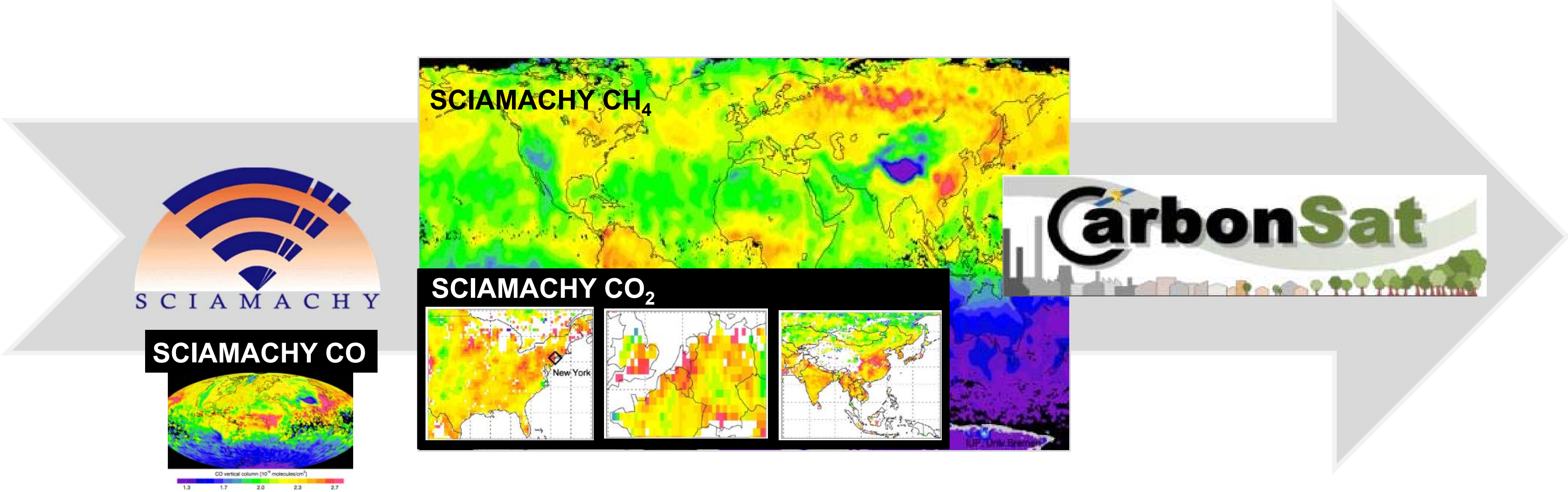
Carbon gases (CO, CO_2) over anthropogenic source regions: From SCIAMACHY to CarbonSat



M. Buchwitz, H. Bovensmann, M. Reuter, O. Schneising, J. P. Burrows
Institute of Environmental Physics (IUP) / Institute of Remote Sensing (IFE),
University of Bremen (UB), Bremen, Germany

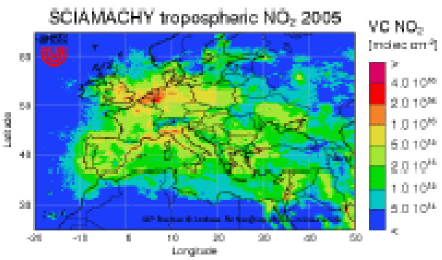
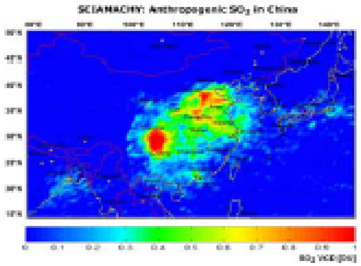
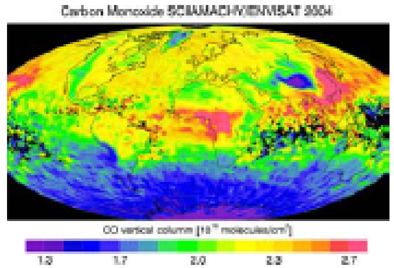
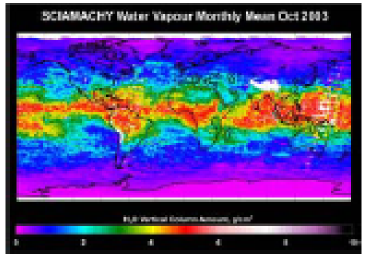
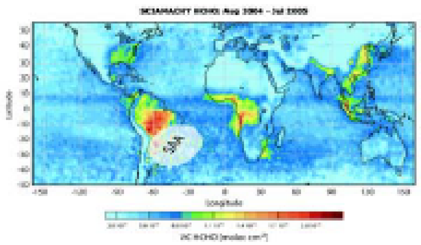
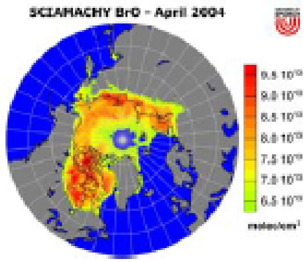
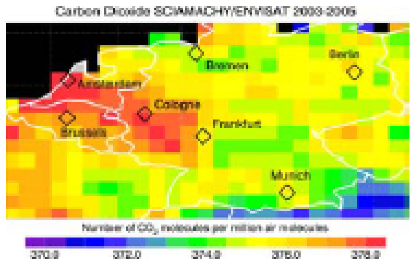
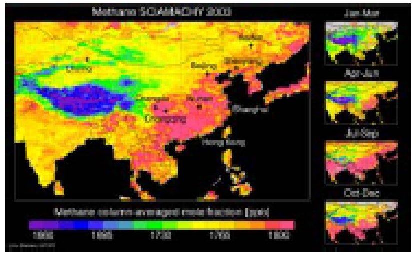
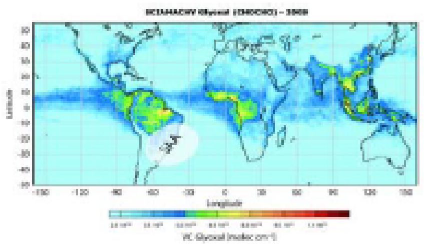
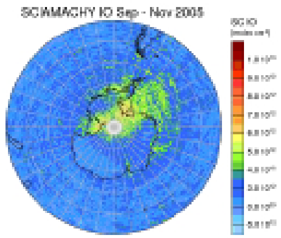
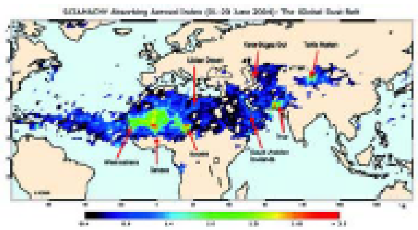
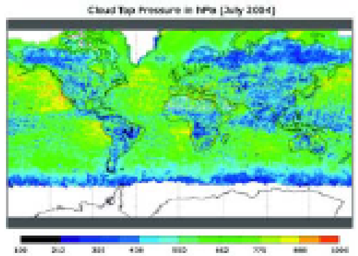
Universität Bremen

Outline

- **SCIAMACHY Carbon Gases**
- **SCIAMACHY:**
  - Carbon Monoxide (CO)
  - Carbon Dioxide (CO_2)
- **CarbonSat:**
  - City CO_2 emissions: Berlin
- **Summary and conclusions**

SCIAMACHY on ENVISAT

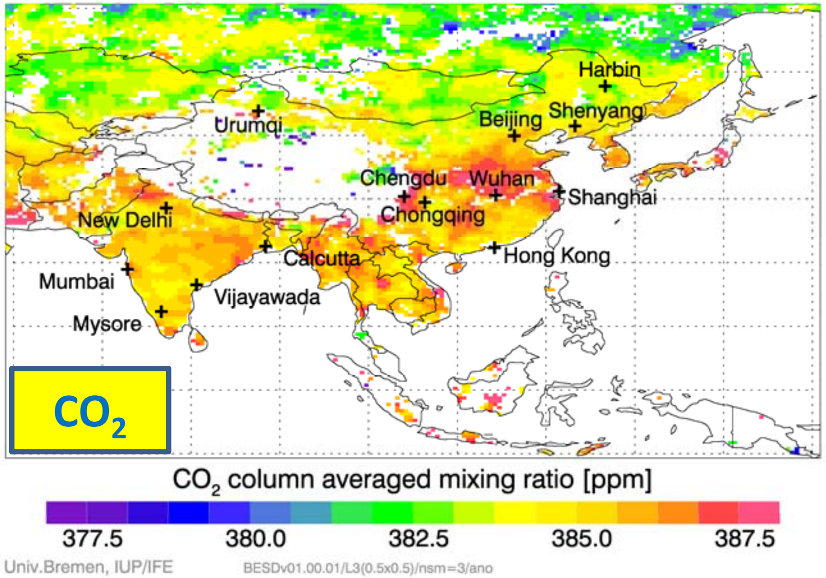
Kind of „all purpose“ atmosphere mission incl. CO, CO_2 , CH_4, …

NO2	SO2	CO	H2O
			
HCHO	**BrO**	**CO2**	**CH4**
			
CHOCHO	**IO**	**Aerosols**	**Clouds**
			

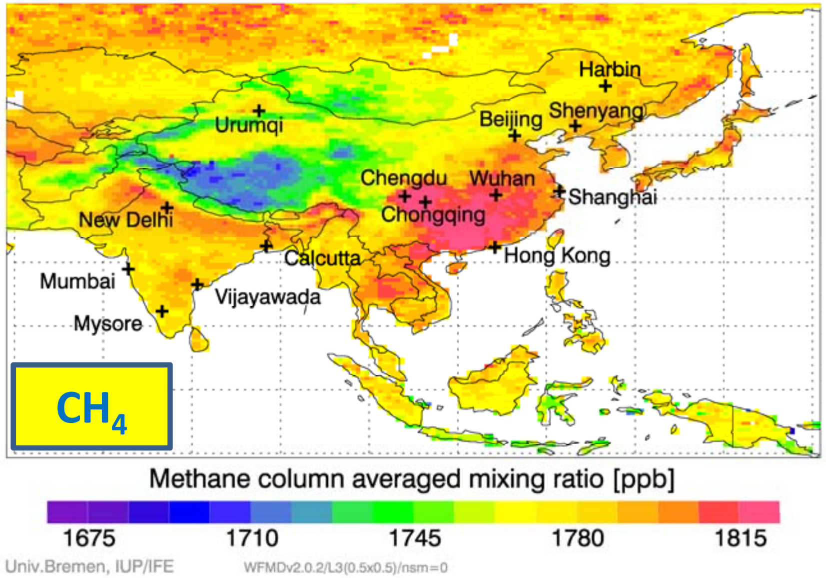
... and many other products...

