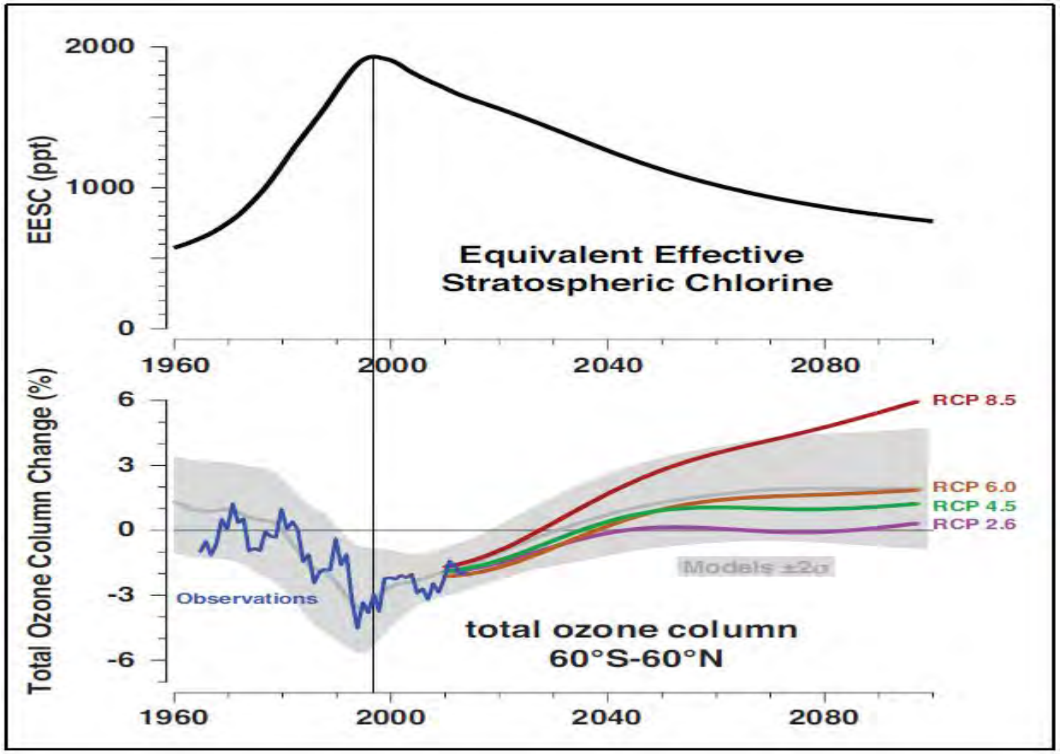
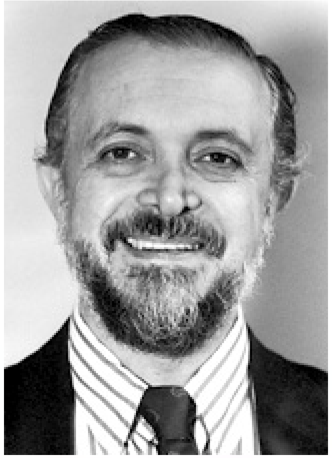
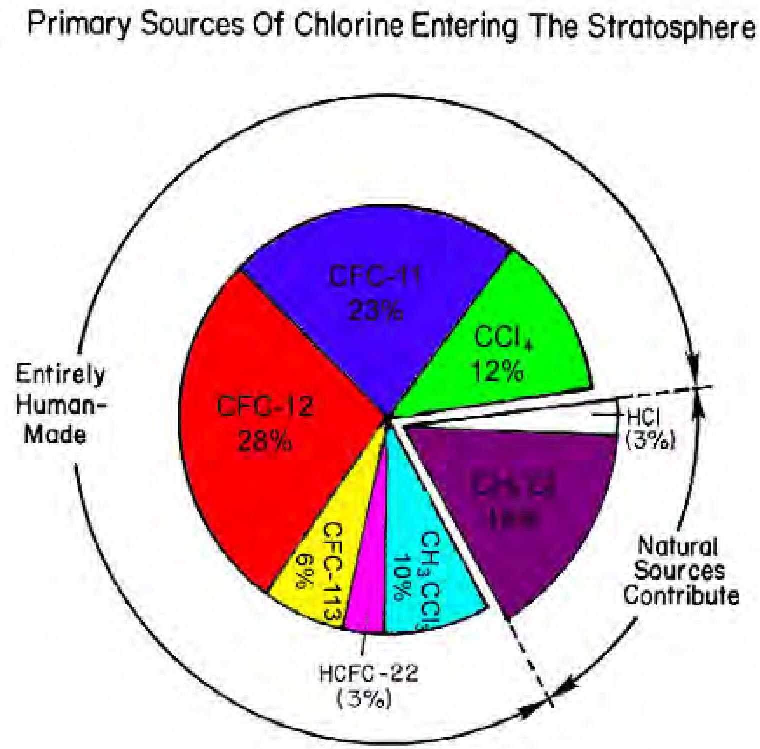


Ozone variability and long-term changes

Michel Van Roozendael, BIRA-IASB

- 1928: start of CFC production
- 1971: 1st observation of CFC in the atmosphere (J. Lovelock)
- 1974: identification of O_3 destruction potential by CFC: Rowland & Molina
- *1995: Nobel prize in chemistry: F. Rowland, M. Molina & P. Crutzen, 1995*

1990: 80% of stratospheric chlorine is of anthropogenic origin

Long term ozone depletion

- Increasing anthropogenic emissions, since industrial revolution, esp. CFCs since 1960
  ↳ increasing concentrations of destructive radicals
  ↳ steady decrease of O_3 on a global scale

- Recurrent spring-time ozone hole at the South pole

- Seasonal ozone depletion in the North pole, strongly modulated by dynamics

Nature, Vol. 315, 16 May 1985

Large losses of total ozone in Antarctica reveal seasonal ClO_x/NO_x interaction

J. C. Farman, B. G. Gardiner & J. D. Shanklin

British Antarctic Survey, Natural Environment Research Council, High Cross, Madingley Road, Cambridge CB3 0ET, UK

the O_3 losses observed.

- First alarming signs of O_3 degradation were given in 1984 and 1985 based on … easurements at … Halley Bay … 7)

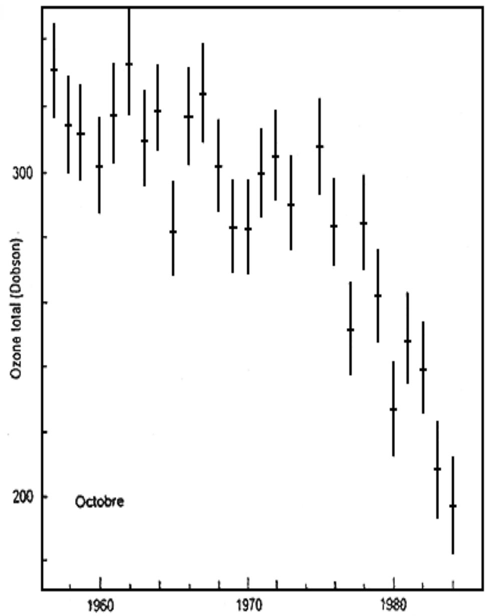
… er thins … lly in the local … vn to ~ 100 DU

… nenon was not

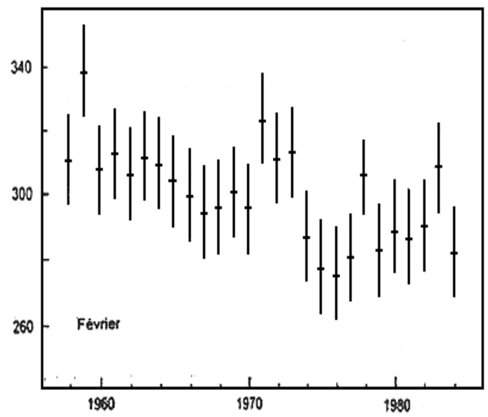
Dr. Shigeru Chubachi at Ozone Commission meeting in Halkidiki (Sept 1984)

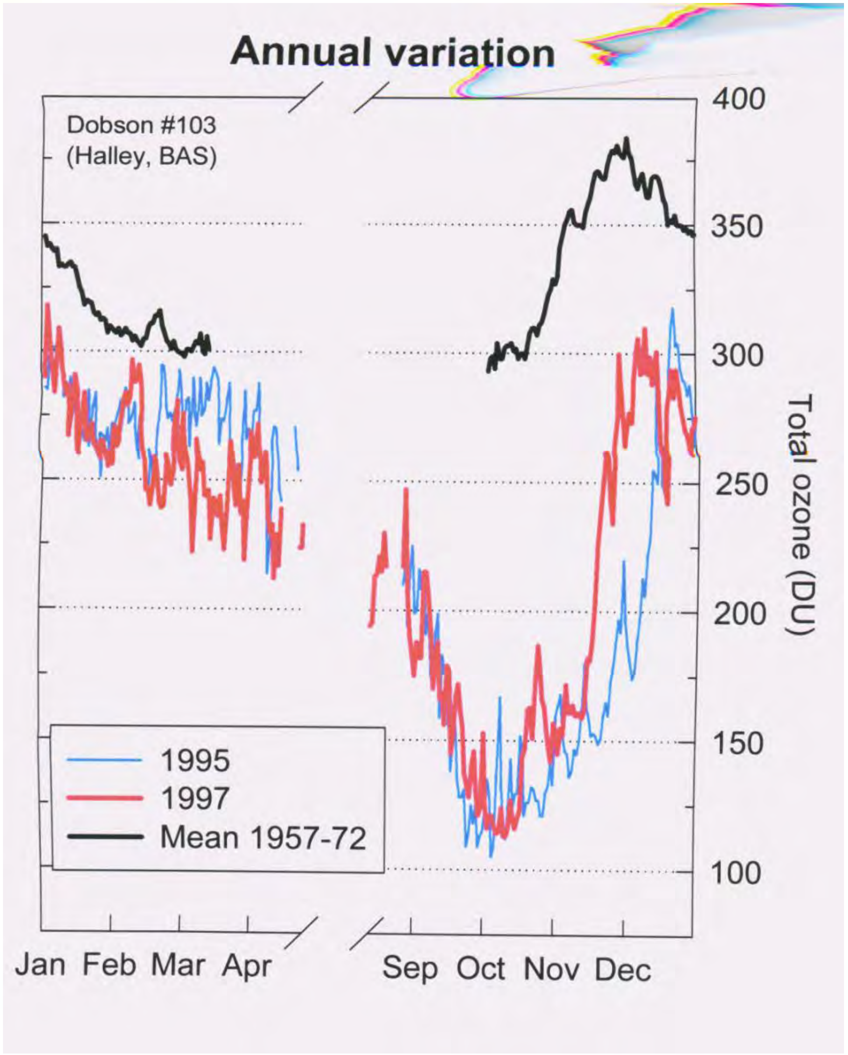
Evolution of average (monthly) O_3 layer thickness between 1956 and 1986

