Remote sensing of trace constituents from space: GOME and SCIAMACHY

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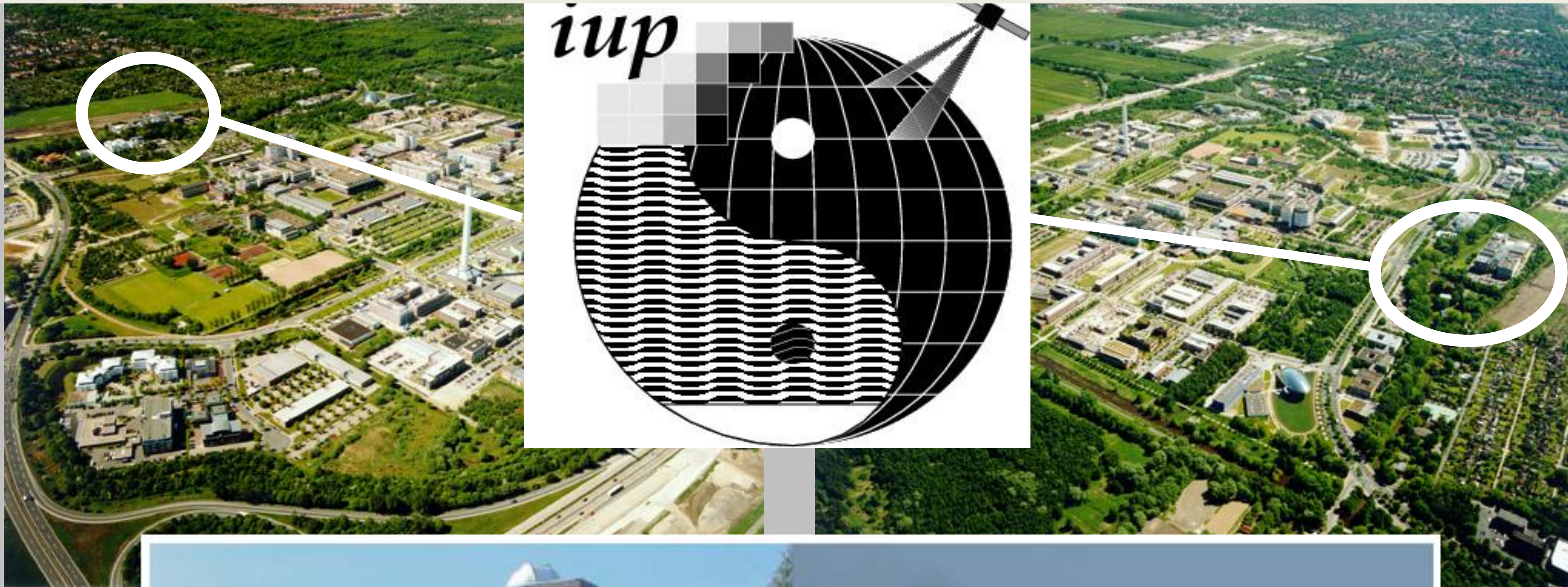
Institute of Environmental Physics, University of Bremen
J. P. Burrows - 1992 to present
Klaus Künzi and Wolfgang Roether 1992 to 2000/ 2004
Monika Rhein and Justus Notholt 2000/2002 to present



SCIAMAC

nSat
lation

Why observe the atmosphere from space?

Conditions in the Biosphere depend on the Sun, the atmosphere, and earth's surface and their non linear feedback.

- Dramatic changes in population and anthropogenic emissions since 1800!
- 2 Billion more People since SCIAMACHY proposed - total now over 7 Billion
- Anthropocene Mankind is changing the Earth-Atmosphere system → Changes in
  - ⇨ Global transport and transformation of pollution
  - ⇨ Climate Change - Chemistry climate feedback
  - ⇨ Global destruction of stratospheric ozone

⇨ It is impossible understand or manage what is not measured!!

⇨ Environmental/Climate Change requires Global Observations

⇨ Evidence base for testing understanding and policymaking

Ozone Production & Catalytic Destruction

Stratospheric Ozone

Stratosphere

$$O_2 + h\nu \longrightarrow O + O$$

$$O + O_2 + M \longrightarrow O_3 + M$$

$$O_3 + h\nu \longrightarrow O_2 + O$$

$$O_3 + O \longrightarrow O_2 + O_2$$

$+h\nu$ O(^{1}D)

Tropopause

Transport Trop.-Strat. Exchange

Chemistry

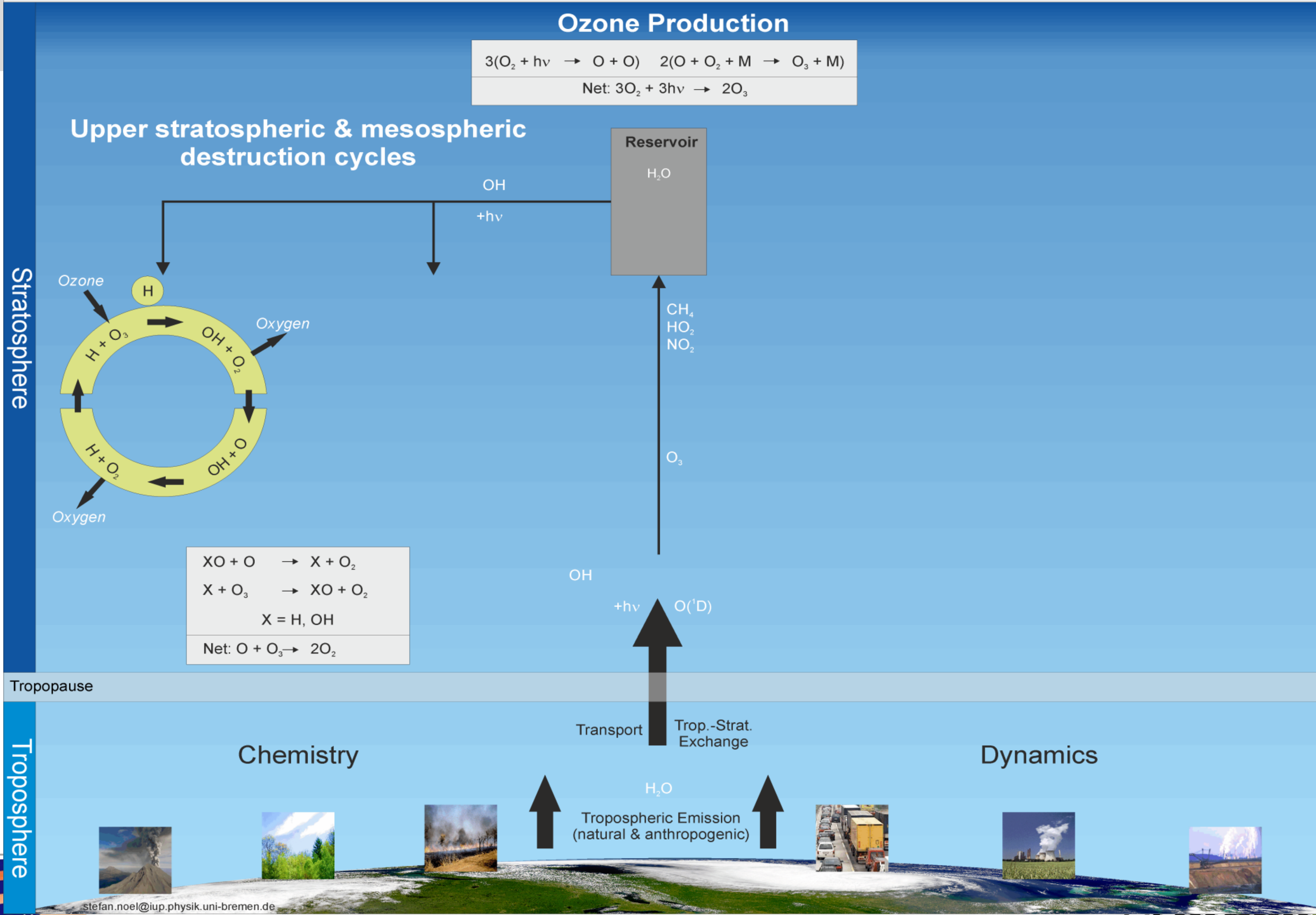
Dynamics

In 1902 the Stratosphere, a temperature inversion above 8-16 km discovered by Leon Philippe Teisserenc de Bort from France and German meteorologist Richard Assmann .
In 1929 Sidney Chapman of Trinity College Cambridge University, explained the observation of Ozone by Dobson Oxford and others. But the reaction $O_3 + O \rightarrow O_2 + O_2$ later discovered to be too slow!

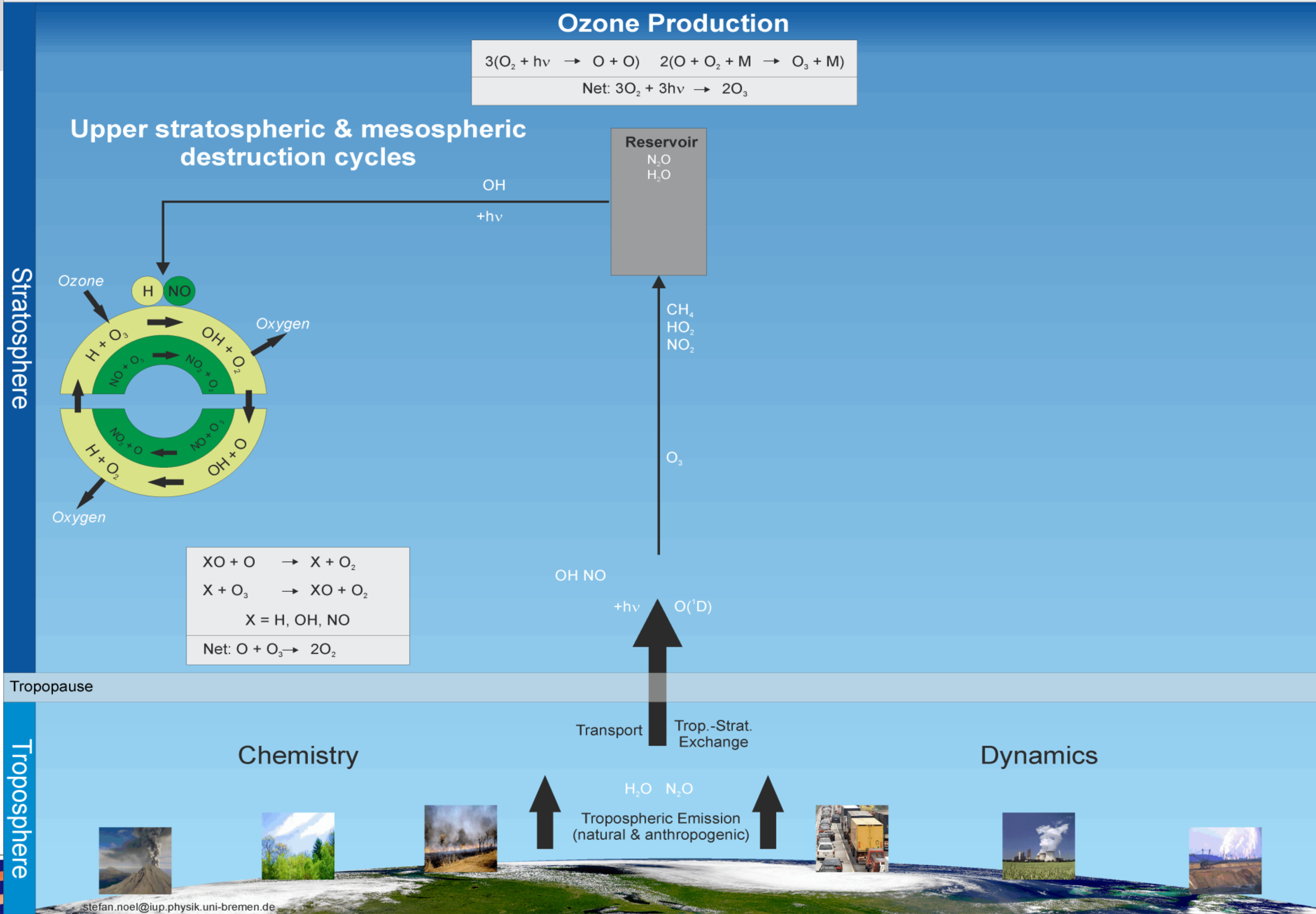
SCIAMACHY

Constellation

Ozone Production & Catalytic Destruction



Ozone Production & Catalytic Destruction



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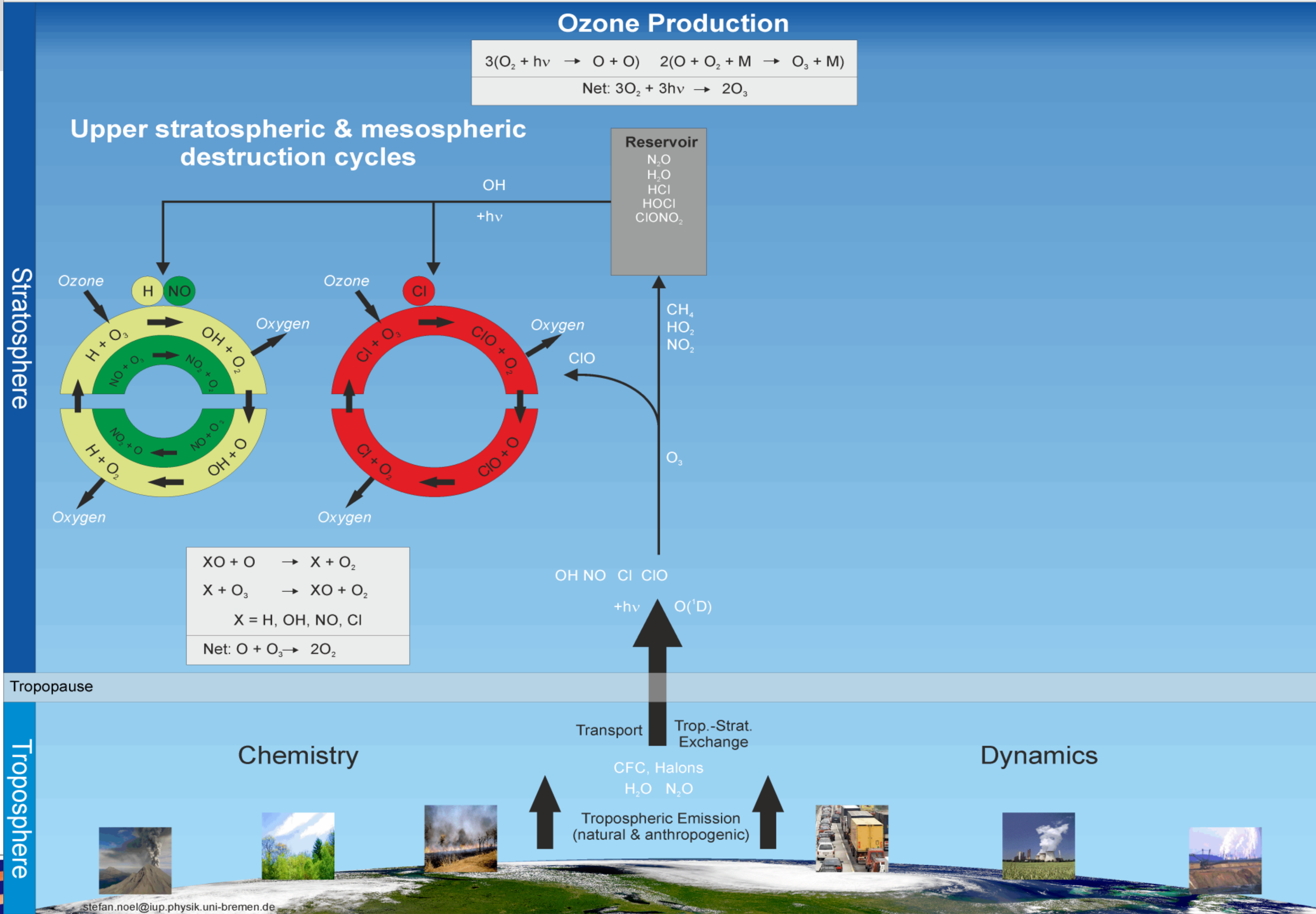
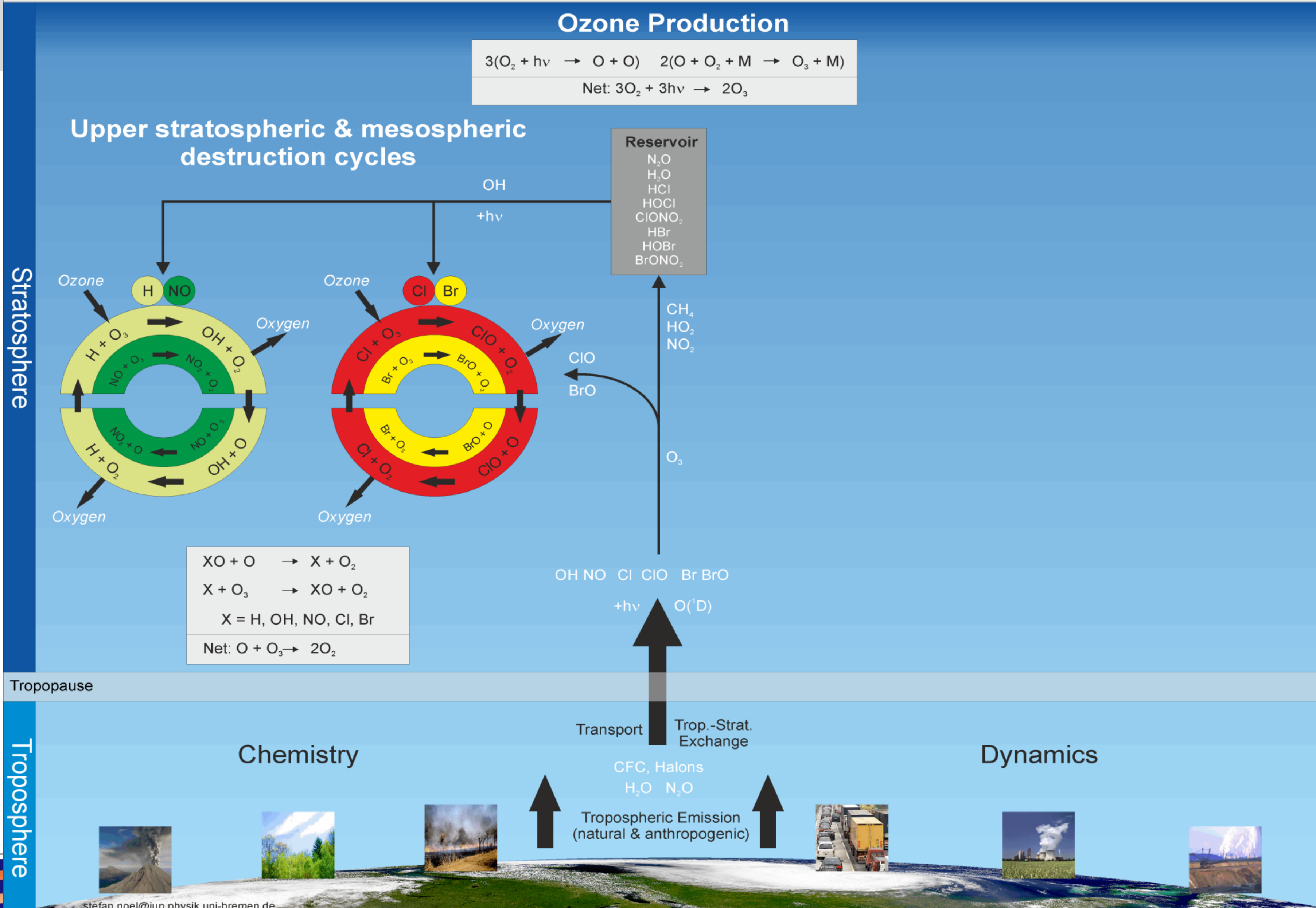
CarbonSat Constellation

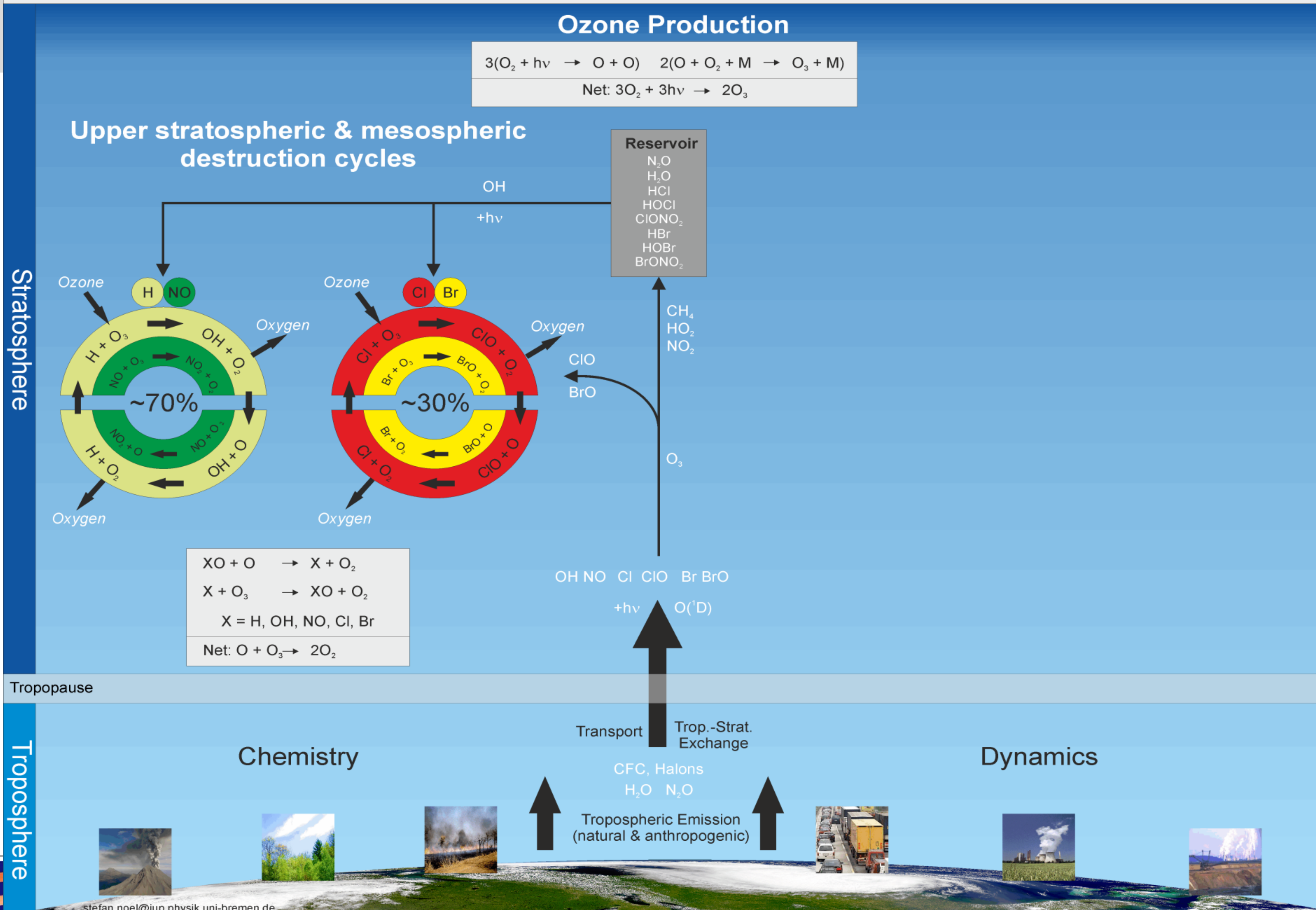
Ozone Production & Catalytic Destruction



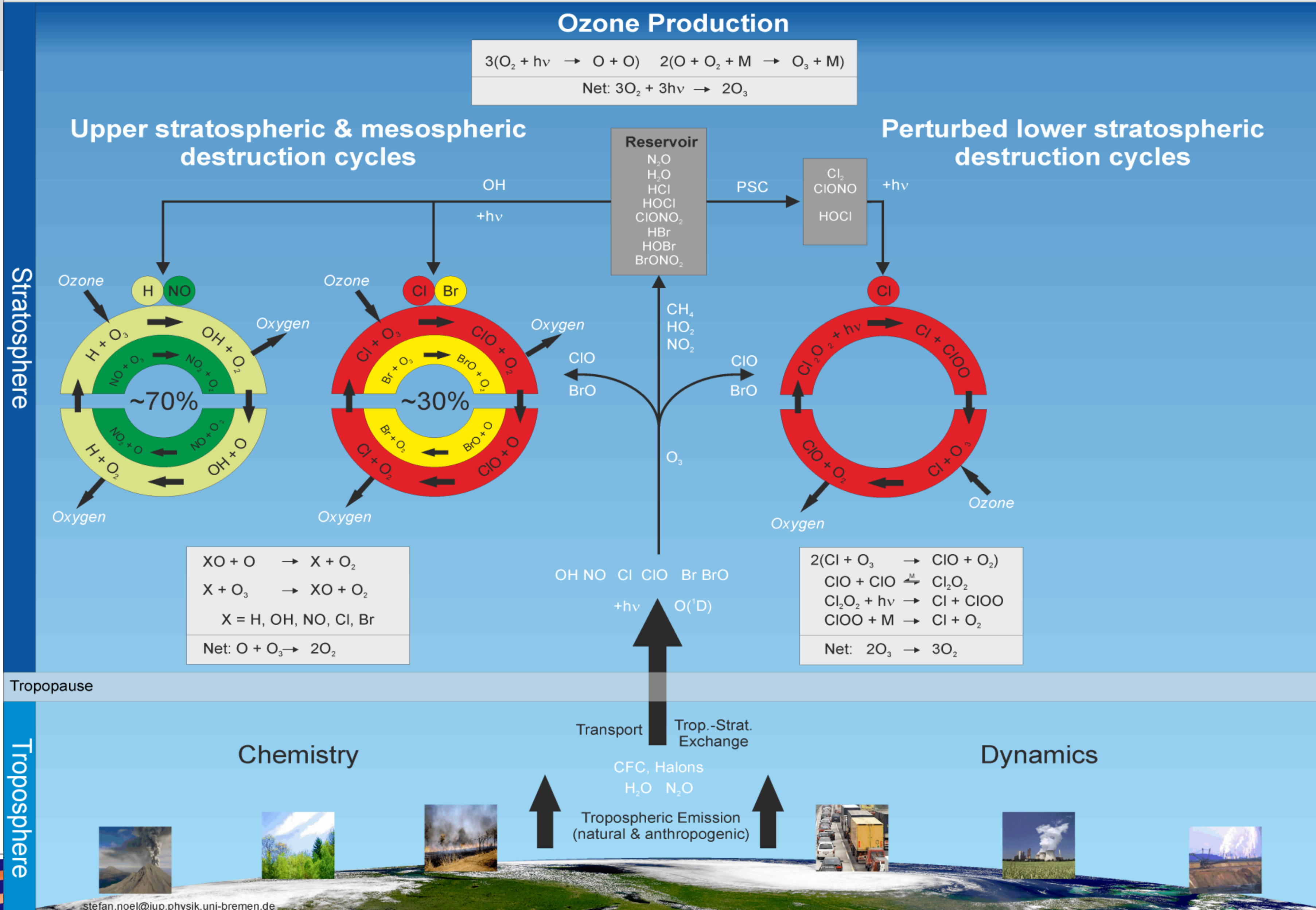
Ozone Production & Catalytic Destruction



Ozone Production & Catalytic Destruction



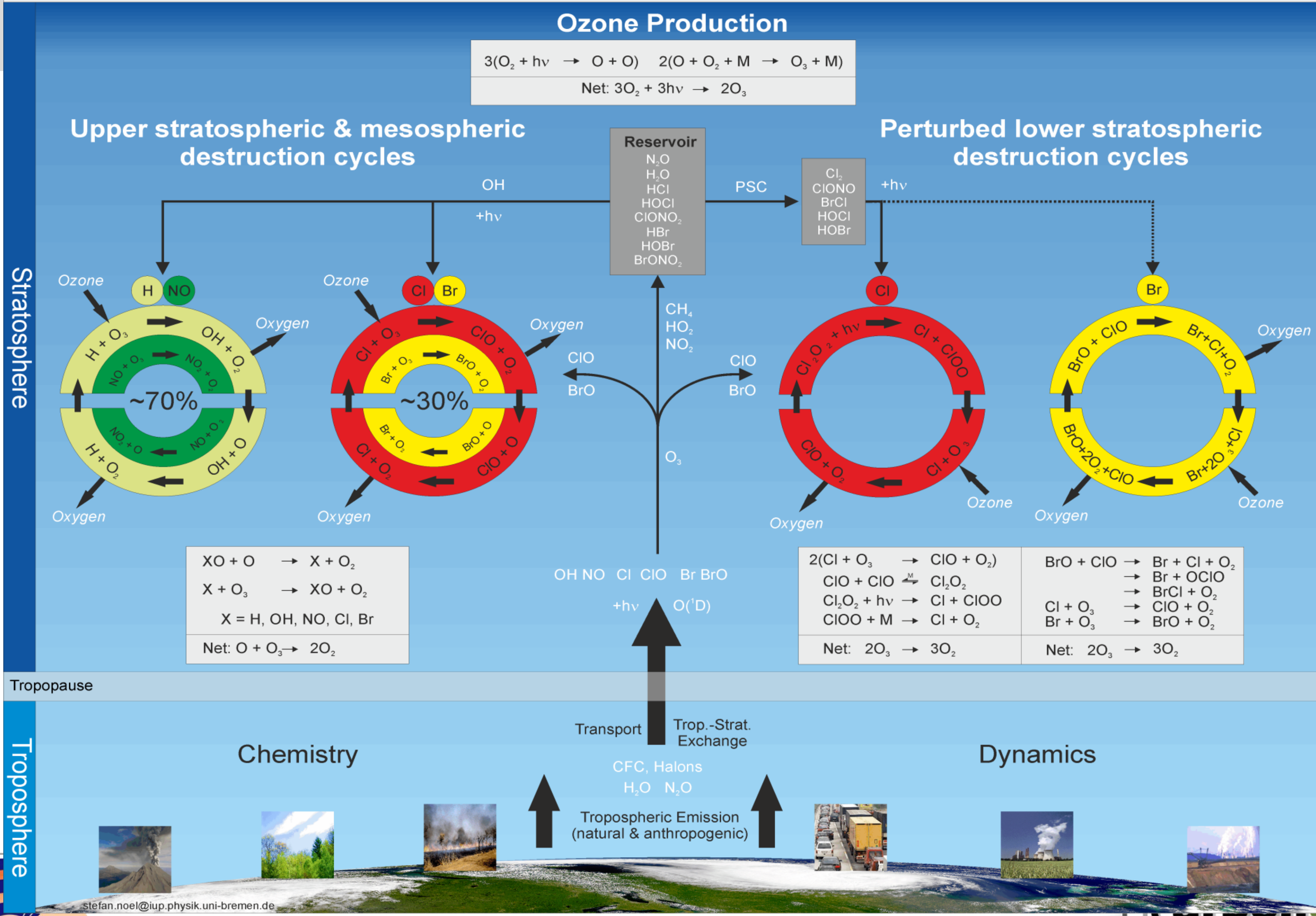
Ozone Production & Catalytic Destruction



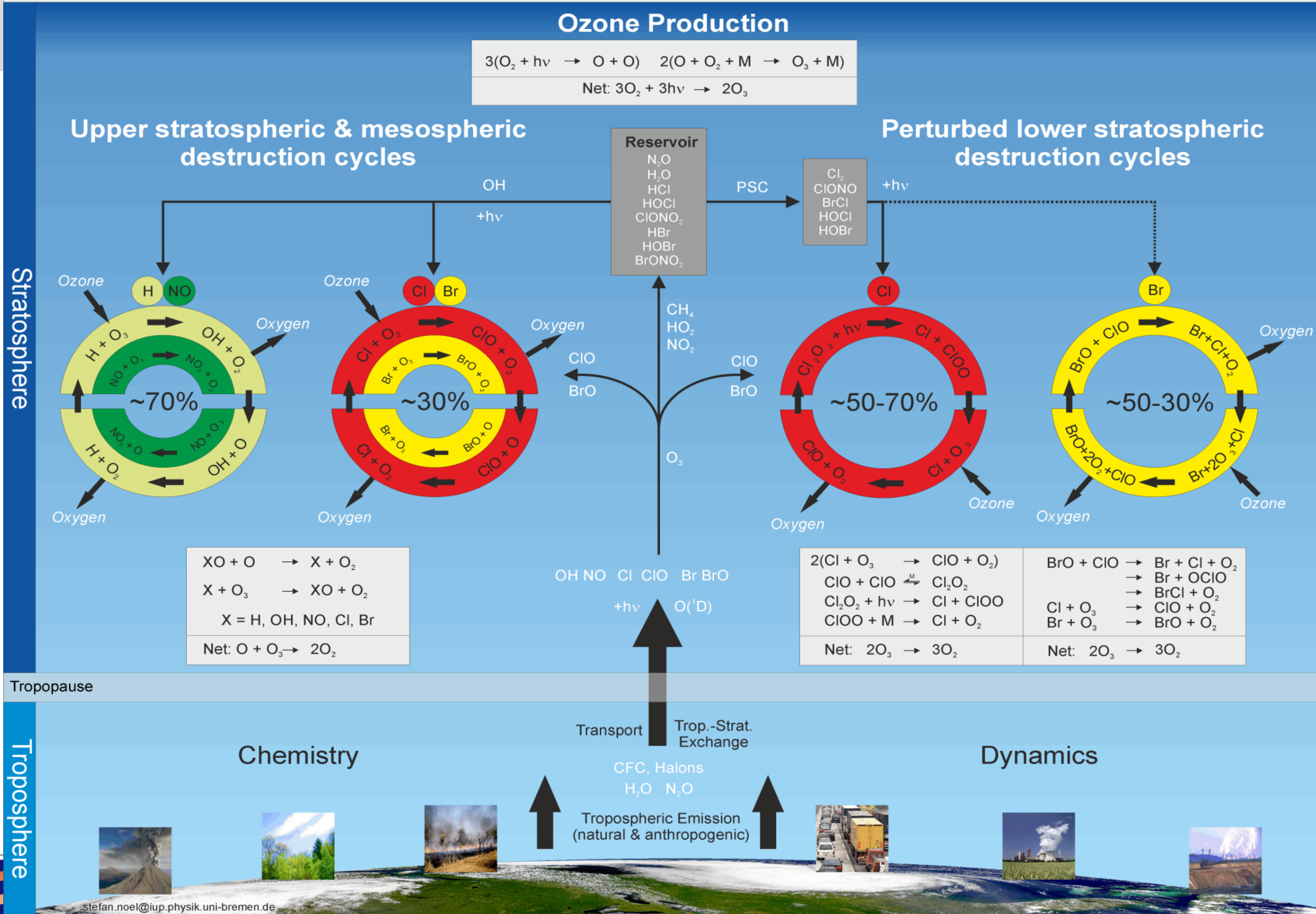
SCIAMACHY

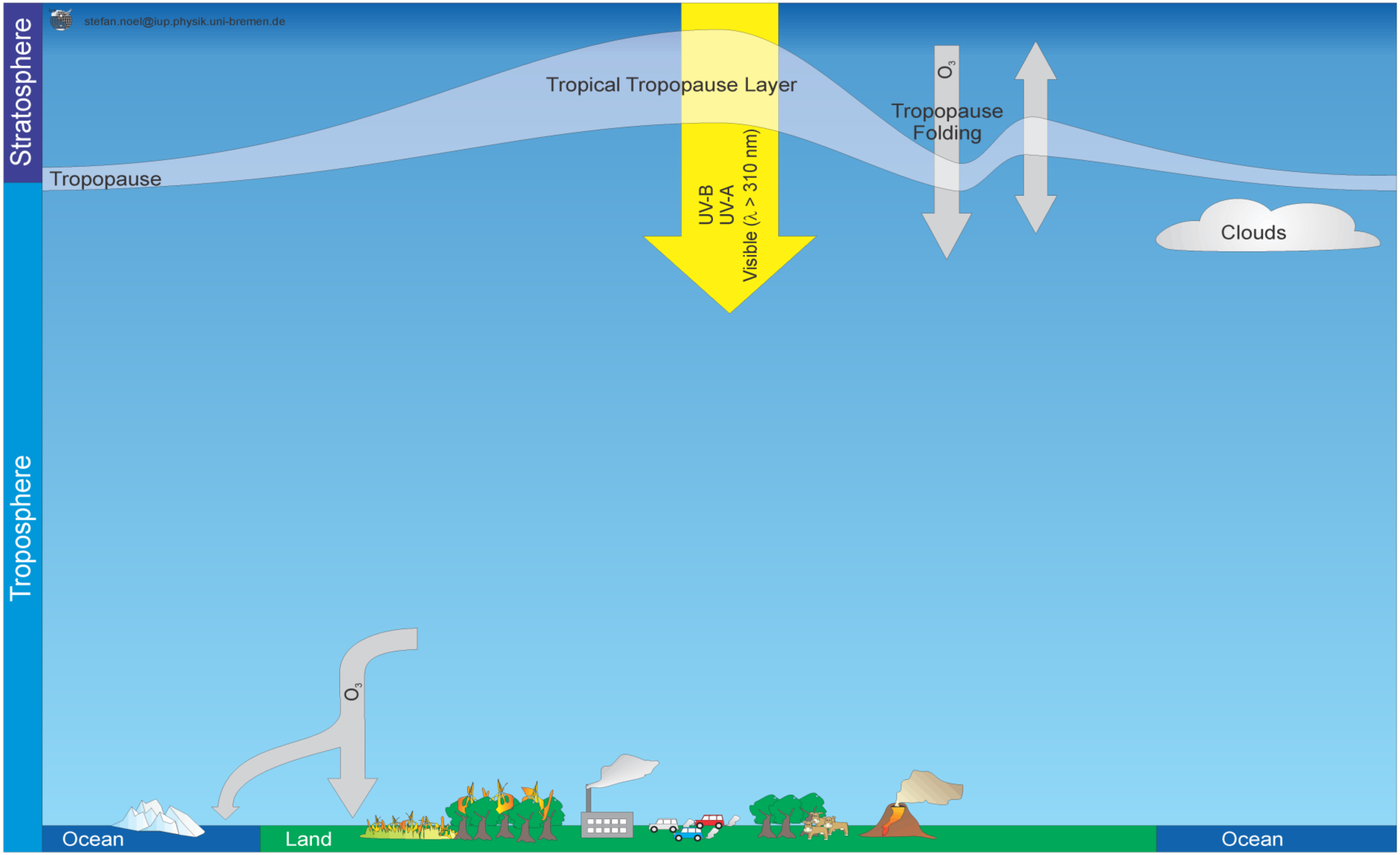
Constellation

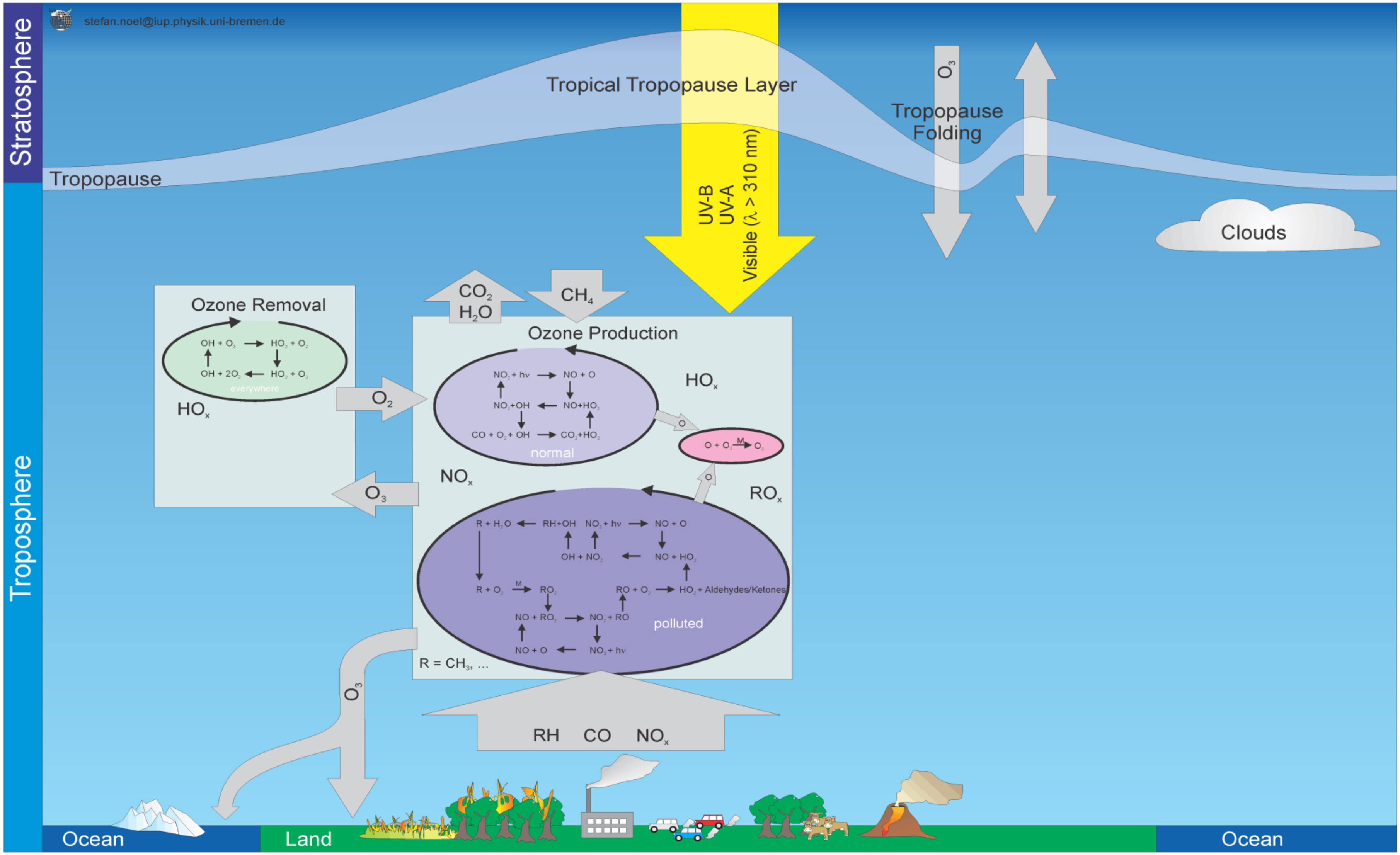
Ozone Production & Catalytic Destruction