„Carbon Gases“ from SCIAMACHY: China & India

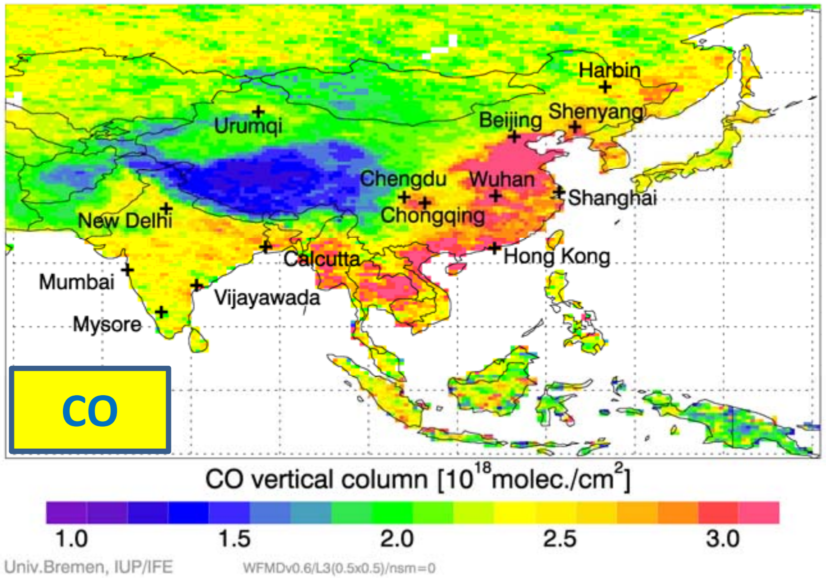
Carbon Dioxide SCIAMACHY/BESD 2006-2011



Methane SCIAMACHY/WFMD 2003-2005



Carbon monoxide SCIAMACHY/WFMD 2004

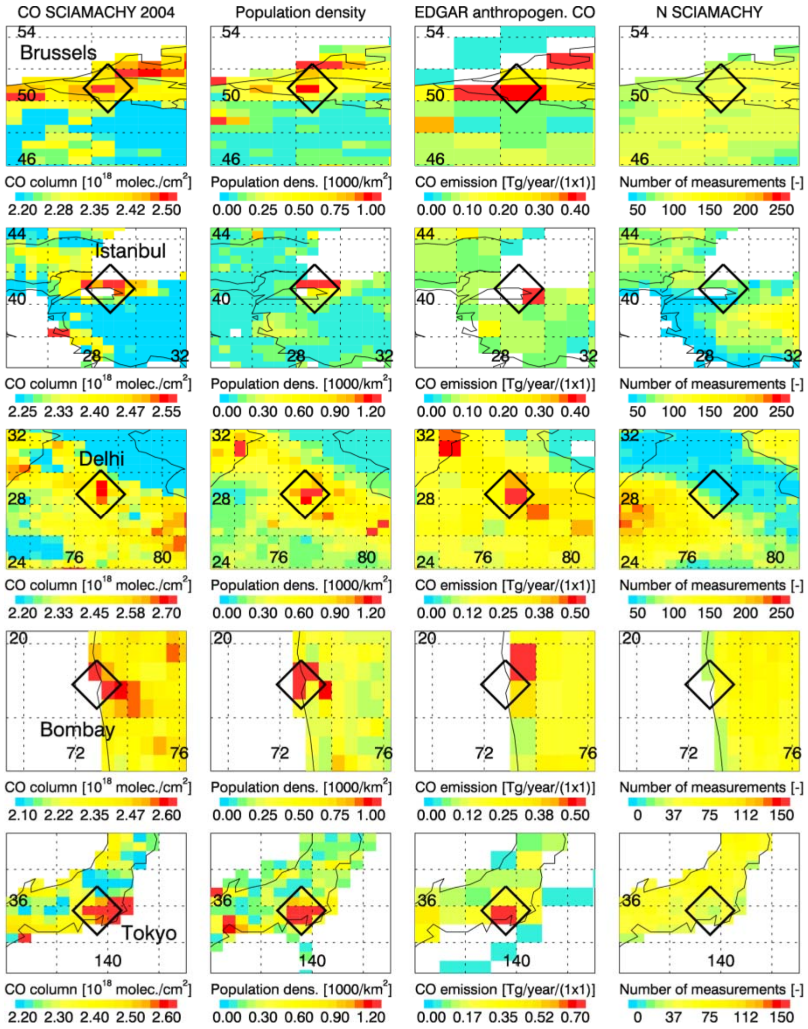


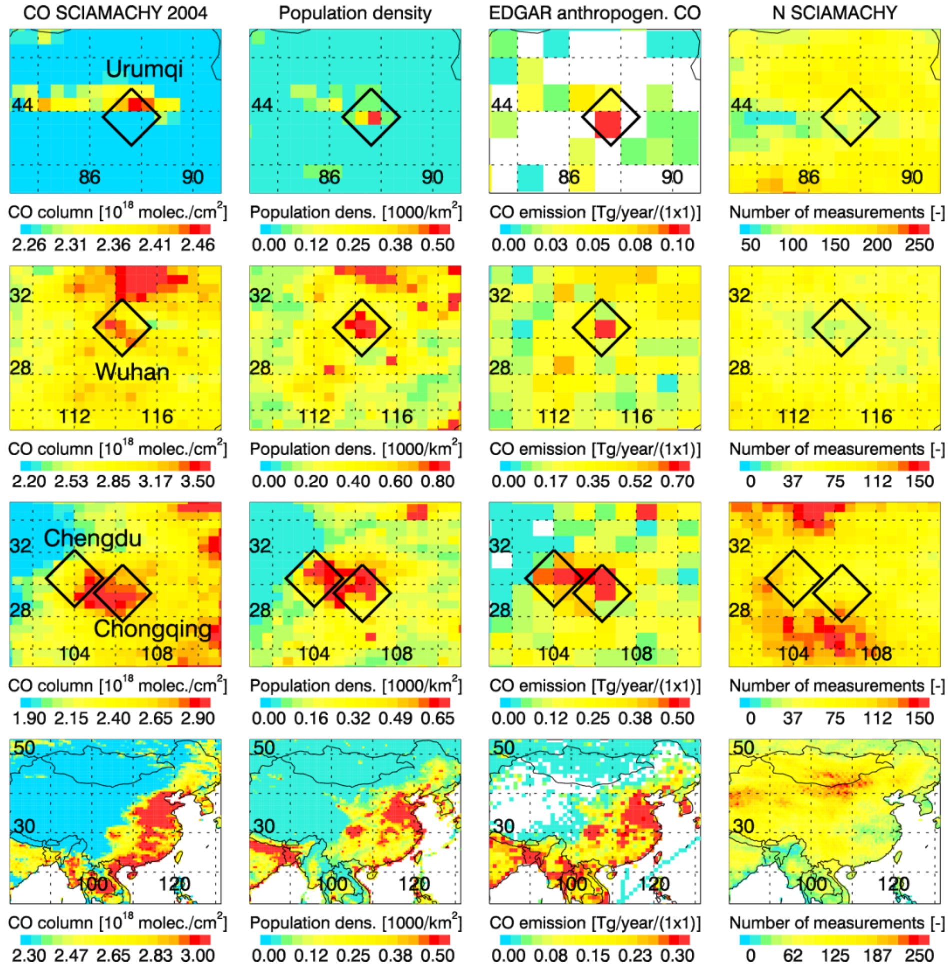
SCIAMACHY

Universität Bremen

iup

SCIAMACHY CO & cities - II

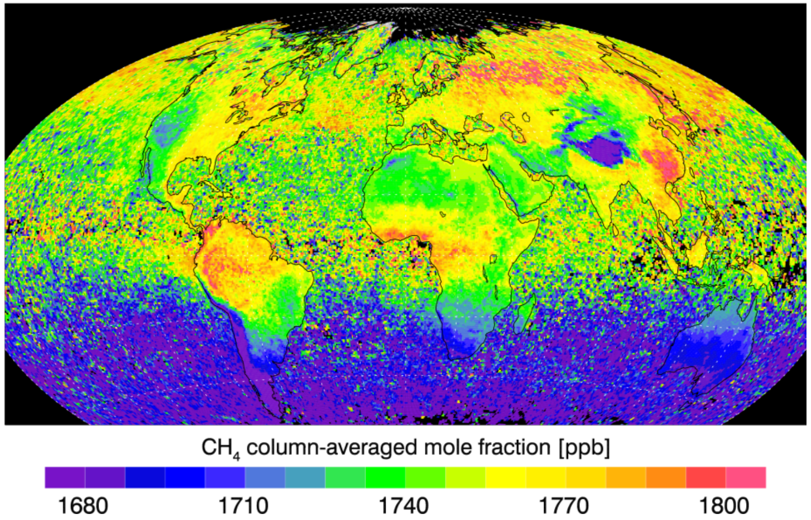


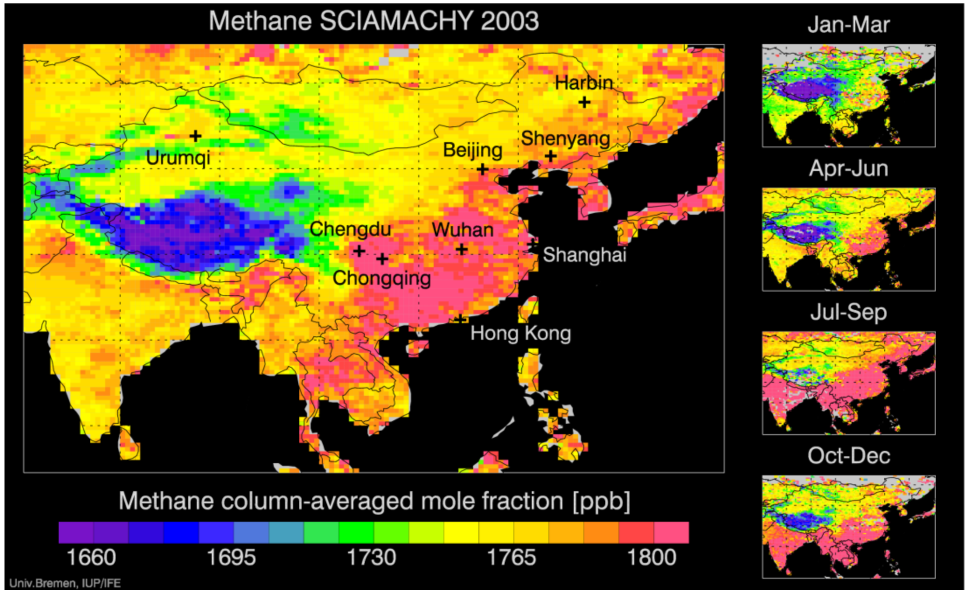


I. Khlystova, PhD thesis, 2010

SCIAMACHY methane (XCH_4)