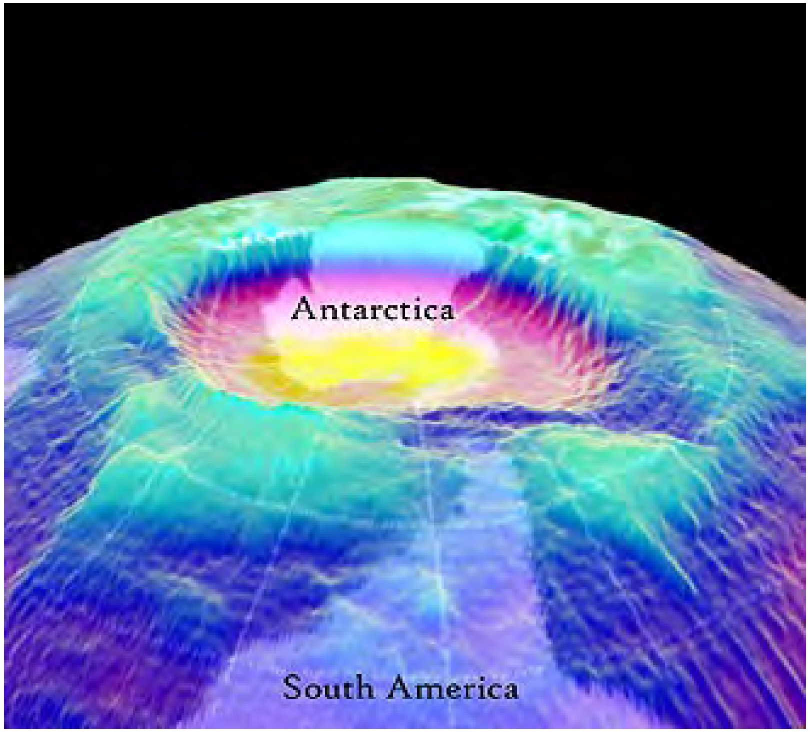
in October



In Februari







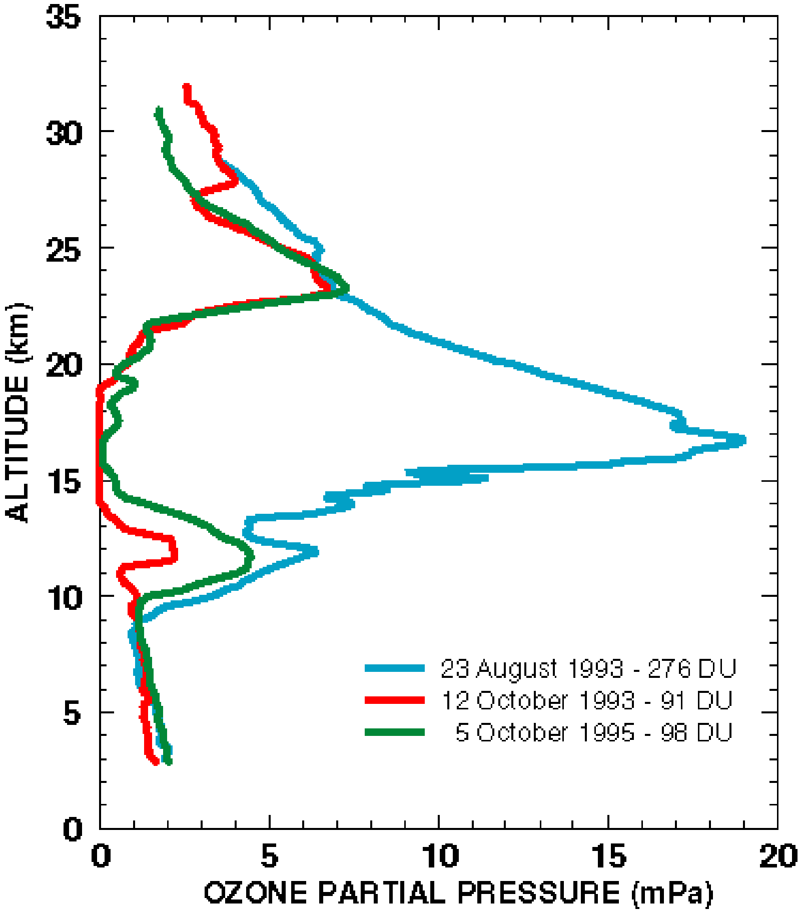
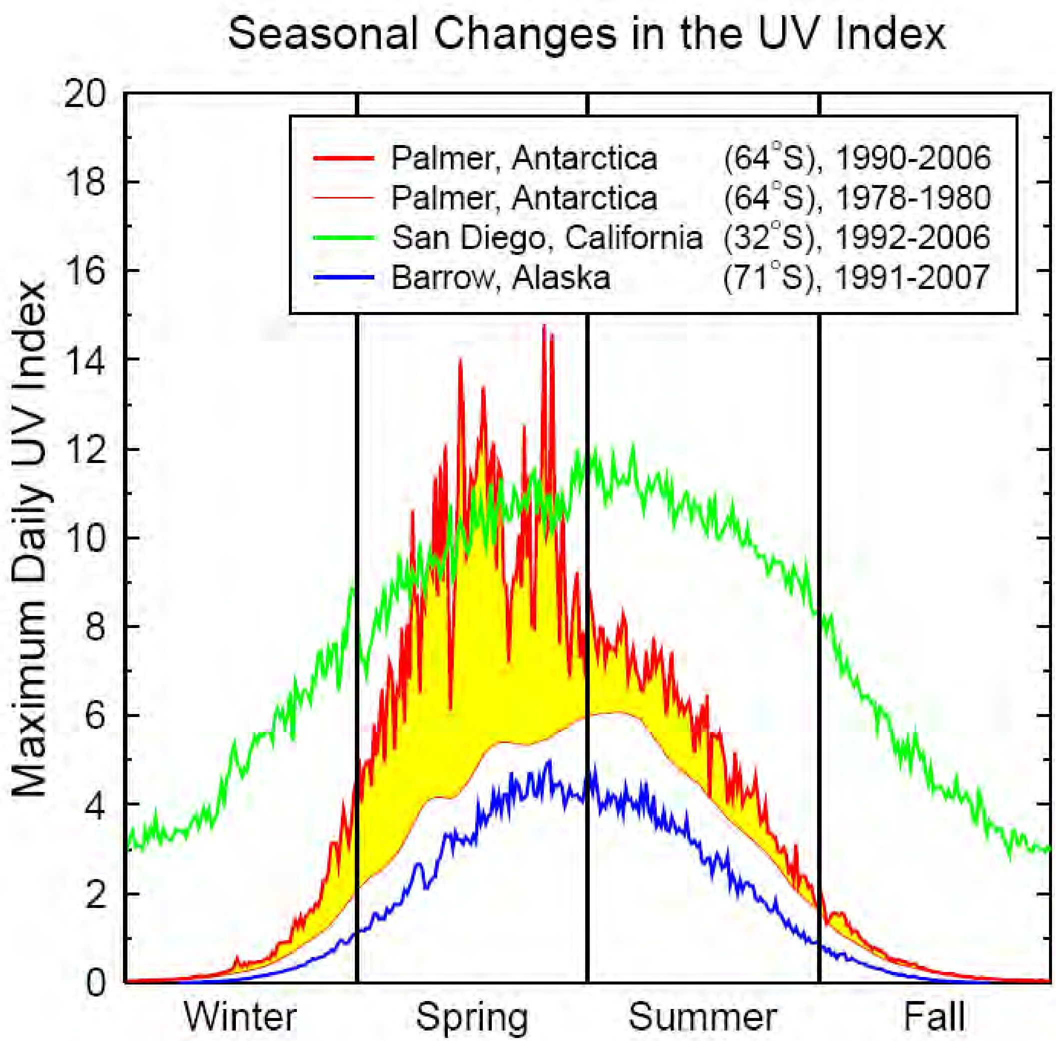


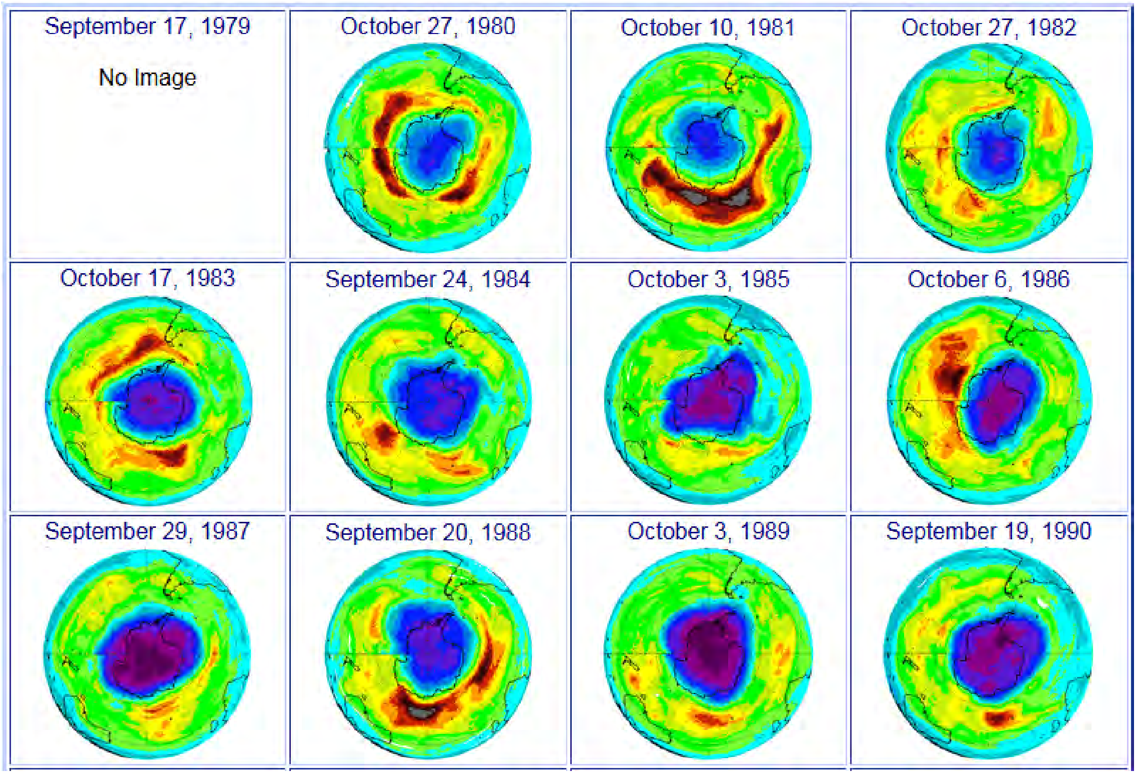
FIG. 16 Ozone profile (partial pressure, mPa) measured by balloon-borne ozonesonde at the South Pole on 5 October 1995 (green line), and comparison to profiles measured in 1993. (Source: CPC)


Seasonal Changes in the UV Index
Maximum Daily UV Index
20
18
16
14
12
10
8
6
4
2
0
Palmer, Antarctica (64°S), 1990-2006
Palmer, Antarctica (64°S), 1978-1980
San Diego, California (32°S), 1992-2006
Barrow, Alaska (71°S), 1991-2007
Winter
Spring
Summer
Fall

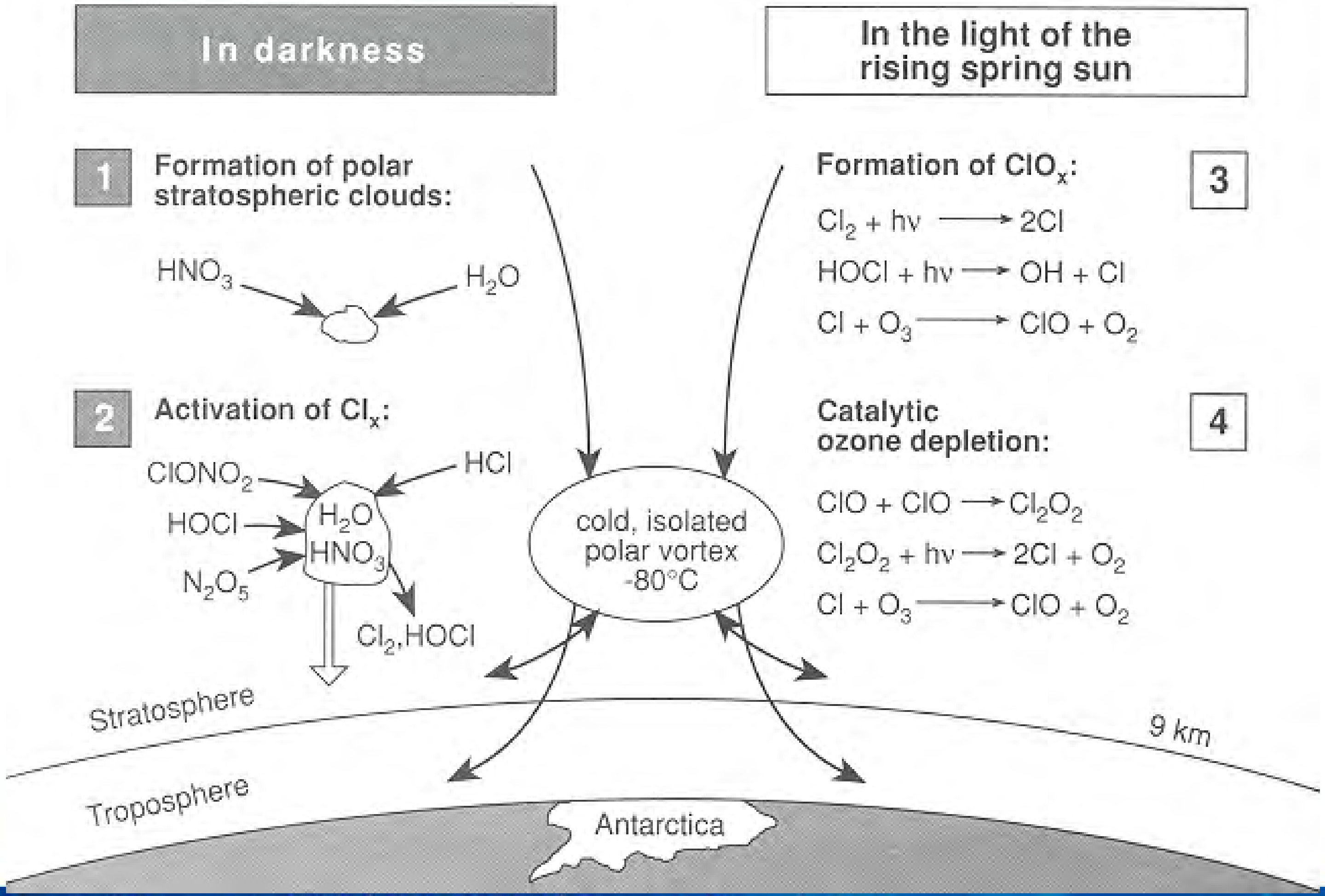
NASA Nimbus 7

When the first TOMS measurements were taken the drop in ozone levels in the stratosphere was so dramatic that at first the scientists thought their instruments were faulty…

TOMS quickly confirmed the results from Farman et al., and the term Antarctic ozone hole entered popular language.



Heterogeneous chemistry on PSCs



Ozone chemistry in polar regions

Main catalytic cycles leading to the formation of the ozone hole

$2\,(Cl + O_3 \rightarrow ClO + O_2)$
$2\,ClO + M \rightarrow Cl_2O_2 + M$
$Cl_2O_2 + h\upsilon \rightarrow Cl + ClOO$
$ClOO + M \rightarrow Cl + O_2 + M$

Net:
$2\,O_3 + h\upsilon \rightarrow 3\,O_2$

- require light !
- require the presence of chlorine and bromine molecules in sufficient amounts

70%

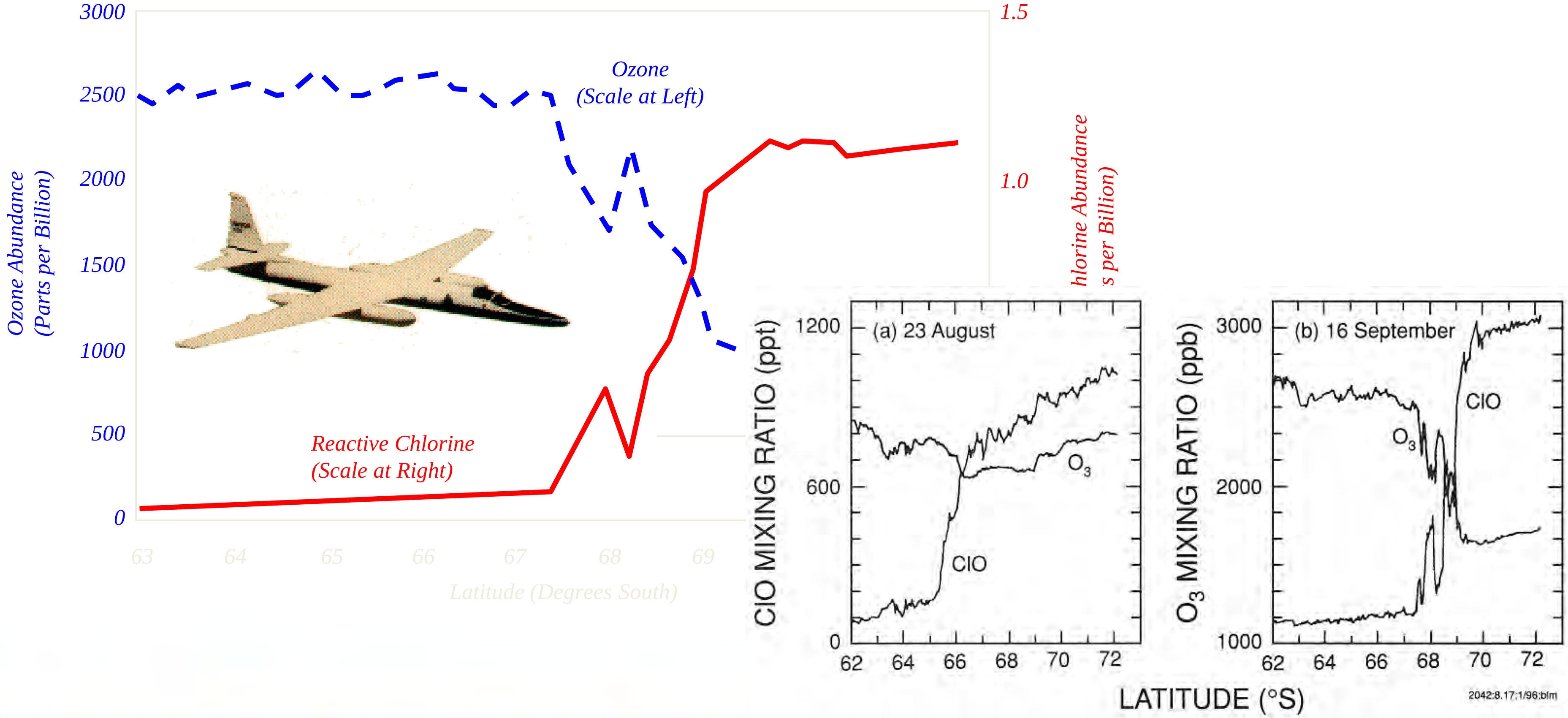
$Br + O_3 \rightarrow BrO + O_2$
$Cl + O_3 \rightarrow ClO + O_2$
$BrO + ClO \rightarrow Br + Cl + O_2$

