The important role of ozone in the atmosphere

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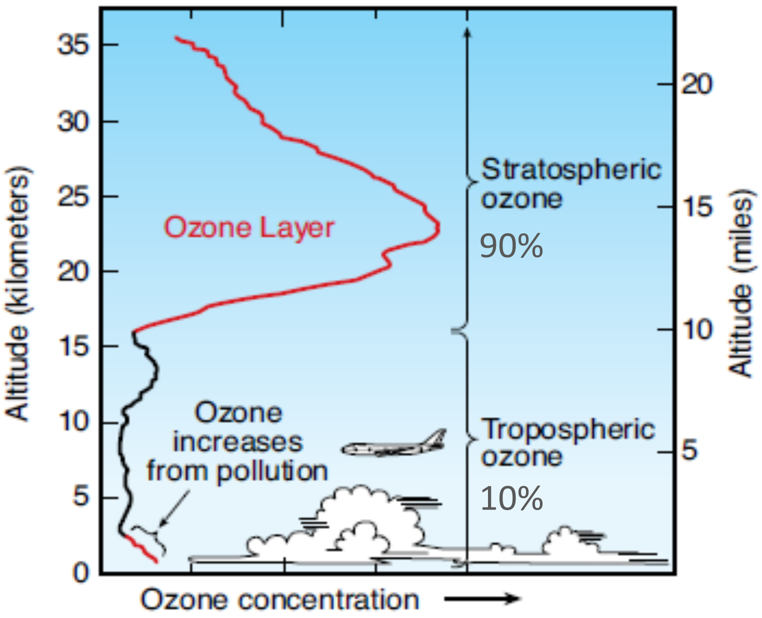
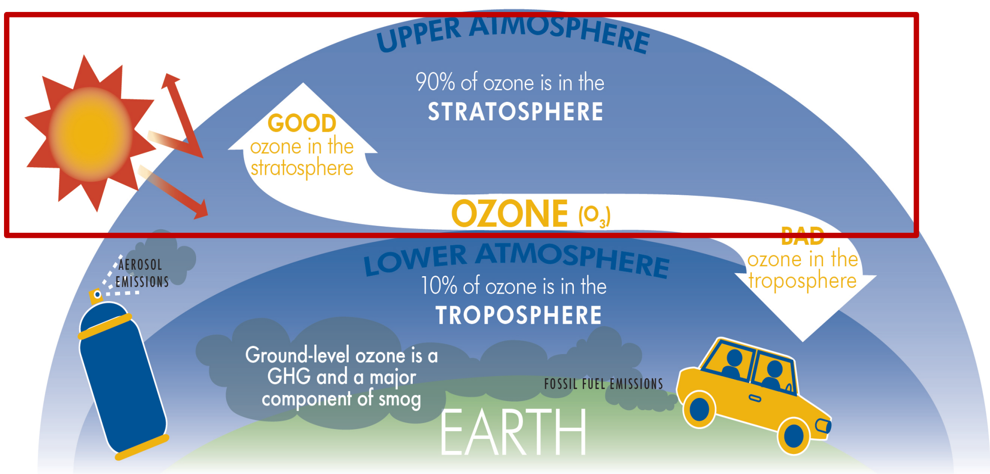
Multiple facets of atmospheric ozone

Ozone layer

All ozone molecules compressed to pressure of 1 atm. and temperature of 0°C :

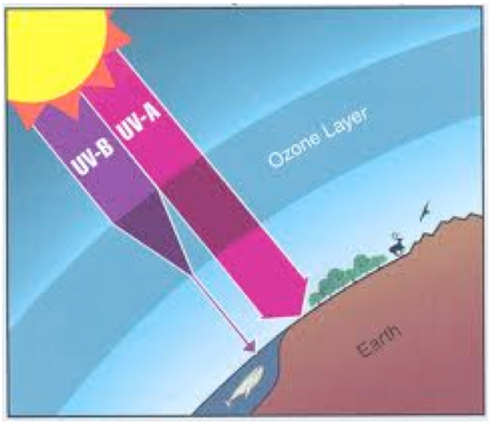
- Whole atmosphere ~ 8 km
- **Ozone layer: 3 mm thickness (300 DU)**





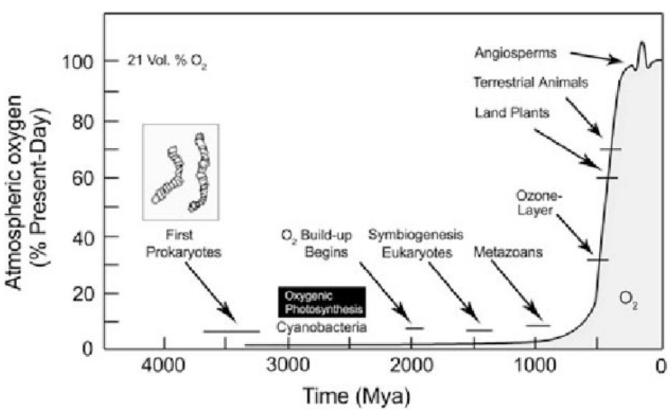
Ozone : a gas essential to life on Earth

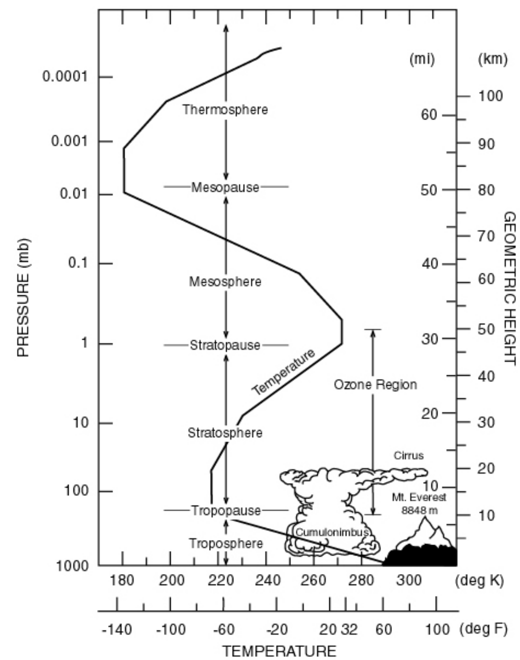
Main atmospheric element filtering solar UV-B radiation (280 – 315 nm)



- UV radiation hazards: DNA damage, skin cancer, eye cataracts, ecosystem damage
- The formation of ozone in the atmosphere has allowed life to emerge from the oceans

Appearance of O_2 ~2 billion years ago
Ozone: ~ 600 million years ago

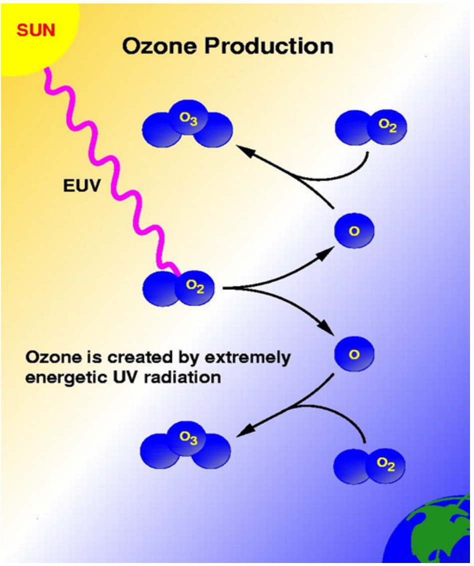




Stratosphere due to the presence of ozone in the atmosphere

Fragile equilibrium of stratospheric ozone

Chemical production



Sources gases emitted at the surface:

N_2O, CH_4, H_2O, CH_3Cl, CFC, …

Catalytic chains:~1000

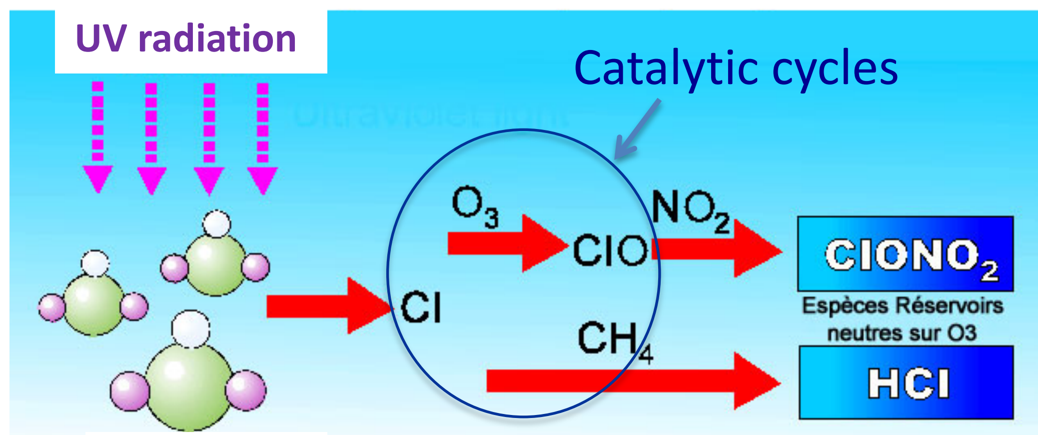
Ozone controled by species 1000 times less abundant

Chemical loss

dissociation of ozone molecules: Reaction with O atom or with radicals produced from source gases emitted at the surface (e.g. nitrogen, hydrogen, chlorine and bromine families).