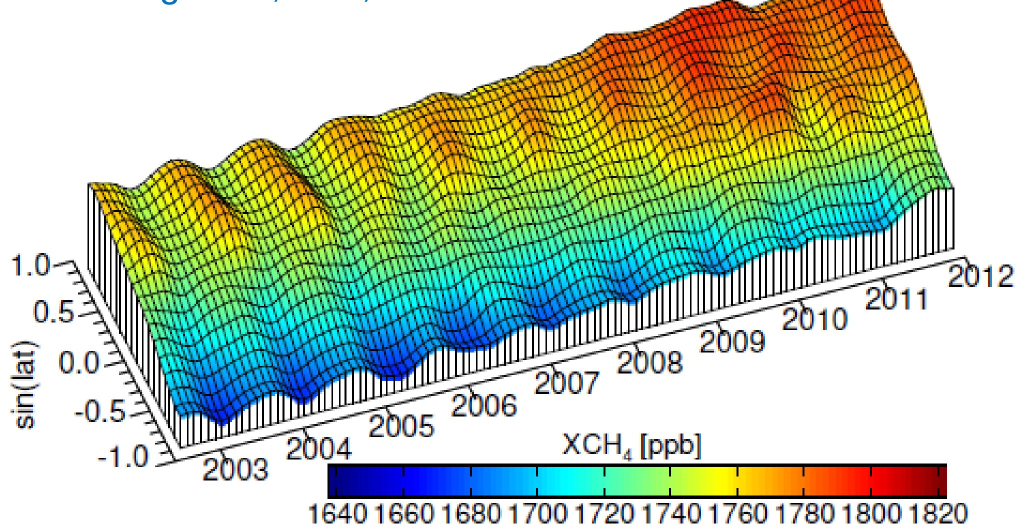
Methane SCIAMACHY/ENVISAT 2003-2005





- **Algorithm:** WFM-DOAS, „Proxy“ (reference gas: CO_2)
- **References:** Buchwitz et al., 2000, 2005, …, Schneising et al., 2009, 2012, …
- **Main issue:** Detector issues incl. severe degradation (esp. after 2005)

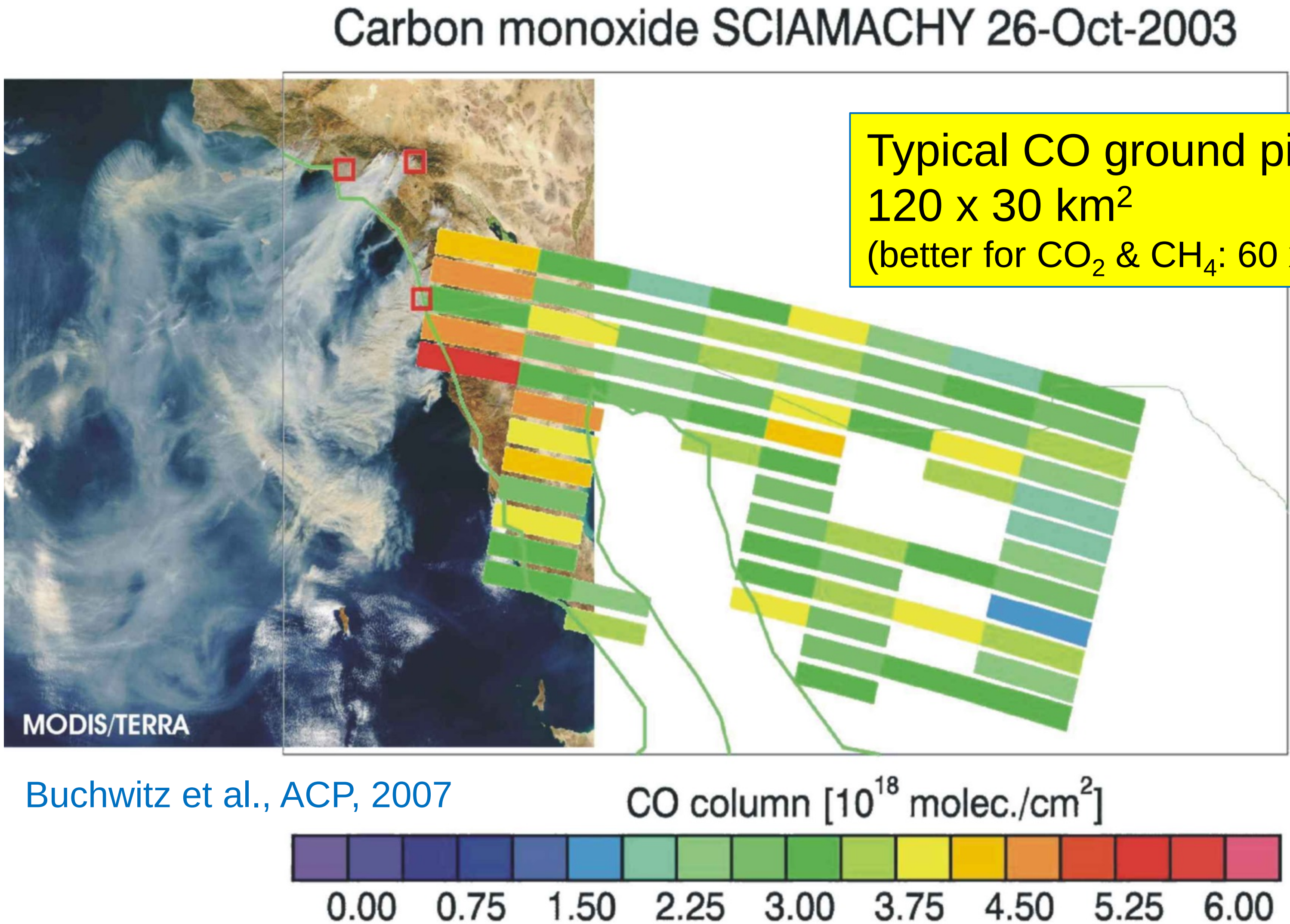
Schneising et al., ACP, 2012



Universität Bremen

iup

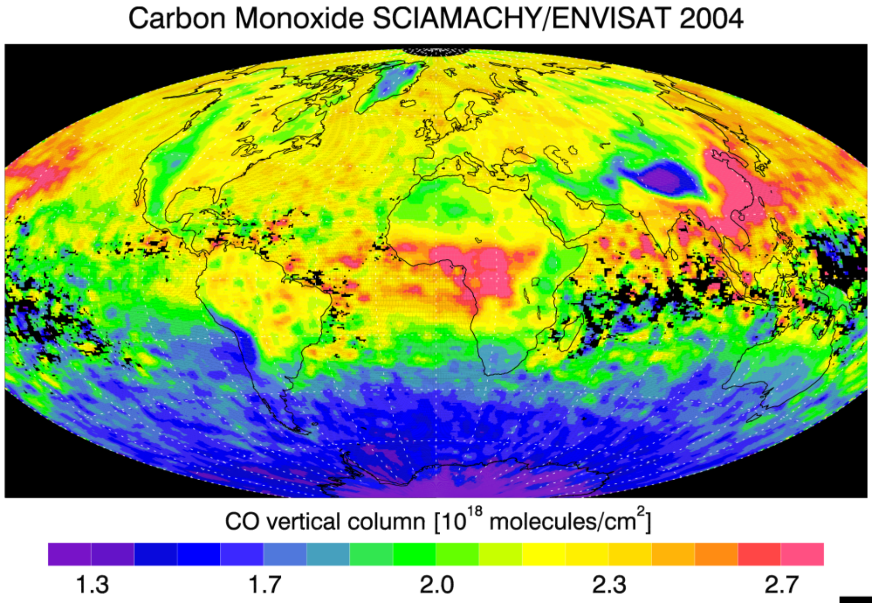
SCIACHY CO columns for single ground pixel