Net:
$2\,O_3 \rightarrow 3\,O_2$

30%

Experimental evidence

Ozone and reactive chlorine measurements from a flight through the ozone hole in Antarctica, 1987



Examples of ozone depleting source gases (ODS)

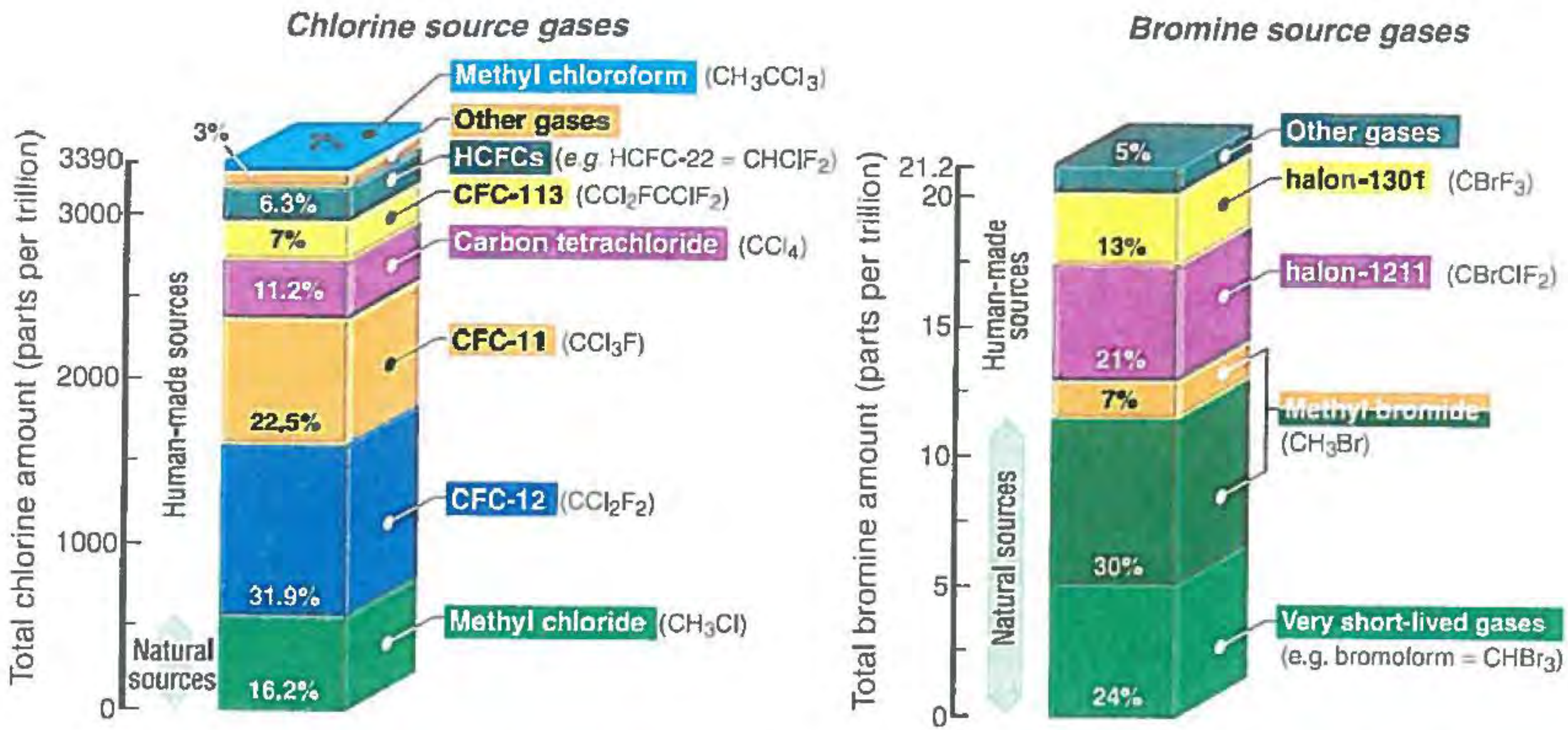


Figure 11.5 Primary sources of chlorine and bromine transported to the stratosphere in 2004. Source: *Scientific Assessment of Ozone Depletion: 2006*. World Meteorological Organization, Global Ozone Research and Monitoring Project. Report No. 50. WMO, 2007.

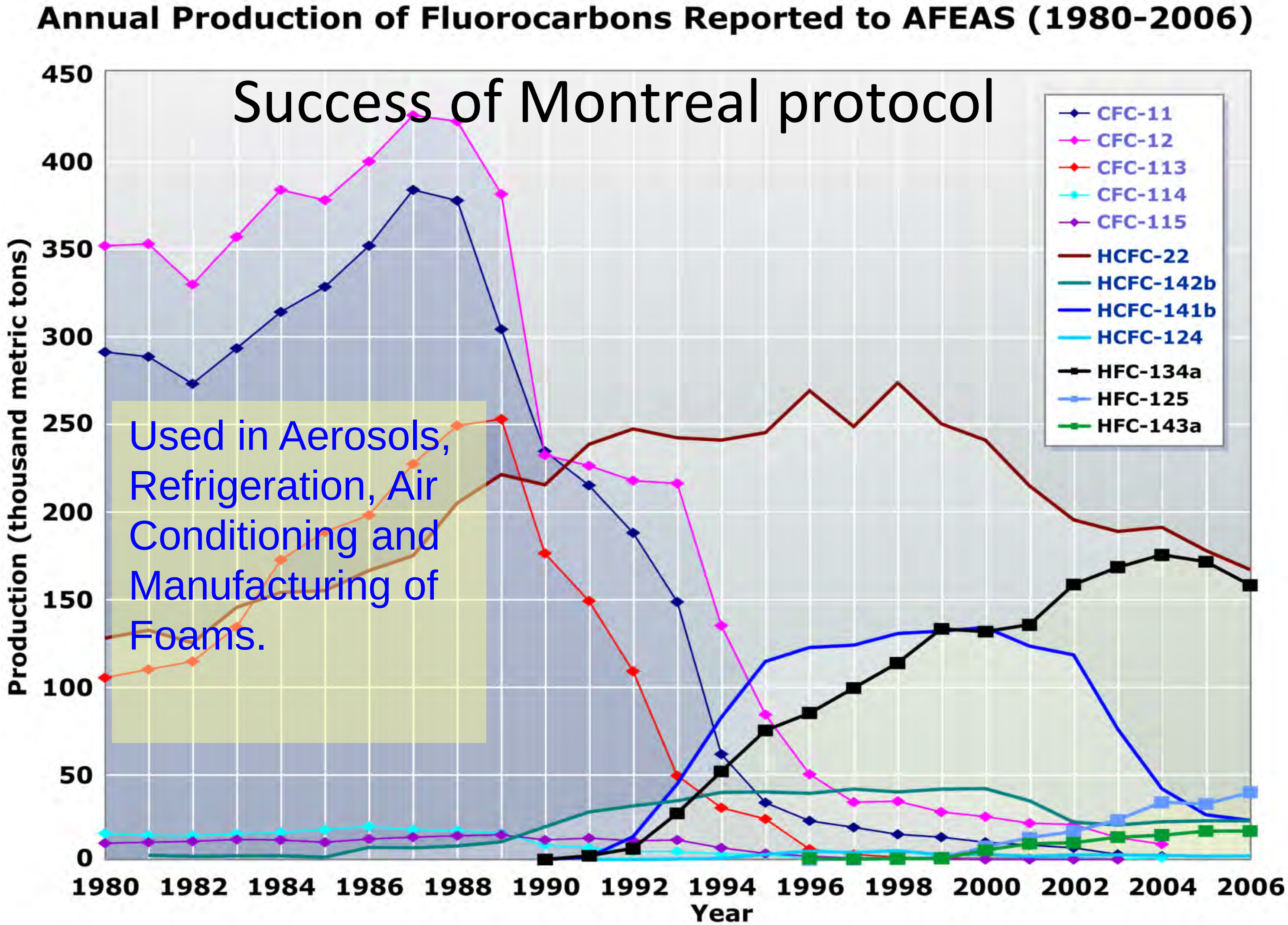
Situation 2004

TABLE 13.3 Atmospheric Lifetimes and Steady-State Ozone Depletion Potentials (ODP) Predicted Using Either a Two-Dimensional Model or a Semiempirical Method[a,b]

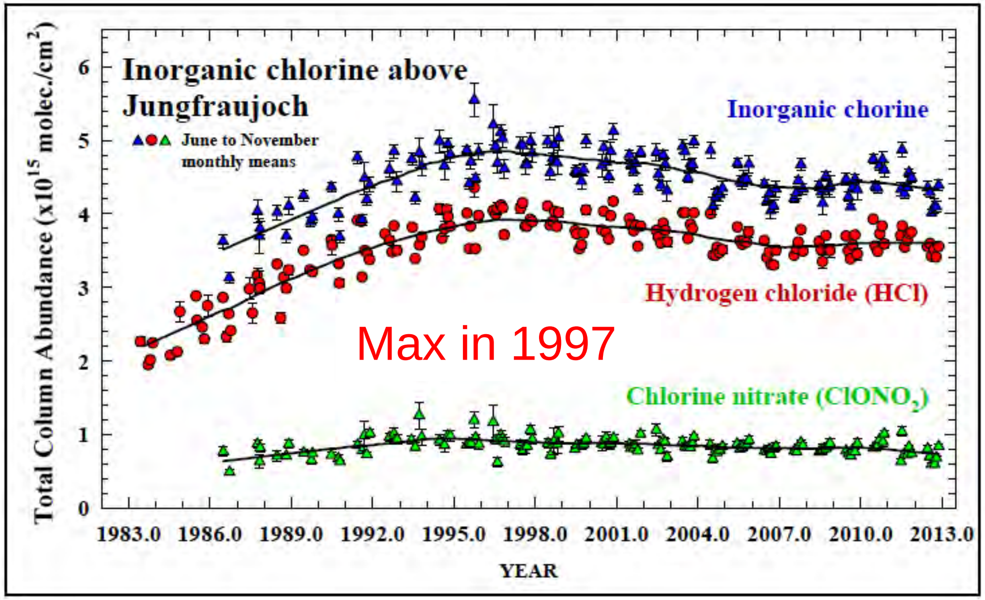
Potential trace gas	Atmospheric lifetime (years)	Steady-state ozone depletion	
		Model	Semiempirical[a]
CFC-11	50	1.0	1.0
CFC-12	102	0.82	0.9
CFC-113	85	0.90	0.9
CH_3CCl_3	5.4	0.12	0.12
HCFC-22	13.3	0.04	0.05
HCFC-123	1.4	0.014	0.02
HCFC-141b	9.4	0.10	0.1
HCFC-142b	19.5	0.05	0.066
HFC-134a	14	$<1.5 \times 10^{-5}$	$<5 \times 10^{-4}$
HFC-125	36	$<3 \times 10^{-5}$	
CH_3Br	1.3 (0.7)[d]	0.64	0.57 (0.39)[d]
H-1301		12	13
H-1211		5.1	5
CH_2ClBr	0.23–0.36[c]	0.098–0.15[c]	
$CH_2BrCH_2CH_3$	0.029[c]	0.026[c]	

Policies Scientific Assessments

	Policies	Scientific Assessments
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. WMO 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	
		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	Beijing (China) Adjustments and Amendment	
2000		*The IPCC third Scientific Assessment, Impacts Assessment …. Reports*
2002		*Scientific Assessment of Ozone Depletion: 2002.* WMO. No. 47
2007		Scientific Assessment of Ozone Depletion: 2006. WMO. No. 50
2007		*The IPCC fourth Assessment Report: Climate Change 2007*
2007	Montreal 19th meeting	of the Parties: *191 countries agree to strengthen protection of the ozone layer by reducing HCFCs*
2008	Doha 20th meeting of	the Parties: Decision making on destruction ODS and funding phase-out HCFCs
2011		***Scientific Assessment of ozone depletion: 2010. WMO No. 52***
2013		***The IPCC 5th assessment report***
2014		***Scientific Assessment of ozone depletion: 2014. WMO No. 55***


Annual Production of Fluorocarbons Reported to AFEAS (1980-2006)
Success of Montreal protocol
Used in Aerosols, Refrigeration, Air Conditioning and Manufacturing of Foams.
Production (thousand metric tons)
Year
CFC-11
CFC-12
CFC-113
CFC-114
CFC-115
HCFC-22
HCFC-142b
HCFC-141b
HCFC-124
HFC-134a
HFC-125
HFC-143a

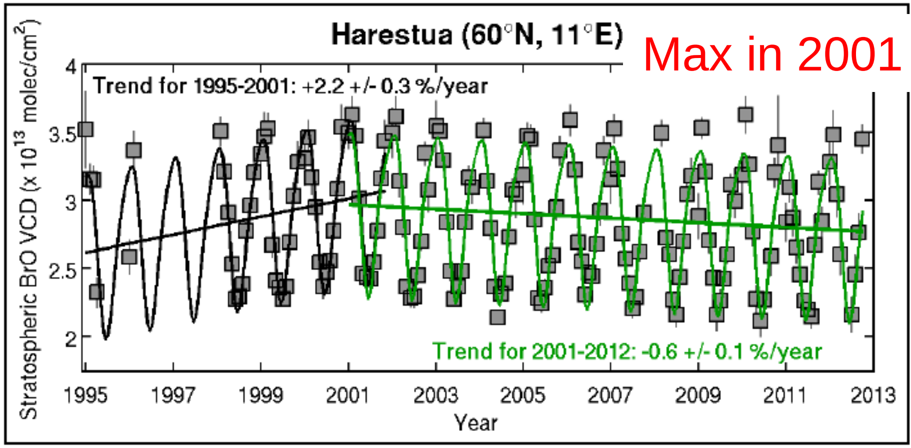
Effect of Montreal Protocol



fits were applied to these data sets (black curves) to provide trends estimates.
E. Mahieu, U. Liège