Loss through catalytic cycles that reform initial radicals

Example of catalytic cycle: chlorine family



CFCs

Reservoir species

Threats on the ozone layer

1974: Molina and Rowland

Stratospheric sink for chlorofluoromethanes : chlorine atomc-atalysed destruction of ozone

Mario J. Molina & F. S. Rowland

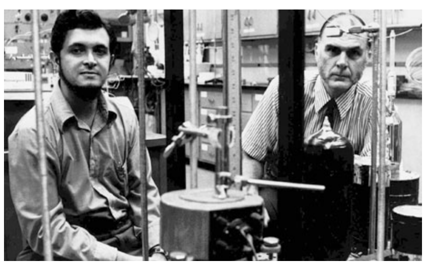
Department of Chemistry, University of California, Irvine, California 92664

Chlorofluoromethanes are being added to the environment in steadily increasing amounts. These compounds are chemically inert and may remain in the atmosphere for 40–150 years, and concentrations can be expected to reach 10 to 30 times present levels. Photodissociation of the chlorofluoromethanes in the stratosphere produces significant amounts of chlorine atoms, and leads to the destruction of atmospheric ozone.

photolytic dissociation to $CFCl_2$ + Cl and to CF_2Cl + Cl, respectively, at altitudes of 20–40 km. Each of the reactions creates two odd-electron species—one Cl atom and one free radical. The dissociated chlorofluoromethanes can be traced to their ultimate sinks. An extensive catalytic chain reaction leading to the net destruction of O_3 and O occurs in the stratosphere:

$$Cl + O_3 \rightarrow ClO + O_2 \quad (1)$$
$$ClO + O \rightarrow Cl + O_2 \quad (2)$$

This has important chemical consequences. Under most conditions in the Earth's atmospheric ozone layer, (2) is the slower of the reactions because there is a much lower concen-



Catalytic destruction of ozone by chlorofluorocarbons (CFC)

1985: Farman et al.

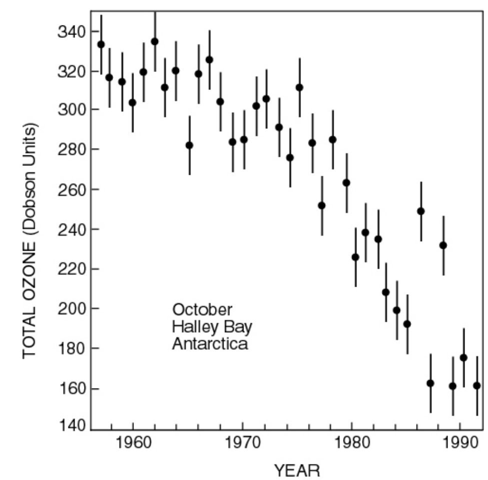
NATURE VOL. 315 16 MAY 1985 — LETTERS TO NATURE

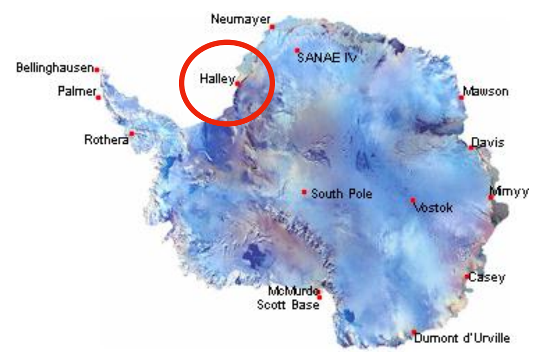
Large losses of total ozone in Antarctica reveal seasonal ClO_x/NO_x interaction

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

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

Recent attempts[1,2] to consolidate assessments of the effect of human activities on stratospheric ozone (O_3) using one-dimensional models for 30° N have suggested that perturbations of total O_3 will remain small for at least the next decade. Results from such models are often accepted by default as global estimates[3]. The inadequacy of this approach is here made evident by observations that the spring values of total O_3 in Antarctica have now fallen considerably. The circulation in the lower stratosphere is apparently unchanged, and possible chemical causes must be considered. We suggest that the very low temperatures which prevail from midwinter until several weeks after the spring equinox make the Antarctic stratosphere uniquely sensitive to growth of inorganic chlorine, ClX, primarily by the effect of this growth on the NO_2/NO ratio. This, with the height distribution of UV irradiation peculiar to the polar stratosphere, could account for the O_3 losses observed.

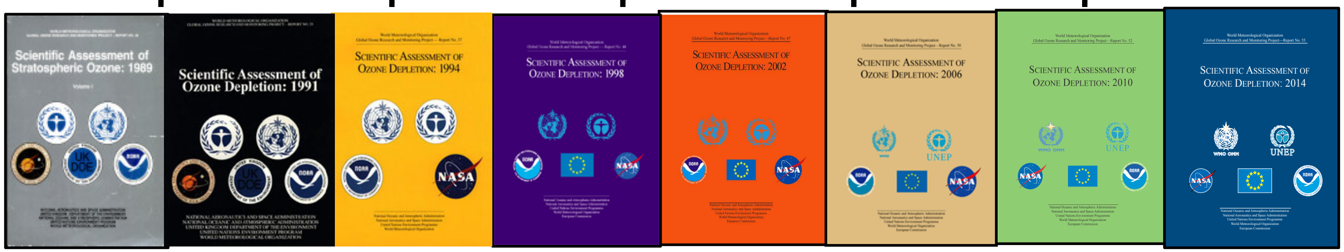




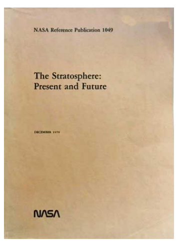
Actions taken to protect the ozone layer

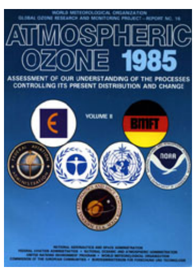
WMO World Plan of Action on the Ozone Layer - 1977

1980 | 1990 | 2000 | 2010

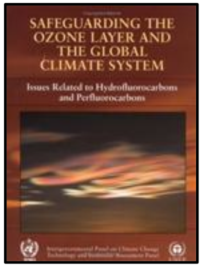


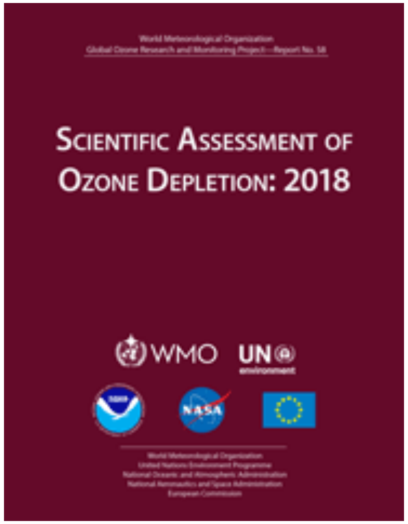
Scientific Assessment of Ozone Depletion:
1989, 1991, 1994, 1998, 2002, 2006, 2010, 2014, 2018 (WMO/UNEP)





Safeguarding the Ozone Layer and the Global Climate System: 2005 (IPCC/TEAP)





1987 **Montreal Protocol** — Ozone depleting substances regulation and ban

1985 **Vienna Convention** — Protection of the ozone layer

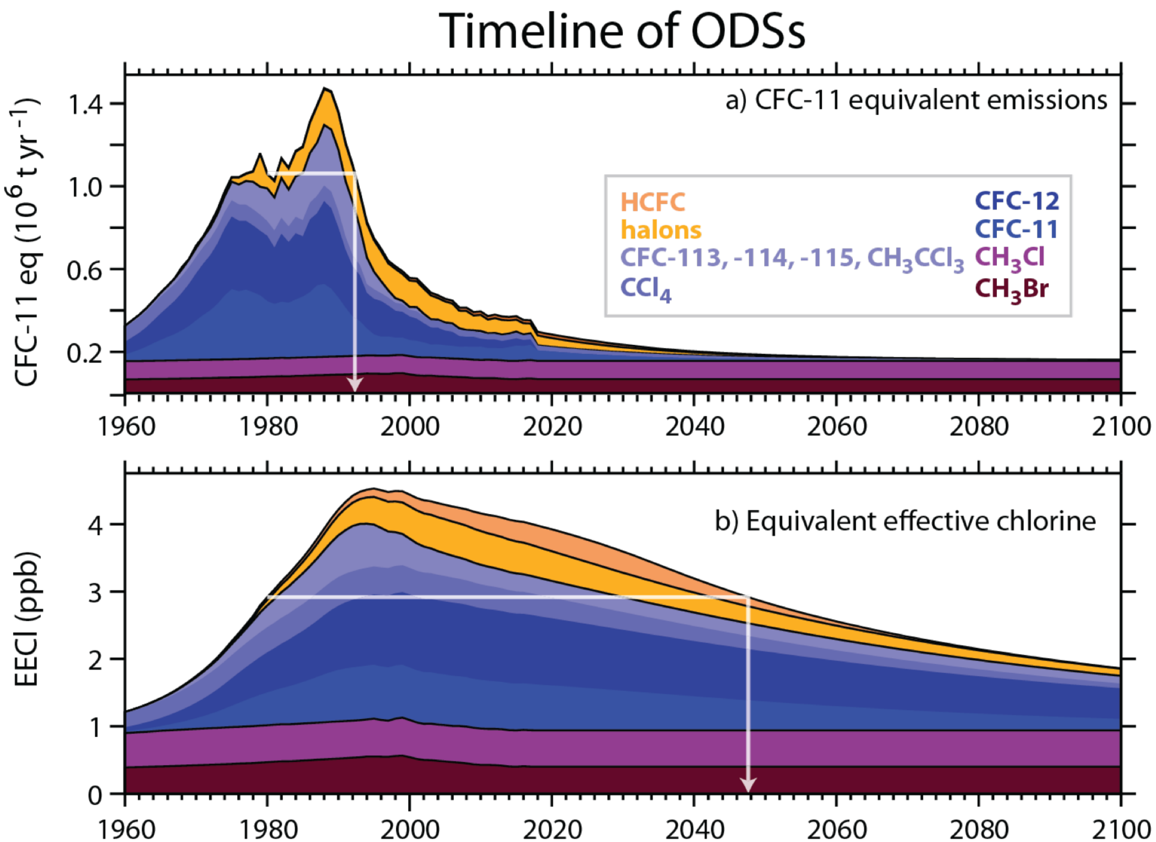
What is the situation 30 years after enforcement of Montreal Protocol in 1989?

