The contribution of GOME and Envisat to ozone research

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Gabriele Stiller3, Hebert Fischer3 and all MIPAS team members
Erkki Kyrölä4, Johanna Tamminen4, Alain Hauchecorne, Jean-Loup Berteaux and all GOMOS team members

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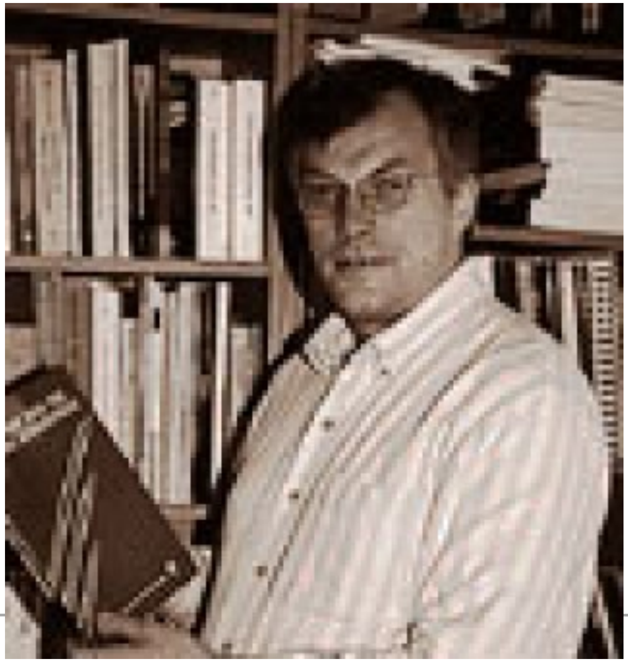
Professor Ivar S. A. Isaksen

This talk is dedicated to celebrating the life of Professor Ivar S. A. Isaksen

Ivar led of our field for the past 50 years, a teacher mentor and a co- investigator of SCIAMACHY. An outstanding academic, athlete, and gentleman.
It was my honour to have known you and your family.



SCIAMACHY

CarbonSat Constellation

Why observe the atmosphere from space?

Earth has entered a new epoch, the Anthropocene (E. F. Stoermer and P. J. Crutzen 2001 IGBP) - the Earth System is changing!

image: NASA

From the Neolithic Revolution to 1800 population rose from 4M to 1B

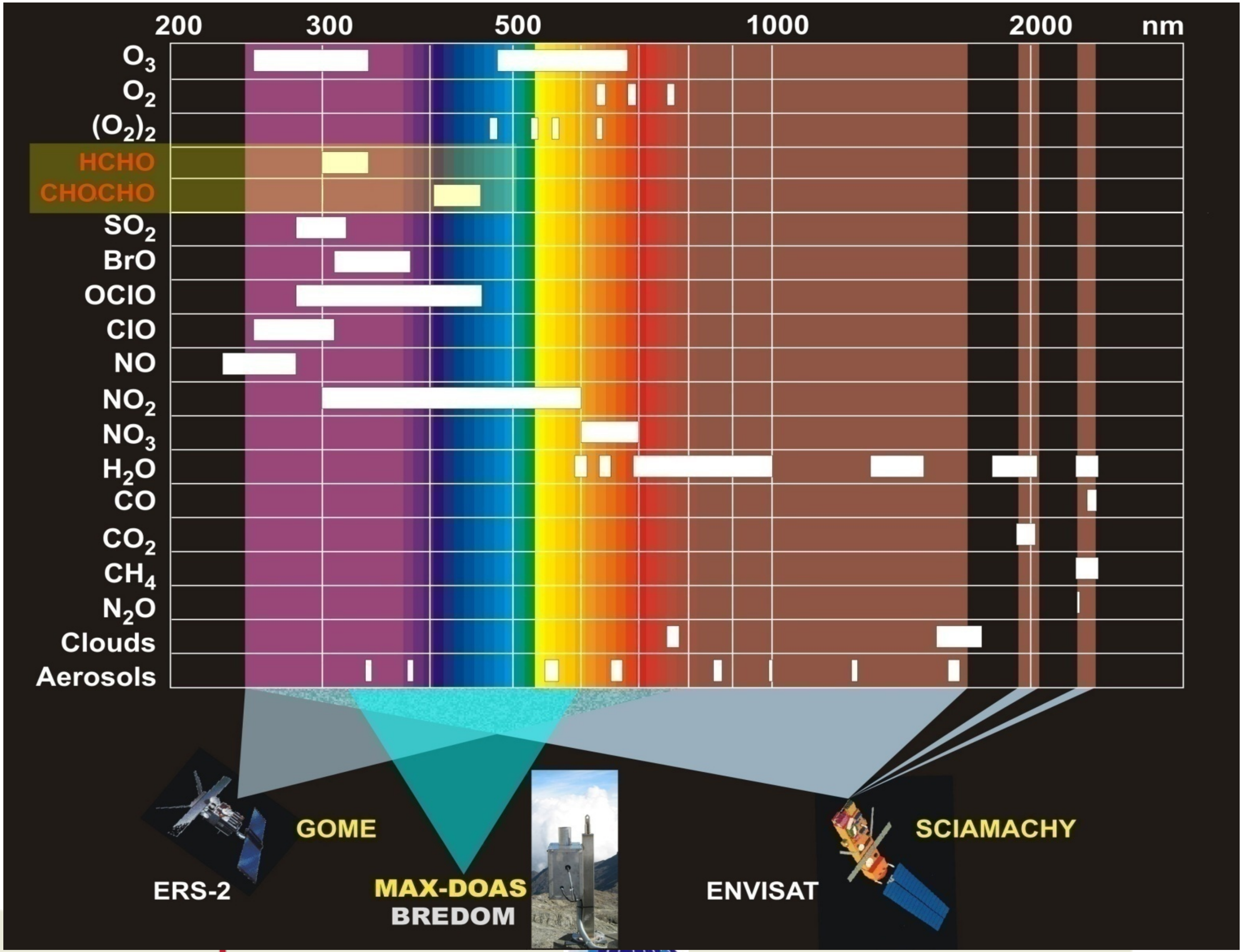
Dramatic changes in population and anthropogenic emissions since 1800! Now + 7B over 50% Urban

Energy supplied primarily by fossil fuel combustion => Release of **Long Lived Greenhouse Gases and Short Lived Climate Pollutants**

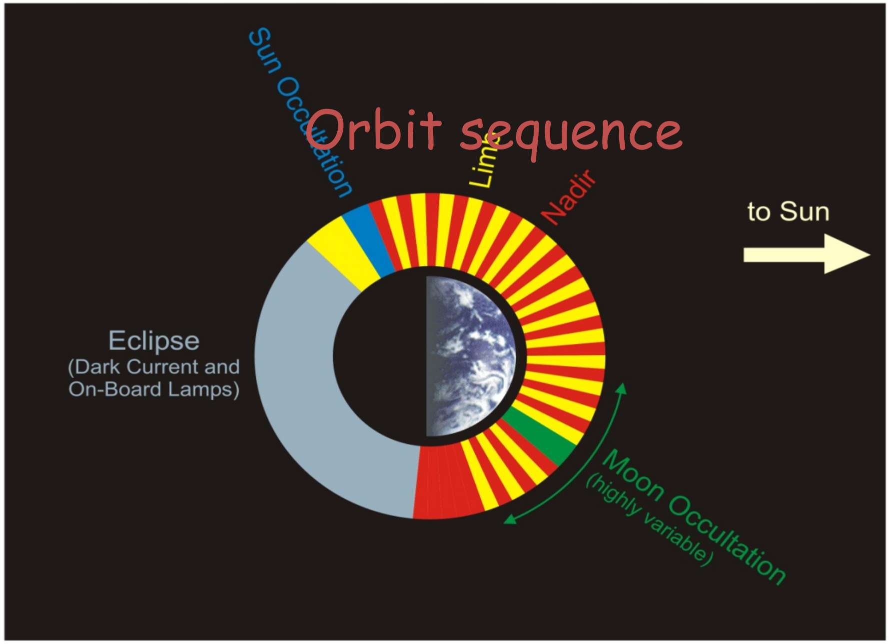
- ⇨ Global transport and transformation of pollution and land use change
- ⇨ Climate Change - Chemistry climate feedback
- ⇨ Global destruction of stratospheric ozone

- ⇨ **It is *impossible* to understand/manage *species or conditions not measured!!***
- ⇨ **Environmental/Climate Change requires Global Observations**
- ⇨ **Evidence base for science (understanding and prediction) and policymaking (mitigation and adaptation)**

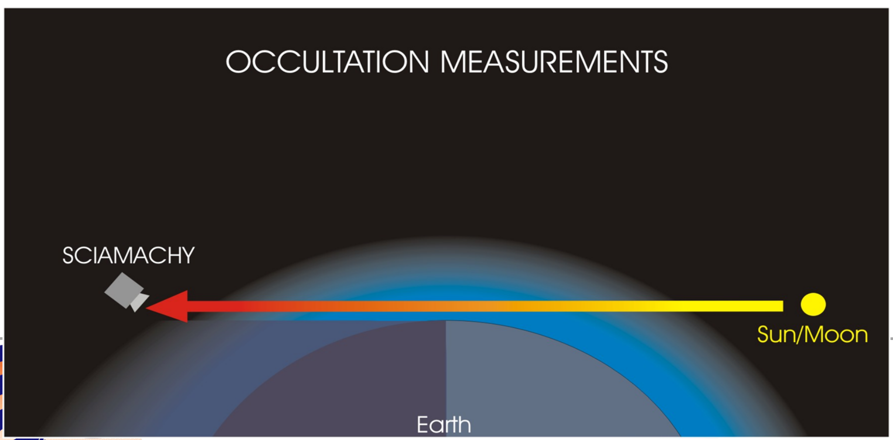
SCIAMACHY: Target Molecules

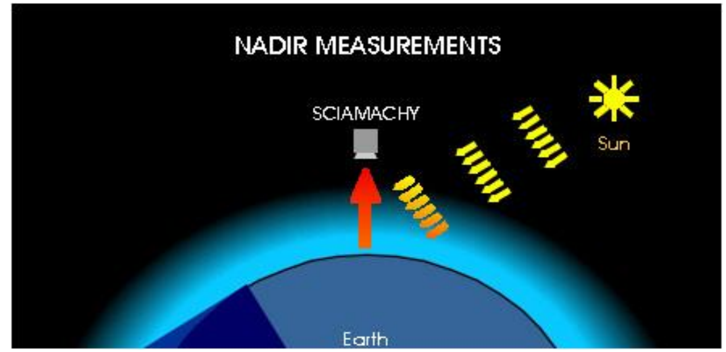


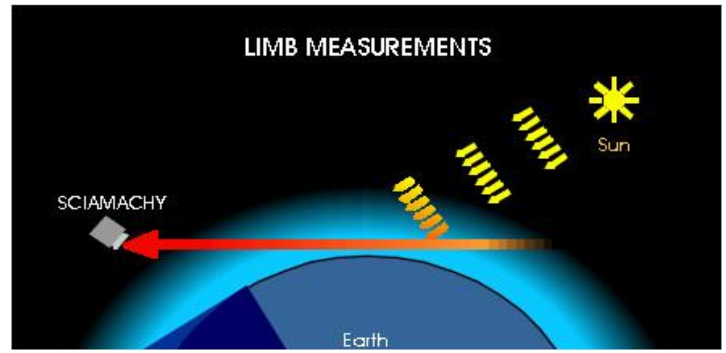
SCIAMACHY: orbit sequence & viewing modes

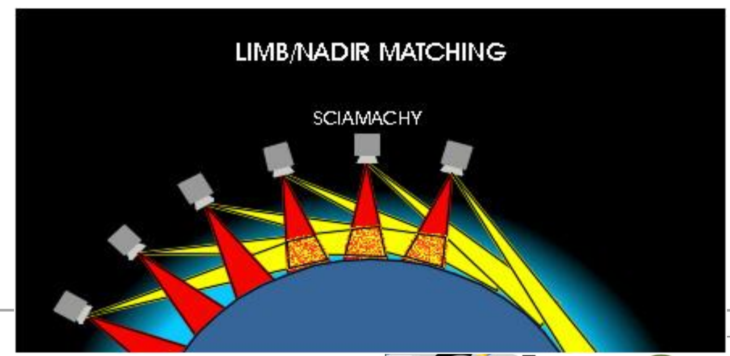


Viewing modes





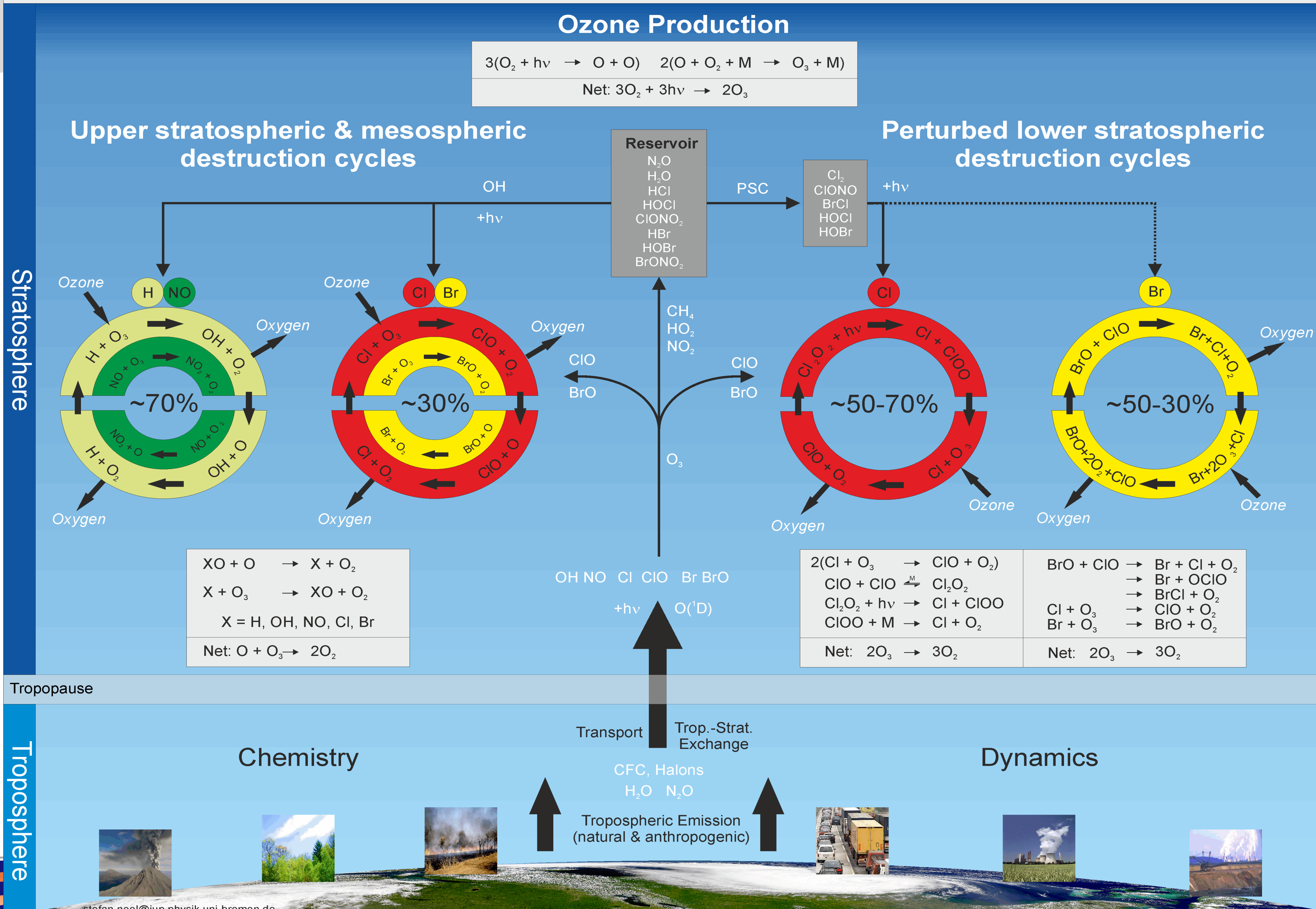




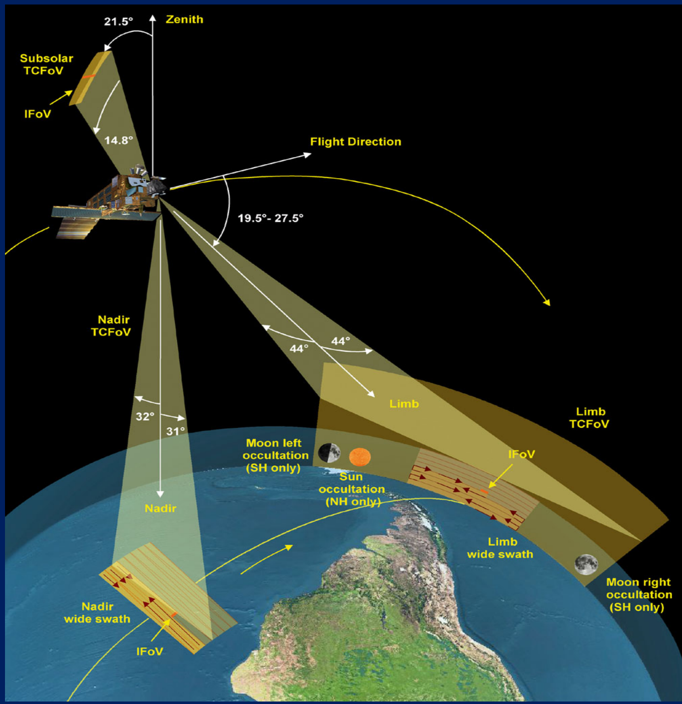
European LEO and GEO Passive Remote Sensing of trace constituents in the Anthropocene - Some Relevant History

