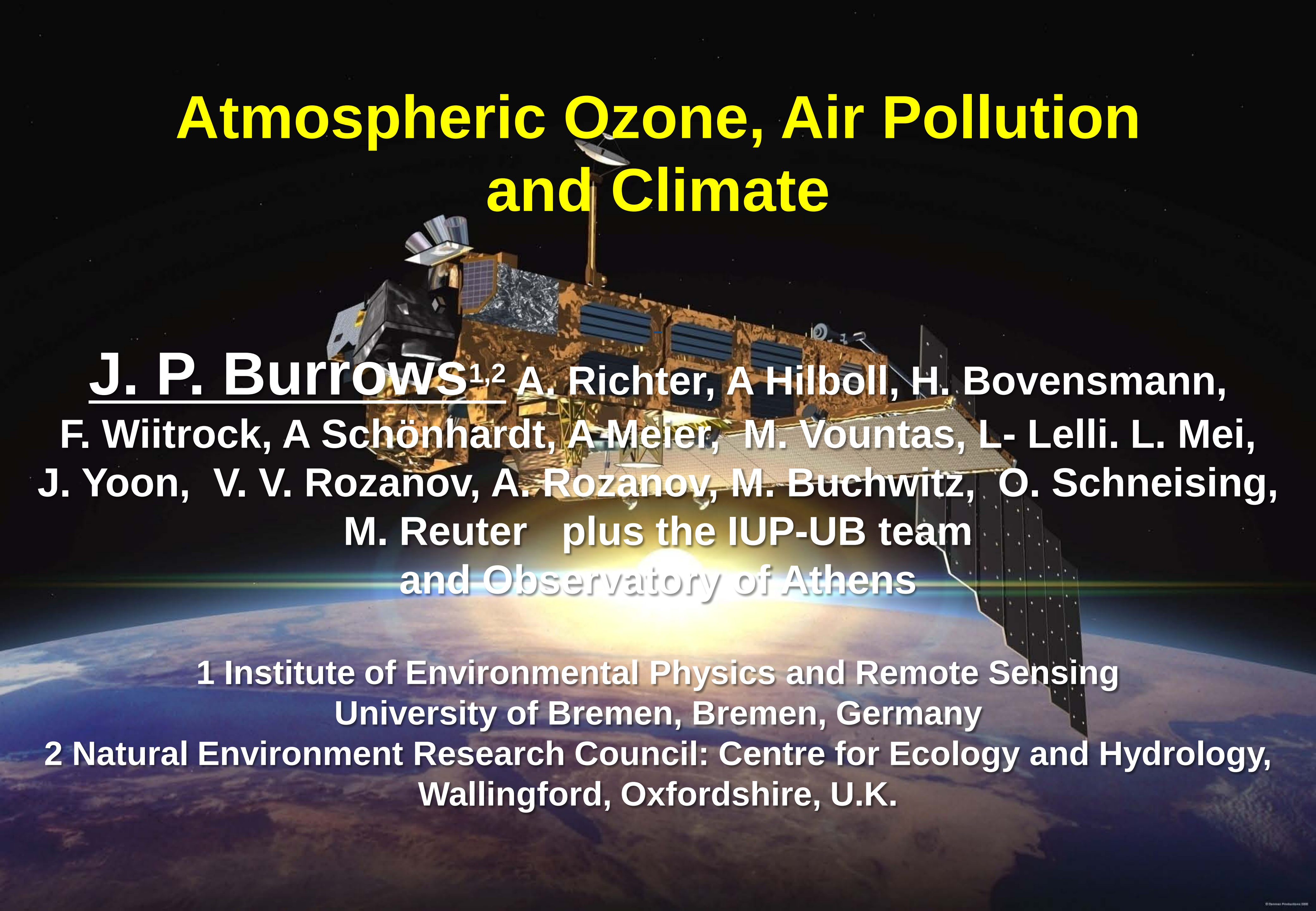
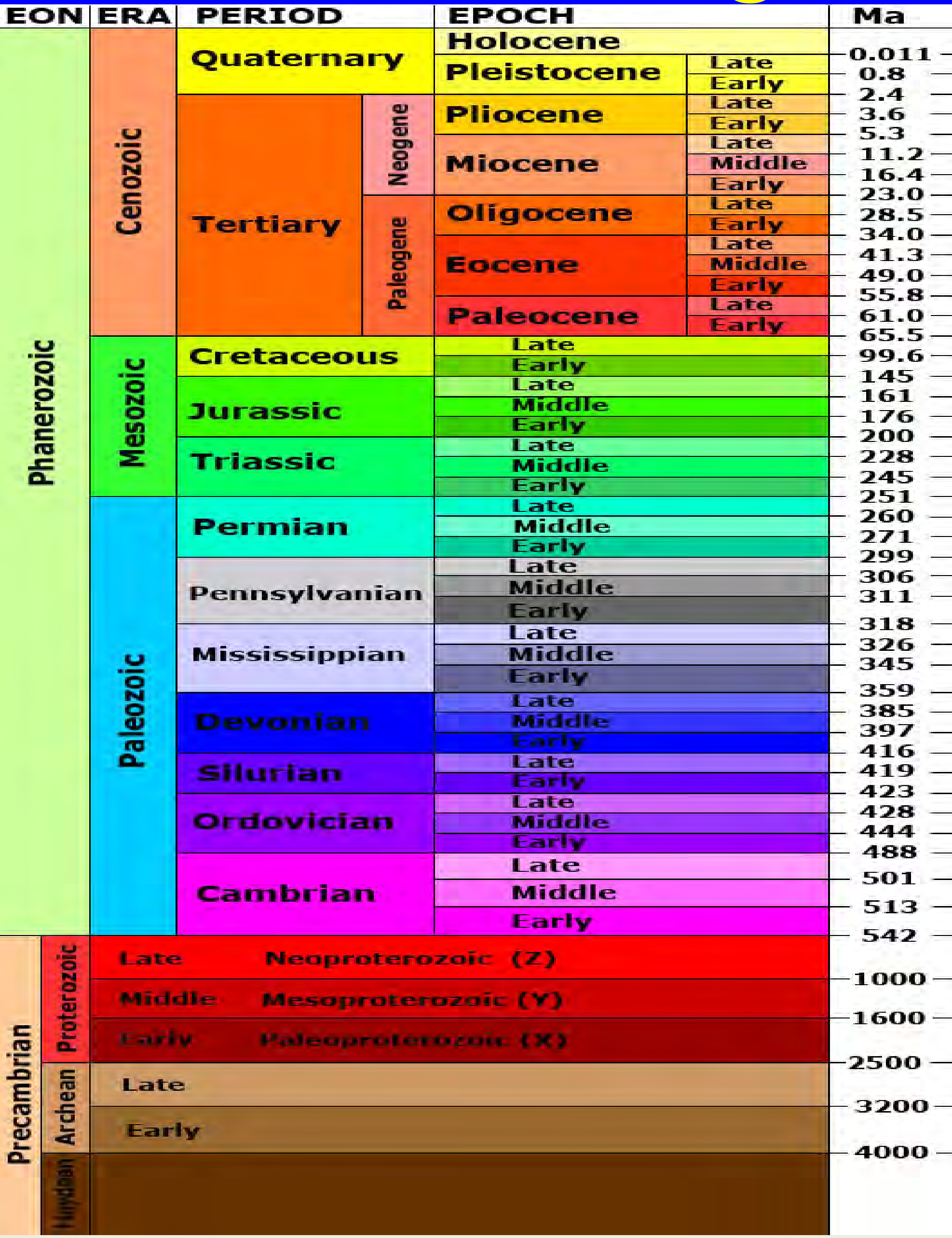


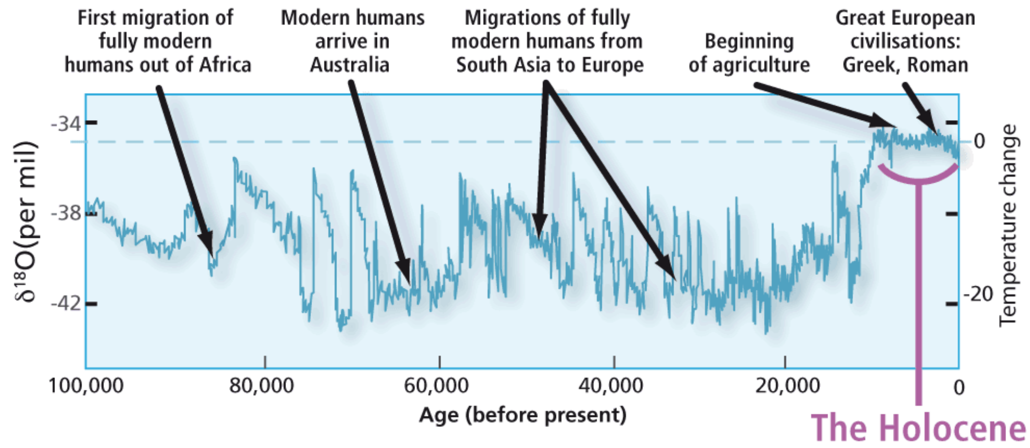
Atmospheric Ozone, Air Pollution and Climate

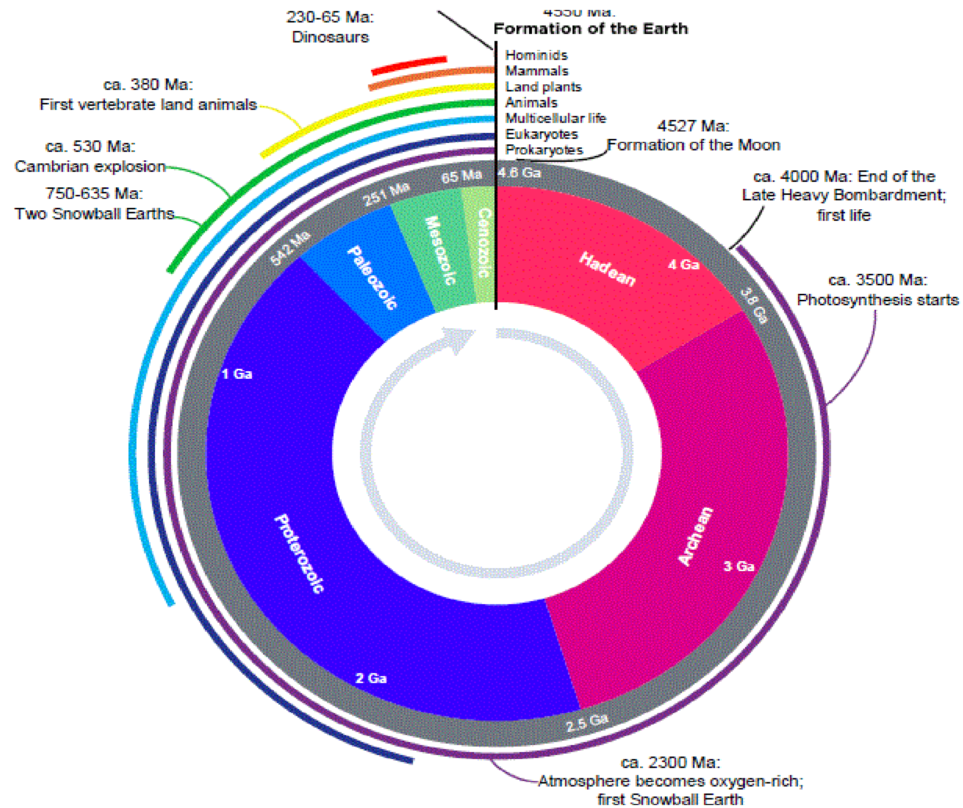
J. P. Burrows[1,2] A. Richter, A Hilboll, H. Bovensmann,
F. Wiitrock, A Schönhardt, A Meier, M. Vountas, L- Lelli. L. Mei,
J. Yoon, V. V. Rozanov, A. Rozanov, M. Buchwitz, O. Schneising,
M. Reuter plus the IUP-UB team
and Observatory of Athens

1 Institute of Environmental Physics and Remote Sensing
University of Bremen, Bremen, Germany
2 Natural Environment Research Council: Centre for Ecology and Hydrology,
Wallingford, Oxfordshire, U.K.

Geological Time Scales



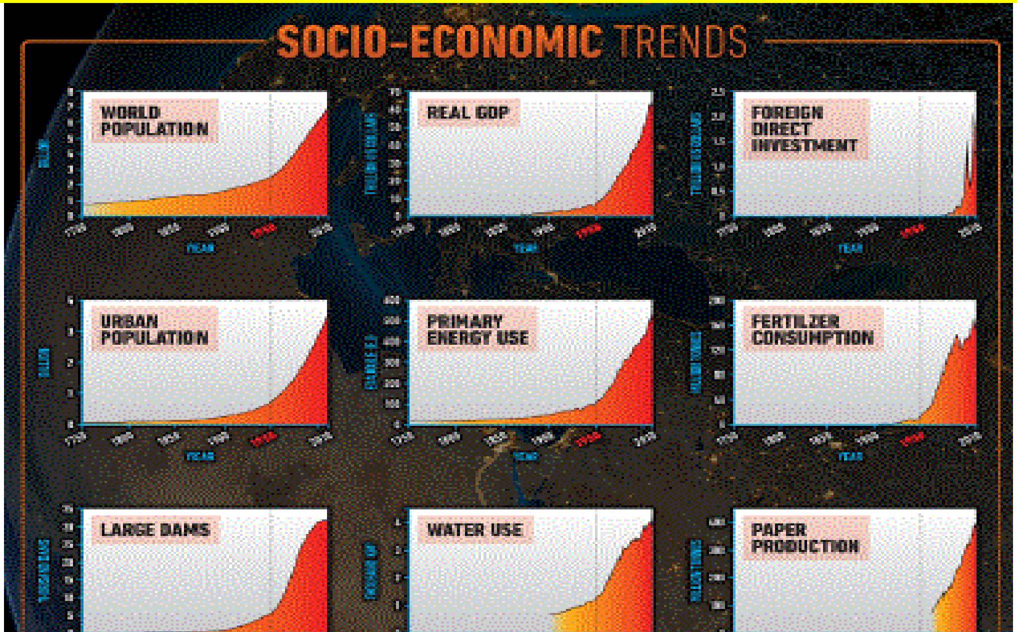




The Anthropocene

THE GREAT ACCELERATION

In September 2015 the nations of the world will meet to agree on Sustainable Development Indicators will be essential to asses progress



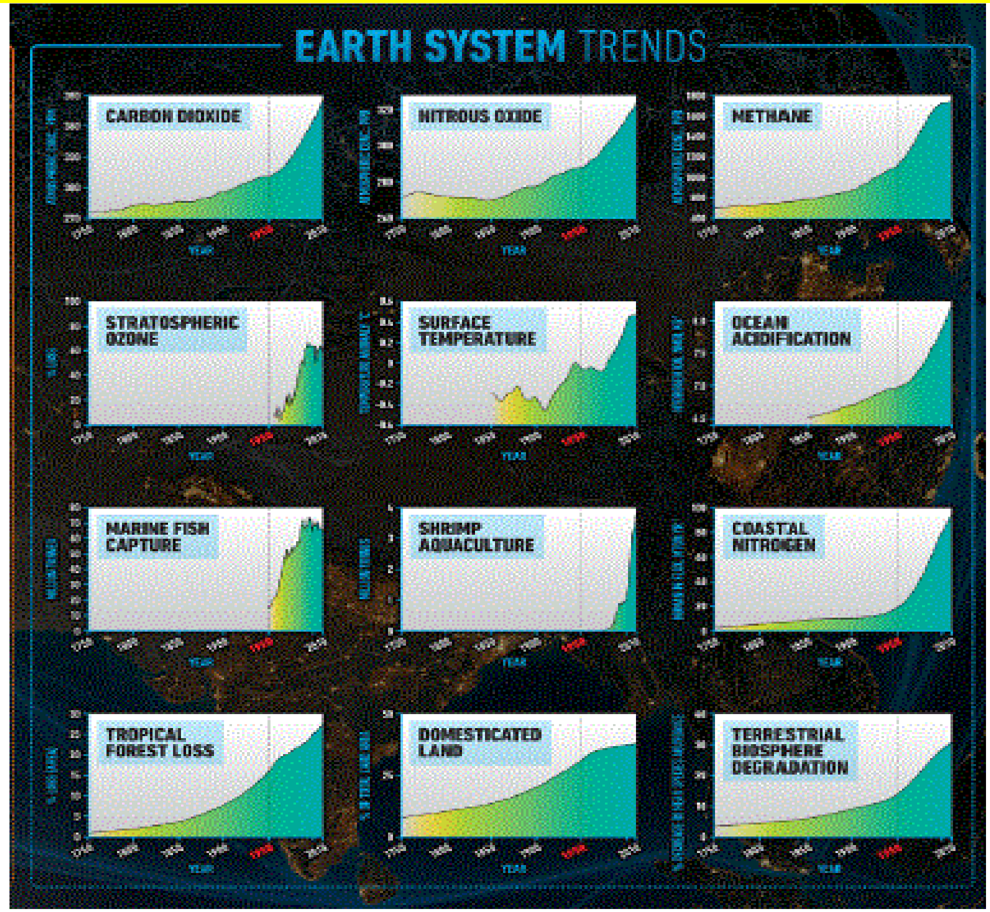


Figure 2: Twelve Earth system trends from 1750 to present.

Why observe the atmosphere from space?

Earth has enter … Stoermer
and P. J. Crutze … ging!

- From the Neolithi
  rose from 4M t
- Dramatic change
  emissions sinc
- Energy supplied
  => Release of

⇨ Global transpo
and land use c

⇨ Climate Chang

⇨ Global destruc

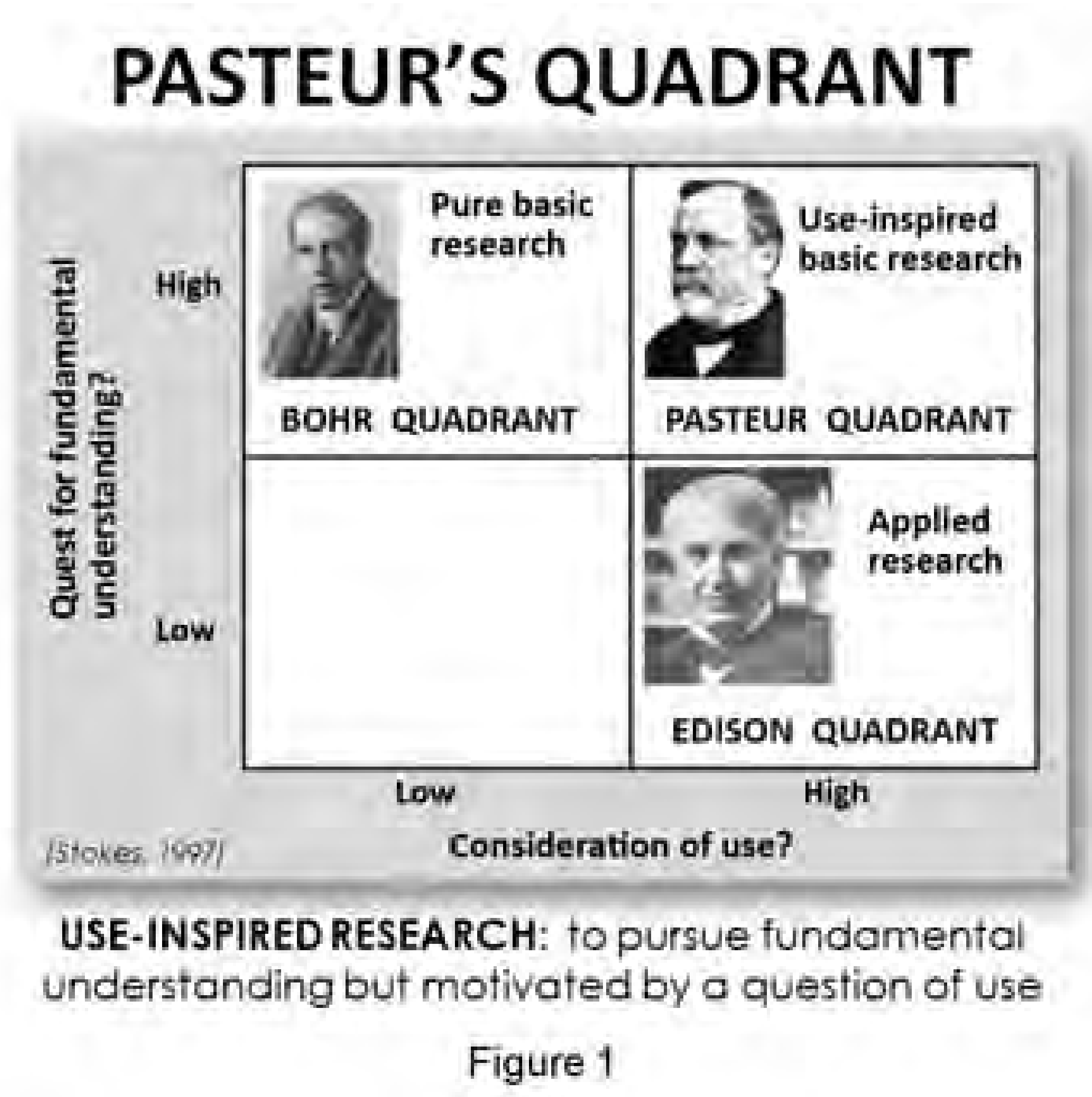


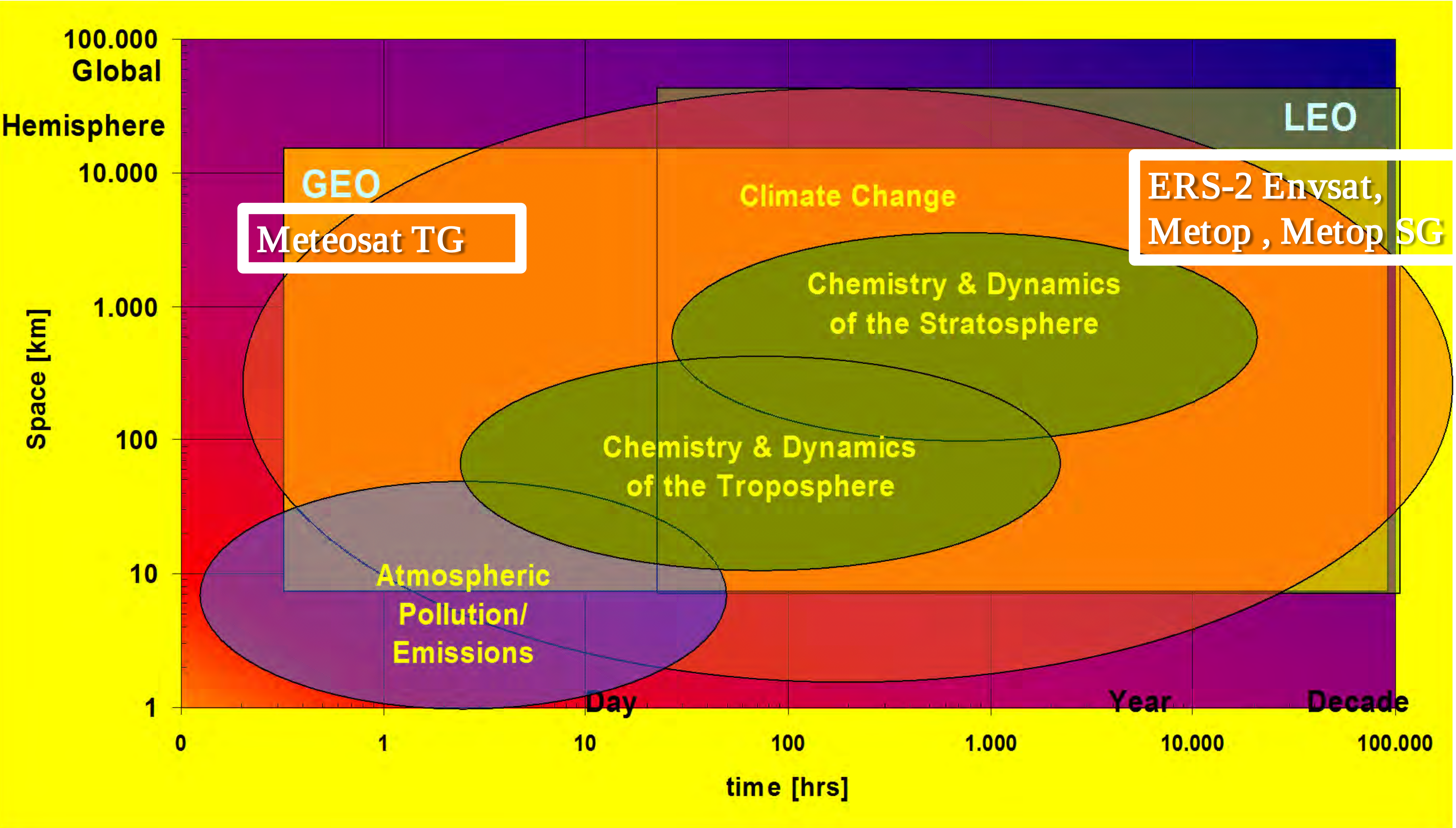
Figure 1

⇨ It is ***impossible*** … ***ot measured!!***

⇨ Environmental/

⇨ Evidence base f

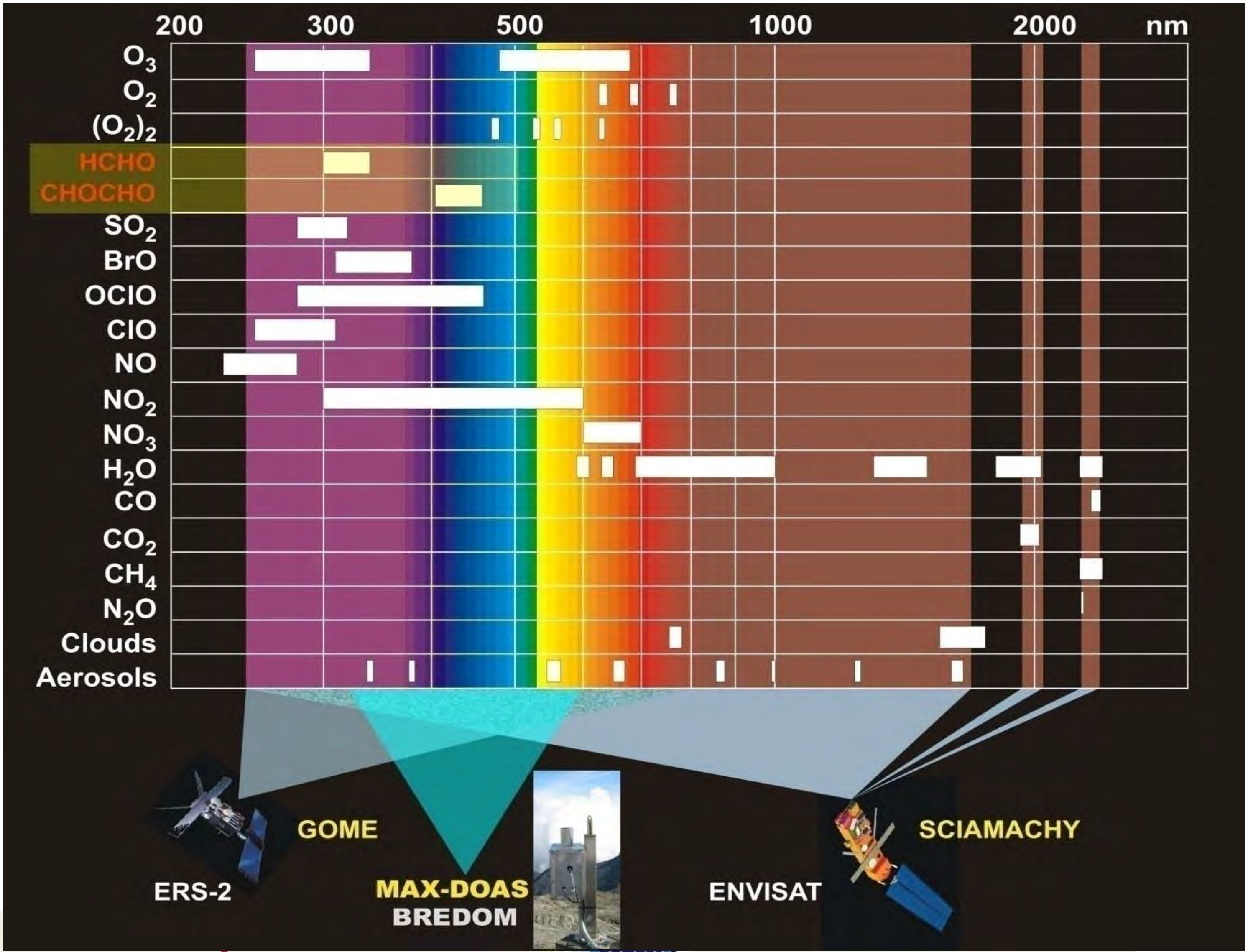
Spatial and Temporal Scales relevant for measurements from LEO and GEO



