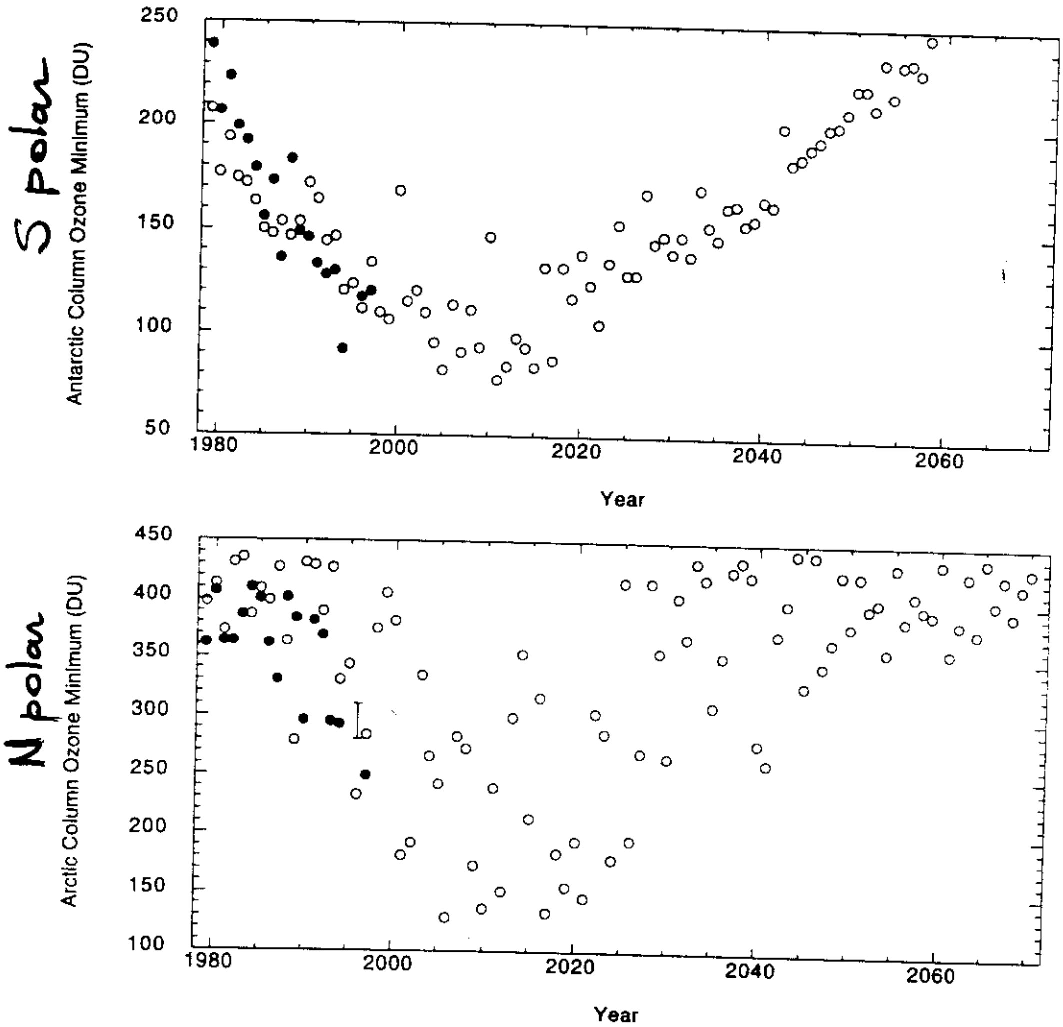
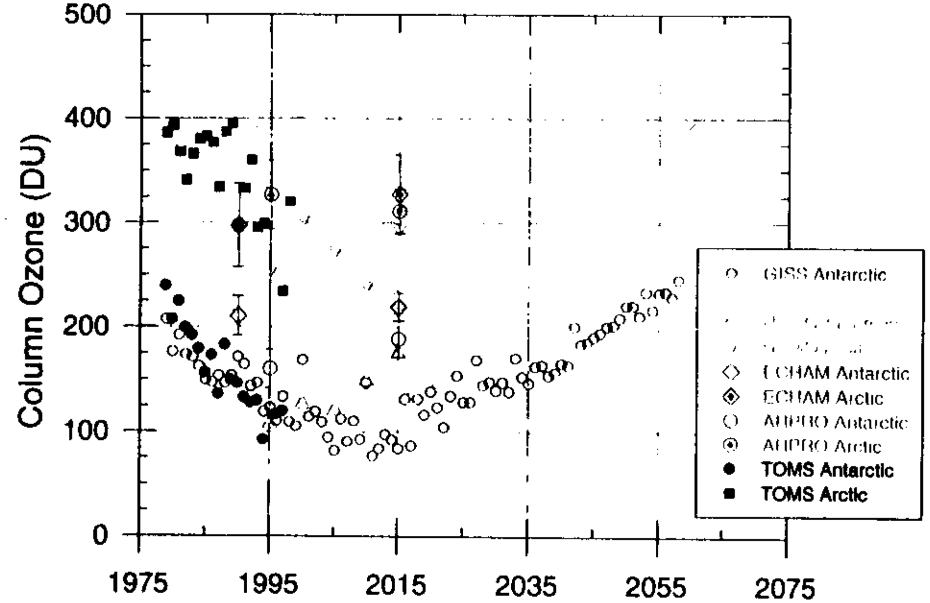

S polar
Antarctic Column Ozone Minimum (DU)
250
200
150
100
50
1980
2000
2020
2040
2060
Year
N polar
Arctic Column Ozone Minimum (DU)
450
400
350
300
250
200
150
100
1980
2000
2020
2040
2060
Year

Figure 4



Column Ozone (DU)
500
400
300
200
100
0
1975
1995
2015
2035
2055
2075
GISS Antarctic
ECHAM Antarctic
ECHAM Arctic
AHPRO Antarctic
AHPRO Arctic
TOMS Antarctic
TOMS Arctic

Ground-based measurements of stratospheric trace gases in the perspective of climate and environment

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