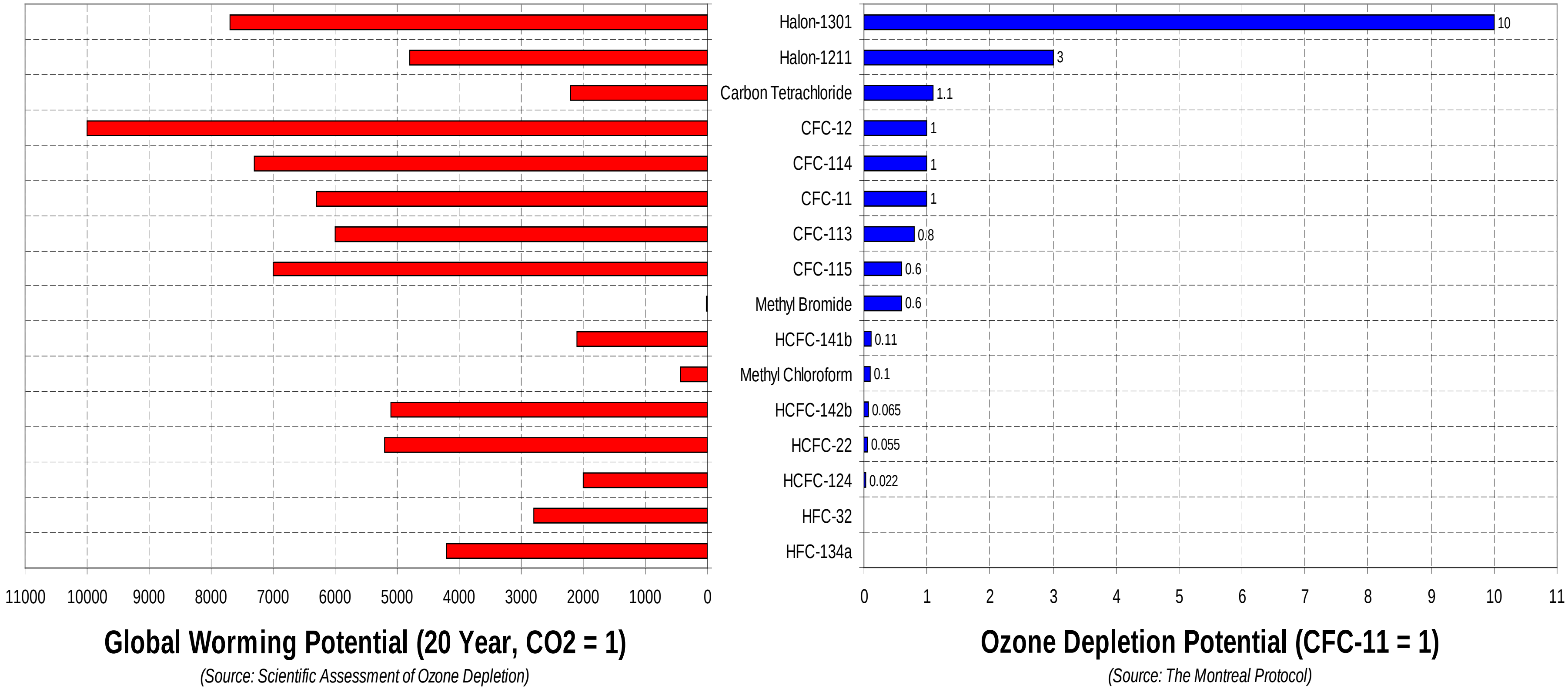
Reduction of chlorine and bromine in the stratosphere follows decrease of concentrations of the surface with a delay of 3 to 5 years

= time to reach from troposphere stratosphere.



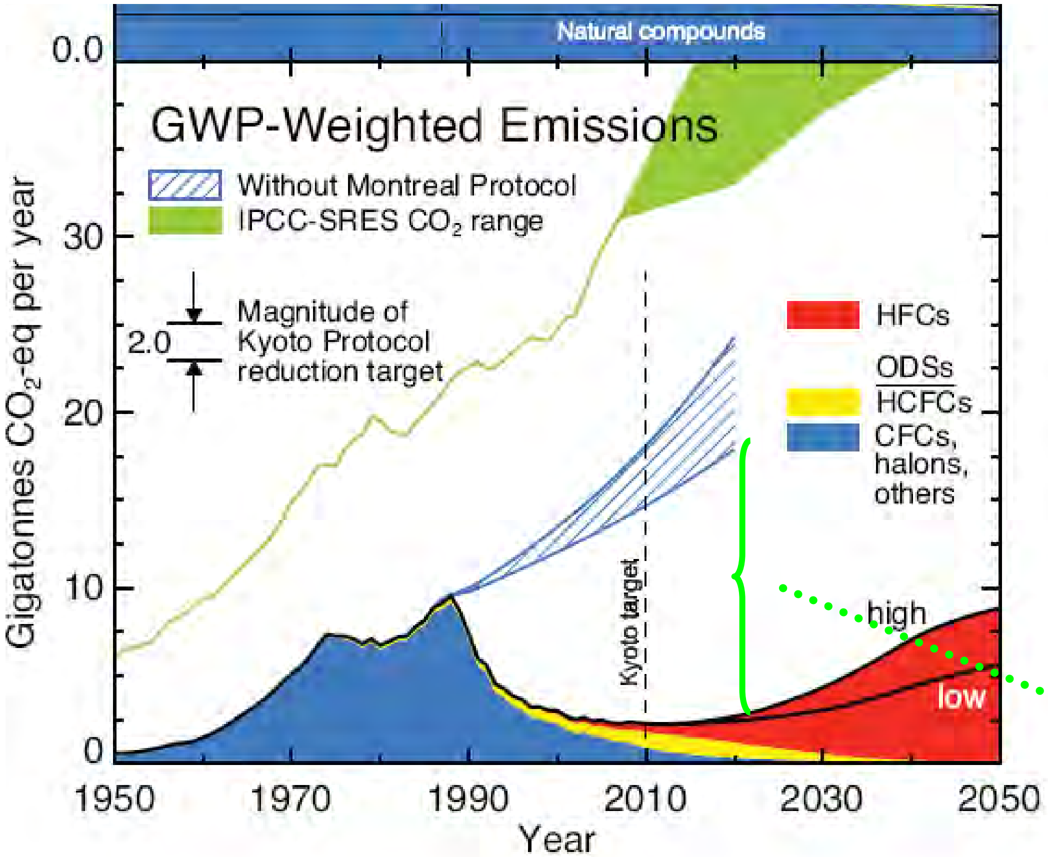
F. Hendrick, IASB

Most ODS are also greenhouse gases!



- Montreal Protocol has been beneficial for our climate
- Challenge: search for CFC substitutes that have a negligible GWP !

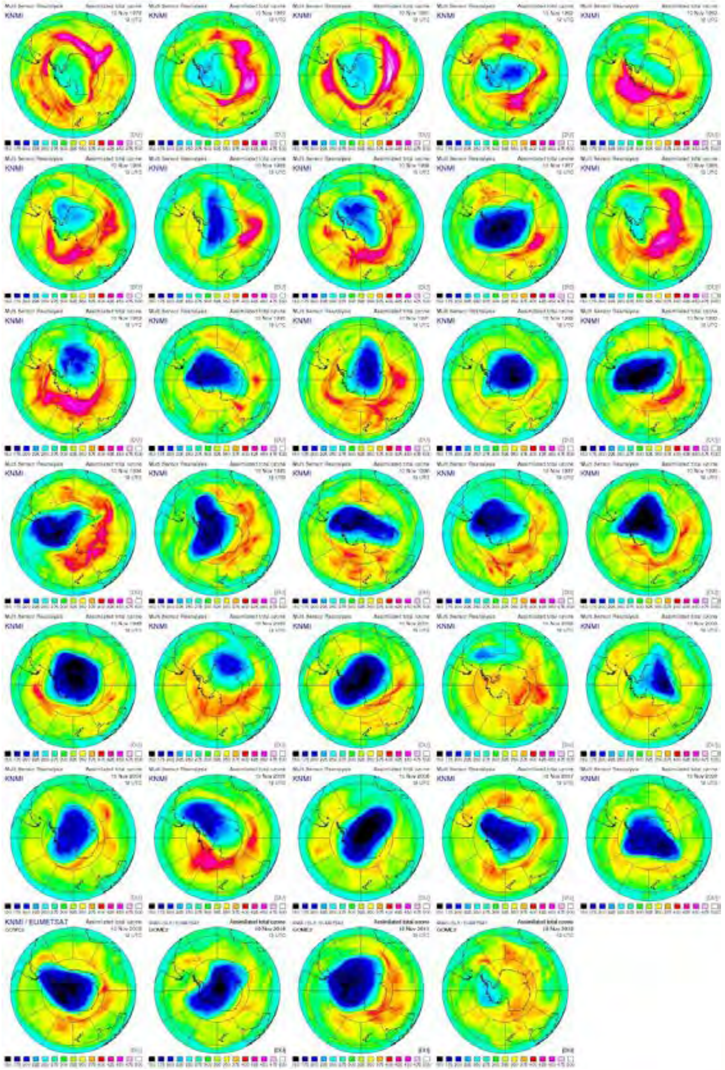
Success of the Montreal Protocol

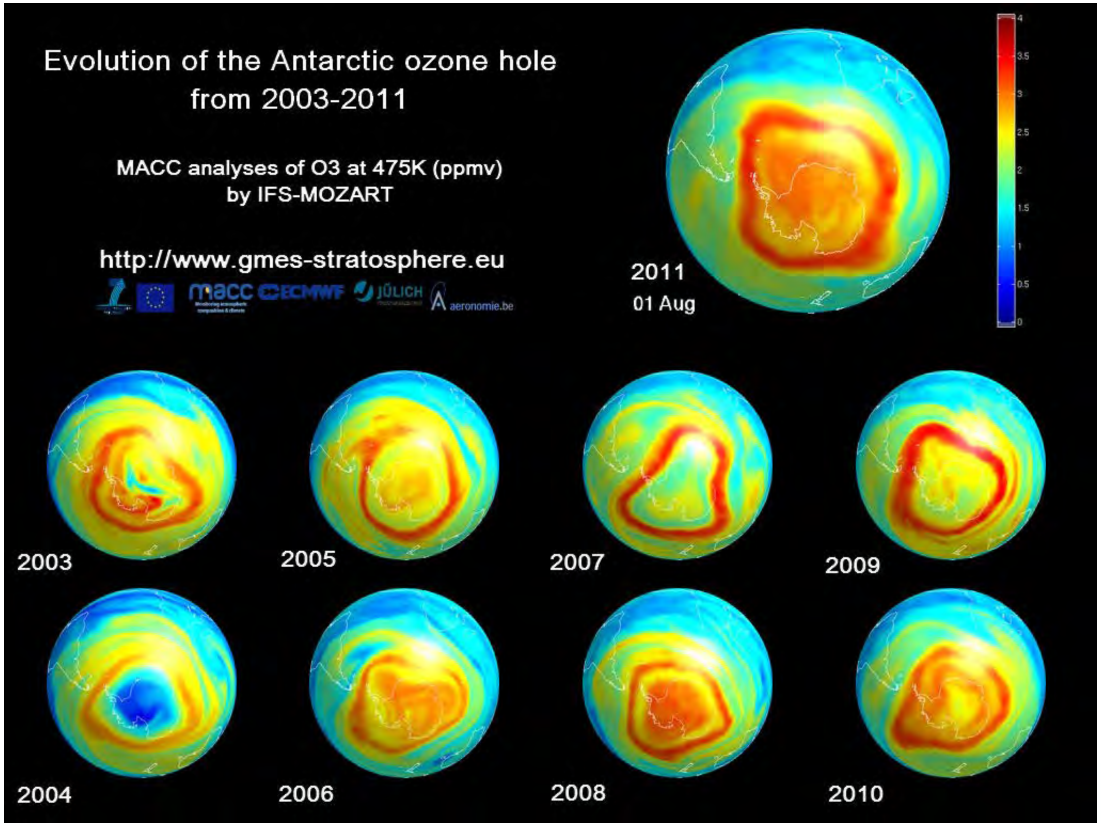


The impact of the Montreal Protocol on climate is of order 5-6 times larger than the objectives of the Kyoto Protocol 2008-2012 !

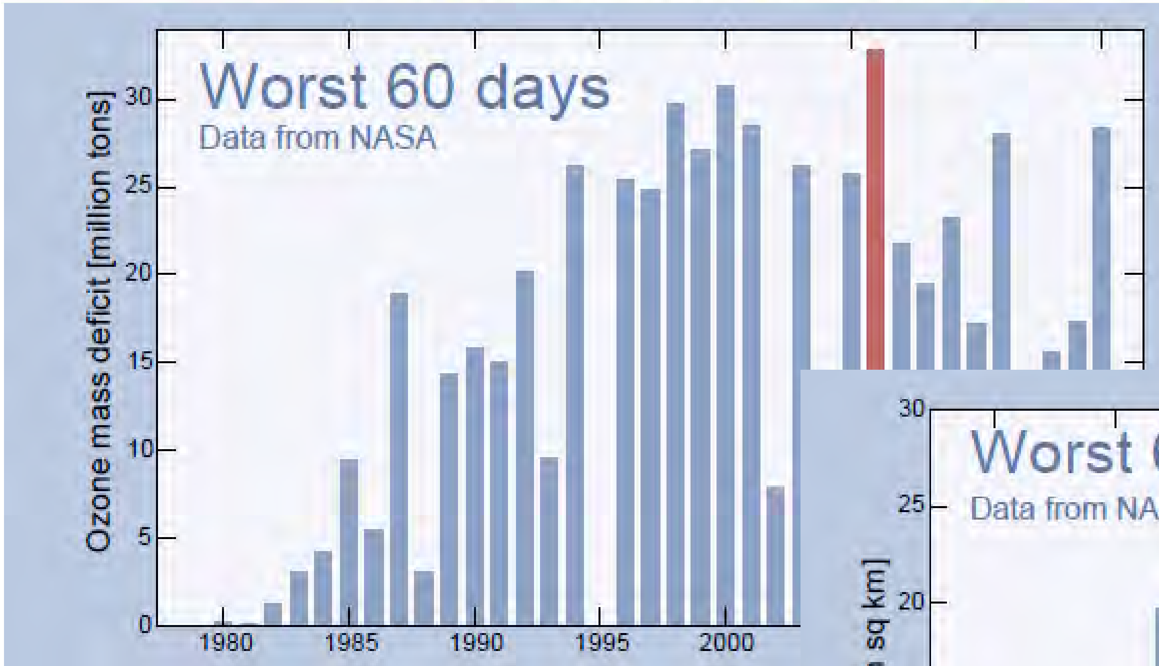
Reduction by Montreal Protocol of ~12 $GtCO_2$-eq/yr