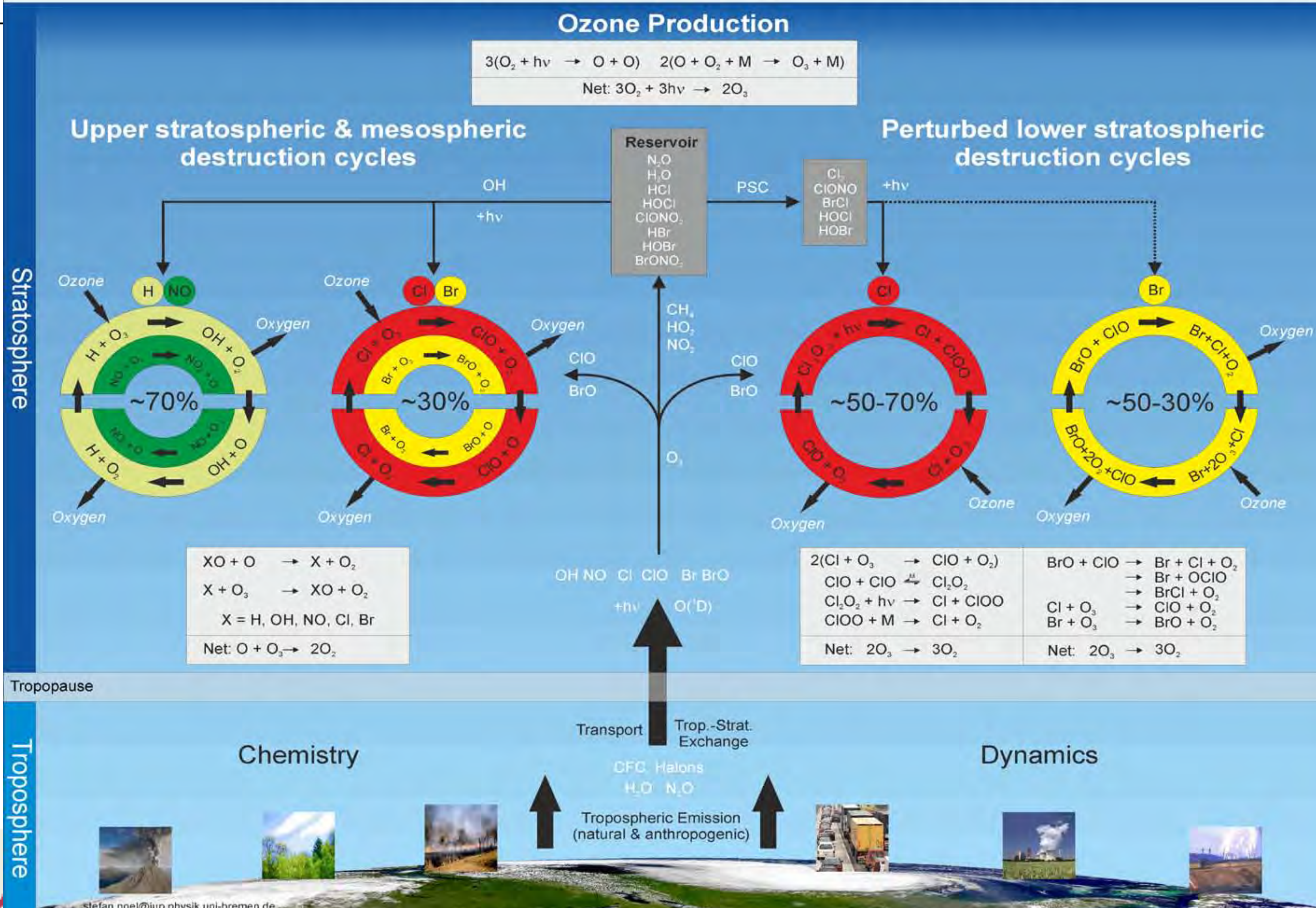
European LEO and GEO Passive Remote Sensing of trace consitutents in the Anthropocene - Some Relevant History

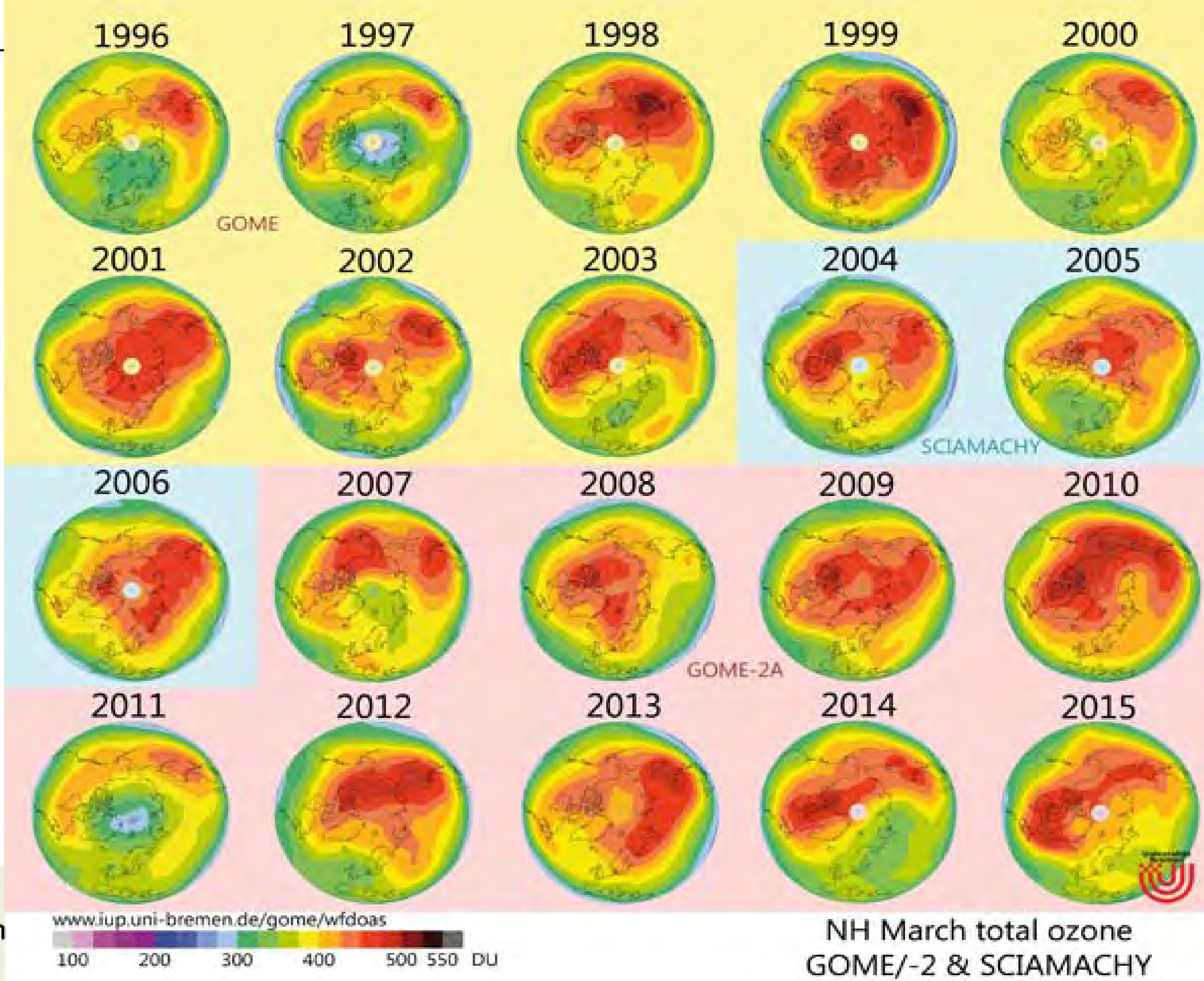
1984-1988	Development and Submission to ESA for POEM/ Envisat AO, of SCIAMACHY (SCanning Imaging Absorption spectroMeter for Atmospheric CHartographY) concept Burrows et al – hunting light
1988	Proposal of SCIA-mini for ERS-2 later descrped to GOME
1989	Selection of SCIAMACHY for ENVISAT
1990	Selection 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
2015	September ESA decision either CarbonSat or FLEX for ESA EE8????

SCIAMACHY: Target Molecules



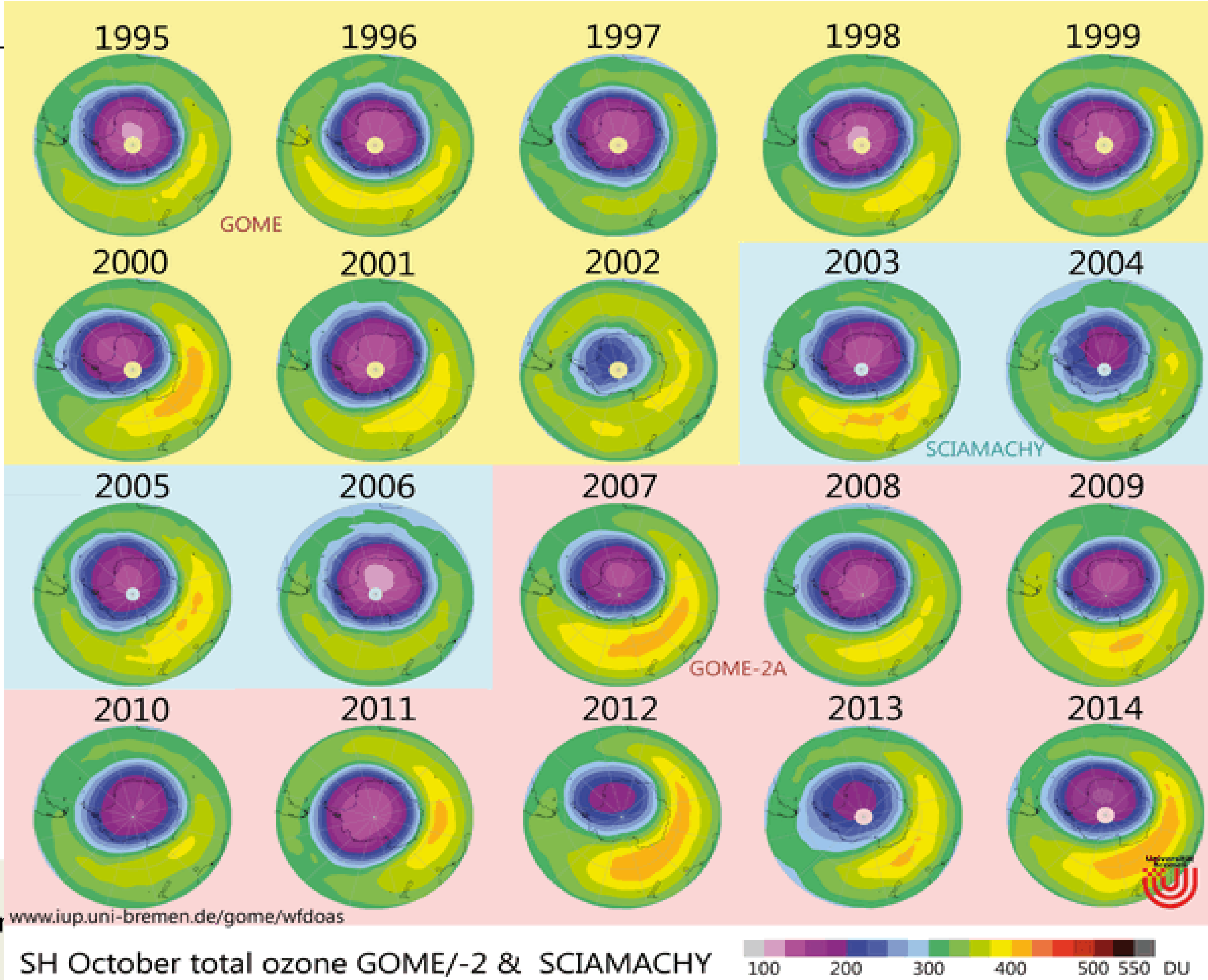
Ozone Production & Catalytic Destruction




1996
1997
1998
1999
2000
GOME
2001
2002
2003
2004
2005
SCIAMACHY
2006
2007
2008
2009
2010
GOME-2A
2011
2012
2013
2014
2015
www.iup.uni-bremen.de/gome/wfdoas
100 200 300 400 500 550 DU
NH March total ozone
GOME/-2 & SCIAMACHY

Un

LENT.


1995
1996
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GOME
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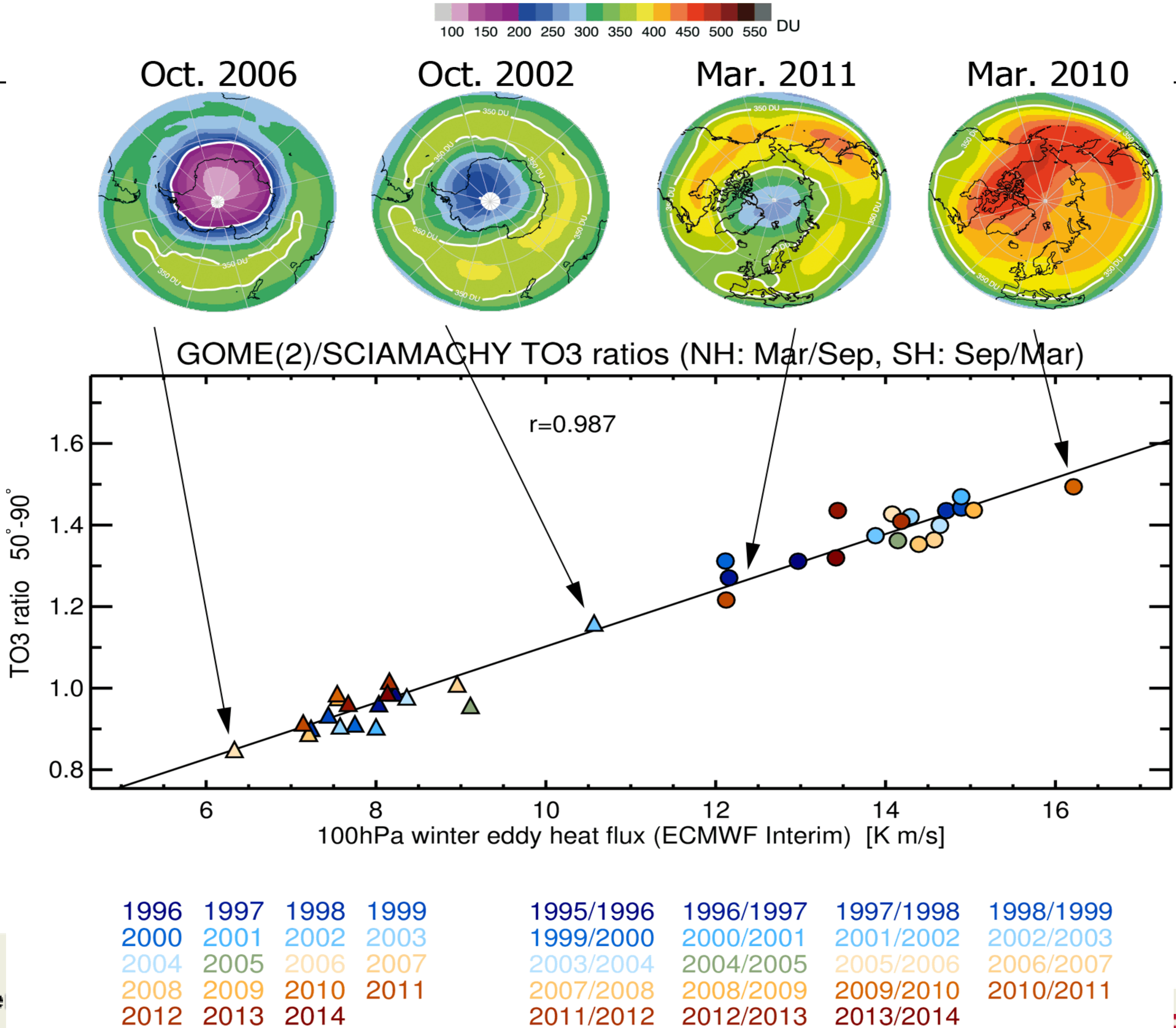
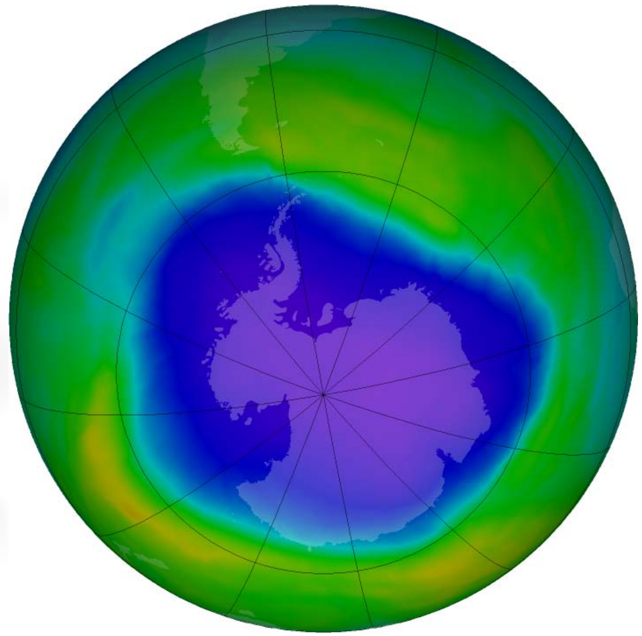
SCIAMACHY
2005
2006
2007
2008
2009
GOME-2A
2010
2011
2012
2013
2014
www.iup.uni-bremen.de/gome/wfdoas
SH October total ozone GOME/-2 & SCIAMACHY
100 200 300 400 500 550 DU

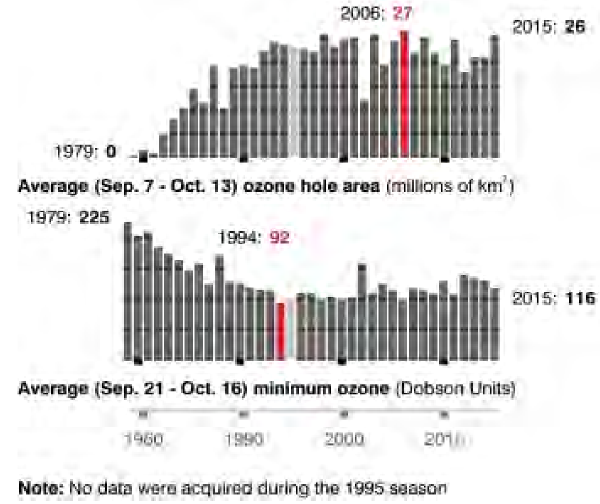


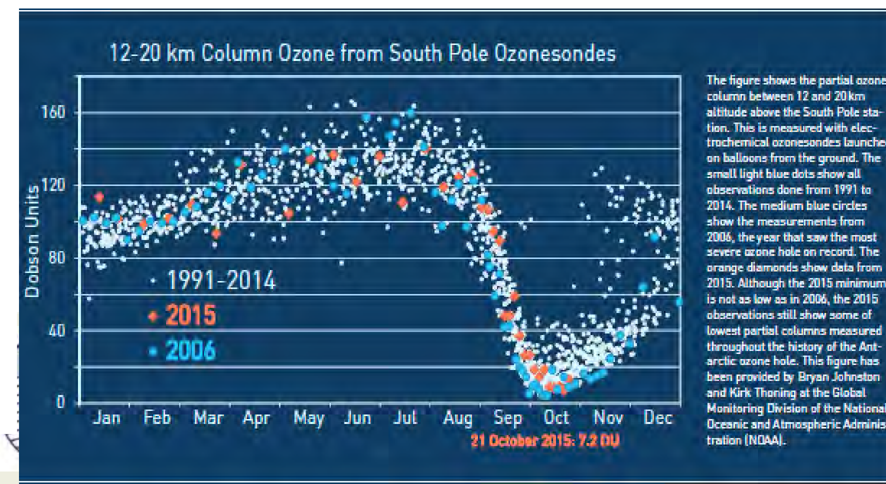
Update Weber et al. 2011, WMO 2014

Ozone hole above Antarctica 2015

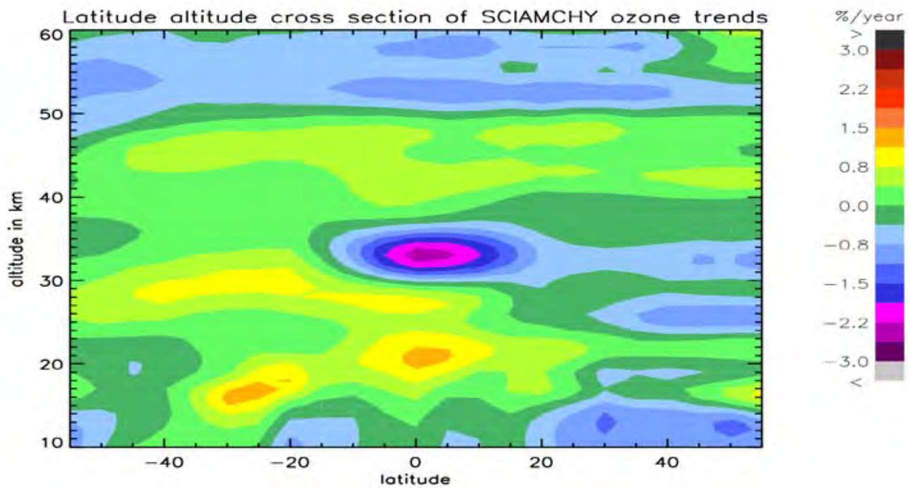
30 October 2015

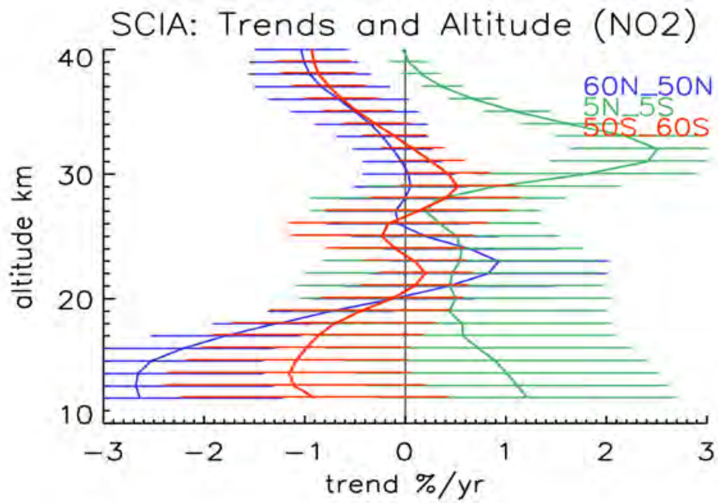






Latitude-altitude dependence of ozone trends
Impact of SST / T-hiatus on BDC





- minimum in the tropical 30-35 km range related slowing BDC and changing NO_X
  Gebhardt et al 2012 OQS and ACP 2013 and Aschmann et al ACP 2014

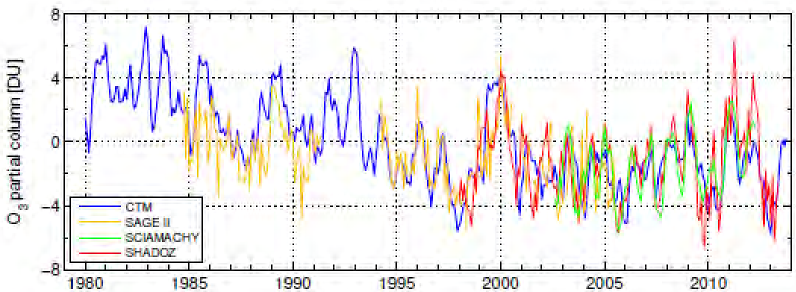


Fig. 2. Observed and simulated tropical (20° N–20° S) LS O_3 partial columns (17–21 km). Anomalies are deviations from the modelled 1980–2013 averages.

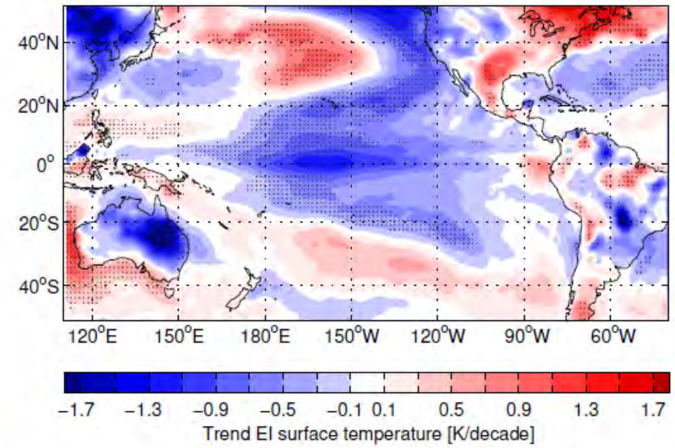
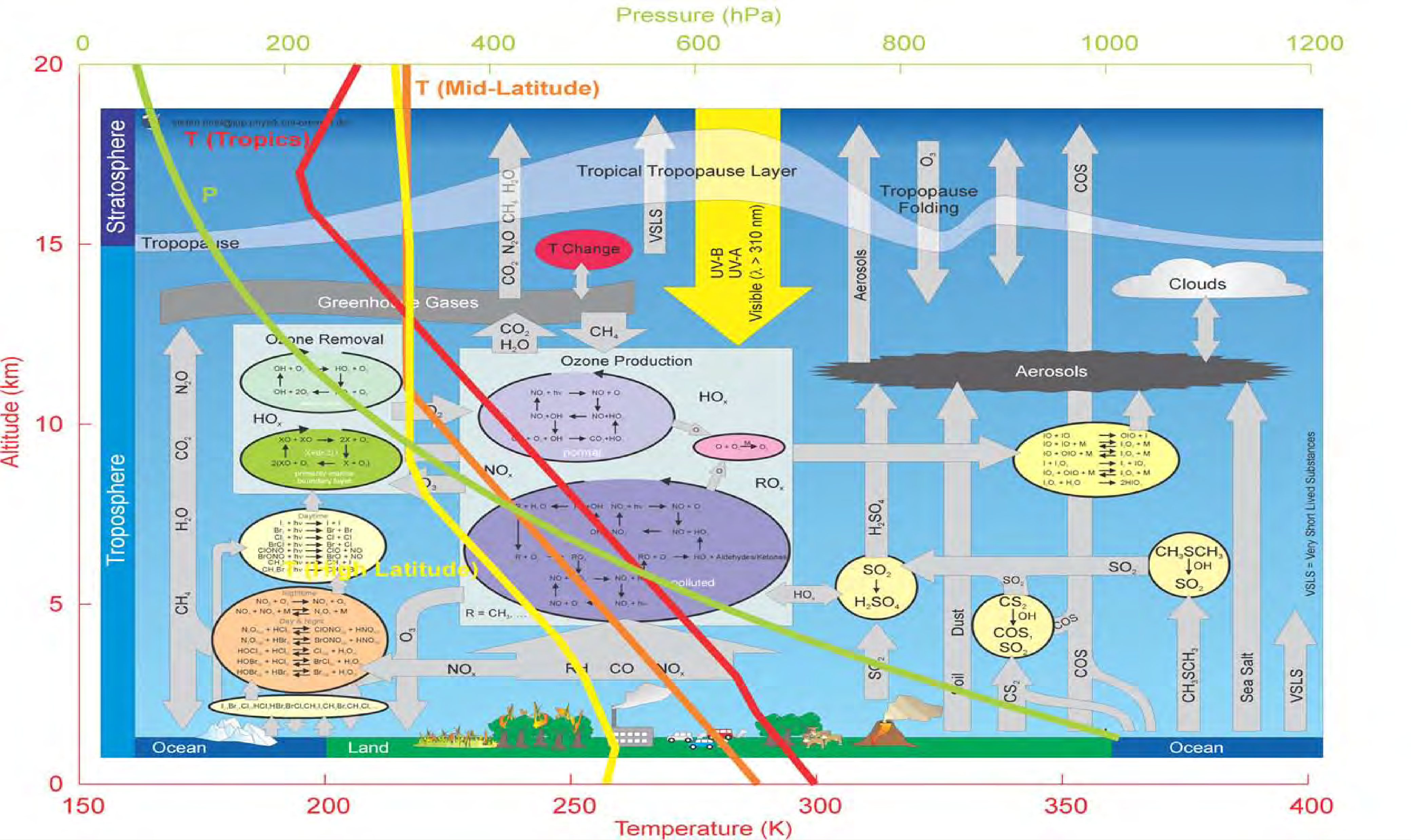
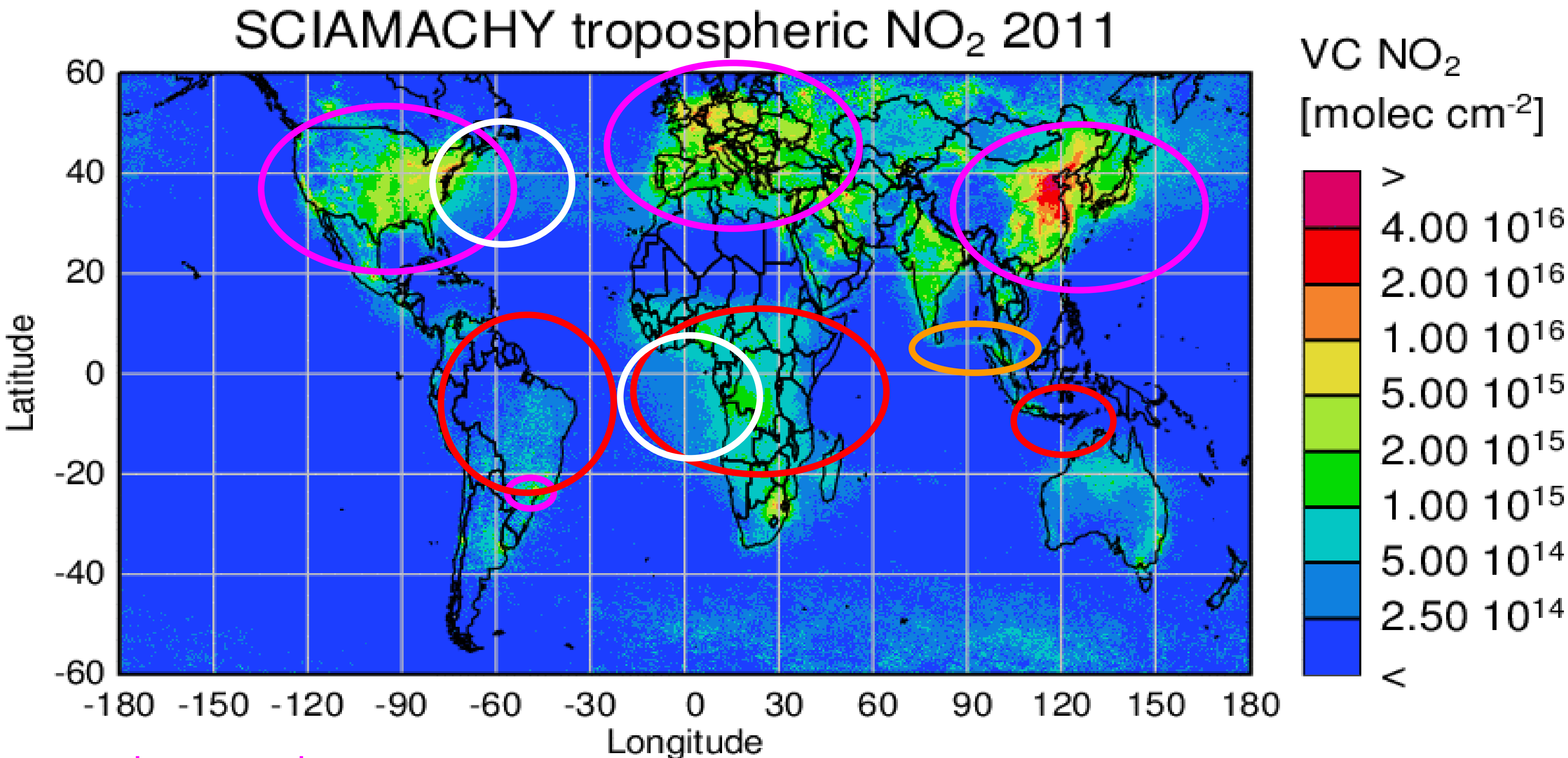


Fig. 5. Linear trends of El surface temperature from 2002–2013. Stippling indicates where the trend exceeds the 95 % confidence threshold. Setup adapted from Kosaka and Xie (2013).