Ozone-depleting substances are declining

Actions related to the Montreal Protocol have led to decrease in ODS abundance and beginning of ozone layer recovery

CFC-11-eq emissions (ODP-weighted)

Equivalent effective chlorine (EECl)



Most ODS have a very long lifetime: They will take time to disappear from the atmosphere

CFC-11 lifetime: 52 yrs
CFC-12 lifetime: 102 yrs

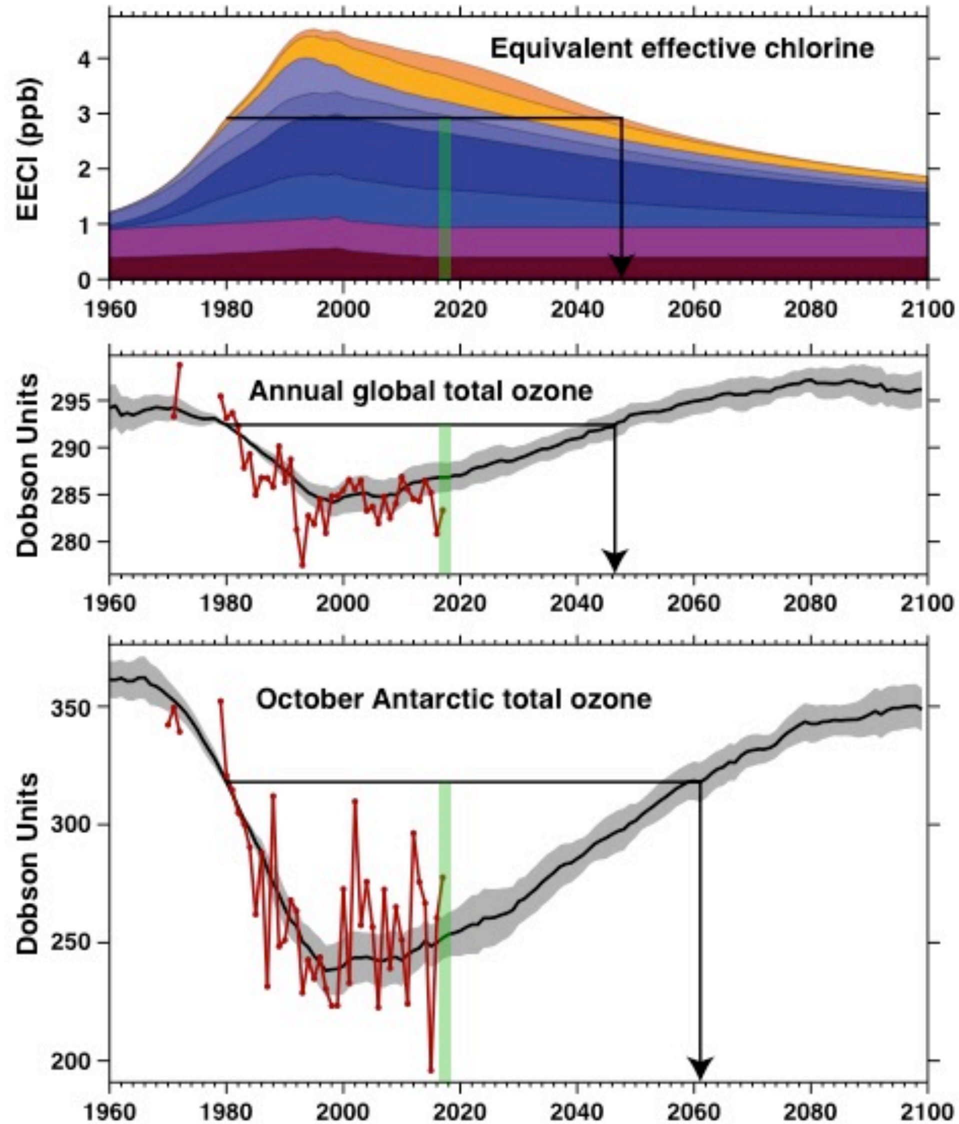
WMO/UNEP 2018

Recovery of the ozone layer

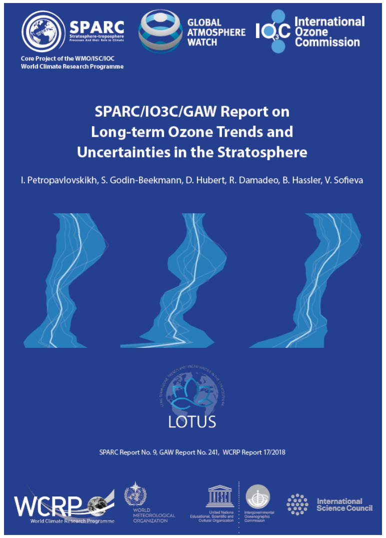
WMO/UNEP 2018

- Ozone layer has stopped decreasing in late 1990s and is now slowly recovering
- Present global average total ozone: ~2% below pre-1980 values
- Return of total ozone to pre-1980 values:
  - Global mean: ~2050
  - Northern mid-latitudes: ~2035
  - Southern mid-latitudes: ~2050
- Disparition of ozone hole: ~2060

But uncertainties linked to ozone-climate interaction



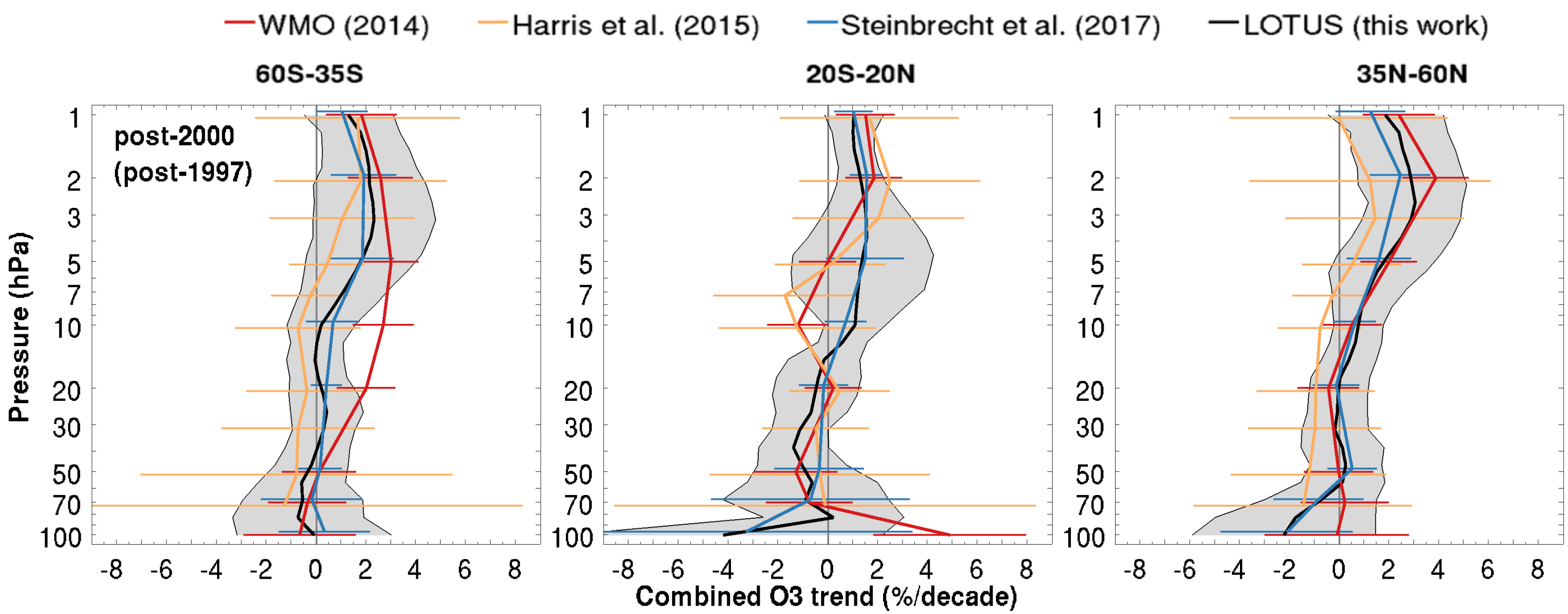
Ozone recovery as a function of altitude