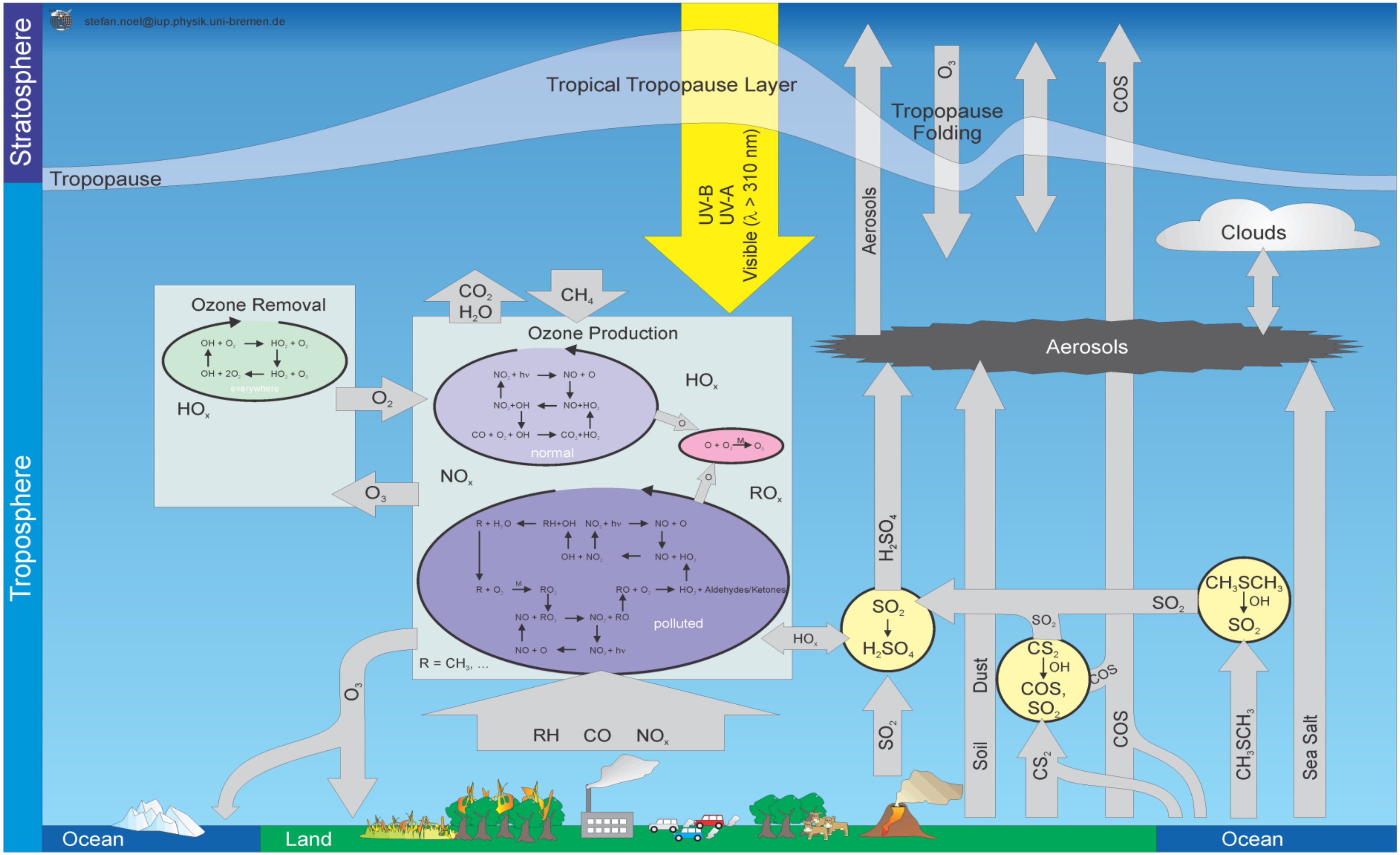
Ozone Production & Catalytic Destruction




Stratosphere
stefan.noel@iup.physik.uni-bremen.de
Tropical Tropopause Layer
O_3
Tropopause Folding
Tropopause
UV-B
UV-A
Visible (λ > 310 nm)
Clouds
Troposphere
O_3
Ocean
Land
Ocean



stefan.noel@iup.physik.uni-bremen.de
Stratosphere
Troposphere
Tropical Tropopause Layer
Tropopause
Tropopause Folding
O_3
UV-B
UV-A
Visible (λ > 310 nm)
Clouds
Ozone Removal
$OH + O_3 \rightarrow HO_2 + O_2$
$HO_2 + O_3$
$OH + 2O_2$
everywhere
HO_x
O_2
O_3
CO_2
H_2O
CH_4
Ozone Production
$NO_2 + h\nu \rightarrow NO + O$
$NO_2+OH \leftarrow NO+HO_2$
$CO + O_2 + OH \rightarrow CO_2+HO_2$
normal
HO_x
$O + O_2 \xrightarrow{M} O_3$
NO_x
RO_x
$R + H_2O \leftarrow RH+OH$
$NO_2 + h\nu \rightarrow NO + O$
$OH + NO_2 \leftarrow NO + HO_2$
$R + O_2 \xrightarrow{M} RO_2$
$RO + O_2 \rightarrow HO_2$ + Aldehydes/Ketones
$NO + RO_2 \rightarrow NO_2 + RO$
$NO + O \leftarrow NO_2 + h\nu$
polluted
R = CH_3, ...
RH CO NO_x
Ocean
Land
Ocean



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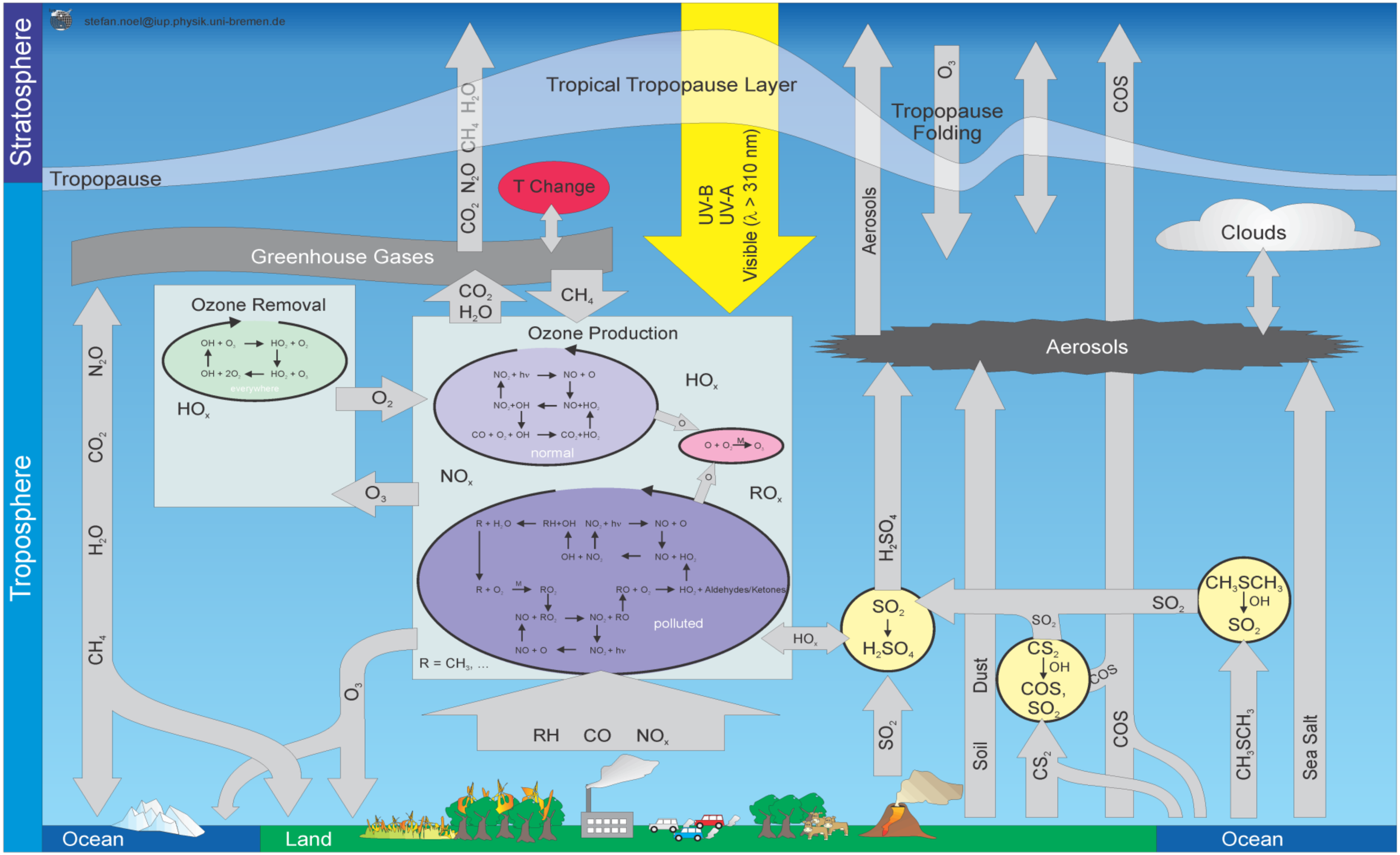
Stratosphere
Troposphere
Tropical Tropopause Layer
Tropopause
Tropopause Folding
UV-B
UV-A
Visible (λ > 310 nm)
Aerosols
O3
COS
Clouds
Aerosols
Ozone Removal
OH + O3 → HO2 + O2
OH + 2O2 ← HO2 + O3
everywhere
HOx
O2
O3
CO2
H2O
CH4
Ozone Production
NO2 + hv → NO + O
NO2+OH ← NO+HO2
CO + O2 + OH → CO2+HO2
normal
HOx
O
O + O2 →M O3
NOx
ROx
R + H2O ← RH+OH
NO2 + hv → NO + O
OH + NO2 ← NO + HO2
R + O2 →M RO2
RO + O2 → HO2 + Aldehydes/Ketones
NO + RO2 → NO2 + RO
NO + O3 ← NO2 + hv
polluted
R = CH3, ...
RH CO NOx
HOx
SO2
H2SO4
H2SO4
SO2
Dust
Soil
SO2
CS2
OH
COS,
SO2
COS
COS
CS2
CH3SCH3
OH
SO2
SO2
CH3SCH3
Sea Salt
Ocean
Land
Ocean



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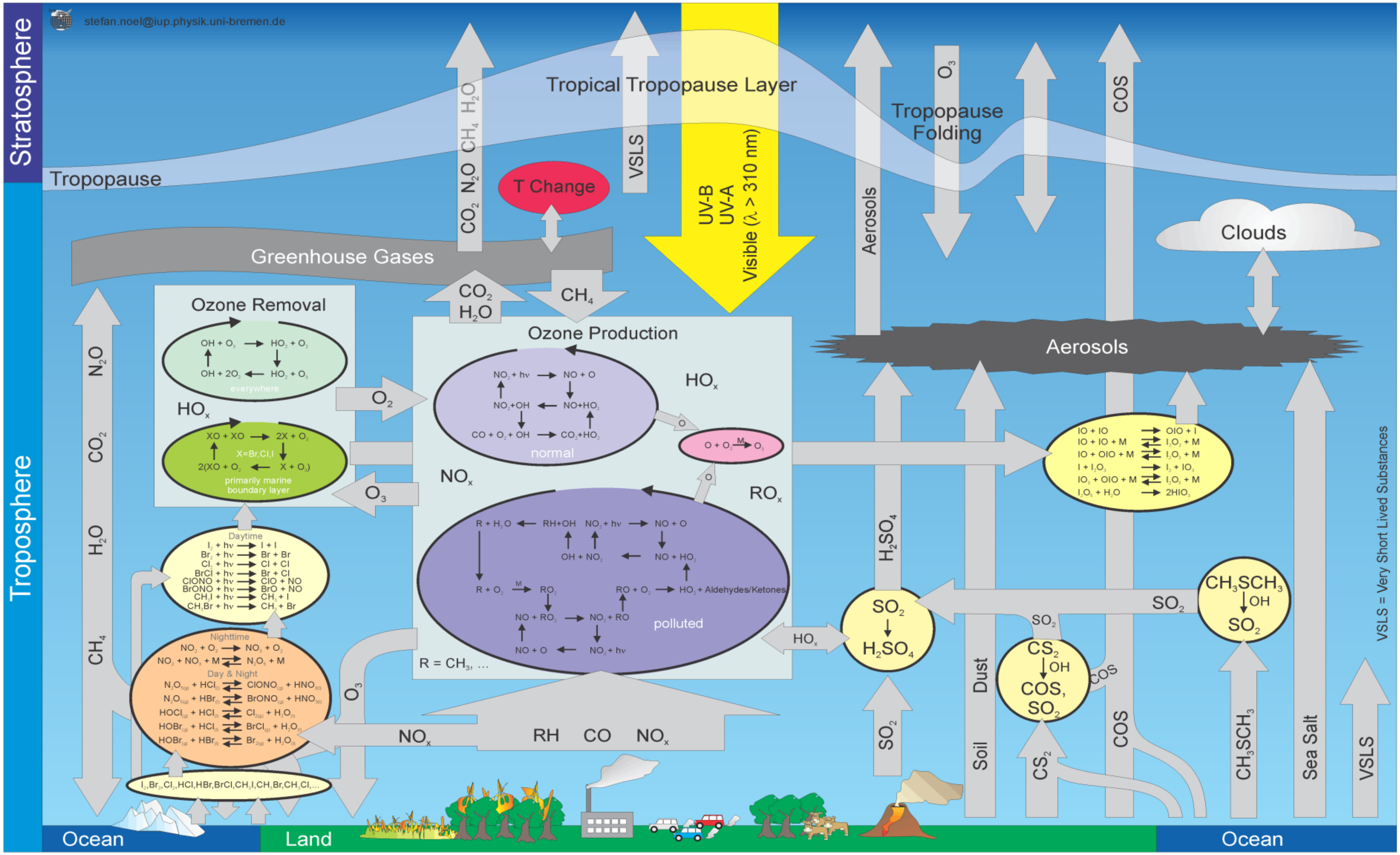
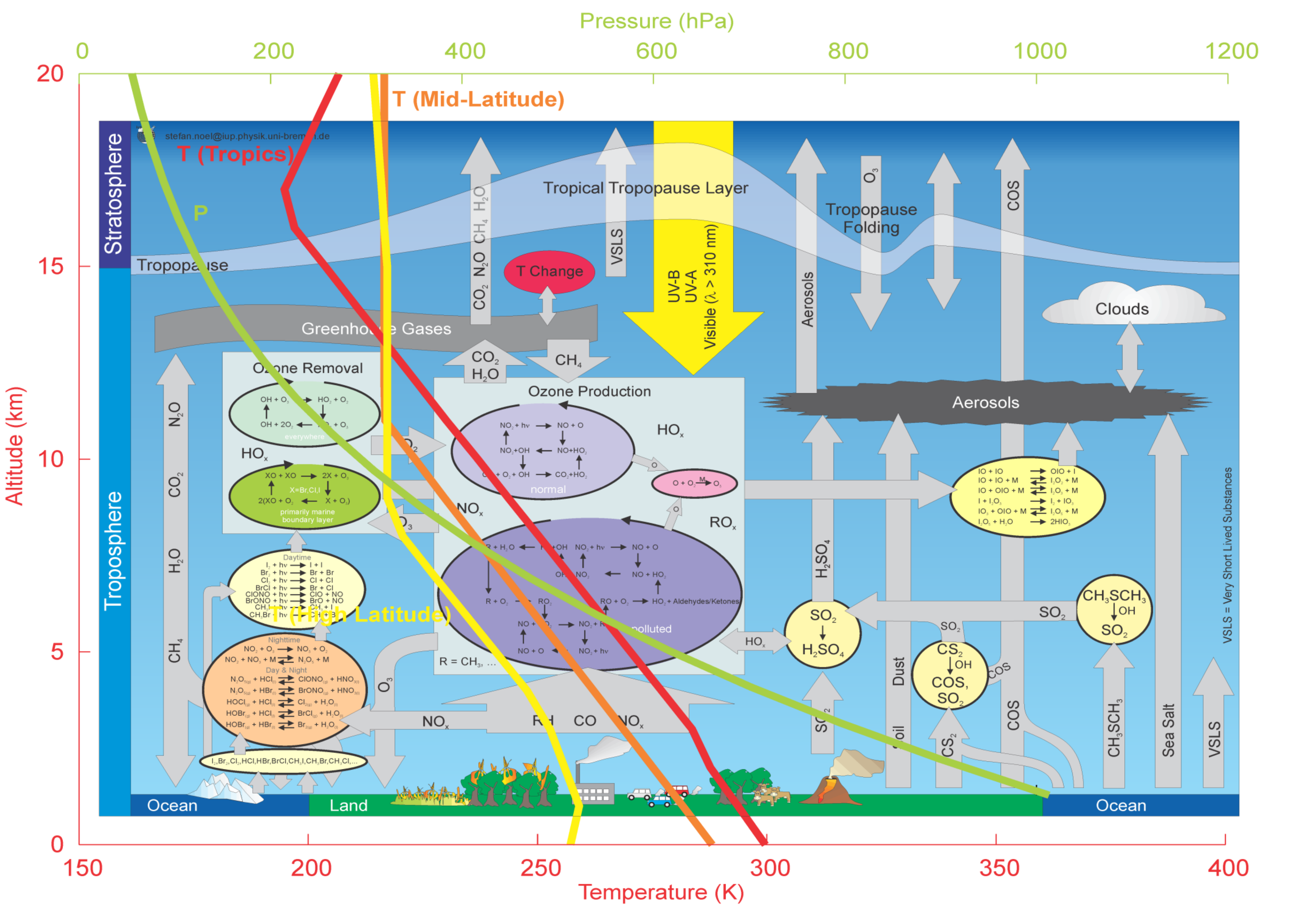
Stratosphere
Troposphere
Tropopause
Tropical Tropopause Layer
Tropopause Folding
T Change
Greenhouse Gases
CO_2 N_2O CH_4 H_2O
UV-B
UV-A
Visible (λ > 310 nm)
Aerosols
O_3
COS
Clouds
Aerosols
Ozone Removal
$OH + O_3$ → $HO_2 + O_2$
$OH + 2O_2$ ← $HO_2 + O_3$
everywhere
HO_x
O_2
O_3
CO_2
H_2O
CH_4
Ozone Production
$NO_2 + h\nu$ → $NO + O$
NO_2+OH ← $NO+HO_2$
$CO + O_2 + OH$ → CO_2+HO_2
normal
HO_x
O
$O + O_2 \xrightarrow{M} O_3$
O
NO_x
RO_x
$R + H_2O$ ← $RH+OH$
$NO_2 + h\nu$ → $NO + O$
$OH + NO_2$ ← $NO + HO_2$
$R + O_2 \xrightarrow{M} RO_2$
$RO + O_2$ → HO_2 + Aldehydes/Ketones
$NO + RO_2$ → $NO_2 + RO$
$NO + O$ ← $NO_2 + h\nu$
polluted
R = CH_3, ...
RH CO NO_x
N_2O
CO_2
H_2O
CH_4
O_3
HO_x
H_2SO_4
SO_2
H_2SO_4
SO_2
Dust
Soil
SO_2
CS_2
OH
COS,
SO_2
COS
COS
CS_2
SO_2
CH_3SCH_3
OH
SO_2
CH_3SCH_3
Sea Salt
Ocean
Land
Ocean


stefan.noel@iup.physik.uni-bremen.de
Stratosphere
Troposphere
Tropopause
Tropical Tropopause Layer
Tropopause Folding
CO2 N2O CH4 H2O
VSLS
UV-B
UV-A
Visible (λ > 310 nm)
T Change
Greenhouse Gases
CO2
H2O
CH4
O3
COS
Aerosols
Clouds
Ozone Removal
OH + O3 → HO2 + O2
OH + 2O2 ← HO2 + O3
everywhere
HOx
XO + XO → 2X + O2
X=Br,Cl,I
2(XO + O2 ← X + O3)
primarily marine boundary layer
O2
O3
Ozone Production
NO2 + hν → NO + O
NO2+OH ← NO+HO2
CO + O2 + OH → CO2+HO2
normal
HOx
NOx
ROx
O + O2 →M O3
polluted
R = CH3, ...
HOx + Aldehydes/Ketones
N2O
CO2
H2O
CH4
Daytime
Nighttime
Day & Night
I2,Br2,Cl2,HCl,HBr,BrCl,CH3I,CH2Br,CH2Cl,...
NOx
RH CO NOx
H2SO4
SO2
H2SO4
SO2
CS2
OH
COS,
SO2
CH3SCH3
OH
SO2
Dust
Soil
COS
CH3SCH3
Sea Salt
VSLS
VSLS = Very Short Lived Substances
Ocean
Land
Ocean



Pressure (hPa)
0
200
400
600
800
1000
1200
Altitude (km)
20
15
10
5
0
Temperature (K)
150
200
250
300
350
400
T (Mid-Latitude)
T (Tropics)
T (High Latitude)
P
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Stratosphere
Troposphere
Tropopause
Tropical Tropopause Layer
Tropopause Folding
Greenhouse Gases
T Change
CO2 N2O CH4 H2O
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Aerosols
O3
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Clouds
CO2
H2O
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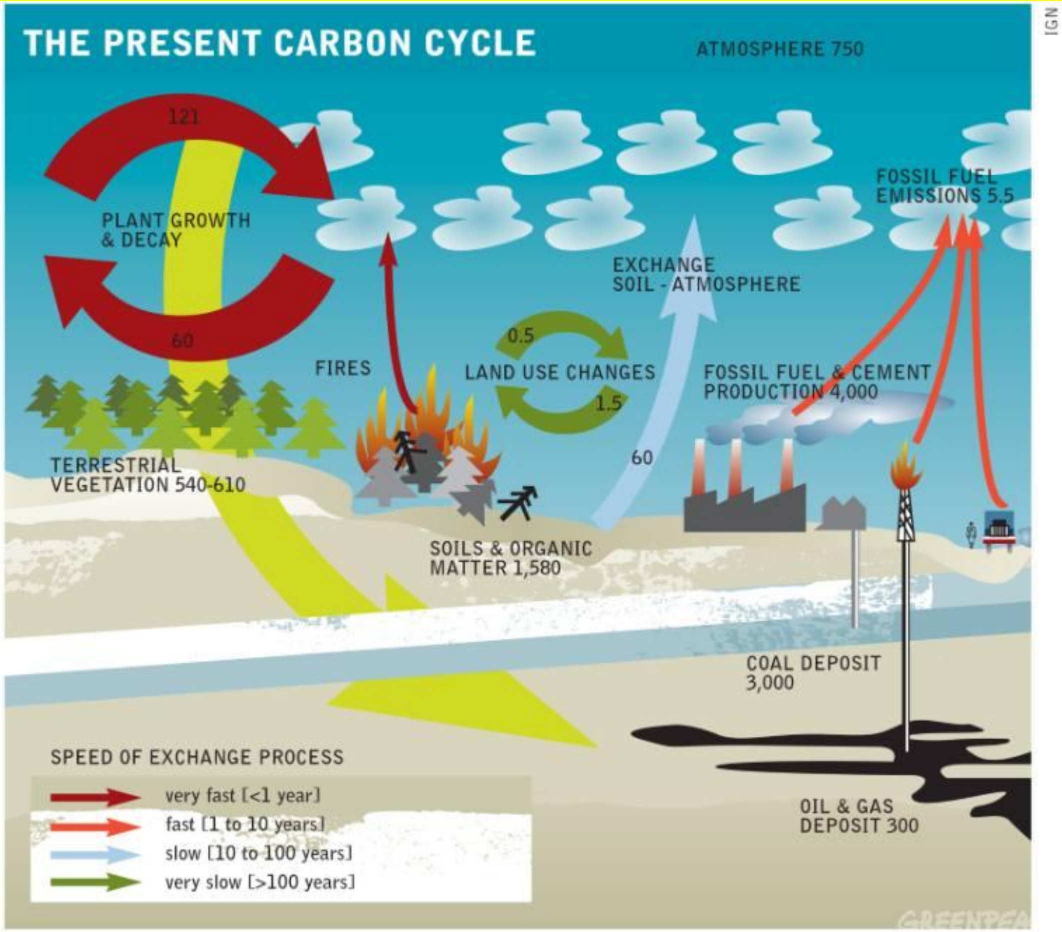
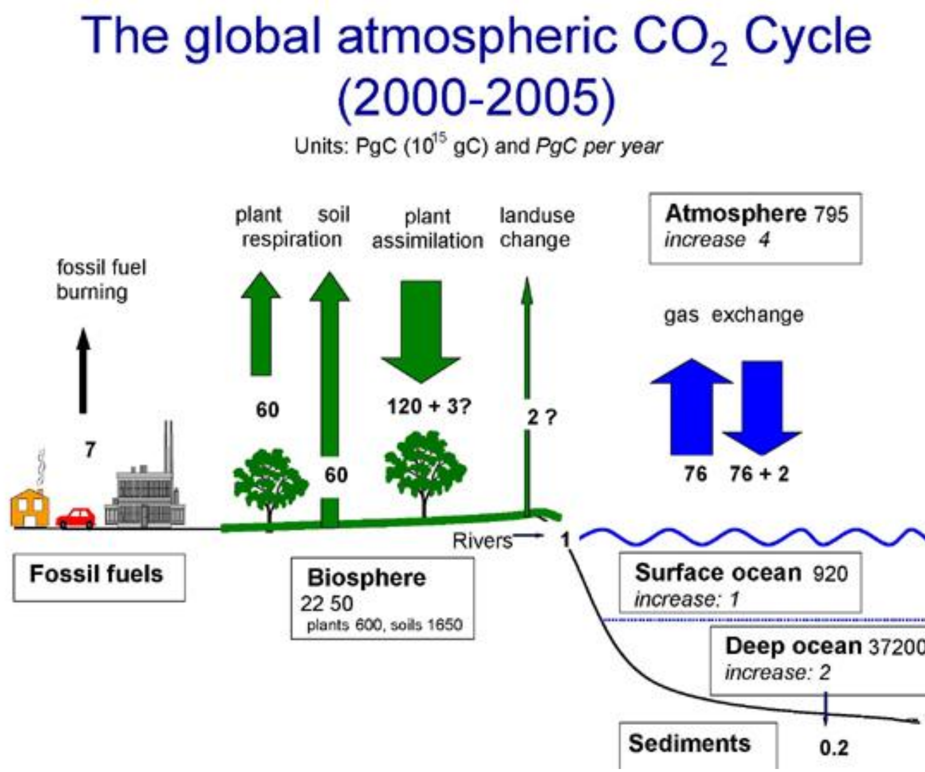
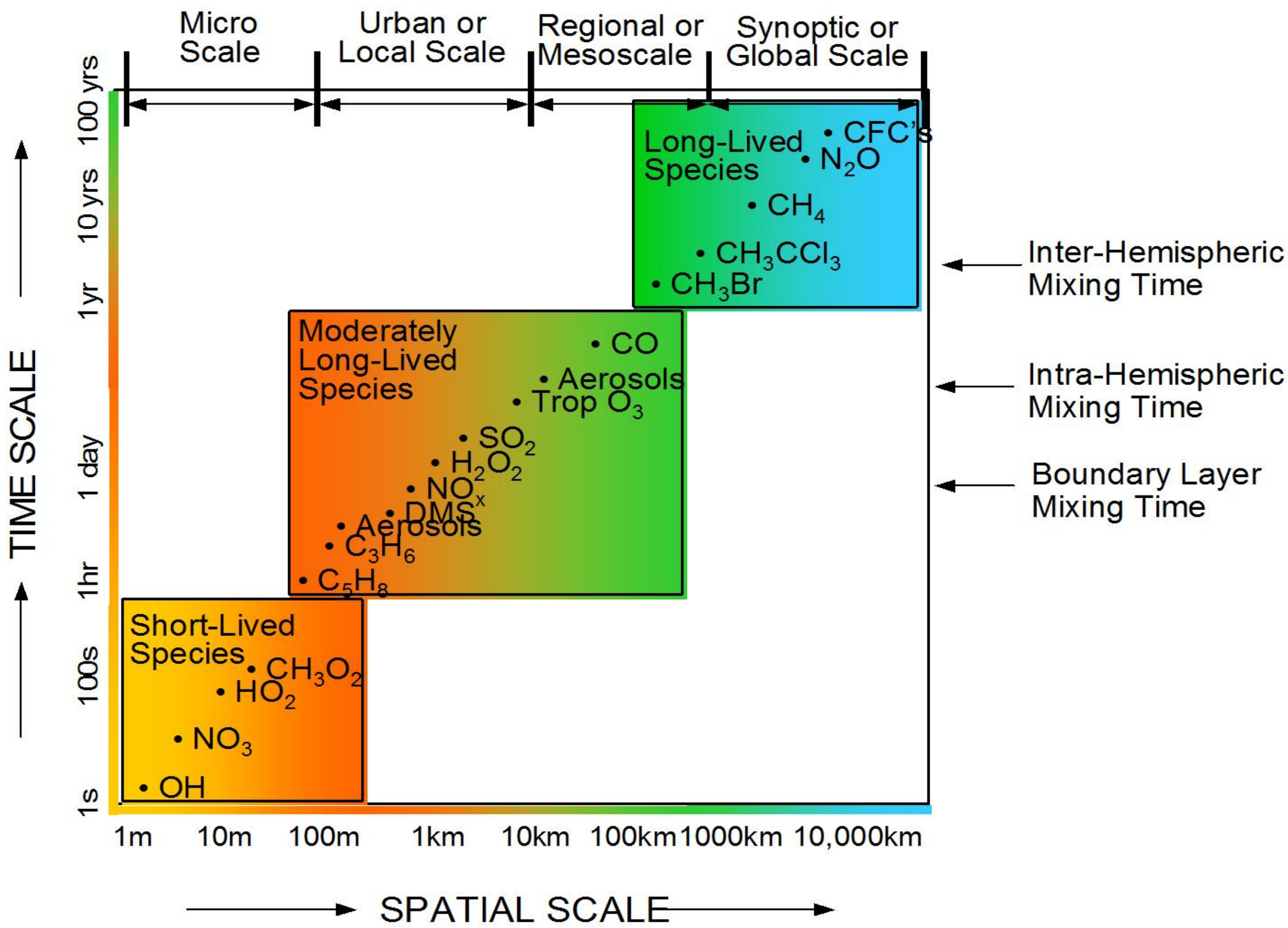
Ozone Removal
everywhere
HOx
X=Br,Cl,I
primarily marine boundary layer
Ozone Production
normal
polluted
HOx
NOx
ROx
R = CH3, ...
Daytime
Nighttime
Day & Night
N2O
CO2
H2O
CH4
NOx
RH
CO
NOx
O3
H2SO4
SO2
H2SO4
HOx
SO2
CS2
OH
COS,
SO2
CH3SCH3
OH
SO2
Dust
Soil
CS2
COS
CH3SCH3
Sea Salt
VSLS
VSLS = Very Short Lived Substances
Ocean
Land
Ocean

Climate Change and The Carbon Cycle





Temporal and Spatial Scales



Anthropogenic vs. Natural ?