Some Key Processes in Global Tropospheric Chemistry/ Chemical Weather ~ 2014



Tropopsheric NO_2 and Sources?



anthropogenic pollution

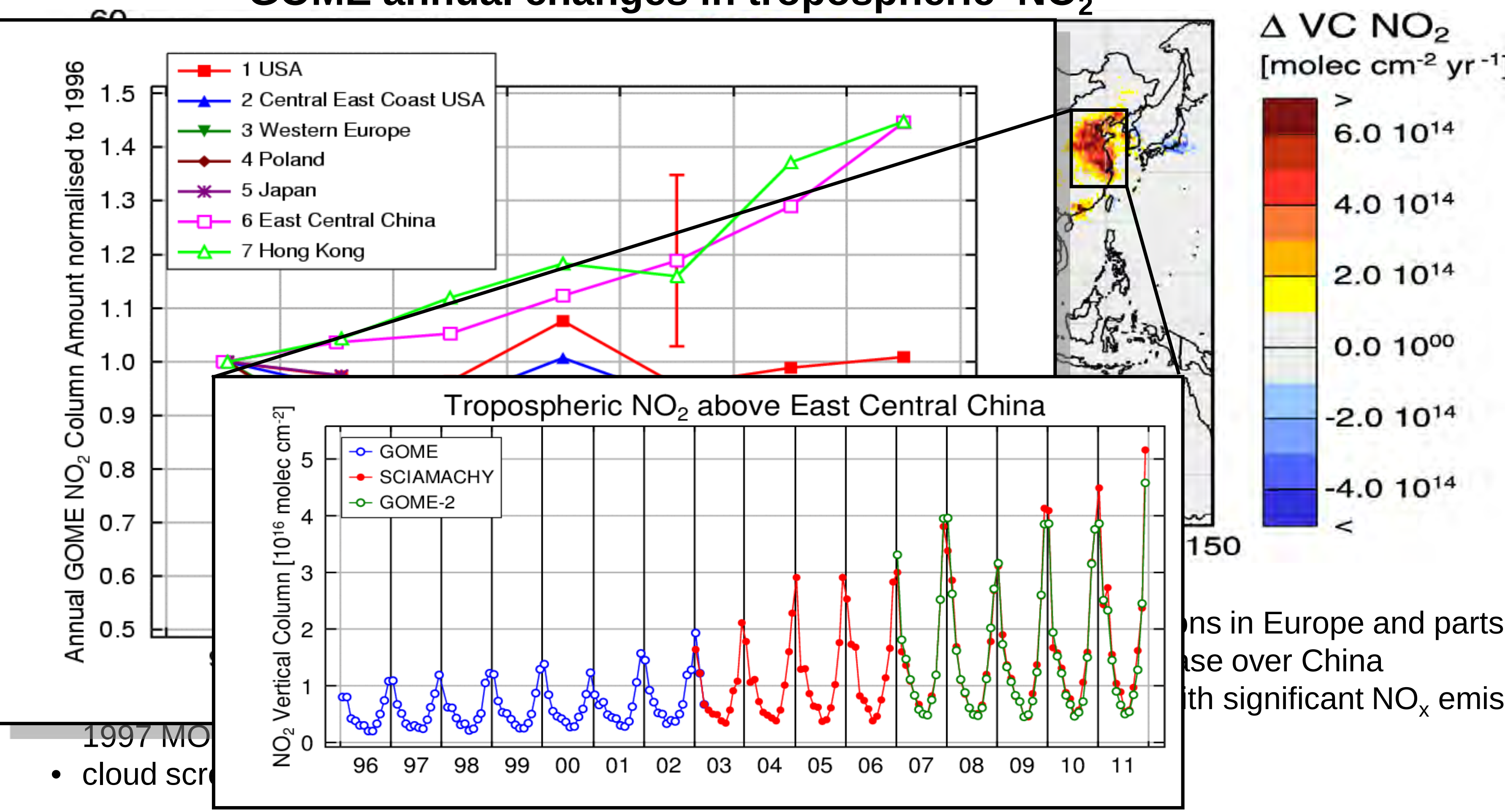
biomass burning

ships

transport

Satellite NO_2 Trends: The Global View 1995-

GOME annual changes in tropospheric NO_2



1997 MO

ns in Europe and parts of the US

se over China

th significant NO_x emission changes

- cloud scr

A. Richter et al., Increase in tropospheric nitrogen dioxide over China observed from space, *Nature*, 437 2005

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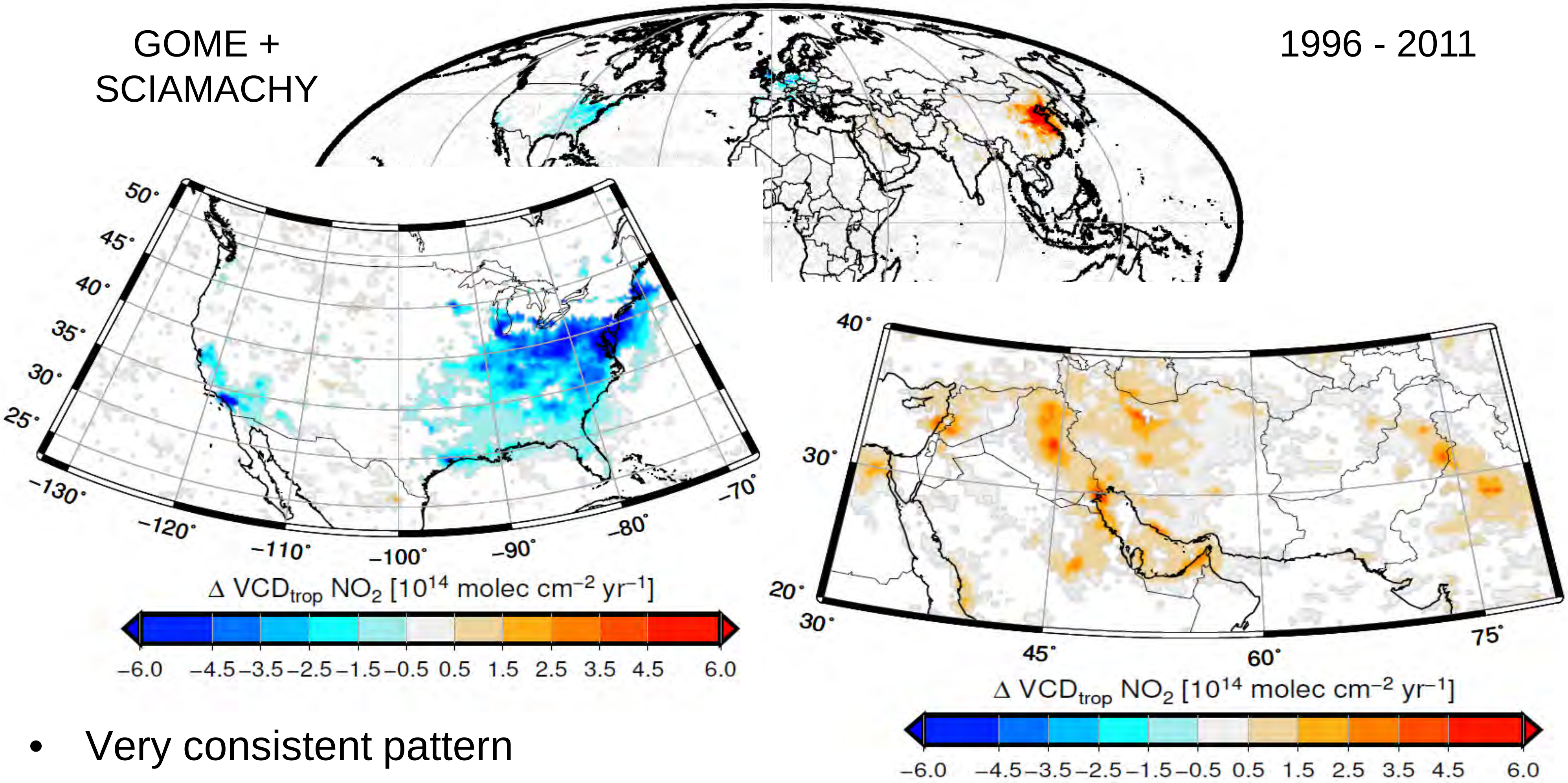
The spatial distribution of satellite NO_2 trends

GOME + SCIAMACHY

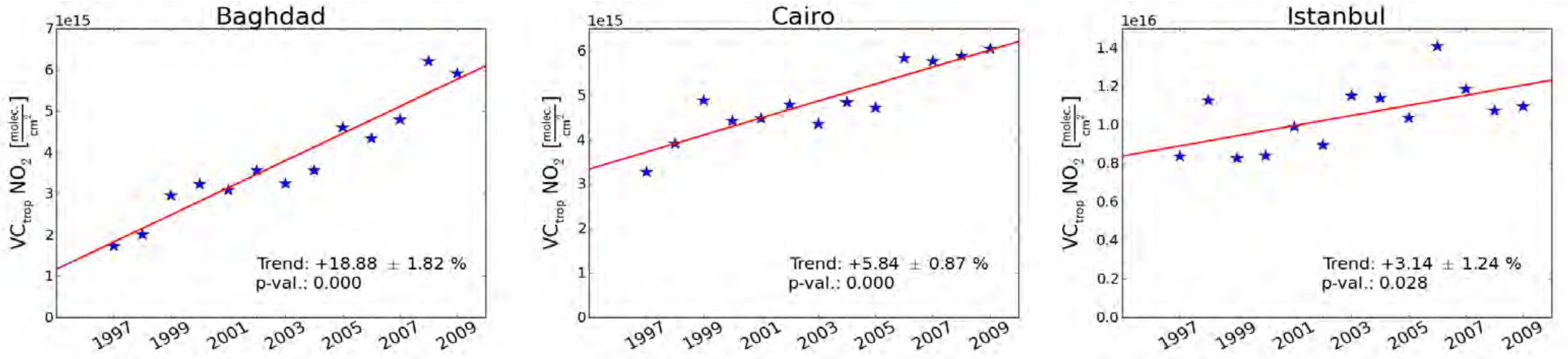
1996 - 2011

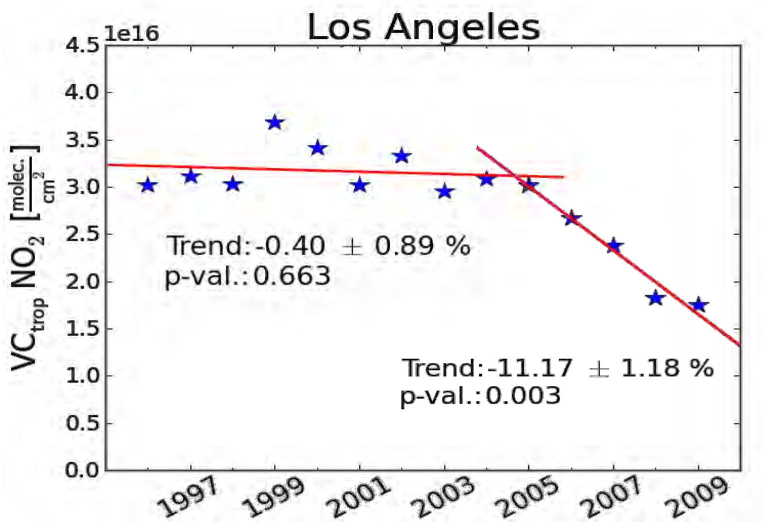


- Very consistent pattern
- Many cities can be identified

Hilboll et al., : Long-term changes of tropospheric NO2 over megacities derived from multiple satellite instruments, *Atmos. Chem. Phys.*, 13, 2013

NO_2 Trends over some Megacities/Urban Aglomerations

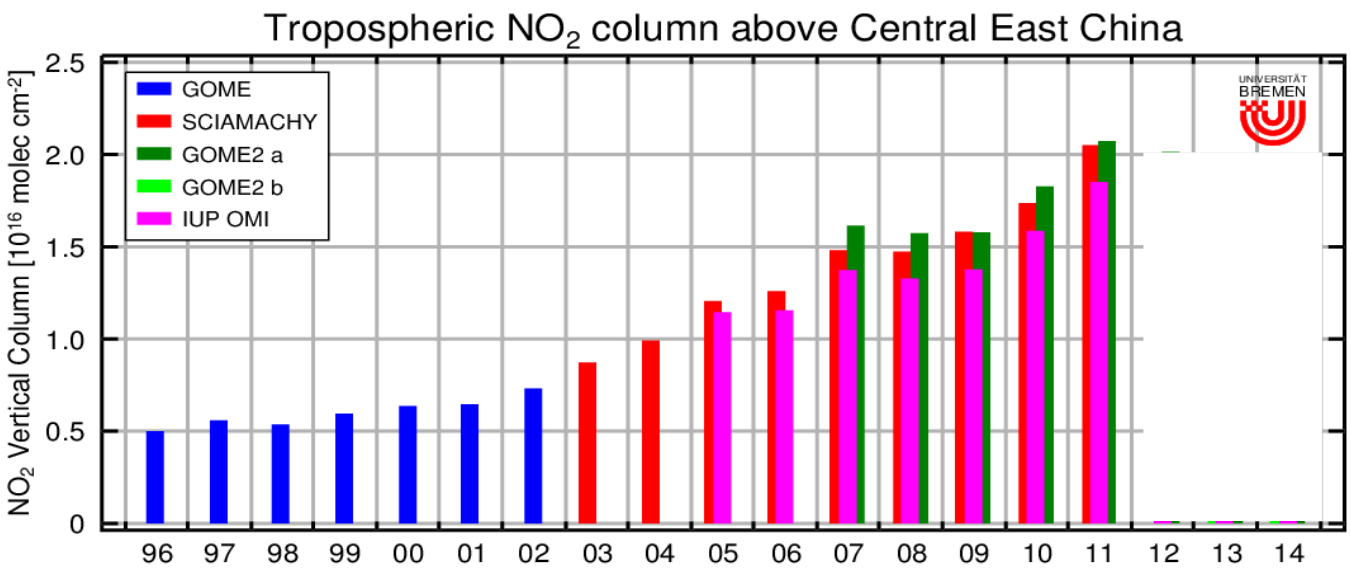




NO_2 levels are changing in cities throughout the world.
Contributing factors are

- Urbanisation
- Population growth
- Increase in standard of living
- changes in fuels used
- Improvements in emission controls

Recent NO_2 Trends above China



- Until 2011, there was continuous increase in NO_2
- After two years of stagnation, 2014 saw a large decrease

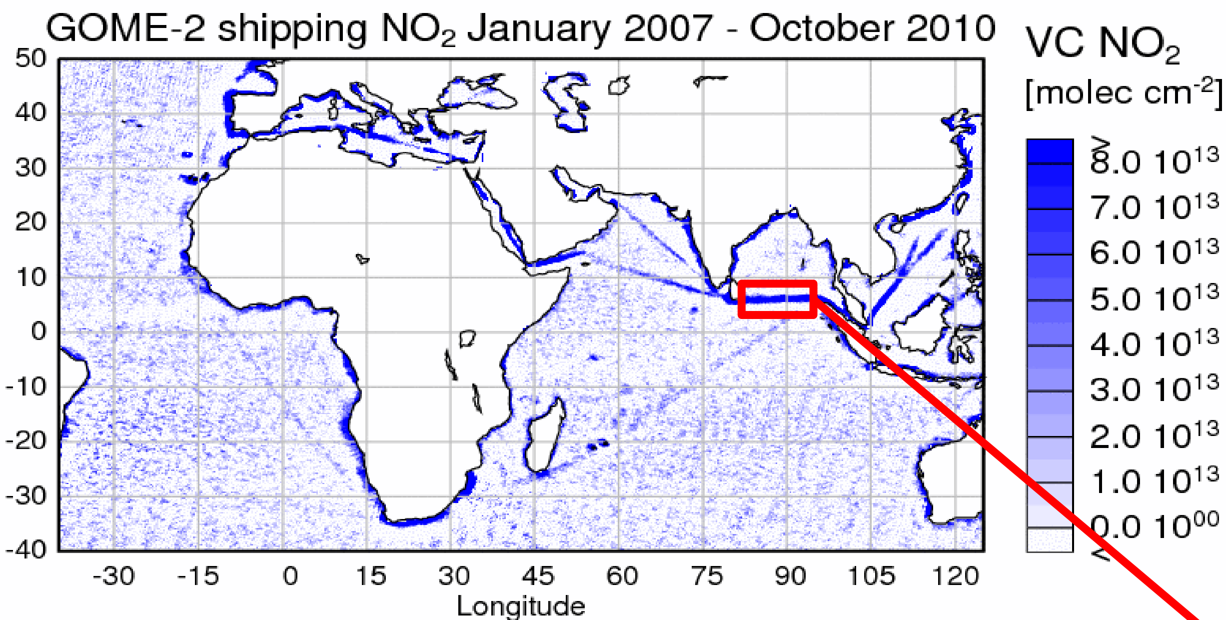
⇒ economic slow down?

⇒ Improved technology?

⇒ Switch in fuels used?

⇒ Other factors?

NOx Emissions from Shipping



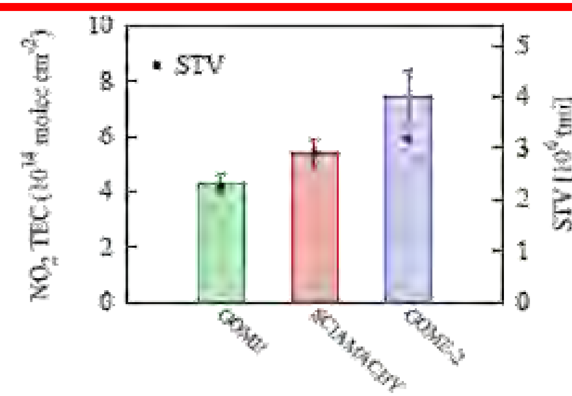
Ship emissions:

- large source of NO_x, SO_x and aerosols
- relevant input into marine boundary layer
- well defined NO_2 patterns in Red Sea and Indian Ocean in GOME-2 data
- consistent with pattern of shipping

With estimate of NO_2 lifetime, NO_x emissions can be estimated => agreement within error bars.

But: error bars mainly from lifetime)

A. Richter et al., Satellite Measurements of NO2 from International Shipping Emissions, *Geophys. Res. Lett.*, 31, L23110, doi:10.1029/2004GL020822, 2004
A. Richter et al..: An improved NO2 retrieval for the GOME-2 satellite instrument, *Atmos. Meas. Tech.*, 4, 1147-1159, doi:10.5194/amt-4-1147-2011, 2011



Franke et al., Atmos. Chem. Phys., 9, 7289-7301, 2009

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Latest Aircraft Instrument IUP UB - AirMap instrument

- Push-broom imager
- 48° field of view
- Swath ~ flight altitude
- Acton 300i spectrometer
- Princeton frame transfer CCD
- Fibre optics
- Only narrow spectral range
- Video camera, GPS
- At typical
  - flight altitude (3000m)
  - aircraft speed (60m/s)
  - Integration time (0.5s)

  $\Rightarrow$ 35 pixels @ **80 x 30 m^2**

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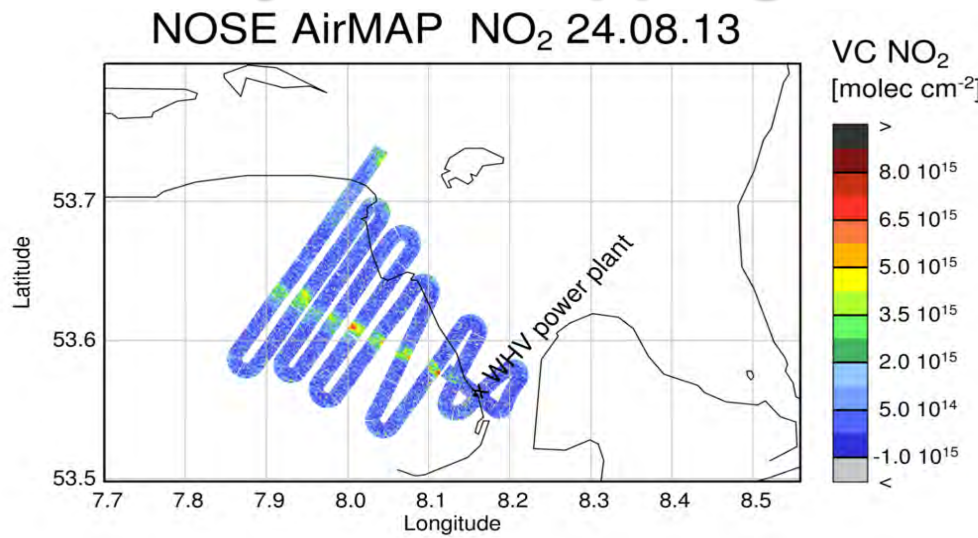
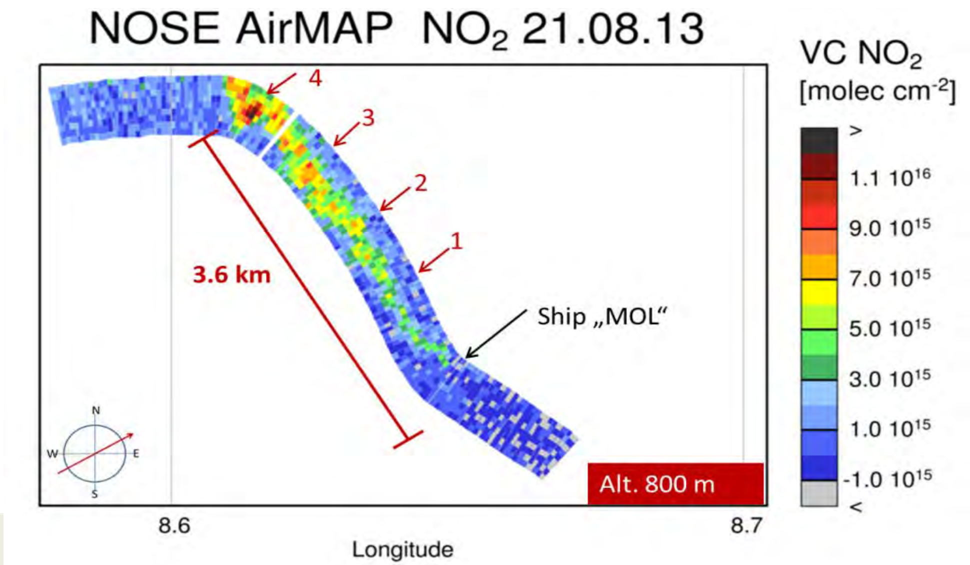
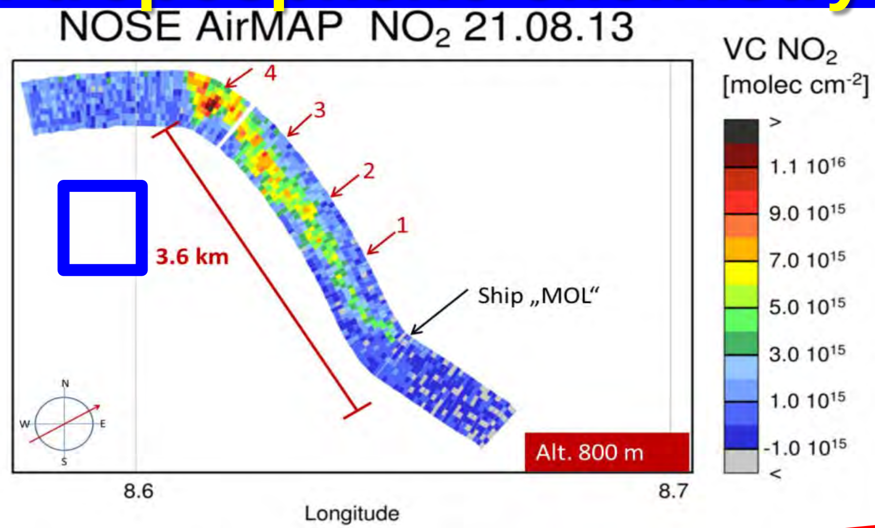
Schönhardt, A., : A wide field-of-view imaging DOAS instrument for continuous trace gas mapping from aircraft, *Atmos. Meas. Tech. Discuss.*, 7, 3591-3644, doi:10.5194/amtd-7-3591-2014, 2014

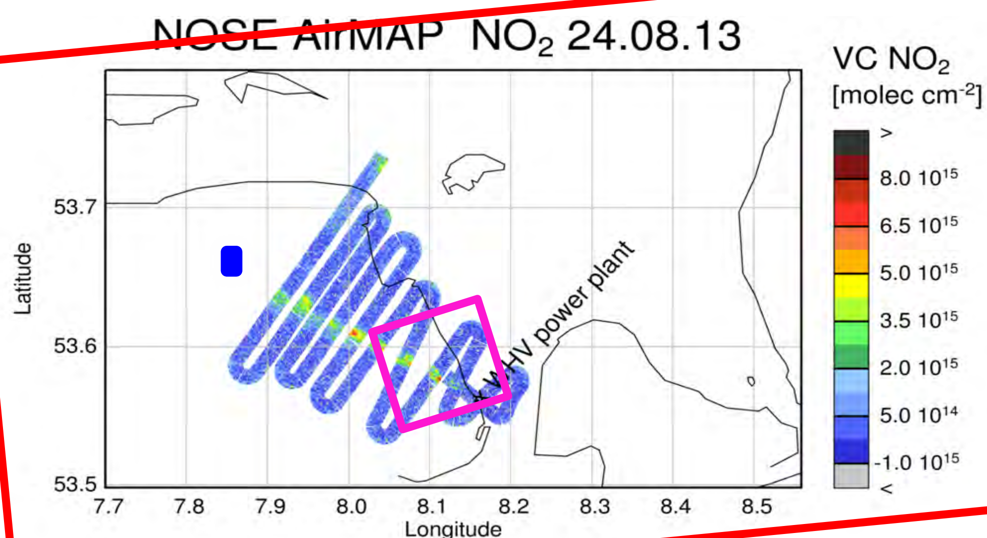
Some Recent AirMap targets – Northern Germany and Shipping





Spatial resolution – the evolution to meet the needs of tropospheric chemistry spatial and temporal scales?





Spatial resolution of satellite instruments is improving:

GOME G3	40 x 320 km^2	1995-2011
GOME HR	40 x 80 km^2	1995-2011
SCIAMACHY	30 x 60 km^2	2002-2012
GOME-2 G1	40 x 80 km^2	2007-2012
GOME-2 HR	40 x 20 km^2	2007-2021+
GOM-2 Tandem	40x40 km2	2012-2021 +
OMI	13 x 24 km^2	2004-
S5P	7.5 x 7.5 km^2	2017-2023+
S5	7 x 7 km2	2017-2034+
S4	8 x 8 km^2	2019-2034
SCIA-ISS/ UVScope	1x1 km^2	2020

New challenges:

- Data have more variability
- 3d effects in radiative transfer become relevant

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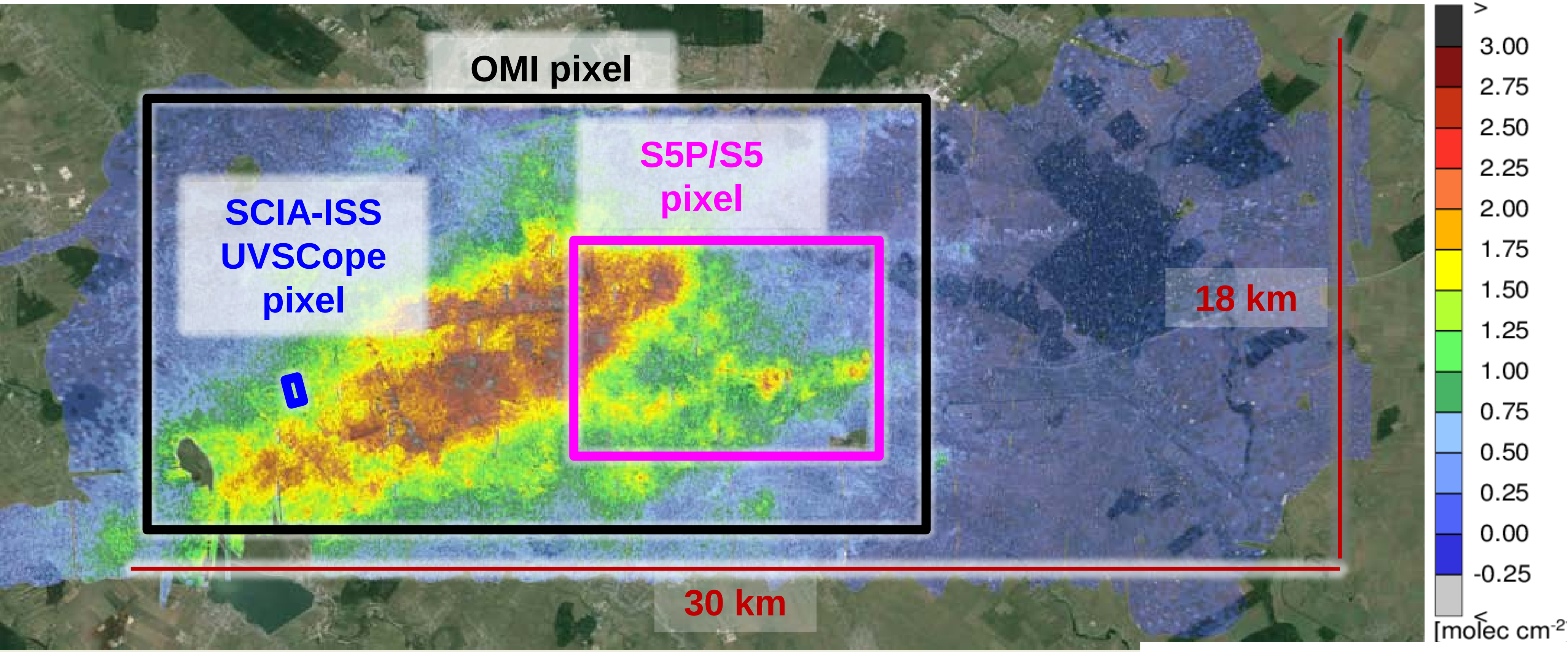
*EXZELLENT.