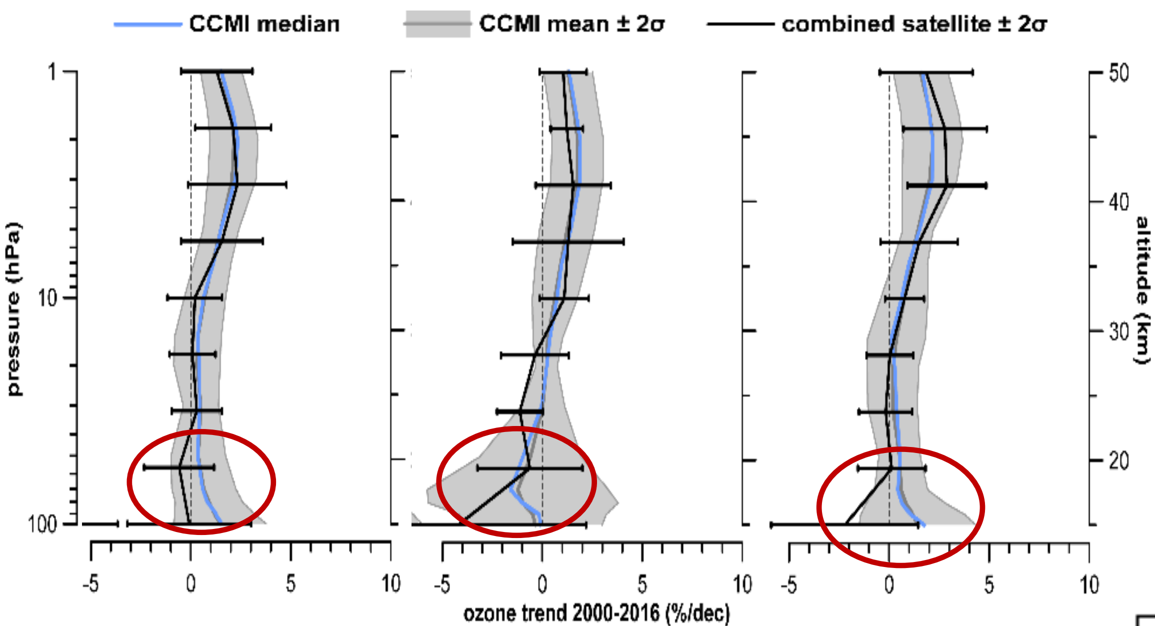
LONG-TERM OZONE TRENDS AND UNCERTAINTIES IN THE STRATOSPHERE

LOTUS

- SPARC/IO3C/WMO on ozone profile trends.
- 1st phase: trend results similar with previous studies but significance of combined trends in large latitude bands differ



Comparison with model results

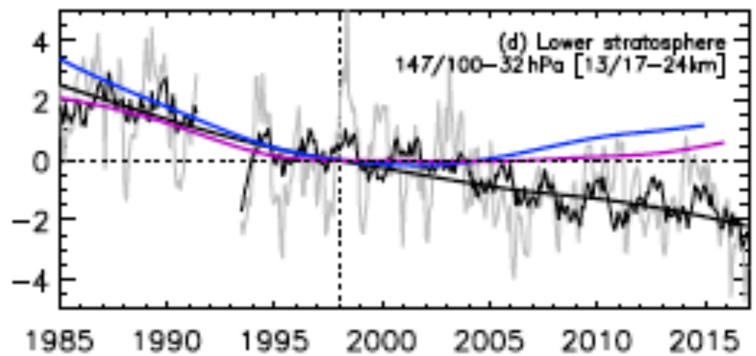


LOTUS

Disagreement between satellite and model trend results in the lower stratosphere

Ball et al., 2018:

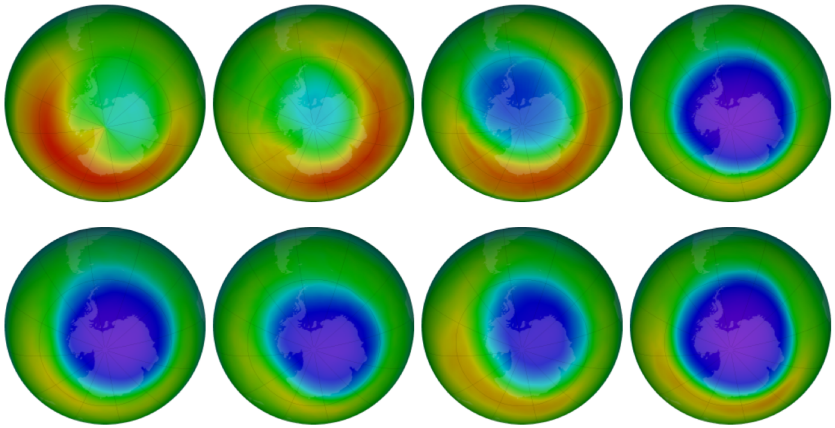
Evidence for a continuous decline in lower stratospheric ozone offsetting ozone layer recovery



Need for accurate ozone monitoring in the Upper troposphere lower stratosphere

Evolution of Antarctic ozone hole

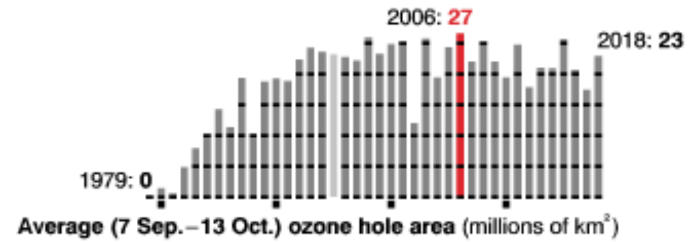
1970 1979 1988 1999



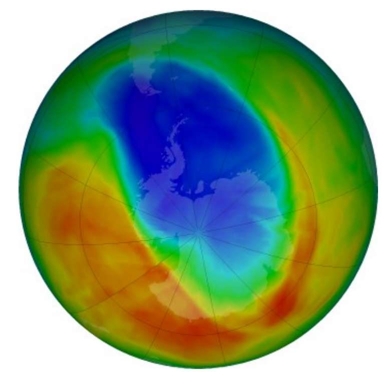
2008 2010 2017 2018

Ozone hole: recurrent seasonal feature in Southern Hemisphere since ~1980

Ozone hole area

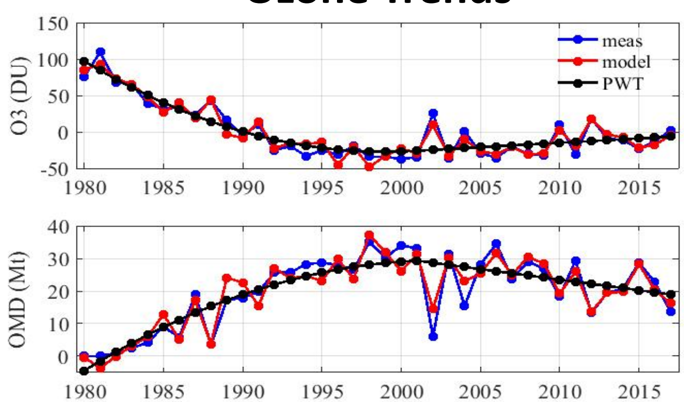


2019



Small ozone hole due to sudden stratospheric warming in late August

Ozone Trends



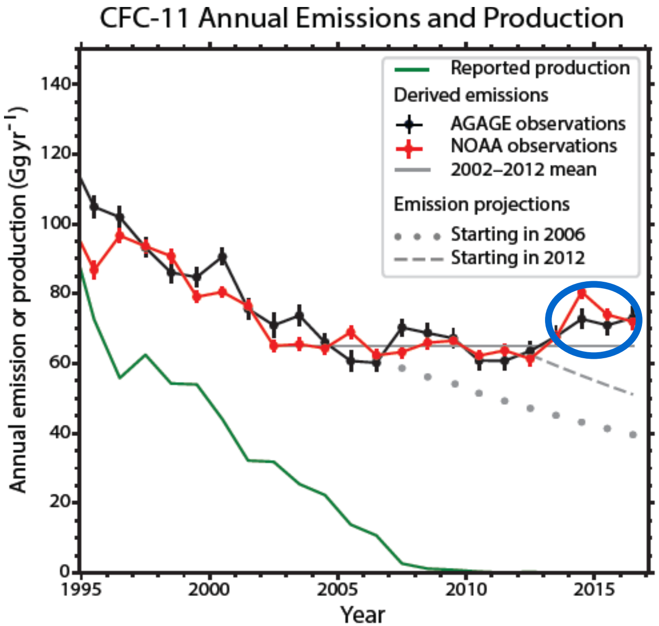
Avg. total ozone within SH polar vortex on 15Sept. – 15 Oct.
~1.5DU.y^{-1} since 2001

Ozone Mass Deficit

Pazmino et al., 2018

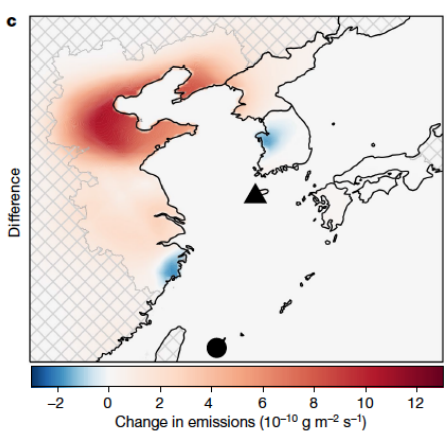
New threats to the ozone layer

Unexpected increase of CFC-11 emissions



Increase of 13 $Gg.y^{-1}$ (25%)