Anthropogenic

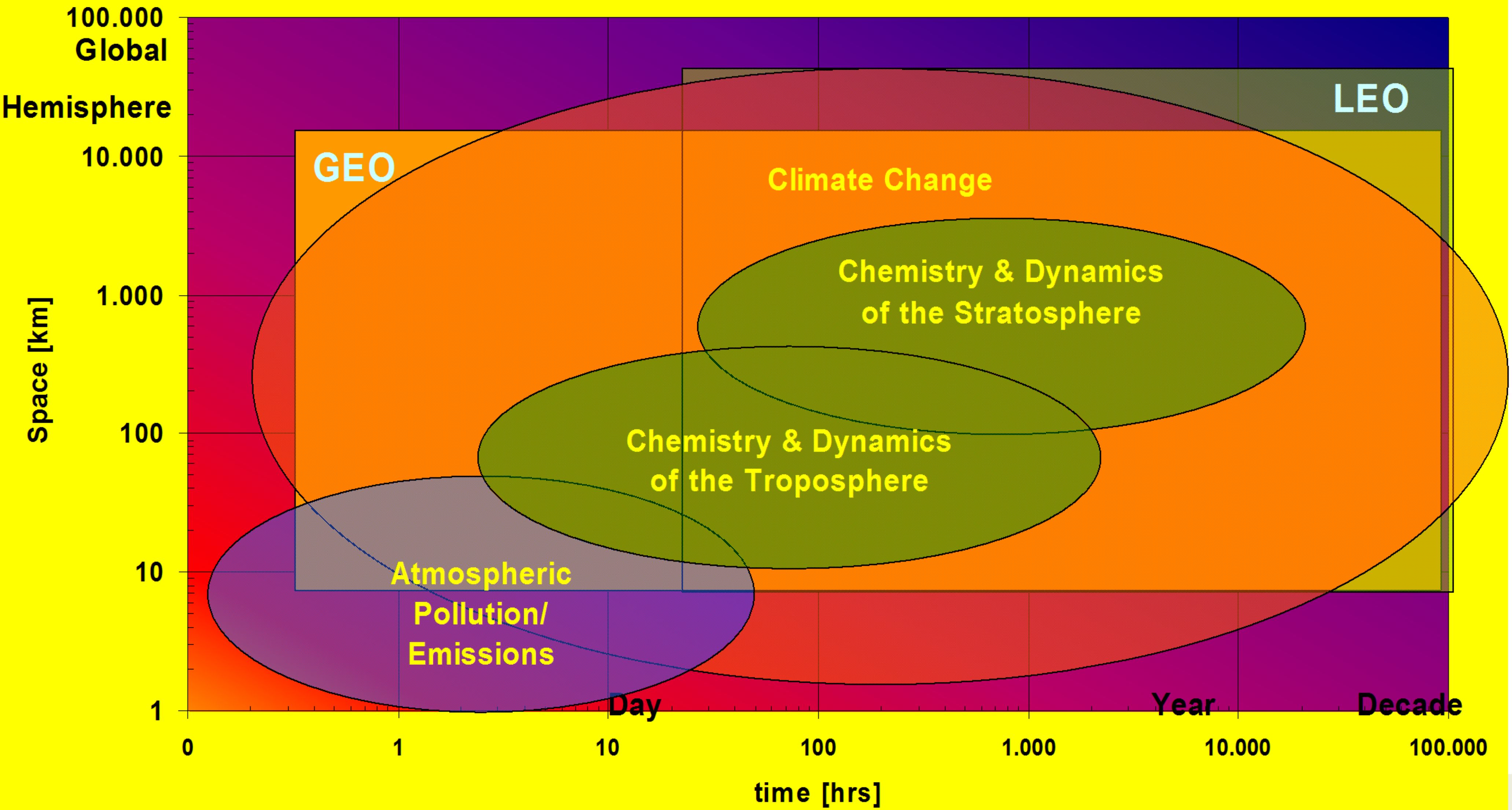
- Biomass Burning
- Pollution/Air Quality
- Acid Deposition
- Oxidising Capacity
- Surface Fluxes
  Greenhouse Gases

Natural

- Biomass Burning
- Lightning
- Volcanoes
- Oxidising Capacity
- Surface Fluxes
  - Emission
  - Deposition

COUPLING

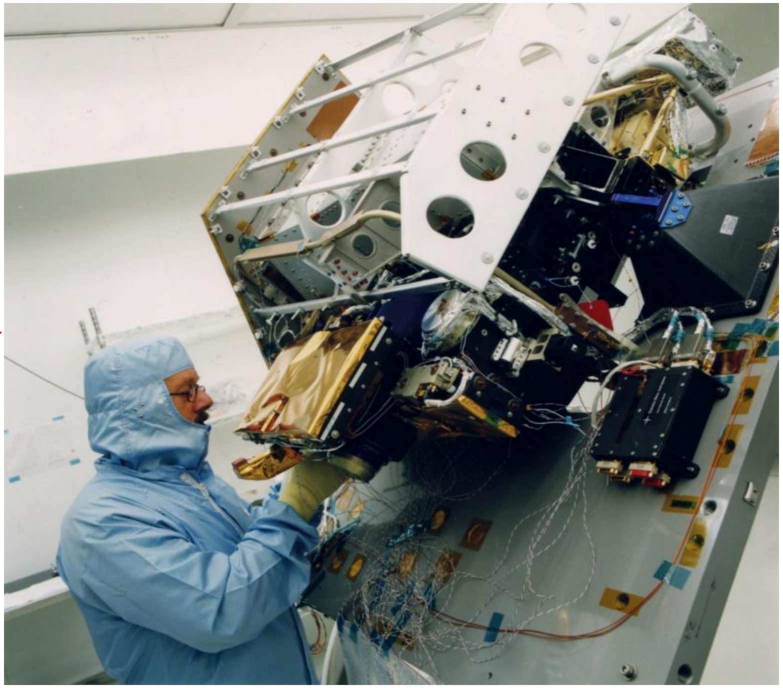
Spatial and Temporal Scales relevant for measurements from LEO and GEO



SCIAMACHY: Abridged History 1/2

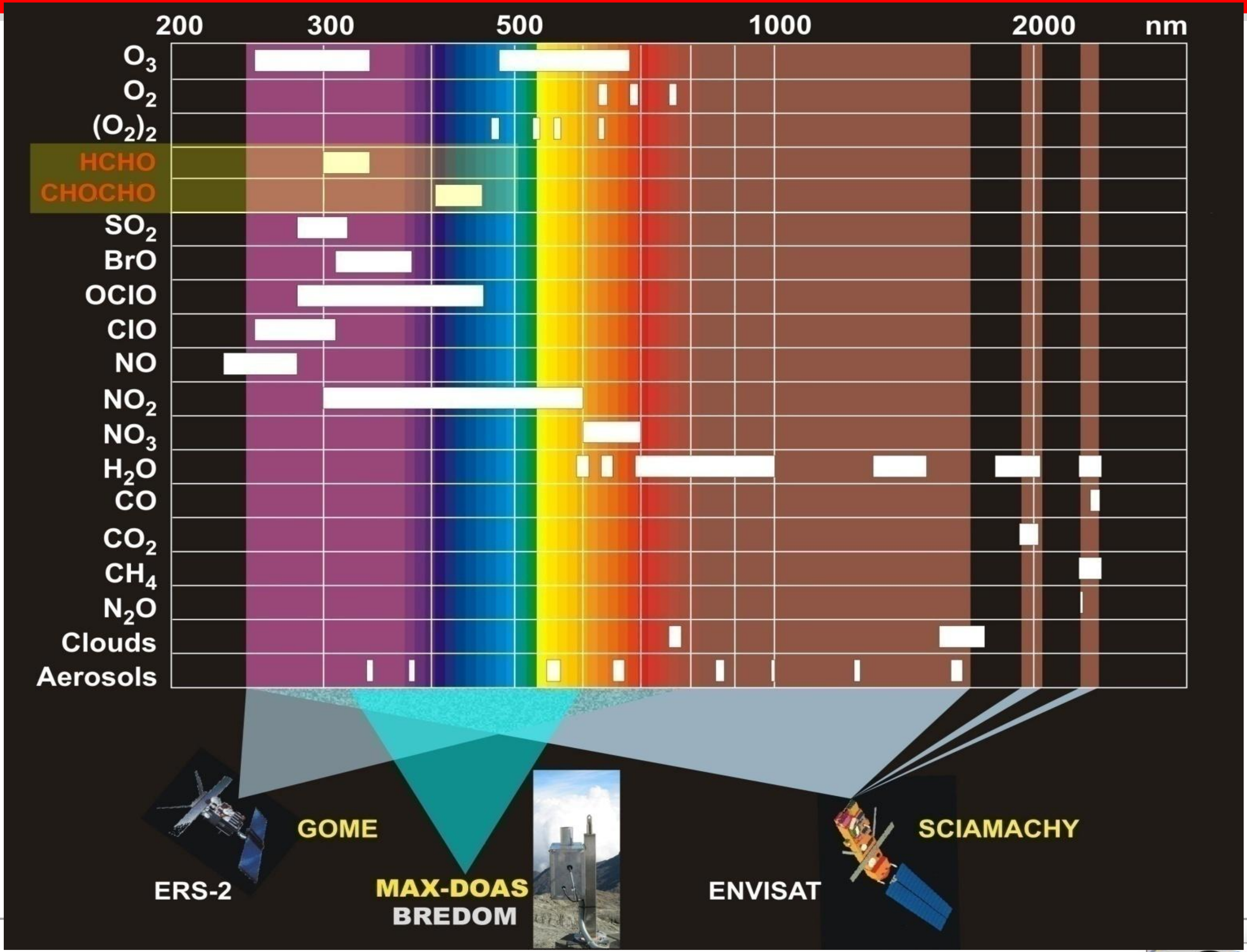
1984/1985	**Mapping of Atmospheric Pollution Proposal of SCIA-like project for ESA EURECA – no interest.**
1985	**Stratospheric ozone hole observed by Farman et al. (Nature)**
1988	***SCIAMACHY proposed to ESA for POEM-1***
1988/89	**Proposal of SCIA-mini/GOME (Global Ozone Monitoring Experiment) for ERS-2**
1989 – 2002	***Design and Development of SCIAMACHY German/Dutch/Belgian contribution***
April 1995	**Launch of ERS-2 with GOME**
1997-2000	**Selection of GOME-2 for the EUMETSAT operational series MetOp**
1998	**GeoSCIA proposed to ESA EE-1/ not chosen**
February 2002	***Launch of ENVISAT with SCIAMACHY***
July 2004	NSASA AURA launch

SCIAMACHY: Scanning **I**maging **A**bsorption spectro**M**eter for **A**tmospheric **CH**artograph**Y**

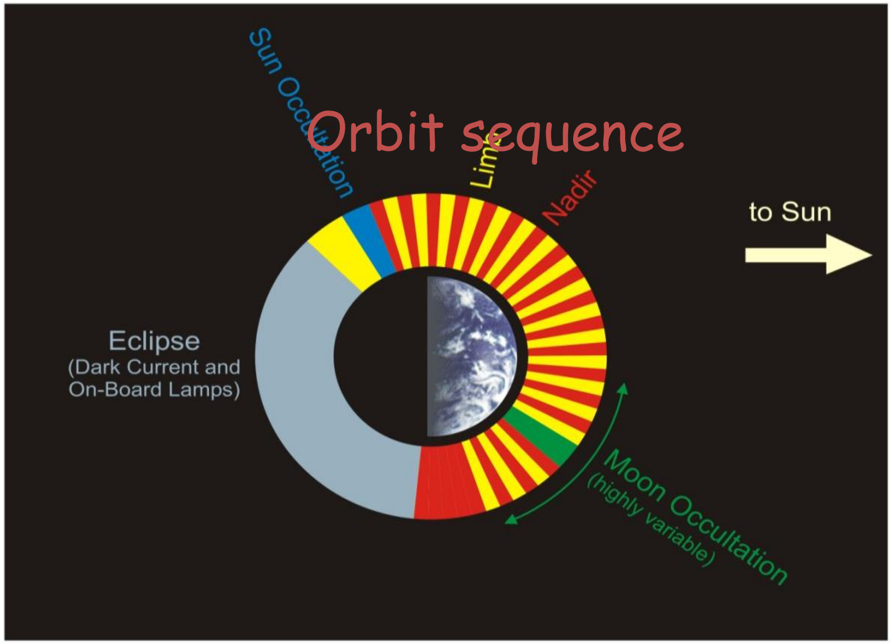


sciamachy /sʌɪ'aməki/ *n.* (also **skiamachy** /skʌɪ-/) *formal* **1** fighting with shadows. **2** imaginary or futile combat. [Greek *skiamakhia* (as SCIAGRAPHY, *-makhia* '-fighting')]

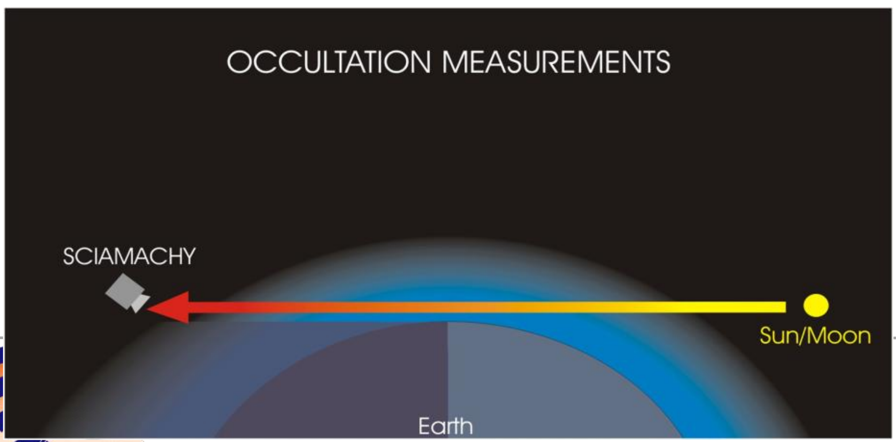
SCIAMACHY: Target Molecules + Parameters

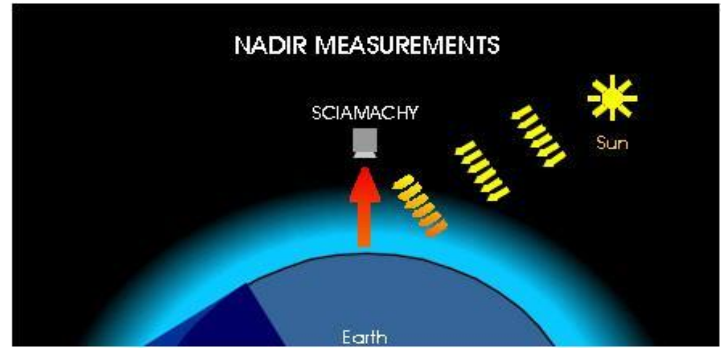


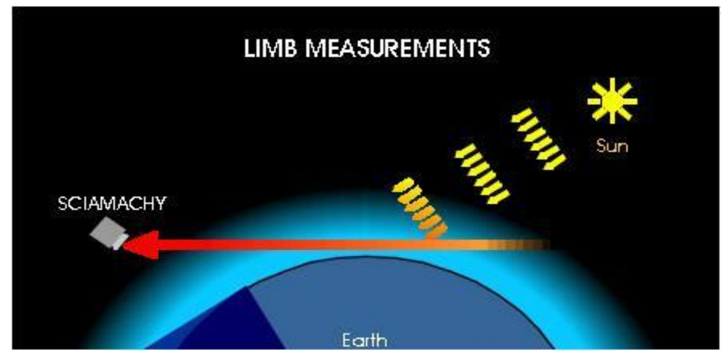
SCIAMACHY: orbit sequence & viewing modes

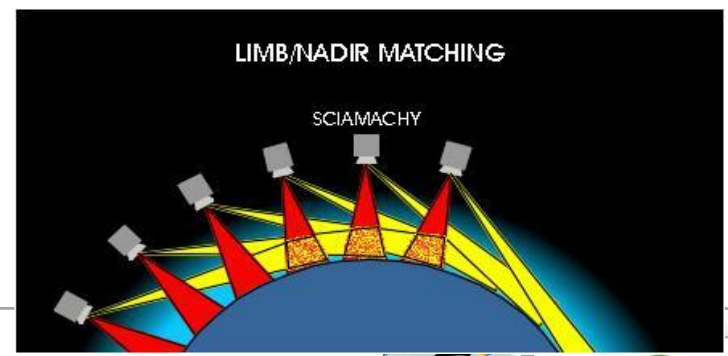


Viewing modes









LEO - Low Earth Orbit – Atmospheric Remote Sensing
Relevant History in Europe

1984—1985	MAPS (Mapping of Atmospheric Pollution) proposal for ESA EURECA platform by Burrows Perner and Crutzen - rejected
1984-1988	Development of SCIAMACHY (SCanning Imaging Absorption spectroMeter for Atmospheric CHartographY) concept Burrows et al – hunting light and shadow
1988	Submission of SCIAMACHY to ESA call for POEM Later called Envisat - Burrows et al
1988	Proposal of SCIA-mini to ESA call for ERS-2 – Burrows et al
1989	Selection of SCIAMACHY for ENVISAT
1990	Selection of GOME, a descoped SCIA-mini, for flight on ERS-2
1995	Launch of GOME on ESA ERS-2 20th April
2000	Selection of GOME-2 for Metop series of platforms
2002	Launch of SCIAMACHY on ENVISAT
2004	Launch of Aura with OMI
2006	Launch of Metop A with GOME-2 19th October
2007	EUMESAT Post Metop Committee recommends GOME-2 follow on UVNS
2008	EU GMES agrees to fund Sentinel 5 for Metop Second Generation
2011	ESA decommission ERS-2 and GOME July to September
2012	Loss of Envisat 9th April
2012	Launch of GOME-2 on Metop-B 17th September
2012	Sentinel 5 funding agreed for Metop Second Generation 2020- 2034

SCIAMACHY Phase A Review by ESA

ESA/PB-EO(88)68, 13 December 1988

The Polar Platform Announcement of Opportunity:
Results of Evaluation of Instrument Proposals:
SCIAMACHY

„The Board agreed that although this was an attractive proposal scientifically, it appeared a little bit over ambitious.“

……

Geostationary Measurement of Trace gases: relevant European history and development

1997 IGAC Conference Toronto, Canada, discussions with Jack Fishman and Arlin Krueger: GeoTropSAT an VULCAN concept

1997 Development of GeoSCIA Concept , targeting SCIA trace gases

1998 Proposal of GeoSCIA UV-VIS-NIR to ESA Earth Explorer Mission EEM-1 IUP – UB led team Burrows et al.

2000 Proposal of GeoSCIA++ UV-VIS-NIR-SWIR-TIR/Lightning/fire to ESA EEM-2 IUP – UB led team Burrows et al.

2002 Proposal of GeoTROPE UV-VIS-NIR-SWIR-TIR to ESA EEM-3 IUP – UB led team Burrows et al.

2003 Proposal of GeoSCIA^{light} UV-VIS (-NIR) to DLR national call IUP – UB led team Burrows et al. – Regional

2005 Proposal of GeoTROPE^{Regional} UV-VIS-NIR + TIR to ESA EEM-3 IUP – UB led team Burrows et al. – Regional

Geostationary Measurement of Trace gases: relevant European history and development

2005 EUMETSAT Meteosat Third Generation advisory Committee recommend UVS Instrument for MTGStudy (EUMETSAT Phase 0)

2006 UVS Instrument for Study (EUMETSAT Phase 0)

2007 EU GMES Working Group 4 recommend GeoSCIA like UVN

2007 GMES Sentinel 4 UVN Study (ESA Phase 0)

2008 ESA/EUGMES/EUMETSAT Decision to fly S4 UVN on METEOSAT Third Generation two instruments planned for 2018 to 2032 flies with IRS, an FTIR yielding H_2O, CO, O_3.. on MTG B – Combination similar to GeoTROPE-R

2009 EU GMES Sentinel 4 UVN (ESA Phase A)

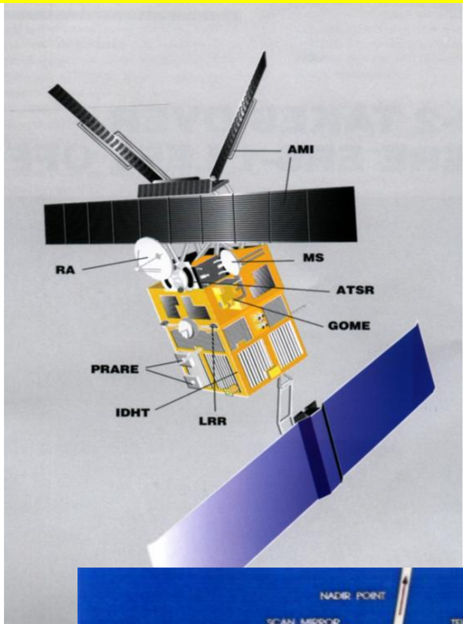
2011 Phase B2/C/D for S4 initiated by ESA

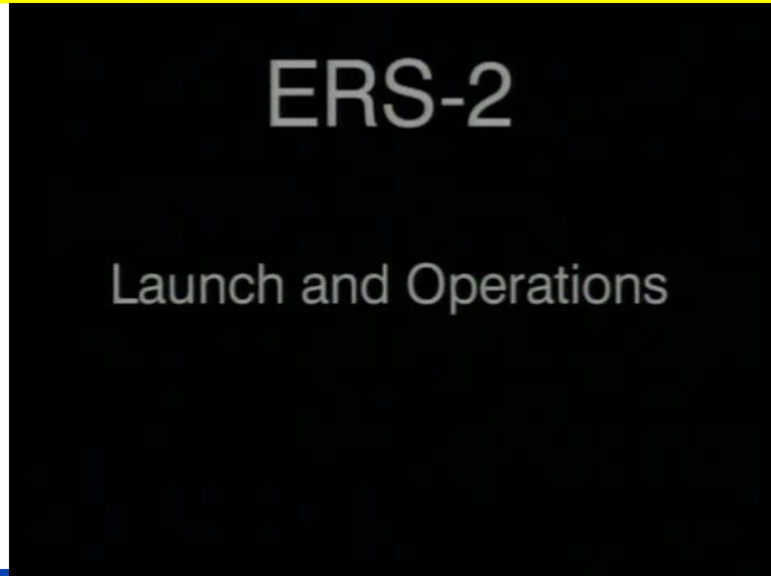
2012 The MTG series comprises four imaging and two sounding satellites.

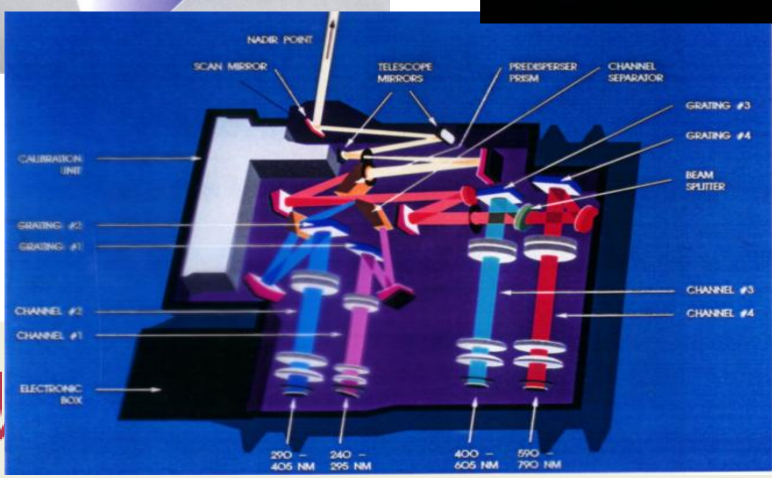
The MTG-I imaging satellites will carry the Flexible Combined Imager (FCI) and the Lightning Imager. The MTG-S sounding satellites will carry an Infrared Sounder (IRS) and an Ultraviolet Visible Near-Infrared spectrometer, which will be provided by ESA as the GMES Sentinel-4 mission. The primary objective of the GMES Sentinel-4 mission will be to support air quality monitoring and forecasting over Europe, in full synergy with the IRS sounder.; now entering phase B. 2018 to 2032.

Global Ozone Monitoring Experiment, GOME
ERS-2 Launch - 20th April 1995

SCIA-mini , proposed in December 1988. 6 months after SCIAMACHY, was descoped to Global Ozone Monitoring Experiment, GOME and built between 1990 and 1994 as part of core ERS-2 payload by ESA at Officine Galileo, TPD, Astrium and University of Bremen

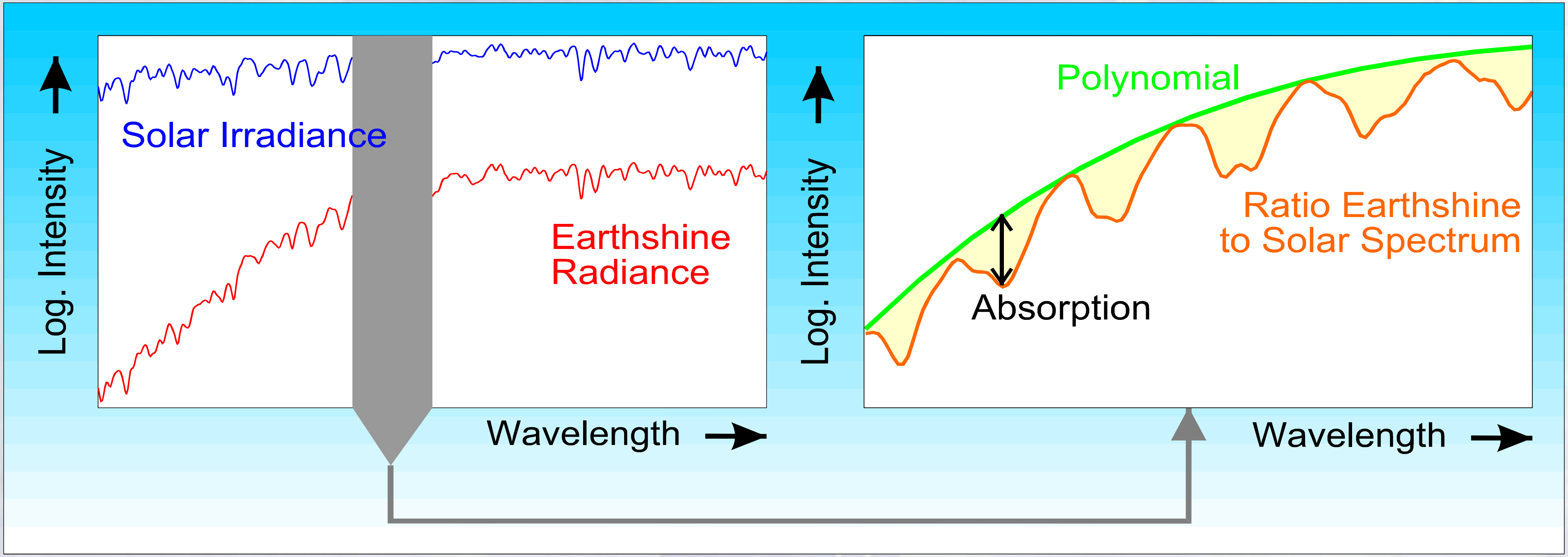






ENVISAT Launch: 1st March 2002, 2:07 CET

Differential Optical Absorption Spectroscopy DOAS – simply explained



Optimal Estimation

Measurement

$$\hat{\mathbf{x}} = \hat{\mathbf{S}}\left(\mathbf{K}^{T}\mathbf{S}_{y}^{-1}\mathbf{y} + \mathbf{S}_{a}^{-1}\mathbf{x}_{a}\right)$$

RTM

Climatology

$$\hat{\mathbf{S}} = \left(\mathbf{K}^{T}\mathbf{S}_{y}^{-1}\mathbf{K} + \mathbf{S}_{a}^{-1}\right)^{-1}$$

Instrument Modell, measurement errors

$\hat{x}$: vector of the atmospheric parameters with a retrieval covariance matrix $\hat{S}$

y: measurement vector with a measurement covariance matrix S_y

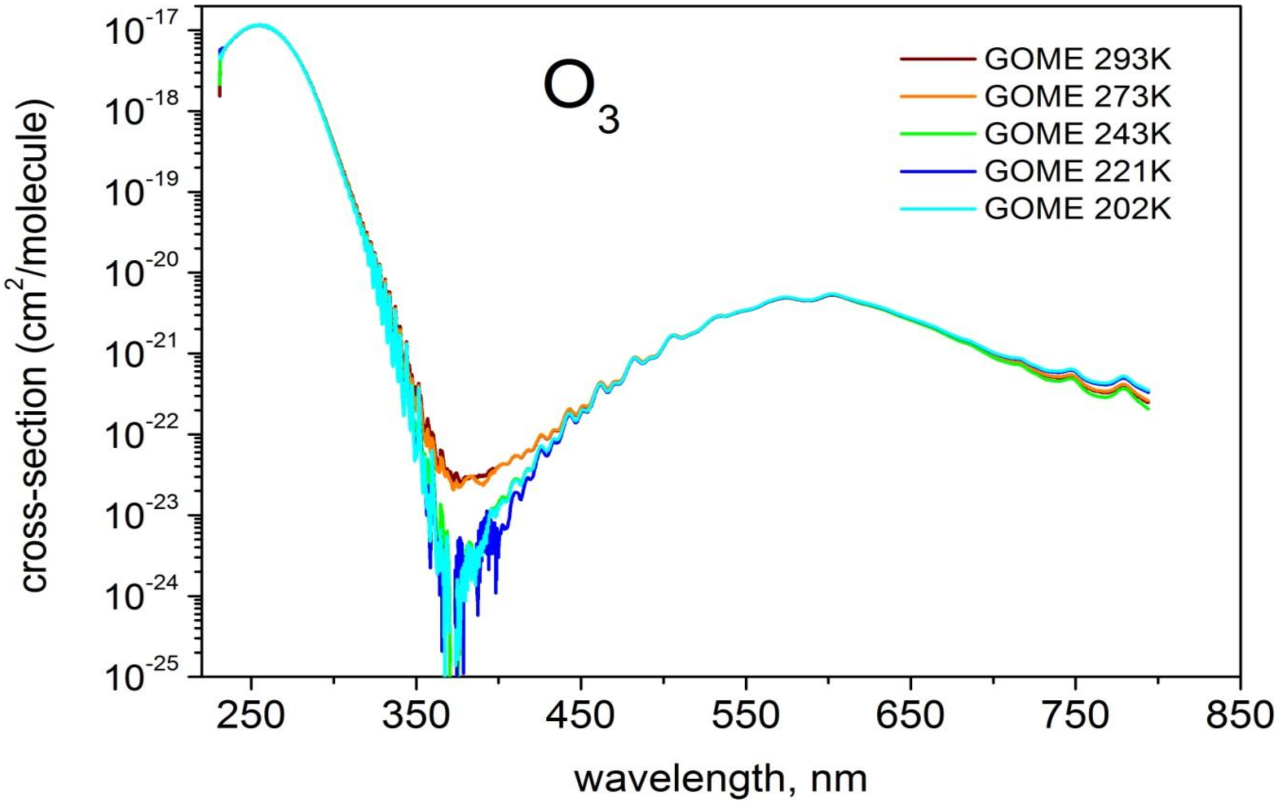
x_a: climatological state vector, apriori covariance matrix S_a

K : weighting function, derived from RTM

GOME O_3 absorption cross-sections

- **J. P. Burrows, A. Dehn, B. Deters, S. Himmelmann, A. Richter, S. Voigt, and J. Orphal.** *JQSRT*, **61**, 509-517, 1999.

- Spectral range: 231 - 794 nm
- 202, 221, 241, 273, 293 K
- Resolution: wavelength dependent 0.2-0.4 nm



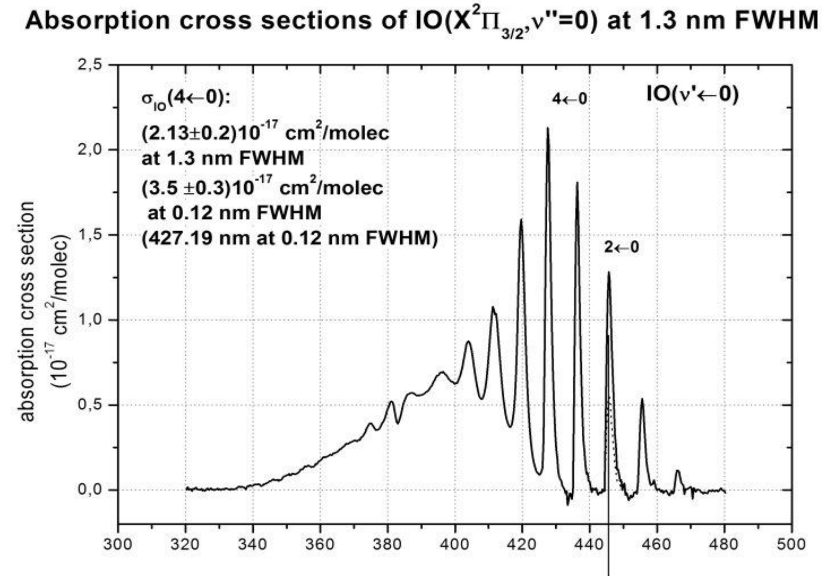
Grating Spectrometer IO absorption cross-sections

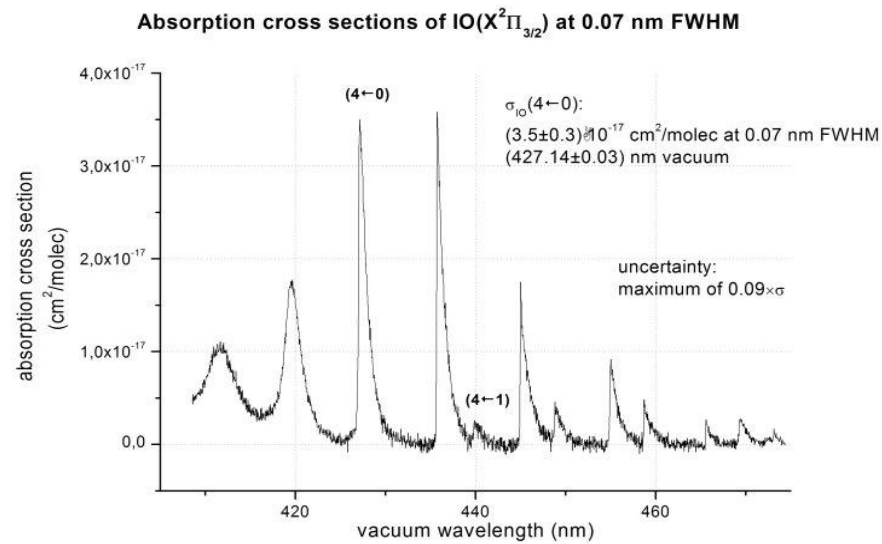
- **Gomez Martin, J.C., P. Spietz, J. Orphal and J. P. Burrows.** Spectro. Chim. Acta A, Vol. 60, pp. 2673 – 2693 , 2004

- Spectral range : 320 – 480 nm
- Resolution: 0.7, 1.3 nm
- 298 K
- Pressure: 15 – 400 mbar

- Absorption cross section:

  Determined by conservation of iodine atoms => Independent of previously determined rate coefficients and models of IO/OIO formation and consumption. Used only absorption cross sections of I2(500 nm) and I(183.038nm)





SCIATRAN RTM

GOMETRAN/SCIATRAN

A radiative transfer model for UV-Vis/NIR (240 – 2400 nm)

Products: Radiance, Weighting functions, Air Mass Factors

Spherical RTMs (CDI/CDIPI)

- SCIAMACHY (limb mode)
- Ground-based DOAS (off-axis)
- Aircraft/balloon

Pseudo-spherical RTM

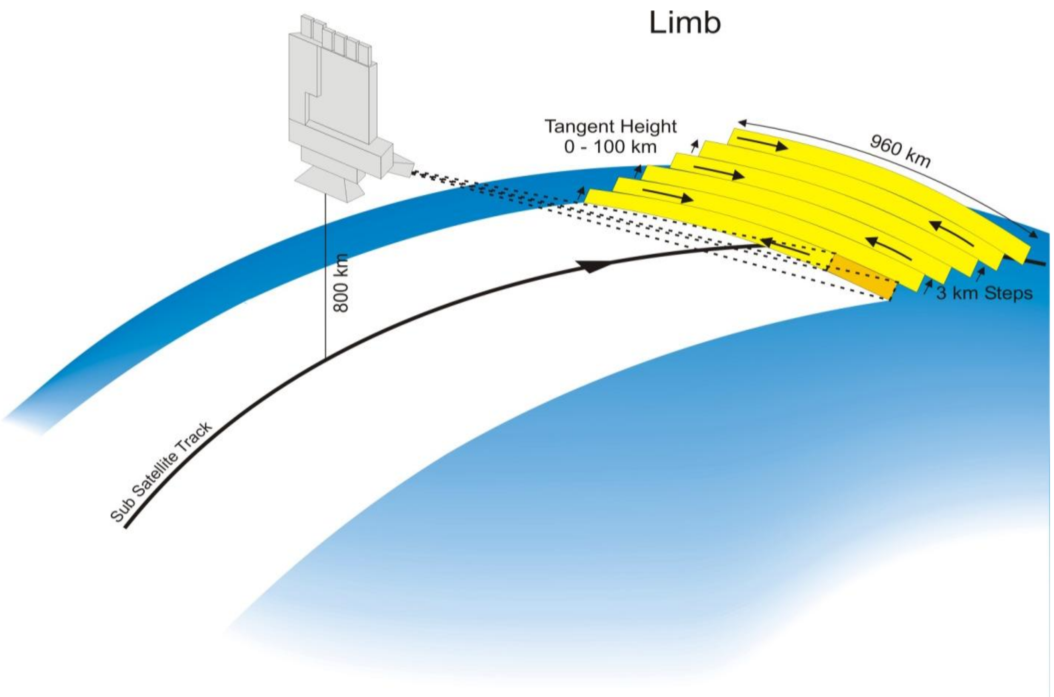
- GOME/SCIAMACHY (near-nadir geometry)
- Ground-based DOAS (near-zenith geometry)

PHOTOST

In pseudo-spherical mode only

- Upwelling flux
- Downwelling flux
- Actinic flux
- Photolysis frequency

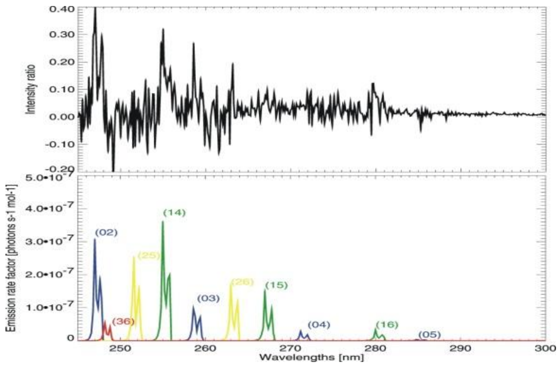
SCIAMACHY Legacy Measurements: Solar Limb and Occultation



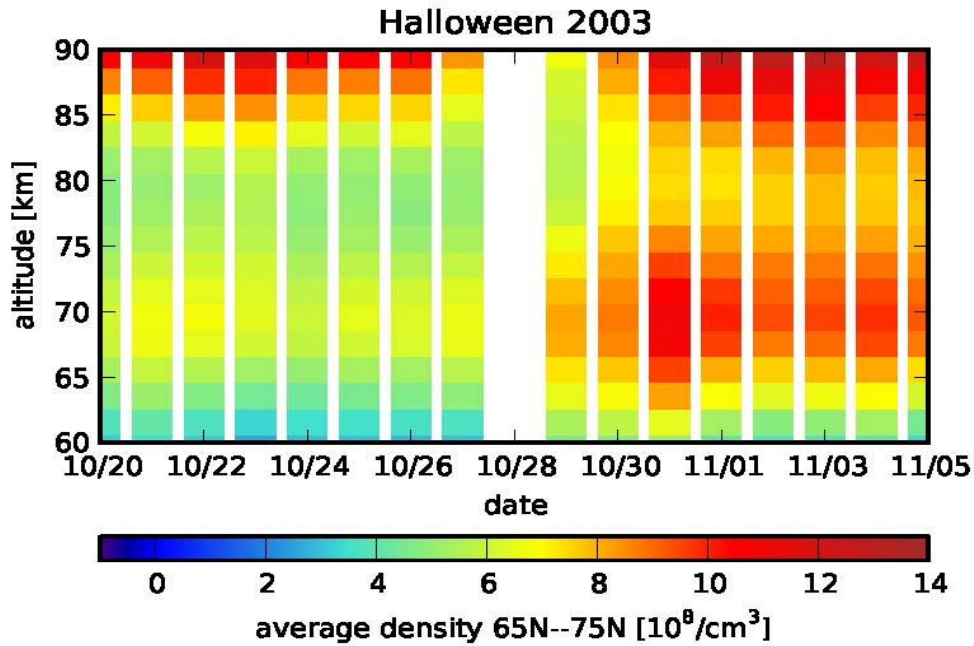
- vertical res.: 3 km
- horizontal resolution in azimuth: 240 km (120 km min.)
- horizontal resolution in flight direction: approx. 400 km
- Observation optimised to match
- limb with nadir measurements
- Duration of sequence: 60 sec.
- Global coverage: 6 days at the equator