1984-1988	Development and Submission to ESA for POEM/ Envisat AO, of SCIAMACHY (Scanning Imaging Absorption spectroMeter for Atmospheric CHartographY)
1988	Proposal of SCIA-mini for ERS-2 later descrped to GOME
1989	Selection of SCIAMACHY for ENVISAT
1990	Selection of GOME for ERS-2
1995	Launch of GOME 20.04.1995
1998	Proposal of GeoSCIA IUP/IFE-UB to ESA EEM-1
2002	Proposal of GeoSCIA++ UV-VIS-NIR-SWIR-TIR/Ligthning/firto ESA EEM-2
2002	Launch of SCIAMACHY on ENVISAT 28.02 2002
2002	Proposal of GeoTROPE UV-VIS-NIR-SWIR-TIR to ESA EEM-3
2004/5	Proposal of GeoSCIA-R and GeoSCIA-Lite
2006	EUMESAT Post Metop Committee recommends GOME-2 follow on UVNS
2006	Methane and carbon dioxide Mapper MaMap 01– Aircraft - UB
2006	EU Copernicus funds UVNS/Sentinel 5 Metop Second Generation
2006	Launch of GOME-2 on MetOp A
2008	CarbonSat and CarbonSat Constellation studies at UB - SCIA Heritage
2010	CarbonSat selected for ESA EE8 Phase AB1 Studies
2011	Start of SCIA-ISS studies UB NICT / Decommssioning of ERS-2
2012	Loss of Envisat 9th April
2012	Launch of GOME-2 on Metop-B 17th September
2013	Sentinel 5 agreed for Metop Second Generation 2020- 2034
2016	Copernicus Carbon initiative started
2017	Planned Launch of Sneitnel 5 Precursor planned for October 2017

Ozone Production & Catalytic Destruction



LEO Early Morning, Afternoon and Geostationary DOAS Instrumentation



LEO Early Morning sun synchronous, Eq.crossing time 10:30 10:00 09:30

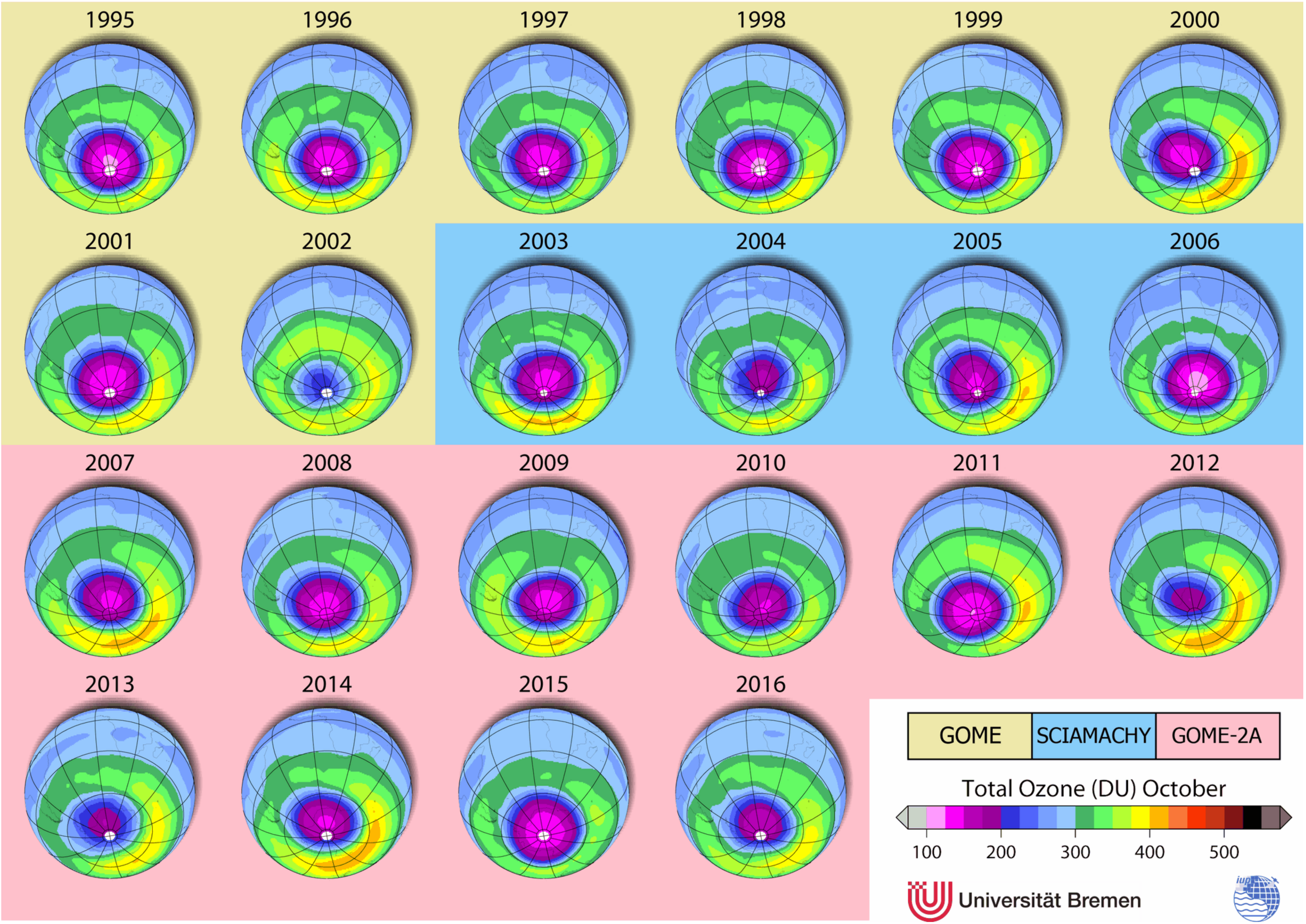
GOME (SCIA-mini) on ESA ERS-2 1995-2011

SCIAMACHY onboard ENVISAT 2002 -2012
relatively high spectral resolution (0.2 nm to 0.5 nm), 240 – 2380 nm
(8 spectral channels), Pixel size: 30 km × 60 km at best;
Nadir/limb alternating measurements.

GOME-2 onboard MetOp-A, -B, -C 2007-2020
(MetOp-A / –B in operation since 2006 / 2012, MetOp-C planned for 2018)
ESA Sentinel 5 on Metop Second Generation 2020-2035

Early Afternoon sun synchronous, Eq.crossing time ~13:30
OMI onboard NASA AURA 2004-present
ESA Sentinel-5P/ TROPOMI to be launched October 2017

GEO Geostationary diurnal variation — all independent to be launched 2019
Sentinel 4 (GeoSCIA) on Meteosat Third Generation — Europe North Africa
GEMS KSA — East Asia



1995
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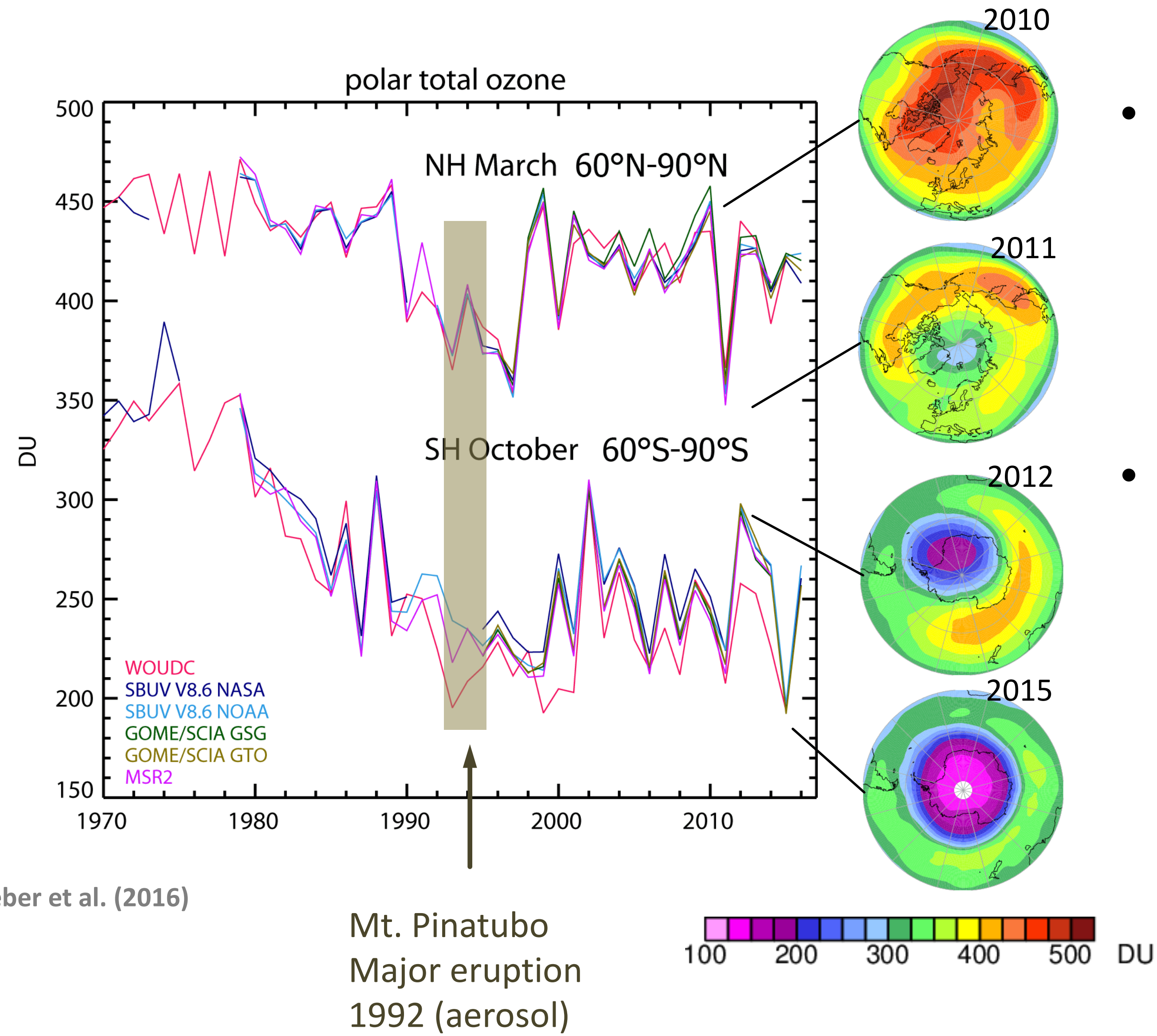
2014
2015
2016
GOME
SCIAMACHY
GOME-2A
Total Ozone (DU) October
100
200
300
400
500
Universität Bremen

Polar ozone timeseries

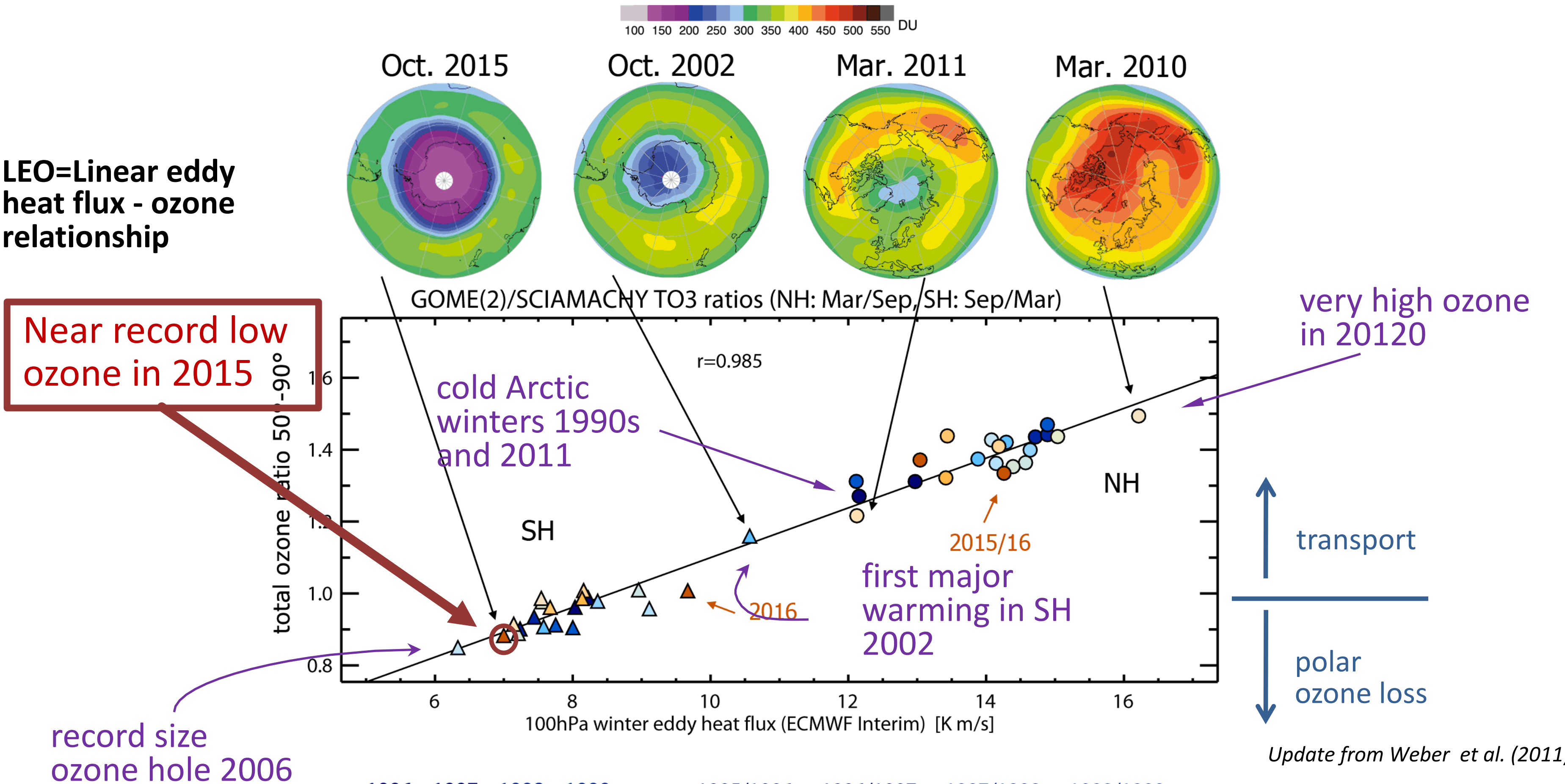


Weber et al. (2016)

- Apart from the large year-to-year variability polar ozone has been „stable“ since ~2000
- Ozone recovery is expected to be slower in the polar region than elsewhere (chemistry-climate-models)

Coupling of transport and chemistry („LEO“)