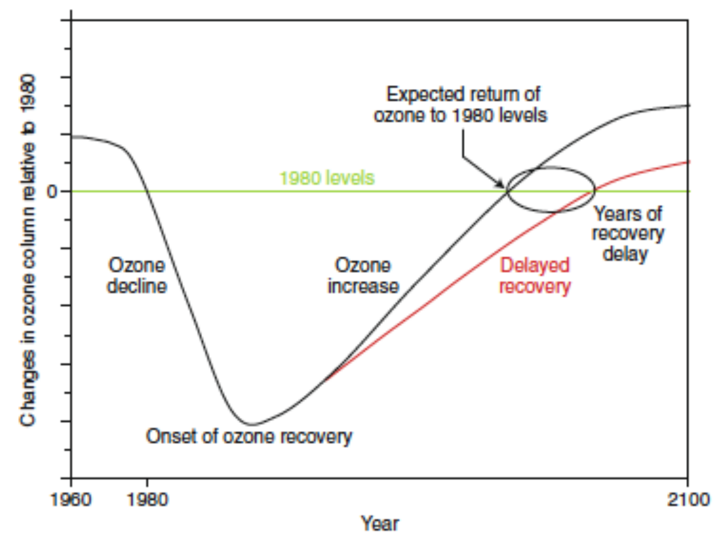
Montzka et al., Nature, 2018



Eastern China

Rigby et al., Nature, 2019

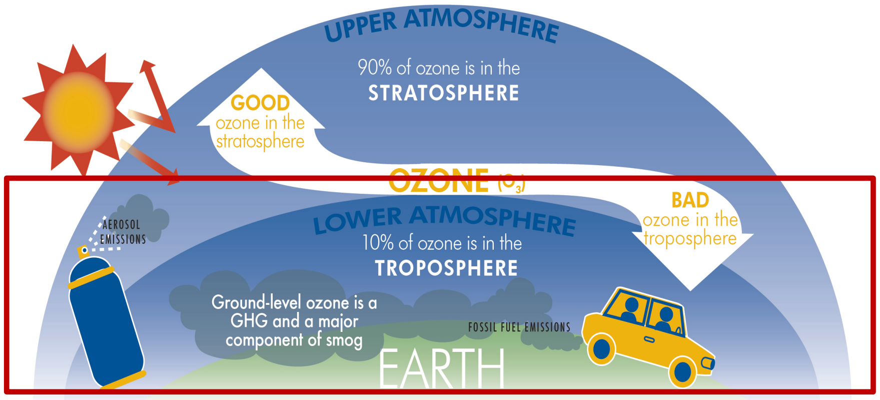
- Slower than expected decrease of CCl_4 and other controled ODS (CFC-13, CFC-113a, CFC-114, CFC-115)
- Increase of VSLS: CH_2Cl_2 and $CHCl_3$
- Increase of stratospheric background aerosols (volcanoes, fires, geoengineering?)



WMO/UNEP, 2018

Fang et al., Nature Geoscience, 2019

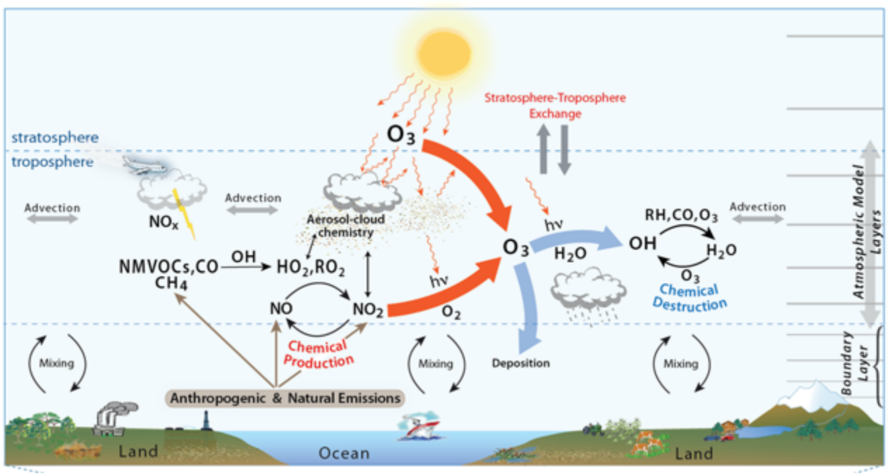
Ozone in the troposphere



Main characteristics

- 10 % of atmospheric ozone
- Strong oxidant detrimental to human health, crops and ecosystems
- Radiative gas: contributes to global warming

Main processes affecting tropospheric ozone

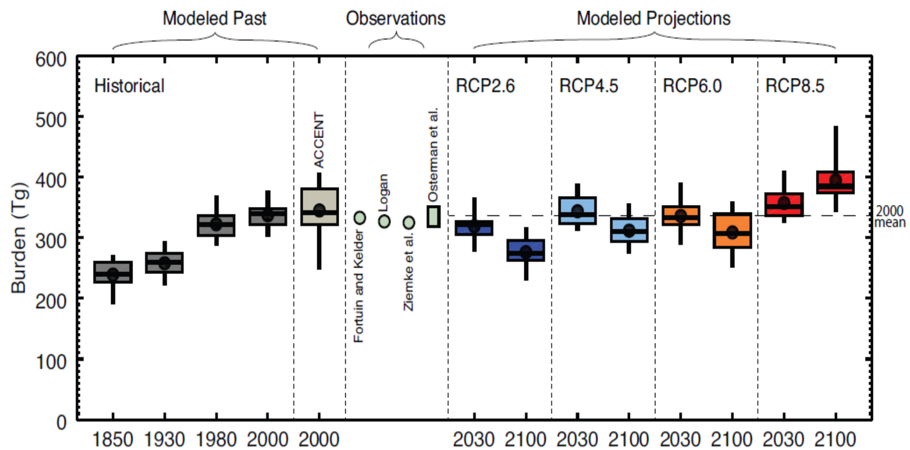


- Stratosphere-troposphere exchange
- Photochemical formation: sun + precursors (NOx, CO and VOC)
- Photochemical destruction in low NOx conditions (OH-HO_2 cycle)
- Dry deposition on the ground

Young et al., 2018

Ozone radiative forcing

Historical evolution of tropospheric ozone



IPCC report, 2013

Ozone 3rd most important greenhouse gas after CO_2 and CH_4

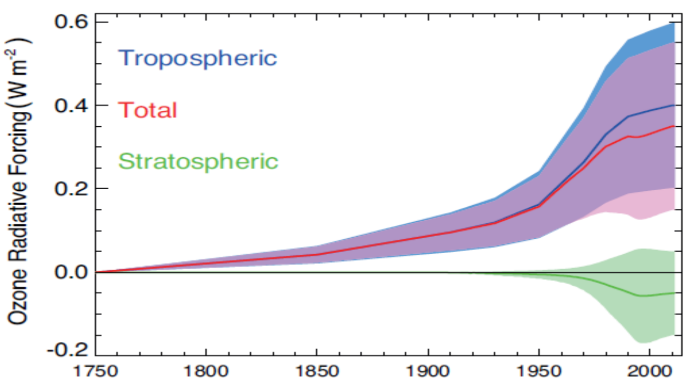


Figure 8.7 | Time evolution of the radiative forcing from tropospheric and stratospheric ozone from 1750 to 2010. Tropospheric ozone data are from Stevenson et al. (2013) scaled to give 0.40 W m^{-2} at 2010. The stratospheric ozone RF follow the functional shape of the Effective Equivalent Stratospheric Chlorine assuming a 3-year age of air (Daniel et al., 2010) scaled to give –0.05 W m^{-2} at 2010.

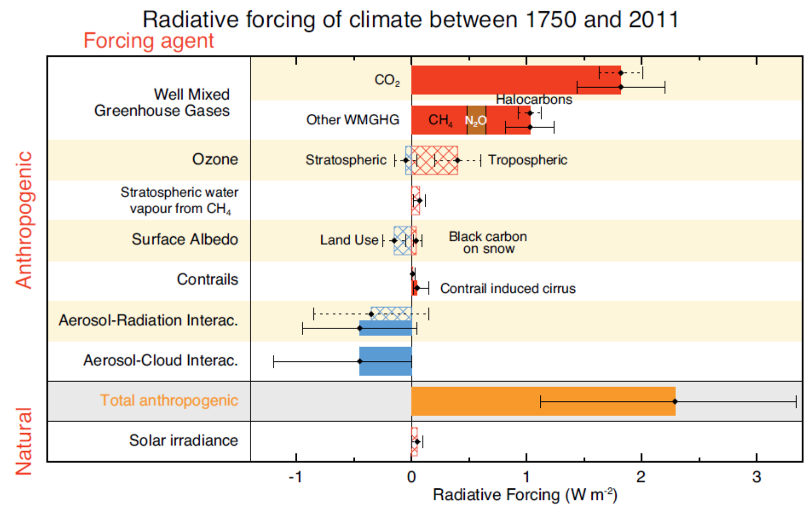
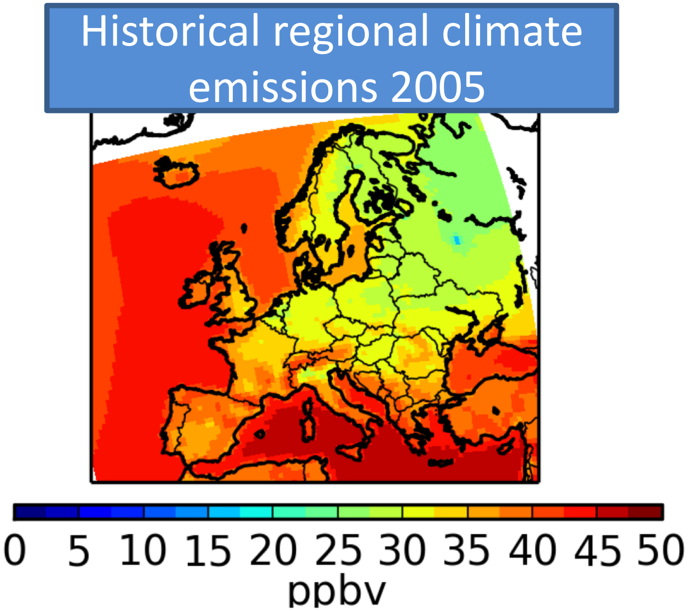
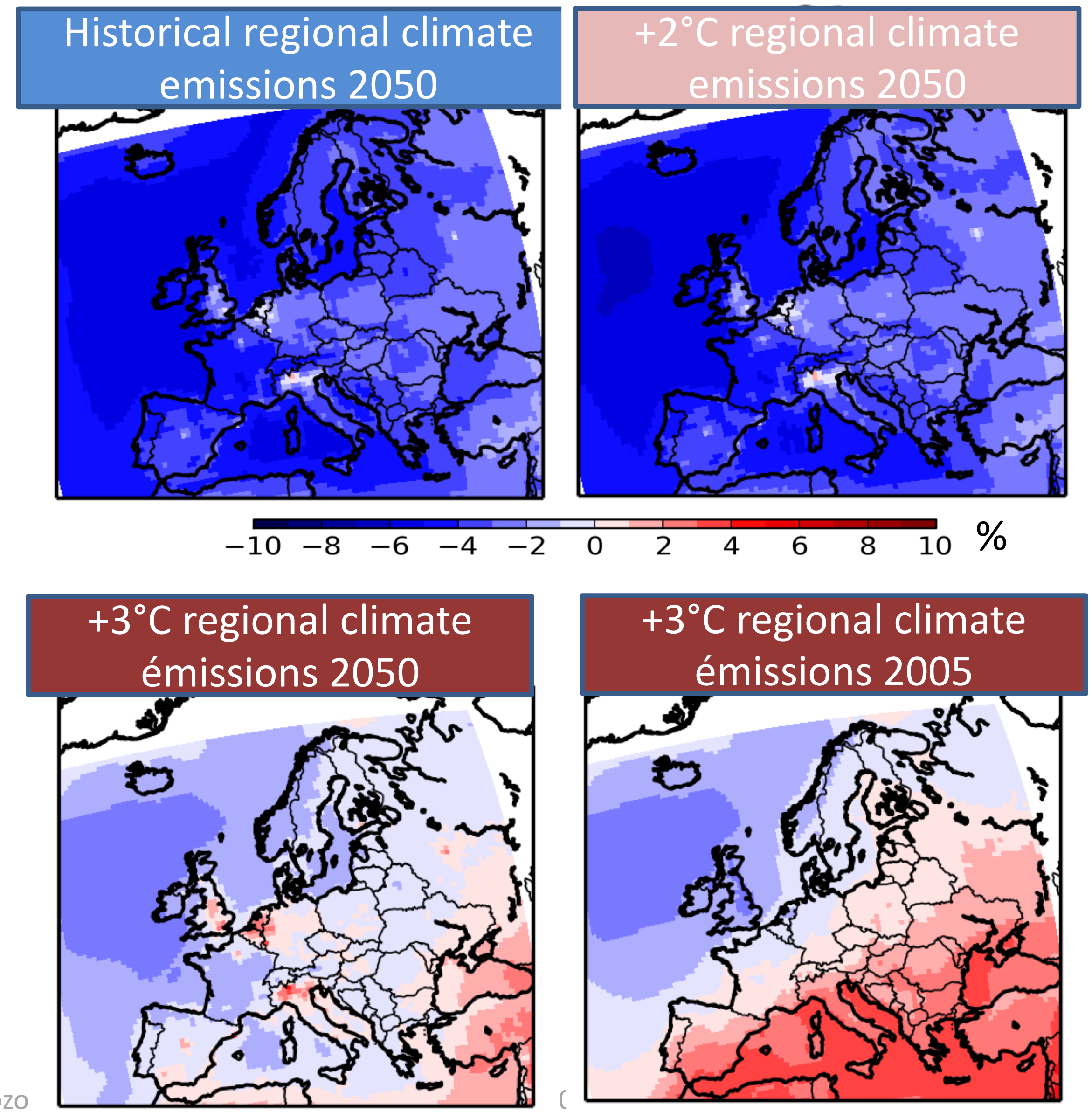