AirMap: Bucharest VC NO_2 08.09.2014

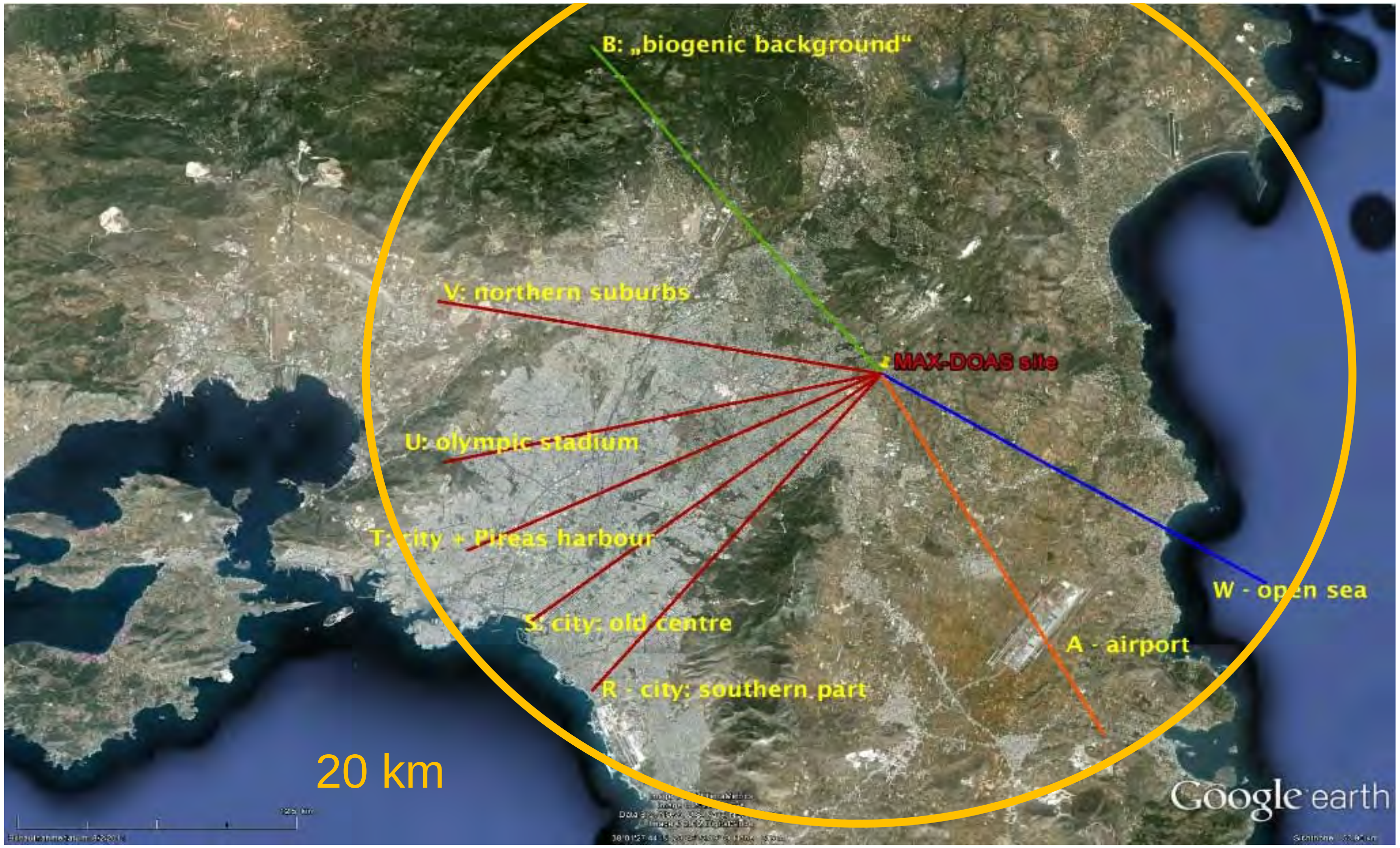
- ESA Campaign
- Composite of the results from the flights on on 14Large values
- Low wind speed (≈ 0 - 1 m/s), alternating directions

NO_2 VC
10^{16} molec cm^{-2}



© A. Meier und A. Schönhardt

MAX-DOAS Measurements in Athens



- 3.2 million inhabitants
- Emissions from industry and transportation
- Intense photochemistry
- Affected by fires and Sahara dust events

- Oct 2012 – now
- 330 – 500 nm
- 8 viewing azimuths
  - Ocean
  - Airport
  - City x 5
  - Background
- -1° .. 30° elevation + zenith
- 15 minutes cycle
- Closest zenith reference

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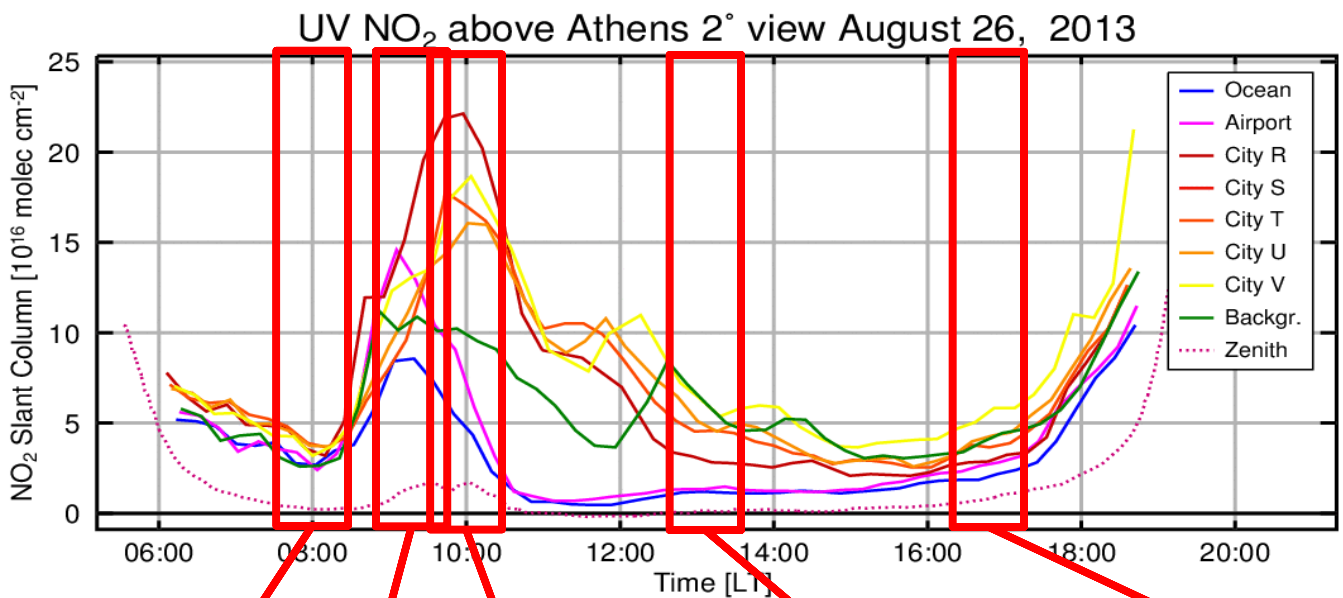
iup

Spatial Gradients City Pollution



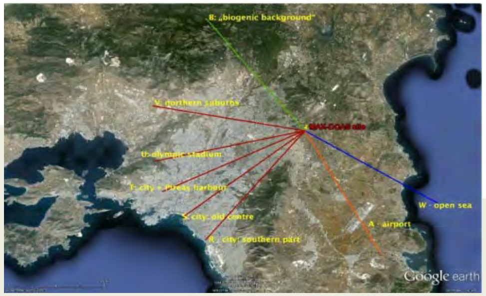
All directions lowest values

Maximum clean regions

Maximum city

Biogenic Background direction largest

Residential area direction highest



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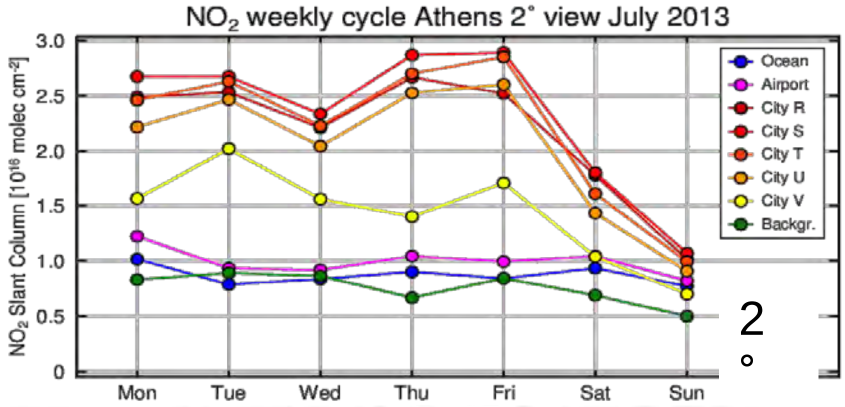
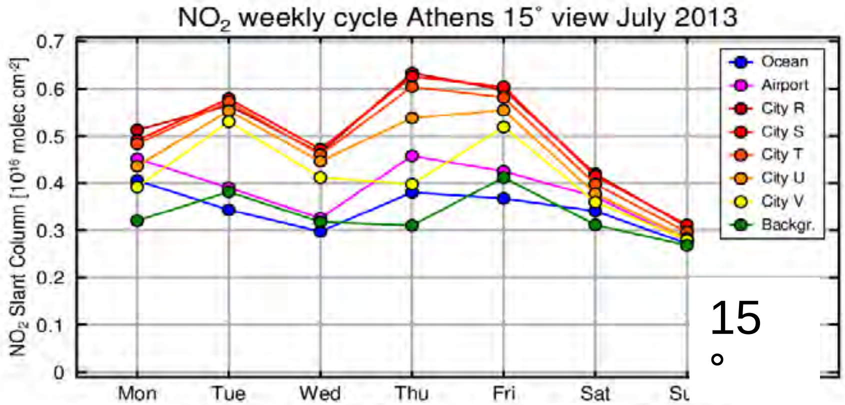
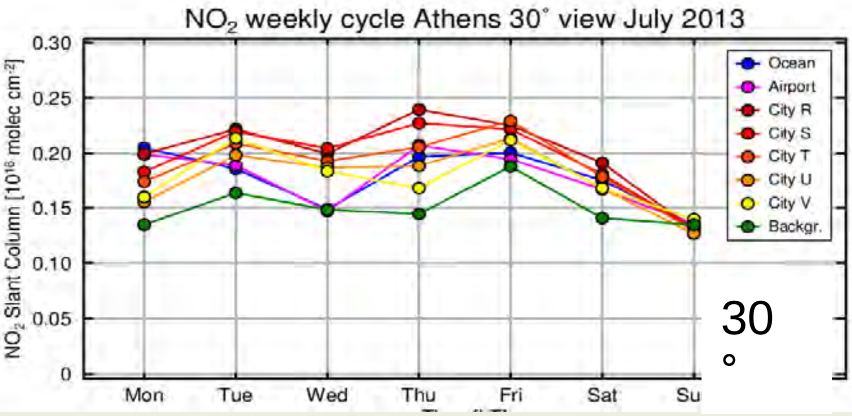
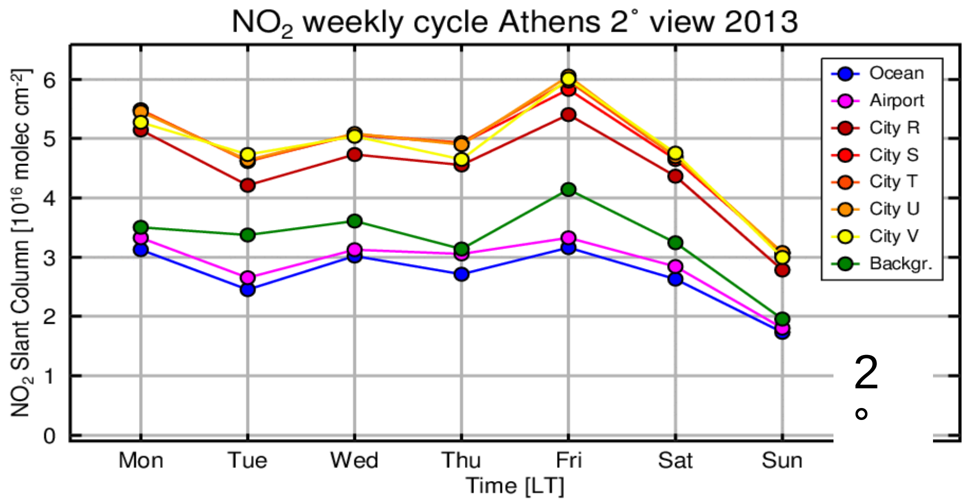
Weekly Cycle in NO2 for Athens



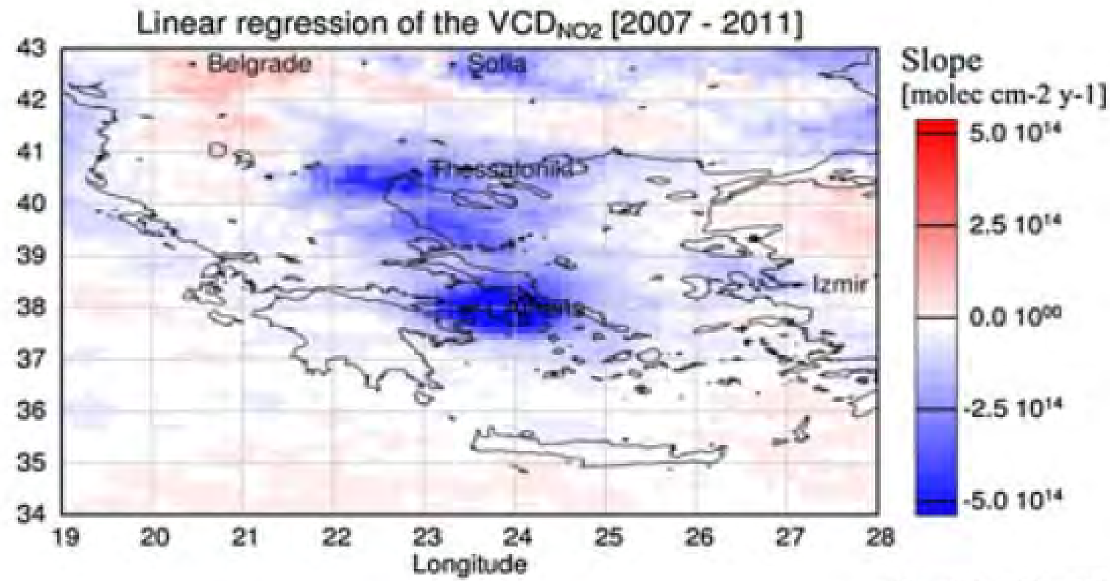




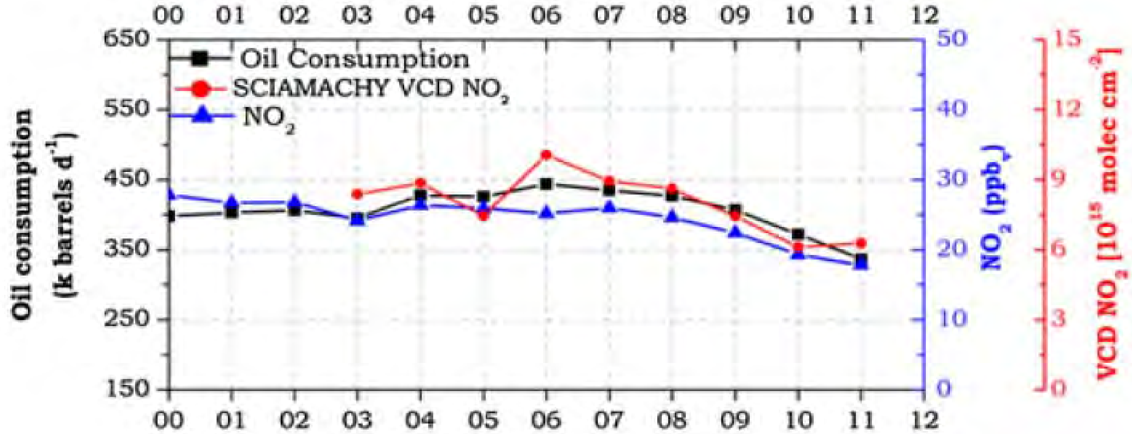


- Very clear weekly cycle
- Most pronounced over city directions
- Most pronounced in lowest elevation angles
- Best seen during summer break

NO_2 Trends above Europe

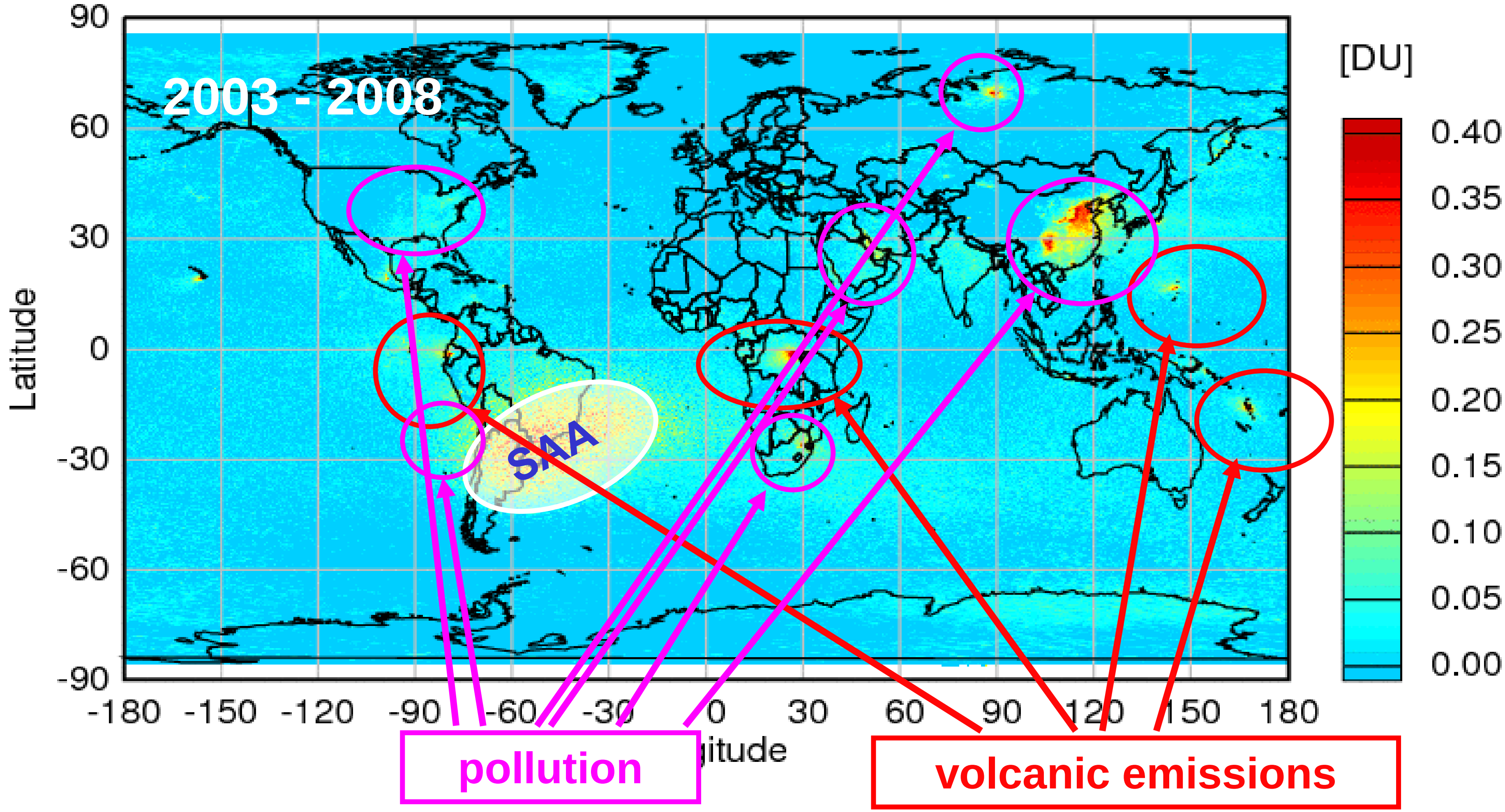


- Decreasing NO_2 trend over Greek cities from 2007 – 2011
- Both in satellite and surface data
- Link to oil consumption
- Effect of economic crisis

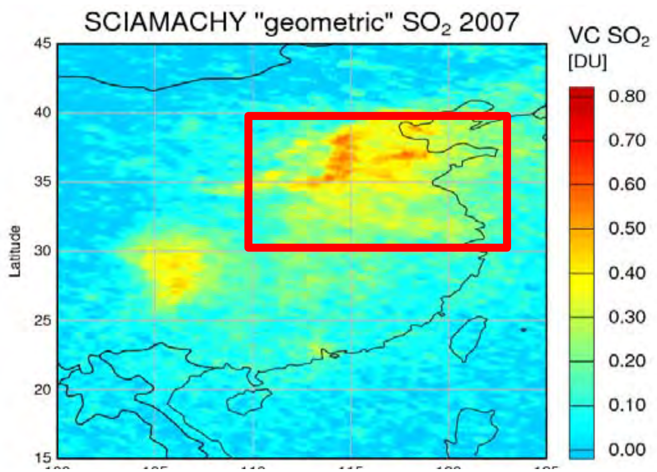


Vrekoussis, M. et al., Economic crisis detected from space: Air quality observations over Athens/Greece, Geophys. Res. L ett., 40, doi:10.1002/grl.50118., 2013

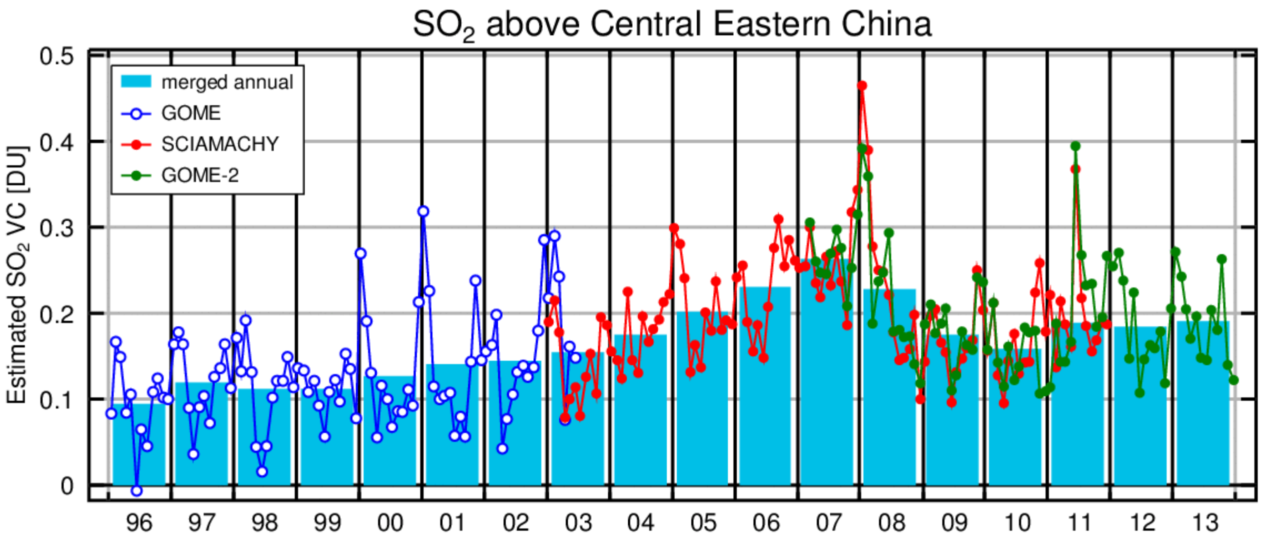
SCIAMACHY SO_2: The global Picture



SO_2 columns above China

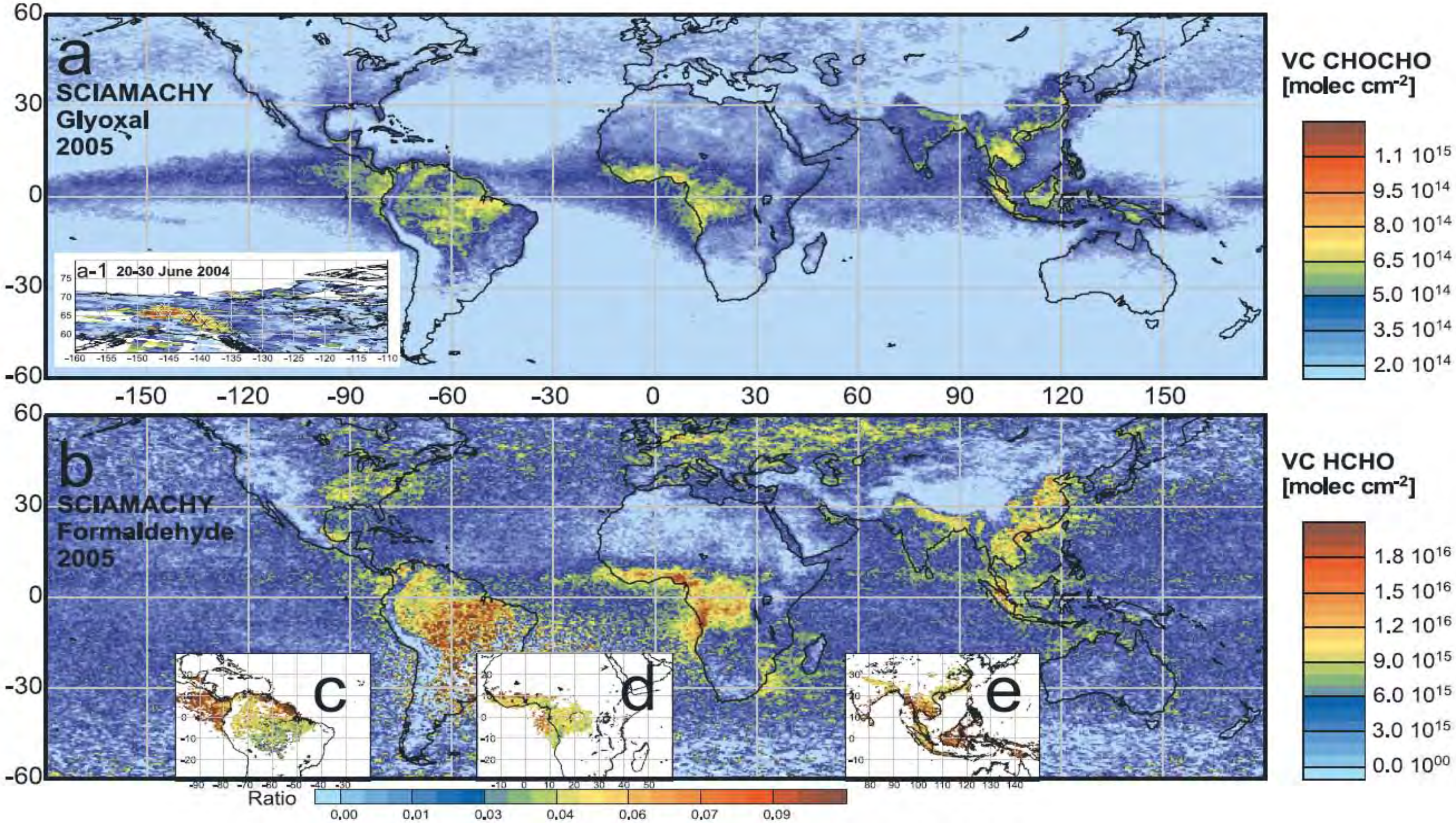


- SO_2 increase in similar regions as NO_2 increase
- Main reason is increase in power generation using coal



- Legislation made flue gas desulphurisation mandatory after 2006
- Marked decrease in SO_2 but small upward trend since 2009 (industrial sources)

NMVOCs: HCHO and glyoxal



Wittrock, F.,et al., (2006), Simultaneous global observations of glyoxal and formaldehyde from space, Geophys. Res. Lett., 33, L16804, doi:10.1029/2006GL026310.