Monitoring of the ozone hole using satellites and models



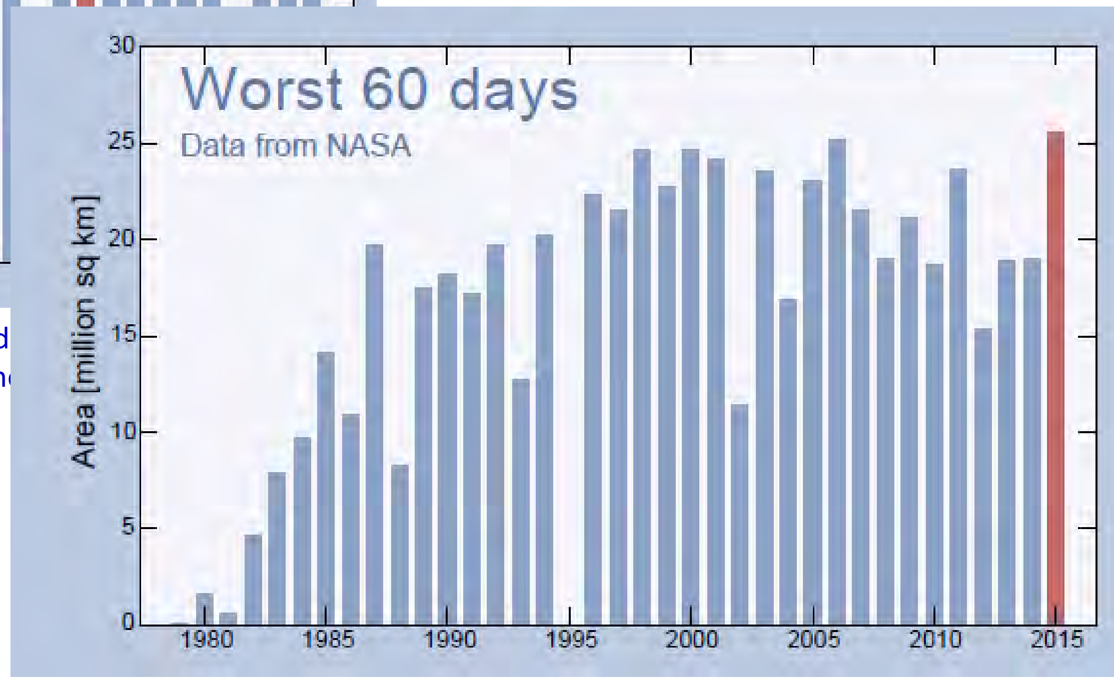


Evolution of ozone hole area: South Pole



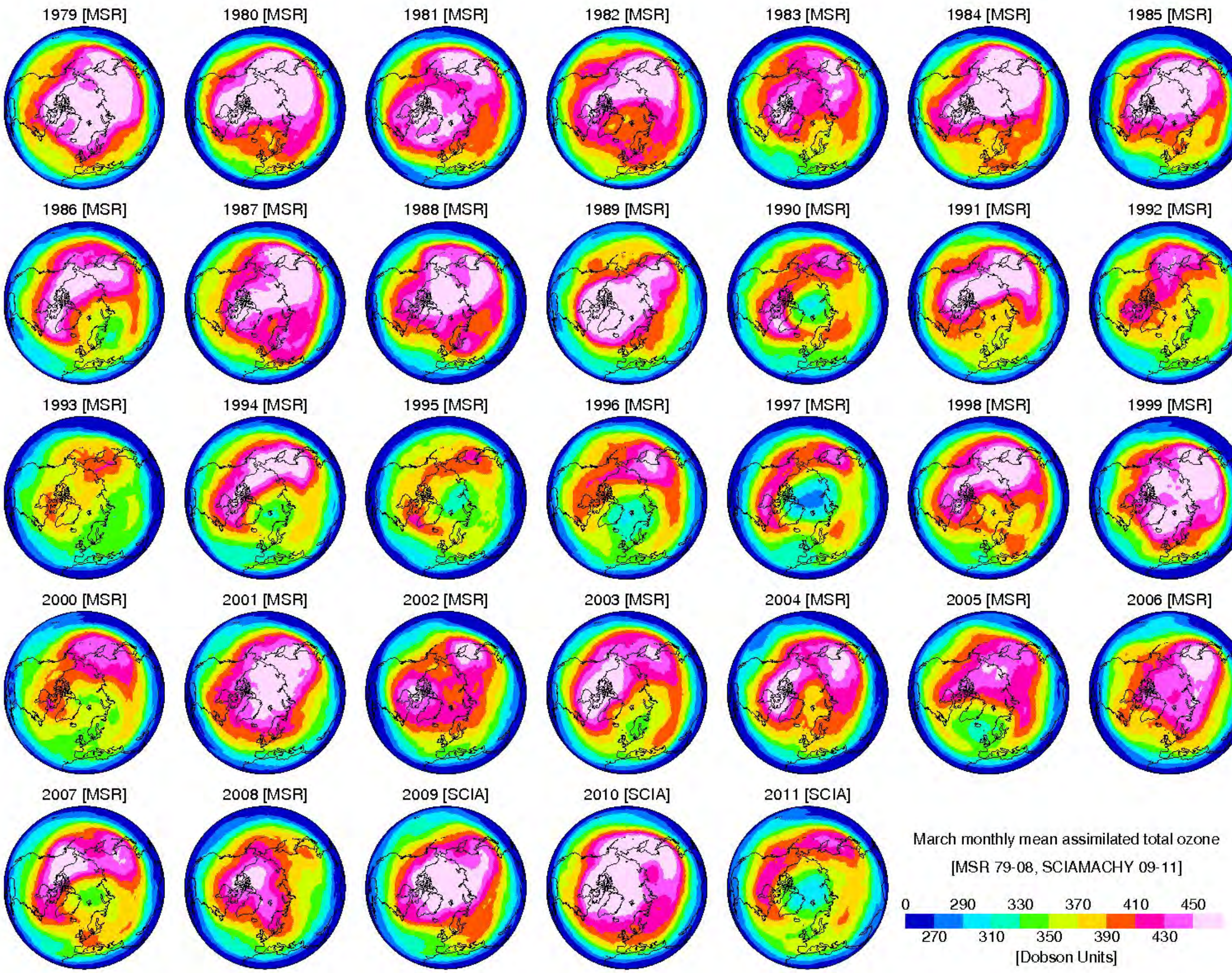
Ozone mass deficit averaged over the 60 consecutive worst d
at WMO based on data from NASA. The NASA data have som
but this does not affect the ranking of the 2015 ozone hole..

http://www.wmo.int/pages/prog/arep/gaw/ozone/



Area of the ozone hole for the years 1979-2015, averaged over the 60 consecutive worst days. The plot is produced at WMO, based on data from NASA. The NASA data have some gaps in the mid 1990s, but this does not affect the ranking of the 2015 ozone hole.

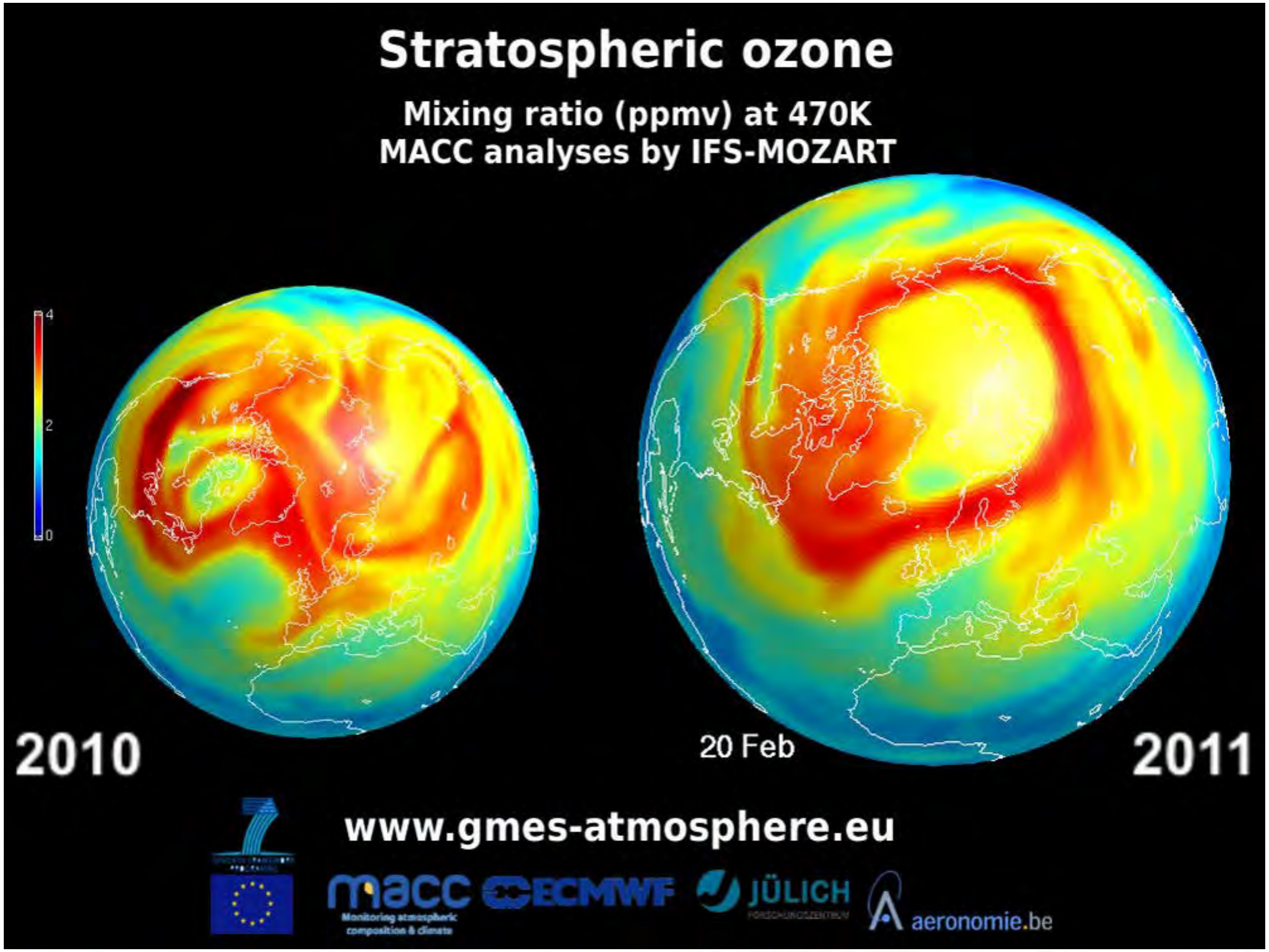
Evolution of the Spring polar ozone over the North Pole from 1979 until 2011



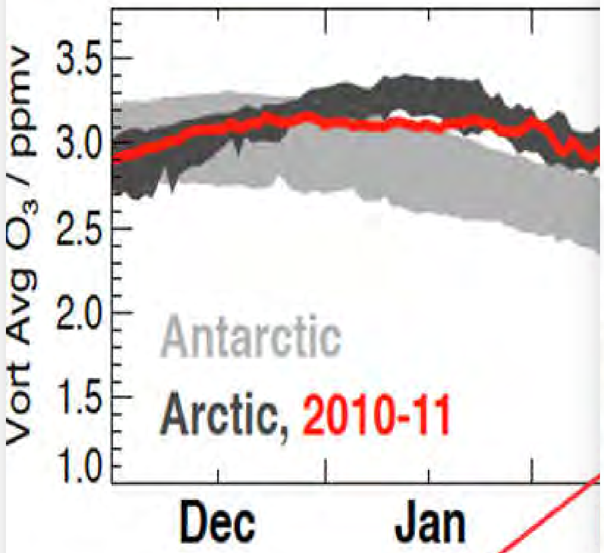
MACC/MSR, KNMI

March monthly mean assimilated total ozone

Most severe Arctic Ozone Hole: 2010-2011

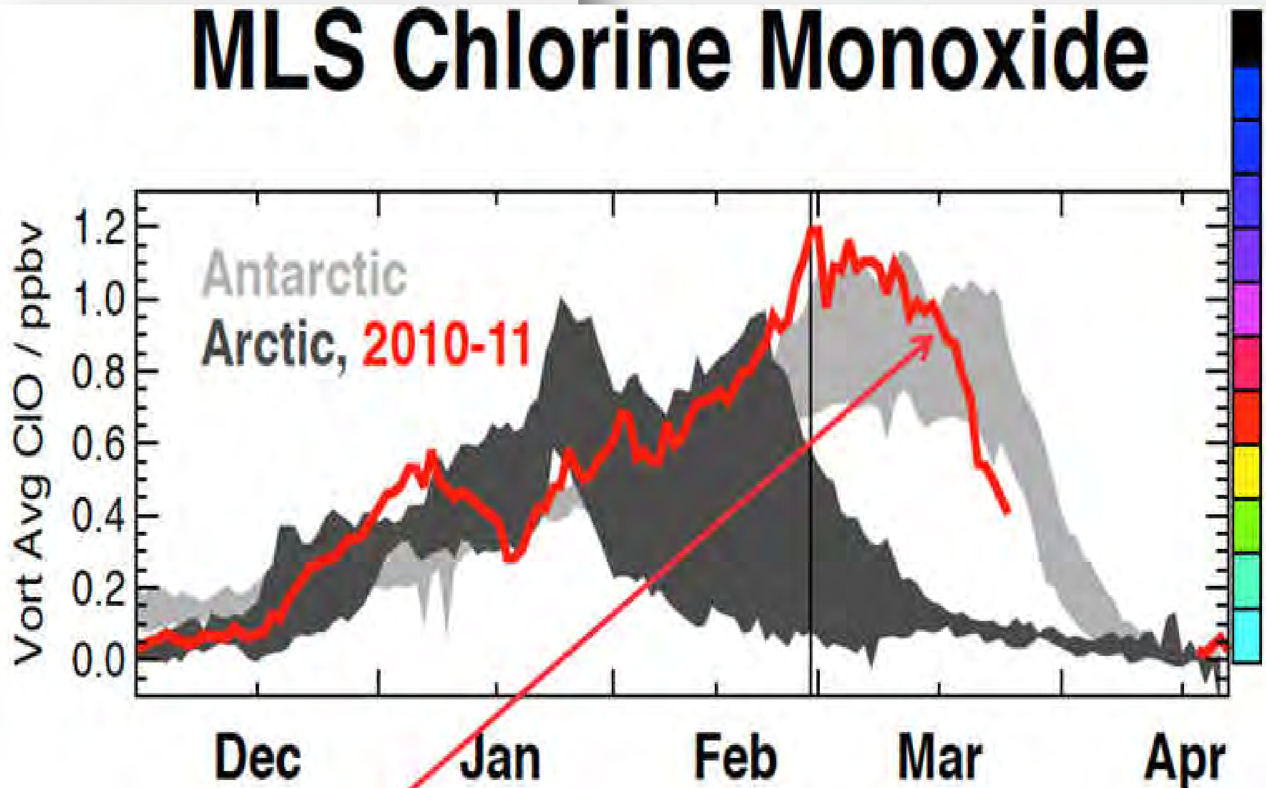


Ozone



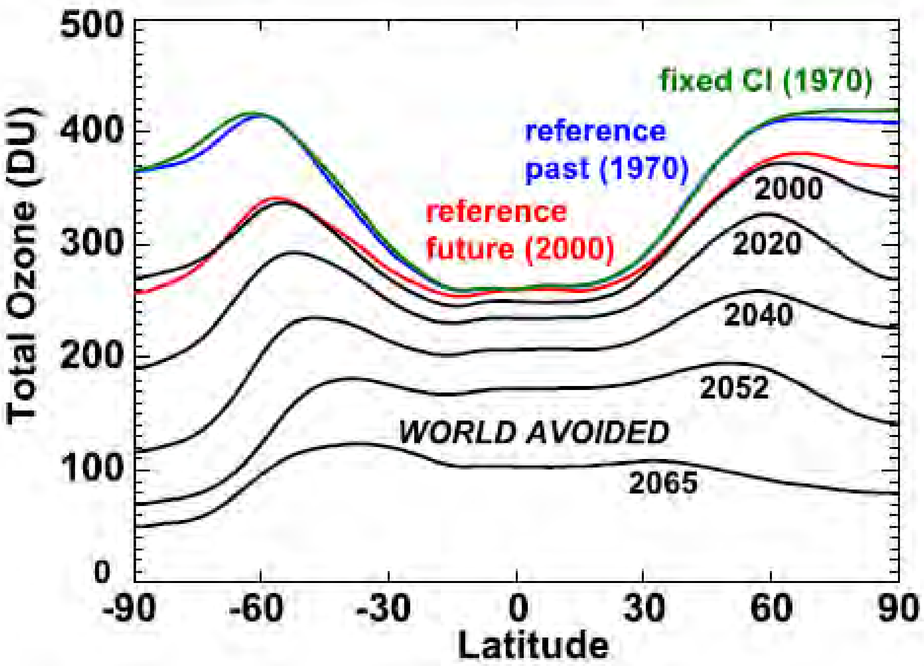
Arctic Ozone in 2011 was
2005-2010 winter observ
as Antarctic ozone.