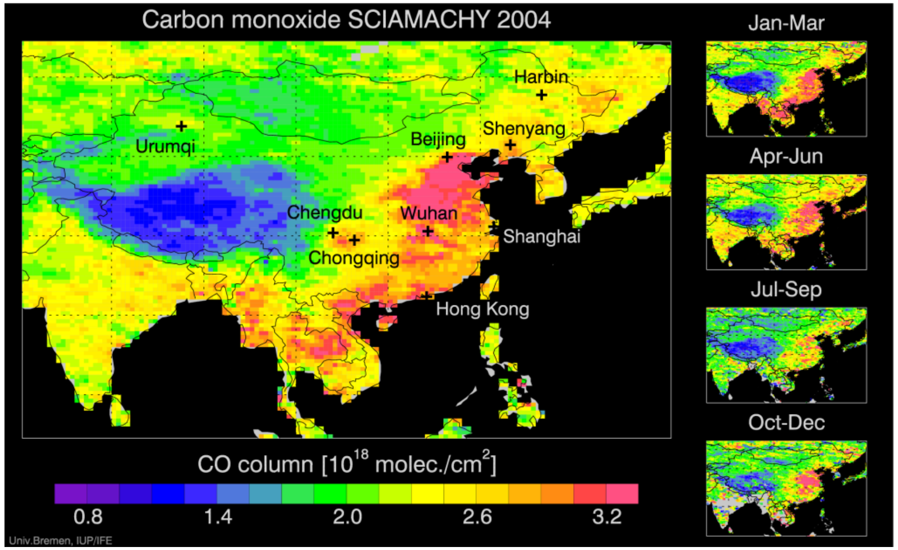


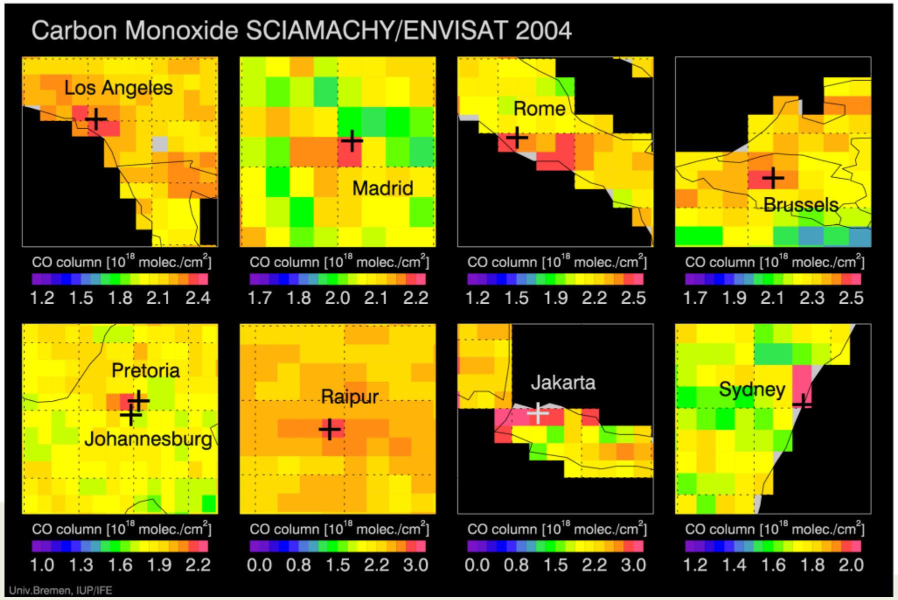
Typical CO ground pixel size:
120 x 30 km^2
(better for CO_2 & CH_4: 60 x 30 km^2)

Buchwitz et al., ACP, 2007

SCIAMACHY CO columns

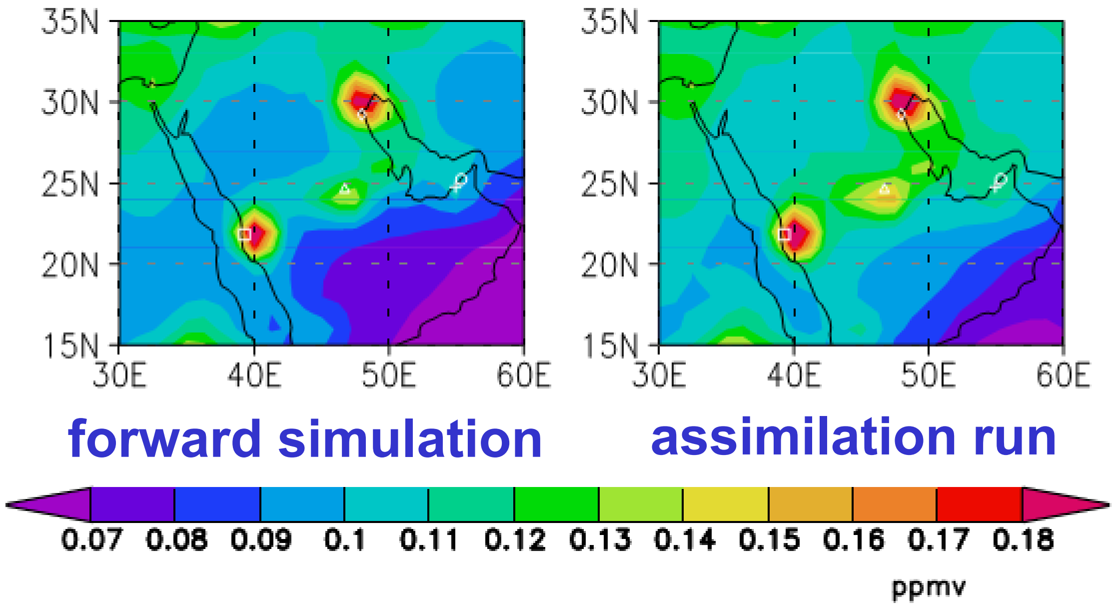






- **Algorithm:** WFM-DOAS, „Proxy“ (reference gas: CH_4)
- **References:** Buchwitz et al., 2000, 2004, …, 2007
- **Main issue:** Detector issues incl. severe degradation -> IUP analysis 2003-2005 „only“

SCIA CO used in regional inverse modelling



- CO field (ppmv) in the lowest model layer averaged over the period 1 September to 31 October 2004
- CO assimilation run using cloud-free SCIA observations in the Middle East.
- Cities: Kuwait City (diamond), Jeddah(square), Riyadh (triangle), Abu Dhabi (cross), and Dubai (circle)
- analysis suggests that CO emissions are significantly higher than those in the 1998 emissions inventory

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 114, D07307, doi:10.1029/2008JD010781, 2009

Click Here for Full Article

Assimilation of SCIAMACHY total column CO observations: Global and regional analysis of data impact

Andrew Tangborn,[1,2] Ivanka Stajner,[1,3] Michael Buchwitz,[4] Iryna Khlystova,[4] Steven Pawson,[1] John Burrows,[4,5] Rynda Hudman,[6,7] and Philippe Nedelec[8]