LEO=Linear eddy heat flux - ozone relationship



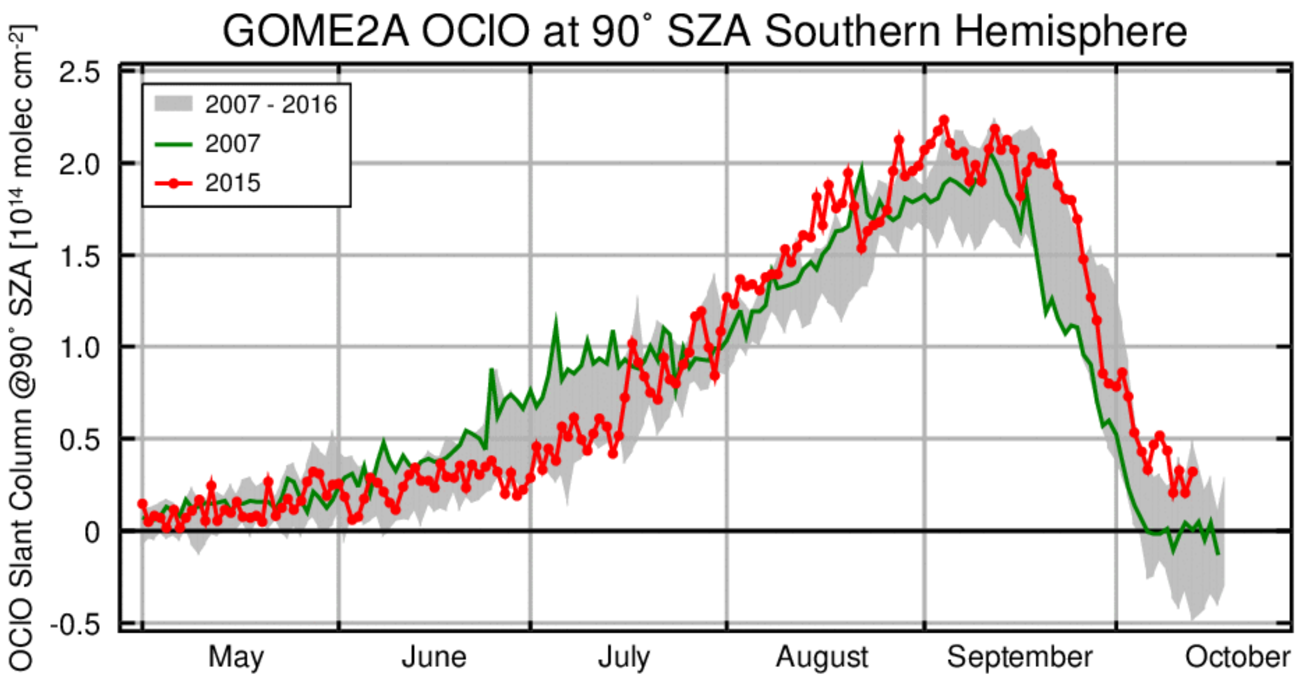
Update from Weber et al. (2011)

1996	1997	1998	1999	1995/1996	1996/1997	1997/1998	1998/1999
2000	2001	2002	2003	1999/2000	2000/2001	2001/2002	2002/2003
2004	2005	2006	2007	2003/2004	2004/2005	2005/2006	2006/2007
2008	2009	2010	2011	2007/2008	2008/2009	2009/2010	2010/2011
2012	2013	2014	2015	2011/2012	2012/2013	2013/2014	2014/2015
2016				2015/2016			

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

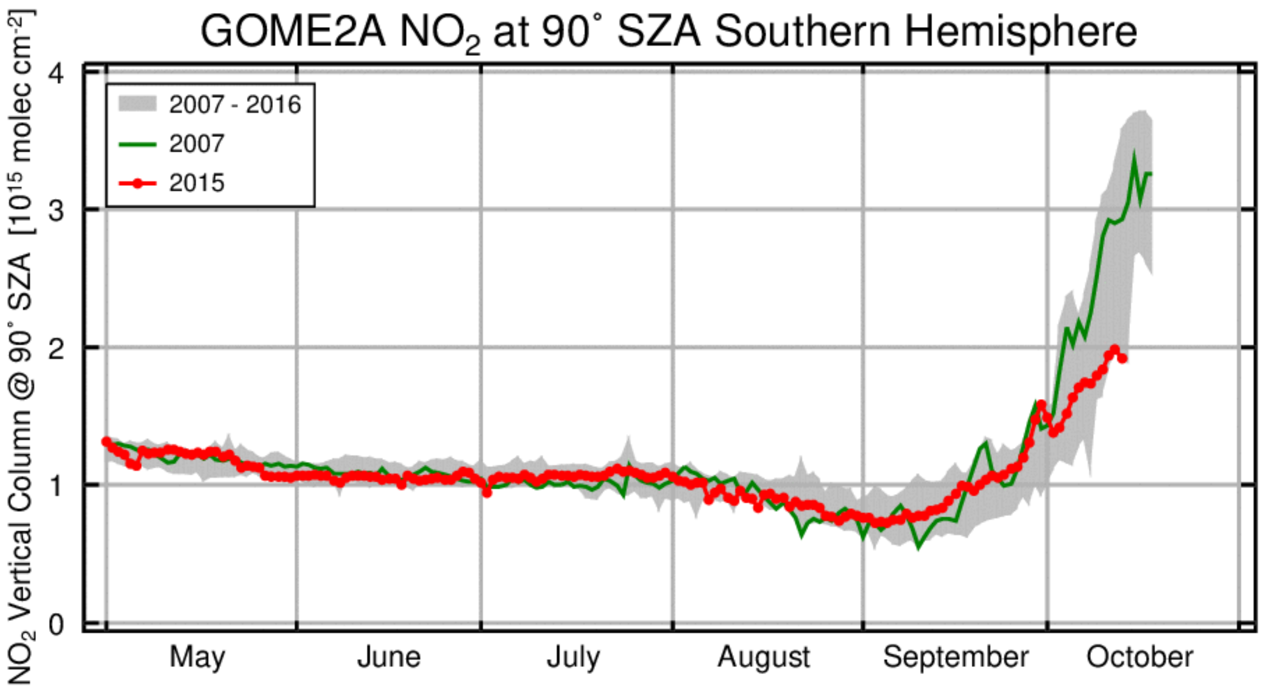
-strong Brewer-Dobson circulation
-high T/weak polar vortex
-enhanced ozone transport

GOME2A OClO Southern Hemisphere



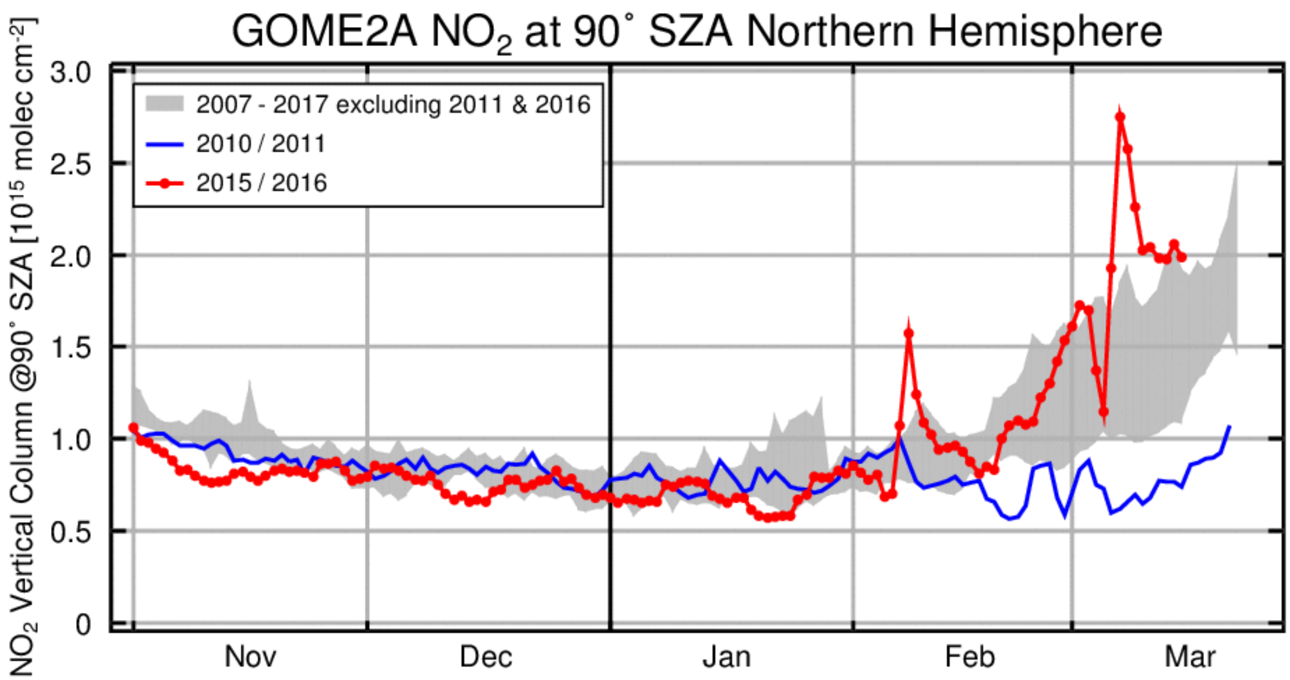
- Little variability in OClO columns in the SH since 2007
- 2015 characterised by relatively late but strong activation
- On most days of August, September and October 2015, OClO was at its maximum

GOME2A NO_2 Southern Hemisphere



- Small variability in NO_2 columns in the SH
- 2015 characterised low values in October (denoxification / denitrification)
- High NO_2 columns in October 2007

GOME2A NO_2 Northern Hemisphere



- Small variability in NO_2 columns in the NH before February
- 2015 / 2016 characterised by low values (denoxification / denitrification)
- High NO_2 columns during warmings in February and March 2016
- 2010 / 2011 winter showed much more persistent low NO_2

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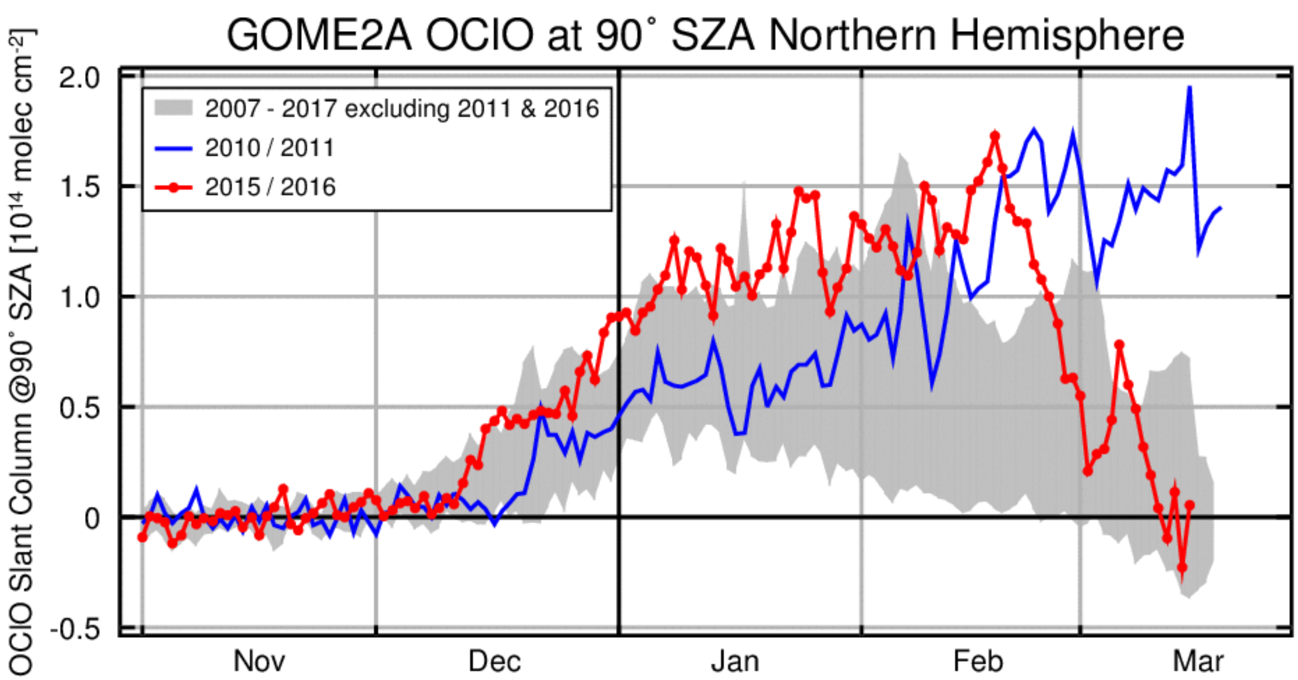
GOME2A OClO Northern Hemisphere



- Large variability in OClO columns in the NH in spring
- 2015 / 2016 characterised by early and strong activation
- On most days from mid December 2015 – mid February 2016, OClO was at its maximum
- Activation stopped earlier than in 2010 / 2011 winter

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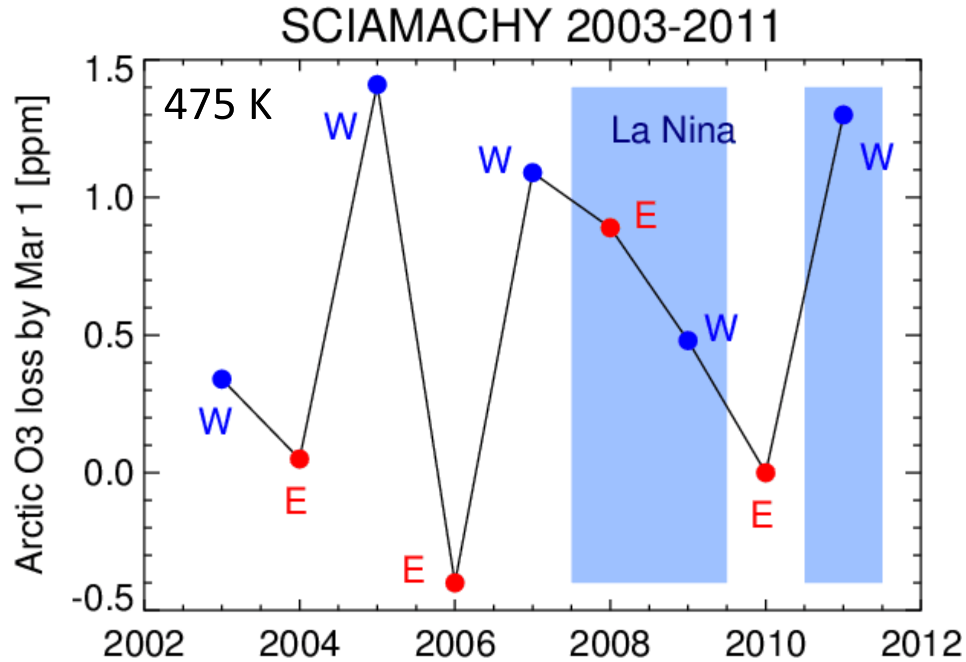
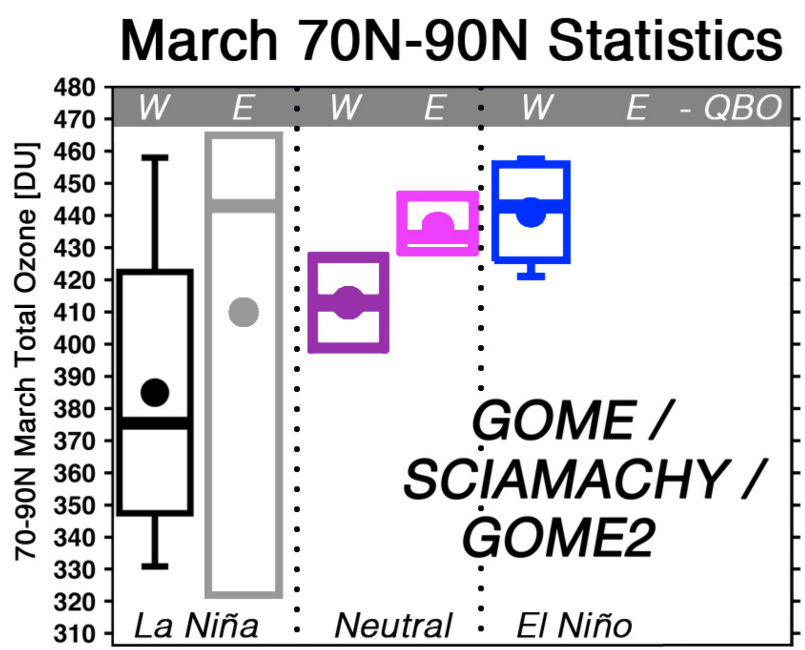
QBO, ENSO and ozone