MLS Chlorine Monoxide

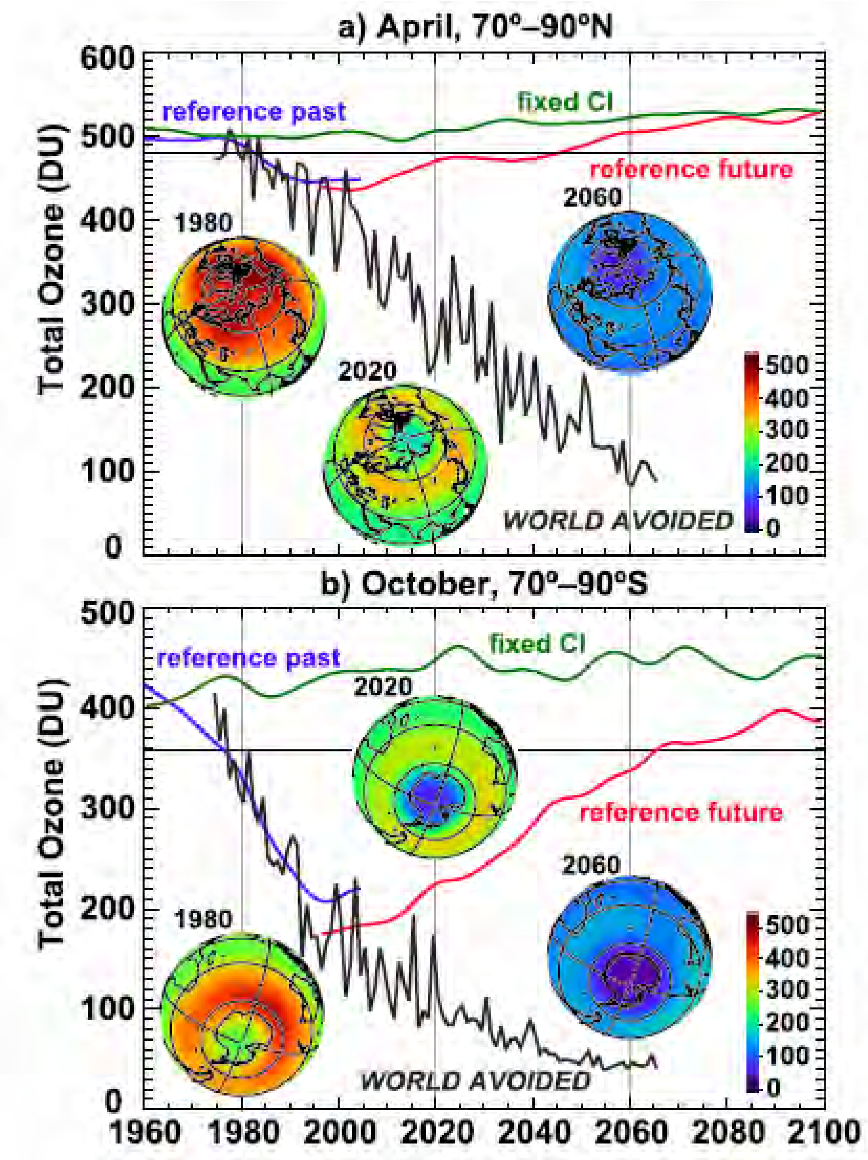


Arctic ClO in 2011 was outside the range of the 2005-2010 winter observations, and comparable to Antarctic ClO.

What would have happened if chlorofluorocarbons (CFCs) ha



Newman et al., ACP, 2009



Current situation

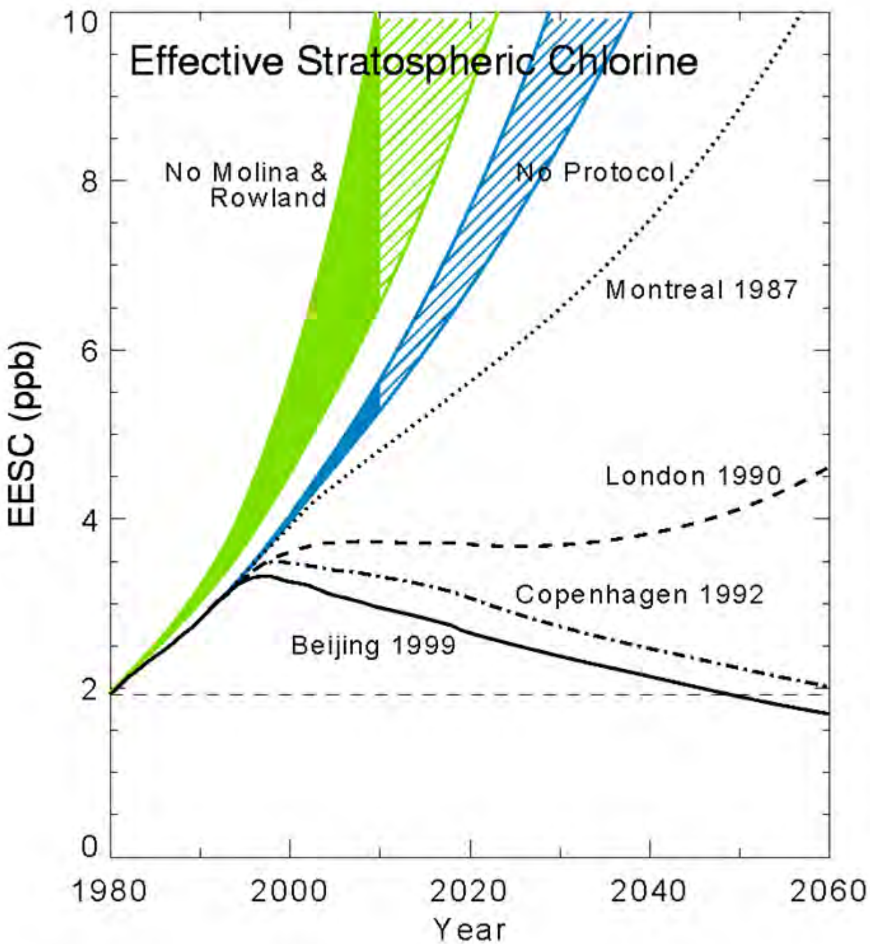
- O_3 in the middle latitude:
  - 6% (3.5%) lower than average in 1964-1980 SH (NH)
  - UV has not increased since the late 1990s
- O_3 hole at the poles is still as in early 1990 (subject variability) i.e. in Antarctica in October, 40% lower than in 1980
- UV on Antarctic is higher by 55 to 85% than in 1963-1980
- Evidences for changes in SH tropospheric summertime circulation due to Antarctic ozone hole
- The stratosphere has cooled a few K between 1980 and 1995 due to ozone depletion; the cooling reinforced by increasing GHG esp. in recent years

Ref: WMO O3 Assessment, 2014

Coupling between ozone and climate

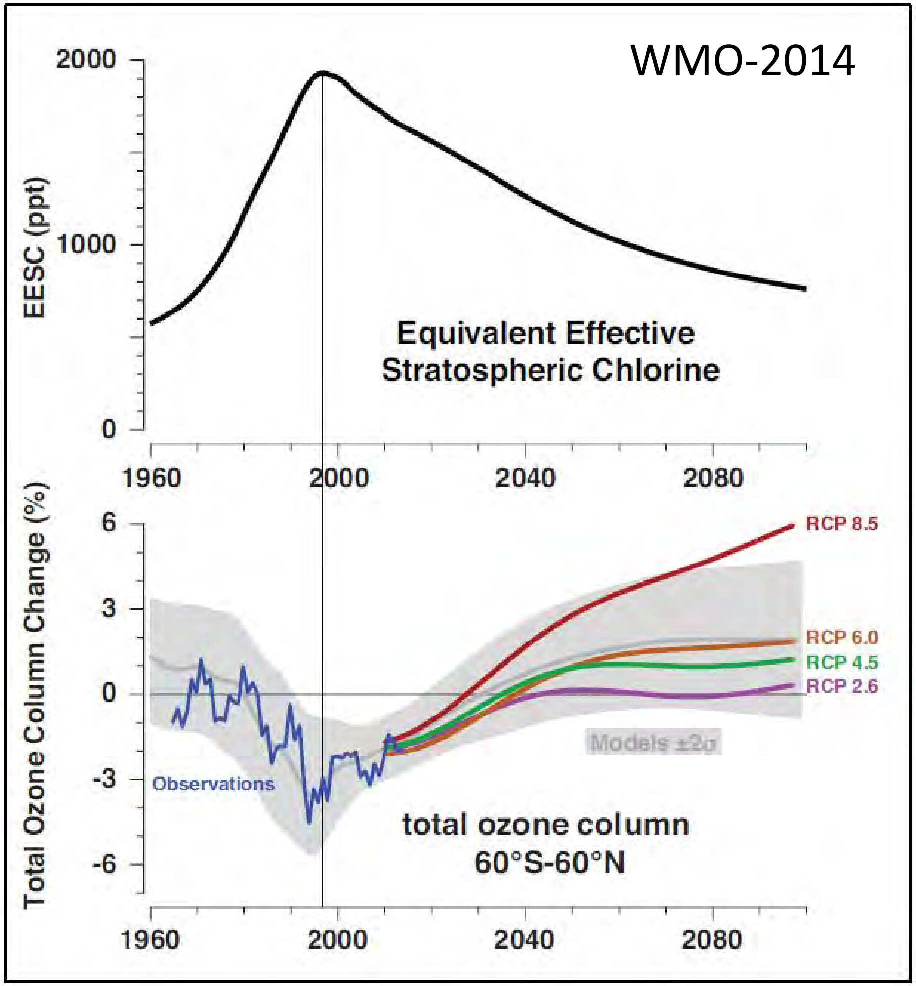
- Concentrations of greenhouse gases (CO_2, CH_4, N_2O,...) rise
- T° rises at the surface; but **decreases** in the stratosphere
- Atmospheric transport changes, rate of chemical reactions changes
- Frequency of formation of clouds, aerosols and PSC change
- Radiation balance changes
- Ozone formation / degradation is influenced, in turn ozone affects UV, T° stratosphere ....

Future evolution of ODS



- EESC back to 1980 levels:
  - in ~2050
  - in ~2065 at the poles (older air)

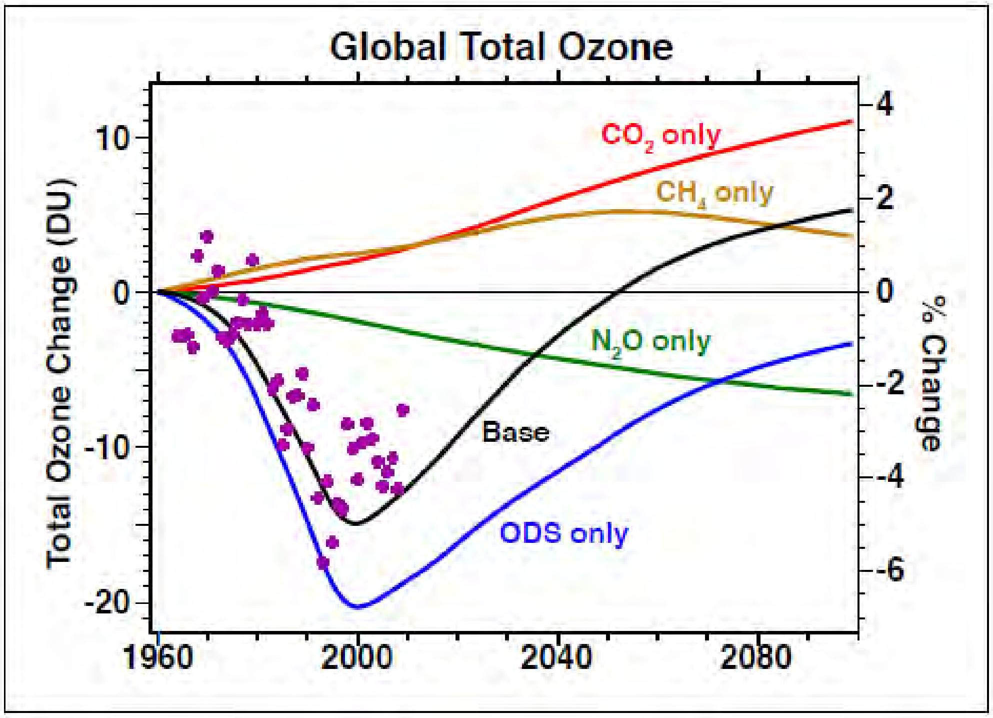
Future evolution of mid-latitude ozone



Average total column ozone changes over the same period, from multiple model simulations compared with observations between 1965 and 2013.