Universität Bremen

iup

SCIAMACHY CO & cities: Annual average 2004

SCIA CO | **Population** | **EDGAR** | **SCIA N**

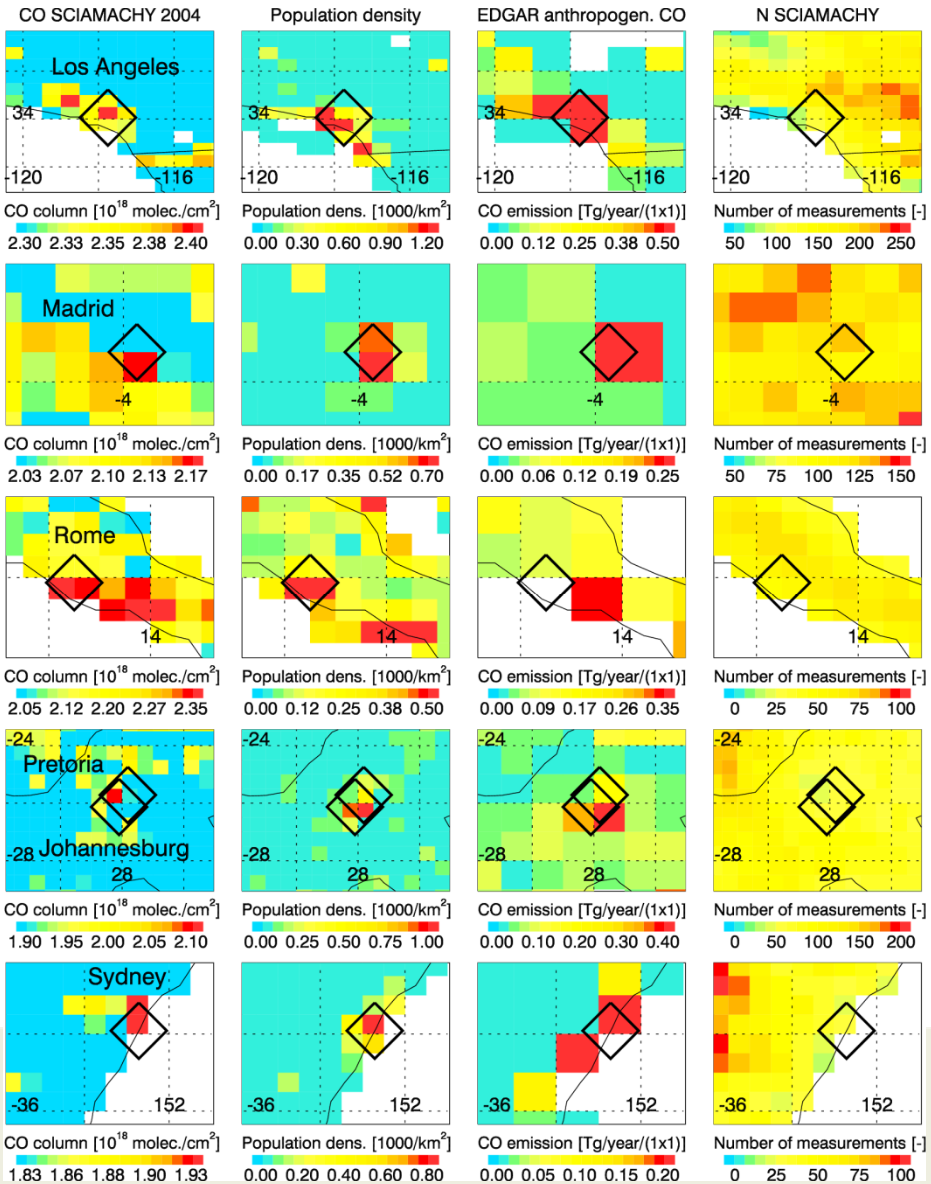
Los Angeles

Madrid

Rome

Pretoria / Johannesburg

Sydney



I. Khlystova,
PhD thesis, 2010

SCIAMACHY CO columns: Publications

Atmos. Chem. Phys., 10, 855–876, 2010
www.atmos-chem-phys.net/10/855/2010/

Atmospheric Chemistry and Physics

Kopacz et al., 2010

Global estimates of CO sources with high resolution by adjoint inversion of multiple satellite datasets (MOPITT, AIRS, SCIAMACHY, TES)

M. Kopacz[1,*], D. J. Jacob[1], J. A. Fisher[1], J. A. Logan[1], L. Zhang[1], I. A. Megretskaia[1], R. M. Yantosca[1], K. Singh[2], D. K. Henze[3], J. P. Burrows[4], M. Buchwitz[4], I. Khlystova[4], W. W. McMillan[5], J. C. Gille[6], D. P. Edwards[6], A. Eldering[7], V. Thouret[8,9], and P. Nedelec[8,9]

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 114, D07307, doi:10.1029/2008JD010781, 2009

Click Here for Full Article

Tangborn et al., 2009

Assimilation of SCIAMACHY total column CO observations: Global and regional analysis of data impact

Andrew Tangborn,[1,2] Ivanka Stajner,[1,3] Michael Buchwitz,[4] Iryna Khlystova,[4] Steven Pawson,[1] John Burrows,[4,5] Rynda Hudman,[6,7] and Philippe Nedelec[8]

Atmos. Chem. Phys., 7, 2399–2411, 2007
www.atmos-chem-phys.net/7/2399/2007/

Atmospheric Chemistry and Physics

Buchwitz et al., 2007

Three years of global carbon monoxide from SCIAMACHY: comparison with MOPITT and first results related to the detection of enhanced CO over cities

M. Buchwitz, I. Khlystova, H. Bovensmann, and J. P. Burrows
Institute of Environmental Physics (IUP), University of Bremen FB1, Bremen, Germany

Atmos. Chem. Phys., 6, 2727–2751, 2006
www.atmos-chem-phys.net/6/2727/2006/

Atmospher Chemist and Physi

Buchwitz et al., 2006

Atmospheric carbon gases retrieved from SCIAMACHY by WFM-DOAS: version 0.5 CO and CH_4 and impact of calibration improvements on CO_2 retrieval

M. Buchwitz[1], R. de Beek[1], S. Noël[1], J. P. Burrows[1], H. Bovensmann[1], O. Schneising[1], I. Khlystova[1], M. Bruns[1], H. Bremer[1], P. Bergamaschi[2], S. Körner[3], and M. Heimann[3]

Atmos. Chem. Phys., 5, 3313–3329, 2005
www.atmos-chem-phys.org/acp/5/3313/
SRef-ID: 1680-7324/acp/2005-5-3313
European Geosciences Union

Atmospheric Chemistry and Physics

Buchwitz et al., 2005

Carbon monoxide, methane and carbon dioxide columns retrieved from SCIAMACHY by WFM-DOAS: year 2003 initial data set

M. Buchwitz[1], R. de Beek[1], S. Noël[1], J. P. Burrows[1], H. Bovensmann[1], H. Bremer[1], P. Bergamaschi[2], S. Körner[3], and M. Heimann[3]

004
5/

Atmospheric Chemistry and Physics

Buchwitz et al., 2004

Global carbon monoxide as retrieved from SCIAMACHY by WFM-DOAS

M. Buchwitz, R. de Beek, K. Bramstedt, S. Noël, H. Bovensmann, and J. P. Burrows
Institute of Environmental Physics (iup), University of Bremen FB1, Bremen, Germany

Received: 18 March 2004 – Published in Atmos. Chem. Phys. Discuss.: 19 May 2004
Revised: 24 September 2004 – Accepted: 27 September 2004 – Published: 30 September 2004

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 105, NO. D12, PAGES 15,231–15,245, JUNE 27, 2000

Buchwitz et al., 2000

A near-infrared optimized DOAS method for the fast global retrieval of atmospheric CH_4, CO, CO_2, H_2O, and N_2O total column amounts from SCIAMACHY Envisat-1 nadir radiances

Michael Buchwitz, Vladimir V. Rozanov, and John P. Burrows
Institut für Fernerkundung, Universität Bremen, Bremen, Germany

SCIAMACHY CO_2 over anthropogenic source regions - I

Atmos. Chem. Phys., 13, 2445–2454, 2013
www.atmos-chem-phys.net/13/2445/2013/
doi:10.5194/acp-13-2445-2013

Atmospheric Chemistry and Physics
Open Access

Schneising et al., 2013

Anthropogenic carbon dioxide source areas observed from space: assessment of regional enhancements and trends

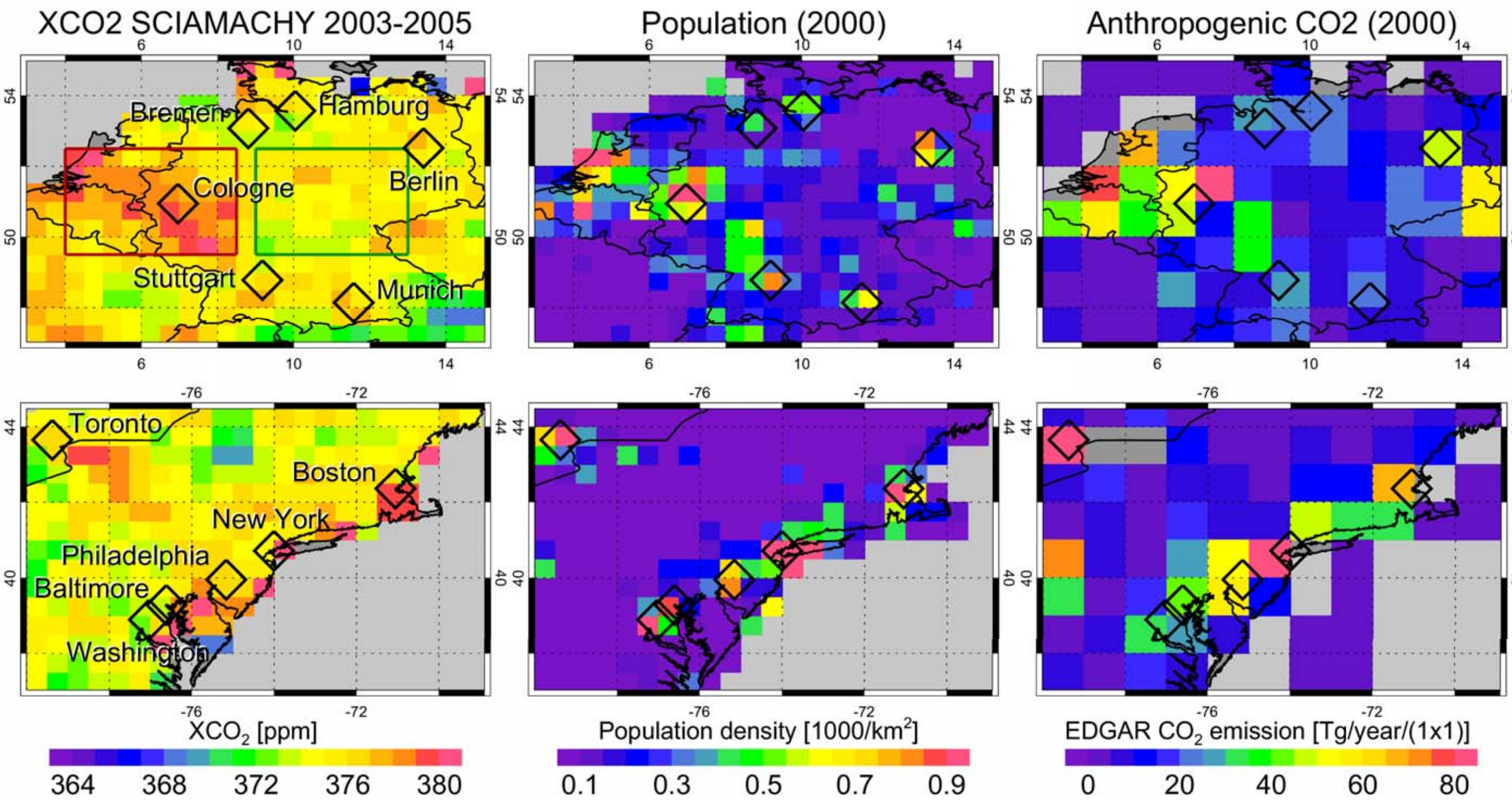
O. Schneising, J. Heymann, M. Buchwitz, M. Reuter, H. Bovensmann, and J. P. Burrows