Sources:

- Biogenic
- Fires
- Fossil fuel
- VOC oxidation

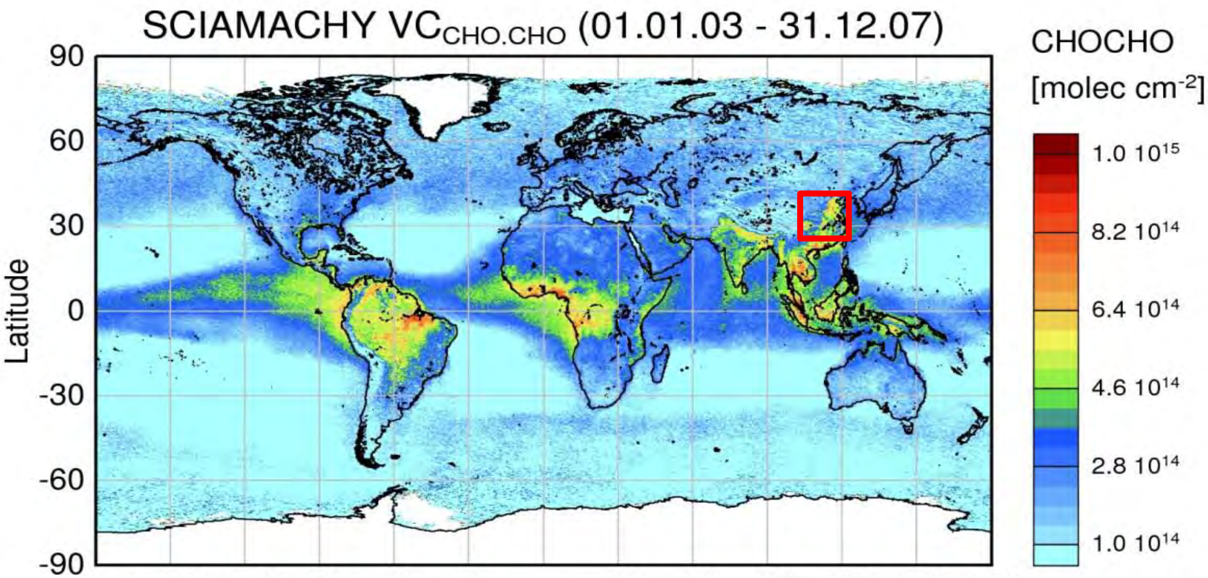
Sinks:

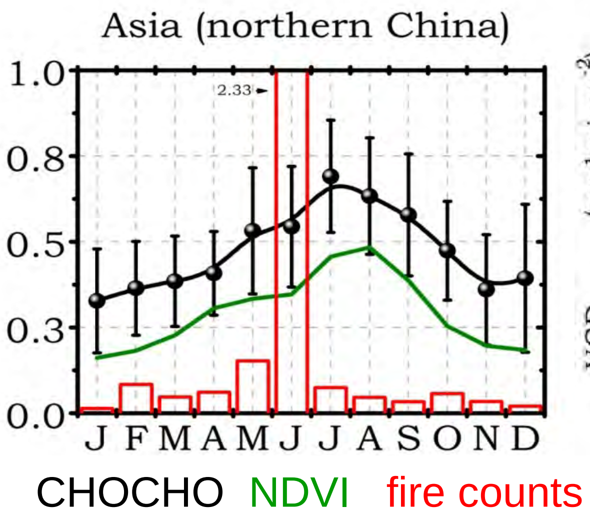
- Photolysis
- OH

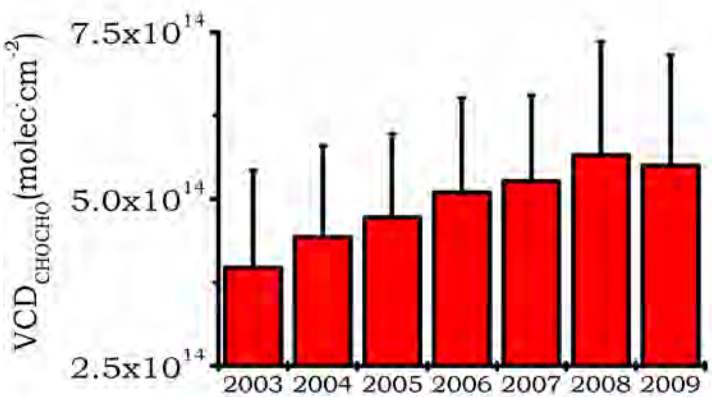
Relevance:

- O_3 production
- SOA

Glyoxal, CHO.CHO columns



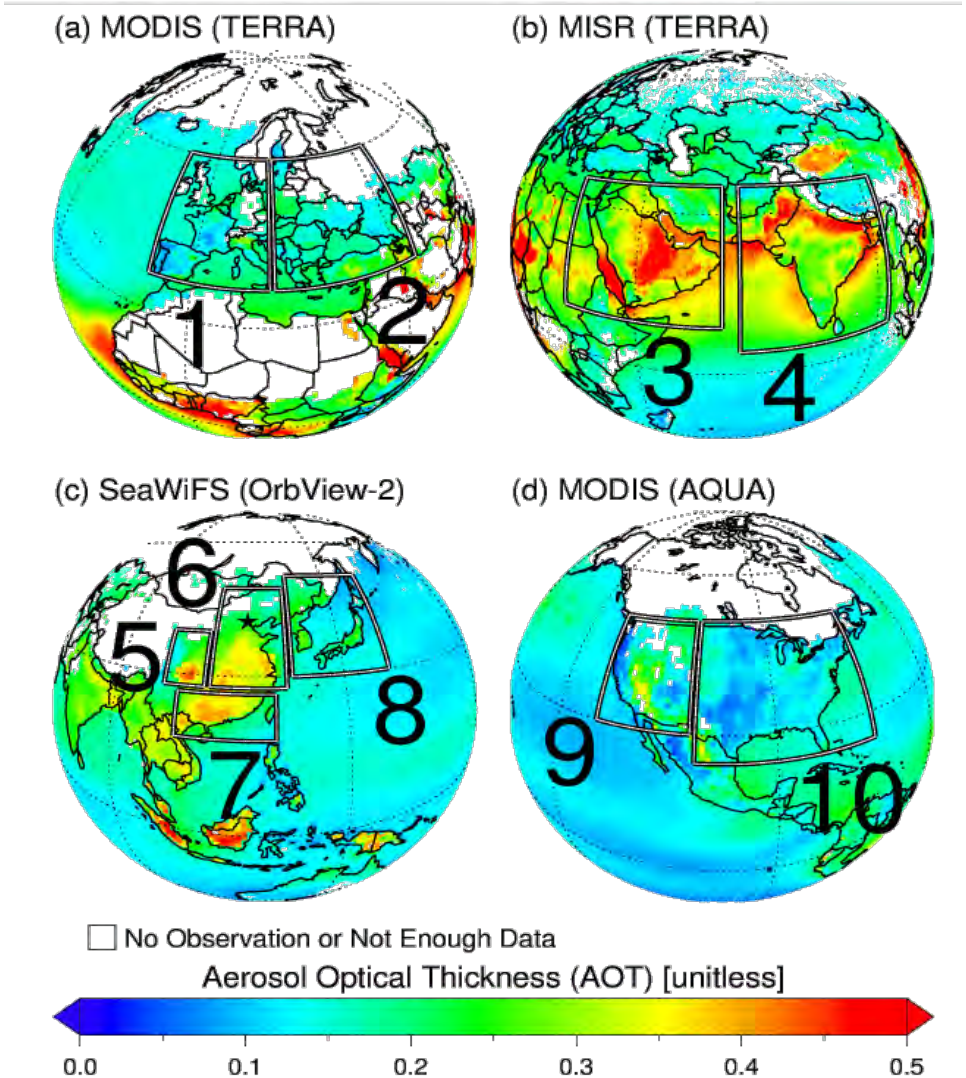




- Glyoxal is a VOC with little primary emission
- Main sources are oxidation of biogenic and anthropogenic VOCs, biomass burning
- Seasonality of glyoxal indicates mainly biogenic precursors
- Consistent upward trend over SCIAMACHY time series
- Additional anthropogenic emissions?
- Land use changes?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

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

Aerosols in the troposphere



Sources

- Sea-salt
- Dust / sand
- Combustion / fires
- Secondary aerosols (SO_2, HNO_3, SOA, …)

Sinks

- Wet & dry deposition

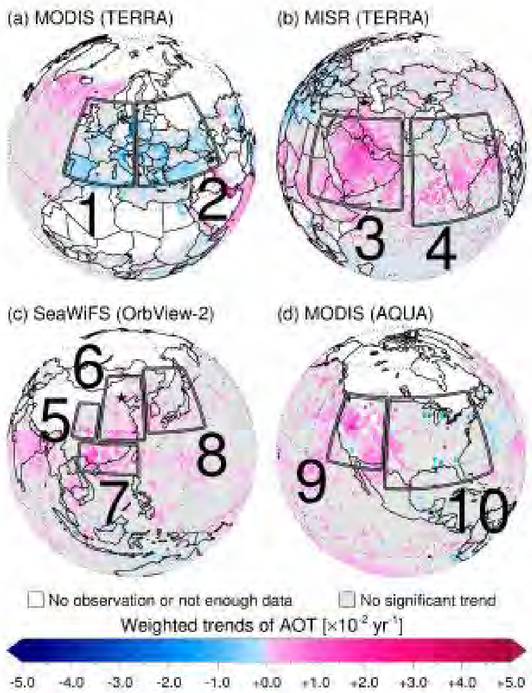
Relevance

- Health
- Scattering

Yoon, J., Changes in atmospheric aerosol loading retrieved from space based measurements during the past decade, Atmos. Chem. Phys. Discuss., 13, 26001-26041, doi:10.5194/acpd-13-26001-2013, 2013.

Changes in aerosol AOT 2003-2008

2003 - 2008



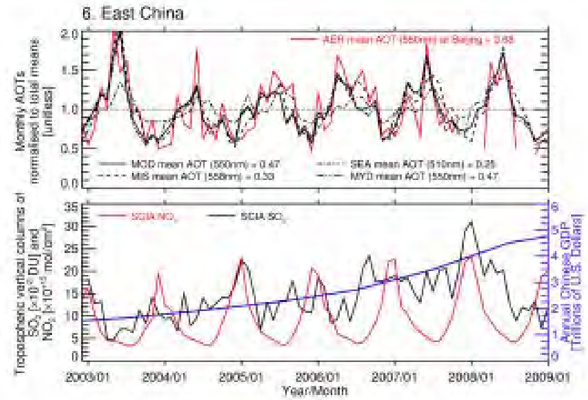
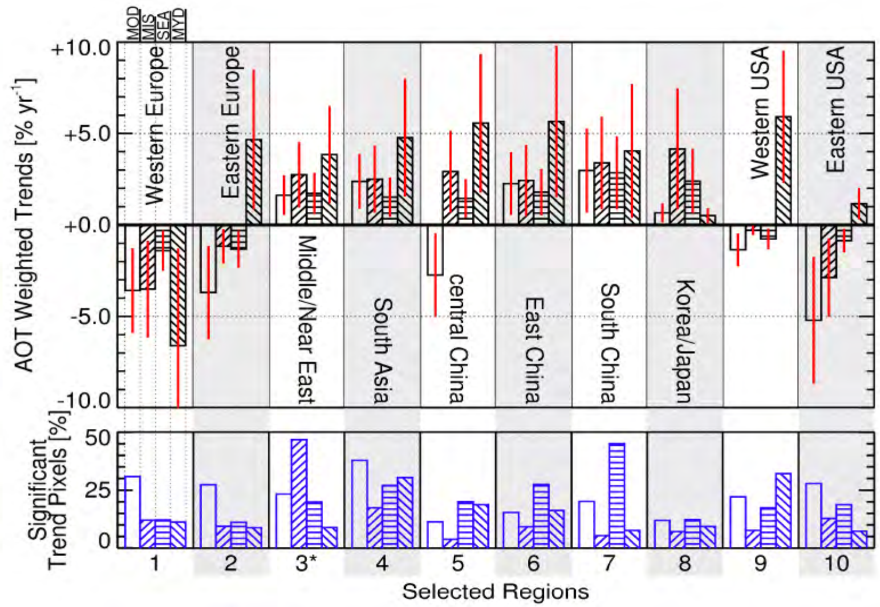


Figure 13. Time series of atmospheric AOTs normalized to their average mean values from the MODIS-Terra (MOD), MISR-Terra (MIS), SeaWiFS-OrbView-2 (SEA), MODIS-Aqua (MYD), and AERONET (AER) data sets; tropospheric nitrogen dioxide and sulfur dioxide columns from SCIAMACHY (SCIA) over eastern China (region 6); and Chinese GDP from 2003 to 2008.



- Downward trend in Western Europe and Eastern US
- Upward trend in Asia
- Some differences between instruments

Yoon, J., Changes in atmospheric aerosol loading retrieved from space based measurements during the past decade, Atmos. Chem. Phys. Discuss., 13, 26001-26041, doi:10.5194/acpd-13-26001-2013, 2013.

Changes in CTH using observations of O_2 A band and SACURA GOME- SCIAMACHY GOME-2

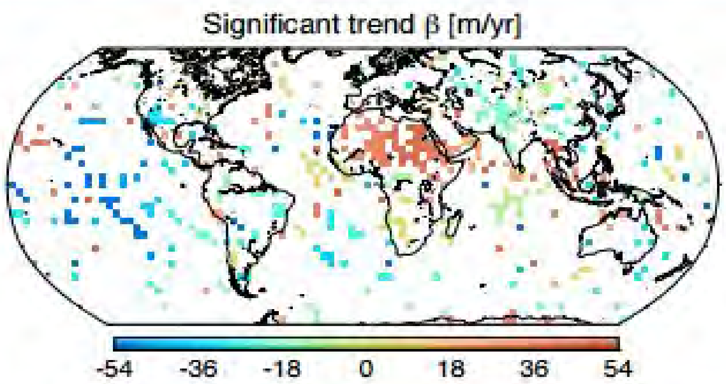


Figure 13. Global trend β in CTH anomaly, statistically significant at 95 % confidence level. Data are gridded onto a mesh of 2°-sided cells.

Table 4. Overview of zonal trends in CTH [m yr^{-1}], ENSO excluded, masking any data within the box 170–120° W, 5° N–5° S. Bootstrap resamples $n = 10^3$. The zonal values are not weighted by the respective land and water abundances.

	Belt		Land + water	Land	Water
With ENSO	Tropics	5° N–5° S	−4.34 ± 5.65	−1.56 ± 4.02	−5.15 ± 8.21
	Tropics	20° N-20° S	−2.16 ± 2.97	+1.83 ± 4.40	−3.39 ± 5.32
	Mid-latitude	30–60° N	−2.17 ± 1.52	−2.85 ± 4.23	−1.52 ± 3.68
	Mid-latitude	30–60° S	−2.71 ± 2.59	−2.70 ± 9.25	−2.71 ± 2.47
Without ENSO	Tropics	5° N–5° S	−1.80 ± 6.00	−1.43 ± 5.05	−1.99 ± 8.52
	Tropics	20° N–20° S	+0.53 ± 3.53	+5.93 ± 5.33	−1.74 ± 4.36
	Mid-latitude	30–60° N	−2.11 ± 3.09	−2.72 ± 4.60	−1.53 ± 3.70
	Mid-latitude	30–60° S	−2.78 ± 2.54	−3.24 ± 8.77	−2.75 ± 2.35

Natural variability and instrument or algorithm error

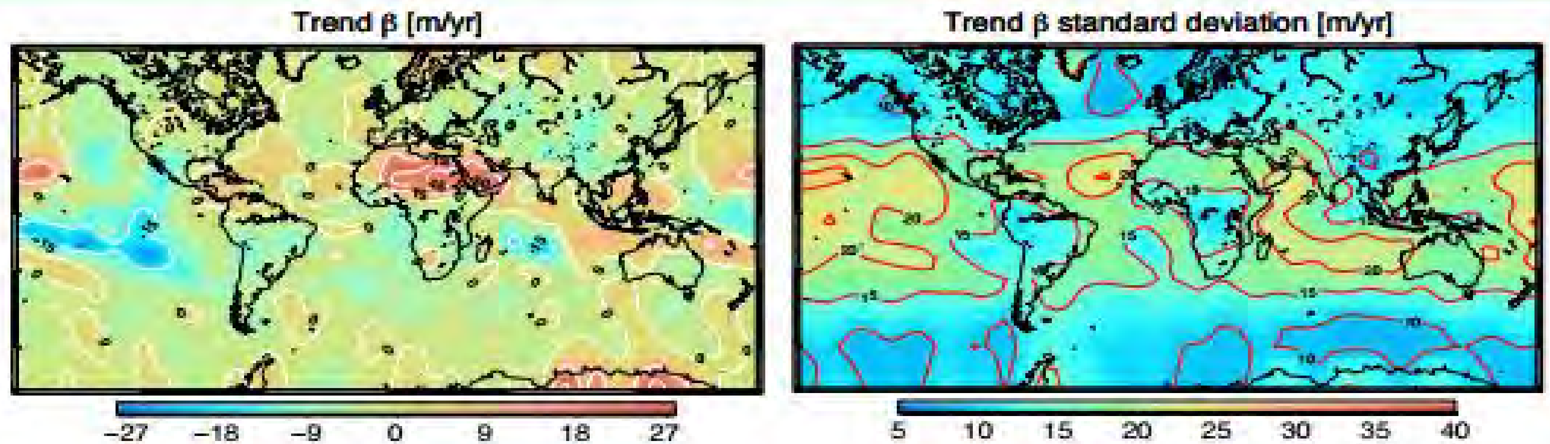
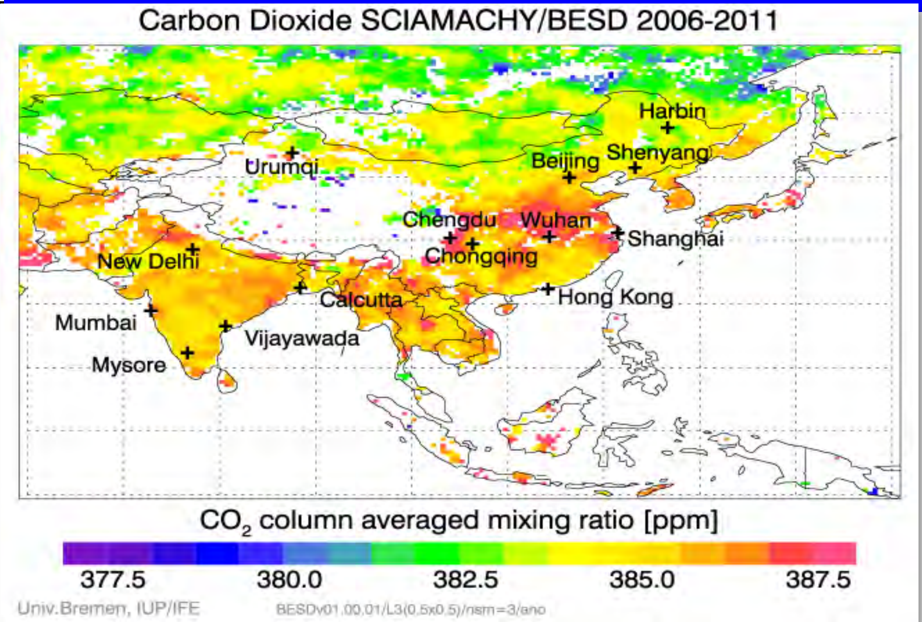
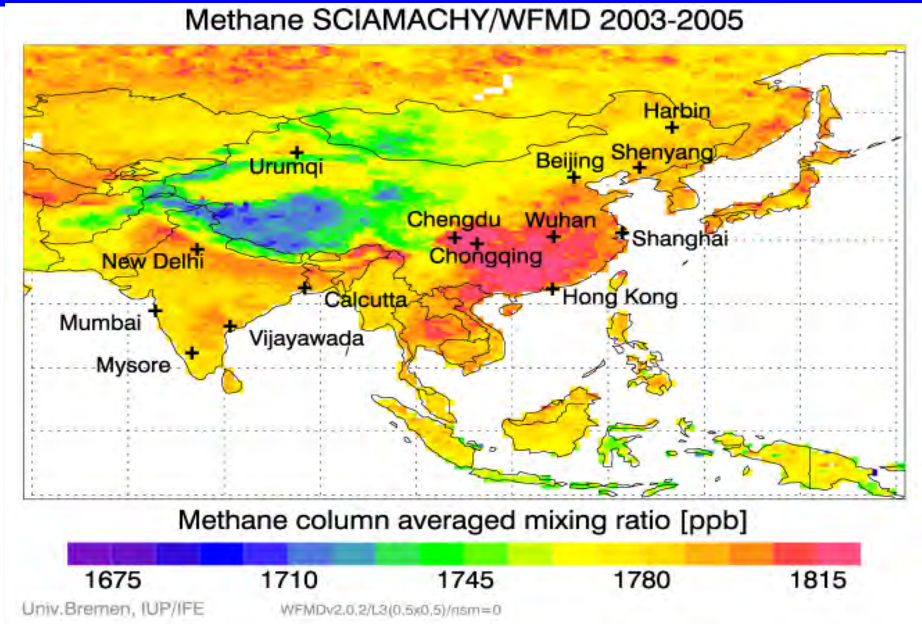


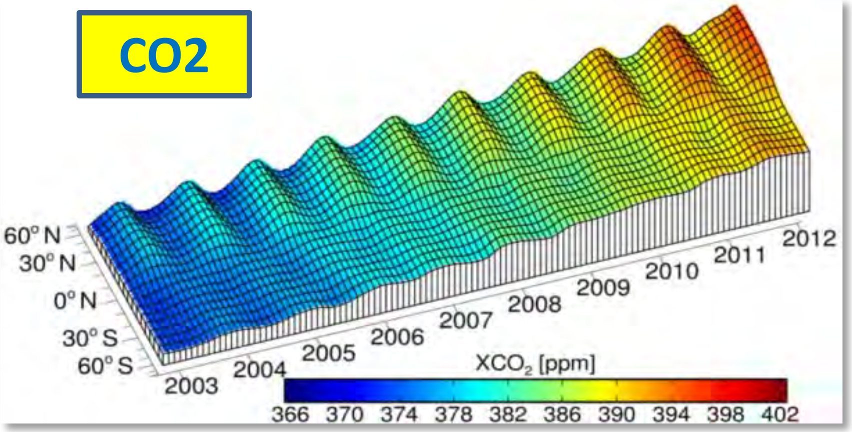
Figure 12. Global map of linear trend β in CTH (left) and standard deviation σ_β (right).

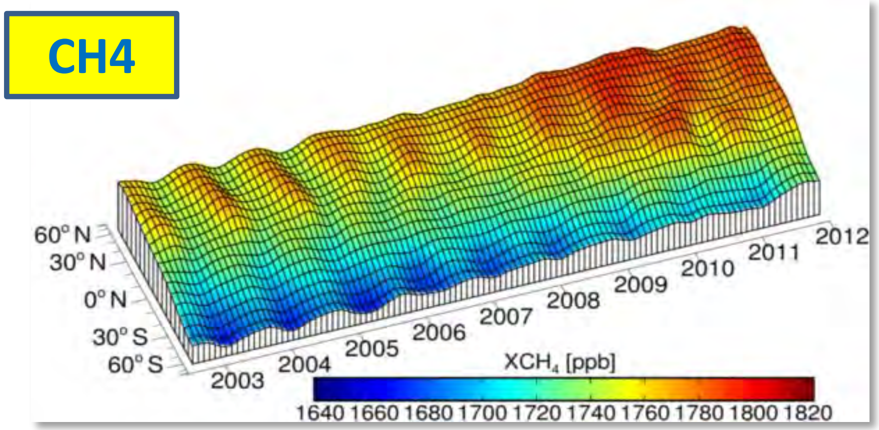
Lelli et al Atmos. Chem. Phys., 14, 5679–5692, 2014 www.atmos-chem phys.net/14/5679/2014/ doi:10.5194/acp-14-5679-2014

SCIAMACHY on ENVISAT: CO_2 & CH_4 from space









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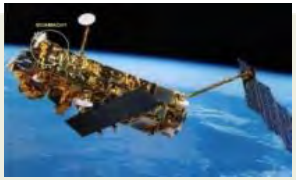
SCIAMACHY

iup



*EXZELLENT.

SCIAMACHY XCO_2: Anthropogenic source regions

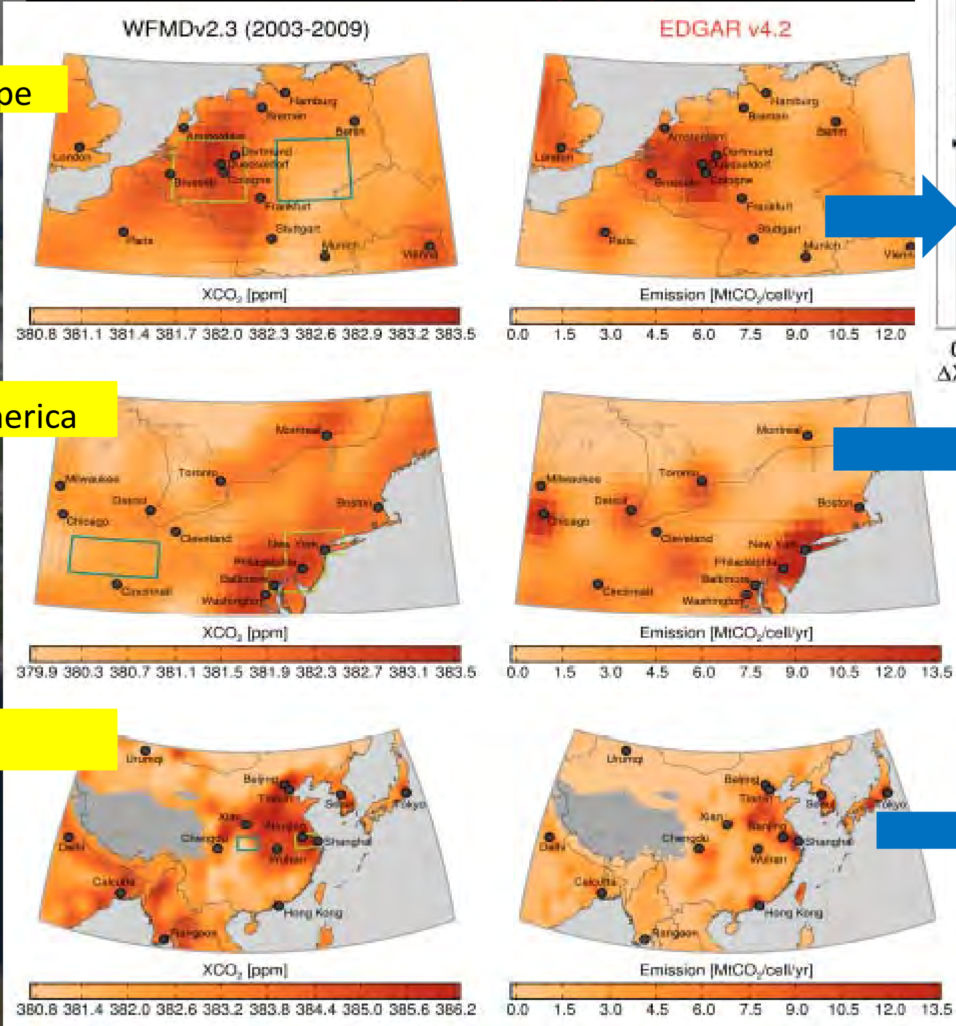
Schneising et al., ACP, 2013

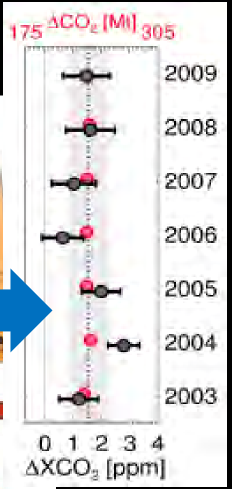
SCIAMACHY XCO2 EDGAR CO2 emissions

NW Europe

East N. America

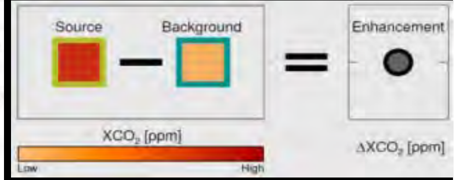
China

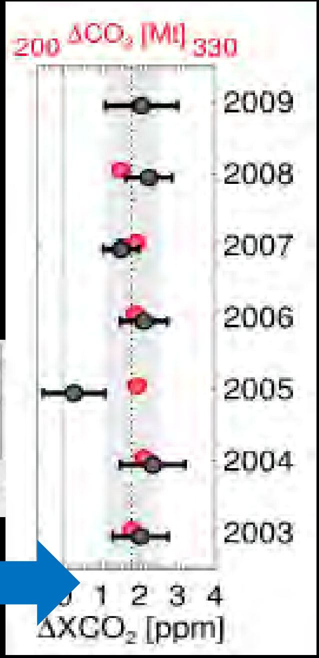


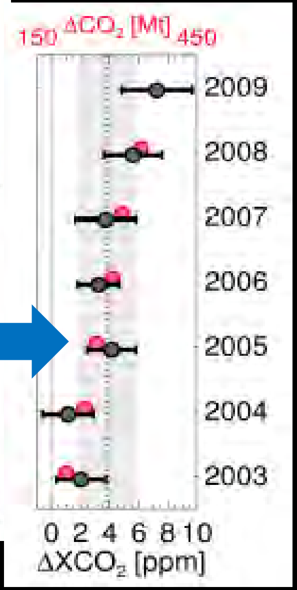


SCIAMACHY
EDGAR

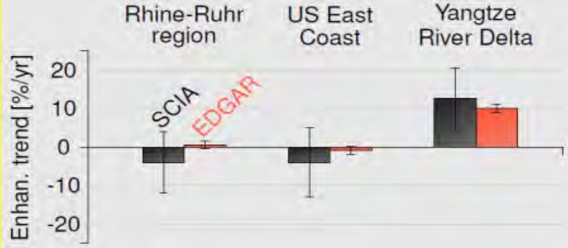
Regional enhancement = Source - Background