Figure 8.15 | Bar chart for RF (hatched) and ERF (solid) for the period 1750–2011, where the total ERF is derived from Figure 8.16. Uncertainties (5 to 95% confidence range) are given for RF (dotted lines) and ERF (solid lines).

Impact of climate change on future surface ozone





- Strong reduction due to European emissions reduction
- Small impact of +2°C climate change
- +3°C: Important increase

→ impact of large scale methane increase

Fortems-Cheney et al., Nature Com., 2017

Some results from TOAR IGAC activity

Coordinated by Owen Cooper
NOAA, USA

up-to-date scientific assessment of tropospheric ozone's global distribution and trends from the surface to the tropopause.

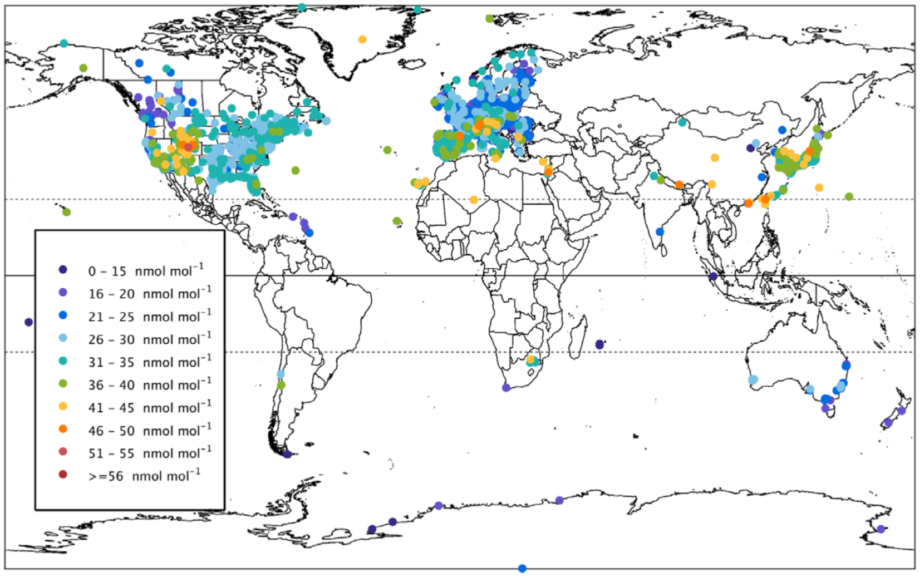
Goals:

- Produce first tropospheric ozone assessment report based on the peer-reviewed literature and new analyses.
- Generate easily accessible and documented data on ozone exposure and dose metrics at hundreds of measurement sites around the world (urban and non-urban), freely accessible for research on the global-scale impact of ozone on climate, human health and crop/ecosystem productivity.

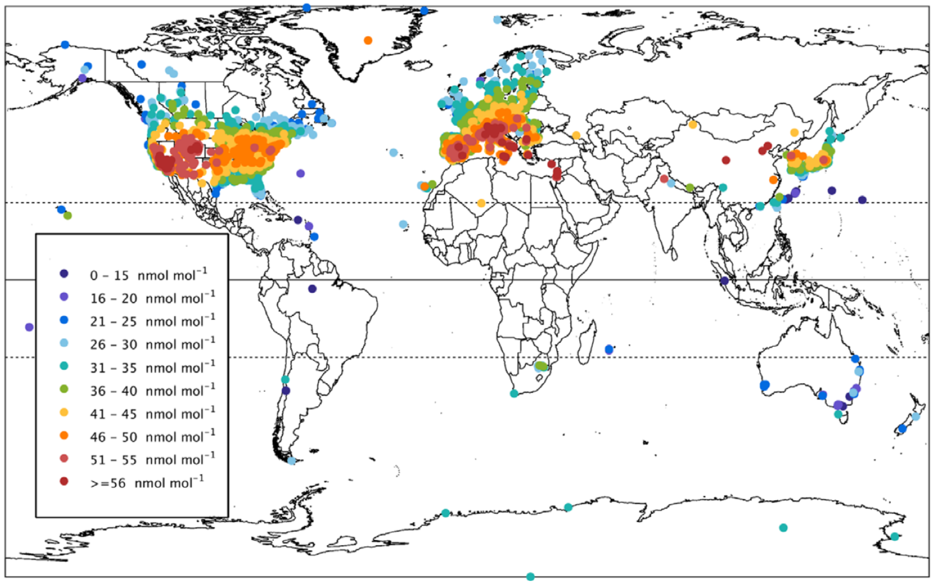
Result articles published in special issue of Elementa
https://collections.elementascience.org/toar