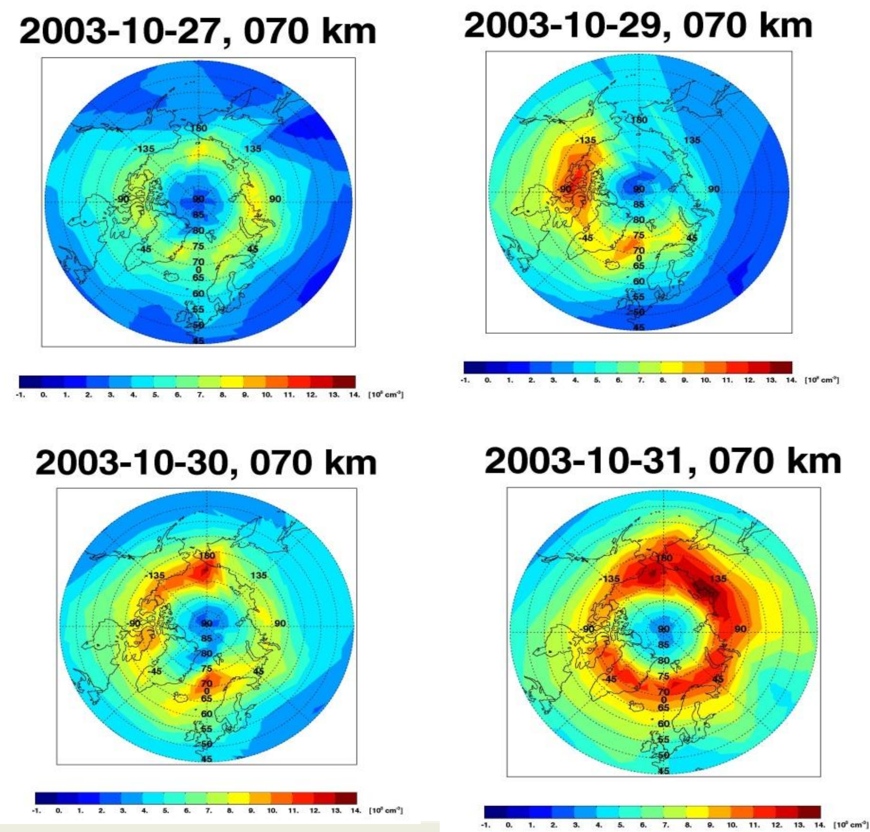
SCIAMACHY: NO Emissions and study of CME during Halloween 2003

Stefan Bender and Miriam Sinnhuber IMK/KIT



NO from SCIAMACHY orbit 798 Northern polar latitudes Limb scan 34 (~100 km) 2002





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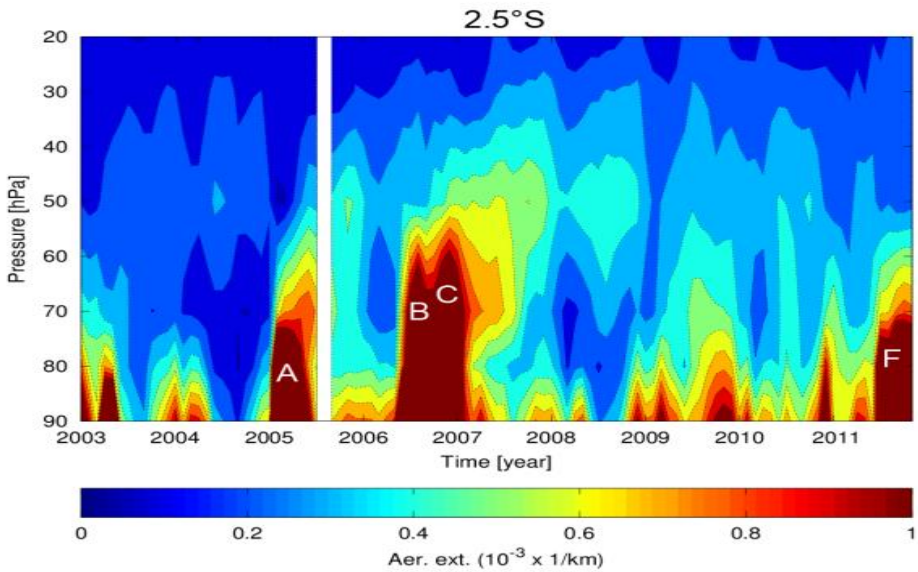
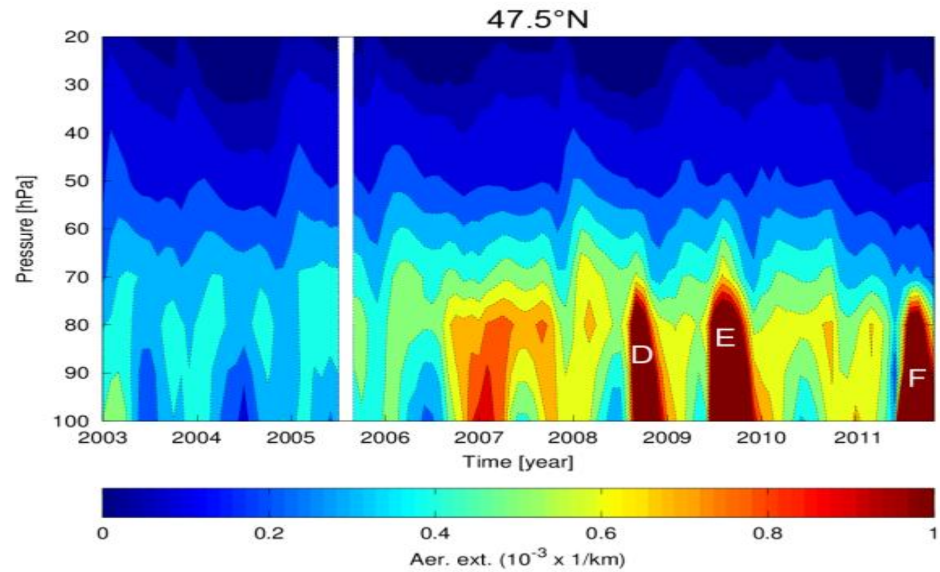
SCIAMACHY Stratospheric Aerosol

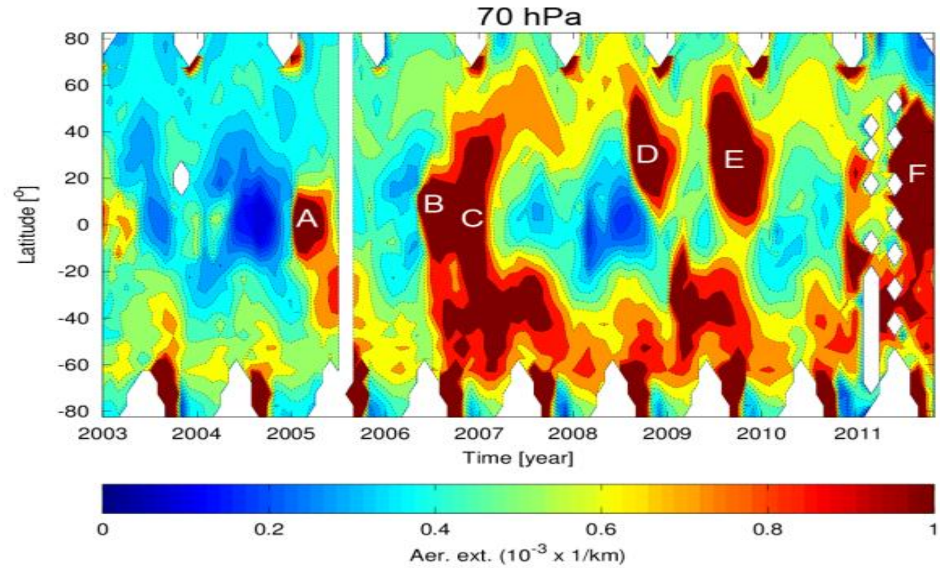
Monthly zonal mean aerosol extinction coefficient at 525 nm 2003 to 2011:



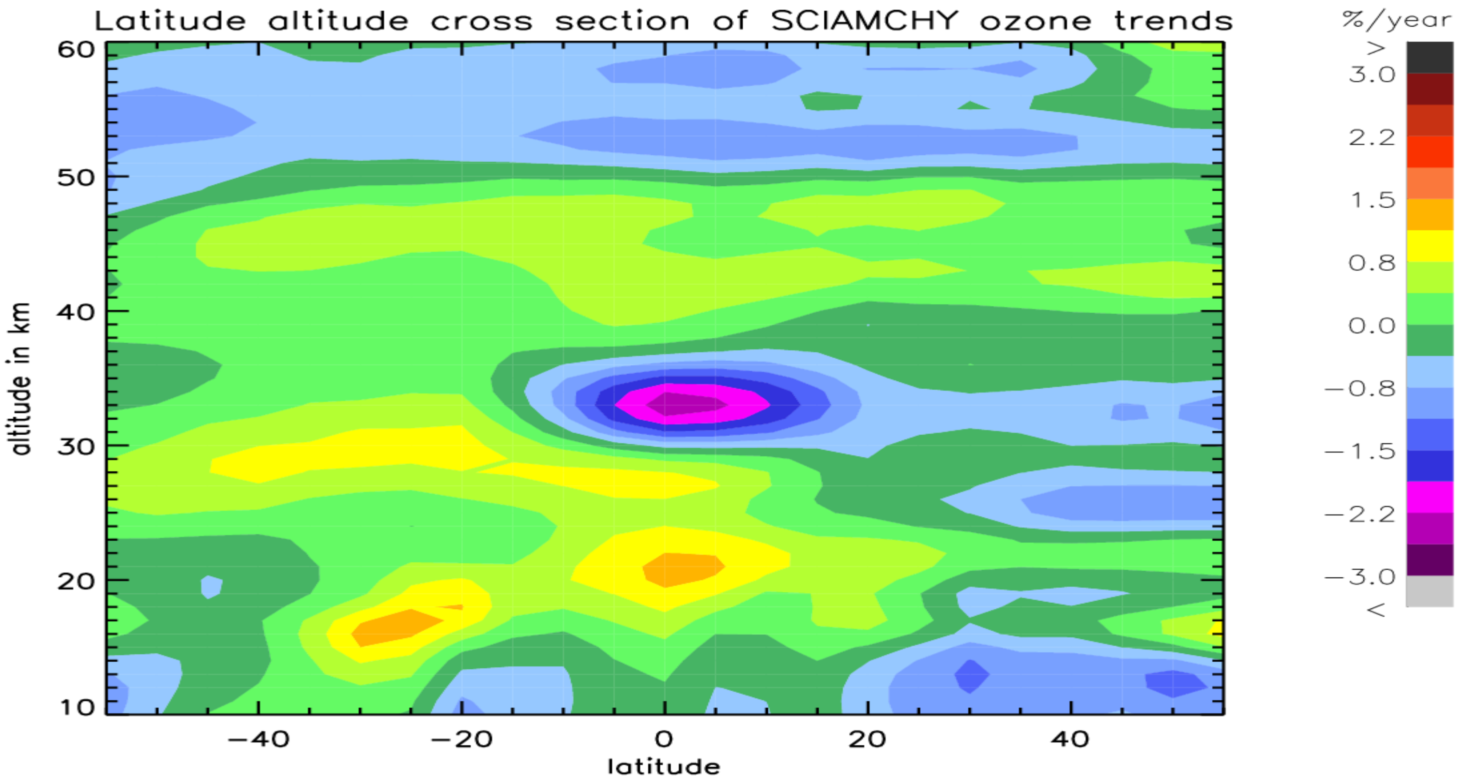


Observed **volcanic eruptions**:

A) Manam (Jan 2005, 4° S)
B) Soufriere Hills (May 2006, 16° N)
C) Tavurvur (Oct 2006, 4° S)
D) Kasatochi (Aug 2008, 52° N)
E) Sarychev Peak (July 2009, 48° N)
F) Nabro (June 2011, 13° N)



Latitude-altitude dependence of ozone trends



- minimum in the tropical 30-35 km range might be related to NO_X

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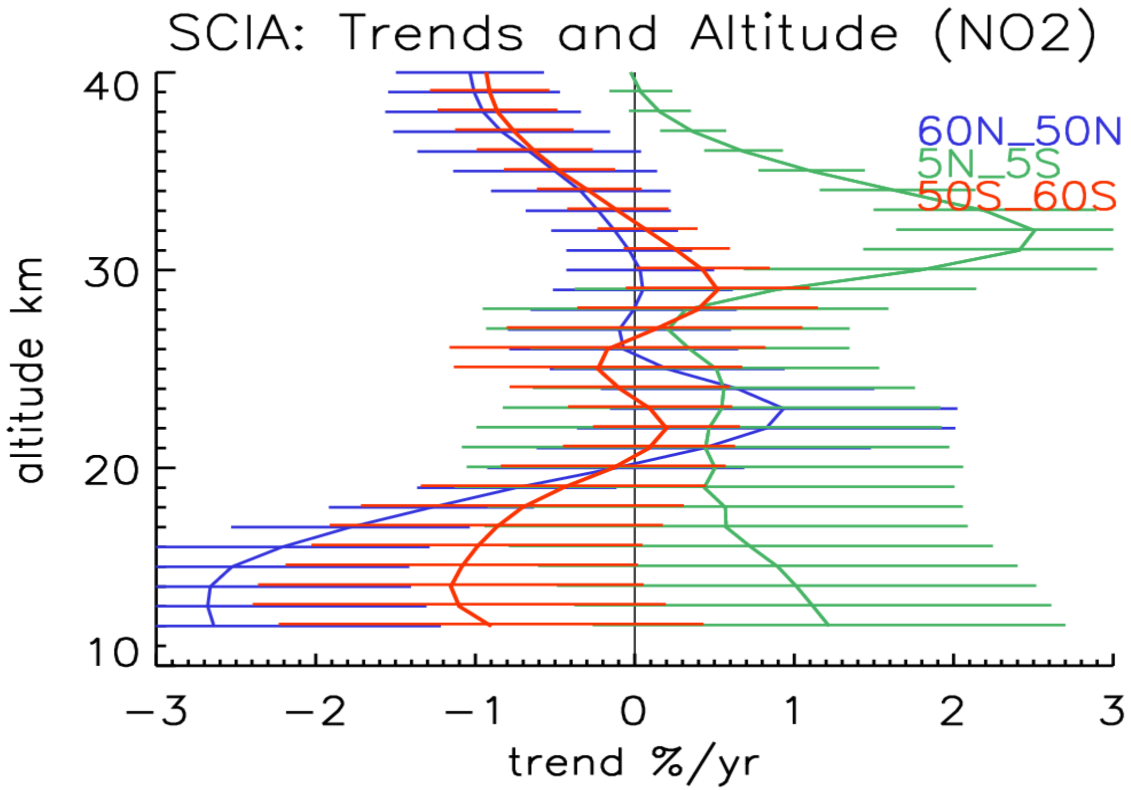
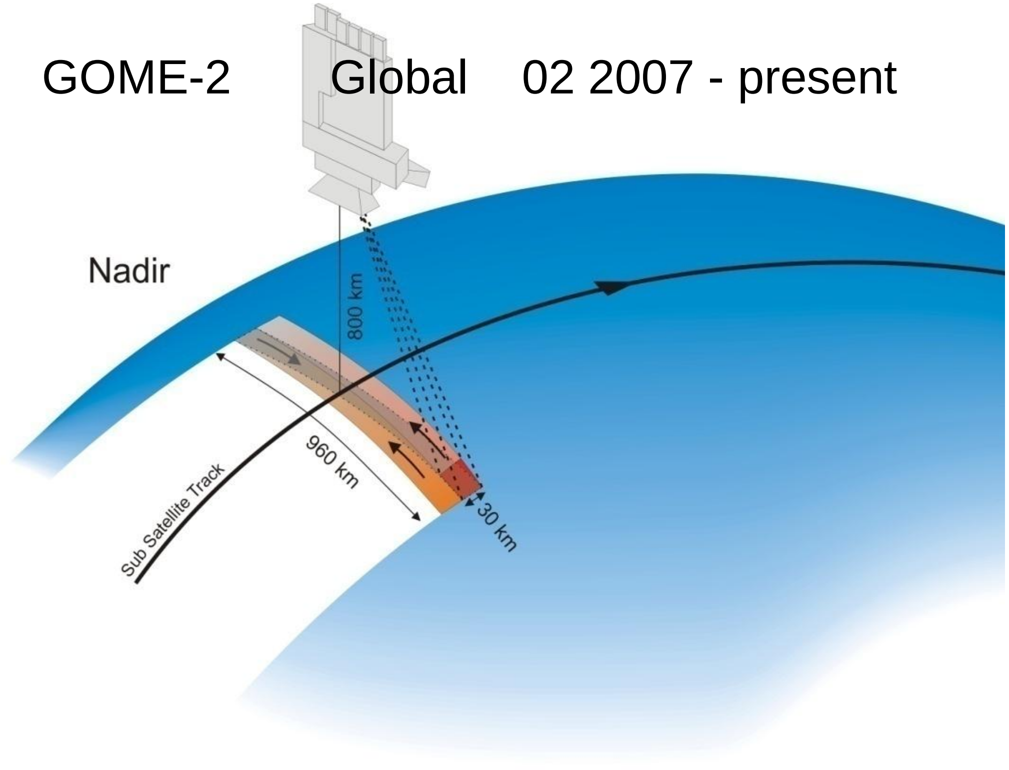
Vertical Variation of NO_2 trends



- In the tropics, maximum in the tropical 30 – 35 km range may be related to negative SCIA ozone trends (see slide before)

Legacy Data Sets : 1995 - present
Nadir Viewing Geometry

GOME	Global	07 1995 - 06 2003
	Regional	07 2003 - 07 2011
SCIAMACHY	Global	08 2002 - 04 2012
GOME-2	Global	02 2007 - present



- **horizontal resolution in across track:**
  - **GOME 80 and 320 km**
    global 1995-2003
    partial 2003- present
  - **SCIAMACHY 30-240 km**
    global 2002- present
  - **GOME-2 40-80 km**
- **horizontal resolution in along track:**
  - **GOME-1 and -2 40 km**
  - **SCIAMACHY 30 km**
- **Global coverage:**
  GOME-1 - swath 960 km - 3 days at the equator 10:30 am crossing time

  SCIAMACHY - swath 960 km 6 - days at the equator 10:00 crossing time
  GOME-2 – swath 1950 km
  ~1 day at the equator – crossing time 09:30 am

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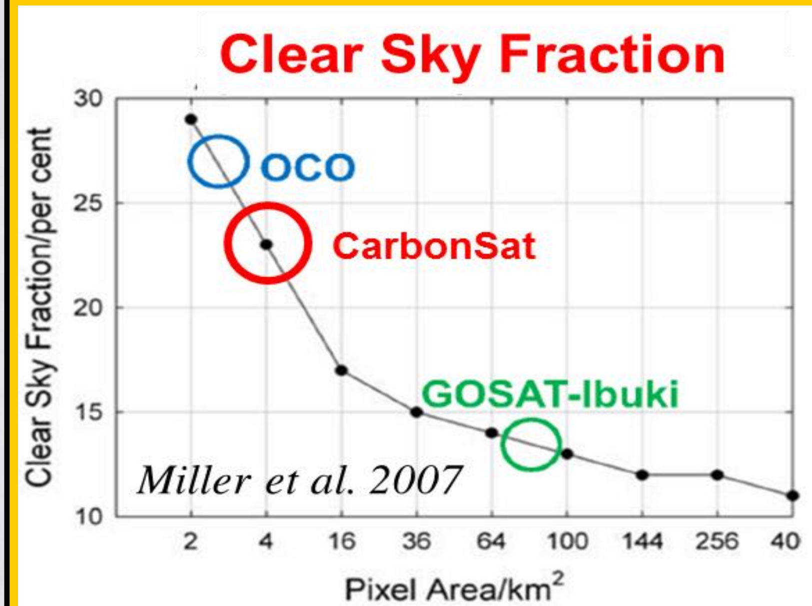
CarbonSat Constellation

Two main issues ?

Cloud free



Spatial Scales dynamics and chemistry

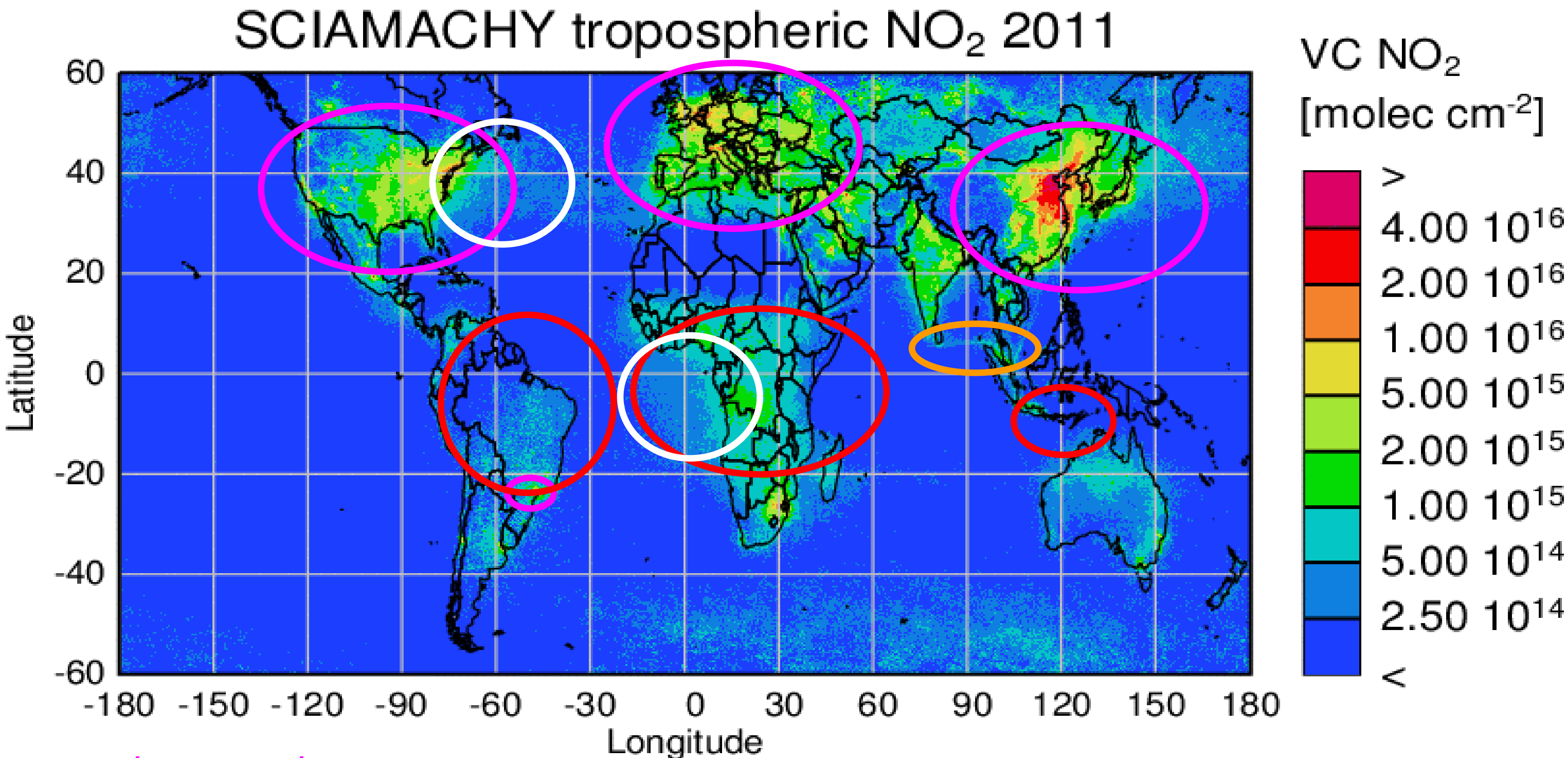
- Biomass Burning
- Lightning 1-5 km^2
- Volcanoes 0.5 km^2
- Oxidising Capacity

and tropospheric processing m^2 to global

- Surface Fluxes
  - Emission
    chimney $1m^2$ upwards
  - Deposition

COUPLING

Tropospheric NO_2 and Sources?



anthropogenic pollution

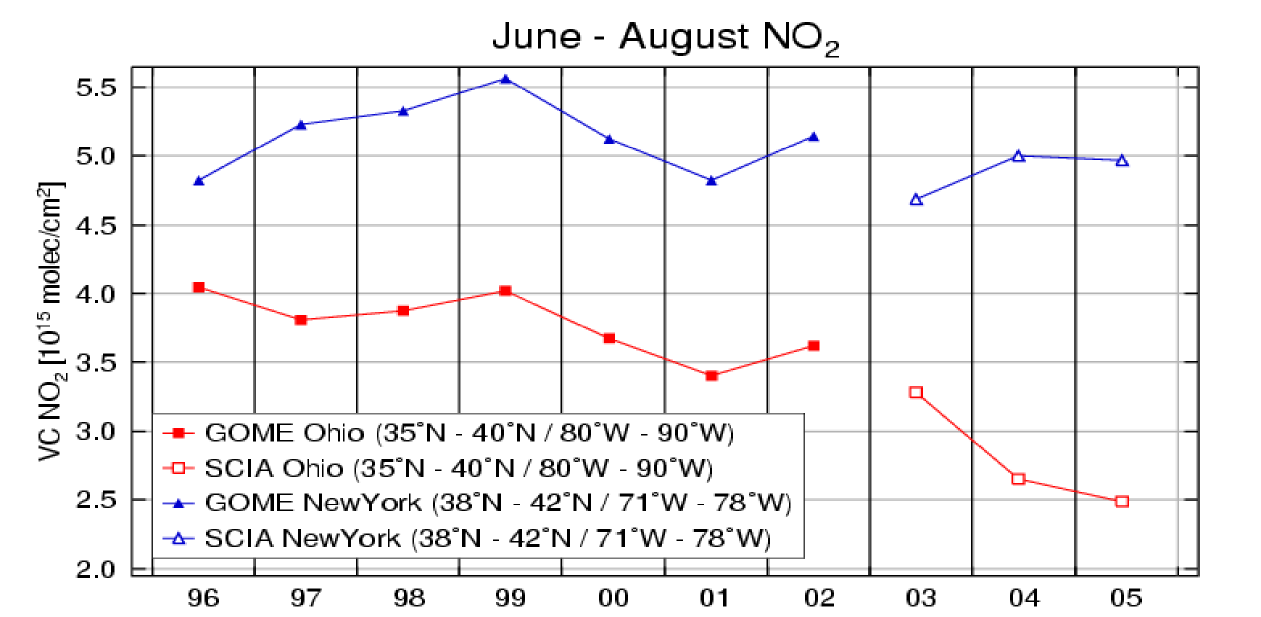
biomass burning

ships

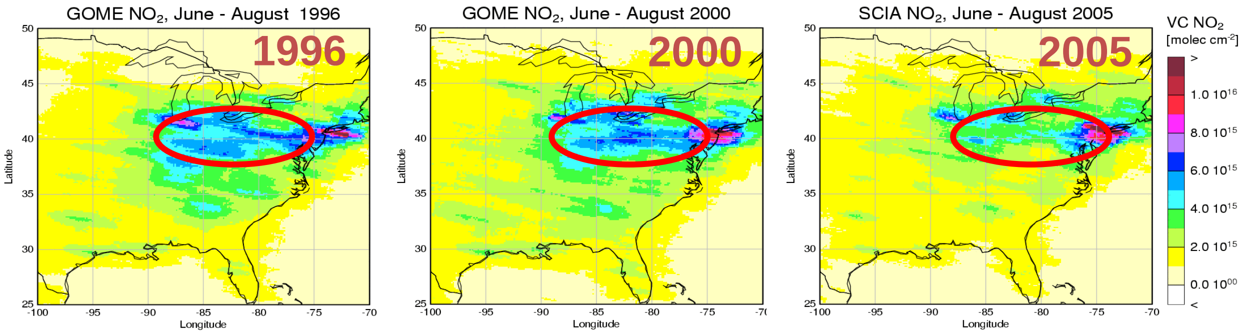
transport

Monitoring Sources/Sinks NO_2: US Power Plant "Denoxification"

Bremen



- GOME NO_2 time-series
- after 2000, clear decrea
- no change in urban are
- size and geographical



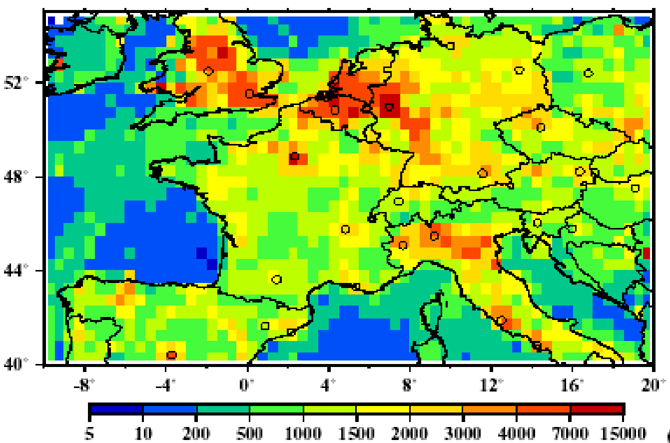
S. Kim, A. Heckel et al 2006 NOAA and University of Bremen
GRL November 2006

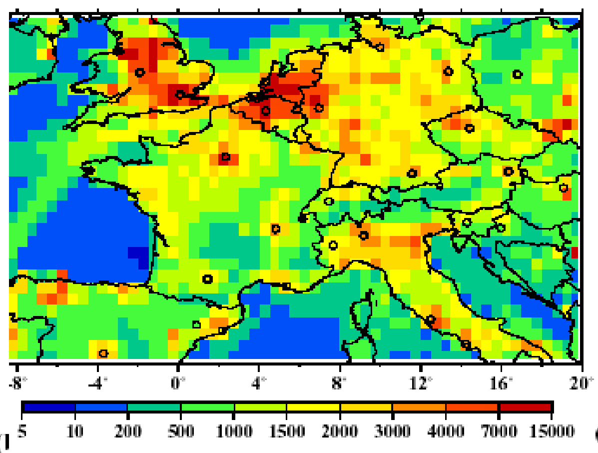
SCIAMACHY

CarbonSat Constellation

NO2 Emission Rates in European Cities

- Top-Down constraint on anthropogenic emis
- Satellite data: GOME and SCIAMACHY
- Model CHIMERE
- A-priori: EMEP data for 2001
- For some cities (as Cologne),neighbouring c
- A posteriori < a priori



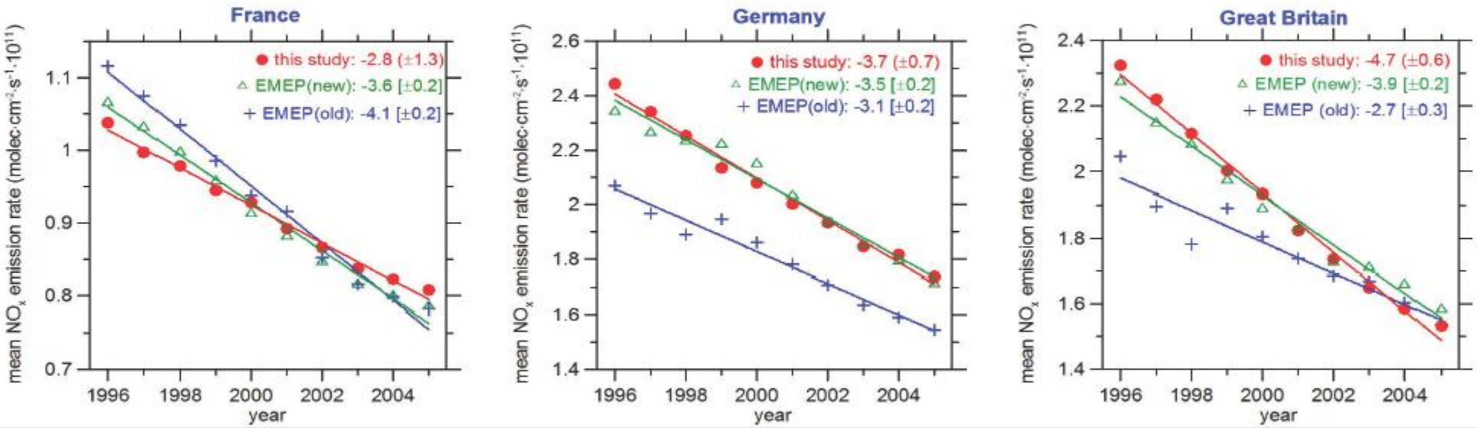


City	A priori	A posteriori
Barcelona	2.79	1.95 (1.2)
Berlin	2.25	1.56 (1.4)
Bern	0.98	1.01 (1.3)
Birmingham	5.07	4.56 (1.2)
Bratislava	1.09	1.12 (1.3)
Brussels	5.00	4.83 (1.3)
Budapest	2.31	2.16 (1.3)
Cologne	5.64	6.18 (1.4)
Geneva	1.04	1.14 (1.3)
Hague	7.25	6.84 (1.4)
Hamburg	2.33	1.69 (1.3)
Liverpool	3.69	3.37 (1.6)
Ljubljana	1.05	1.14 (1.3)
London	7.76	4.75 (1.4)
Lyon	1.73	1.65 (1.2)
Madrid	2.23	2.73 (1.2)
Marseille	1.93	1.68 (1.2)
Milan	3.13	3.37 (1.2)
Munich	2.03	1.93 (1.2)
Naples	1.98	2.25 (1.1)
Paris	4.68	3.92 (1.3)
Poznan	0.57	0.69 (1.3)
Prague	2.18	2.09 (1.2)
Rome	3.20	3.28 (1.2)
Toulouse	0.86	0.74 (1.3)
Turin	1.41	2.29 (1.3)
Vienna	1.87	1.69 (1.3)
Zagreb	1.15	0.88 (1.3)
Zaragoza	1.41	1.36 (1.5)

Konovalov, et al. 2005, 2007

NO_2 Change in Europe

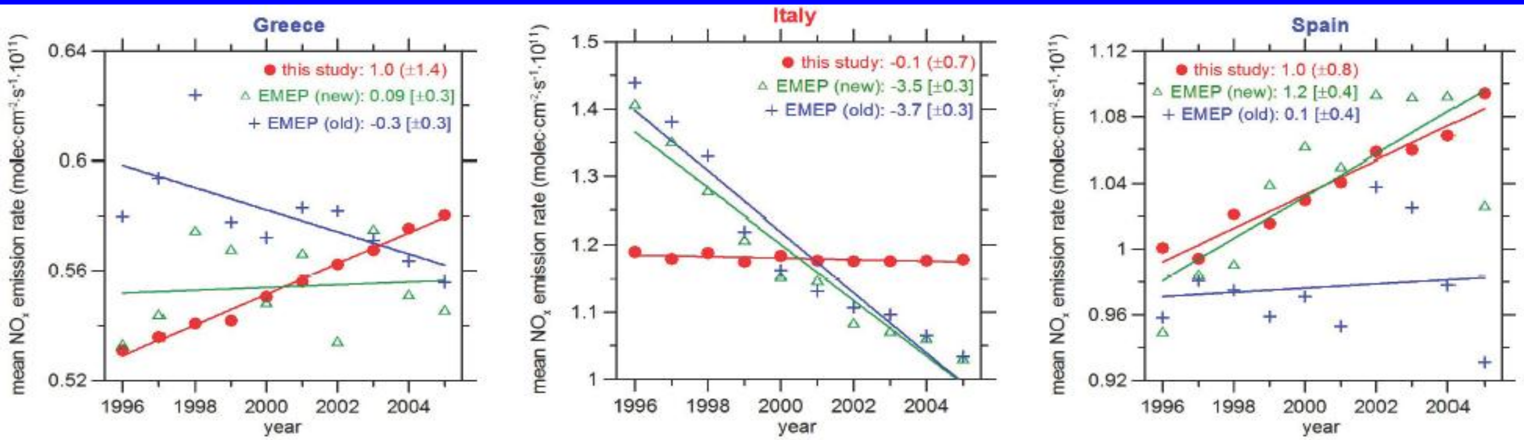
innovativ! Bremen



GOME and SCIAMACHY data over Europe + CHIMERE

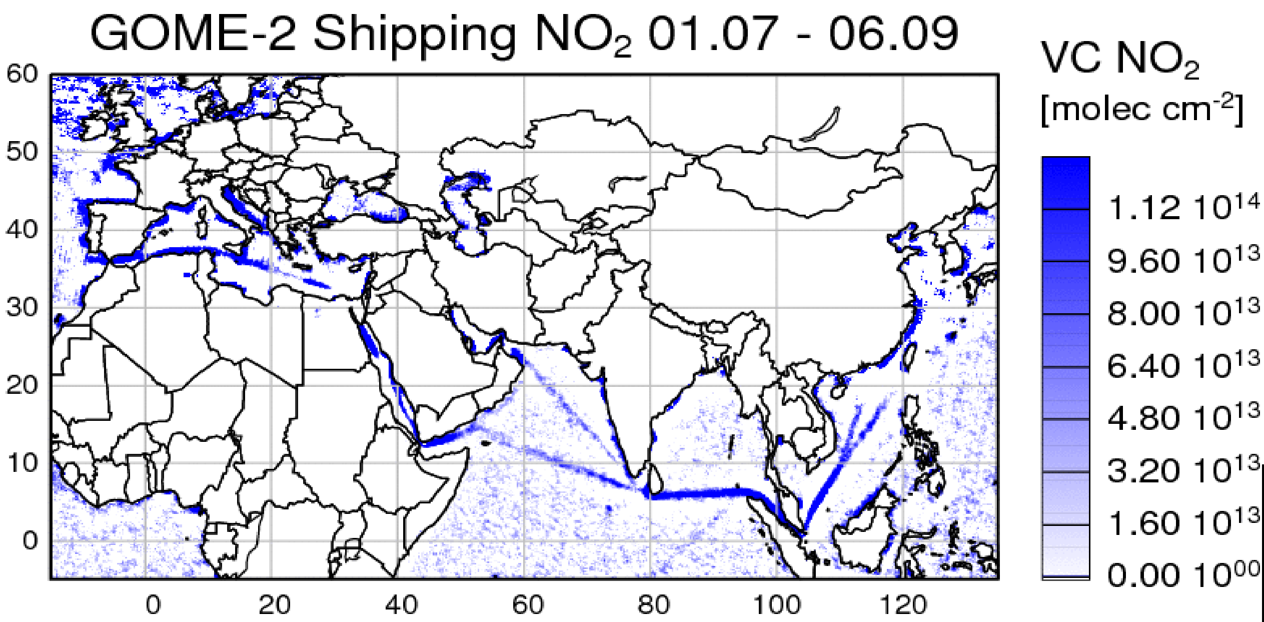
Comparison to two versions of EMEP emissions

Excellent agreement with latest EMEP in NE, disagreement in SE.