Trend [%CO2/yr]



EDGAR are emissions consistent with SCIAMACHY

Highlights GHG

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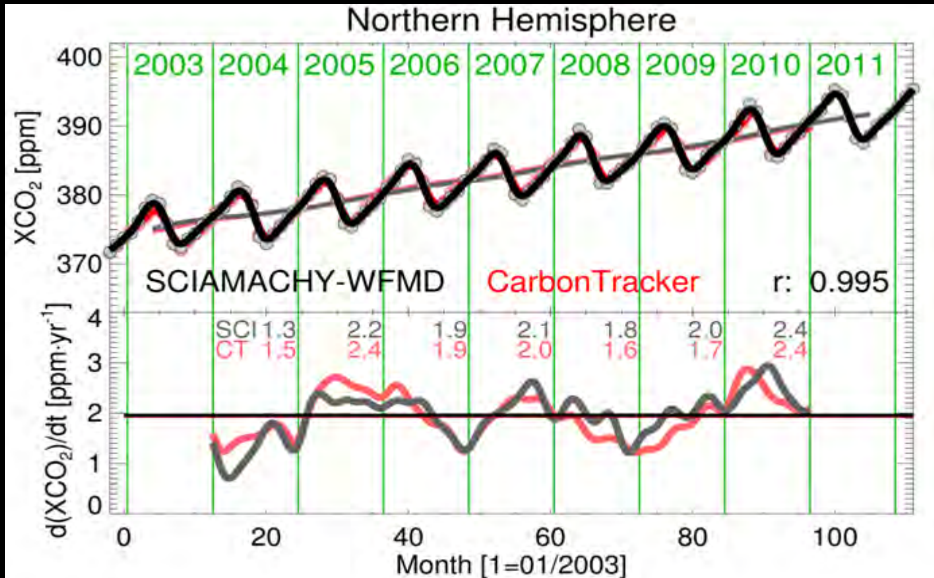
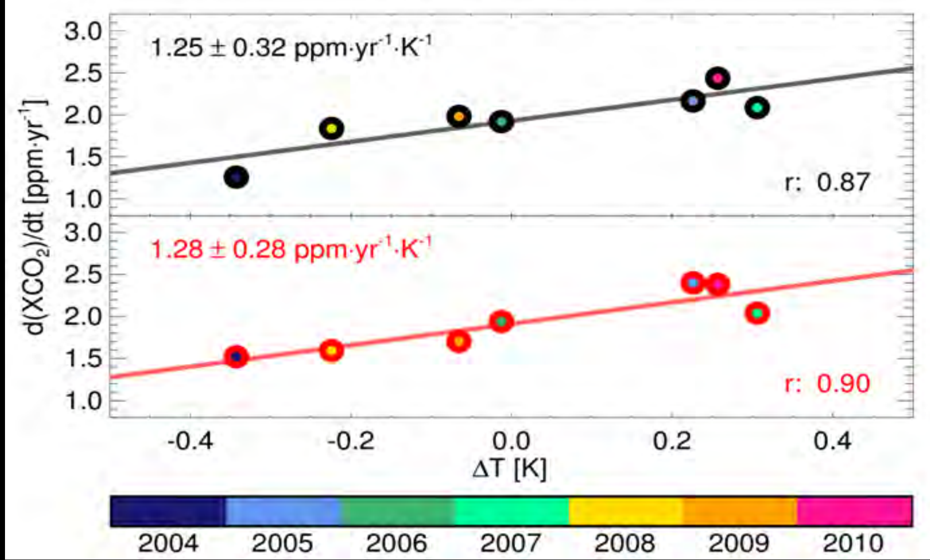
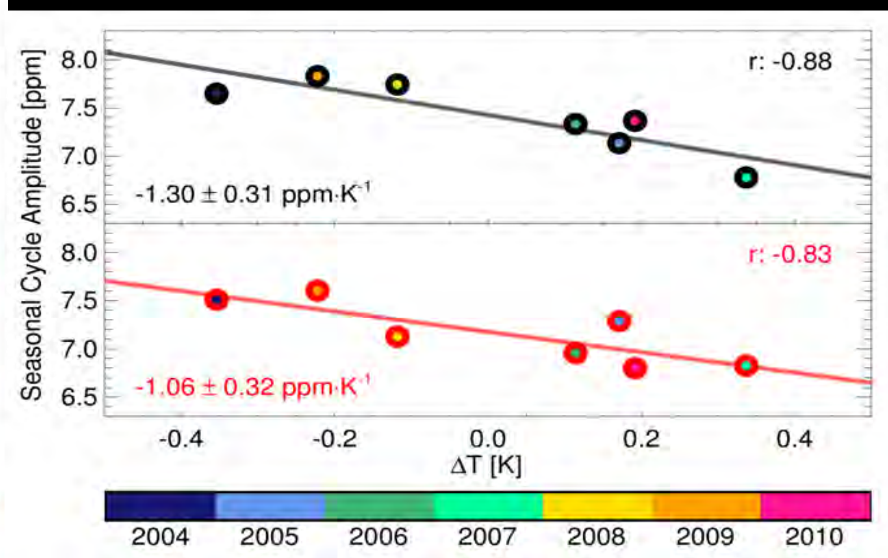
Temperature response of terrestrial carbon sink

(Schneising et al., 2014, ACP)



- Years with **higher surface temperatures** during the growing season are associated with **larger CO_2 growth rates** and **smaller seasonal cycle amplitudes** (reduced net carbon uptake by vegetation)
- **Temperature sensitivity:** 2.7 ± 0.7 GtC/yr/K
- **Positive carbon-climate feedback** unless the biosphere adapts its carbon storage under warming conditions in the longer term





Highlights GHG

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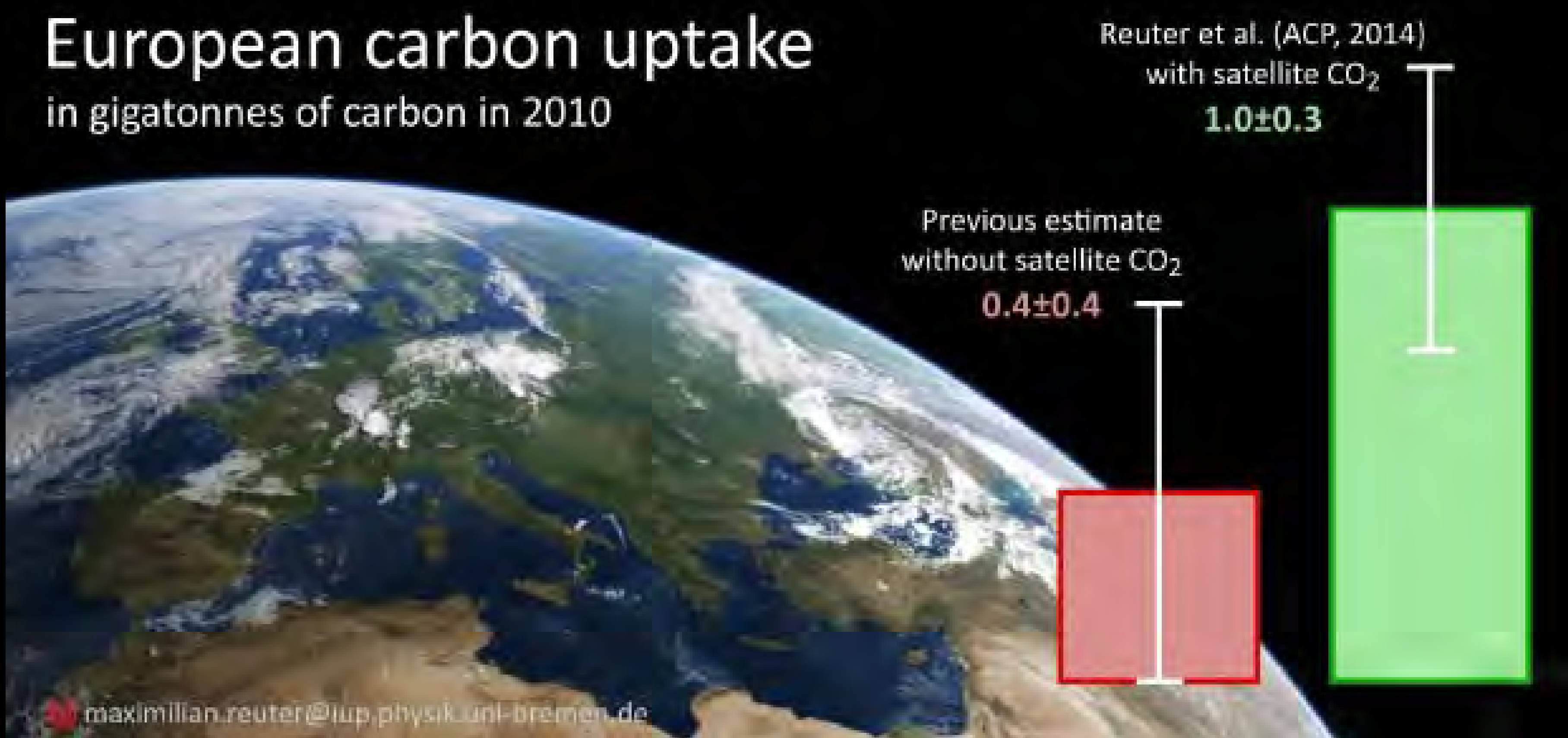
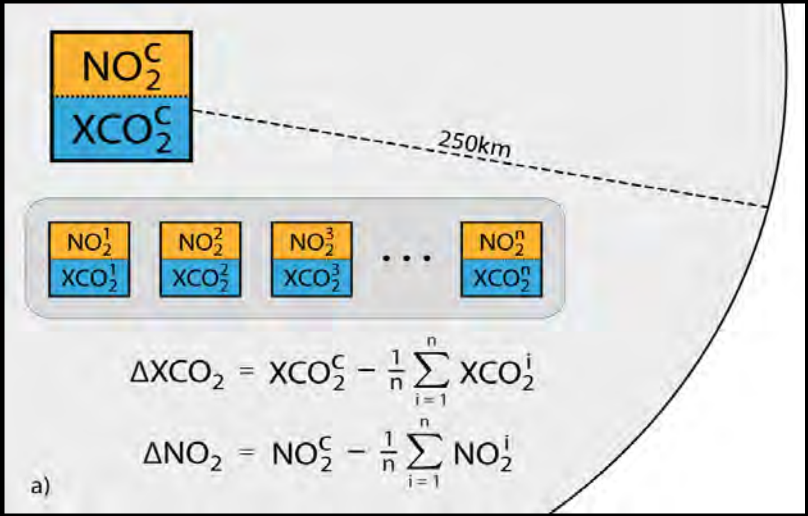
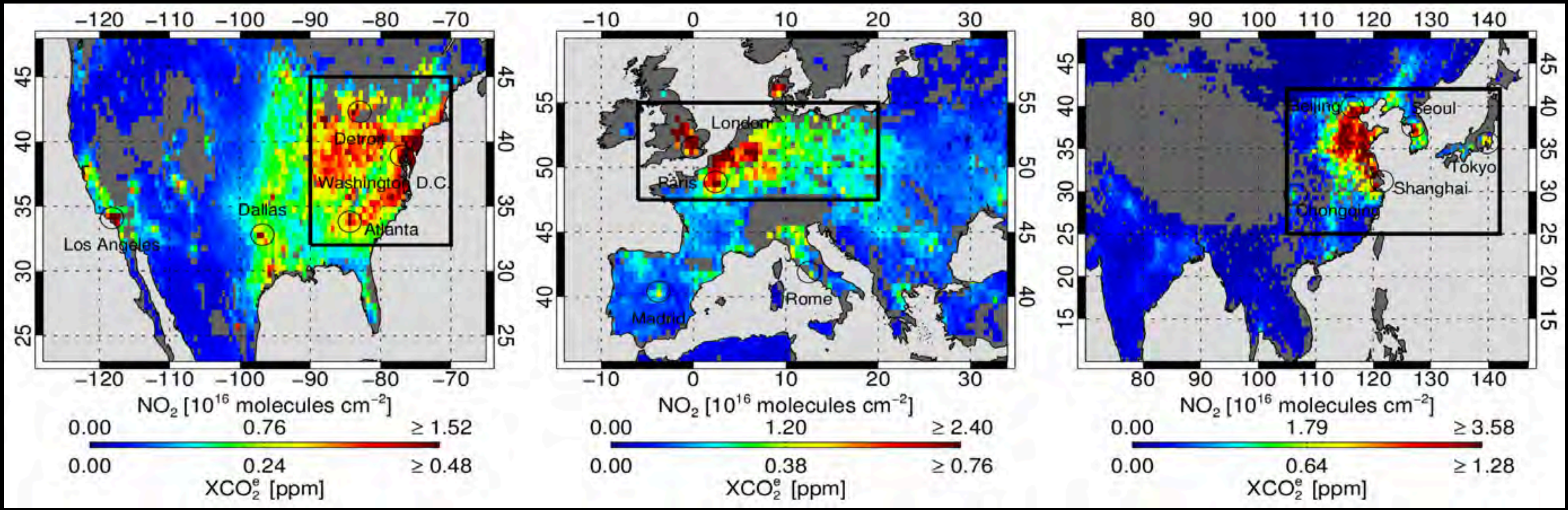
European Carbon Dioxide Surface Flux estimated from SCIAMACHY (and some GOSAT data)



Anthropogenic CO_2 and NO_x emissions (Reuter et al., 2014, nat. geosci.)

- **CO_2 and NO_x** are **co-emitted** species in anthropogenic fossil fuel combustion processes.
- A **spatial high-pass filtering** method is used to derive co-located regional anomalies ΔXCO_2 and ΔNO_2.
- A **statistical relationship** between ΔXCO_2 and ΔNO_2 allows to conclude on **CO_2 with anthropogenic origin**.





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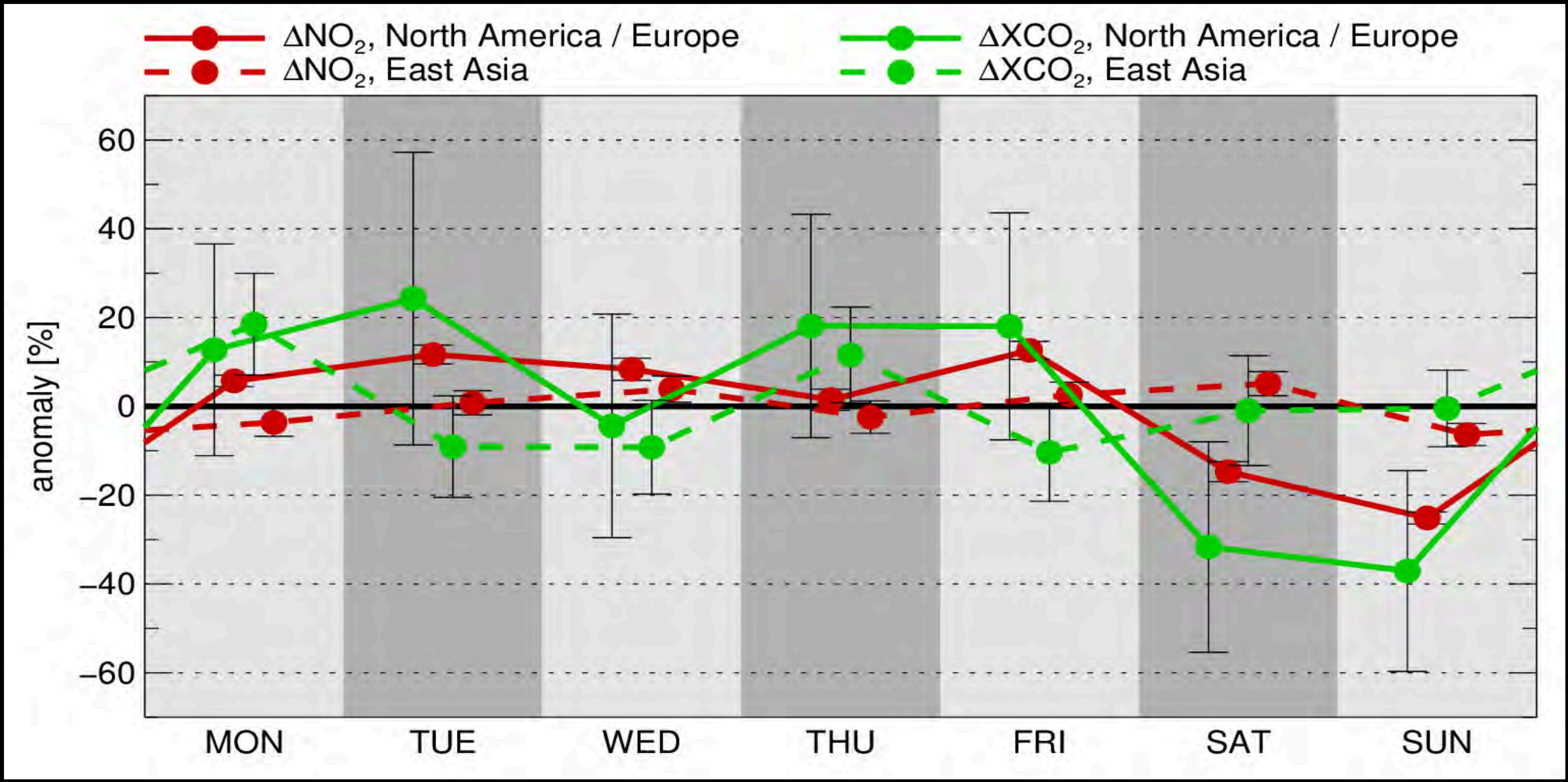
Anthropogenic CO_2 and NO_x emissions (Reuter et al., 2014, nat. geosci.)



- We find significantly **lower ΔXCO_2 levels at weekends** in North America and Europe but not in East Asia.
- The weekend effect of XCO_2 is a tiny signal and this is its **first detection from space**.
- It underlines that the analyzed CO_2 signals originate from **anthropogenic activities**.

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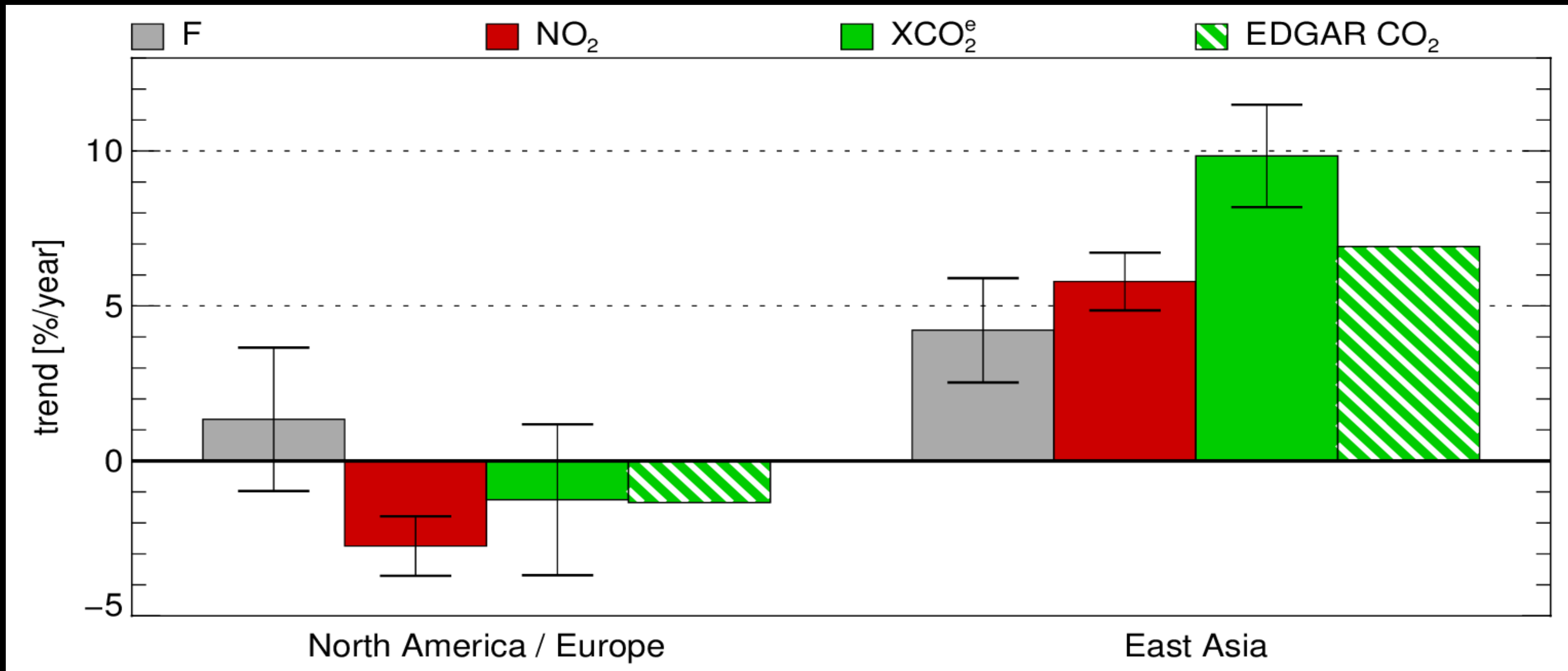
Anthropogenic CO_2 and NO_x emissions (Reuter et al., 2014, nat. geosci.)



- **North America and Europe:** satellite data show a small **downward trend in emissions** of both, NO_x and CO_2 albeit associated with a large uncertainty.
- **East Asia:** CO_2 emissions increased on average at a rate of 9.8%/a but NO_x increased “only” by 5.8%/a, i.e., significantly less compared to CO_2 (**increasing CO_2-to-NO_x emission ratio F**).
- **Interpretation: technology** used in East Asia is **getting cleaner** thus emitting less toxic nitrogen gases per amount of fossil fuel burned.

Highlights GHG

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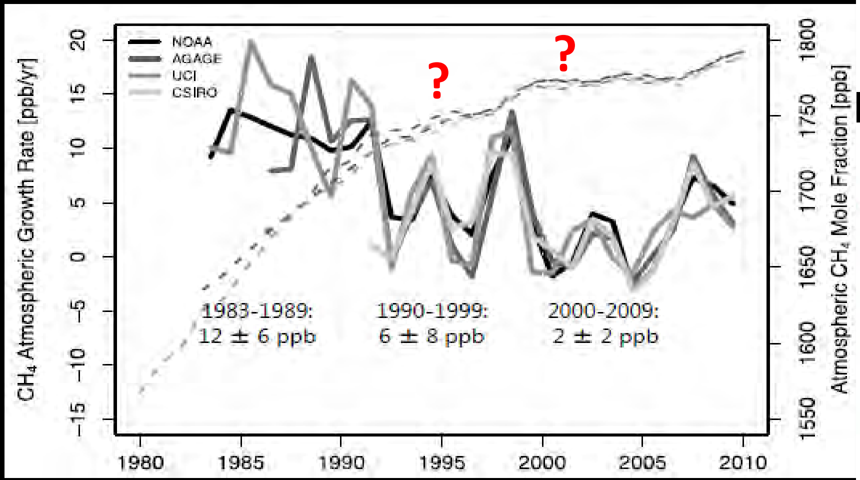
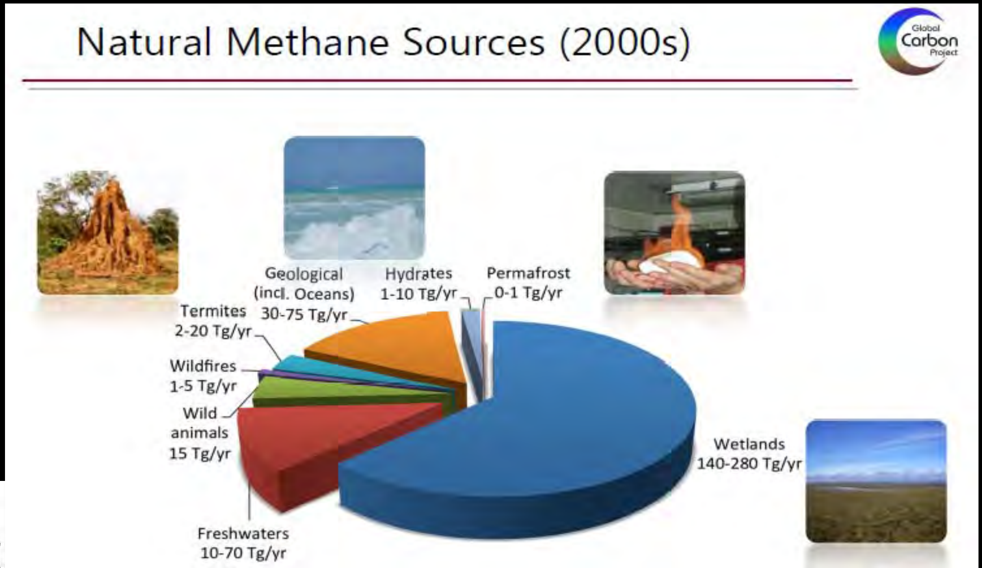
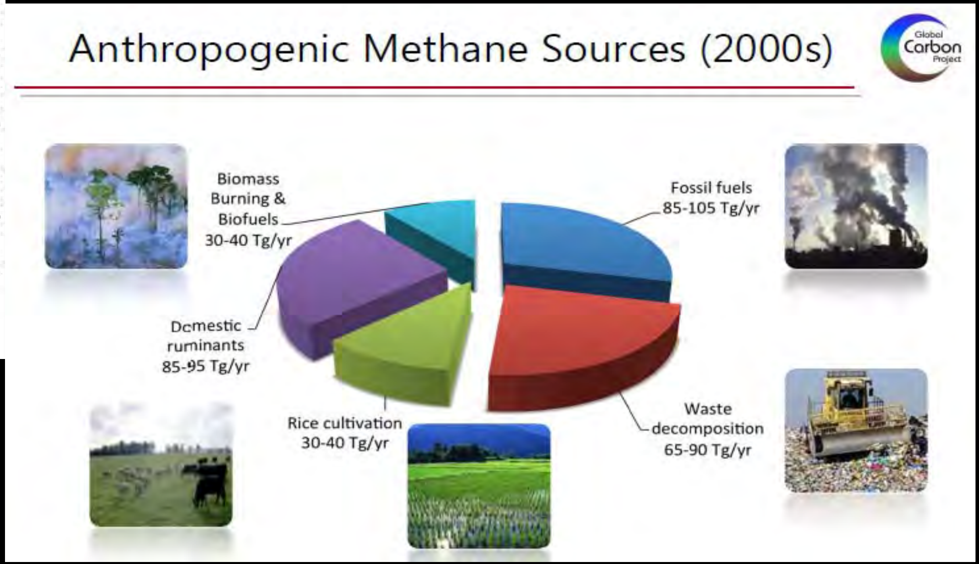
Methane

- **Second most important anthropogenic GHG (directly after CO_2)**
- **Important precursor of O_3 in global tropospheric Chemistry**
- **Many anthropogenic and natural sources; large uncertainties**