- 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)

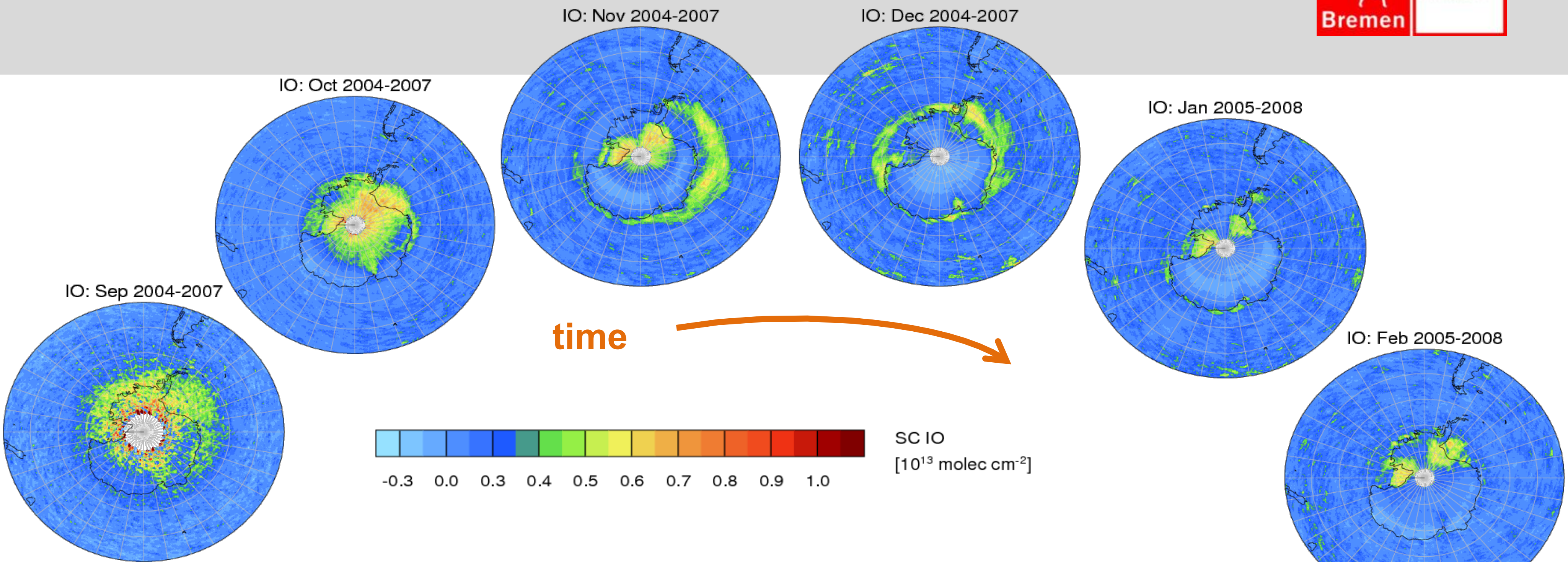


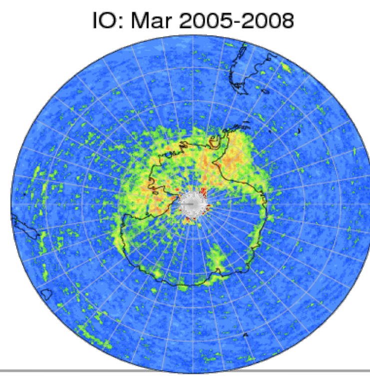
Update from Sonkaew et al., 2013 and Hommel et al., 2013



Hommel et al., in preparation

IO in Antarctica - monthly variation



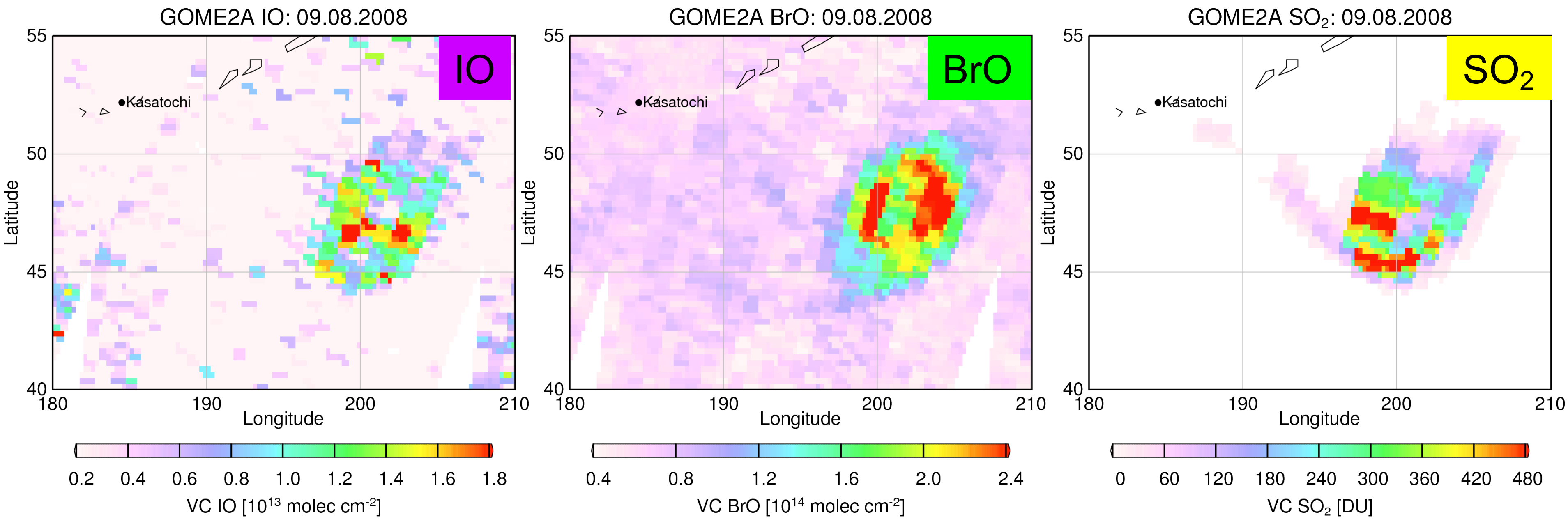


Locations where IO is observed:

- Ice shelves / continent: Enhanced IO is surprising
  - → Direct sources? Possibly transport & recycling
- Coast lines / sea ice : Vicinity to ocean
  - → Release from marine domains (organic or inorganic)

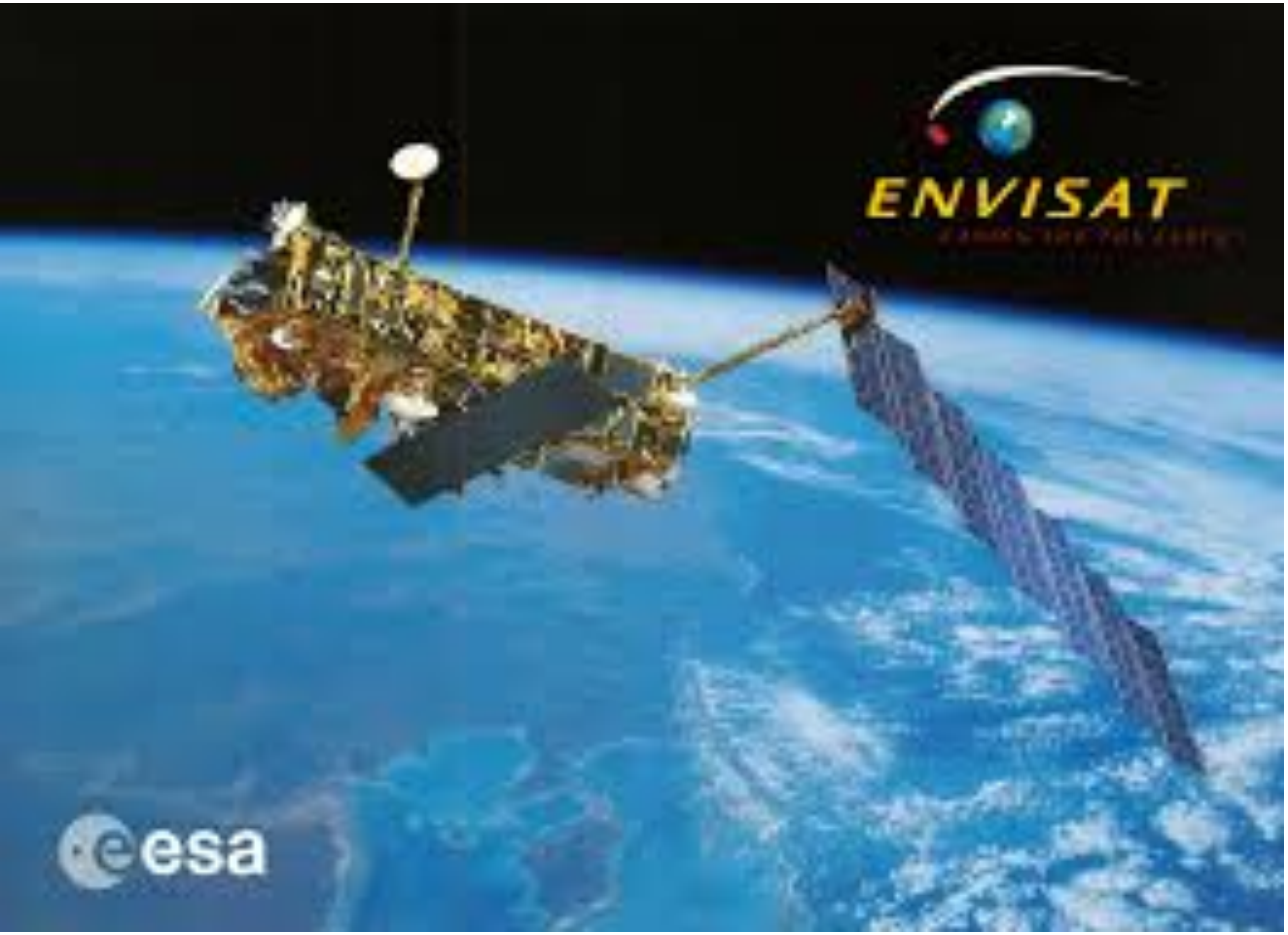
Spatial distribution: Comparison between IO, BrO and SO_2

Example day: 09.08.2008



- Overall plume is in the same location
- Details, e.g., where trace gas maxima are found differ quite strongly
- Differences between halogens and SO_2, but also between IO and BrO

ESA ENVISAT Limb and Occultation 2002 to 2012



GOMOS - Global Ozone Monitoring by Occultation of Stars F + ESA

MIPAS The Michelson Interferometer for Passive Atmospheric Sounding ESA

SCIAMACHY – Scanning Imaging Absorption spectroMeter for Atmospheric CHartographY D, + NL + B + ESA.

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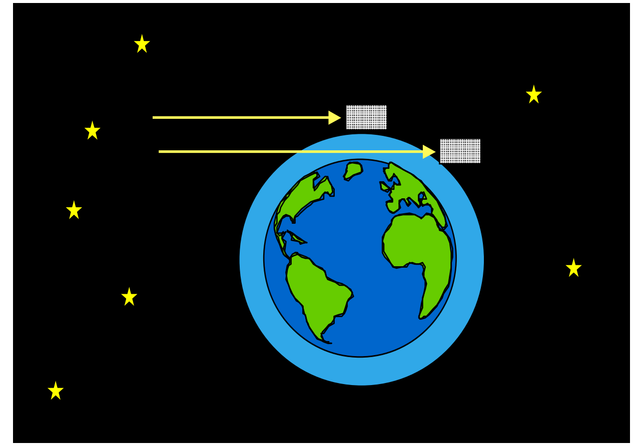
ENVISAT Launch: 1st March 2002, 2:07 CET

GOMOS on ENVISAT 2002-2012

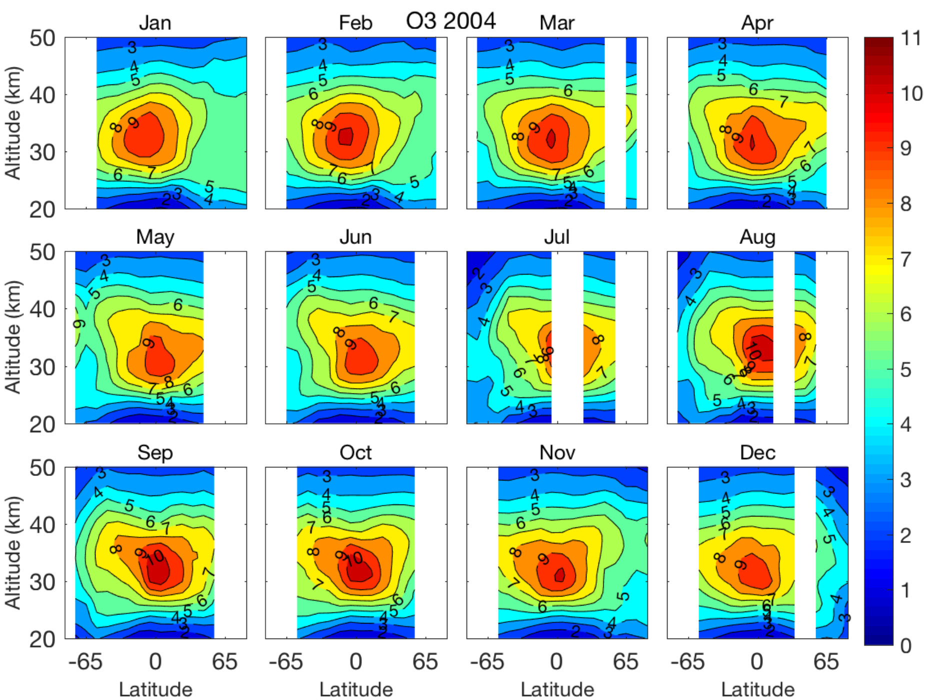
450 000 night occultations
430 000 day occultations

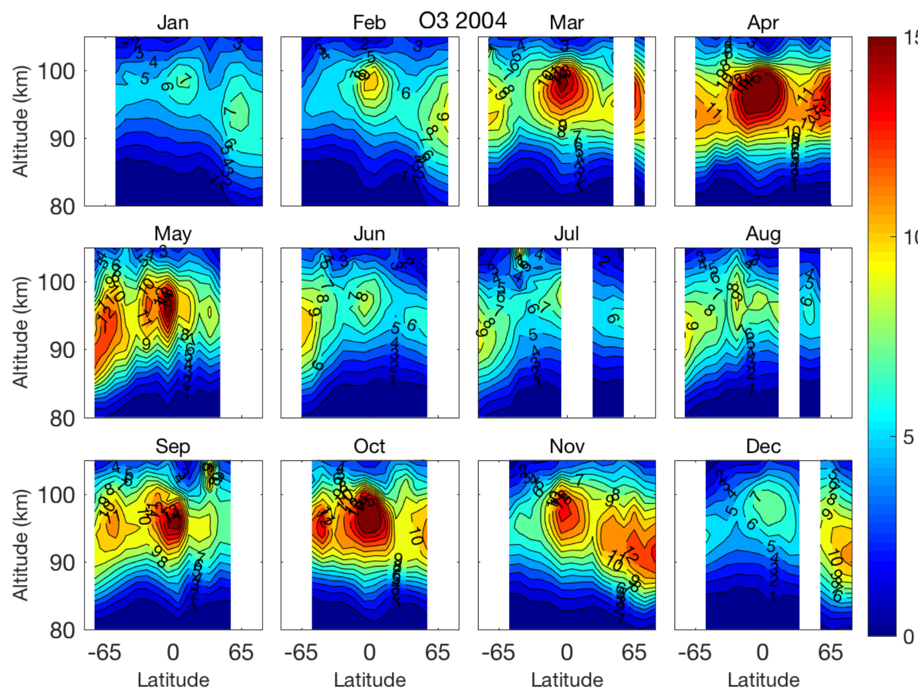
Vertical high resolution profiles of **O_3, NO_2, NO_3, aerosols, temperature (18-35 km)**

Climatologies of nighttime **O_3, NO_2, NO_3, aerosols, OClO, Na, turbulence, temperature, NLC**