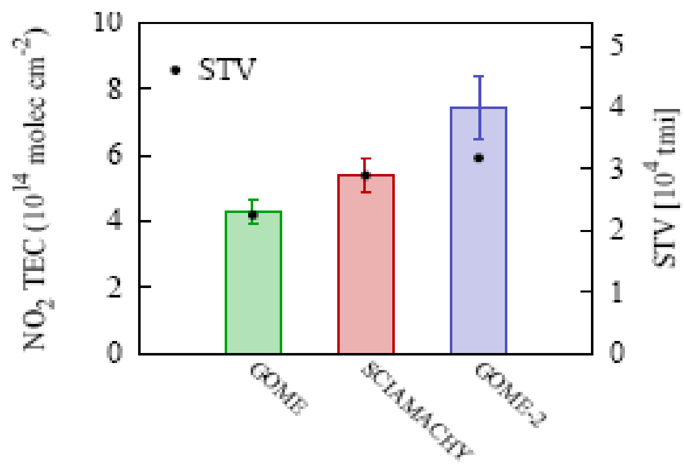


Konovalov, I.et al., Satellite measurement based estimates of decadal changes in European nitrogen oxides emissions, Atmos. Chem. Phys. Discuss., 8, 2013-2059, 2008

Shipping NO_2 data



- Large fitting window GOME-2 NO_2 retrievals have very low no
- Very clear shipping signals



Franke et al., Atmos. Chem. Phys. Discuss., 8, 15997–16025, 2008

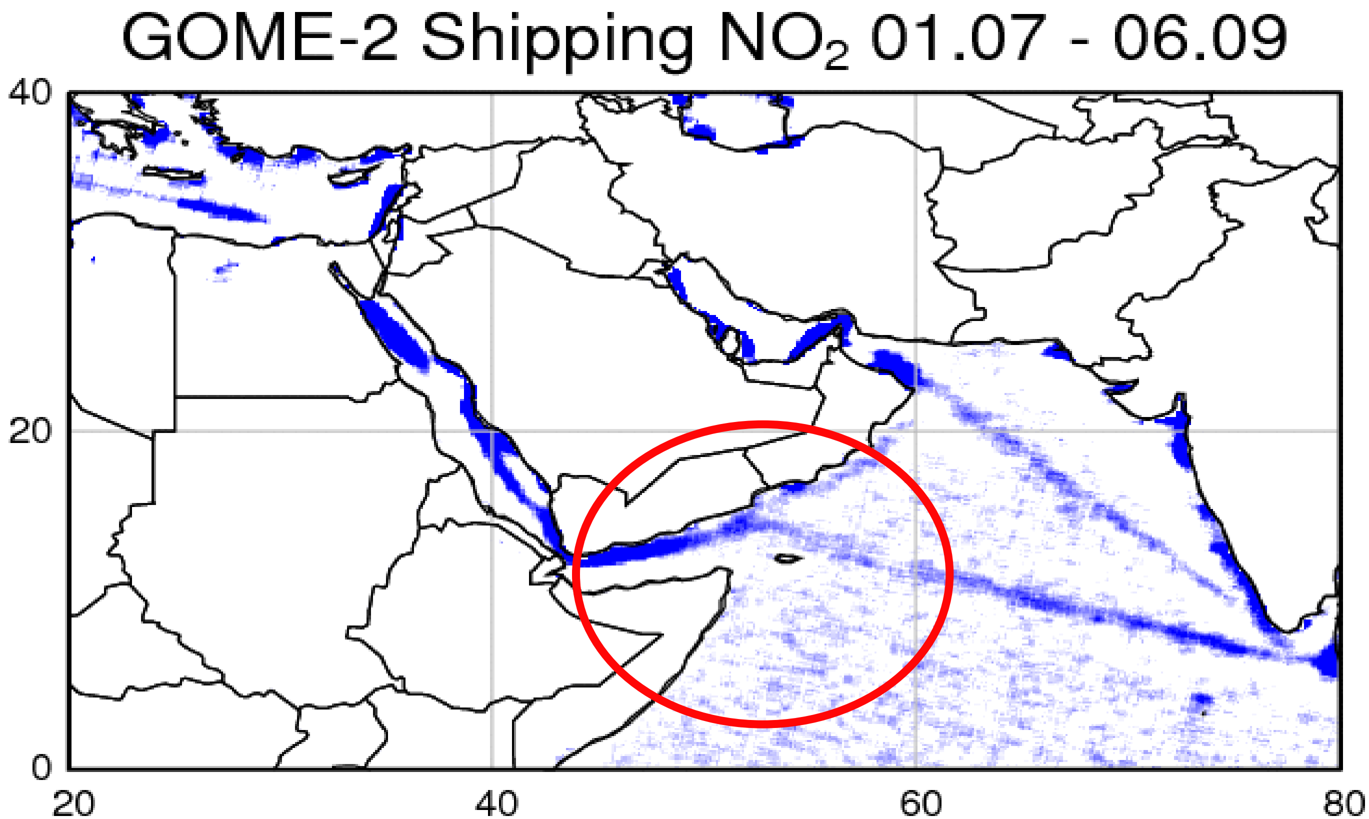
SCIAMACHY

CarbonSat Constellation

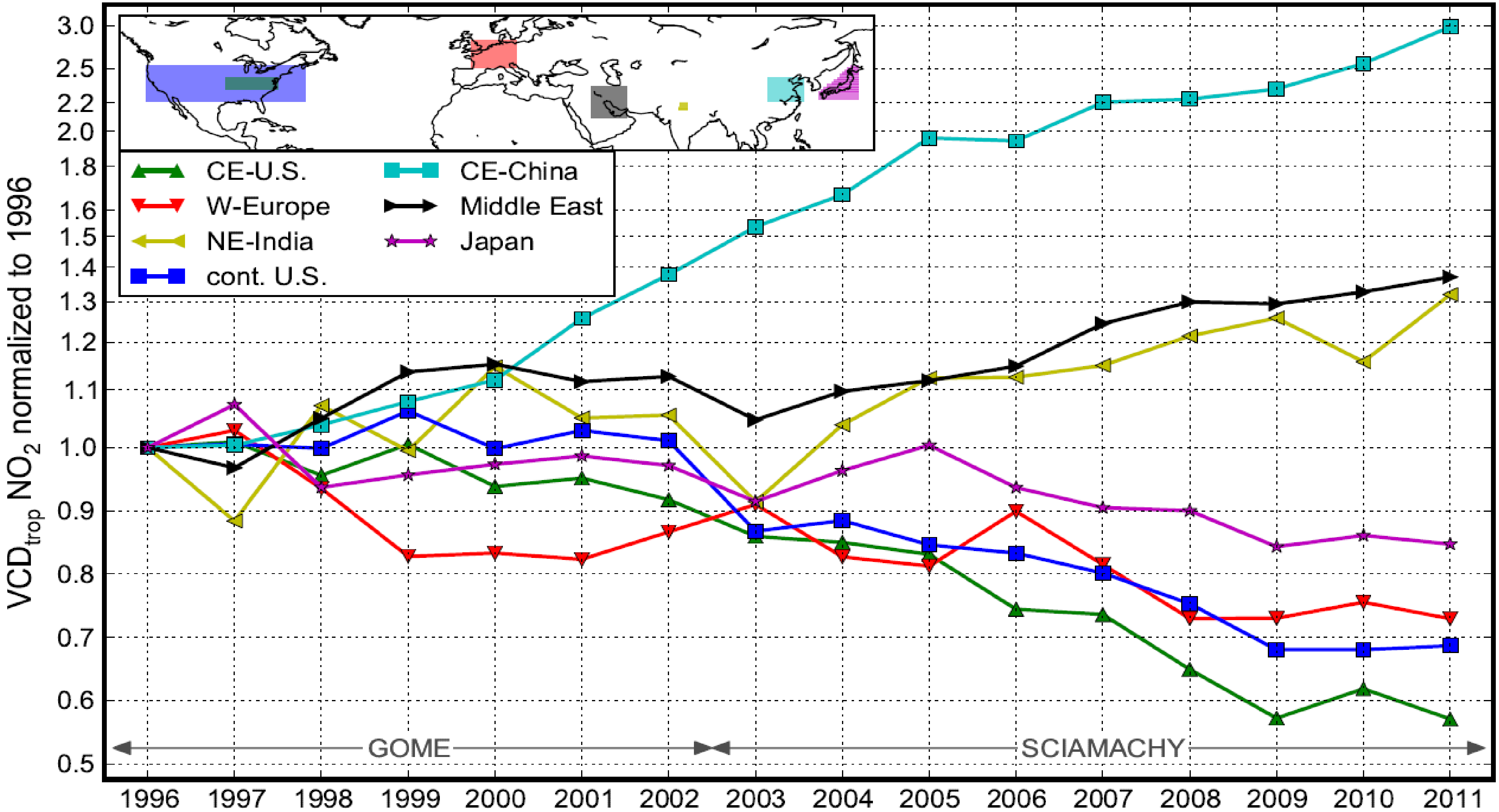
Bremen innovativ!

Shipping NO_2 in GOME-2 data

- Pattern of shipping NO_2 close to Somalia has changed in 2007
- Probably as an attempt to evade pirates



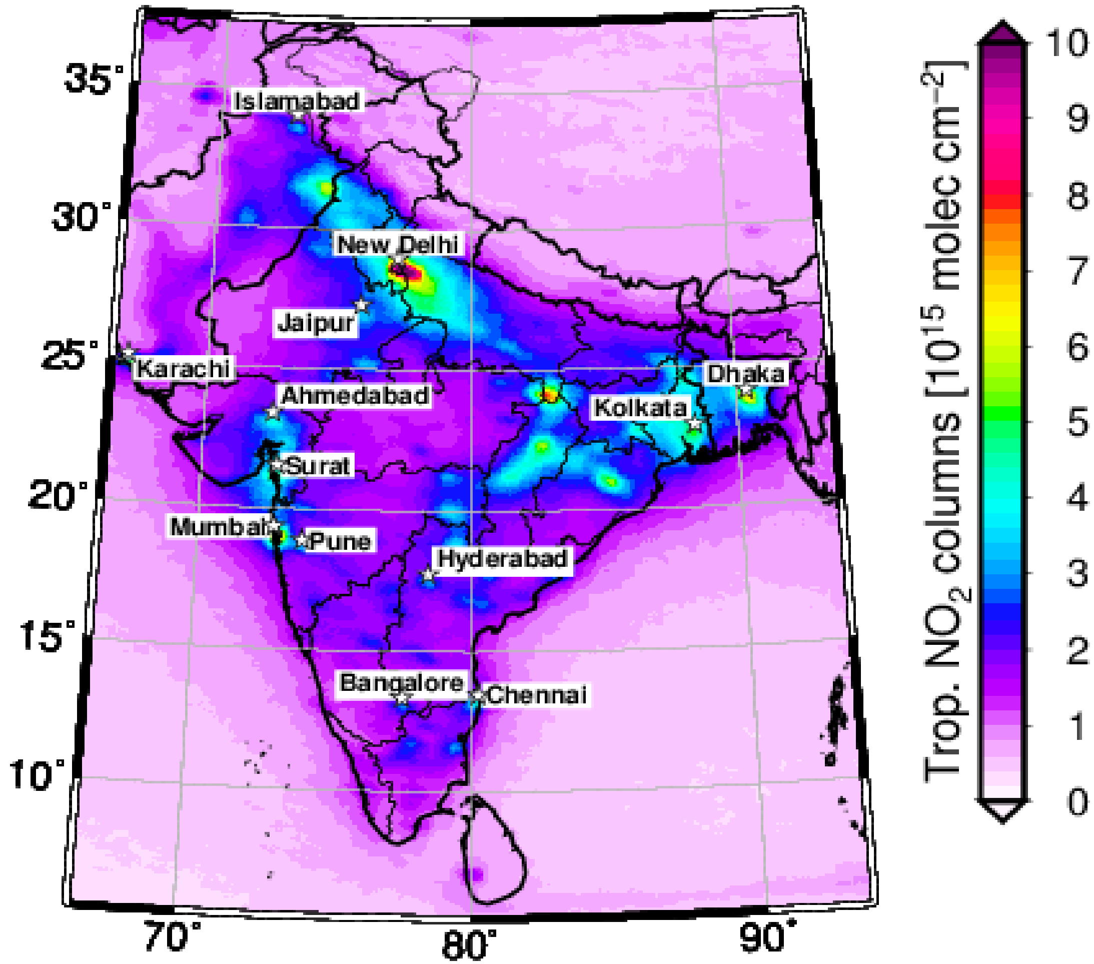
NO_2 Changes over Regions Hilboll et al., 2012/2013



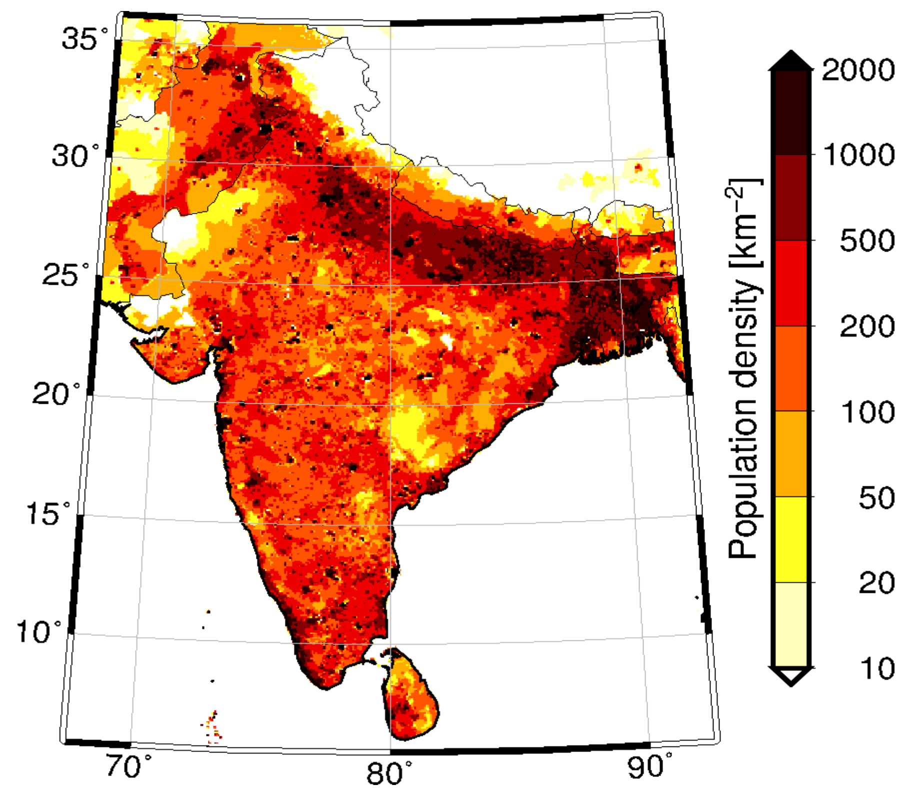
Hilboll, A., Richter, A., and Burrows, J. P.: Long-term changes of tropospheric NO2 over megacities derived from multiple satellite instruments, Atmos. Chem. Phys., 13, 4145-4169, doi:10.5194/acp-13-4145-2013, 2013.

SCIAMACHY

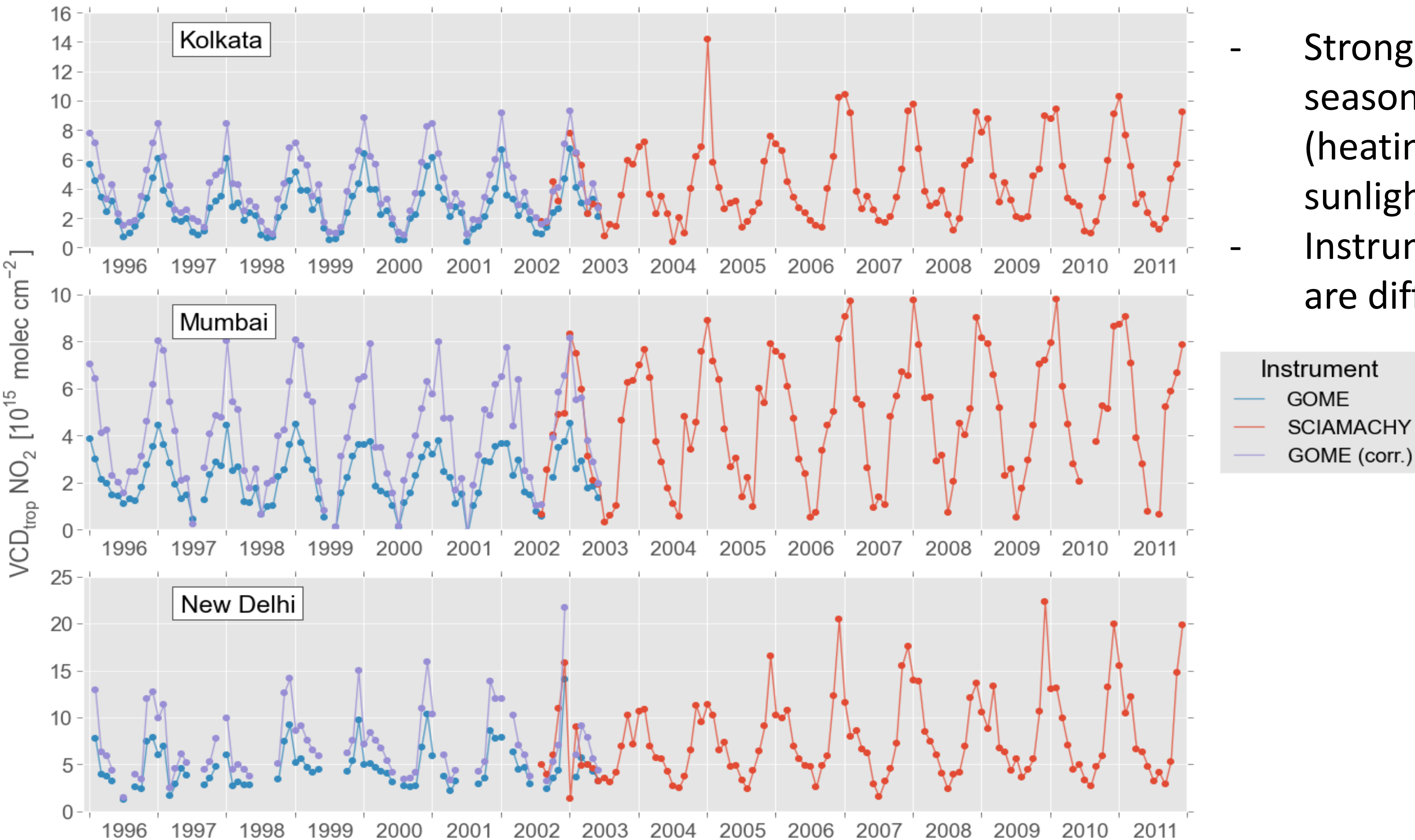
Tropospheric NO_2 column over Indian Subcontinent observed from space: SCIAMACHY (2003-2011)



Centres of Population are clearly visible

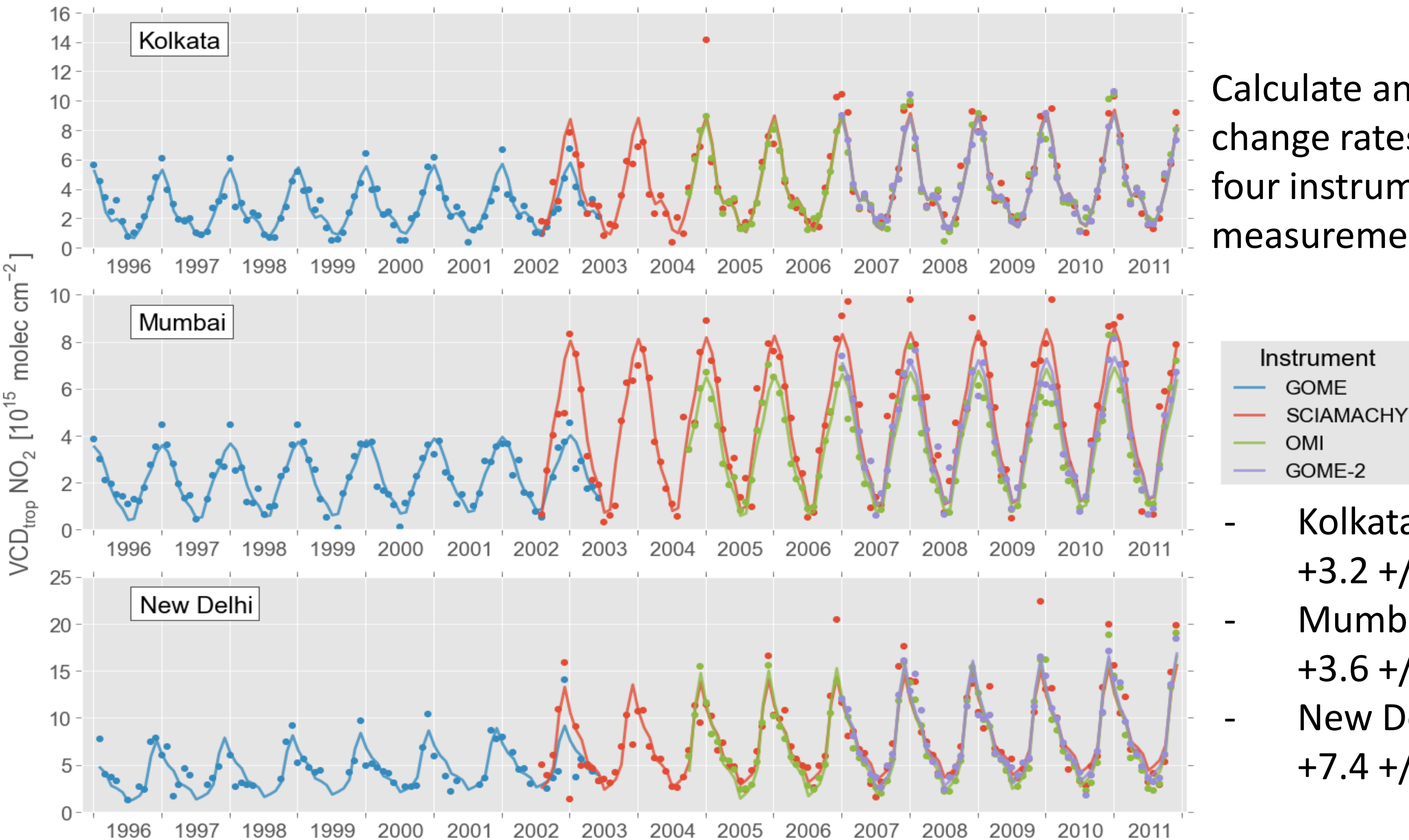


Timeseries over Megacities



- Strong seasonality (heating, sunlight)
- Instruments are different

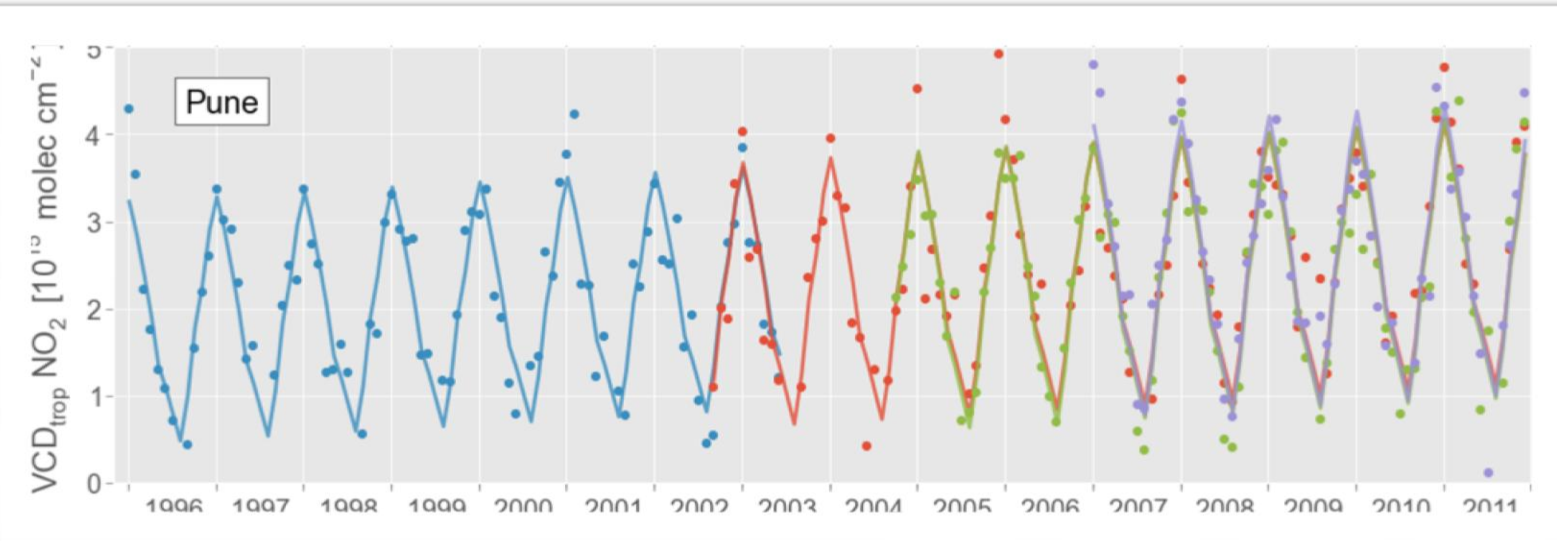
Calculation of annual change rates

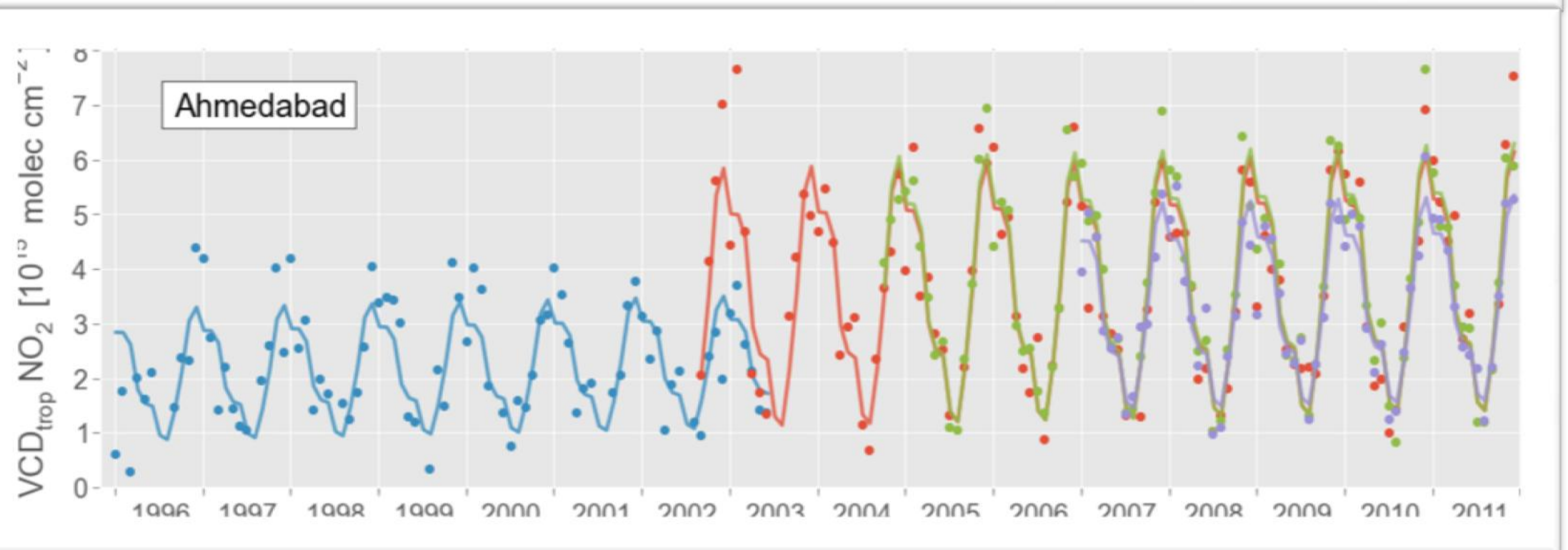


Calculate annual change rates from all four instruments' measurements:

- Kolkata: +3.2 +/- 1.0 %
- Mumbai: +3.6 +/- 1.1 %
- New Delhi: +7.4 +/- 1.7%

Pune and Ahmedabad

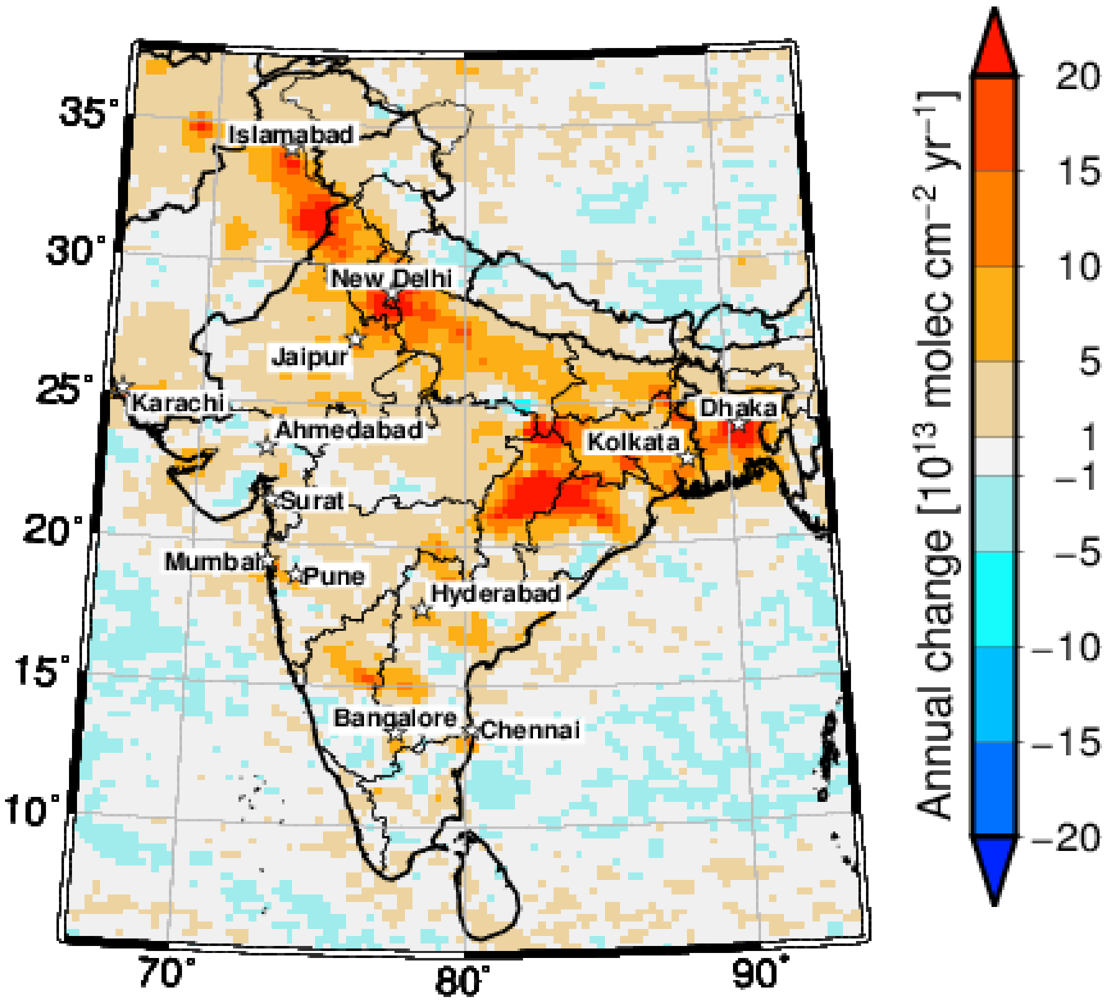




Pune shows a statistically significant upward trend of $(+5.6\pm1.6)\times10^{13}$ per year. In relative terms, this is $+3.1\pm0.9$ %

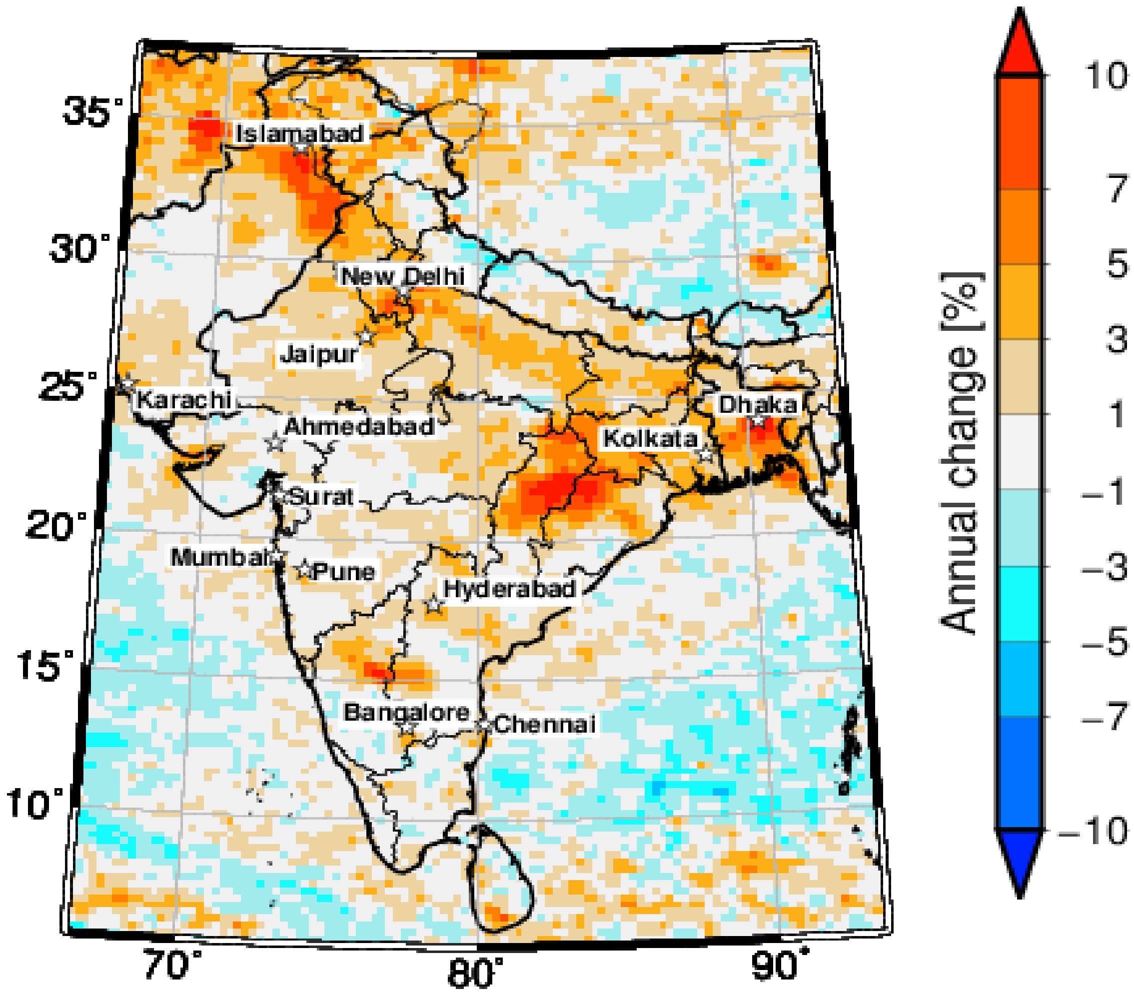
Ahmedabad has an increase of $(+3.4\pm2.3)\times10^{13}$ (in relative terms, $+1.6\pm1.1$ %) per year..