Kirschke et al.,

Highlights GHG

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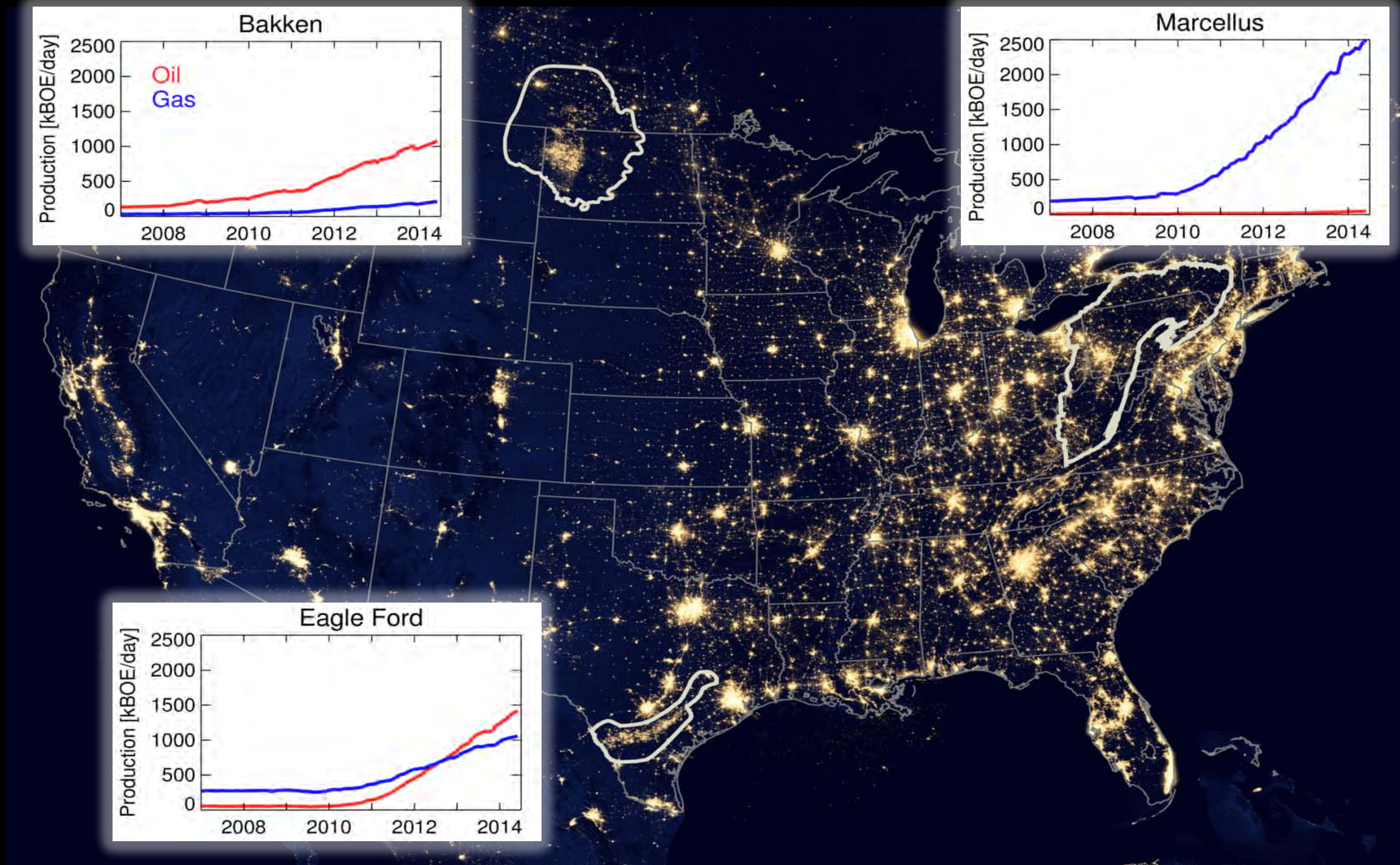
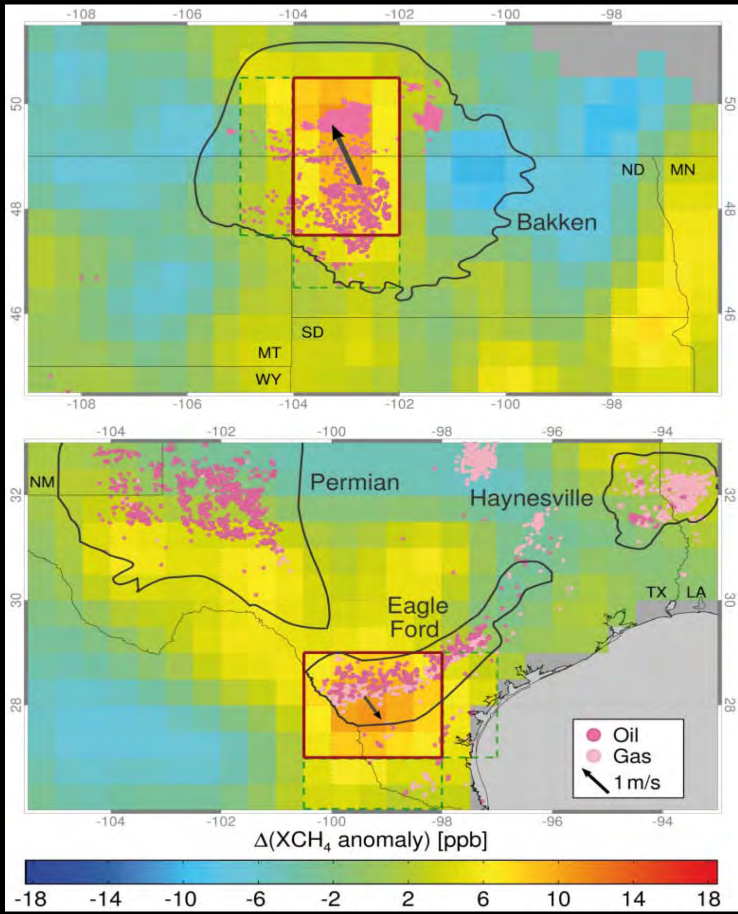
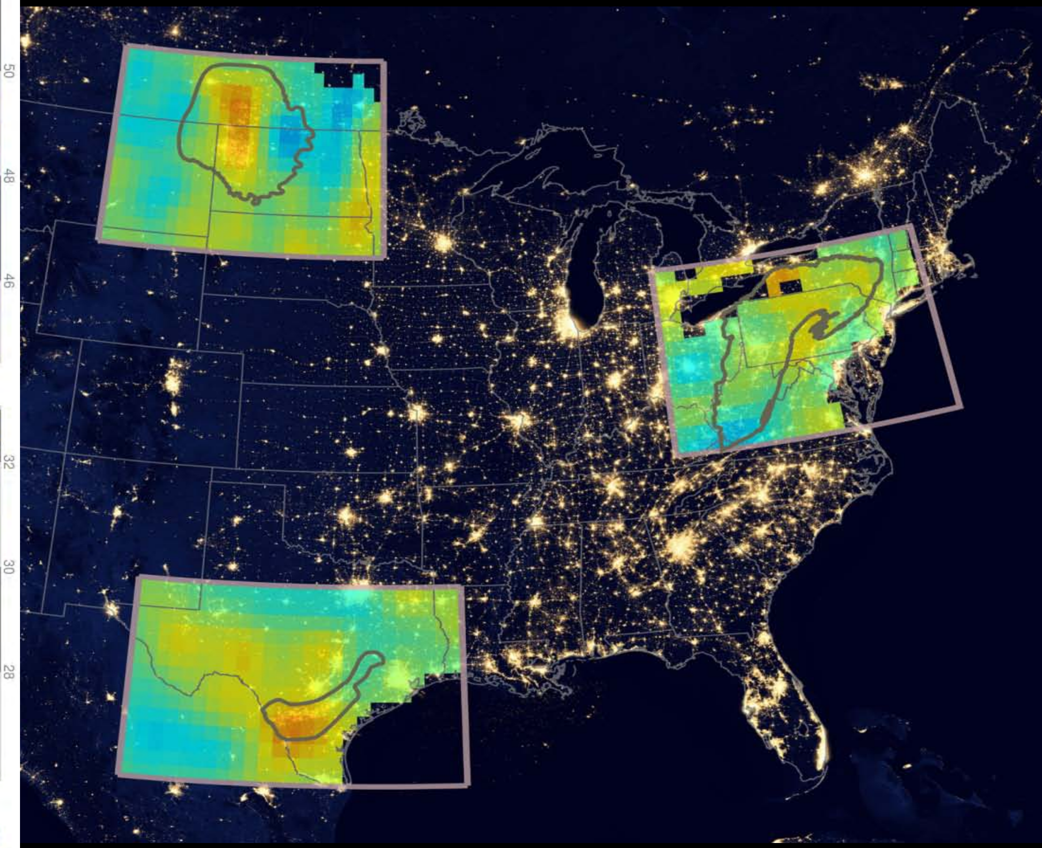
Fugitive methane emissions from oil and gas production (Schneising et al., 2014, Earth's Future)



- We analyse **methane enhancements** over the fastest growing production regions in the U.S.
- Flaring in **Bakken** and **Eagle Ford** is so extensive that both regions stand out clearly in satellite measurements of nighttime lights from VIIRS onboard Suomi NPP.

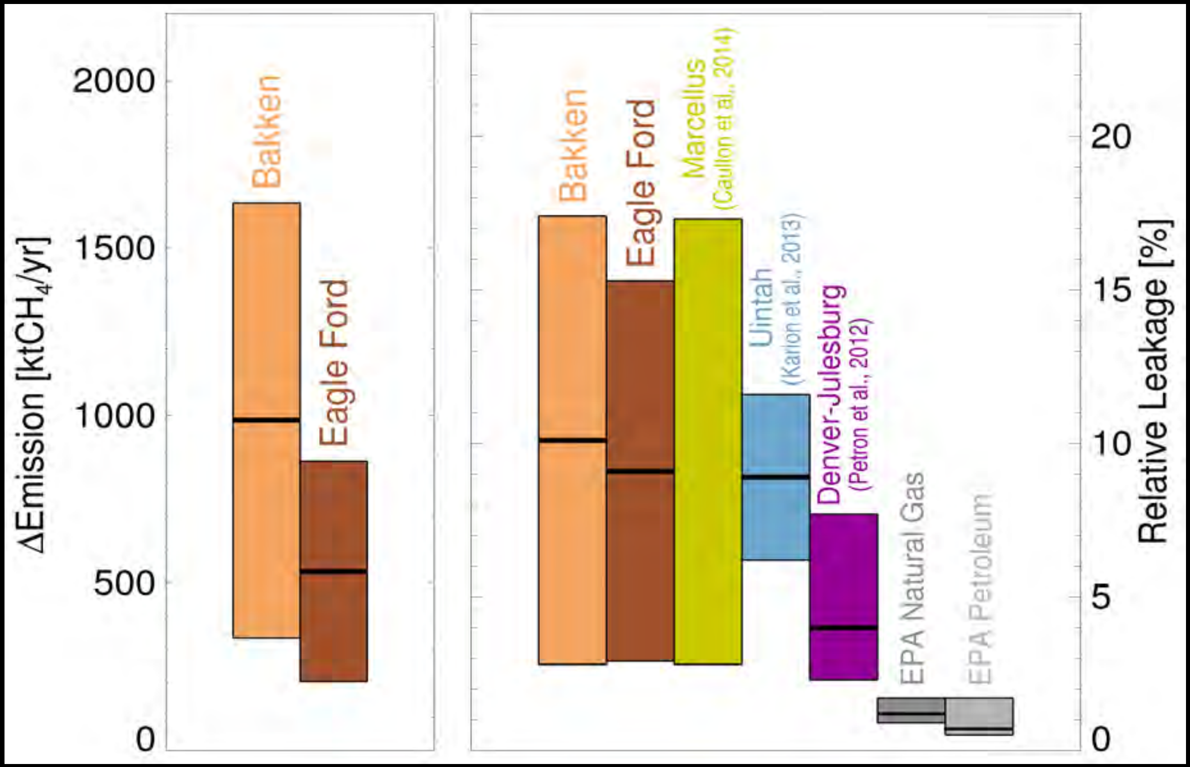
Fugitive methane emissions from oil and gas production (Schneising et al., 2014, Earth's Future)





- To filter out large-scale seasonal variations or global increase, **XCH_4 anomalies** are computed by subtracting regional monthly means from the individual measurements.
- The shown **differences of the anomalies** for the period **2009-2011** relative to the period **2006-2008** highlight the changes in atmospheric methane abundance.
- Anomaly differences exhibit **increases aligning with the analysed oil and gas fields.**

Fugitive methane emissions from oil and gas production (Schneising et al., 2014, Earth's Future)



Bakken

Emission Increase:

990 ± 650 $ktCH_4/yr$

Leakage rate:

10.1 ± 7.3 %

Eagle Ford

Emission Increase:

530 ± 330 $ktCH_4/yr$

Leakage rate:

9.1 ± 6.2 %

- The **emission increase** is quantified by a mass-balance approach using the net enhancement relative to the background upwind of the prevailing wind direction and average horizontal boundary layer wind speed.
- The **leakage rate** is defined as the ratio of the emission increase between 2006-2008 and 2009-2011 divided by the production growth between these two periods.
- **Results:** Current inventories likely underestimate fugitive emissions from Bakken and Eagle Ford. Climate benefit of transition to unconventional oil and gas is questionable.

Highlights GHG

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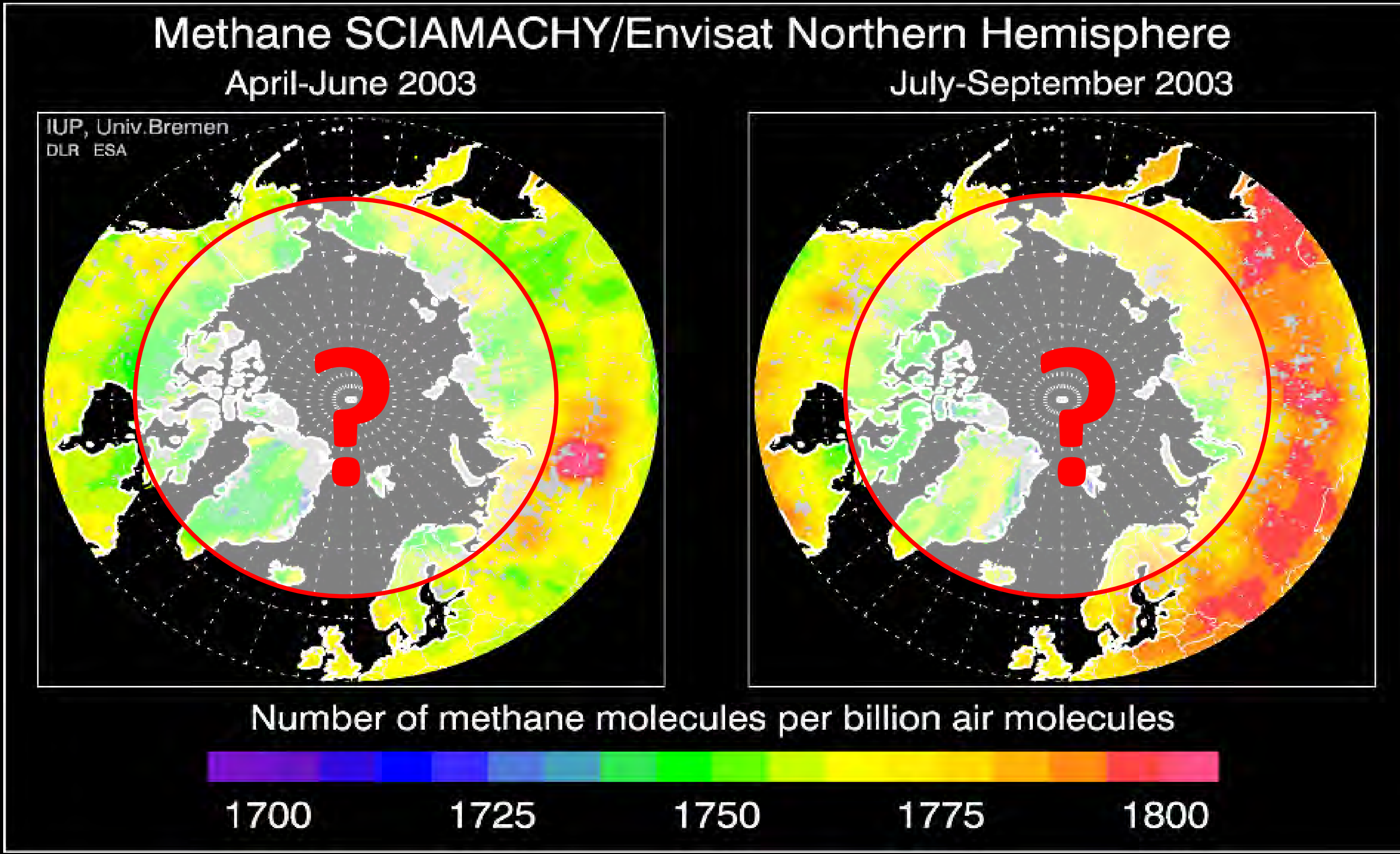
CarbonSat: Methane @ high latitudes



CarbonSat sun-glint mode allows observation of methane in vulnerable high latitude regions including Arctic sea and shelf areas

Highlights GHG

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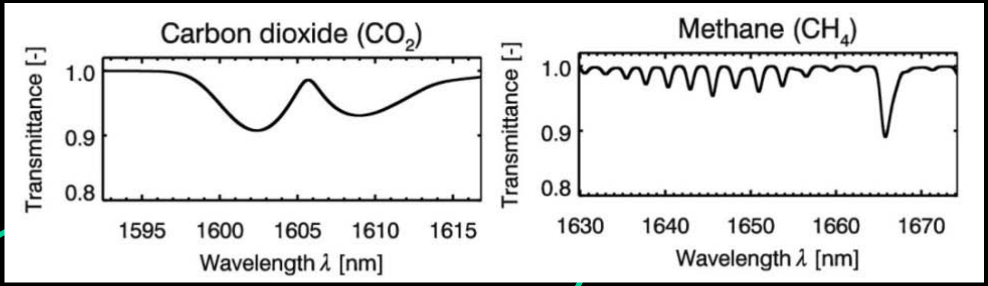
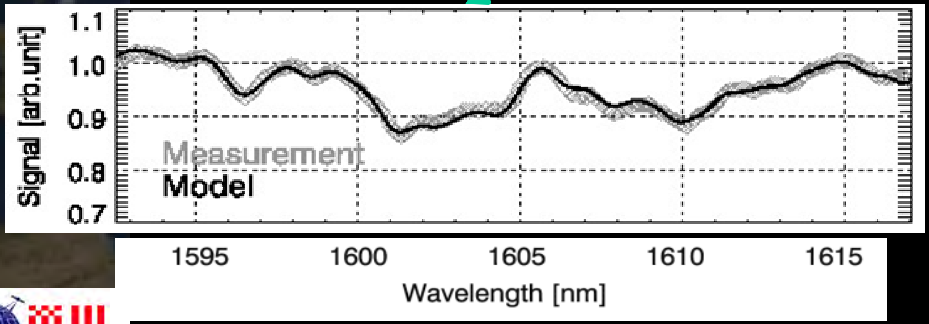
The MAMAP instrument

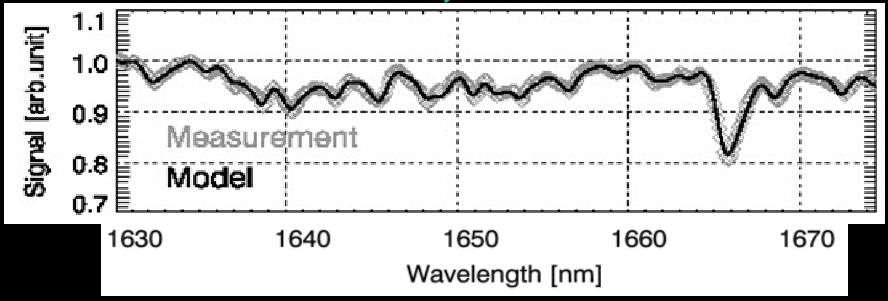
→ Methane and carbon dioxide Airborne Mapper
a passive remote sensing instrument using absorption NIR and SWIR spectroscopy

- **SWIR channel**
  spectral range : around 1590 nm to 1680nm
- **spectral resolution: 0.9 nm**



Real measurements / measured spectra





GHG

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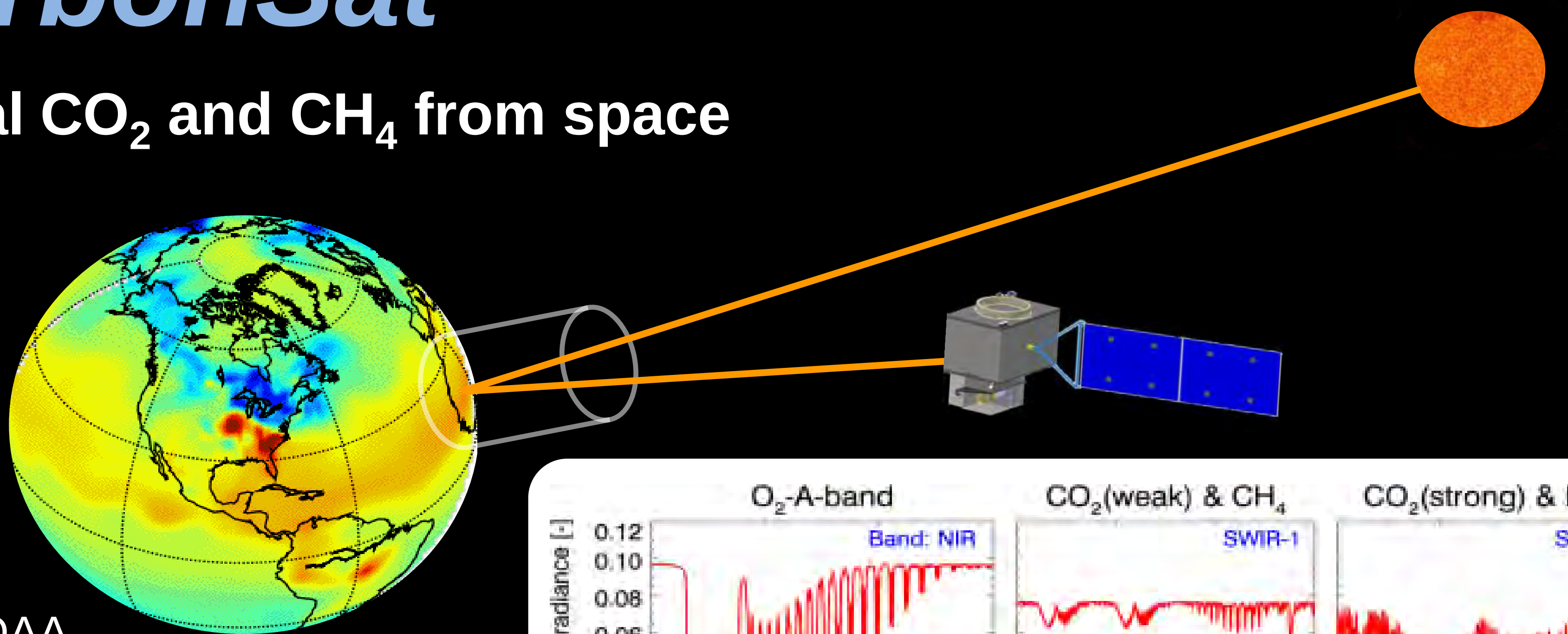
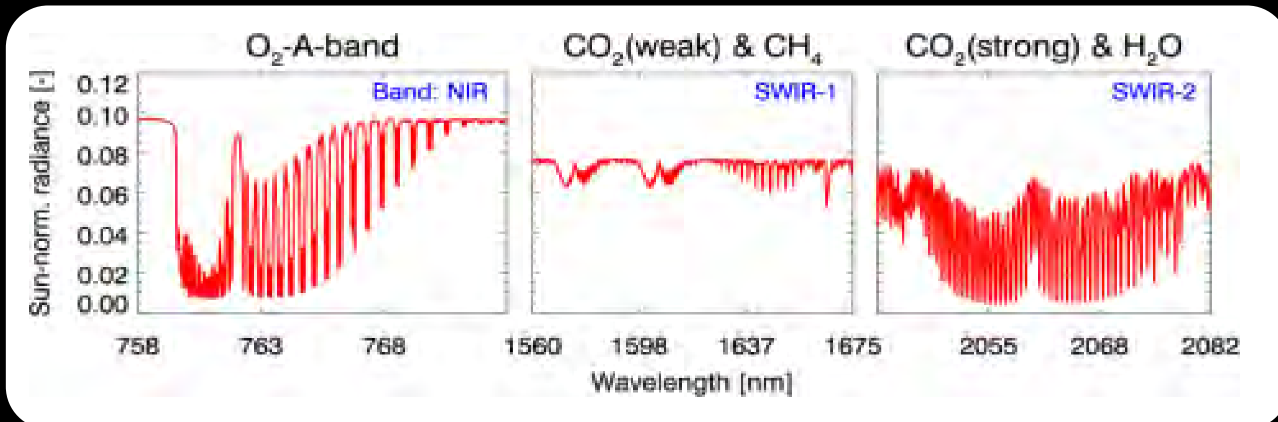
CarbonSat – ESA EE8 Candidate

CarbonSat

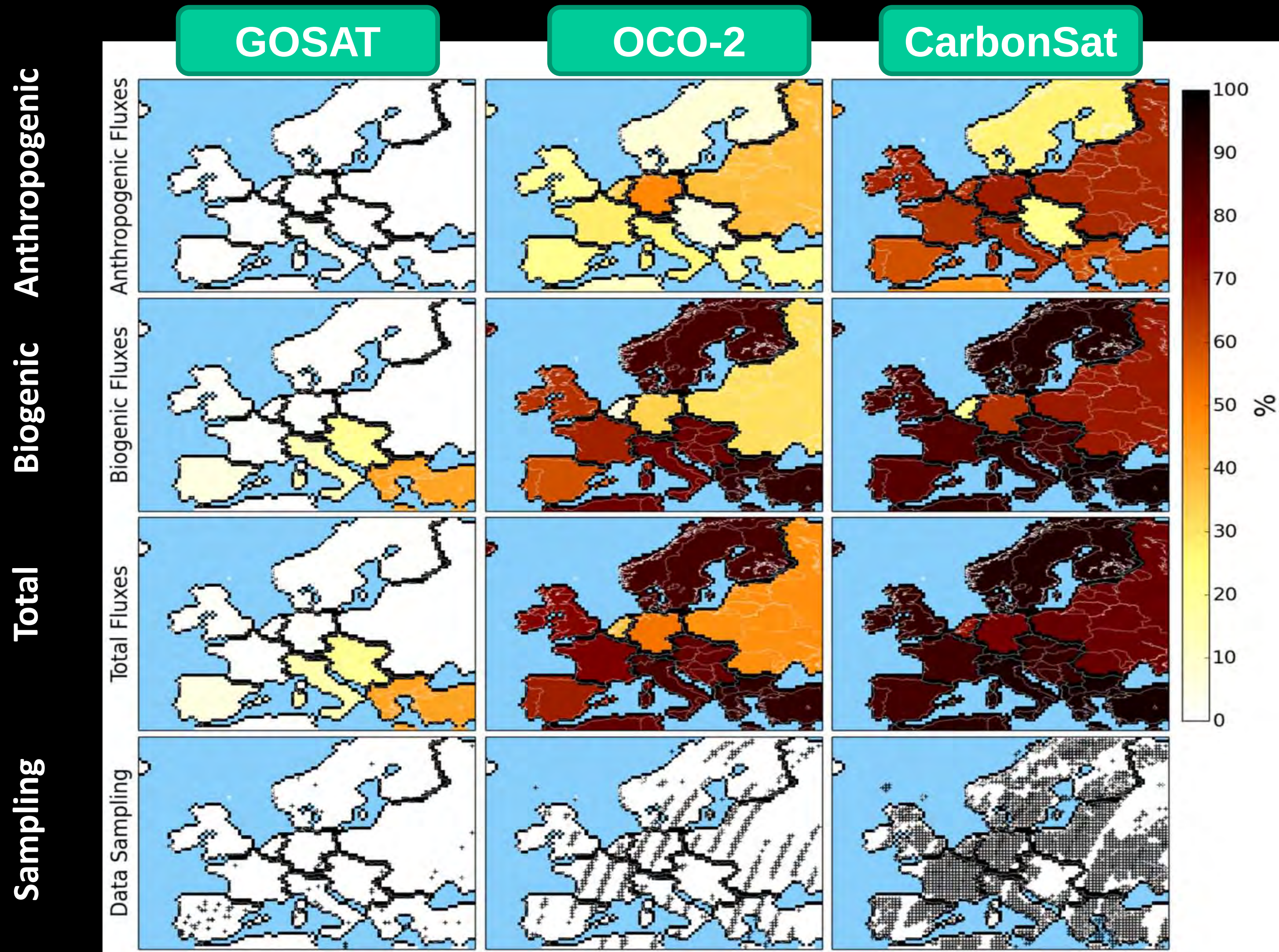
Global CO_2 and CH_4 from space



NOAA
CarbonTracker



CarbonSat's unique contribution at national scales



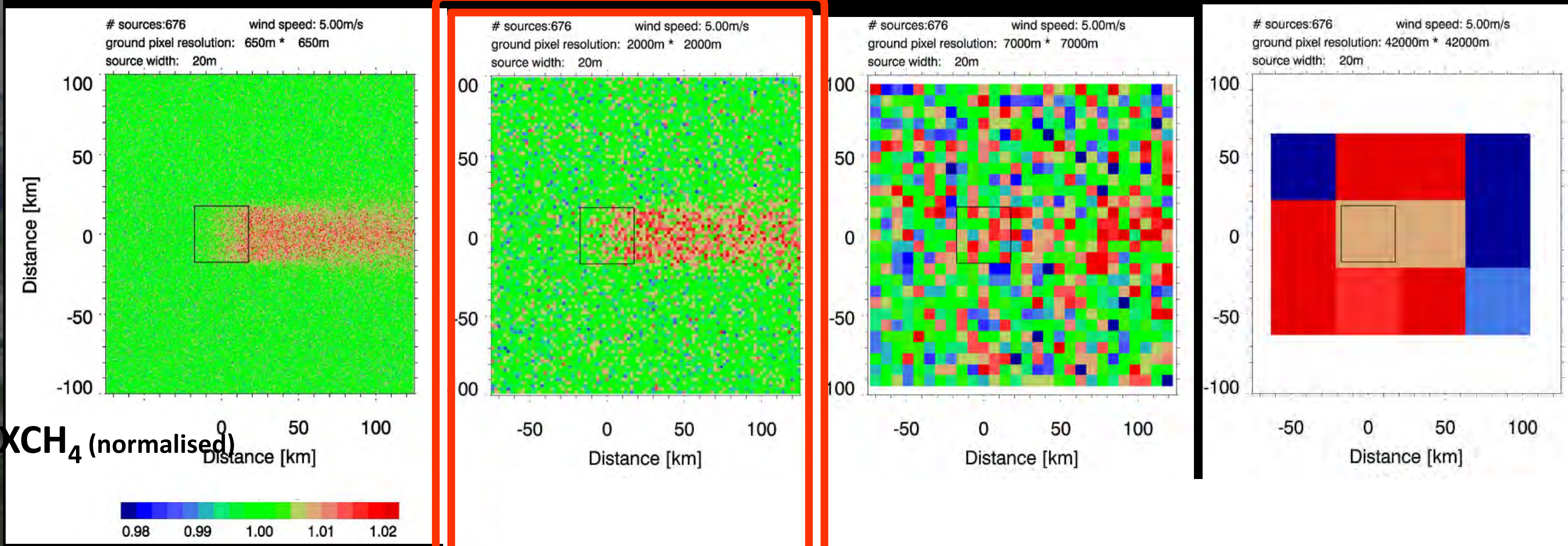
Uncertainty reduction

Highlights GHG

Prelimina

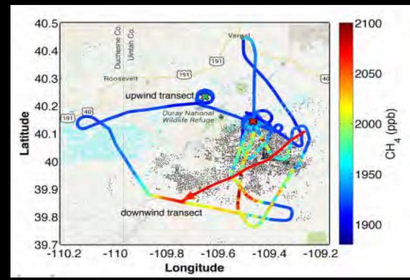
Methane Leackage from Gas Production

Simulation of XCH_4: Emission rate of = 482 $ktCH_4$/yr on an area of ca. 35 km x 35 km (*), 5 m/s wind speed, instrument resolution and single measurement precision as below:



Airborne	CarbonSat	Sentinel 5P	SCIAMACHY
0.5 km x 0.5 km	2 km x 2 km	7 km x 7 km	30 km x 60 km (#)
7 ppb	9 ppb	18 ppb	50 - 80 ppb

(*) Similar as gas fields in Uintah county, Utah, USA (Karion et al., GRL, 2013)



Bovensmann et al., ESA Living Planet Symposium, Edinburgh, 2013
based on Krings et al.