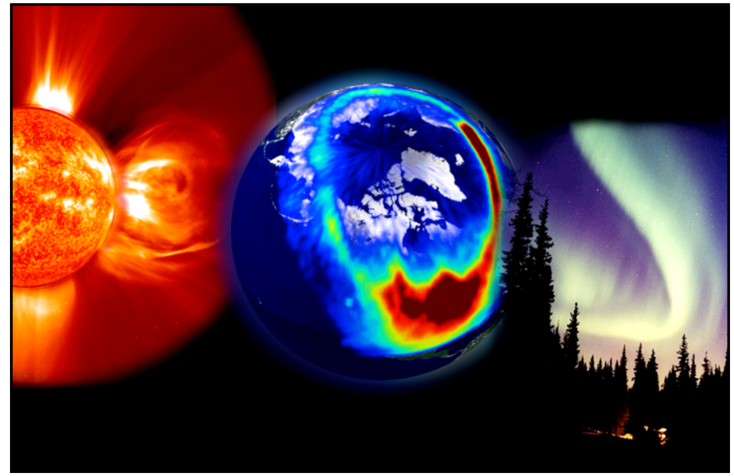
Global Ozone Monitoring by Occultation of Stars



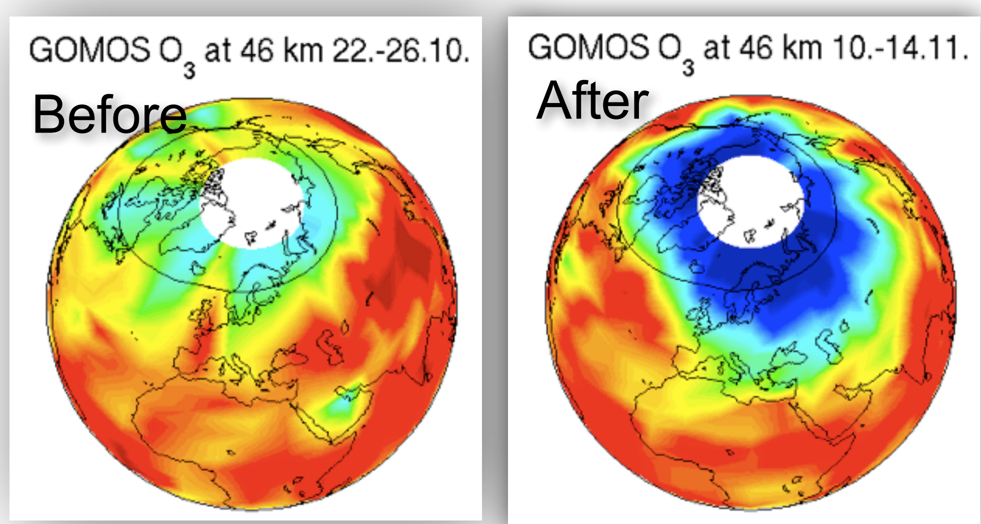


Ozone mixing ratio climatologies in the stratosphere and mesosphere 2004

Solar Storm effects on atmospheric composition



GOMOS observations were the first to show ozone loss from solar storms in the polar wintertime atmosphere.

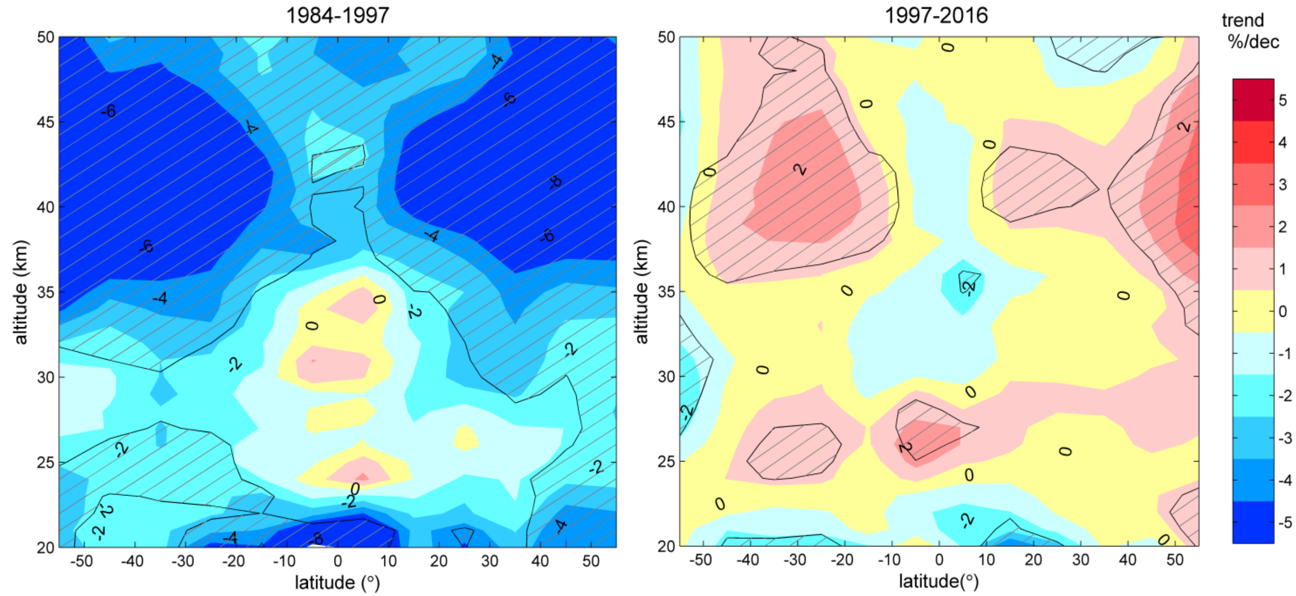


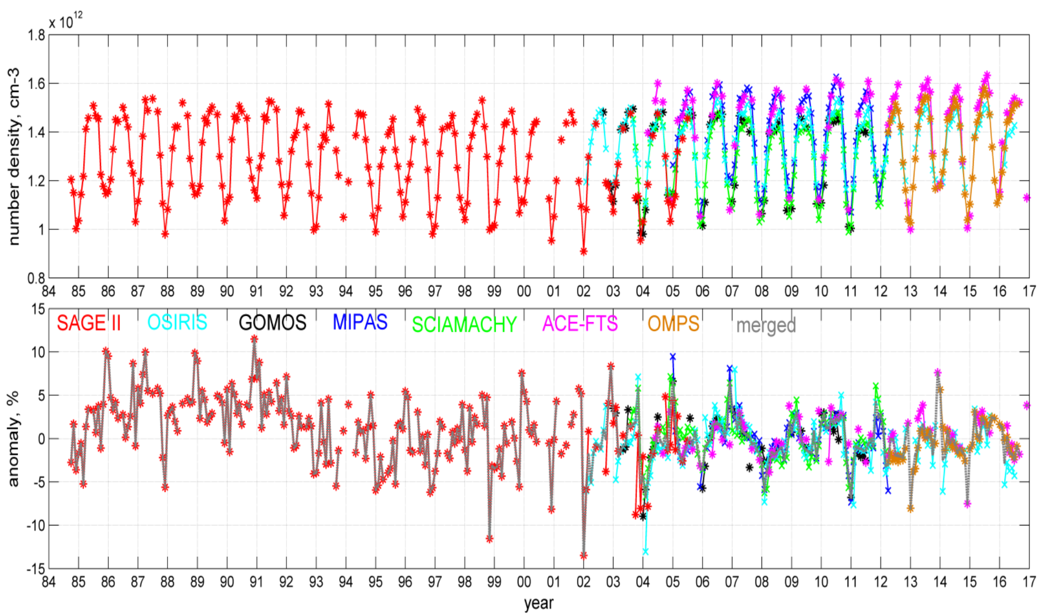
Big solar storms in Oct-Nov 2003 resulted in large amounts of charged particles being blasted out from the Sun. Storms travel through the space and arrive at Earth causing beautiful displays of Aurora in the polar regions. GOMOS observations showed that these particles also lead to large ozone loss in the polar atmosphere.

Seppälä et al. GRL, 2004

Merged SAGE II - Ozone_cci - OMPS dataset for evaluation of stratospheric ozone trends

- The merged SAGE-CCI-merged dataset of ozone profiles is created in the framework of ESA Climate Change Initiative (Ozone_cci)
- 7 satellite datasets: SAGE II, MIPAS, SCIAMACHY, GOMOS, OSIRIS, ACE-FTS and OMPS are merged into a long-term climate data record (1984-2016)



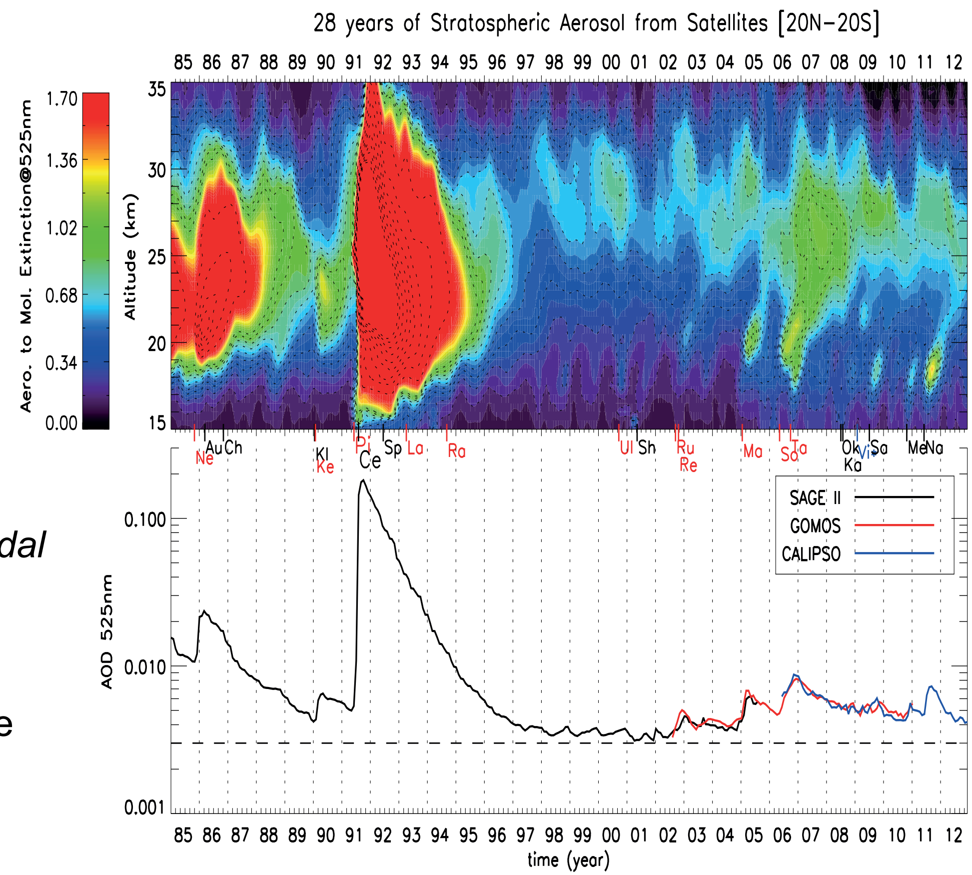


- The new dataset is used for evaluating ozone trends in the stratosphere
- Negative ozone trends in the upper stratosphere are observed before 1997 and positive trends after 1997
- The upper stratospheric trends are statistically significant at mid-latitudes and indicate ozone recovery
- Details: Sofieva, V. F. et al. (2017), Merged SAGE II, Ozone_cci and OMPS ozone profiles dataset and evaluation of ozone trends in the stratosphere, *Atmos. Chem. Phys. Discuss., 2017*, 1–28, accepted.

GOMOS aerosol data used in climate studies

Combined stratospheric aerosol dataset based on SAGE II, GOMOS and CALIPSO measurements.
By Vernier et al, GRL, 2011

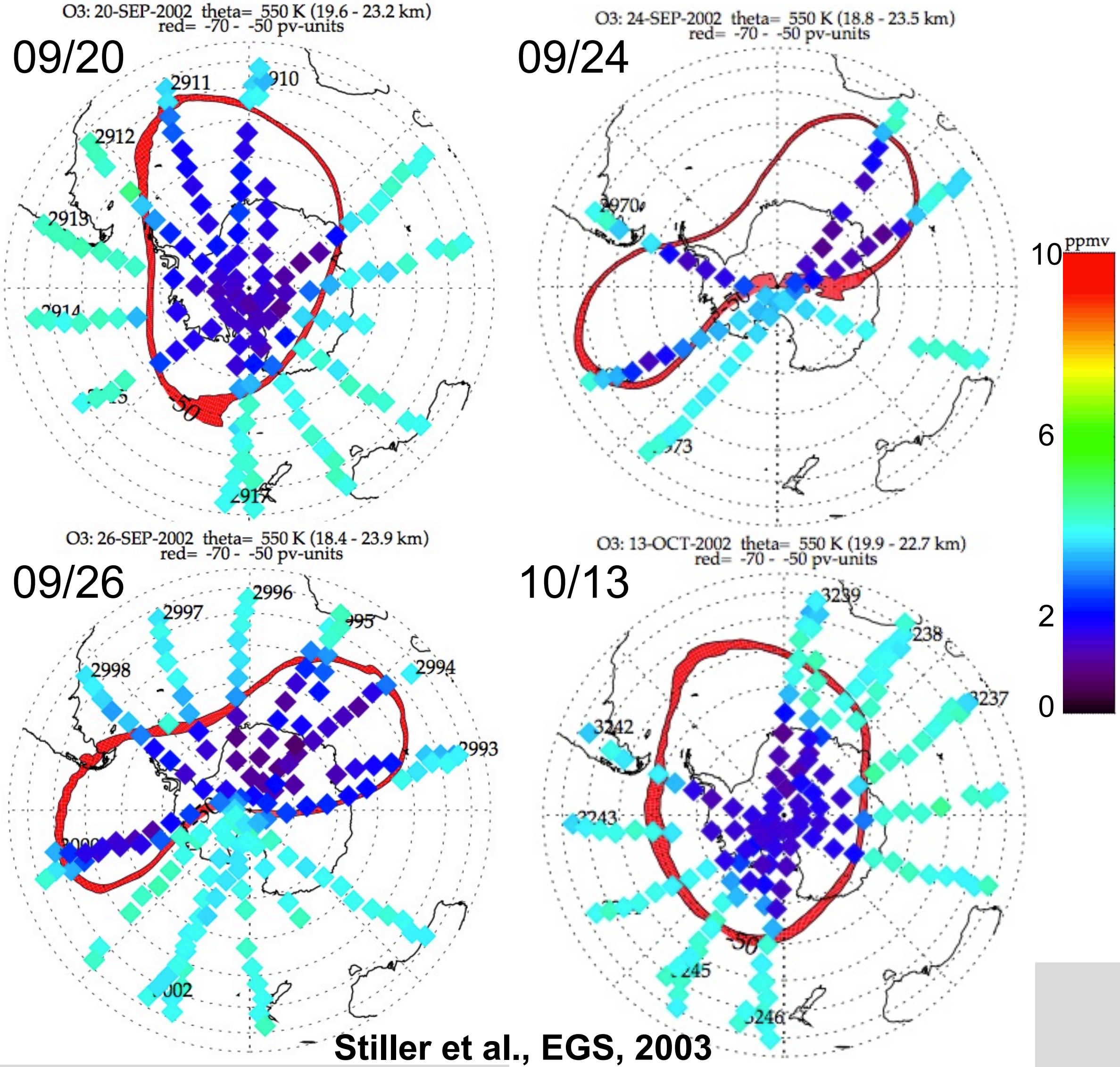
- S. Solomon et al *The persistently variable "background" stratospheric aerosol layer and global climate change*, Science, 2010
- B. Santer et al, *Volcanic contribution to decadal changes in tropospheric temperature*, Nature Geoscience, 2014
- IPCC 2013, Chapter 8.4.2: Volcanic radiative forcing