Tropospheric NO_2 column over the Indian Subcontinent is increasing strongly



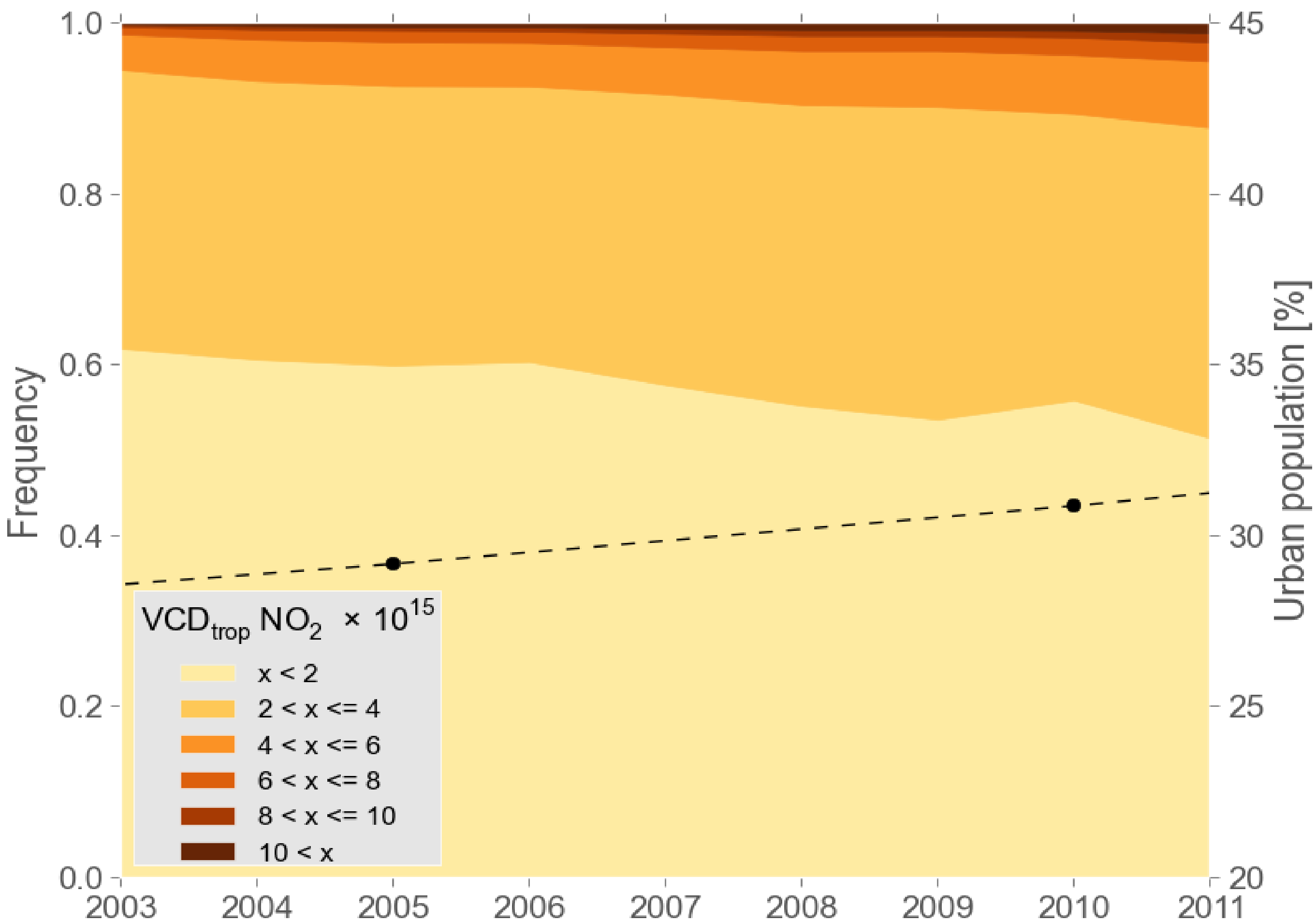
- Tropopsheric NO_2 strongly increases in major centres of population
- Attributed to fossil fuel, domestic heating and cooking and related
- Strongest relative increase is in Odisha and Chhattisgarh
- Attributed to heavy industry + electricity

Tropospheric NO_2 over India is strongly increasing in populated regions



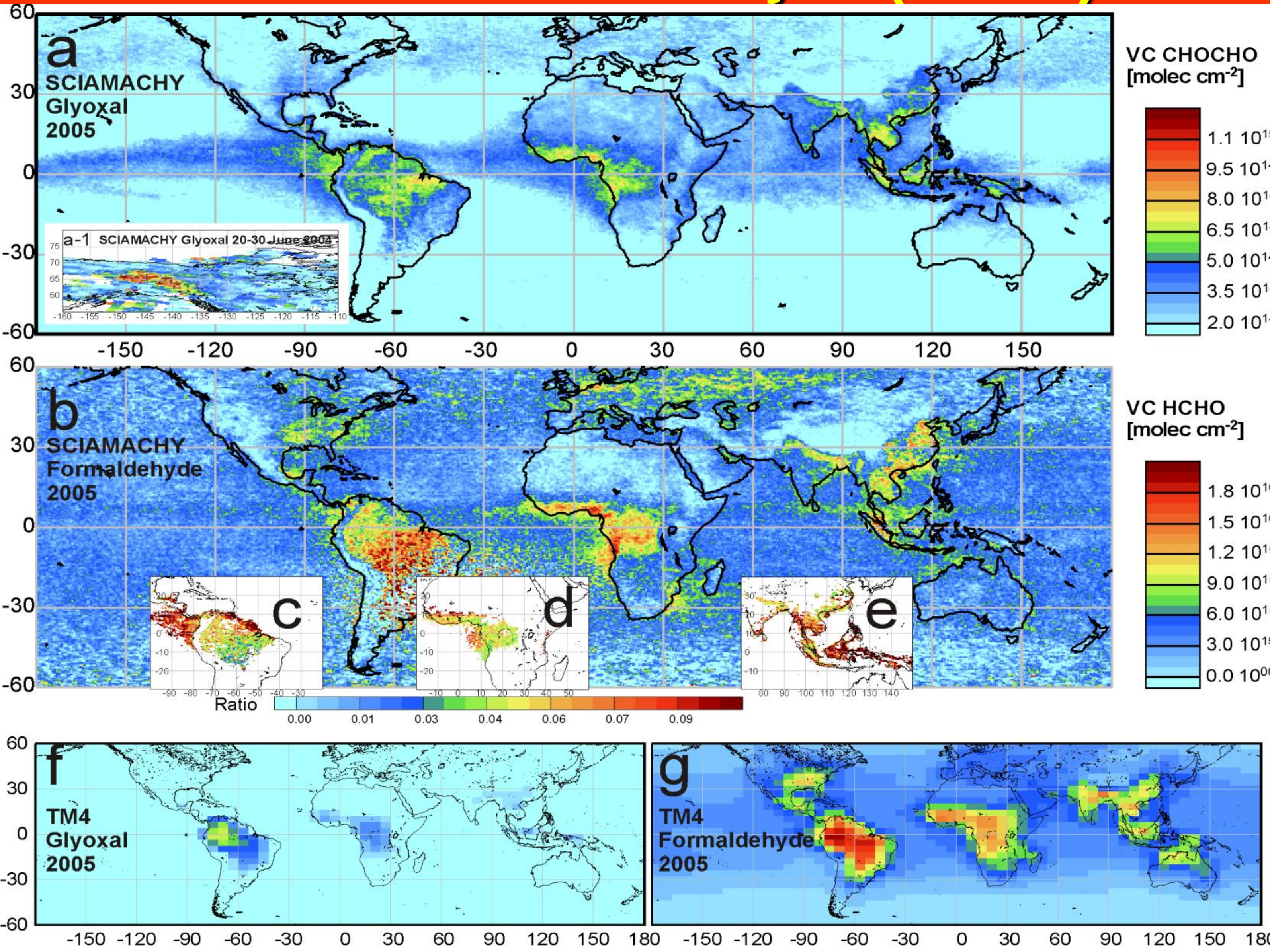
Strong increases in conurbations and other centres of population

The area of regions with high NO_2 pollution are growing



- **Percentage of area with higher NO_2 pollution is increasing**
- **The area of pristine i.e. low NO_2 decreases**
- **Attributed to emissions resulting from urbanization trend and population increase**

SCIAMACHY: Glyoxal (CHO.CHO) and Formaldehyde (HCHO) in 2005



U. Crete TM4 + Chemistry

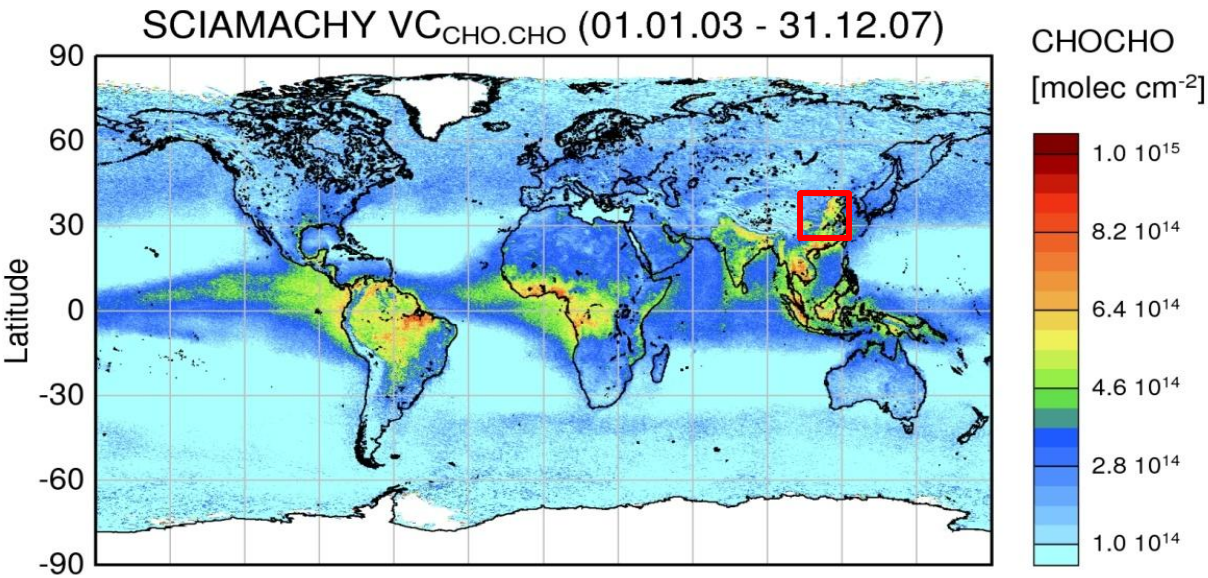
Additional sources of HCHO and CHO.CHO required over the ocean: Transport of longer lived VOC, release from POA or SOA,

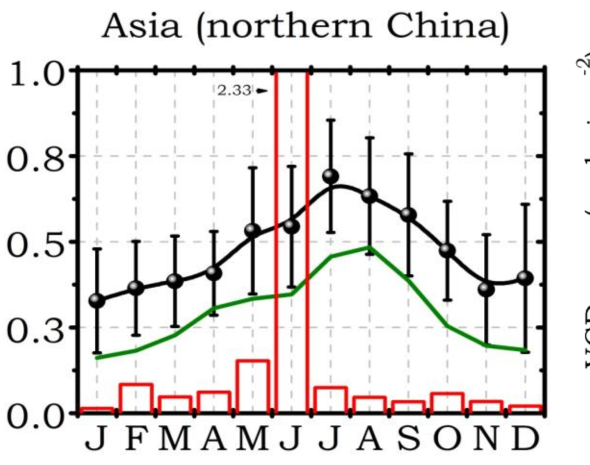
Local Source?

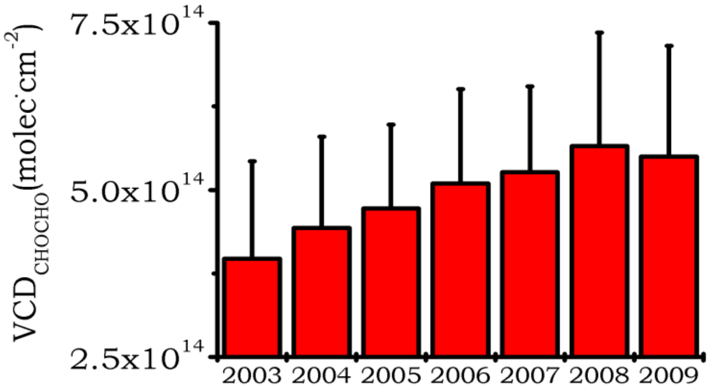
SCIAMACHY

CarbonSat Constellation

Glyoxal, CHO.CHO columns



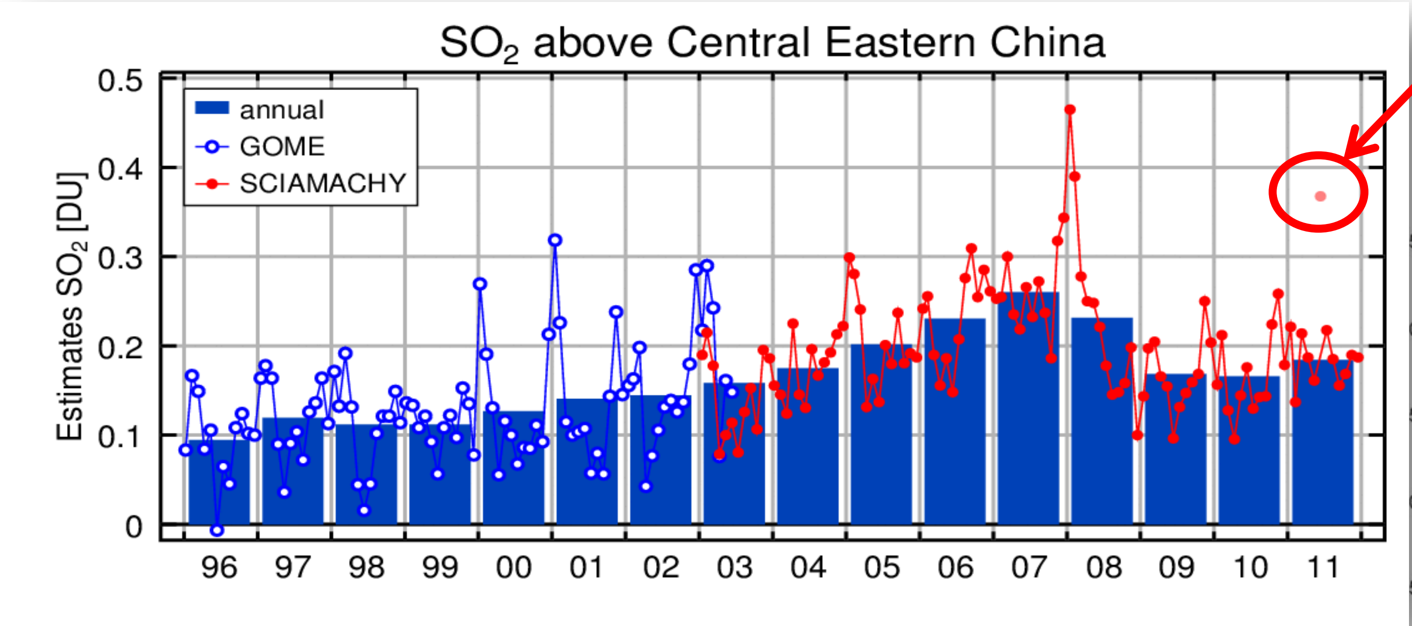


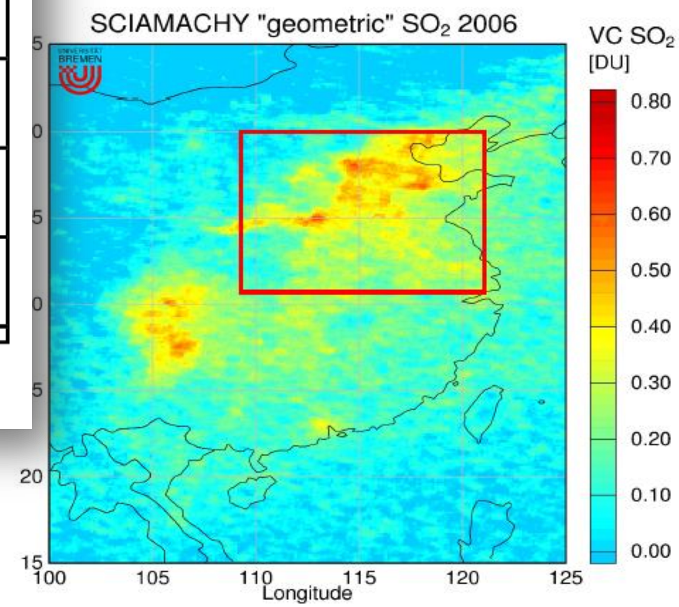


- Glyoxal is a VOC with little primary emission
- Main sources are oxidation of biogenic and anthropogenic VOCs, biomass burning
- Seasonality of glyoxal indicates mainly biogenic precursors
- Consistent upward trend over SCIAMACHY time series
- Additional anthropogenic emissions?
- Land use changes?
- More biomass burning?

Vrekoussis, M.,et al., Temporal and spatial variability of glyoxal as observed from space, *Atmos. Chem. Phys.*, 9, 4485-4504, 2009

GOME and SCIAMACHY SO_2 over China





- SO_2 emitted from lignite/ brown coal fired power plants
- Large increase in SO_2 loading observed from 2000 to 2007 Turnover in 2007
- Decrease to 2003 / 2004 levels but now increasing again.

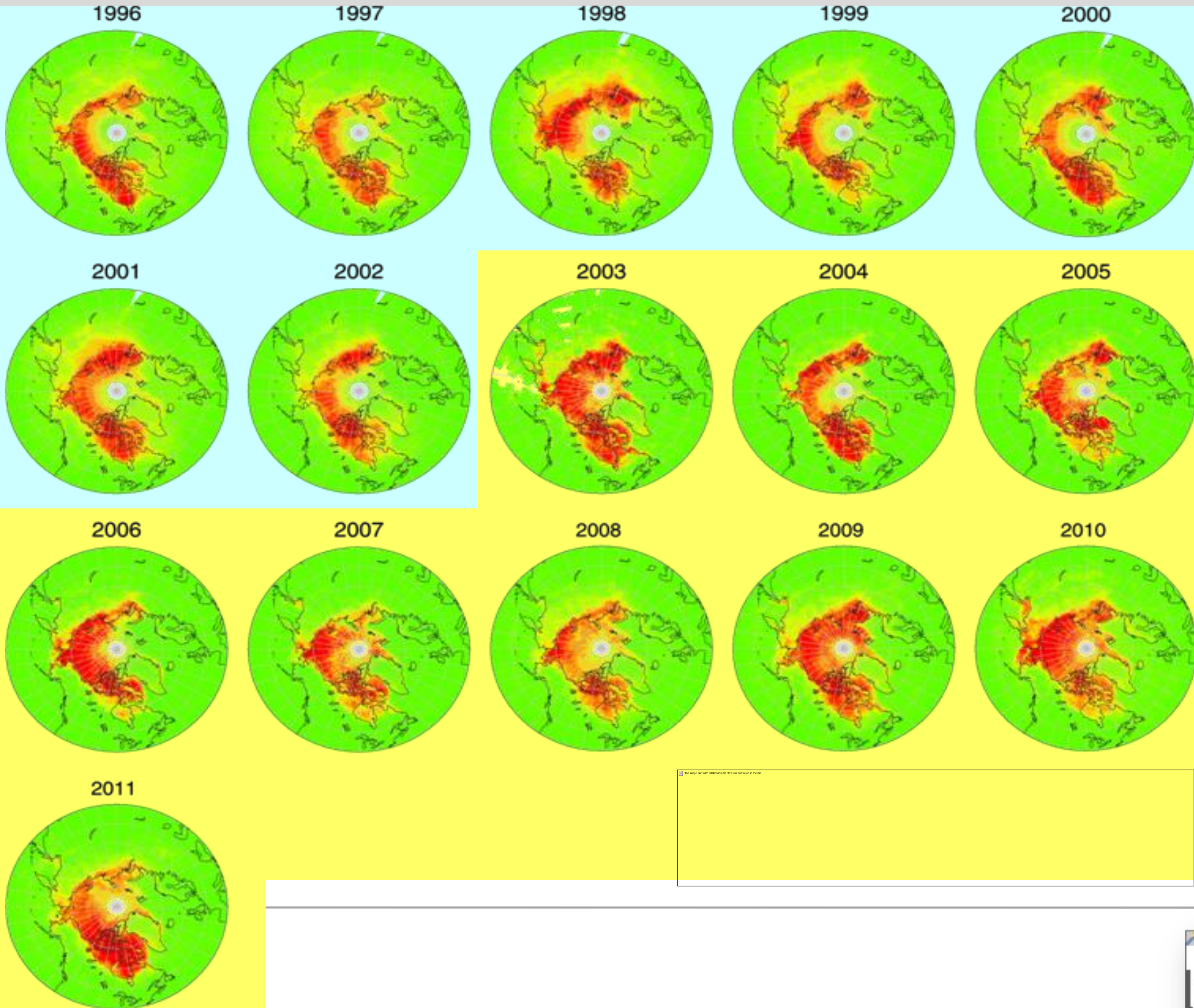
Result of legislation requiring flue-gas desulphurization of power plants

Not all power plants have been equipped other sources are on the rise

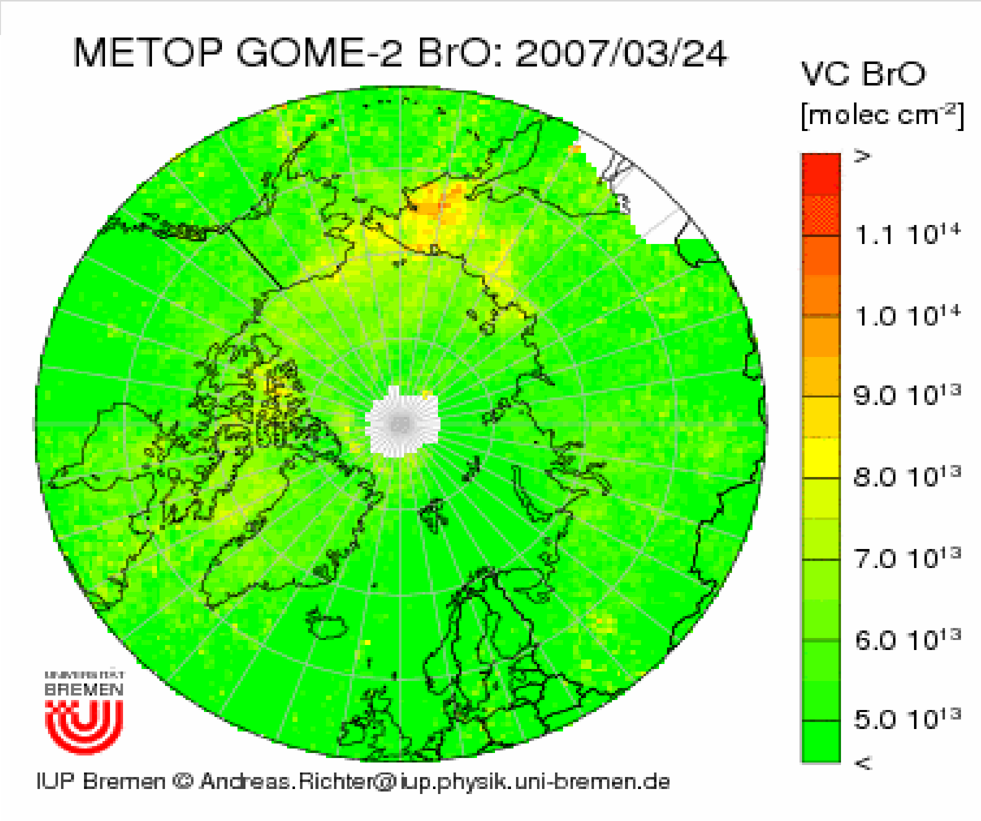
BrO Columns April, NH

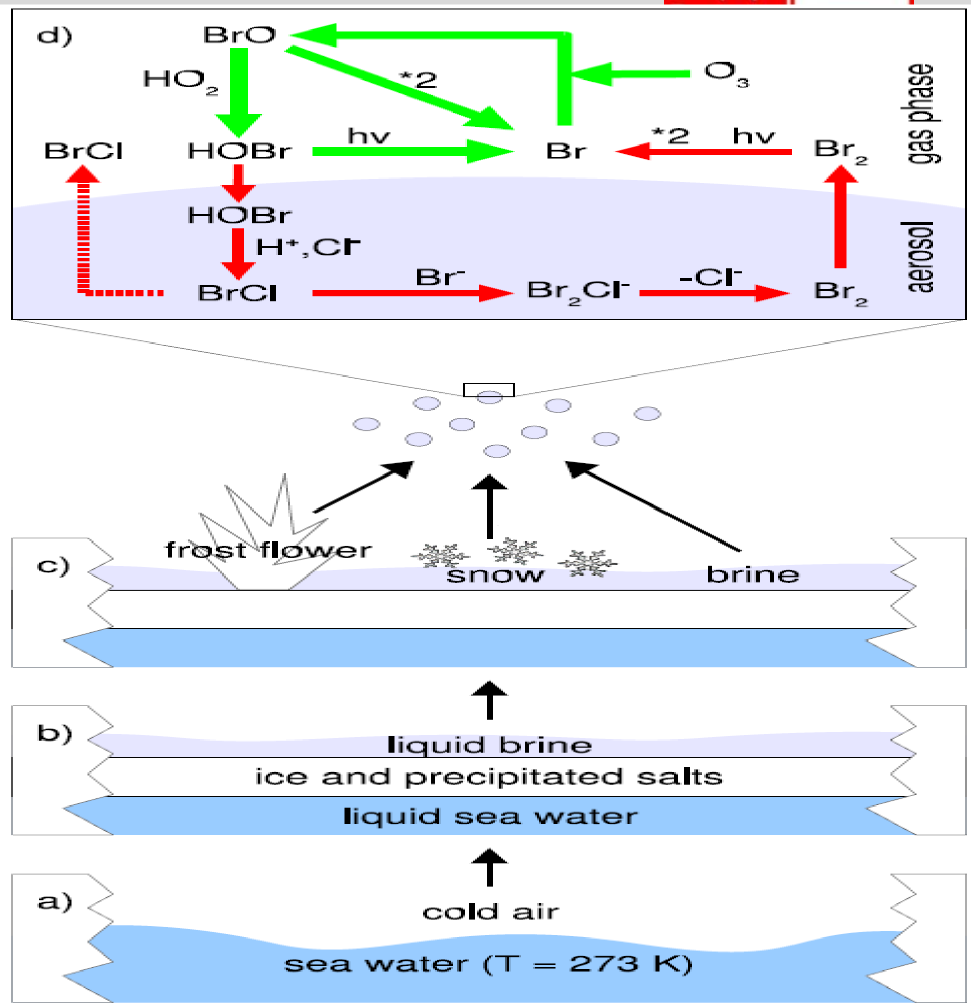
GOME

SCIA



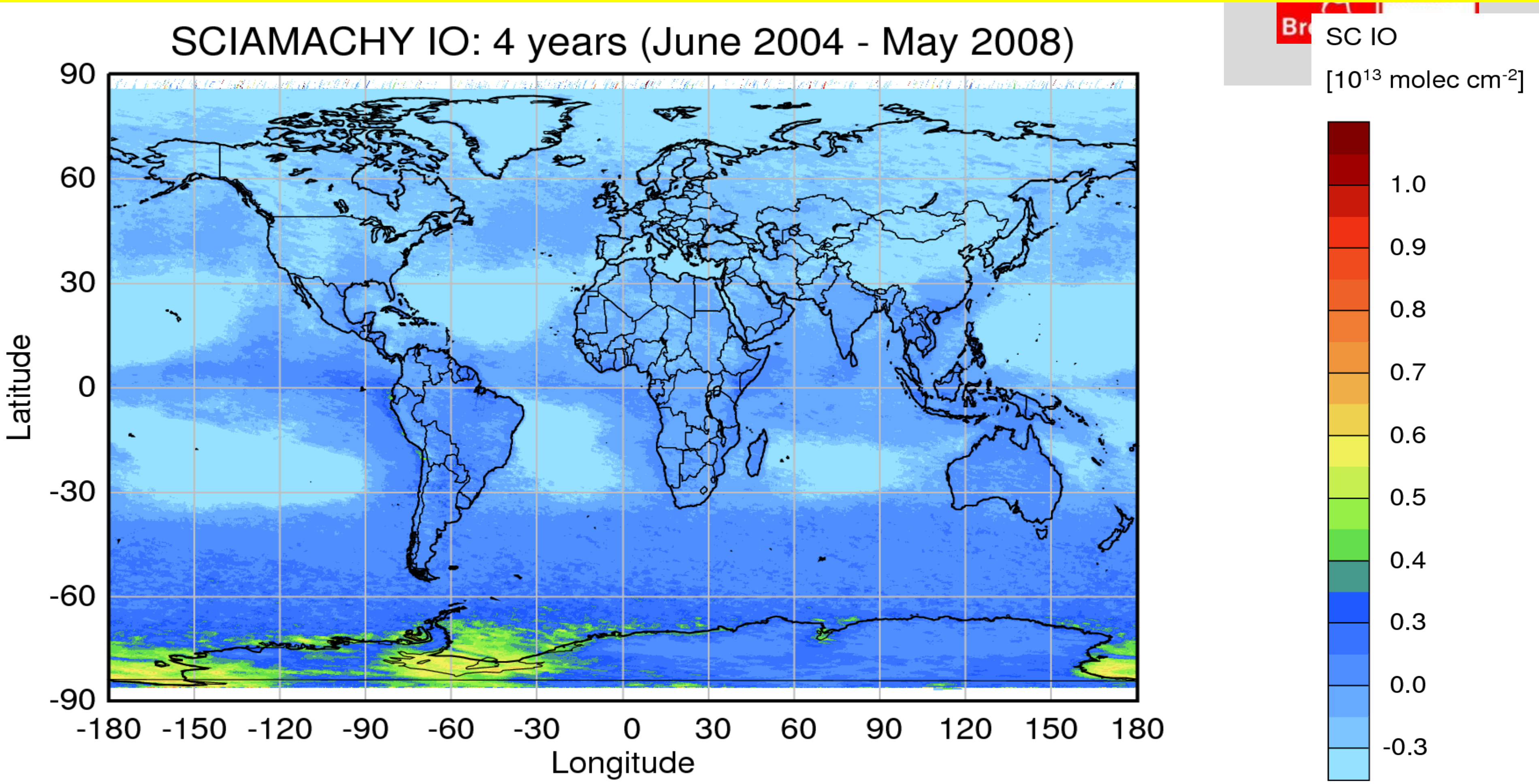
GOME-2 Results: BrO





Potential Frost Flower PFF regions of cold brine either at the surface or lofted – precipitation of Metal ions, and cold temperature trigger a very effective bromine explosion

SCIAMACHY IO Columns



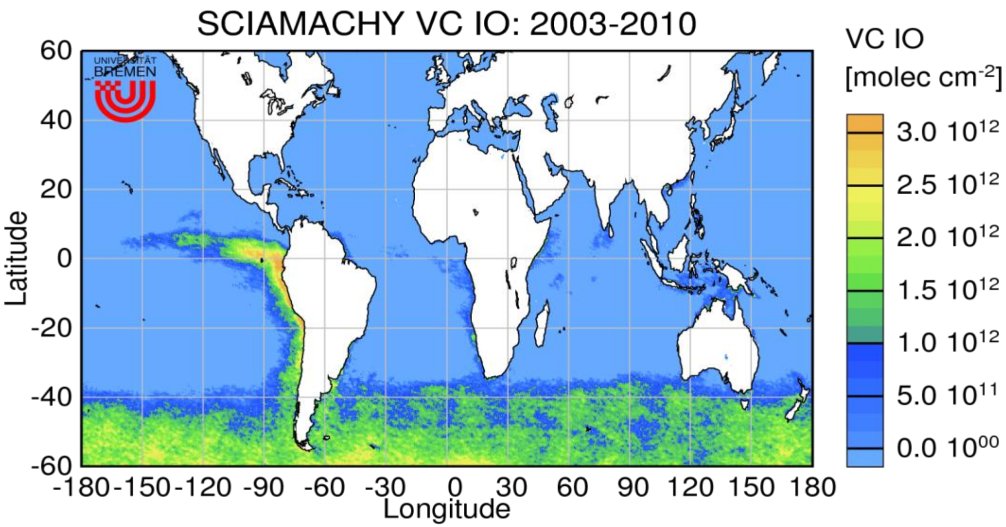
→ Enhanced IO amounts in oceanic upwelling region

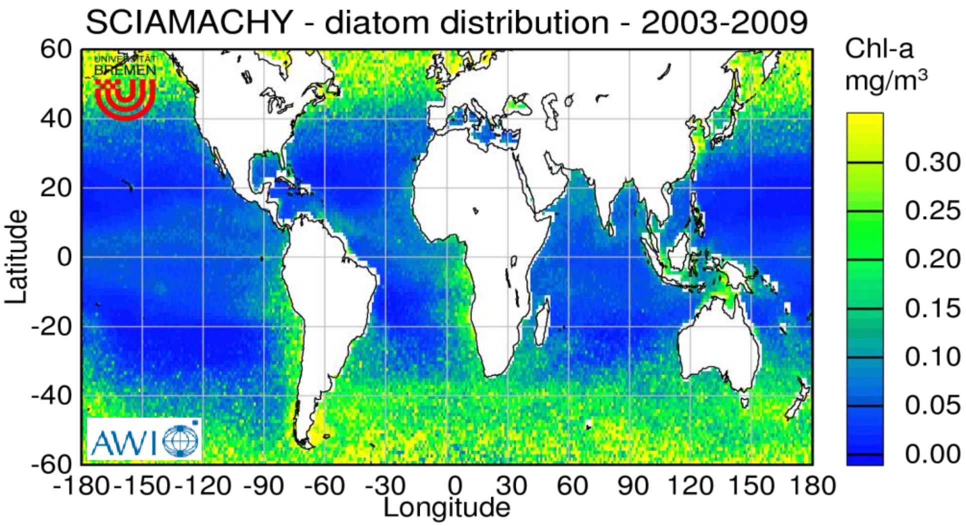
→ Humboldt current from the South: nutrient rich, high diatom concentration

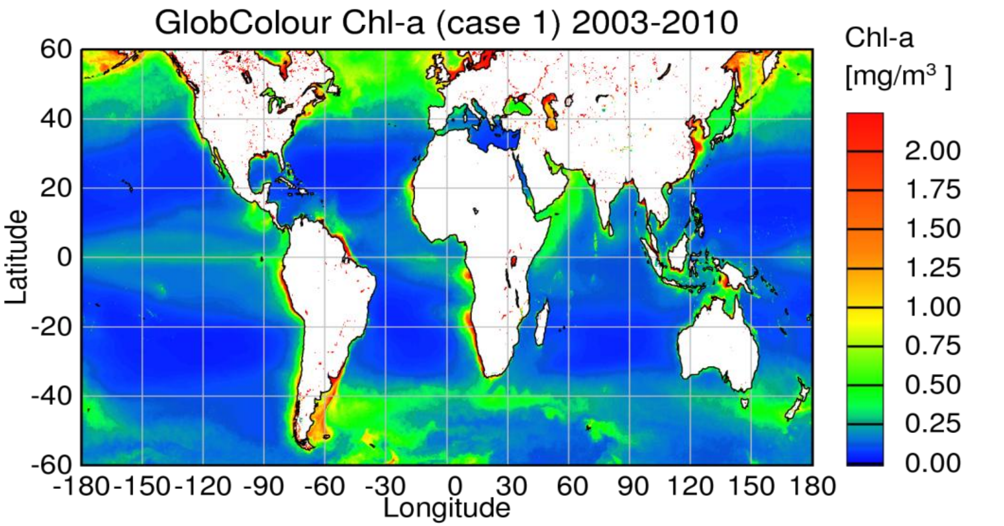
IO, Chl-a and diatom distributions

IO: consol. lv1 data 2003-2010
AMF@5% reflectance

- Long-term observations of IO and diatoms, both from SCIAMACHY, and total Chl-a (GlobColour)
- Diatom distributions as diatom Chl-a in mg/m³ from PhytoDOAS retrieval (Bracher et al., 2009)







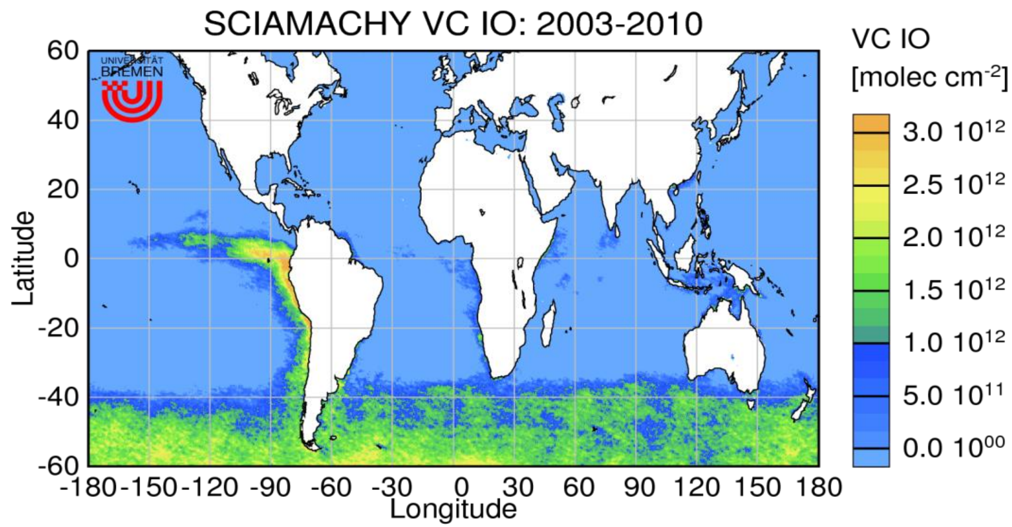
IO, CHOCHO and HCHO distributions

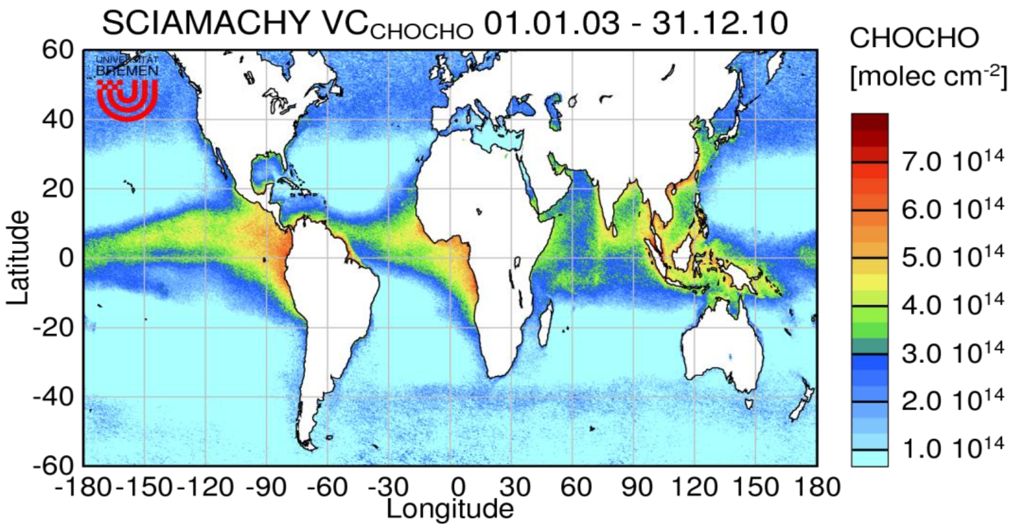
IO: consol. lv1 data 2003-2010
AMF@5% reflectance