Present day distribution of surface ozone

Present-day global daytime average ozone (nmol mol^{-1}) 2010 – 2014



December–January–February
2702 non-urban sites

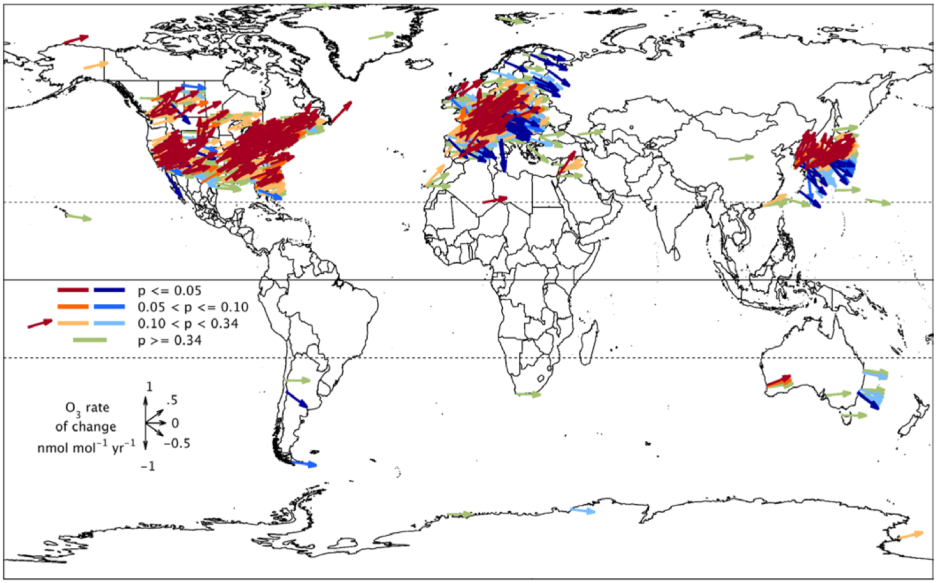


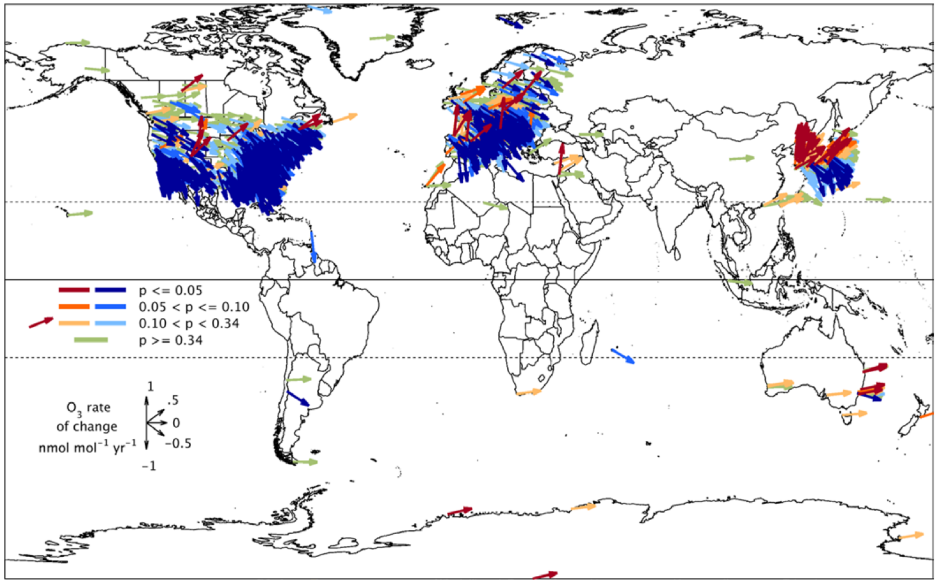
June–July–August
3136 non-urban sites

Gaudel, A, et al. 2018. Tropospheric Ozone Assessment Report: Present-day distribution and trends of tropospheric ozone relevant to climate and global atmospheric chemistry model evaluation. Elem Sci Anth, 6: 39. DOI: https://doi.org/10.1525/elementa.291

Surface ozone trends

2000 – 2014 trends of daytime average ozone (nmol mol^{-1} yr^{-1})





December–January–February
1375 non-urban sites

June–July–August
1786 non-urban sites

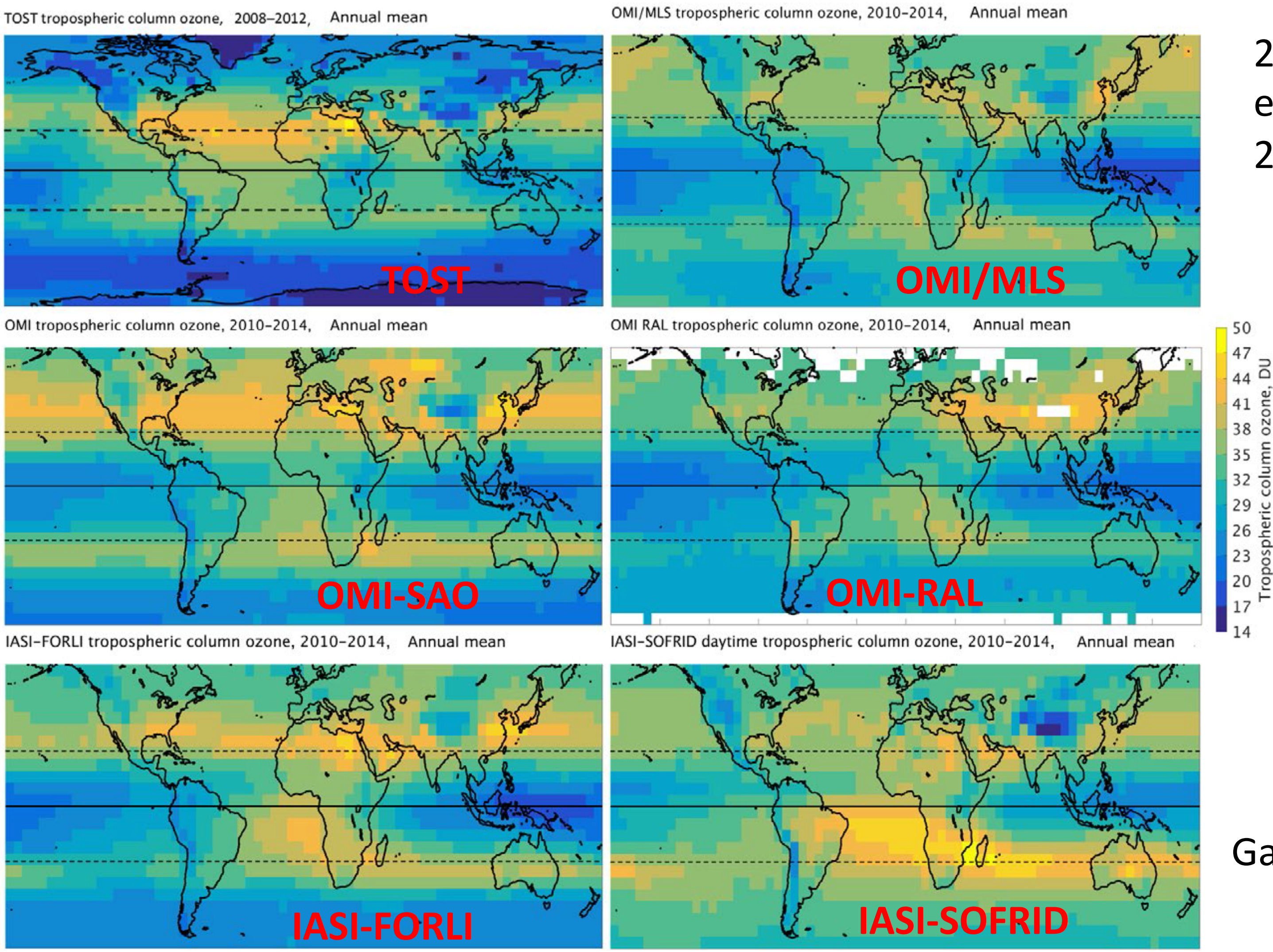
Vector colors: p-values on the linear trend for each site

blue: negative trends,
orange: positive trends
green: weak or no trend

Gaudel et al., 2018

Tropospheric column ozone

Annual mean TCO (DU) from five satellite products and ozonesondes (TOST)