Time series of stratospheric aerosols. From *IPCC 2013*

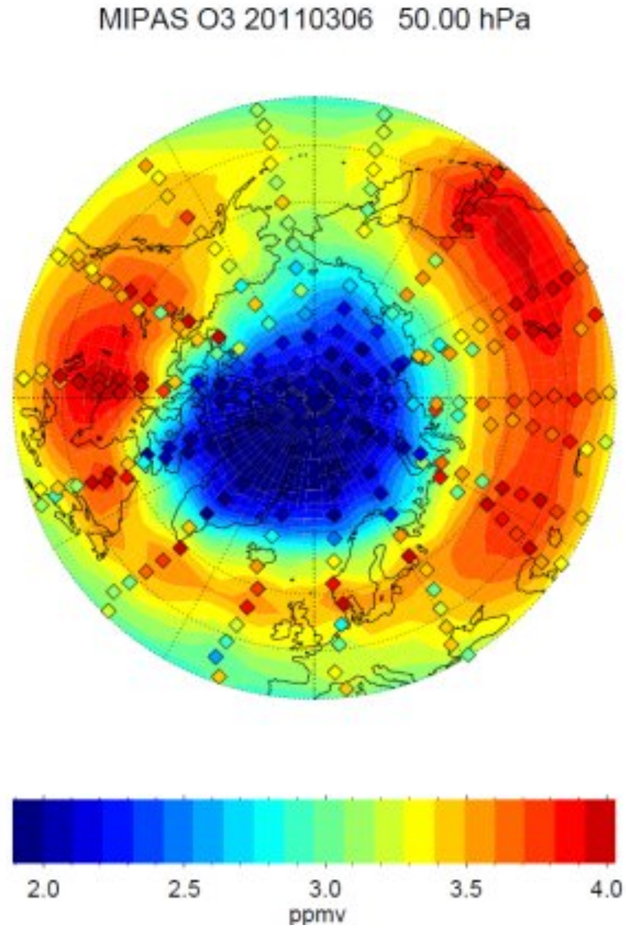
MIPAS monitoring of polar winter ozone: special events

The SH vortex split in Sep 2002



Stiller et al., EGS, 2003

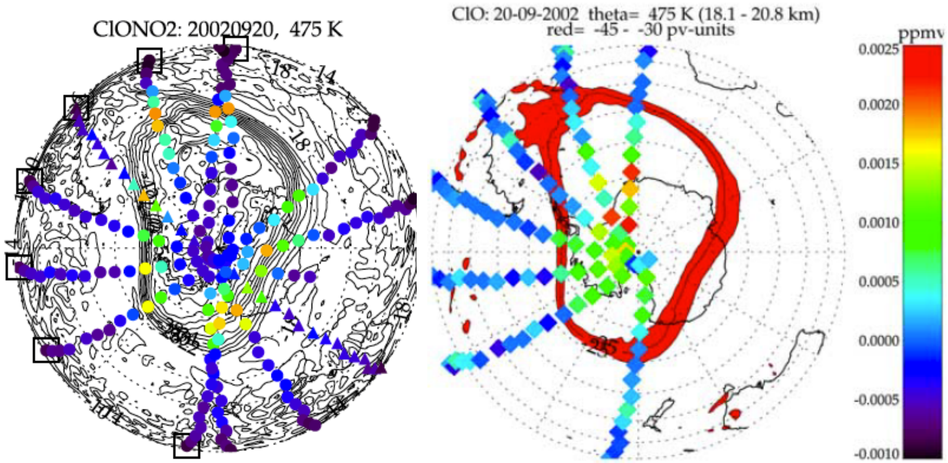
The “ozone hole” in NH winter 2011

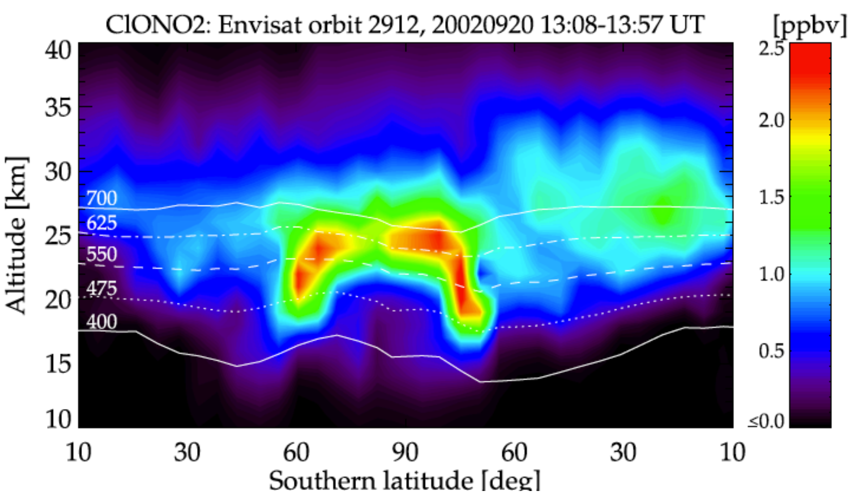


Sinnhuber et al., GRL, 2011

Observation of chemical reactants and PSCs

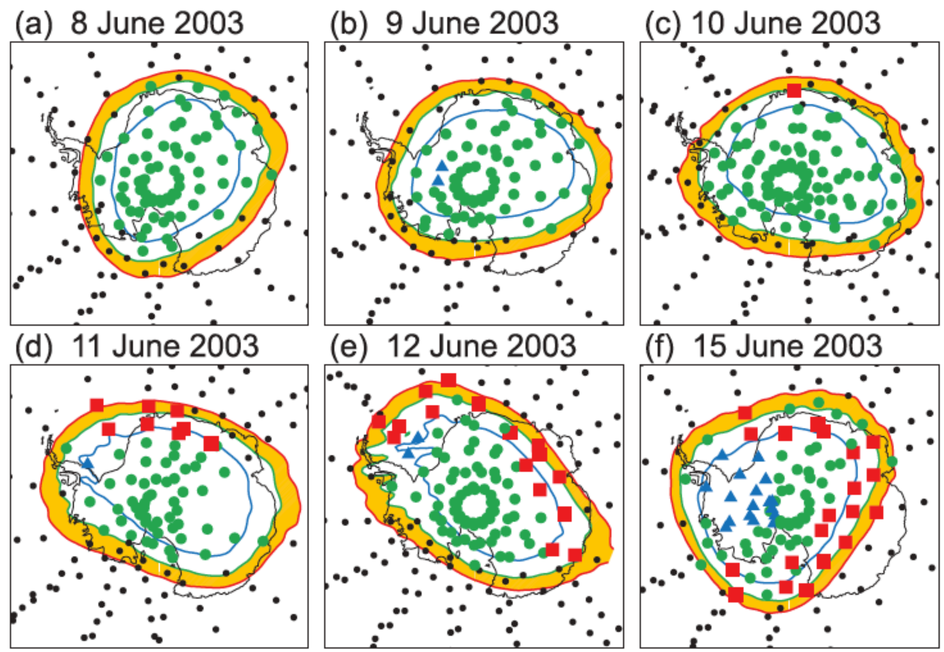
ClONO2 (left) and daytime ClO (right) observations on 20 Sep 2002 of the SH polar vortex at 475 K





ClONO2 altitude cross-section along one orbit

Höpfner et al., JGR, 2004; Glatthor et al., JGR, 2004



MIPAS observations of PSCs at 21 km altitude in SH winter 2003

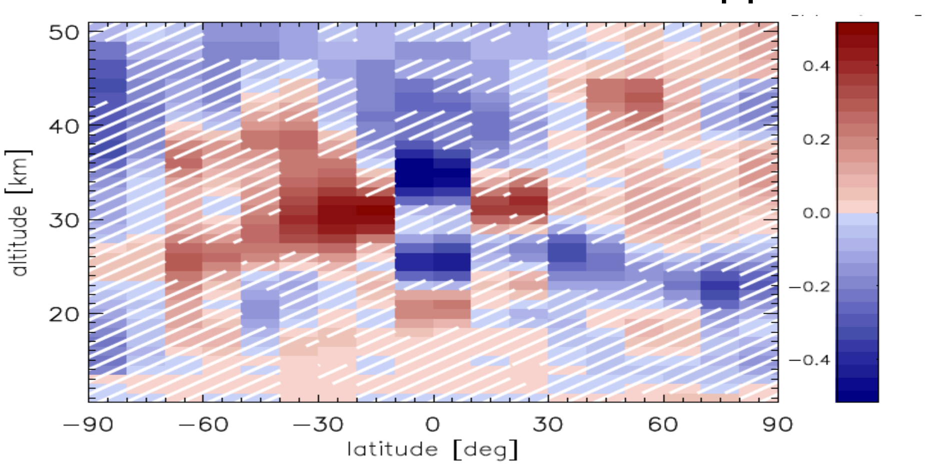
NAT ice other (STS or very large NAT)

Orange belt: $T_{STS} < T < T_{NAT}$

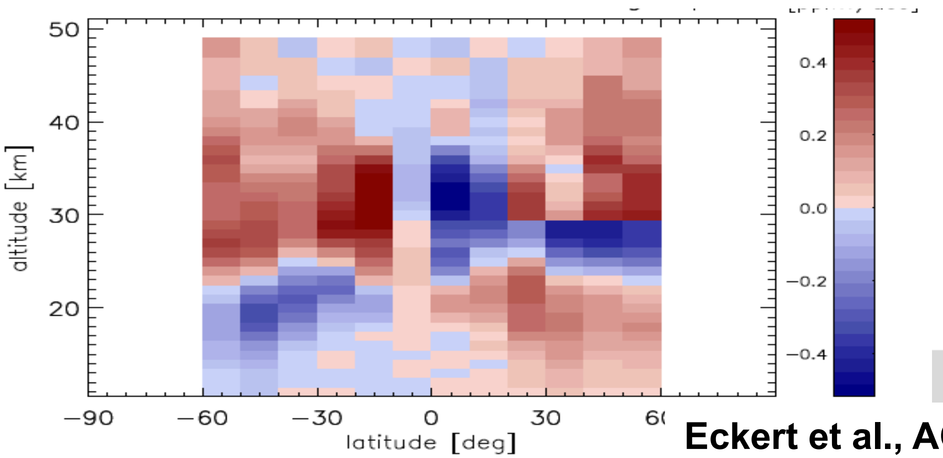
Höpfner et al., ACP, 2006; Eckermann et al., GRL, 2009

Ozone trends

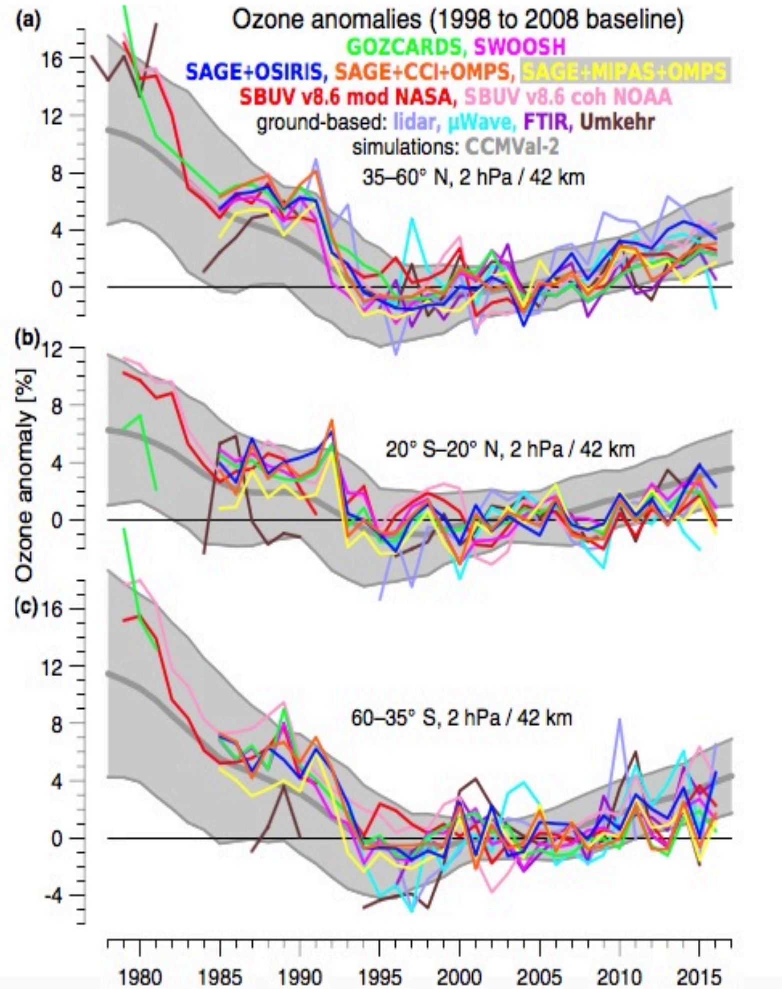
Observed ozone trends vs. altitude and latitude
2002-2012 ppmv/dec



Pattern can be largely explained by the shift of the ozone distribution to the South by 5 deg caused by the variation of the latitudinal position of the tropical pipe (simulation below)



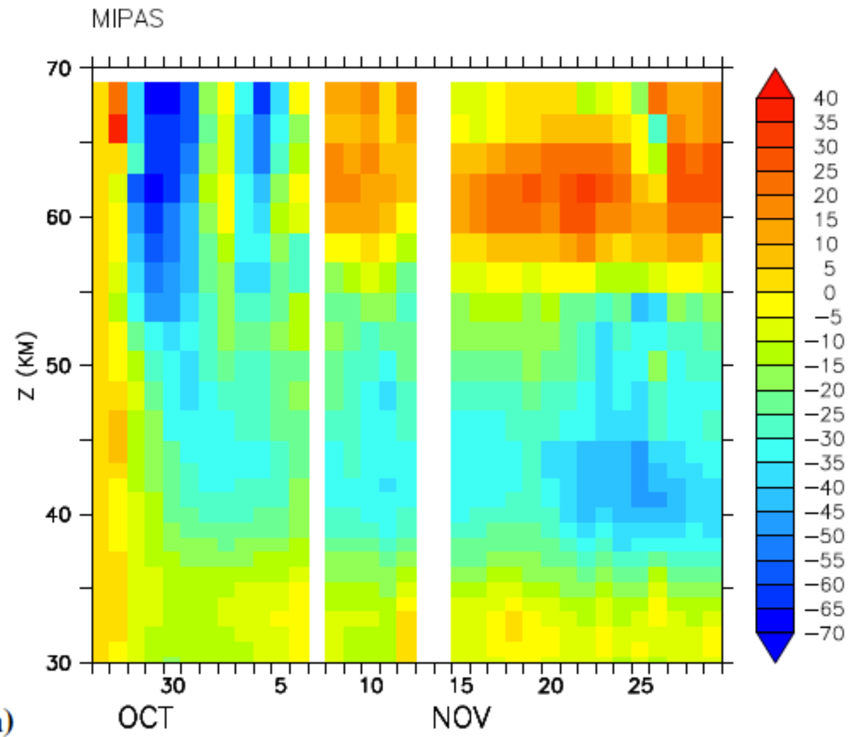
Eckert et al., ACP, 2014



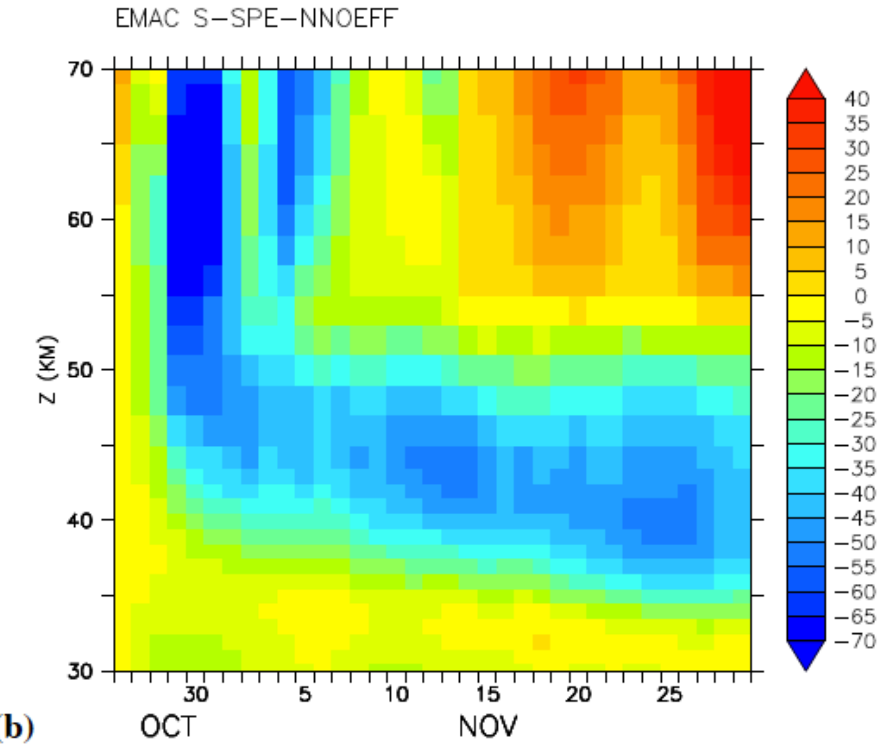
Steinbrecht et al., ACP, 2017

Impact of high energetic particle precipitation on polar winter ozone

NH (70-90 N) polar winter ozone loss due to NOx and HOx formation after strong solar proton events on 28 Oct and 3 Nov 2003