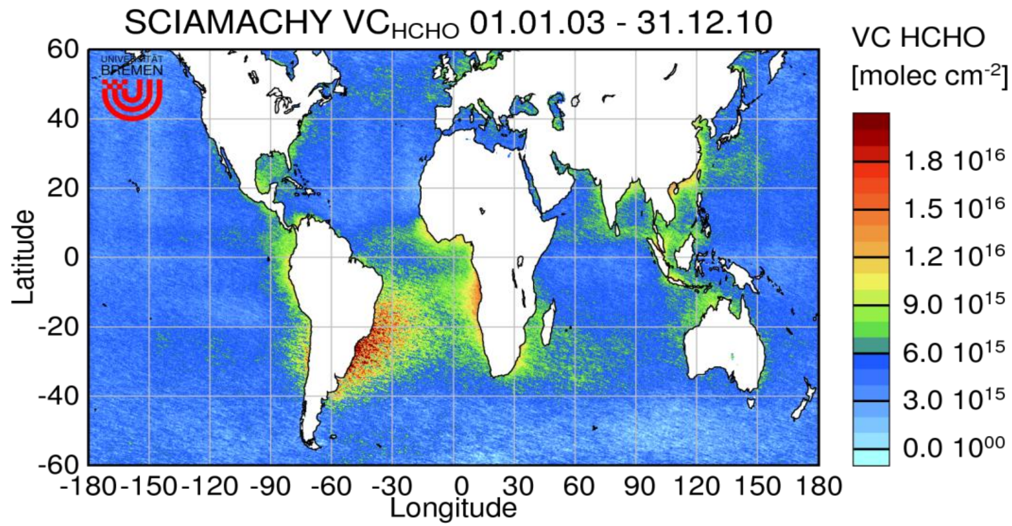
Long-term observations :

IO, CHOCHO and HCHO from

SCIAMACHY UV / vis measurements



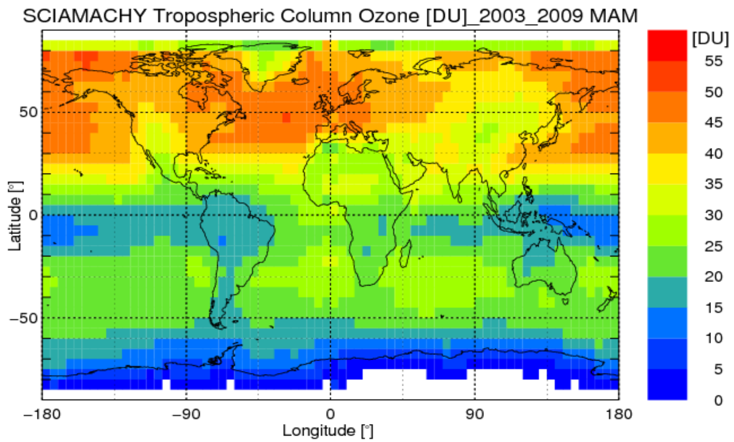


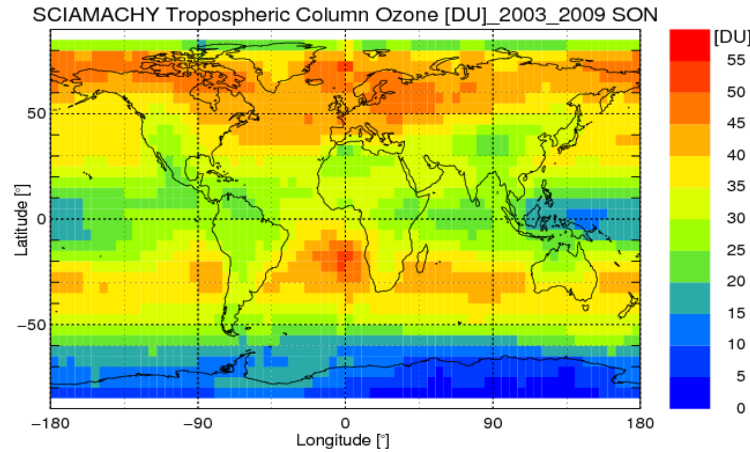


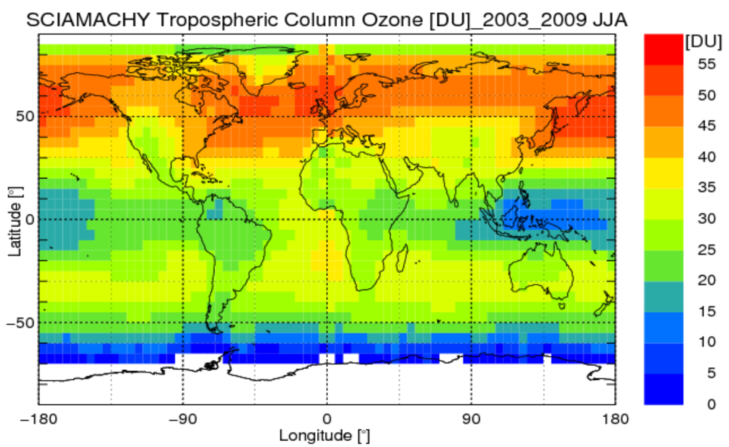
Anja.Schoenhardt@iup.physik.uni-bremen.de

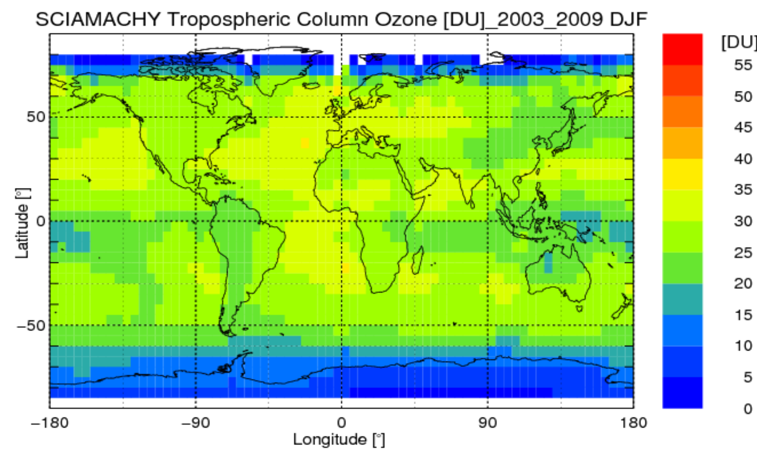
HCHO & CHOCHO:
Wittrock et al., 2006

SCIAMACHY Tropospheric O_3:
Total (Nadir) – Summed Profile above Tropopause (Limb)





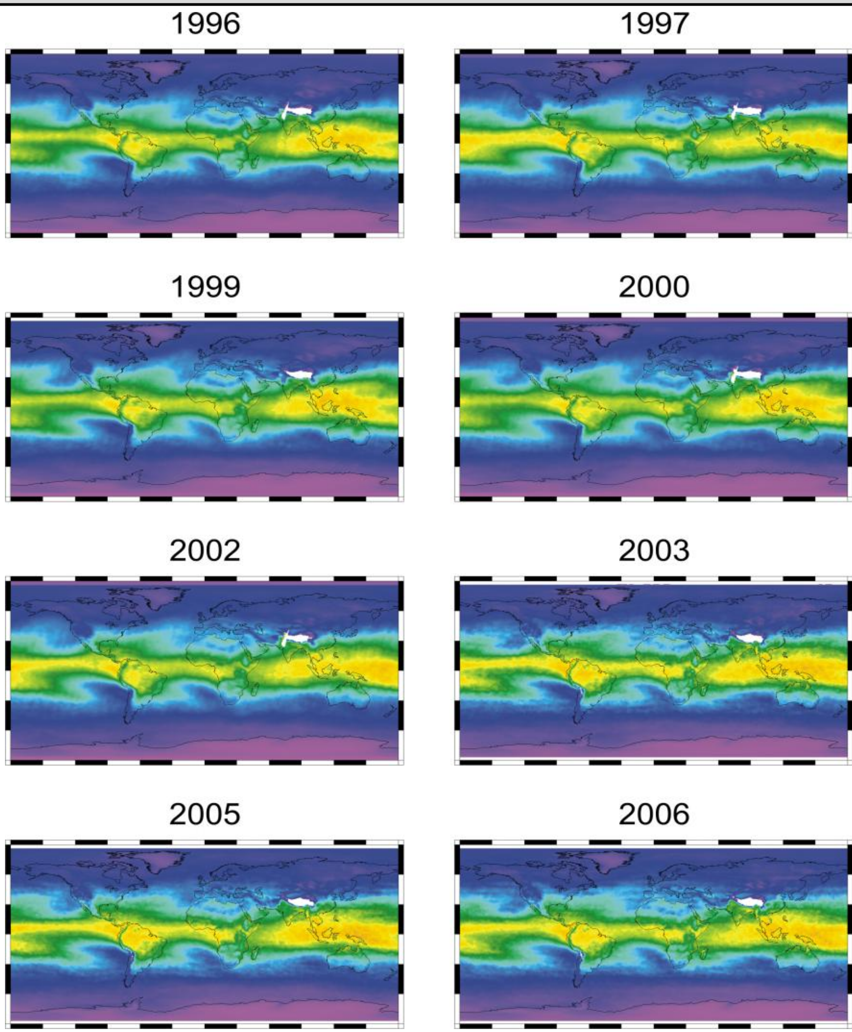




SCIAMACHY

CarbonSat Constellation

GOME & SCIAMACHY Water Vapour Data Set 1996-2006

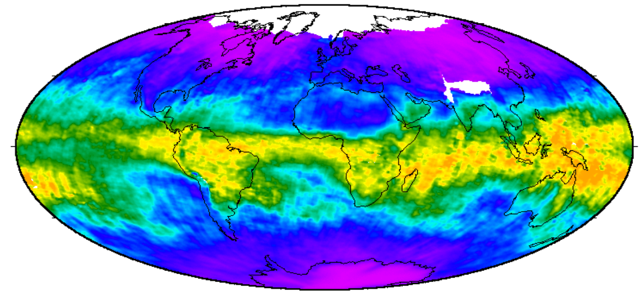


Annual Means

H_2O vertical column amount (g/cm^2)

Monthly Means

01 / 1996



H_2O vertical column amount (g/cm^2)

GOME: 1996 – 2002

SCIAMACHY: 2003 – 2006

GOME & SCIAMACHY AMC-DOAS data V1.0
(spatially gridded to 0.5° x 0.5°)

SCIAMACHY

CarbonSat Constellation

H_2O Trend/Change Analysis

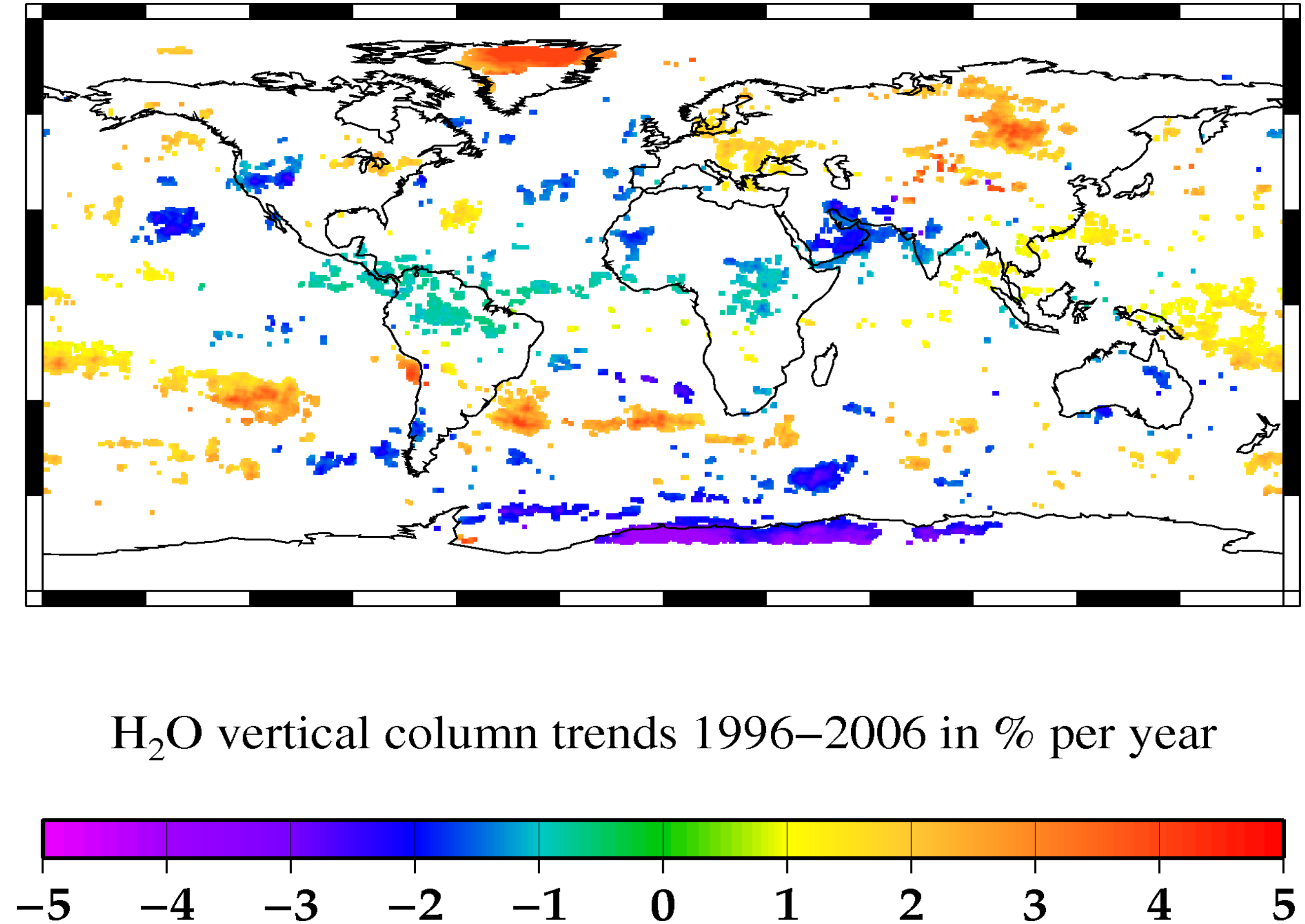
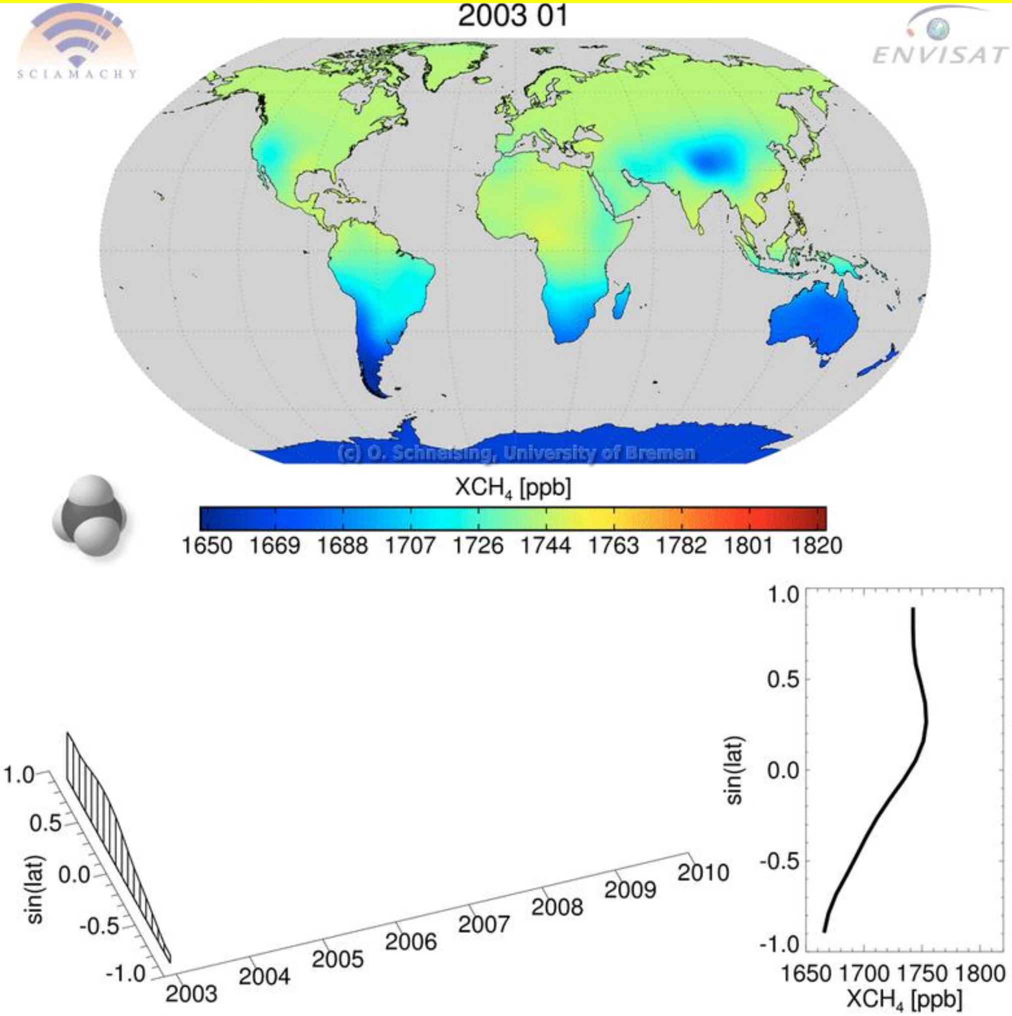


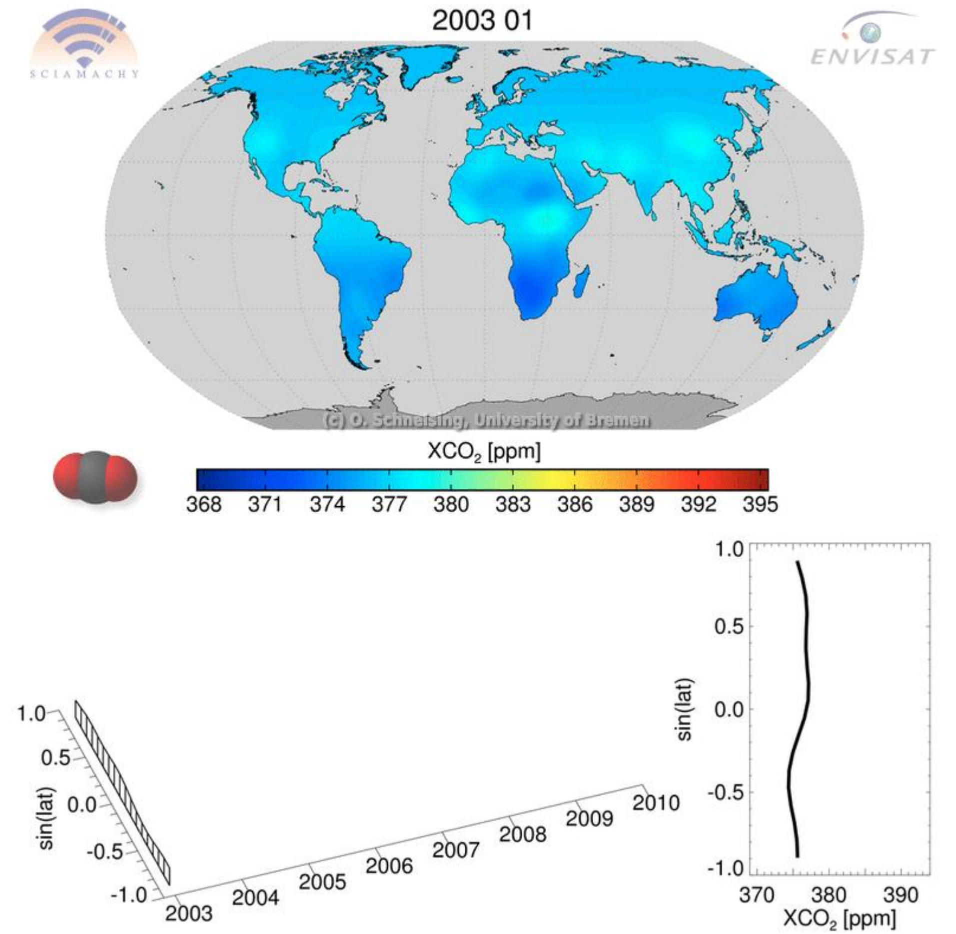
Figure and data by S. Mieruch

- The combined GOME-SCIAMACHY data set has been used to determine global water vapour change 1995 to 2006
- In addition to strong impact of ENSO in Tropics
- Regions identified as having statistically significant positive and negative changes over 11 years are detected

Mieruch et al ACP 2007

SCIAMACHY dry columns CH_4 and CO_2 over land 2003 to 2010

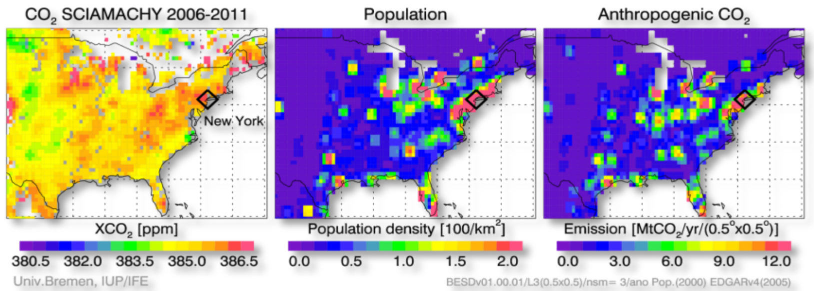




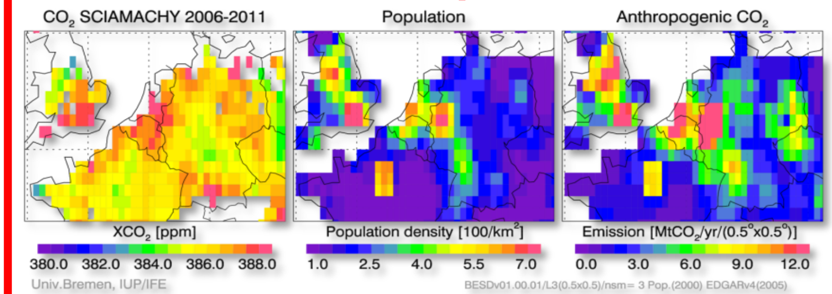
SCIAMACHY CO_2: Anthropogenic emissions ?

Approach: Long-term averaging for detection to improve SNR and „remove“ transport

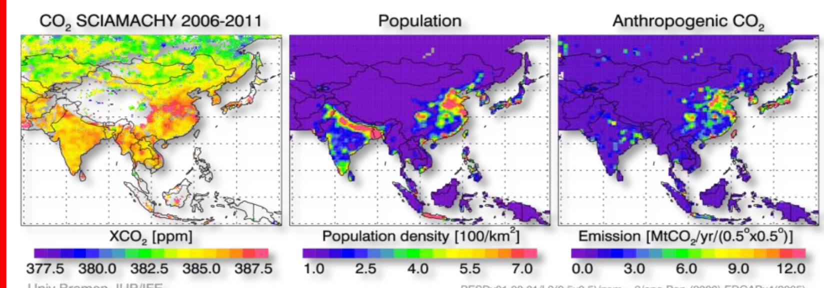
US - East



Europe

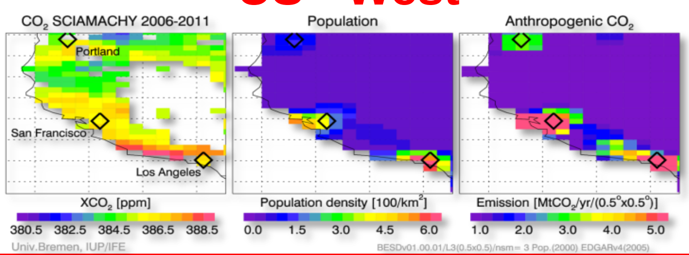


China & India

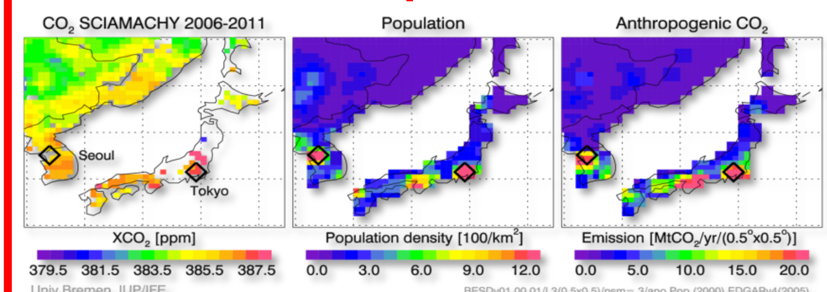


Algorithm: BESD
(Reuter et al., 2010, 2011)

US - West



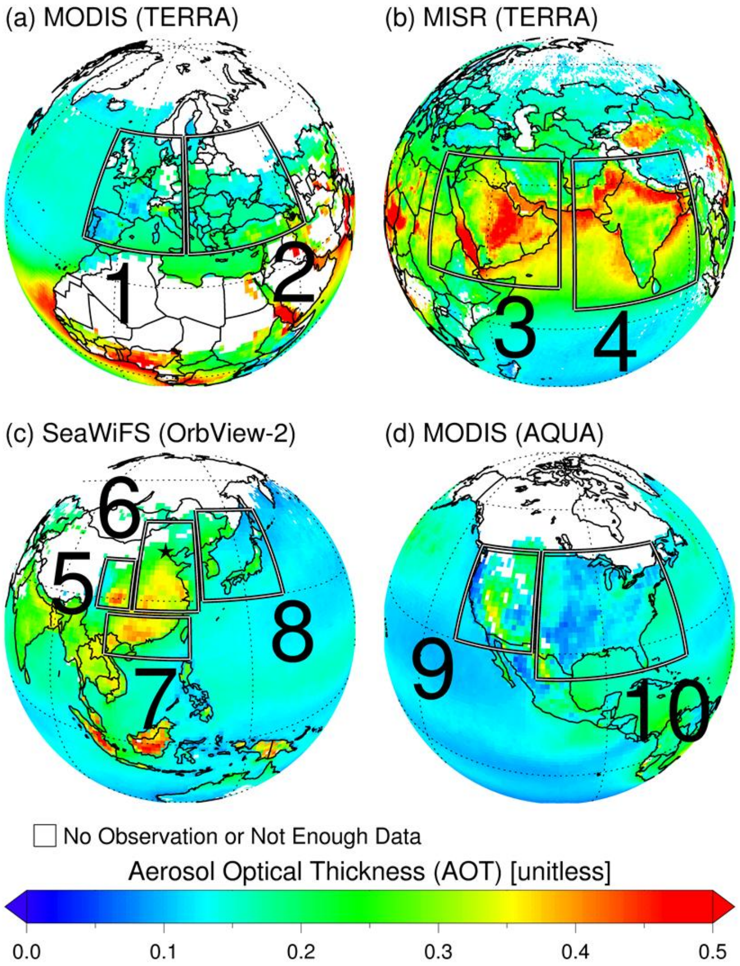
Japan

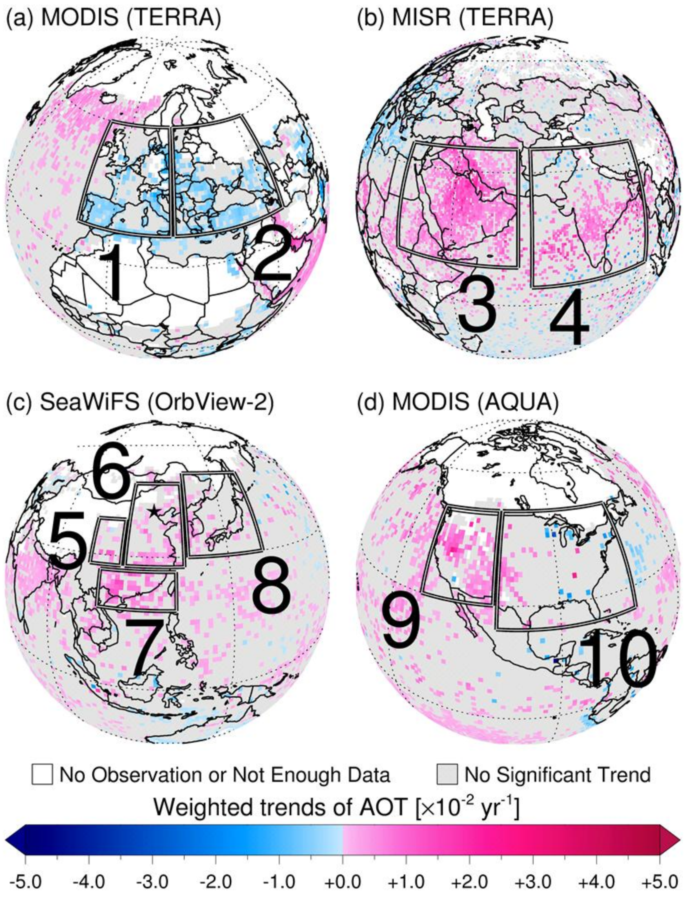


Findings:

- Detection possible but quantification requires optimized mission (e.g., CarbonSat)

AOT changes from 4 Instruments
1998 – 2012 period





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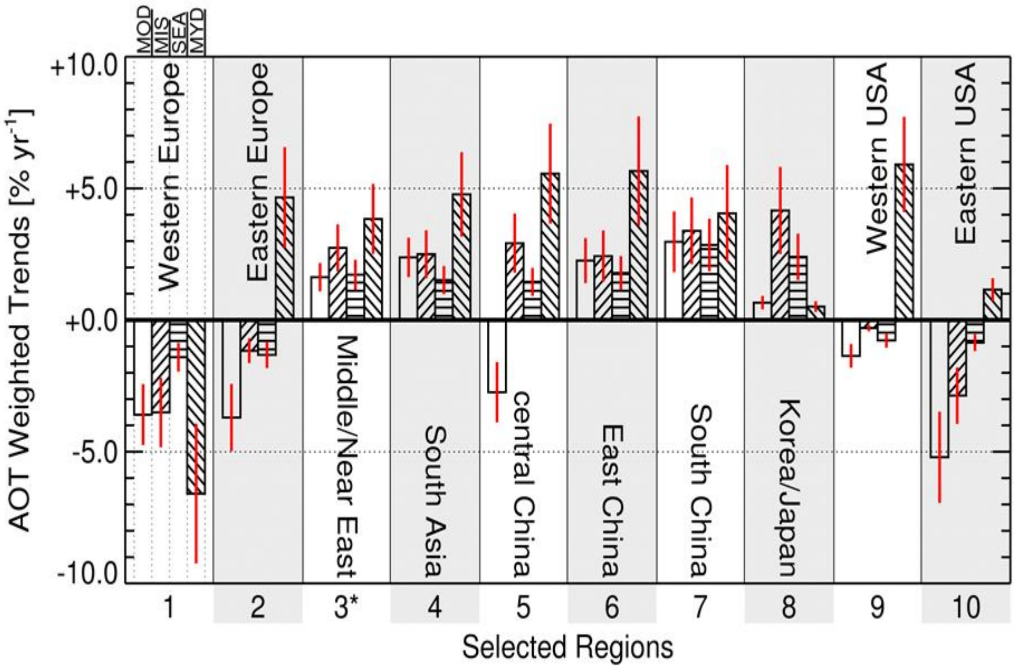
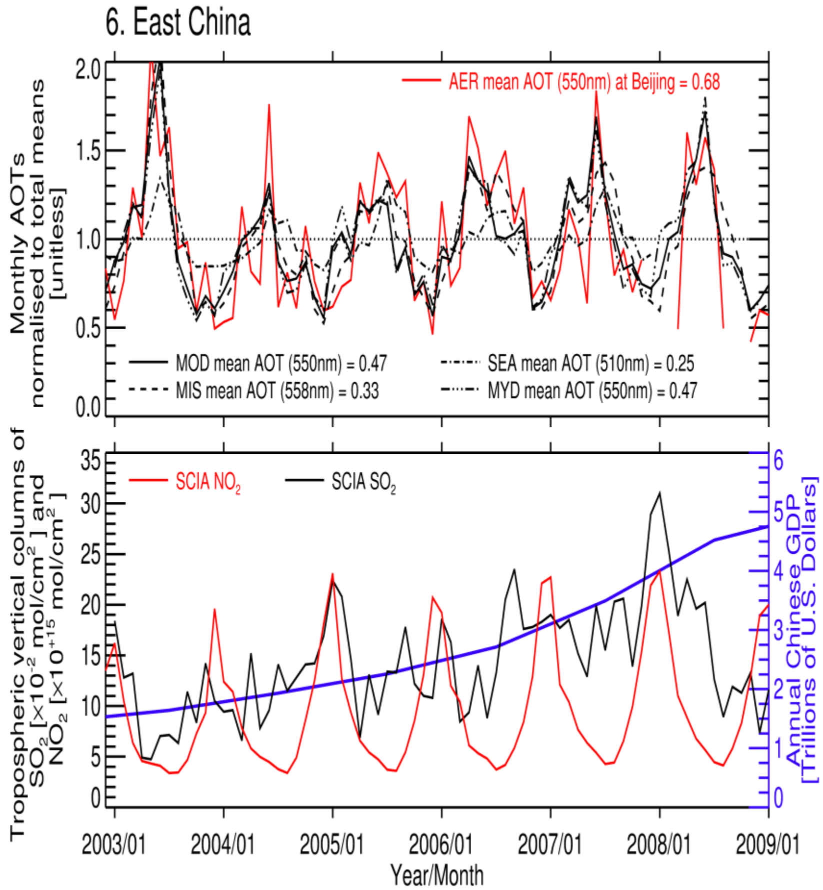
Changes in AOT from 4 Instruments





Yoon et al 2013 in submission

Desert Dust in spring summer dominates
SO2 correlates well in autumn and winter

Universität Bremen

Summary

We have had a pioneering age of success, which ended with the loss of Envisat.

In Europe we have a nadir programme but it is not adequate, i.e. does not meet need e.g.

- **no solar measurements**
- **no limb/occultation profiling**
- **no CO_2 before 2020 + GHG**

New passive remote sensing composition missions to replace and improve

- **Limb/occultation measurements**
- **Greenhouse gases**

Summary

• "Hot spot" emission sources such as power plants seeps etc. need to be monitored objectively, routinely and globally!

• CarbonSat/CarbonSat Constellation meet this need/ requirement for the measurements the key carbon GHG, delivering the required and needed high spatial resolution information on CO_2 and CH_4 at an adequate sampling!

•Apollo/Anu SCIA-ISS is a new opportunity for high spatial resolution measurements – makes use of the ISS for EO! 1 km spatial resolution 2016/17 onwards??

Drummond Burrows Psychological Phasing of Satellite Remote Sensing from Space.