Highlights GHG

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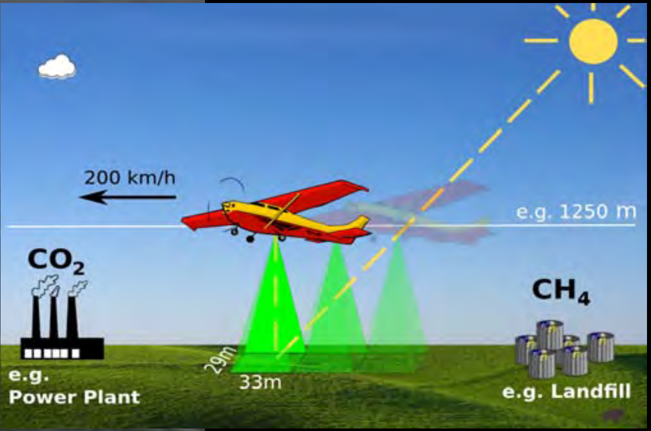
C-MAPExp Campaign Results: Power Plant CO_2



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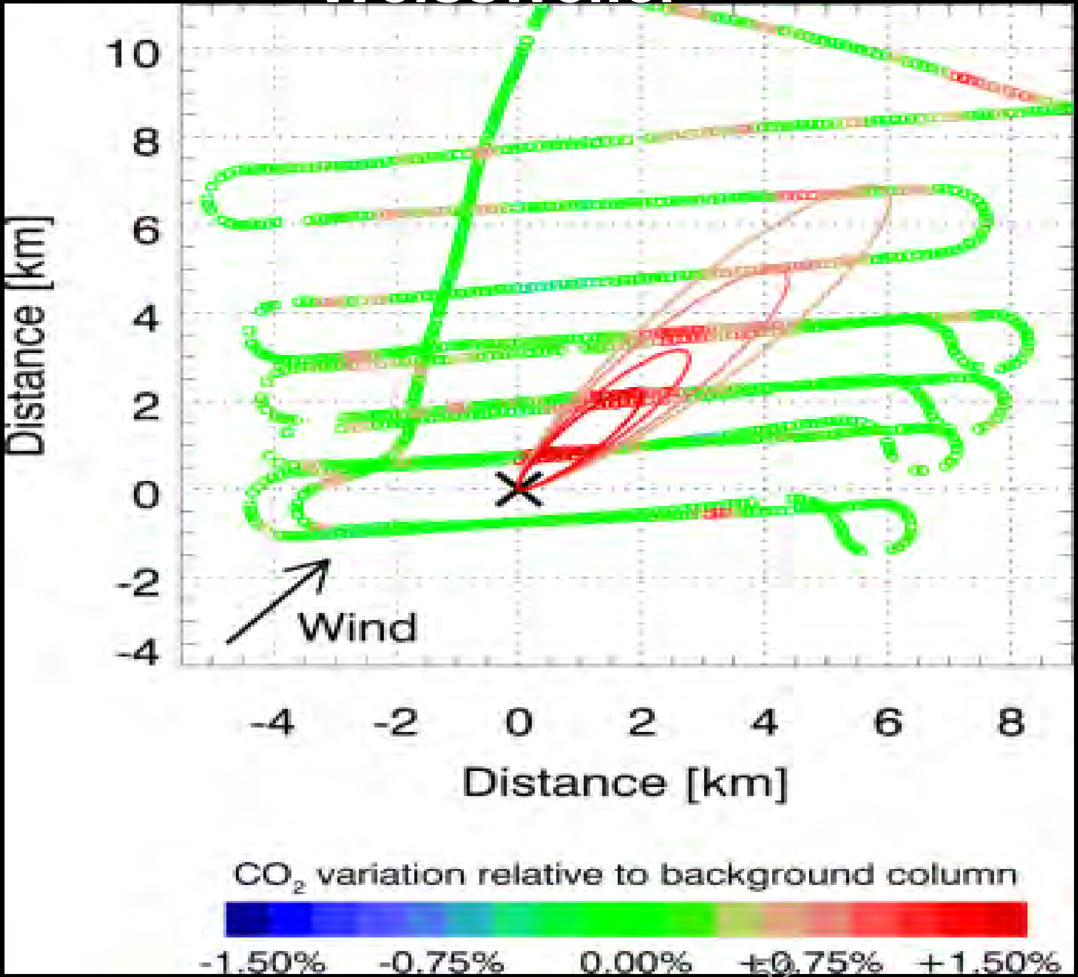
MAMAP Airborne remote sensing and in-situ observations on 18.8.2012:

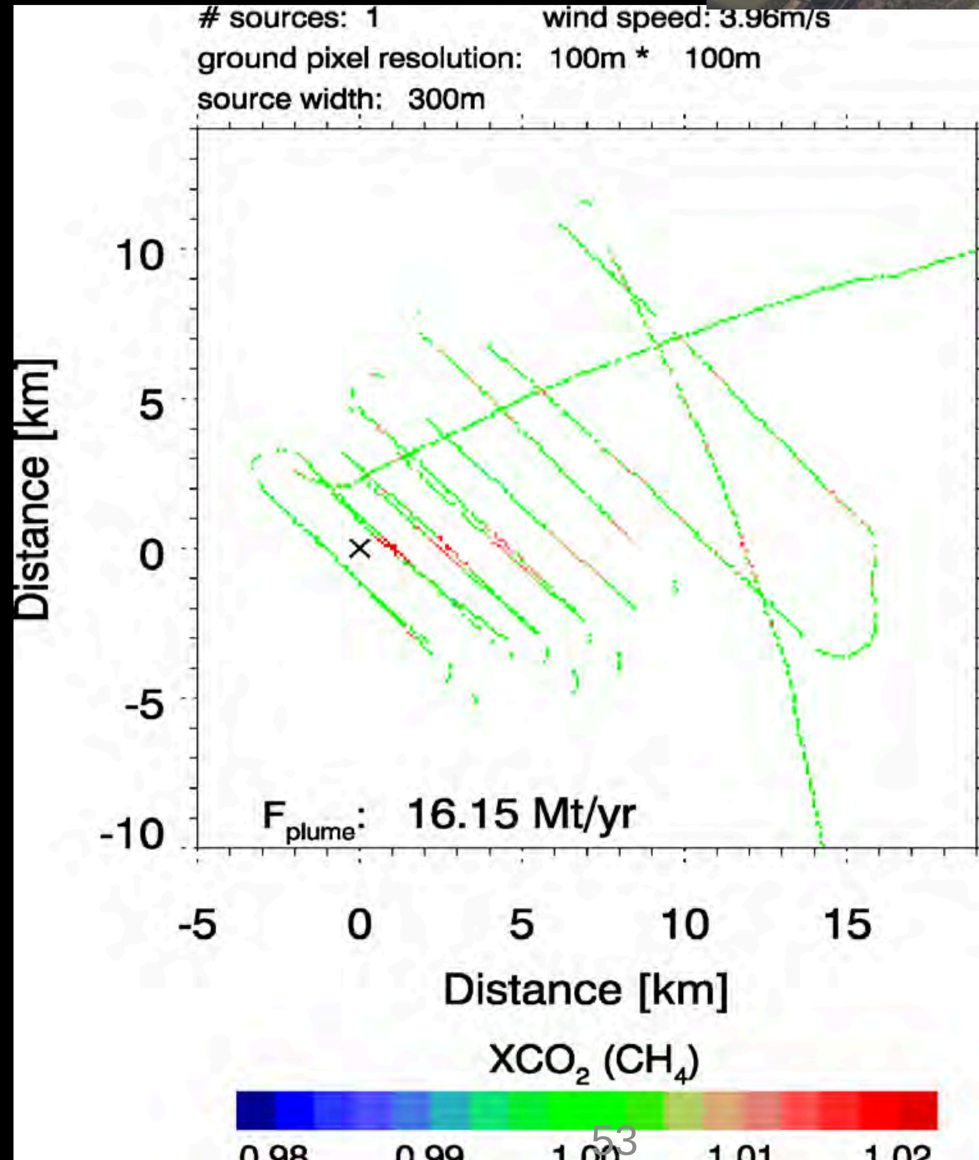
Lignite Coal fired power plant Weissweiler



CO_2 emitting Power Plant Weissweiler

MAMAP aircraft observations:

- **Remote sensing data at MAMAP resolution (approx. 100m x 100m) including plume inversion result**
- **Filtered for instrument inclination angle ≤10°**
- **Derived emission: 16.15 $MtCO_2$/yr at the time of measurements**
- **But what would be detected from space?**



Highlights GHG

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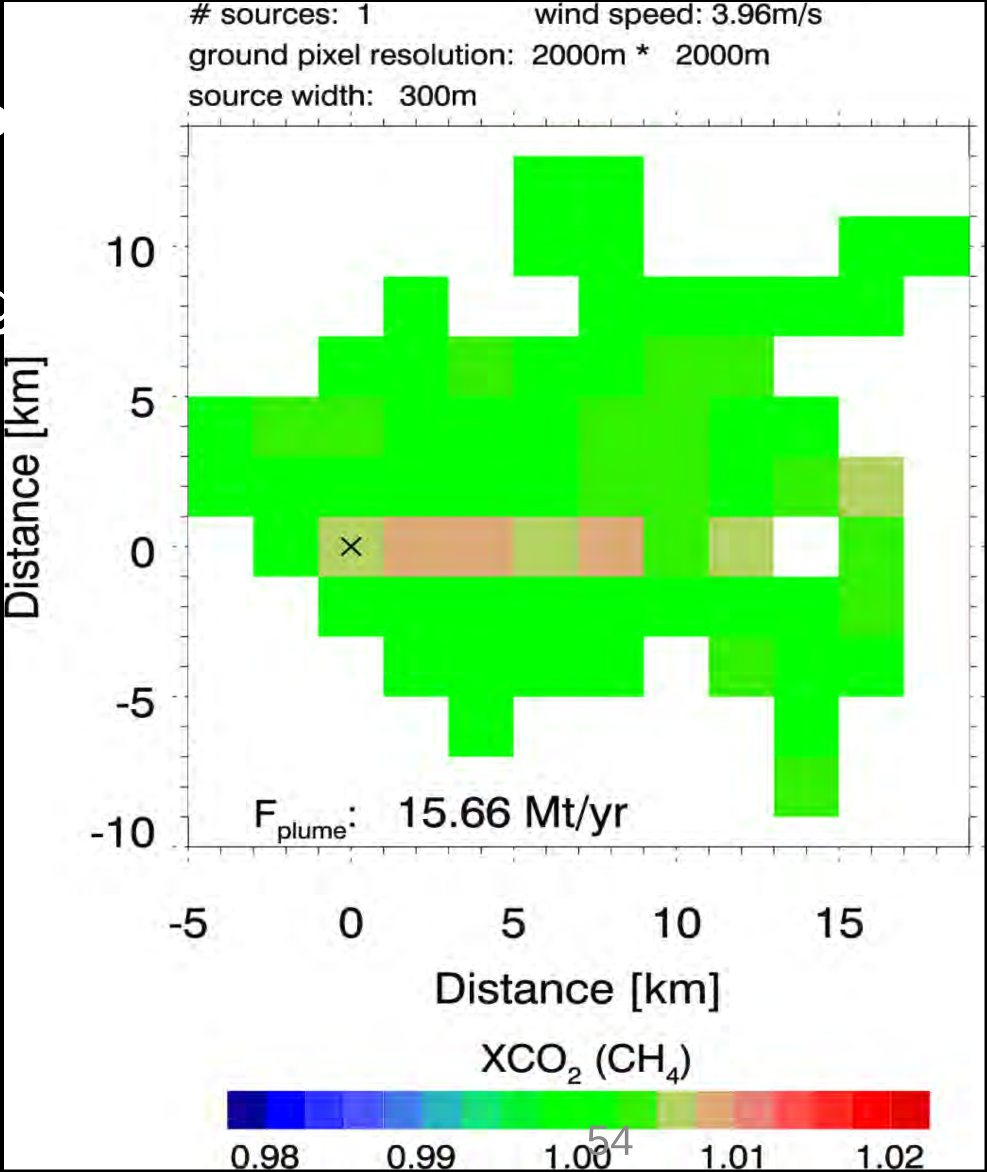
CO_2 emitting Power Plant Weissweiler

What CarbonSat will yield:

MAMAP data „converted“ to CarbonSat ovservations:

- **Recorded remote sensing data gridded to spatial resolution of approx. 2 km x 2 km**
- **Including plume inversion result**
- **Derived emission: 15.7 $MtCO_2$/yr at the time of measurements**



Highlights GHG

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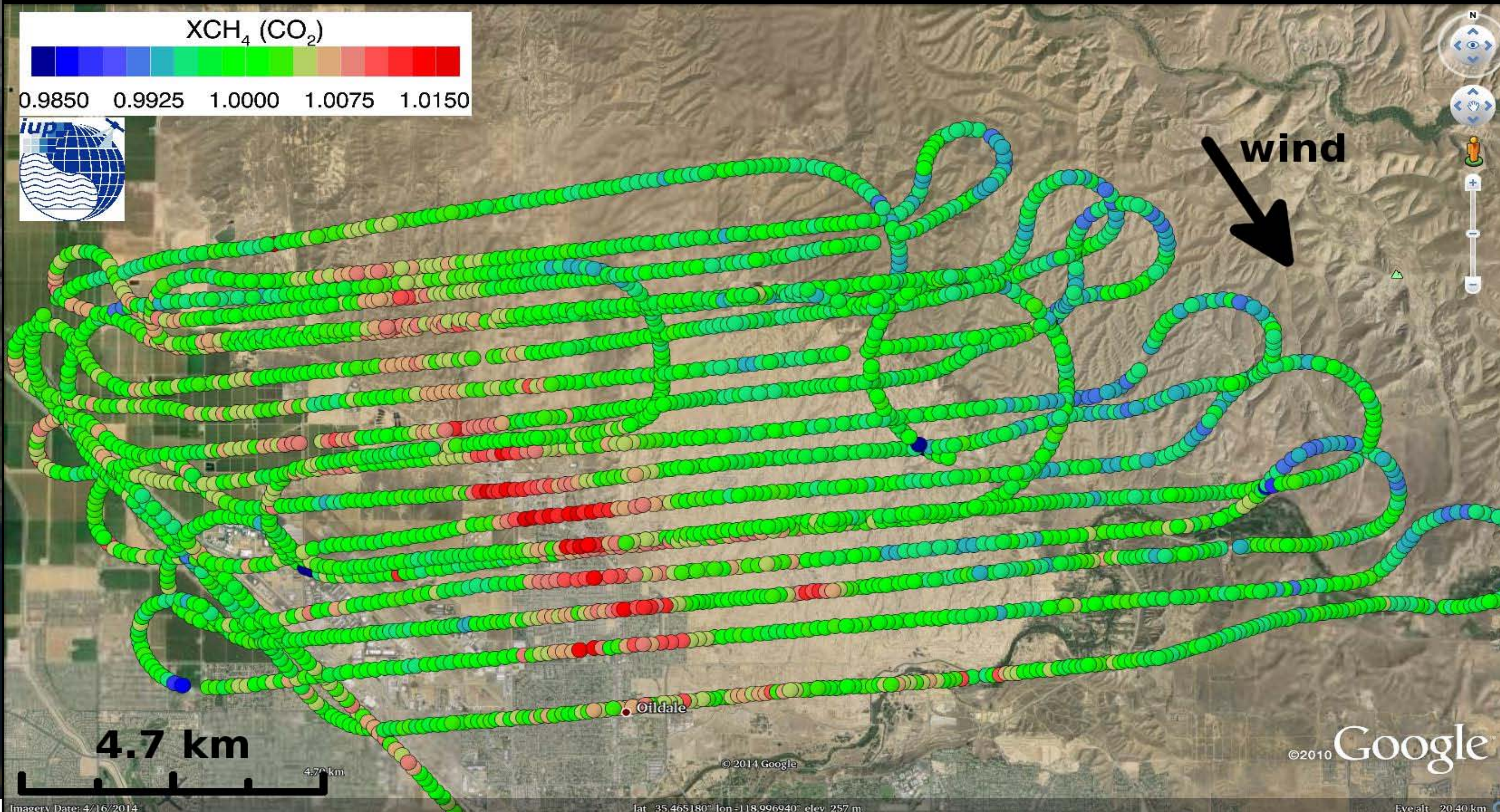
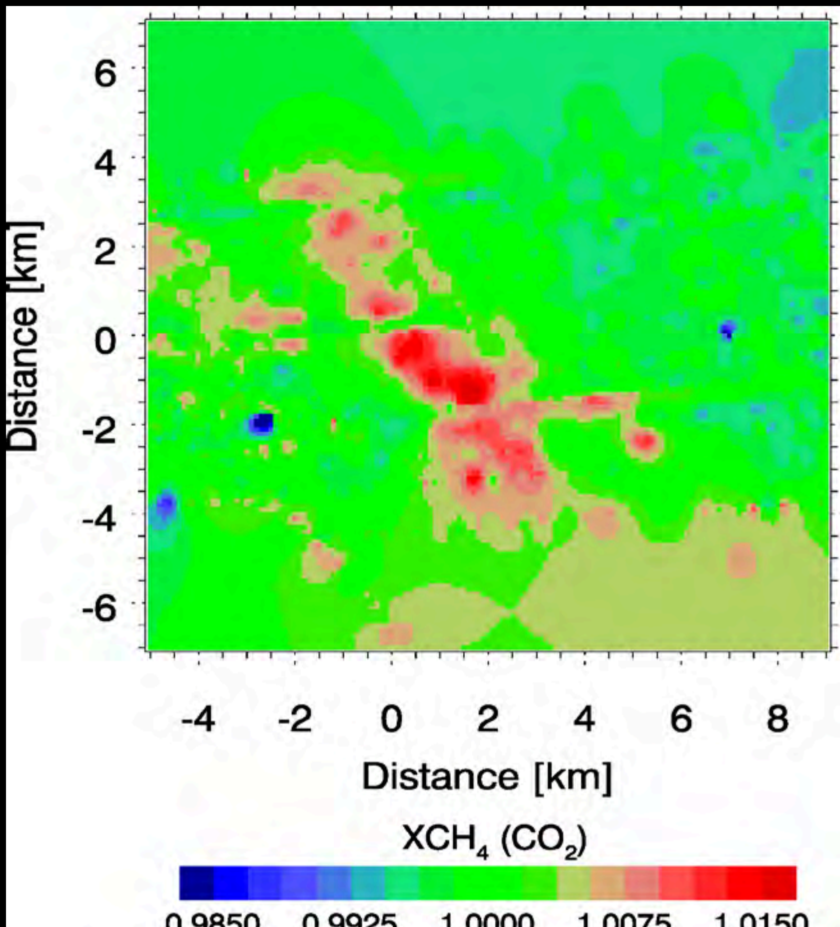
COMEX Campaign (USA) Results: Oil Field CH_4

Airborne remote sensing data (MAMAP) from California, August/Sept. 2014

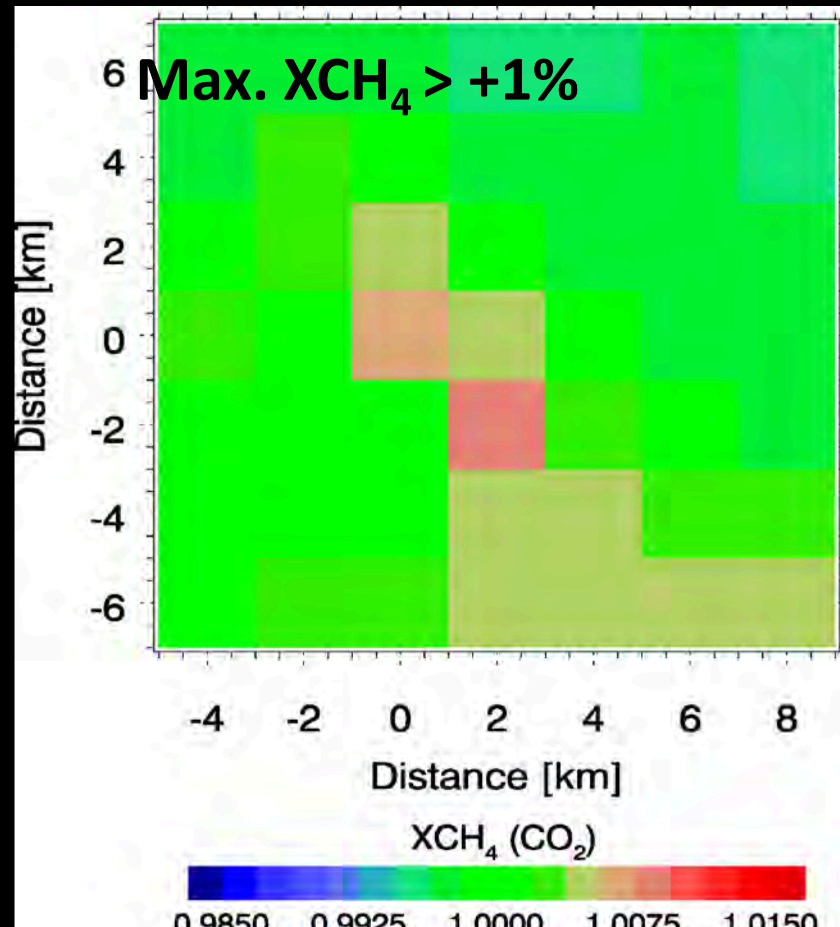


California Oil Field CH_4

MAMAP interpolated:



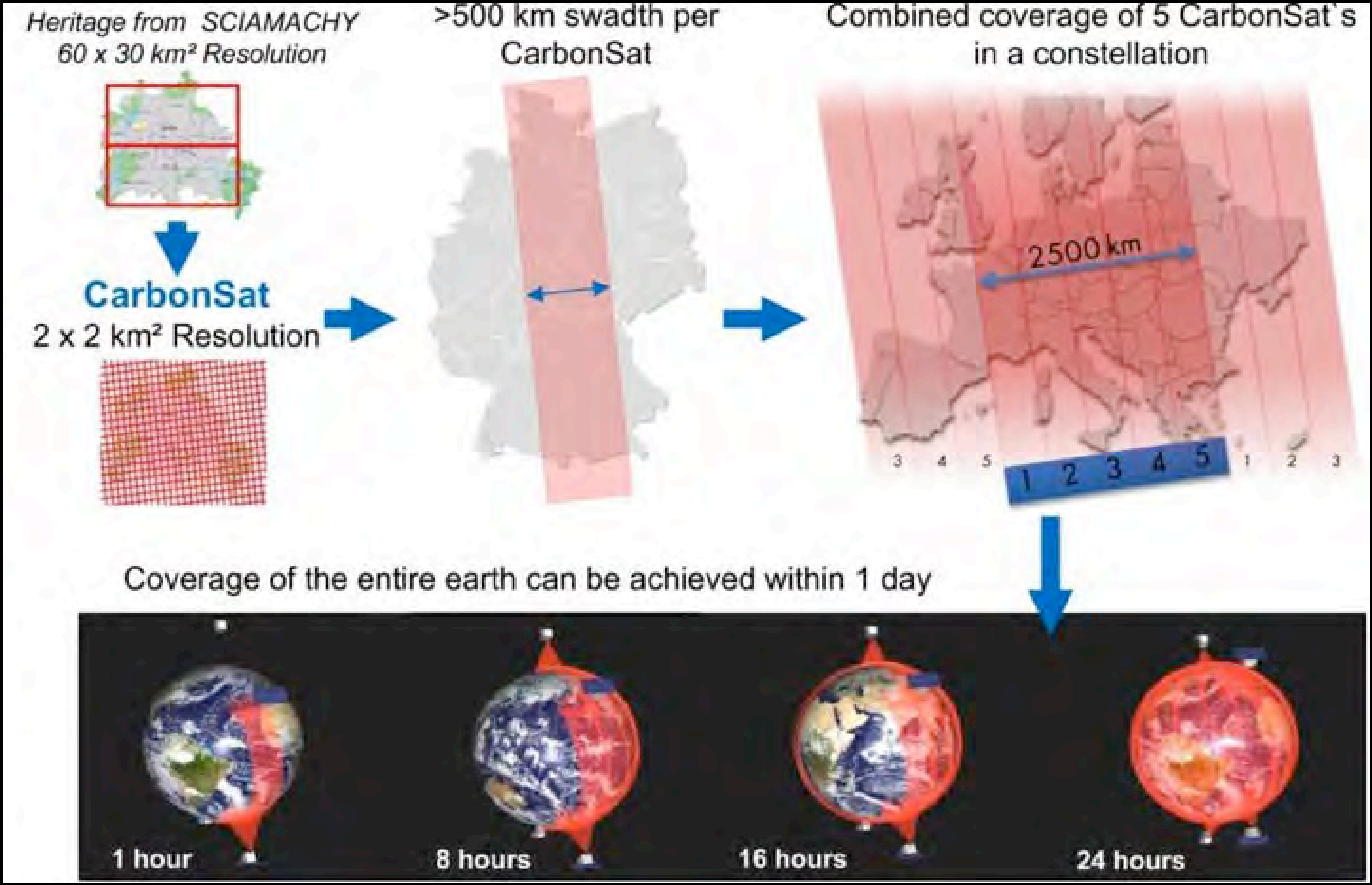
What CarbonSat will see at $2x2\ km^2$ resolution:



Highlights GHG

Universität Bremen

CarbonSat Constellation



Highlights GHG

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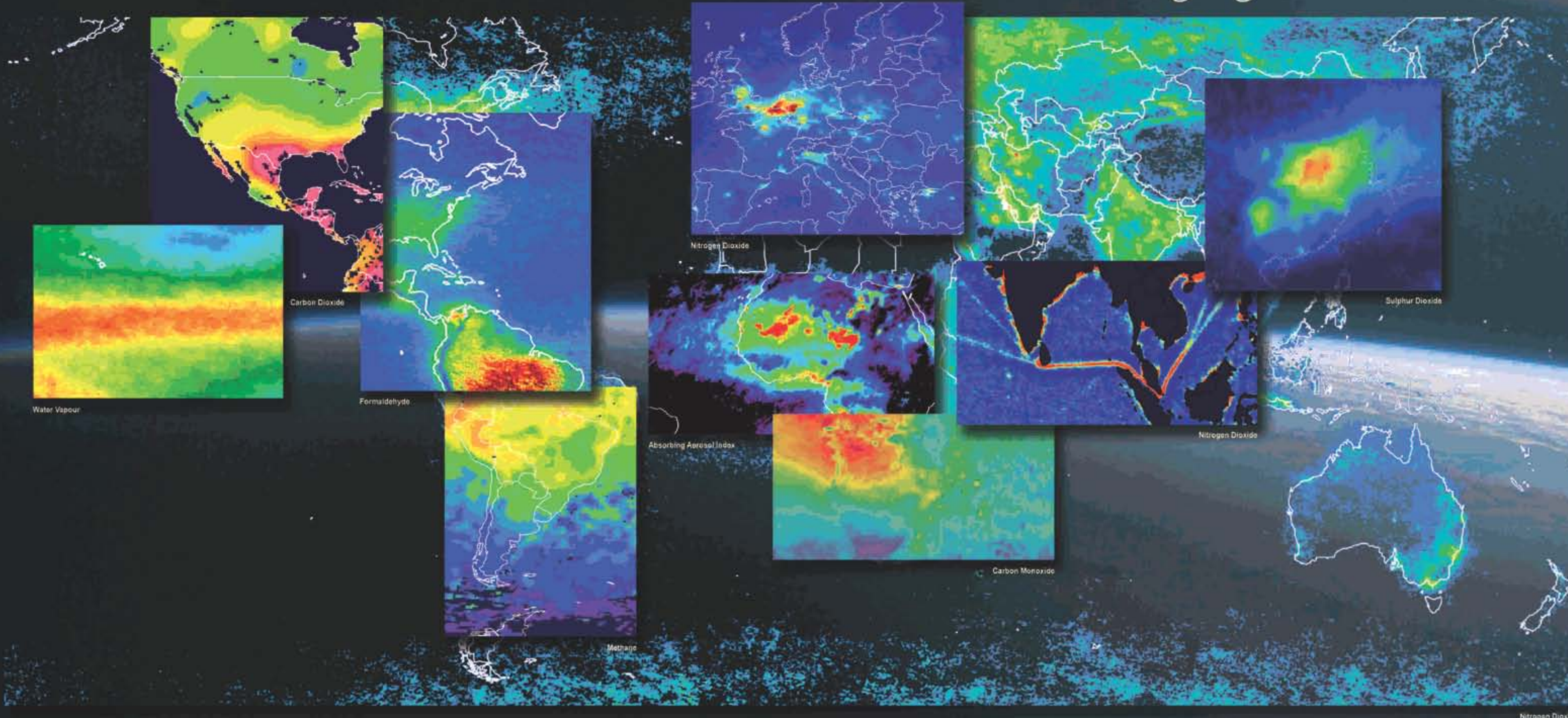
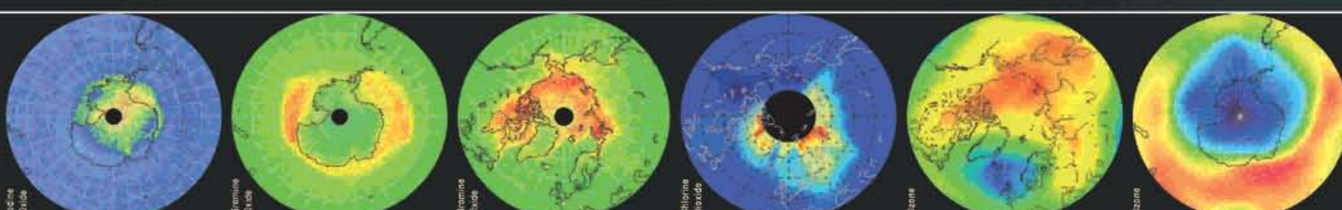
hunting light and shadows





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