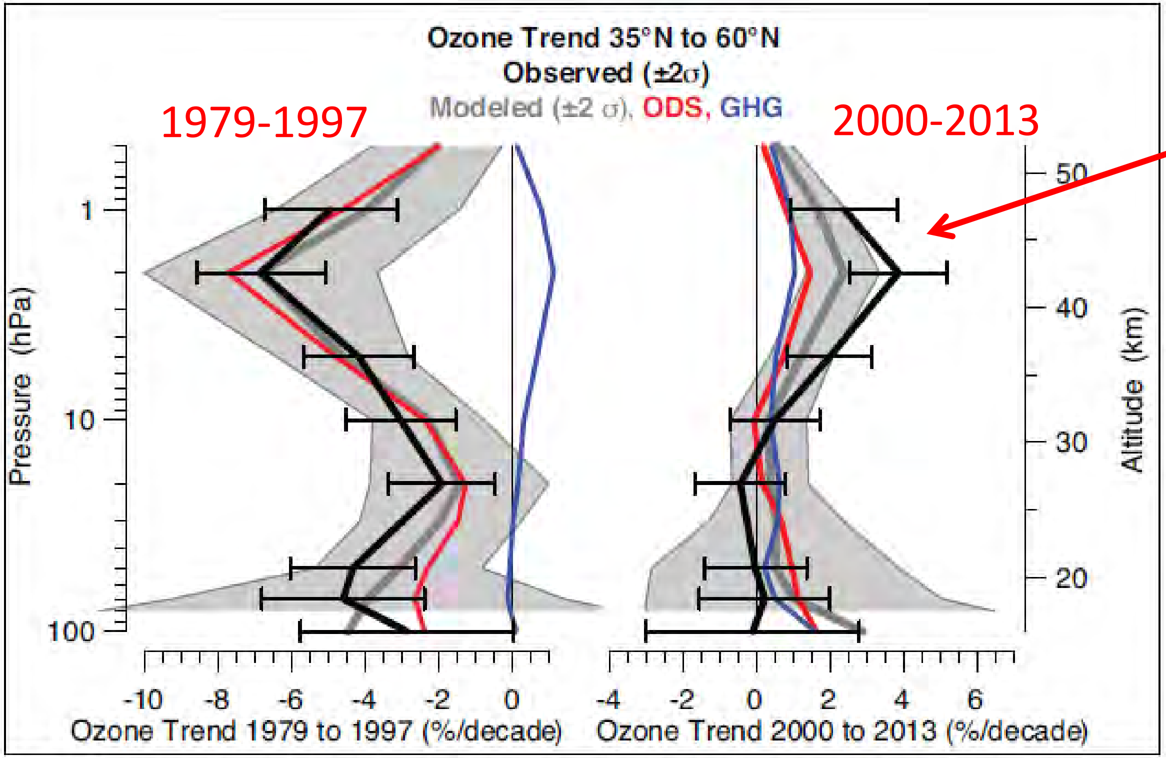
Four possible greenhouse gas (CO_2, CH_4, and N_2O) futures are shown. The four scenarios correspond to +2.6 (**purple**), +4.5 (**green**), +6.0 (**brown**), and +8.5 (**red**) W m^{-2} of global radiative forcing

Impact of projected changes in GHGs on ozone



- Increased CO_2, CH_4 and N_2O cools the stratosphere, which tends to increase O_3 because of temperature-dependent chemistry (reduced efficiency of loss)
- Increased CH_4 and N_2O also have further chemical impact on O_3
  - CH_4 increases O_3 by mitigating the effect of halogen-driven O_3 destruction catalytic cycles
  - N_2O decreases O_3 through enhancing the efficiency of the NOx-driven catalytic cycles

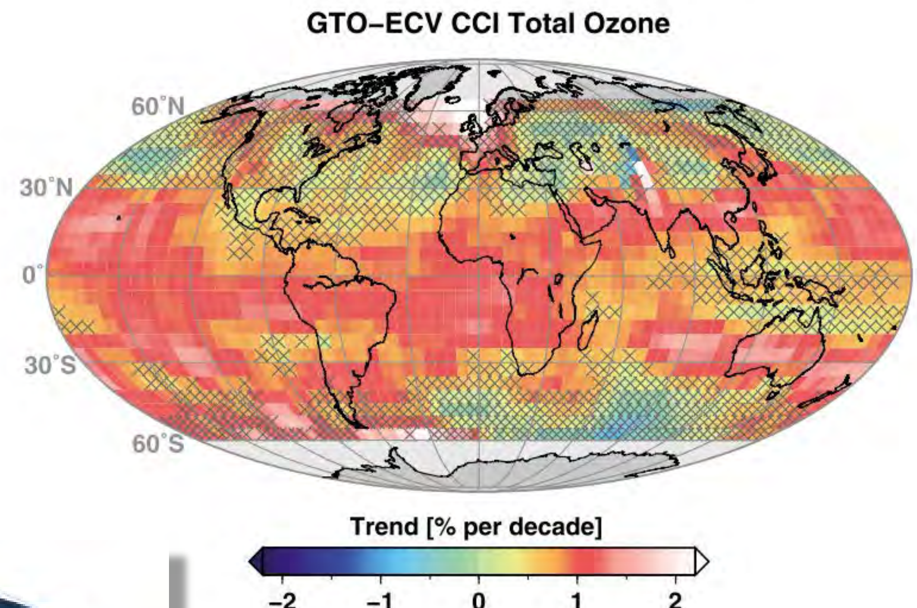
Evidence for O_3 recovery in upper stratosphere



O_3 recovery at 45 km altitude is due to combination of reduction in ODS (Montreal protocol) reinforced by cooling due to GHG increase

Regional ozone trend analysis

- Regional trends in total ozone estimated from harmonised multi-sensor satellite data set (1995-2013)
- Trends in middle latitudes still not significant; recovery masked by natural variability; additional 5-10 years of observations are required



Coldewey-Egbers et al., GRL, 2015

AGU PUBLICATIONS

Geophysical Research Letters

RESEARCH LETTER
10.1002/2014GL060212

Key Points:
- Global assessment of ozone trends using 18 years of European satellite data
- Natural variability masks ozone recovery in middle latitudes
- Additional 5–10 years of observations are required to detect expected onset

Correspondence to:
M. Coldewey-Egbers

A new health check of the ozone layer at global and regional scales

Melanie Coldewey-Egbers[1], Diego G. Loyola R.[1], Peter Braesicke[2], Martin Dameris[3], Michel van Roozendael[4], Christophe Lerot[4], and Walter Zimmer[1]

[1]Remote Sensing Technology Institute, German Aerospace Center, Weßling, Germany, [2]Karlsruhe Institute of Technology, Institute for Meteorology and Climate Research, Karlsruhe, Germany, [3]Institute for Physics of the Atmosphere, German Aerospace Center, Weßling, Germany, [4]Belgian Institute for Space Aeronomie BIRA-IASB, Brussels, Belgium

Abstract In this study, we provide a new perspective on the current state of the ozone layer using a comprehensive long-term total ozone data record which has been recently released within the framework

3 Fingerprints of Ozone Hole recovery

Science | 30 June 2016 release | *RESEARCH ARTICLES*

Cite as: Solomon *et al.*, *Science* 10.1126/science.aae0061 (2016).

Emergence of healing in the Antarctic ozone layer

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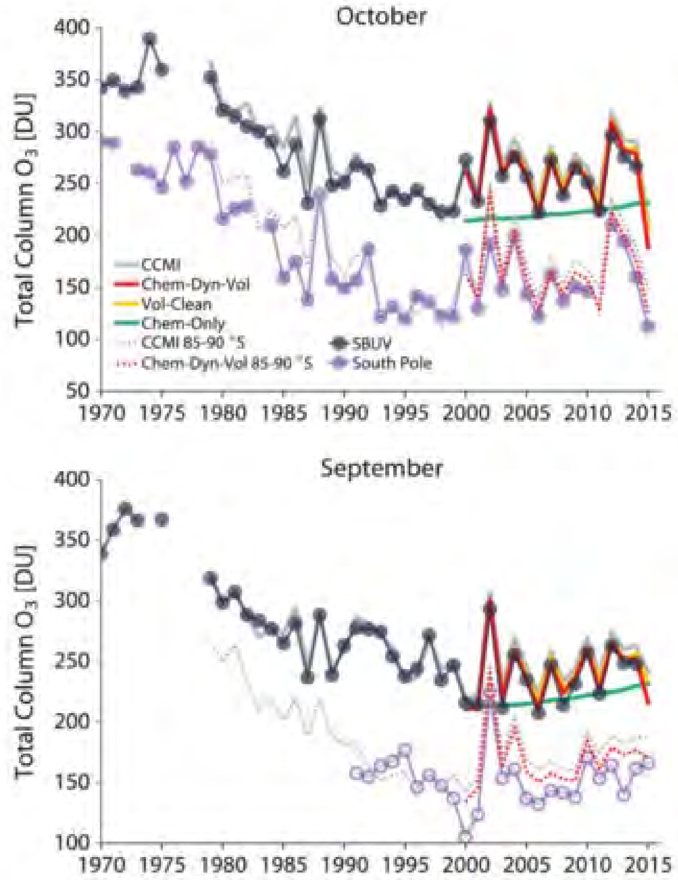
[1]Department of Earth, Atmospheric, and Planetary Science, Massachusetts Institute of Technology, Cambridge, MA 02139, USA. [2]Atmospheric Chemistry Observations and Modeling Laboratory, National Center for Atmospheric Research, PO Box 3000, Boulder, CO 80305, USA. [3]School of Earth and Environment, University of Leeds, Leeds, UK. [4]National Centre for Atmospheric Science, University of Leeds, Leeds, UK.

*Corresponding author. Email: solos@mit.edu

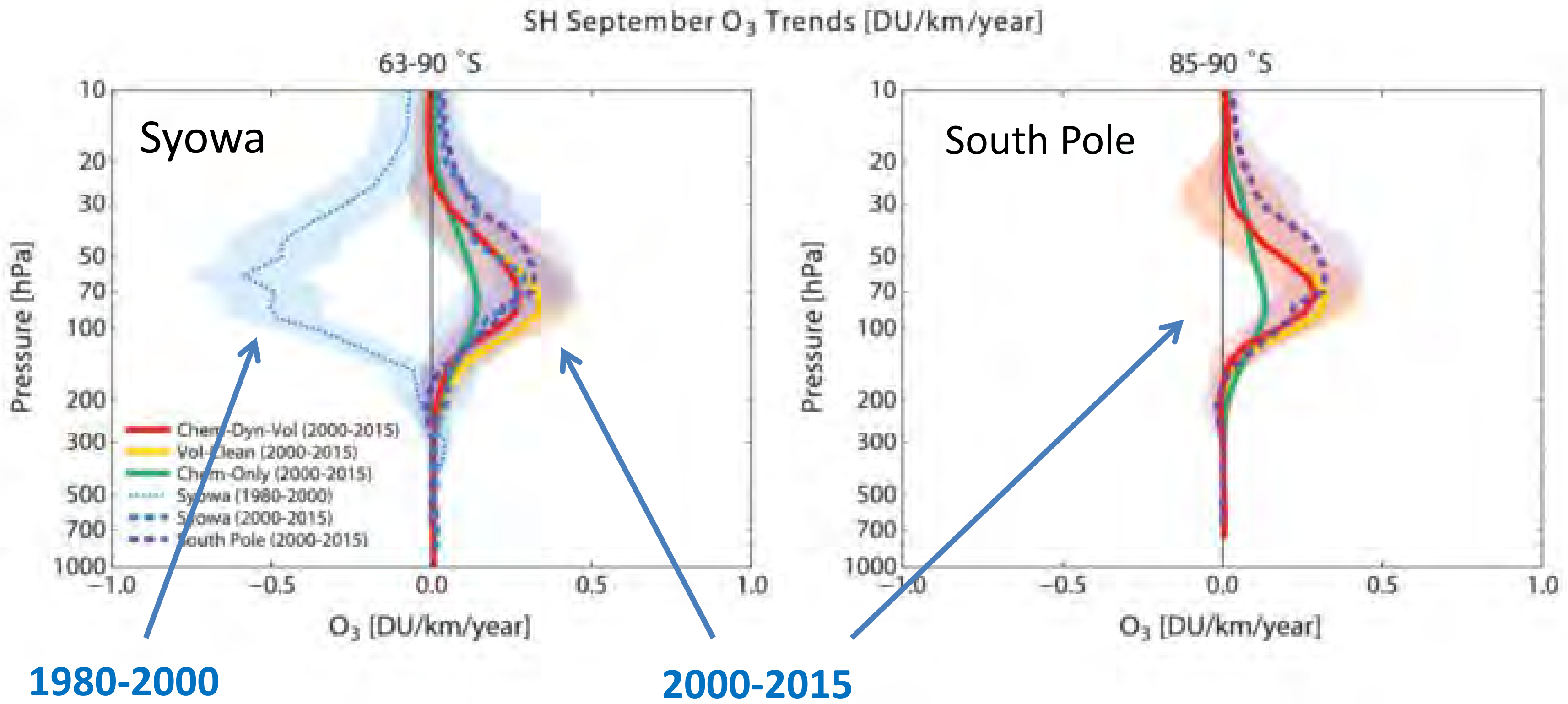
Industrial chlorofluorocarbons that cause ozone depletion have been phased out under the Montreal Protocol. A chemically-driven increase in polar ozone (or "healing") is expected in response to this historic agreement. Observations and model calculations taken together indicate that the onset of healing of Antarctic ozone loss has now emerged in September. Fingerprints of September healing since 2000 are identified through (i) increases in ozone column amounts, (ii) changes in the vertical profile of ozone concentration, and (iii) decreases in the areal extent of the ozone hole. Along with chemistry, dynamical and temperature changes contribute to the healing, but could represent feedbacks to chemistry. Volcanic eruptions episodically interfere with healing, particularly during 2015 (when a record October ozone hole occurred following the Calbuco eruption).