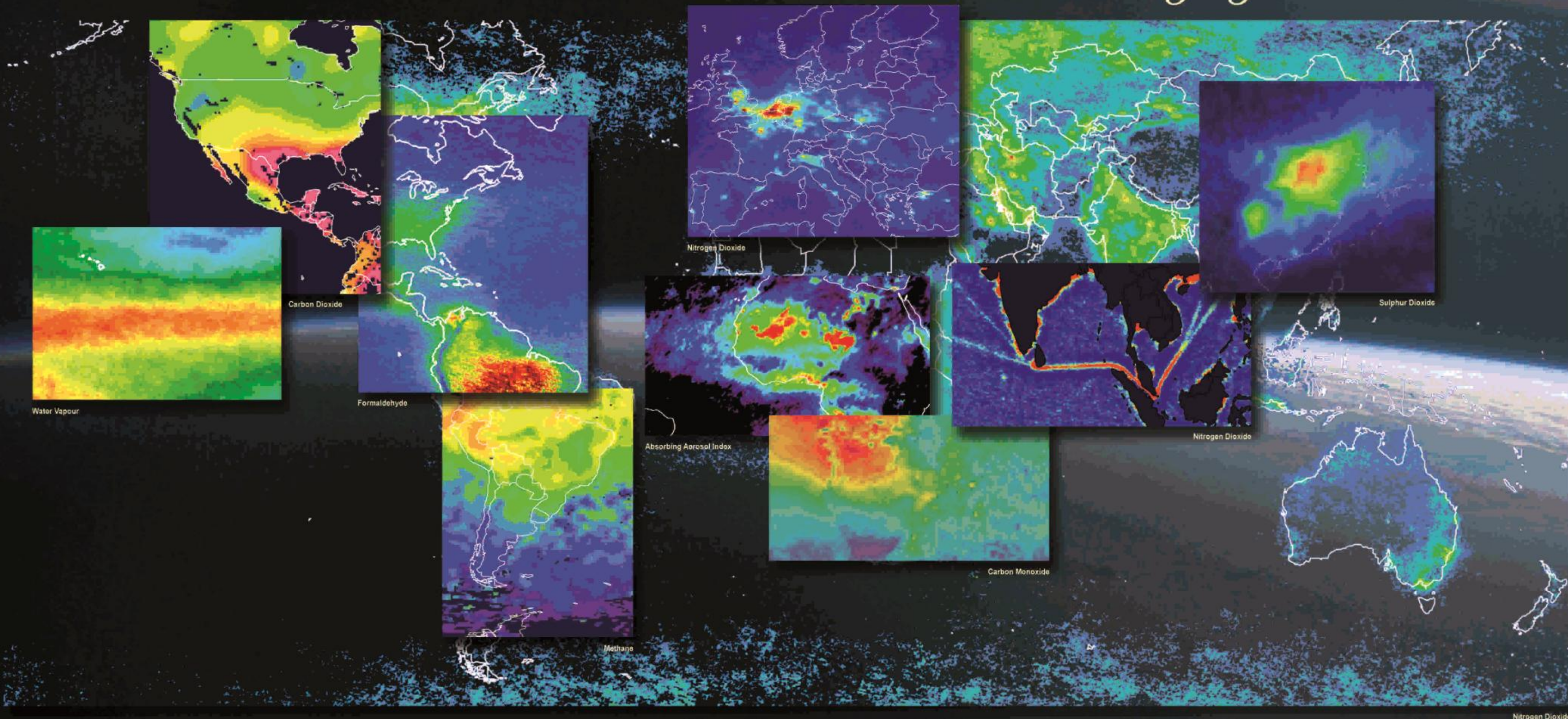
1st Phase - Proposal Disbelief - It is impossible not worth doing anyway

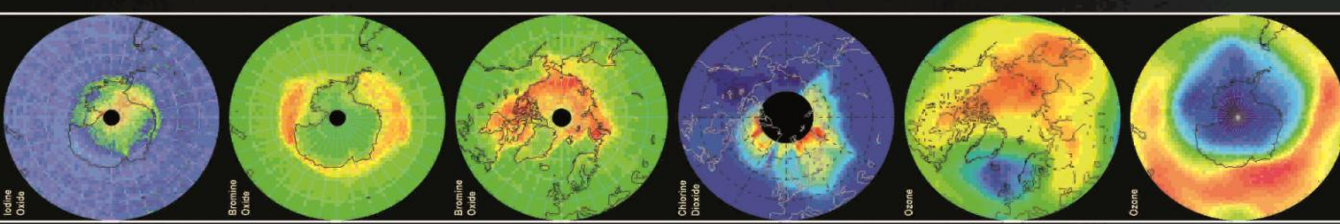
2nd Phase - Pre-flight Acquiescence - well as we have to do something, industry needs projects, your team could help but the concept has to be descoped etc.

3rd Phase - Critical Acclaim Post-Launch and In-Flight - How come it does not work better, poor resolution and sampling, how come it cost so much, could you not do better etc.!

SCIAMACHY 2002-2012

hunting light and shadows





DLR · Netherlands Space Office · Universität Bremen · KNMI · belspo · esa · SRON Netherlands Institute for Space Research · Max-Planck-Institut für Chemie

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

My thanks go the Institute of Environment Physics and the University of Bremen

Annual Rates of tropospheric NO_2 Change for Indian States

Region	abs. Trend (1E13 molec / cm^2 /yr)	rel. Trend (%)	Significance
Indian States			
Andaman & Nicobar	-0.76 ± 0.48	-1.37 ± 0.83	
Andhra Pradesh	+1.91 ± 0.86	+1.06 ± 0.5	S
Arunachal Pradesh	-0.74 ± 0.82	-0.85 ± 0.92	
Assam	+0.31 ± 0.93	+0.30 ± 0.92	
Bihar	+3.99 ± 1.10	+2.25 ± 0.58	S
Chhattisgarh	+7.21 ± 1.46	+3.60 ± 0.75	S
Dadra & Nagar Haveli	+3.52 ± 1.87	+1.73 ± 0.92	
Daman & Diu	+4.94 ± 2.26	+2.41 ± 1.08	S
Delhi	+28.79 ± 8.45	+7.37 ± 2.17	S
Goa	+1.79 ± 1.06	+1.48 ± 0.92	
Gujarat	+2.44 ± 0.98	+1.43 ± 0.58	S
Haryana	+10.82 ± 2.98	+3.06 ± 0.83	S
Himachal Pradesh	+1.40 ± 1.30	+1.14 ± 1.08	
Jammu & Kashmir	+2.10 ± 0.80	+2.16 ± 0.83	S
Jharkhand	+6.78 ± 1.34	+2.92 ± 0.58	S
Karnataka	+1.52 ± 0.91	+0.97 ± 0.58	
Kerala	-0.12 ± 0.94	-0.09 ± 0.75	
Lakshadweep	-0.48 ± 0.77	-0.84 ± 1.33	
Madhya Pradesh	+2.18 ± 0.97	+1.13 ± 0.5	S
Maharashtra	+2.02 ± 0.86	+1.08 ± 0.5	S
Manipur	+0.50 ± 1.12	+0.49 ± 1.08	
Meghalaya	+0.37 ± 1.27	+0.29 ± 1	
Mizoram	+0.29 ± 1.43	+0.23 ± 1.08	
Nagaland	+0.45 ± 1.07	+0.47 ± 1.17	
Odisha	+4.34 ± 1.10	+2.41 ± 0.58	S
Puducherry	+1.44 ± 1.11	+1.14 ± 0.92	
Punjab	+nan ± nan	+nan ± nan	
Rajasthan	+3.93 ± 1.68	+1.70 ± 0.75	S
Sikkim	-0.71 ± 0.90	-0.67 ± 0.83	
Tamil Nadu	+0.23 ± 0.83	+0.16 ± 0.58	
Tripura	+3.11 ± 1.46	+1.85 ± 0.83	
Uttar Pradesh	+6.58 ± 1.58	+2.77 ± 0.67	S
Uttarakhand	+0.47 ± 1.18	+0.28 ± 0.67	
West Bengal	+6.54 ± 1.55	+2.96 ± 0.67	S

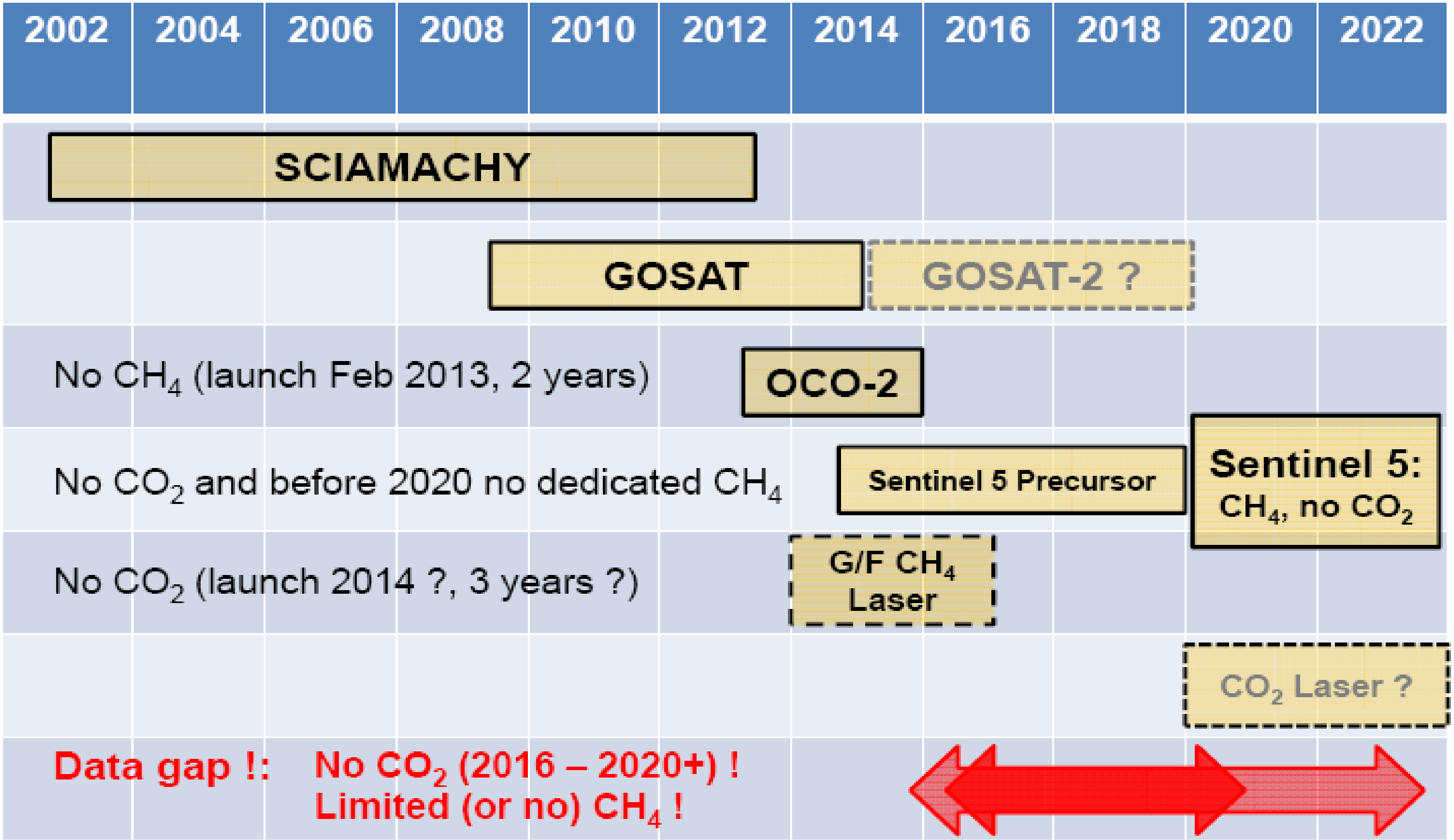
Annual Rates of tropospheric NO_2 Change for countries in sub continent

Region	**abs. Trend (1E13 molec / cm^2 /yr)**	**rel. Trend (%)**	**Significance**
Countries			
Bangladesh	+6.45 ± 1.32	+3.66 ± 0.75	S
Bhutan	-1.81 ± 0.84	-1.73 ± 0.83	
India	+3.14 ± 0.73	+1.74 ± 0.42	S
Myanmar	-0.44 ± 0.63	-0.40 ± 0.58	
Nepal	+0.67 ± 0.73	+0.58 ± 0.67	
Pakistan	+1.31 ± 0.69	+1.16 ± 0.58	
Megacities			
Karachi	+8.5 ± 2.5	+6.0 ± 1.8	S
Dhaka	+34.1 ± 5.4	+24.0 ± 3.8	S
Region	**abs. Trend (1E13 molec / cm^2 /yr)**	**rel. Trend (%)**	**Significance**
Visited cities			
Ahmedabad	+3.37 ± 2.33	+1.63 ± 1.13	
Pune	+5.58 ± 1.61	+3.05 ± 0.88	S

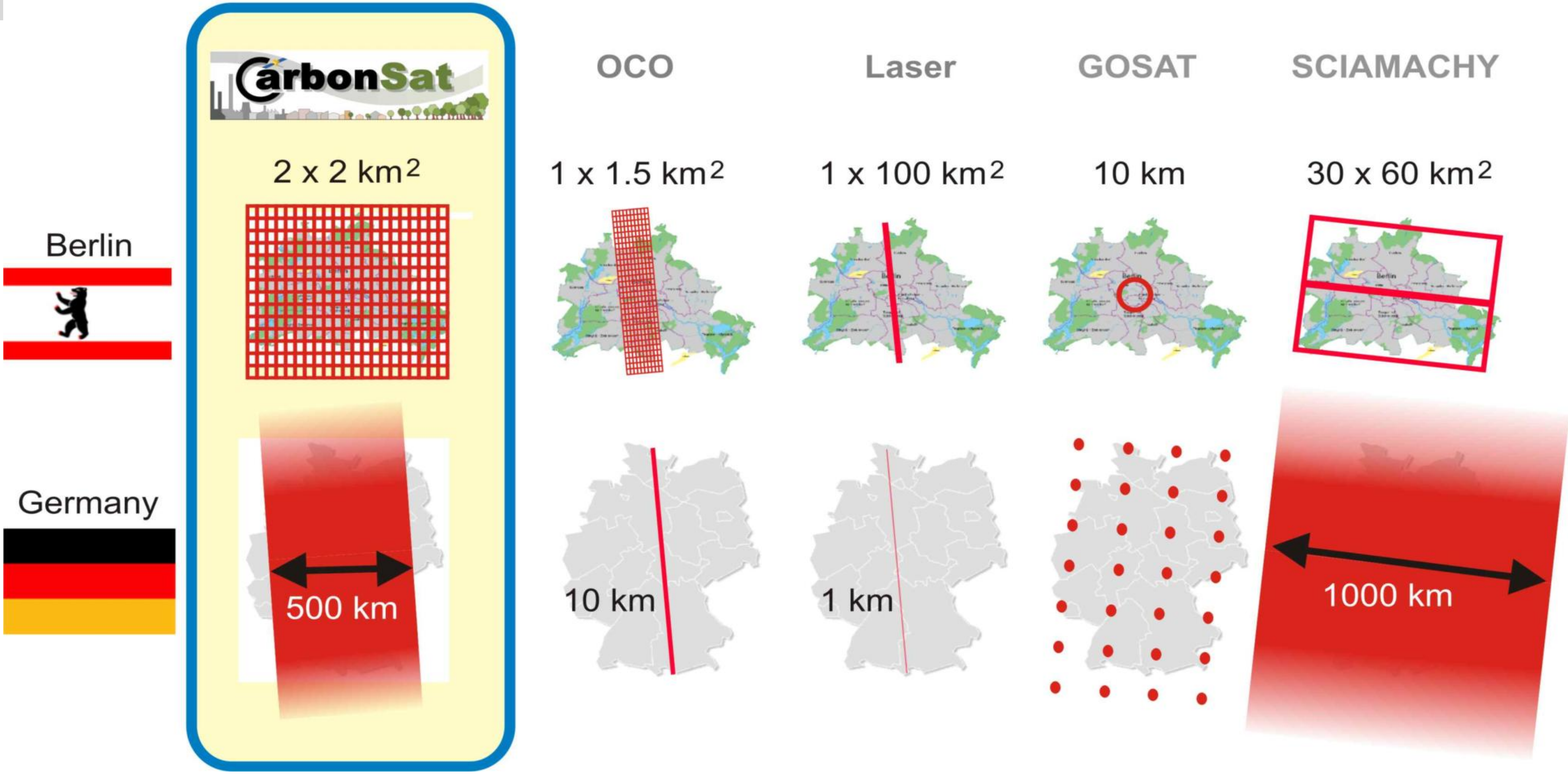
Current State of European Component of Global Atmospheric Composition Observing System

- No plans for Tropics and Southern Hemisphere measurements from GEO!
- No measurements of dry column mixing ratio of CO_2 and CH_4 planned from GEO.
- No replacements yet planned in the near future for limb measurements of Envisat payloads
- Progress too slow and not fit for purpose
  Time from proposal of GeoSCIA-mini to launch of GOME = 6 years
  Time from proposal of GeoSCIA to launch of Sentinel 4 = 21 years + ?
- Kyoto protocol failed and the national governments seem not to be recognising the changes from an anthropocene having 7 billion people, soon to become 9-10 billion, on air quality, the upper atmosphere, the climate and the environment.
- We urgently need a measurement system “fit for purpose” to address the science and provide early warning of the future and the evidence base for environmental policymaking from the local to the global scale
- So are we moving forward or backwards?

GHG Missions yielding emissions



CarbonSat - Spatial resolution & coverage



CarbonSat enables new important application areas:
CO_2 and CH_4 emission „hot spot“ detection and monitoring (power plants, …)

German/French Climate Mission MERLIN

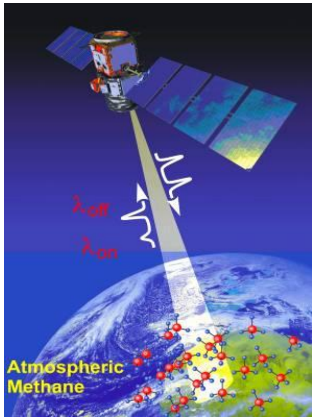
IPCC Statement: "*Carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) are the most important of the Earth's greenhouse gases and whose concentration has been directly modified by human activities*"

Major Mission Objective

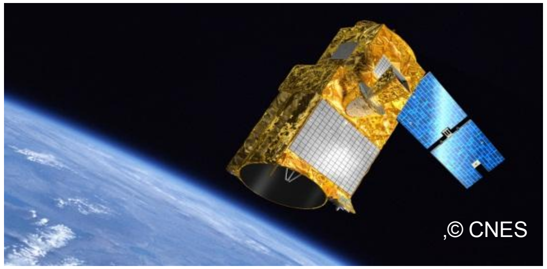
- Measurement of atmospheric Methane from Space by using a Differential Absorption Lidar
- Calculation of Intensity of Methane Sources on Ground through inverse Modelling

Start: in the time-frame of 2016

Industrial Partners: ASTRIUM, KAYSER-THREDE, Fraunhofer ILT, JENOPTIK, DLR

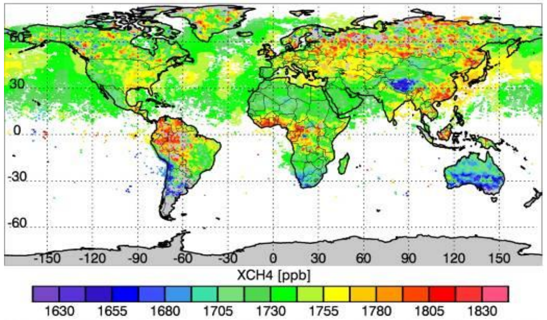


MERLIN measurement principle. The CH_4 Lidar Instrument (DLR) is carried by a MYRIADE Evolutions Platform (CNES).

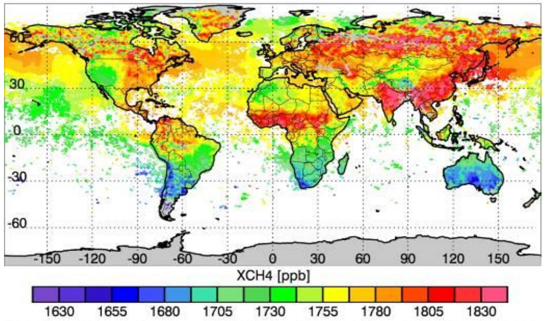


Measured seasonal atmospheric CH4 concentrations:

Methane SCIAMACHY AMJ 2005



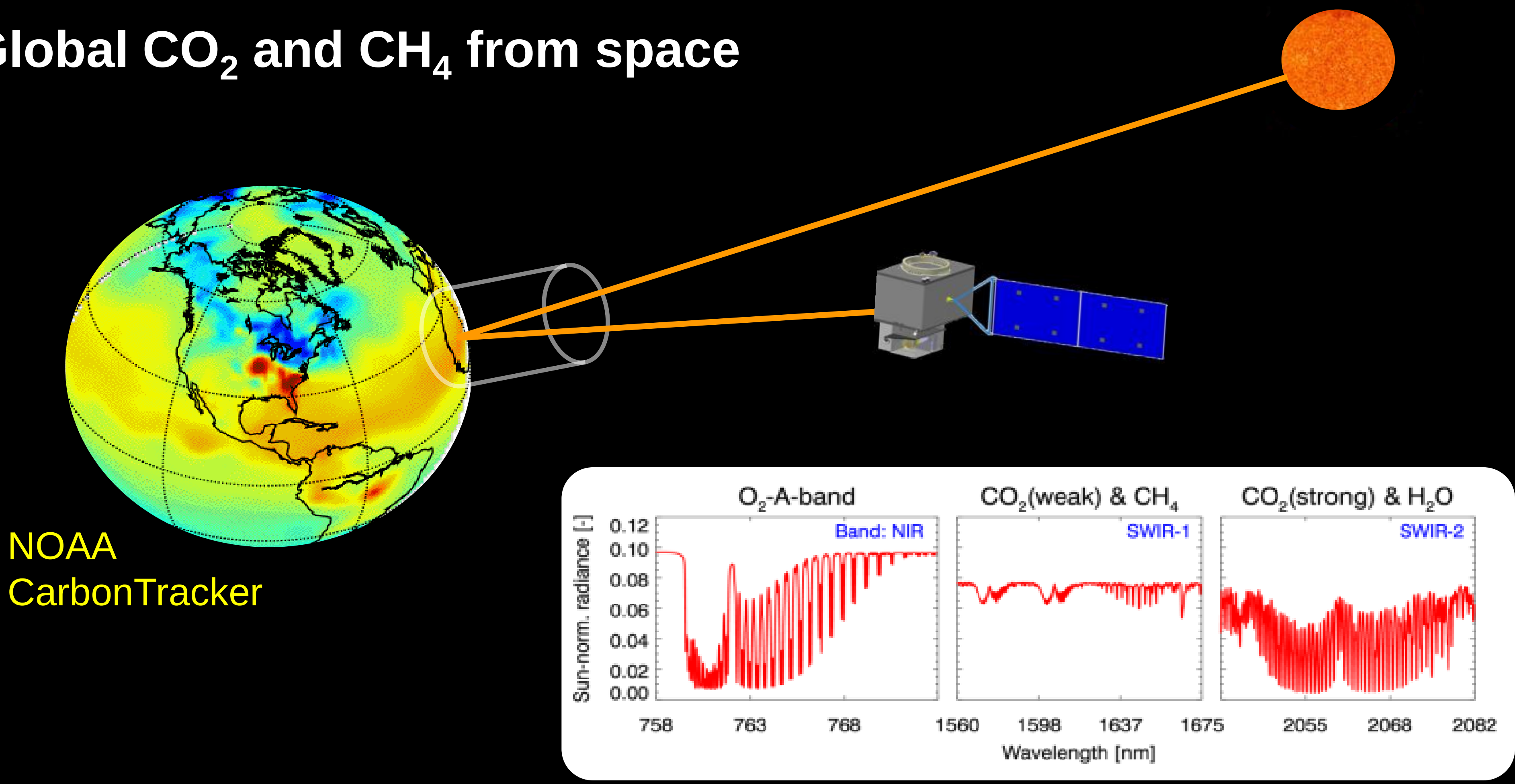
Methane SCIAMACHY JAS 2005



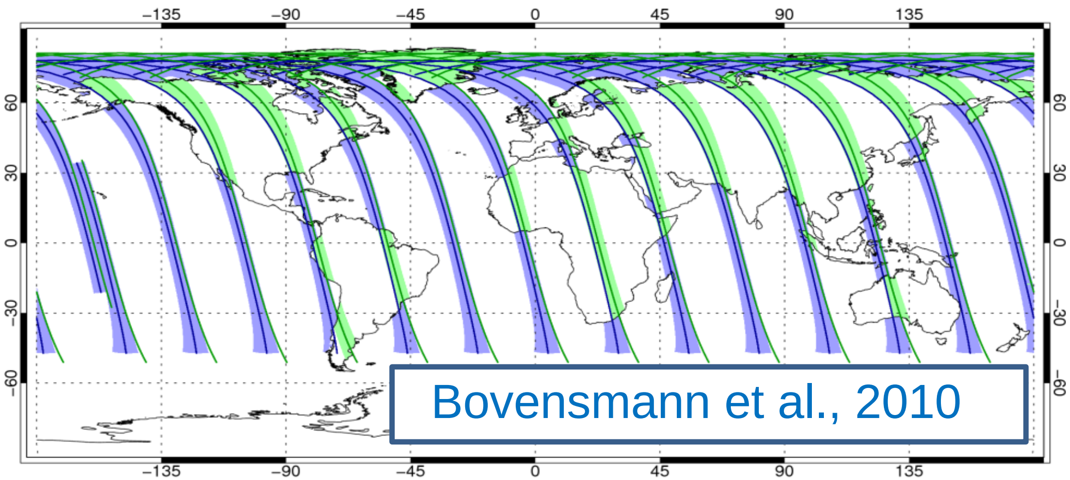
Carbon Monitoring Satellite – EE8 Proposal

CarbonSat

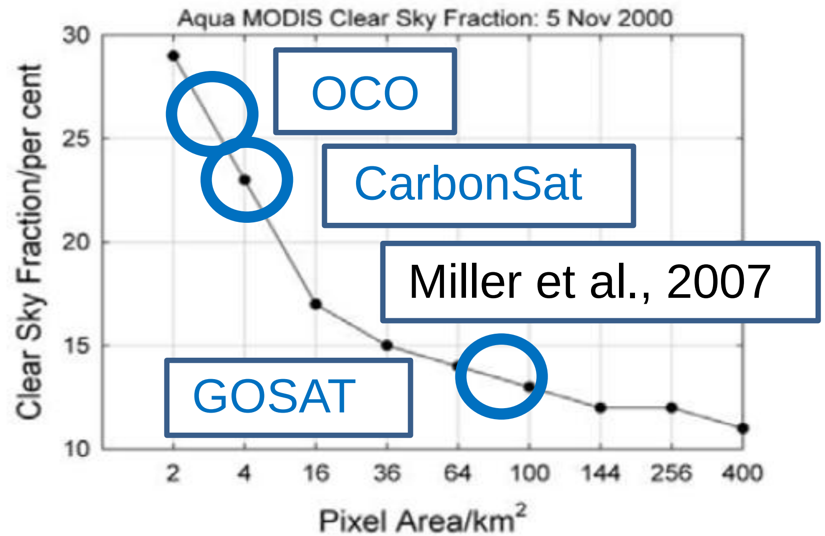
Global CO_2 and CH_4 from space



CarbonSat Daily Orbital Coverage



Clear Sky Fraction



- XCO_2 & XCH_4
- 500 km swath
- 2 km x 2 km pixel
- 250 meas. per 0.3 s

6 million cloud free observations / day !

CarbonSat Number of Clear-Sky Observations				
Instrument	**Spatial resolution [km²]**	**Total number observations per day**	**Clear-sky frequency**	**Total number clear-sky observations per day**
CarbonSat	**4**	**28,000,000**	**23%**	**6,440,000**
OCO	3	1,680,000	27%	453,600
GOSAT	85	10,000	13%	1,300
SCIAMACHY	1800	70,000	5%	3,500

Comparison of PBL sensitive GHG satellite missions

Application area & other criteria	SCIAMACHY	GOSAT	OCO	Sentinel 5 Precursor	CH_4 Laser (MERLIN)	CarbonSat
Regional CO_2 fluxes						
Regional CH_4 fluxes						
CO_2 „hot spots“ (e.g. power plants)						
CH_4 „hot spots“ (e.g. oil fields)						
Technical maturity						
Daytime						
Day & night						

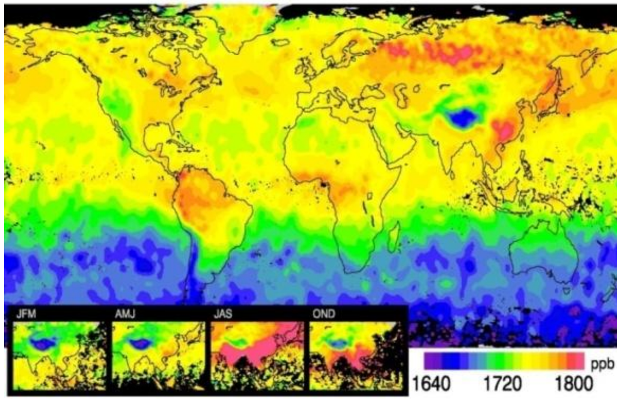
CarbonSat achieves the required spatial and temporal sampling

innovativ! Bremen

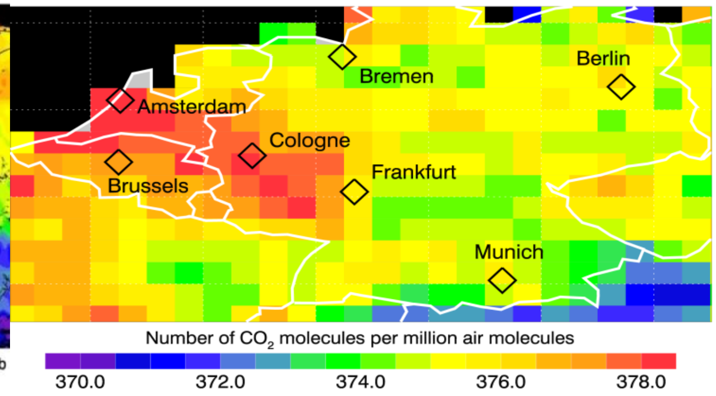
SCIAMACHY was the First Greenhouse Gas Measurement in Space

- **Unique greenhouse gas measurements from space (IUP, University of Bremen)**
- **However, SCIAMACHY requires averaging of 3 years of data to detect man-made emissions**

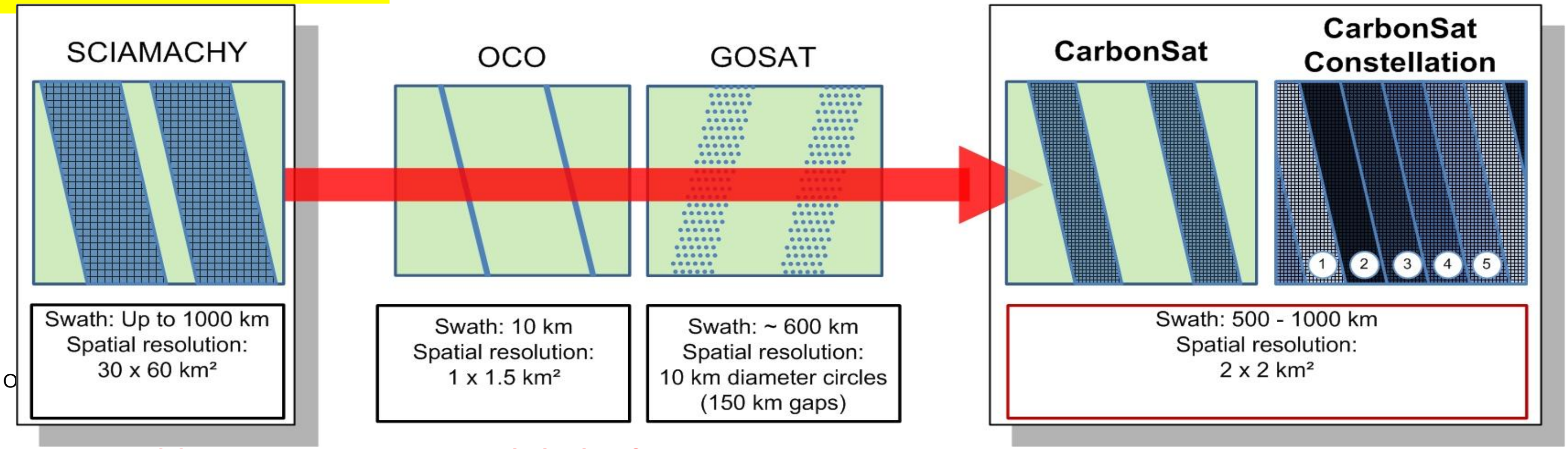
Methane SCIAMACHY/ENVISAT 2003-2005



Carbon Dioxide SCIAMACHY/ENVISAT 2003-2005



Global CO_2 and CH_4 measurement from SCIAMACHY on ENVISAT



Satellites can add important missing global information
but timely, higher resolution and accuracy measurement are required

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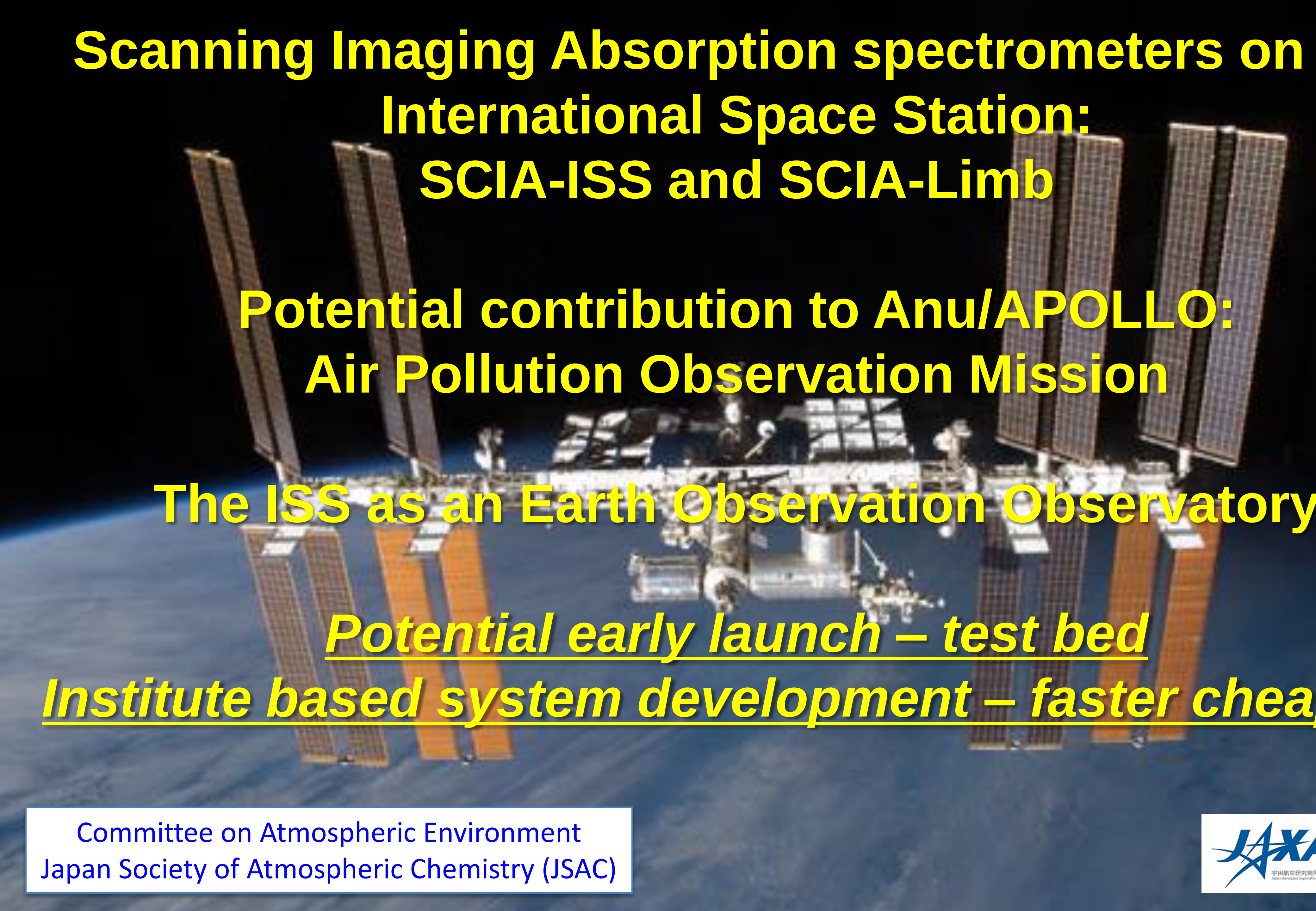
CarbonSat Constellation



Scanning Imaging Absorption spectrometers on International Space Station: SCIA-ISS and SCIA-Limb

Potential contribution to Anu/APOLLO: Air Pollution Observation Mission

The ISS as an Earth Observation Observatory

Potential early launch – test bed

Institute based system development – faster chea

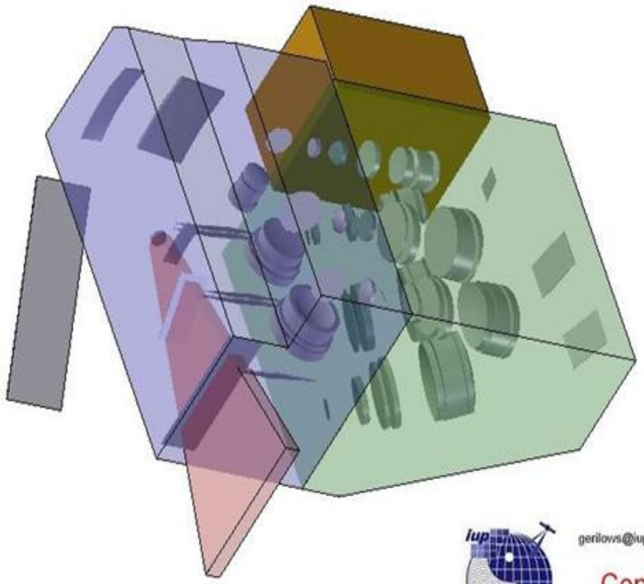
Committee on Atmospheric Environment
Japan Society of Atmospheric Chemistry (JSAC)

Phase-0 preliminary SCIA-ISS hardware design for APOLLO

J. P. Burrows Konstantin Gerilowski and IUP Team

Bremen innovativ!

	UV-VIS	NIR	SWIR-1
Detector	H2RG (HyViSi) (baseline, TBC) **(1000x200 binned Pixel)**	H2RG (HyViSi) (baseline, TBC) **(1000x200 binned Pixel)**	H2RG (MCT) (baseline,TBC) **(1000x200 binned Pixel)**
Swath	~ 200 km	~ 200 km	~ 200 km
Ground Scene	1x1 km (baseline)	1x1 km (baseline)	1x1 km (baseline)
Spectral Band	305-505 nm	718-812 nm (TBD)	1559-1675 nm
FWHM	~ 0.6 nm	~ 0.28 nm	~ 0.34 nm
Sampling	3 pixel/FWHM	3 pixel/FWHM	3 pixel/FWHM
OBM F#	F# ~ 5.2	F# ~ 2.6	F# ~ 2.6



gerilows@iup.physik.uni-bremen.de

Confidential

	UV-VIS	NIR	SWIR-1
Det. Cooling	active to 120 K	active to 120 K	active to 120 K
OBM-Cooling	active stabilized	active stabilized	active to ~ 260 K
SNR @ L-nom **[for binned Det. Pixel]**	~ 1:1350 (for NO2)	~ 1:1130	~ 1:730
L-nom **[phot./nm/s/cm²/sr]**	4e13 (for NO2)	1.5e13	5.09e12
Det. Pixel Size **[binned, spat. x spect.]**	180 µ x 32 µ	180 µ x 32 µ	180 µ x 32 µ
ADC	14 (16) Bit	14 (16) Bit	14(16) Bit

SCIAMACHY

CarbonSat Constellation