2010 – 2014
except TOST:
2008–2012

Gaudel et al., 2018

Tropospheric ozone column trends

TOST
2003-2012

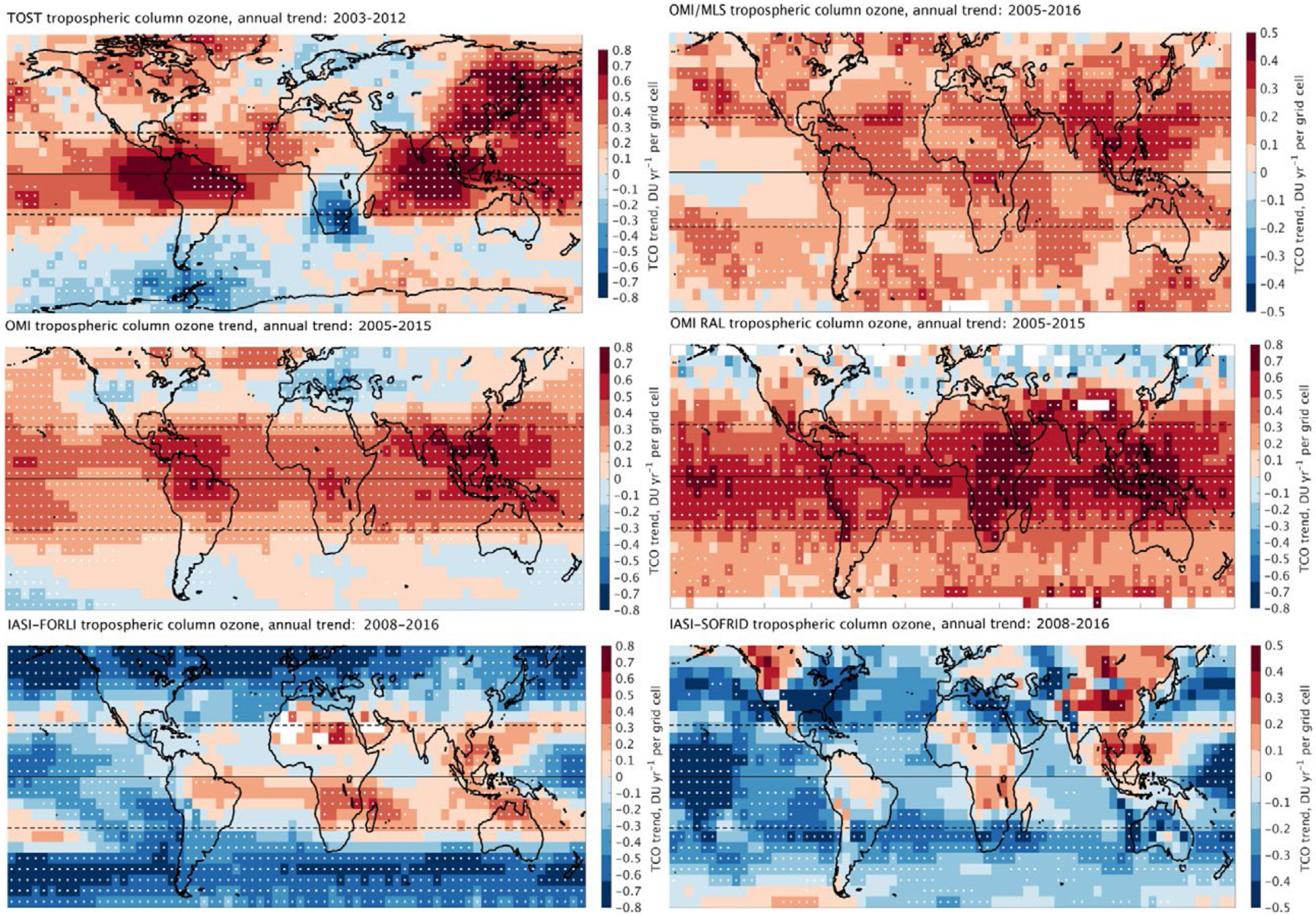
OMI/MLS
2005 - 2016

OMI-SOA
2005-2015

OMI-RAL
2005 - 2015

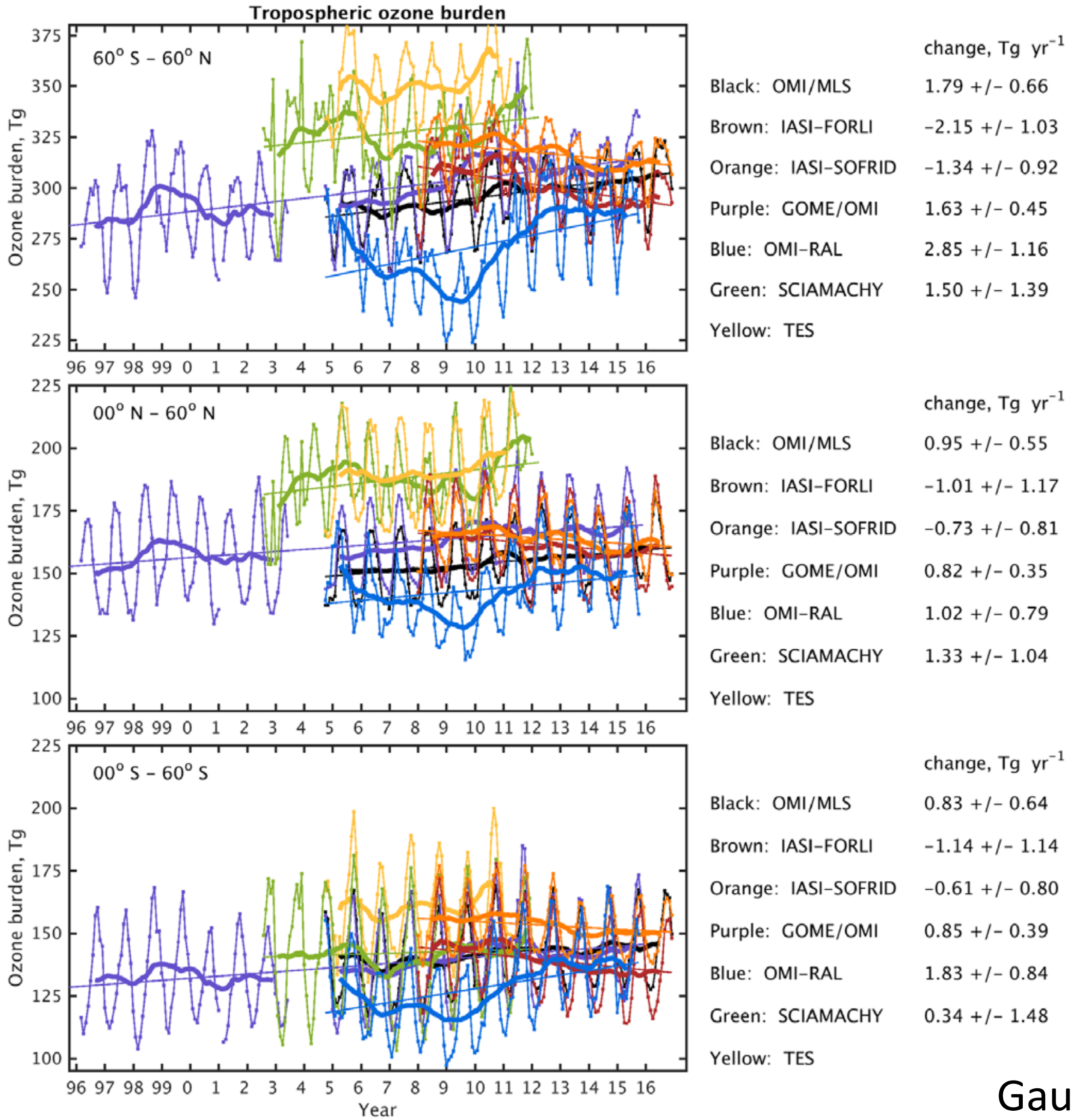
IASI-FORLI
2008-2016

IASI-SOFRID
2008 - 2016



Gaudel et al., 2018

Evolution of tropospheric ozone burden



Discrepancies in tropospheric column ozone is a problem also for interpreting total ozone trends at global scale

Gaudel et al., 2018

Conclusions

- Ozone very important gas in the atmosphere for climate and health
- Thanks to the Montreal Protocol, ozone layer should return to pre-1980 level by the second half of 21st century.
- Non compliance to Montreal Protocol, increase of unregulated ODS and other parameters (N_2O, aerosol including geoengineering) could delay the recovery
- MP pioneers verification of compliance to environmental treaties
- Climate benefits of MP are significant since ODS are powerful greenhouse gases (Kigali amendment for HFC)
- Issues in the evaluation of UTLS and tropospheric ozone trends
- Evaluation of future ozone levels needs an adequate ozone monitoring system: **ground-based ozone records such as the very long Uccle ozone sonde time series are extremely precious**

Collaboration between IRM and CNRS related to ozone soundings

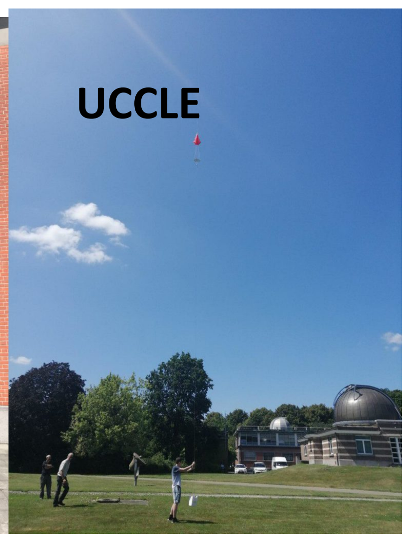
GEOPHYSICAL RESEARCH LETTERS, VOL. 23, NO. 9, PAGES 1033-1036, MAY 1, 1996

Climatology of tropopause folds at midlatitudes

Philippe Van Haver and Dirk De Muer
Royal Meteorological Institute of Belgium

Matthias Beekmann and Christelle Mancier
Service d'Aéronomie du CNRS, Université Paris 6

On the average 4.8 % of the ozone soundings performed at Uccle show the presence of a tropopause fold, while only 2% at OHP. Although this difference has a considerable statistical uncertainty, due to the small absolute number of folds detected at OHP, it might reflect that the more northerly Uccle station is located closer to the average position of the polar jet stream.



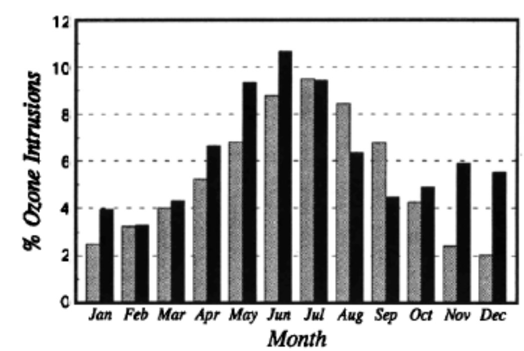
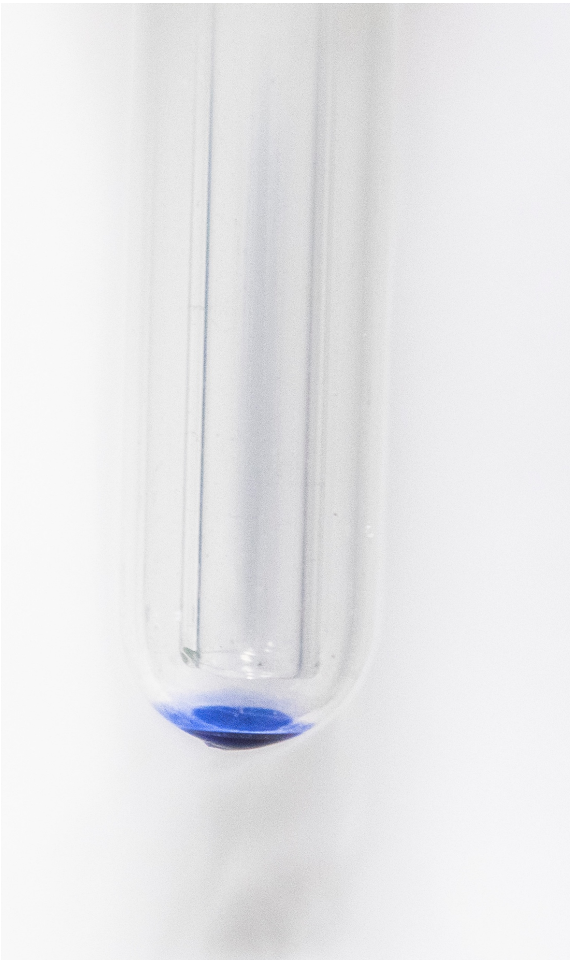


Figure 4. Three monthly running mean of the percentage of stratospheric ozone intrusions observed at Uccle (grey) and the OHP (black), obtained from cases where the conditions 1-3 and an adjusted condition 4 (absence of a jet stream), are fulfilled.

The true color of ozone



Credit: Christof Janssen, CNRS

Thank you !