Solomon et al., 2016

(i) increases in ozone column amounts →

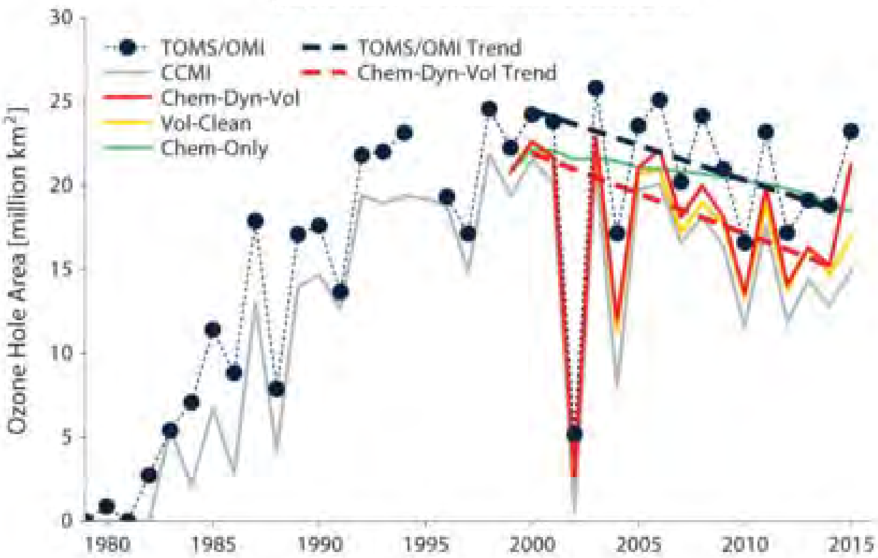


(ii) changes in the vertical profile of ozone concentration

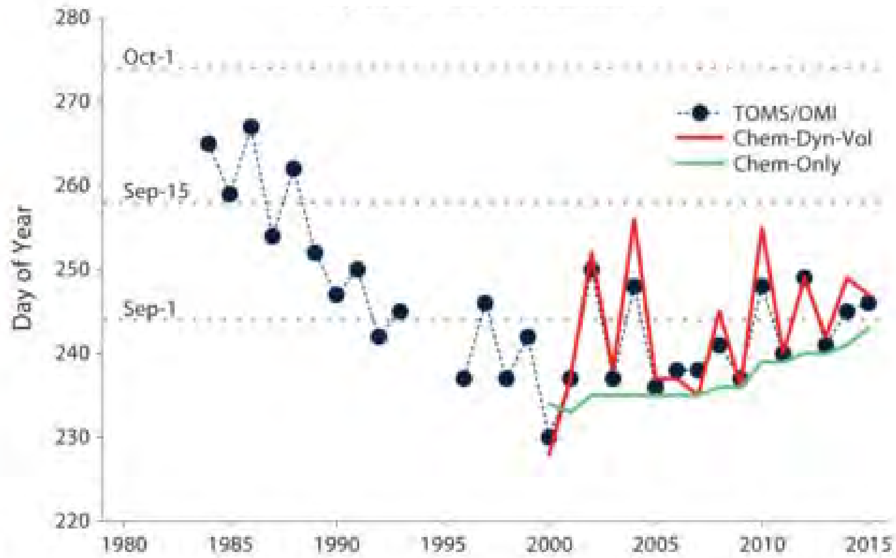


(iii) decreases in the areal extent of the ozone hole

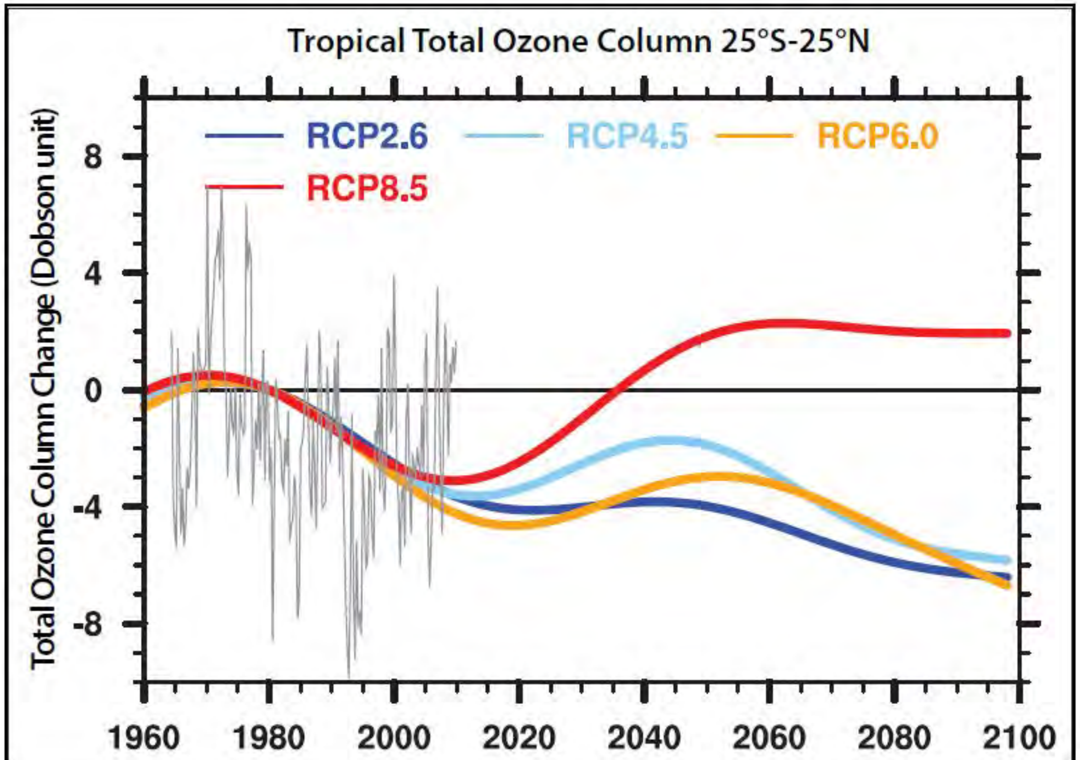
Ozone hole area



Day ozone hole area > 12 million km^2



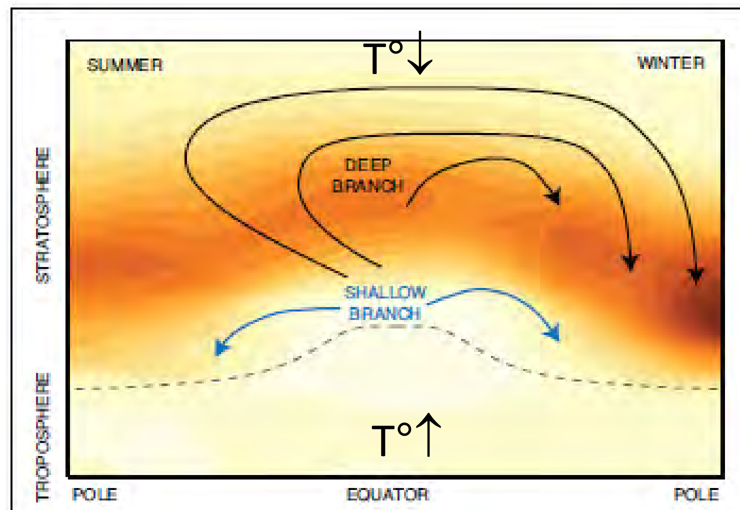
Predicted reduction of the tropical ozone layer



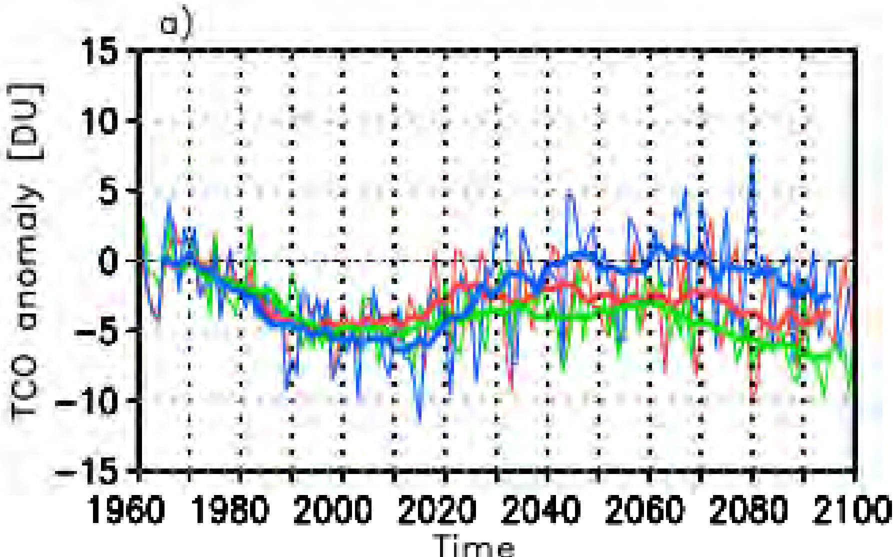
WMO-2014

Recent evidence for changes in tropical upwelling and higher latitudes downwelling due to climate change

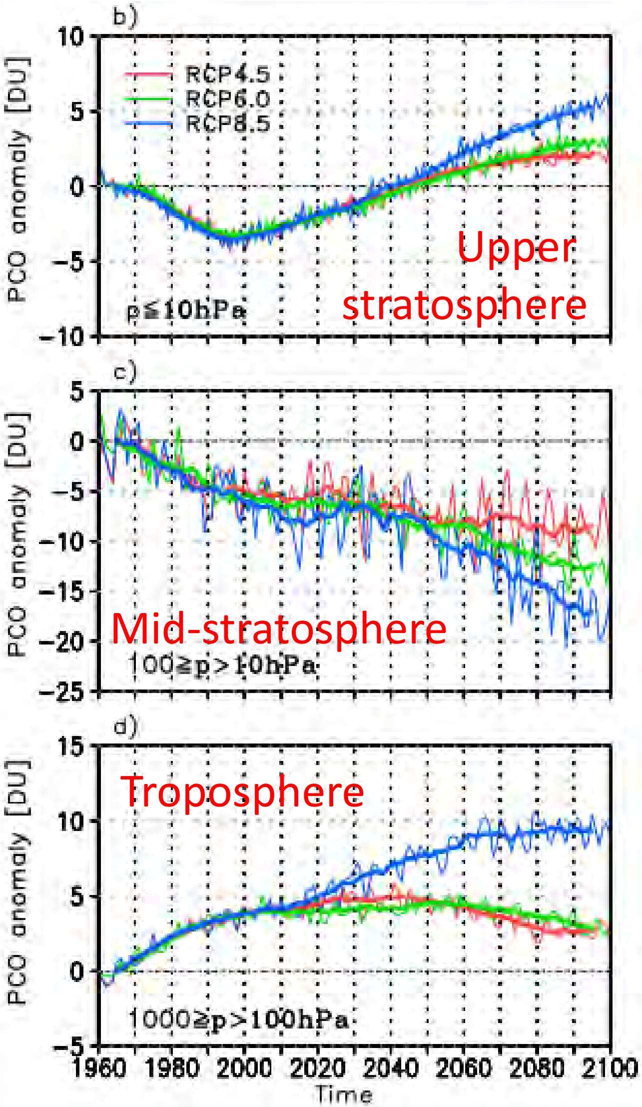
→ Impact on ozone distribution



Impact of rising GHG on tropical ozone

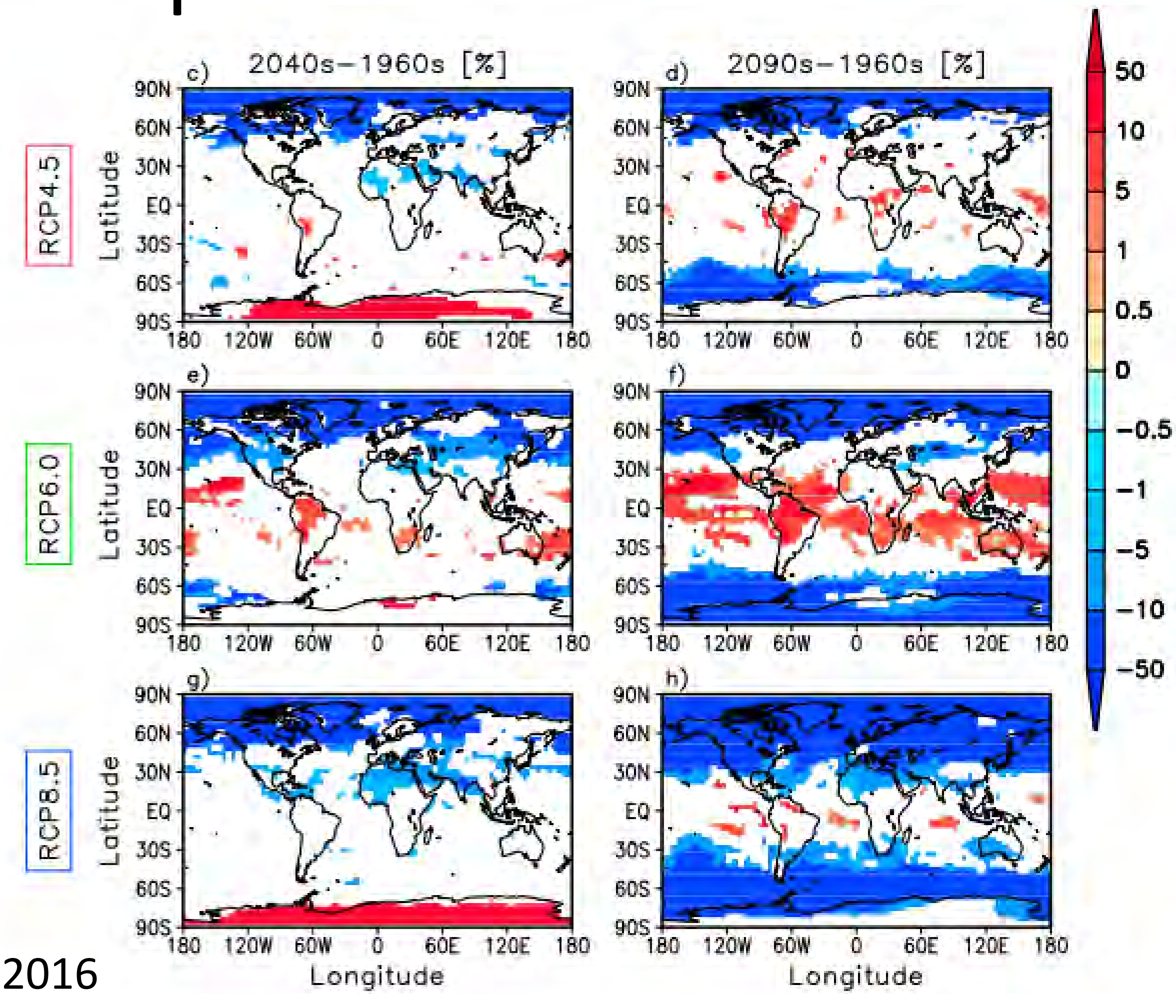


Meul et al., GRL, 2016



Conclusion: Mid-strat ozone decrease due to change in circulation (partly) compensated by increases to chemical effects at other altitudes

Impact on UVB irradiance



Meul et al., GRL, 2016

Summary

- O_3 on a global scale will return to state from 1980 by 2050, i.e. faster than ODS, namely:
  - Around 2030-2040 in middle latitudes of both hemispheres
  - Around 2045-2060 in Antarctica
  - The increase of ozone will be accelerated in a colder stratosphere under the impact of GHGs
- As result, at the end of the 21st century the stratospheric ozone concentration will be higher than in 1980
- Tropical ozone might decrease due to climate-change induced changes in the Dobson-Brewer circulation

- Large uncertainties in future emission scenarios and resulting impacts


WHY DON'T THE GREENHOUSE GASES ESCAPE THROUGH THE HOLE IN THE OZONE LAYER?