(a)



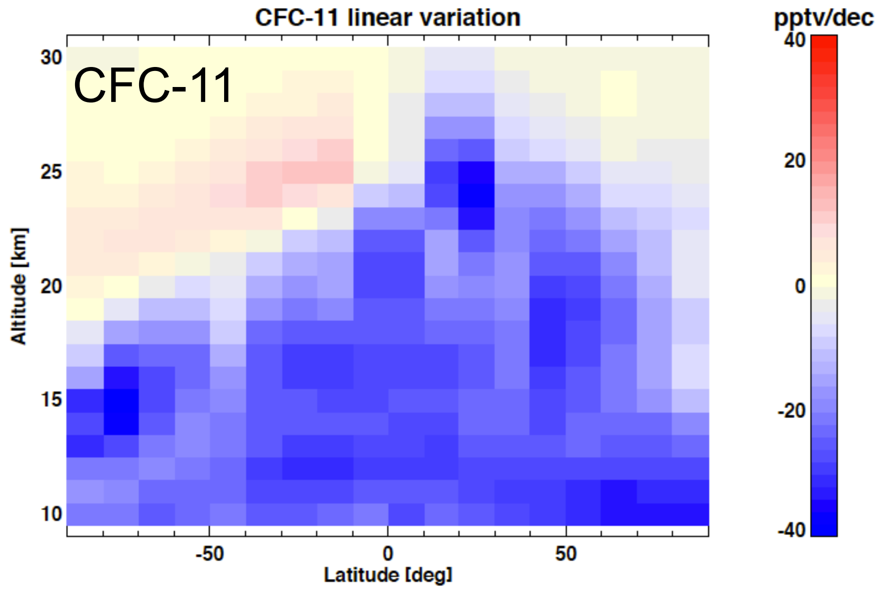
(b)

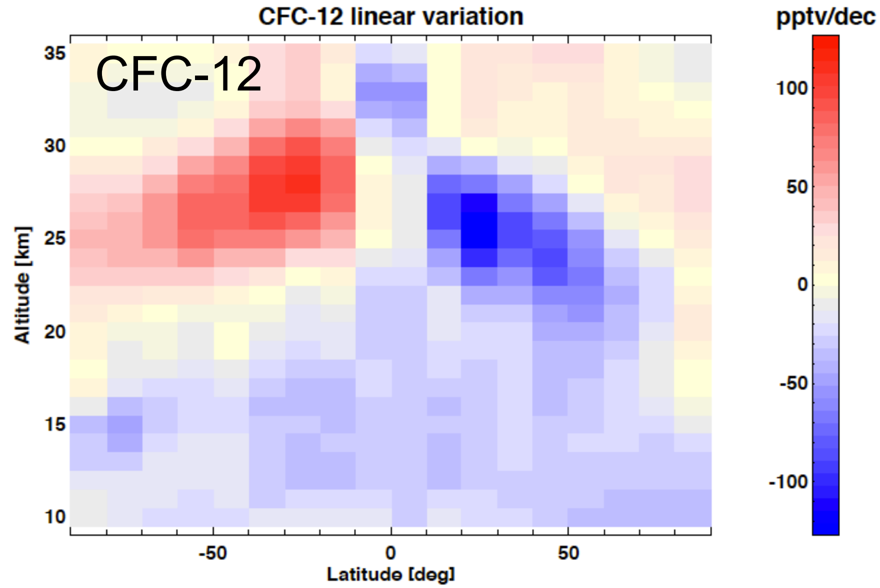
Percentage ozone change relative to 26 Oct observed by MIPAS …

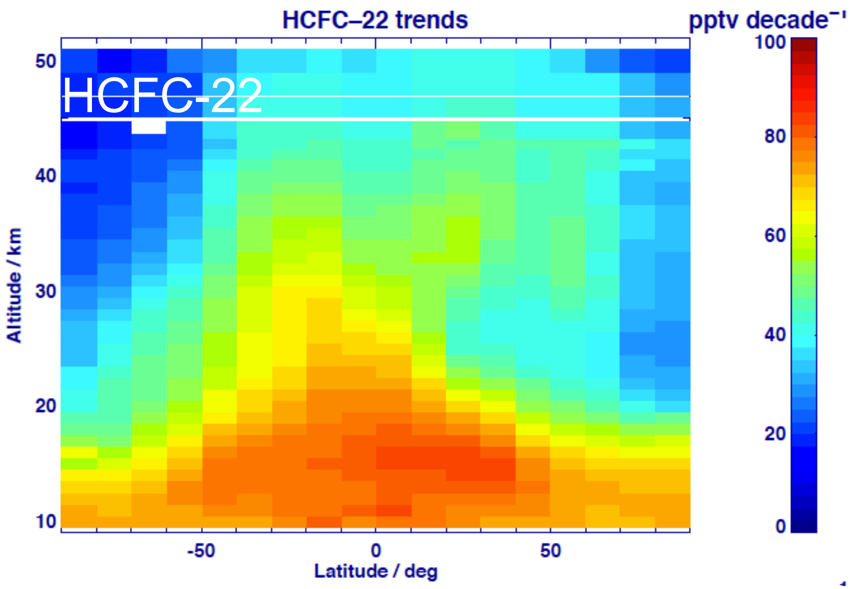
… and modelled with CCM EMAC

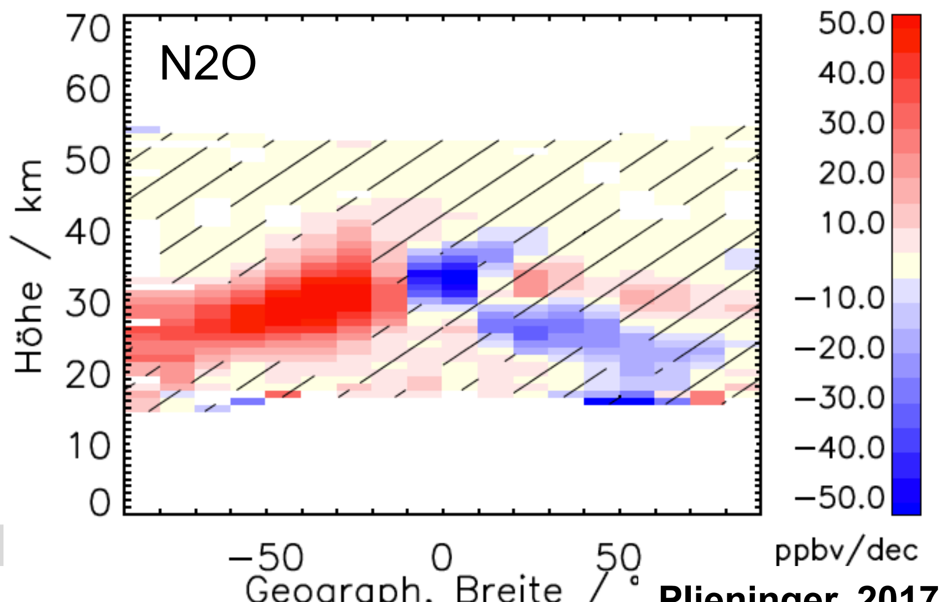
Baumgaertner et al., ACP, 2010

Monitoring decadal trends of ozone-depleting substances 2002 - 2012









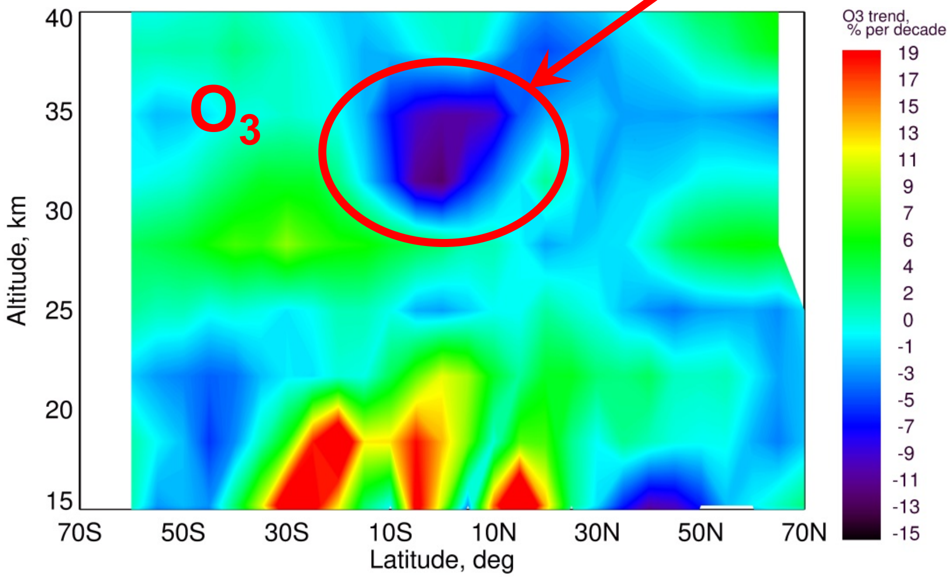
Kellmann et al., ACP, 2012; Chirkov et al., ACP, 2016

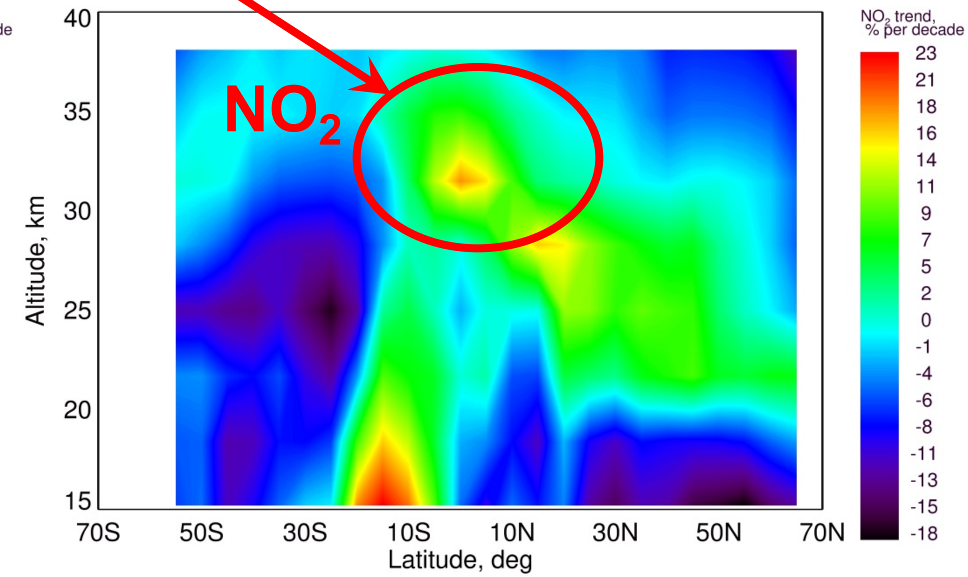
Plieninger, 2017

SCIAMACHY long-term changes: O_3 and NO_2

Significant decrease in O_3 VMR between 30 and 35 km is observed (~10% per decade)

Highly correlated with increased VMRs of NO_2 (~18% per decade)





Global long term changes from January 2004 to March 2012

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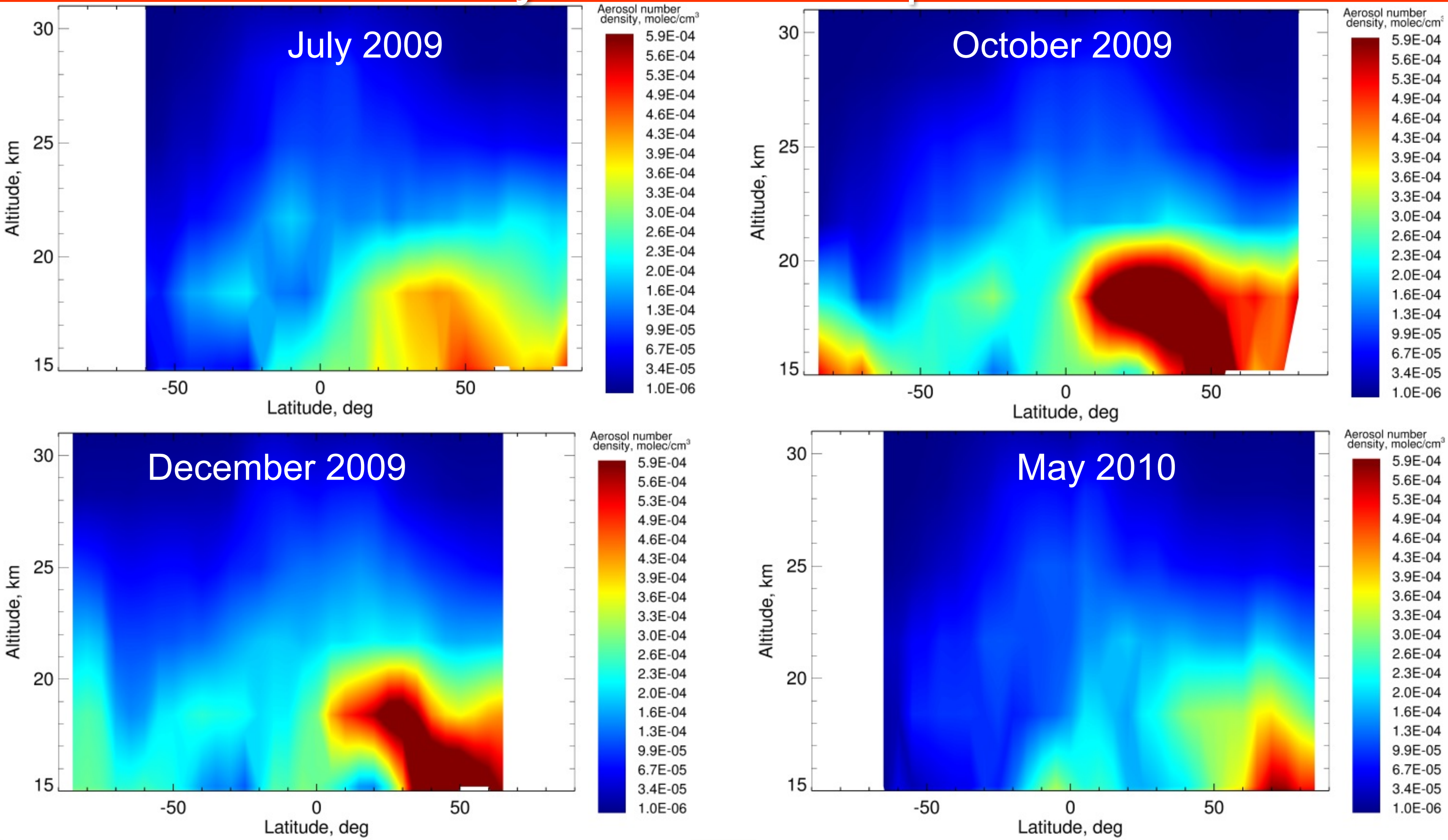
SCIAMACHY