Institute of Environmental Physics (IUP), University of Bremen FB1, Bremen, Germany

Correspondence to: O. Schneising (oliver.schneising@iup.physik.uni-bremen.de)

Received: 13 November 2012 – Published in Atmos. Chem. Phys. Discuss.: 6 December 2012
Revised: 21 February 2013 – Accepted: 22 February 2013 – Published: 4 March 2013

SCIA CO_2 over anthropogenic source regions: 1st results



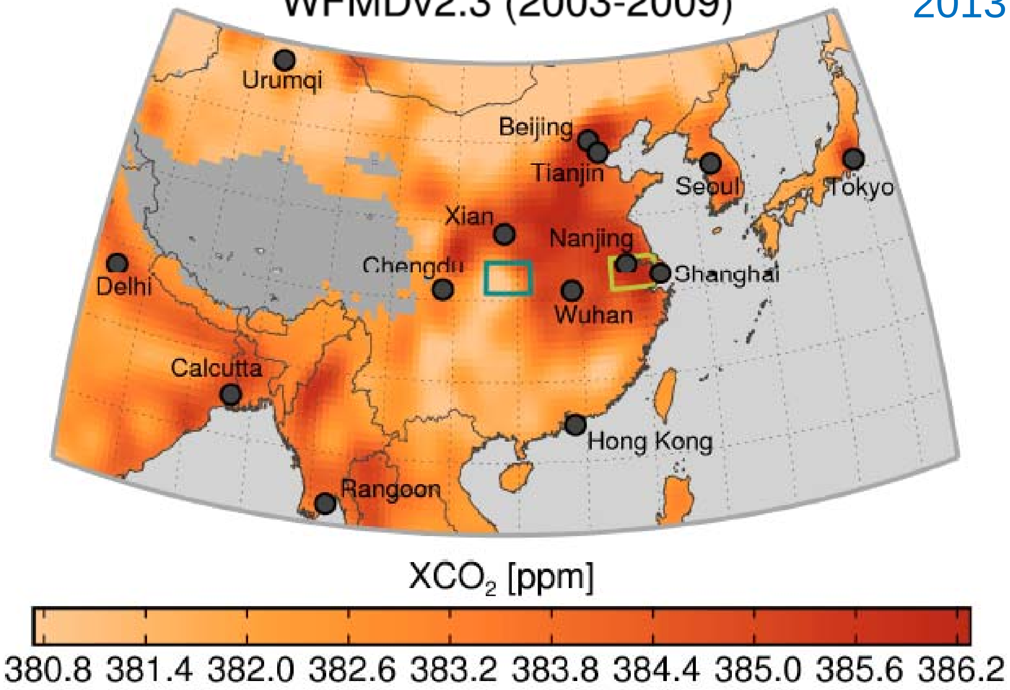
Algorithm: WFMD (Schneising et al., 2008)

Universität Bremen

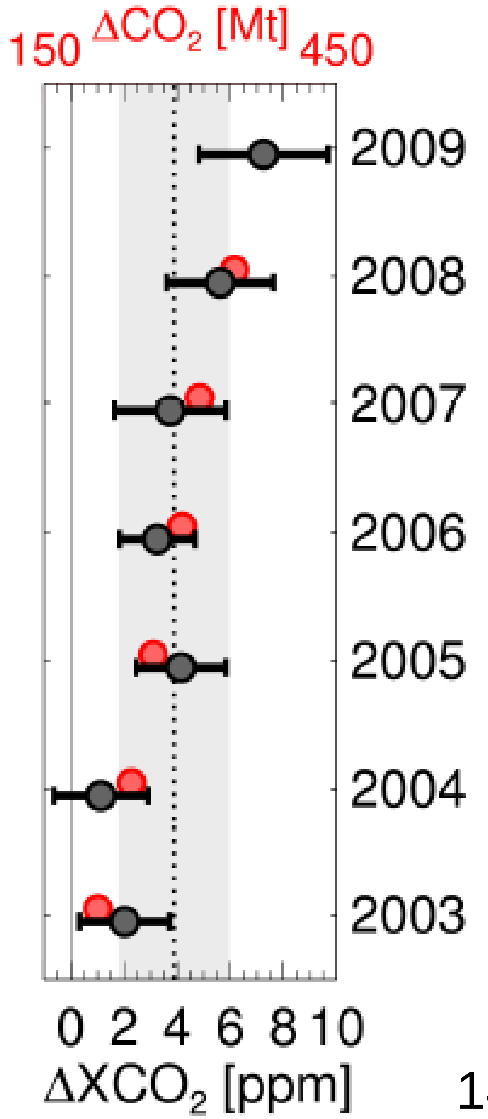
iup

SCIAMACHY CO_2 over anthropogenic source regions - II

SCIAMACHY XCO_2
WFMDv2.3 (2003-2009)

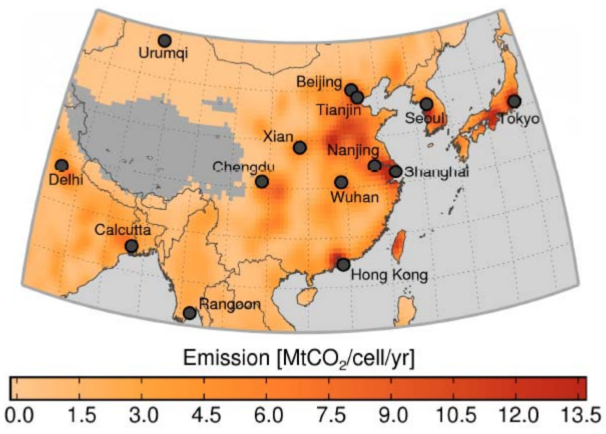


Schneising et al., 2013



EDGAR CO_2 emissions

EDGAR v4.2

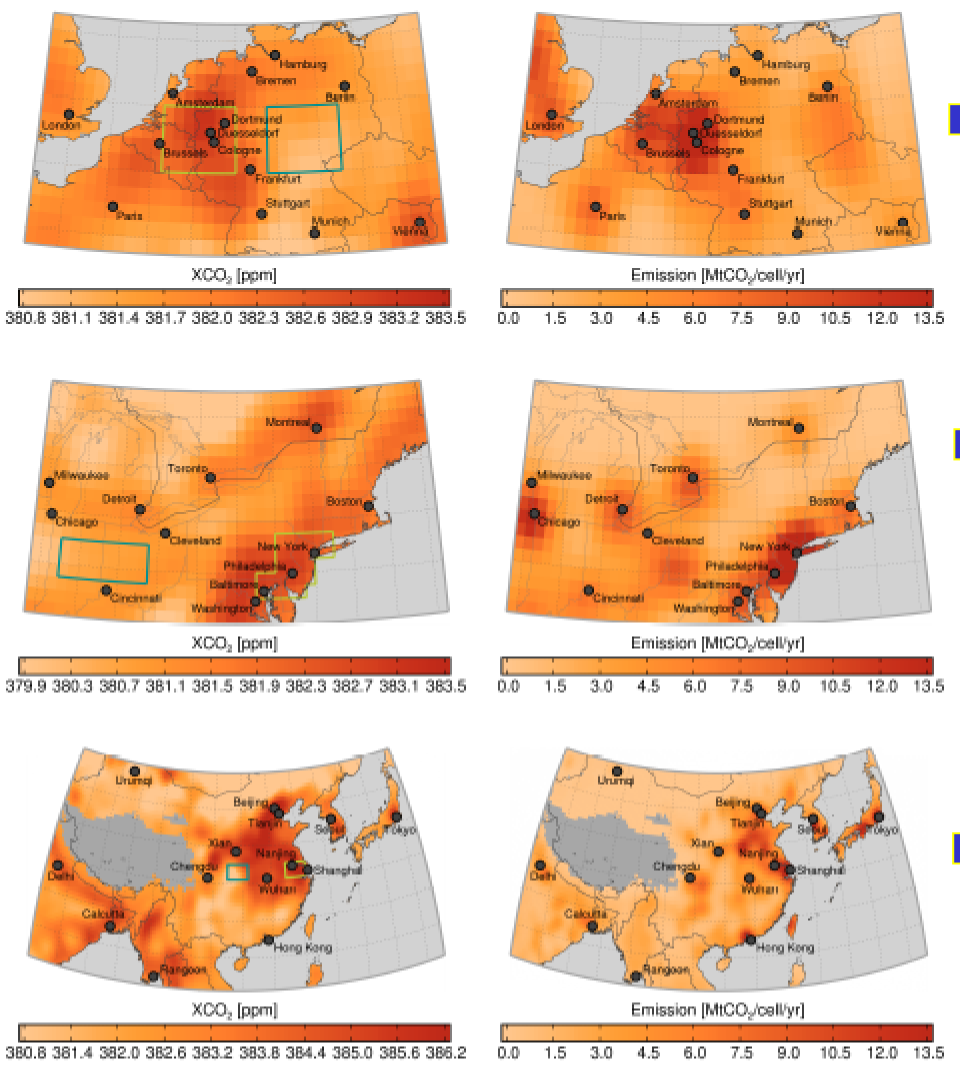


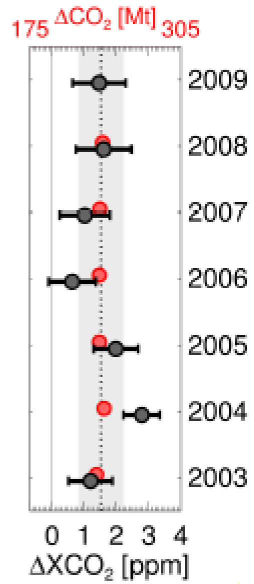
SCIAMACHY CO_2 over anthropogenic source regions - III

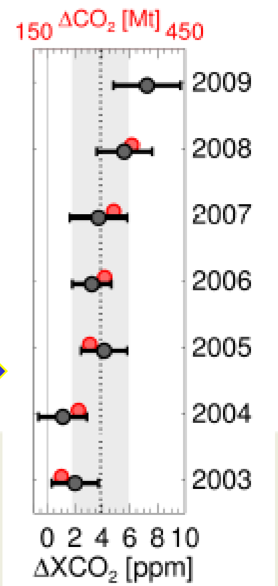
Schneising et al., 2013

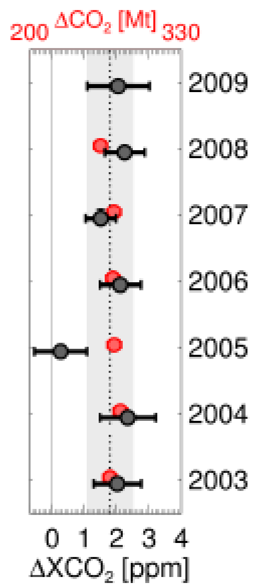
SCIAMACHY XCO_2

EDGAR CO_2 emissions

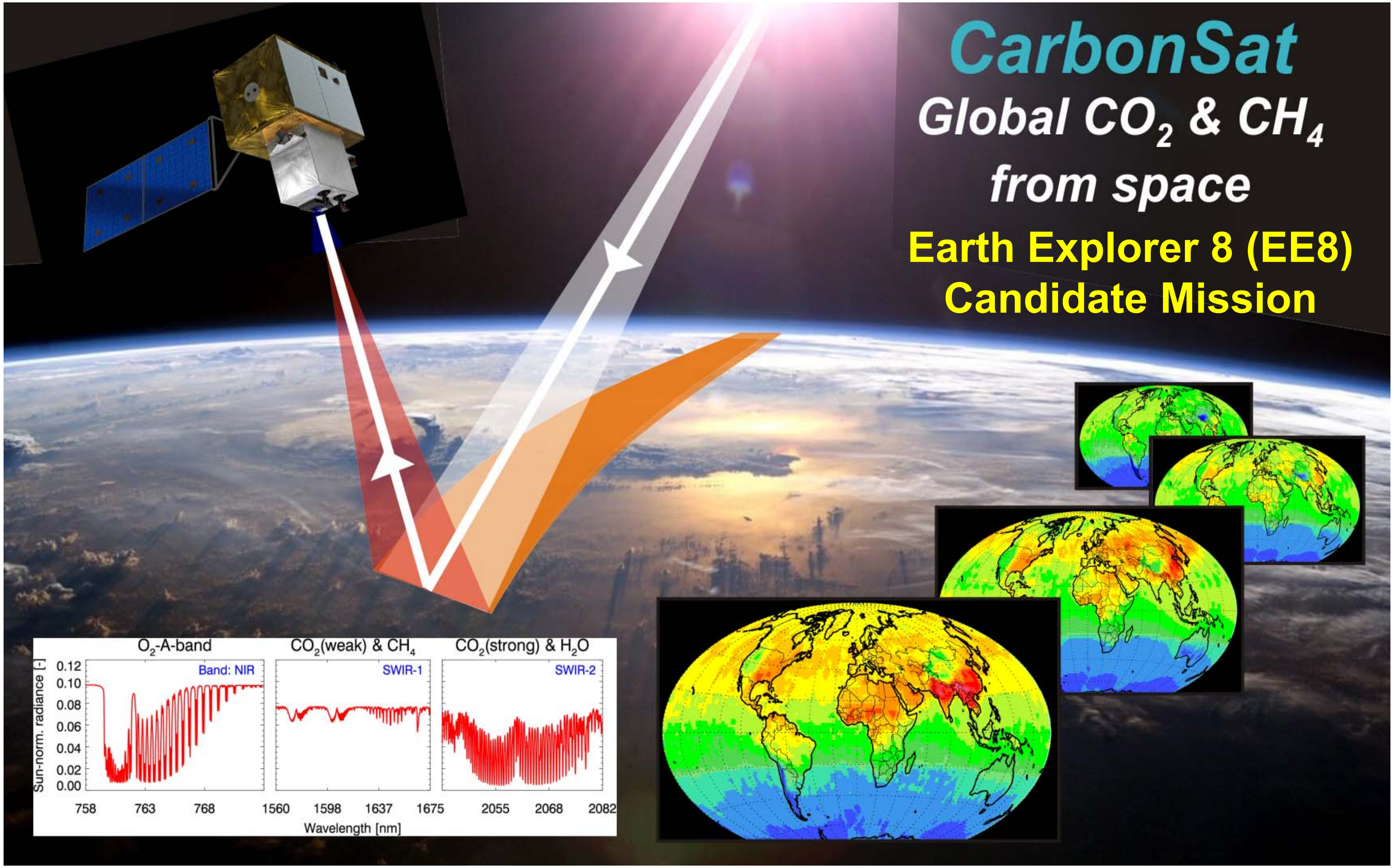








Beyond ENVISAT ?

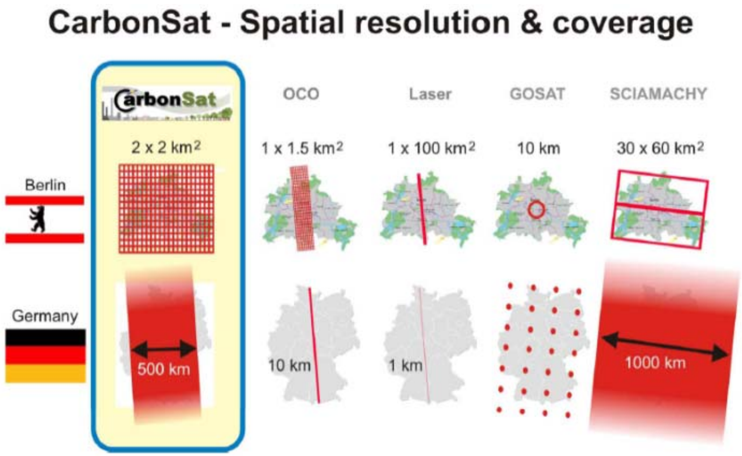


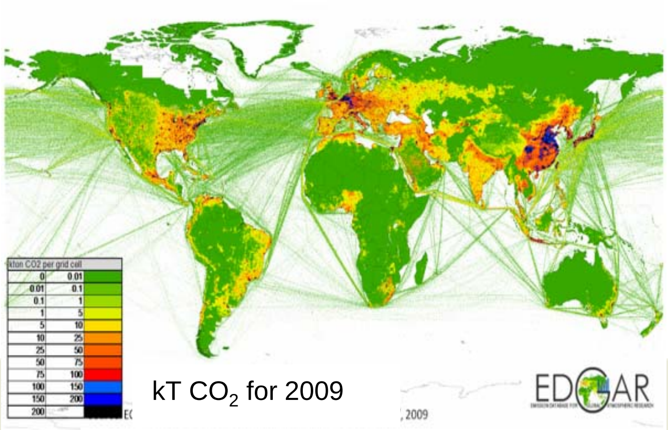
CarbonSat Mission Goals

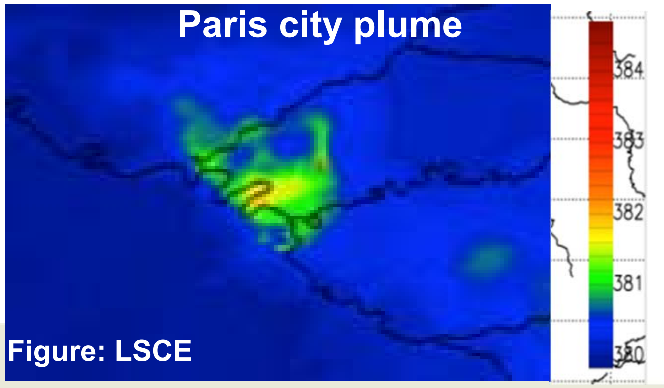
CarbonSat aims at better separating natural and anthropogenic fluxes with global **XCO2 and XCH4** (secondary: vegetation fluorescence) data and **“imaging”** of strong localised CO2 and CH4 emission areas.