Aerosol extinction observed from SCIAMACHY after the Sarychev Peak eruption



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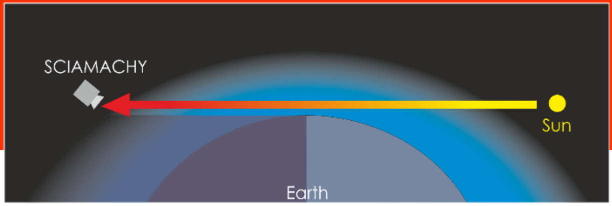
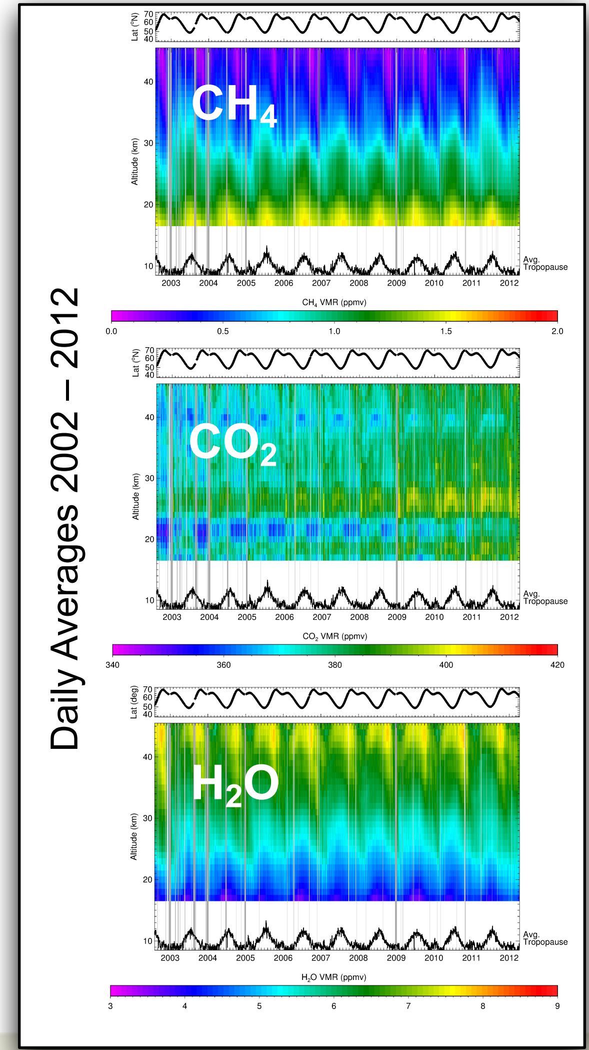
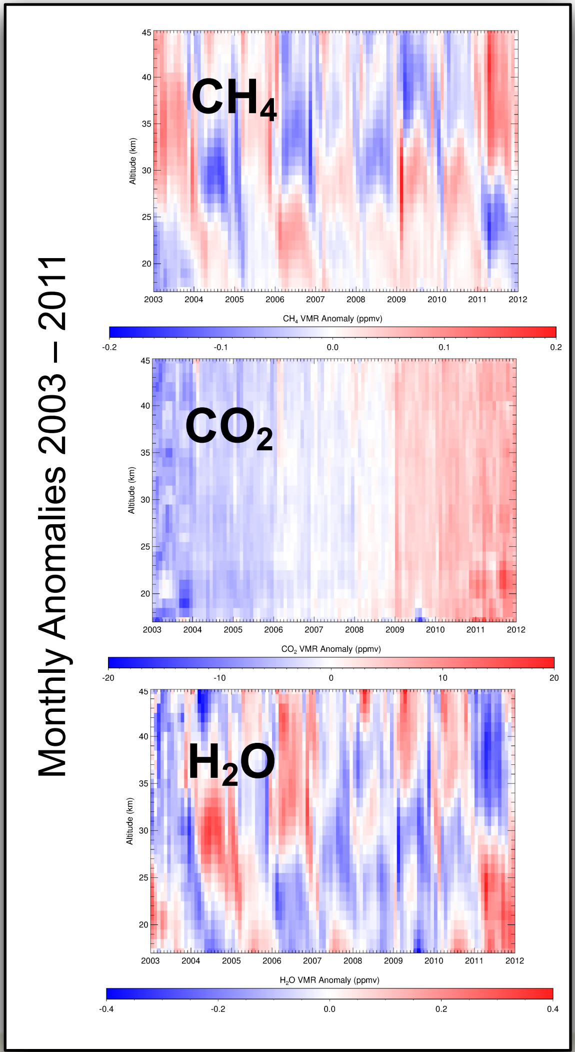
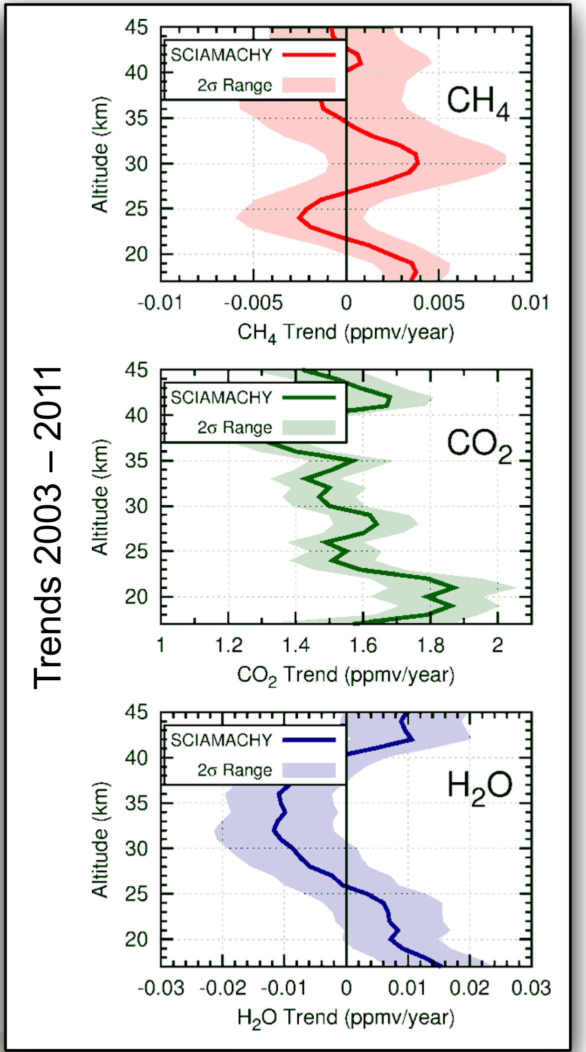
Stratospheric GHG Profiles from SCIAMACHY Solar Occultation









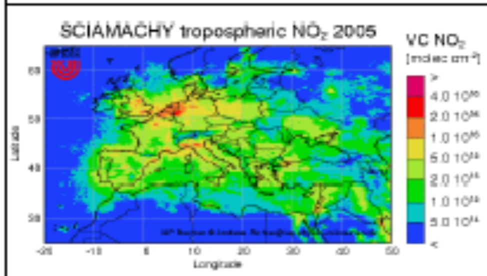
~ 50° – 70° N

See also Noël et al., AMT, 2016

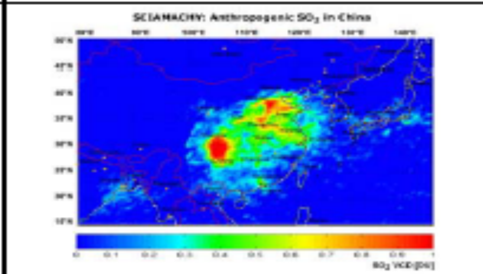
SCIAMACHY on ENVISAT

Kind of „all purpose“ atmosphere mission incl. CO_2 and CH_4

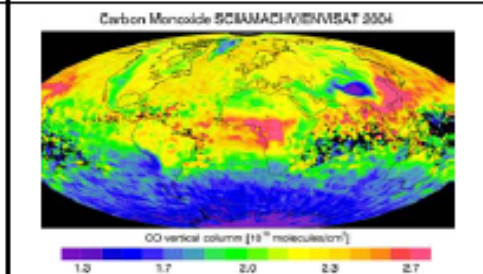
NO2



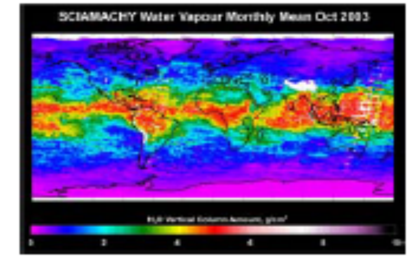
SO2



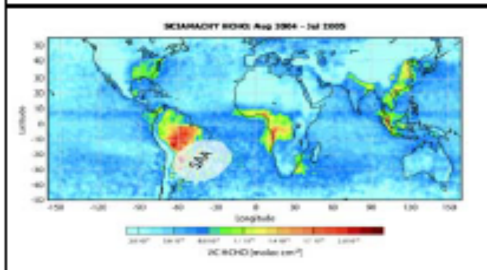
CO



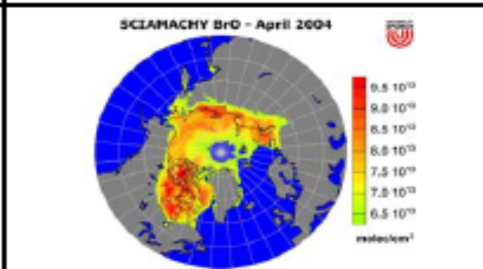
H2O



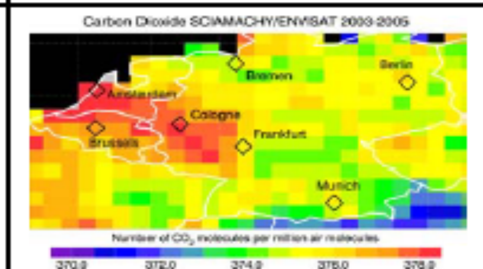
HCHO



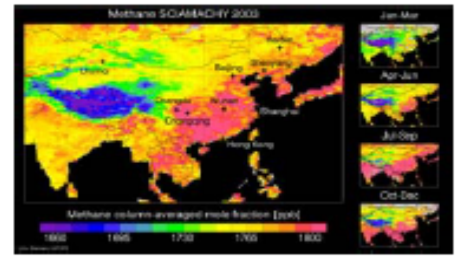
BrO



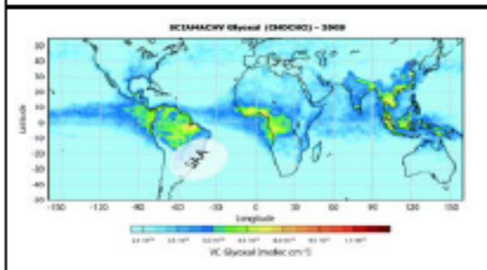
CO2



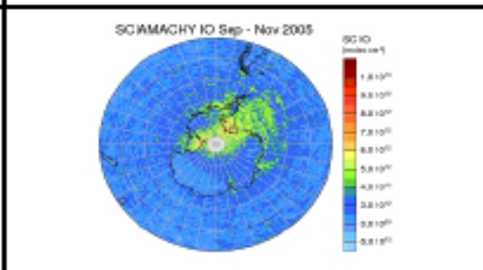
CH4



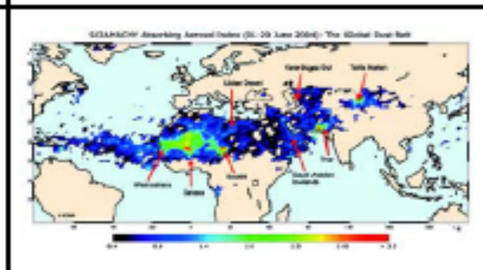
CHOCHO



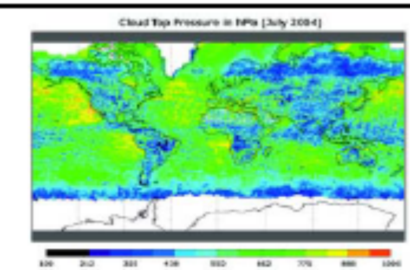
IO



Aerosols



Clouds



... and many other products ...

Summary

ESA Envisat Mission (GOMOS, MIPAS and SCIAMACHY) and the SCIAMACHY project have been a remarkable success – thanks to scientific community, industry and agencies.

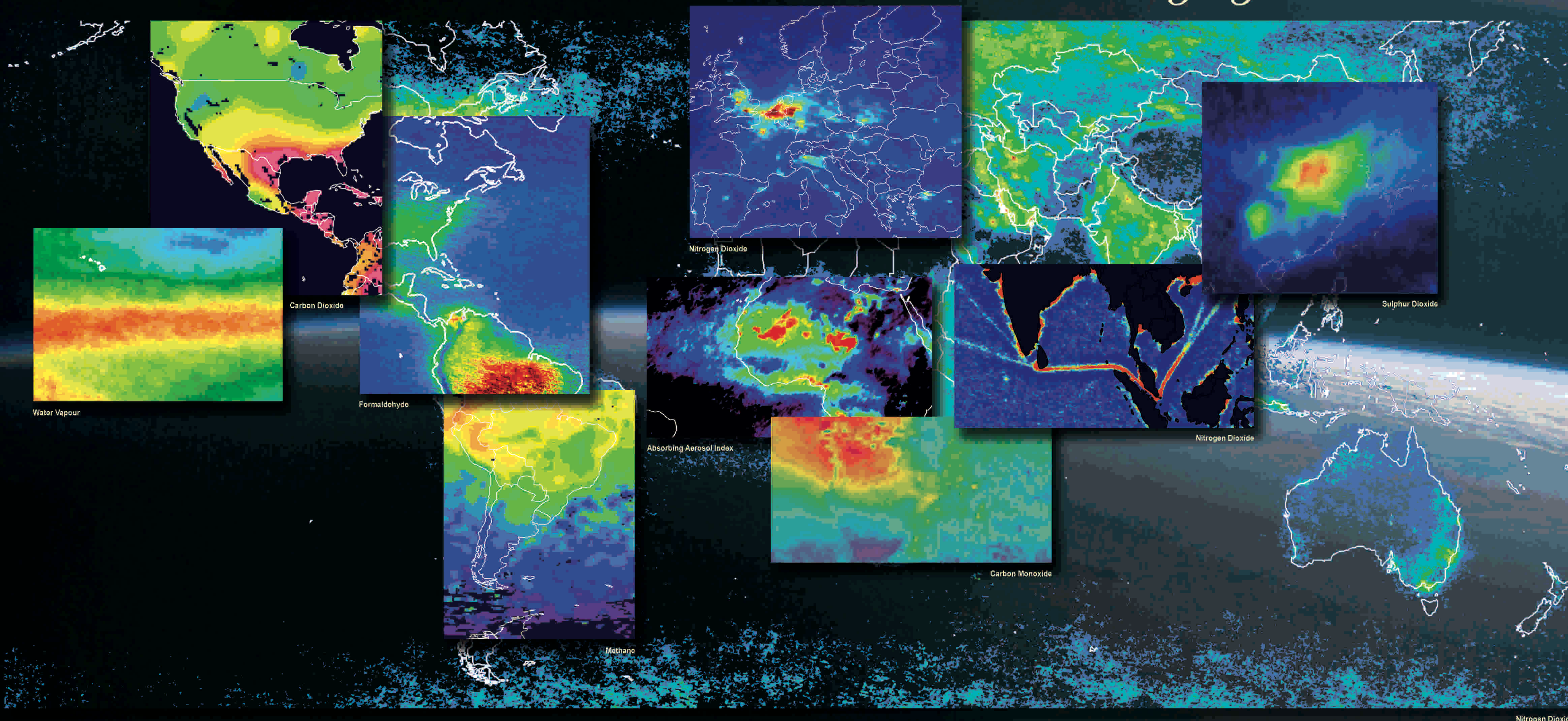
It has demonstrated that nadir, and limb and occultation observation of back scattered solar radiation and upwelling thermal infrared red are uniquely important to deliver scientific measurements, required to monitor the earth atmosphere system in particular the stratosphere and troposphere during a critical phase of the anthropocene.

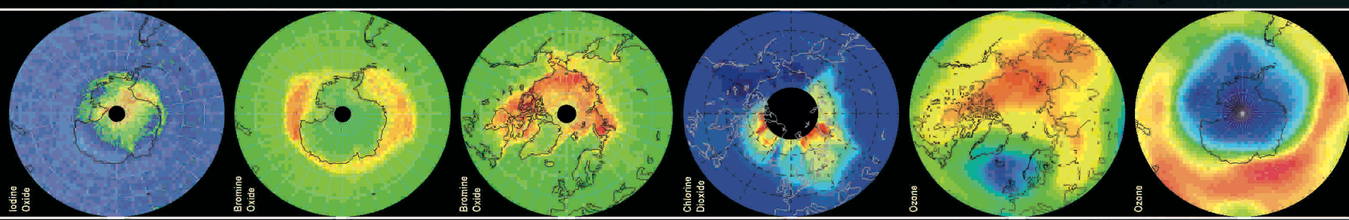
The loss of ENVISAT remains a huge loss for global monitoring of atmospheric species from limb and occultation in Europe.

New Missions are urgently needed to minimise the gap of observations of Limb and GHG – ESA Altius is a good start!

SCIAMACHY 2002-2012

hunting light and shadows





Images: DLR, IUP-IFE University of Bremen, SRON, KNMI, IASB-BIRA, MPI for Chemistry, ESA, NASA