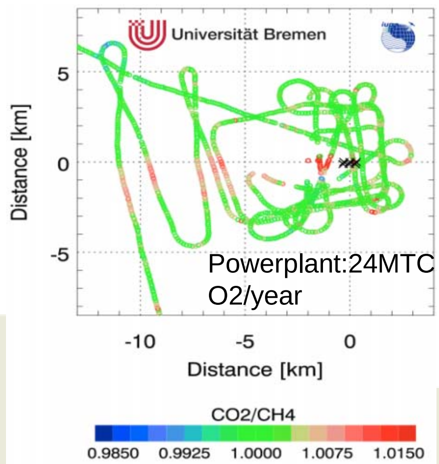
In combination with **inverse modelling** and robust **validation (TCCON)** this will address:

- Better top-down constrain on regional and country scale flux inversions (mainly natural fluxes)
- **New: MegaCity scale top-down constraints**
- **New: local scale top-down constraint**









CarbonSat Mission Requirements

Data Products

- XCO2 precision 1-3 ppm, accuracy < 0.3 (G) / 0.5 (T) ppm
- XCH4 : goal 6 ppb precision & < 3 ppb accuracy (threshold: 12 ppb/5 ppb)
- Secondary (tbc) products:
  Vegetation Chlorophyll Fluorescence, Aerosol, Cirrus, H2O, psurface

Orbit: LEO polar-sun-sync, AM ~11:30

High spatial resolution AND coverage:

- 2×2 km^2 ground pixel (threshold)
- Swath: 240 km breakthrough, 500 km (goal)

Measurement Modes:

- Nadir imaging, glint, calibration modes

Mission Lifetime: 3-5 years

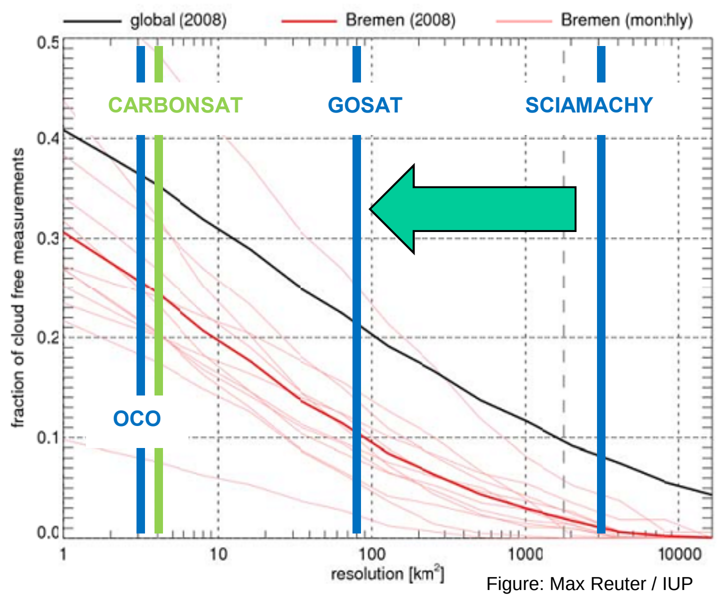
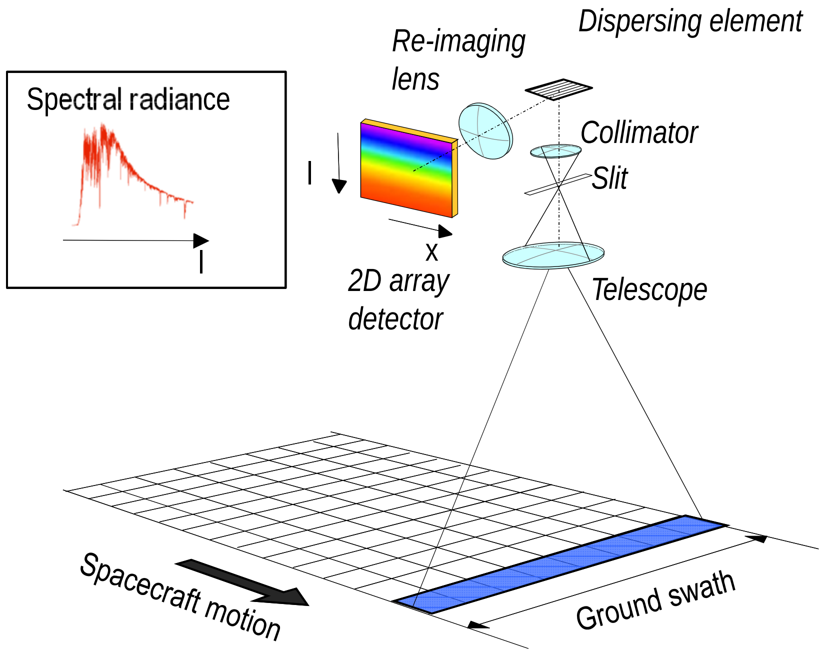


Figure: Max Reuter / IUP

CarbonSat Number of Clear-Sky Observations				
Instrument	Spatial resolution [km^2]	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

CarbonSat Instrument Concept

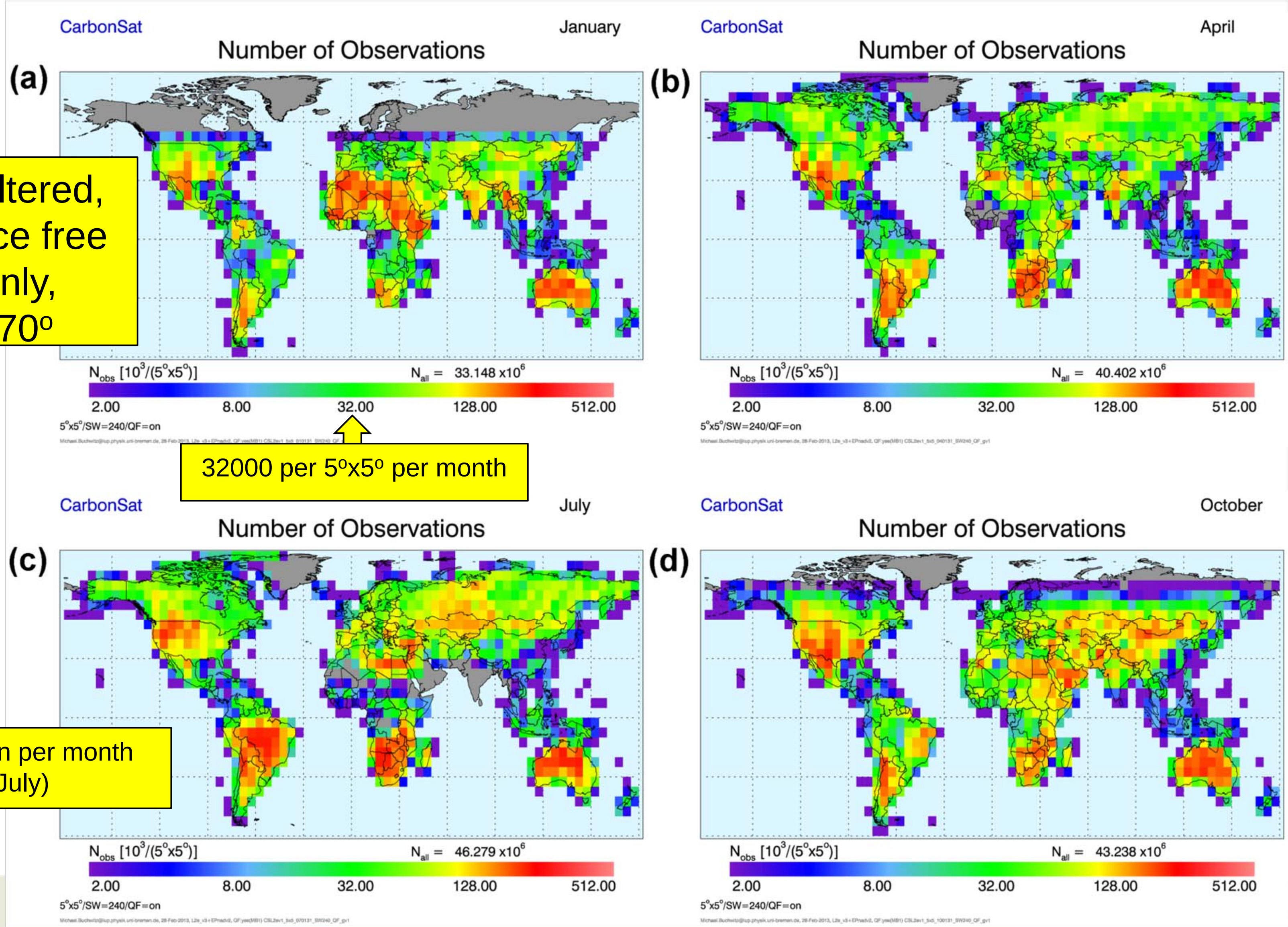
	Band		
	NIR	**SWIR-1**	**SWIR-2**
Data Products	aerosol, cloud, p_{surf}, fluorescence	CO_2, , CH_4,	CO_2, H_2O scattering correction, cirrus
	spectral requirements		
Spectral range [nm]	747 – 773	1590 – 1675	1925 – 2095
Spectral resolution [nm]	0.1	0.3	0.55
Spectral Sampling	3 – 6	3 - 6	3 – 6
	parameters for the SNR requirement		
L_{ref} [phot/s/nm/cm²/sr]	3.0 x 10^{12}	1.0 x 10^{12}	3.0 x 10^{11}
SNR_{ref} (T)	150	160	130
SNR_{ref} (G)	300	320	260



- Pushbroom (across track), along track scanning via spacecraft motion
- 3 imaging grating spectrometers with good spatial and spectral imaging capabilitities
- 2-D detectors cooled
- High SNR
- High performance on-board calibration sources (diffusers, lamp, LED, tbc)

CarbonSat: Nobs (monthly, 5ºx5º, swath=240 km)

Quality filtered, snow & ice free land only, SZA<70º



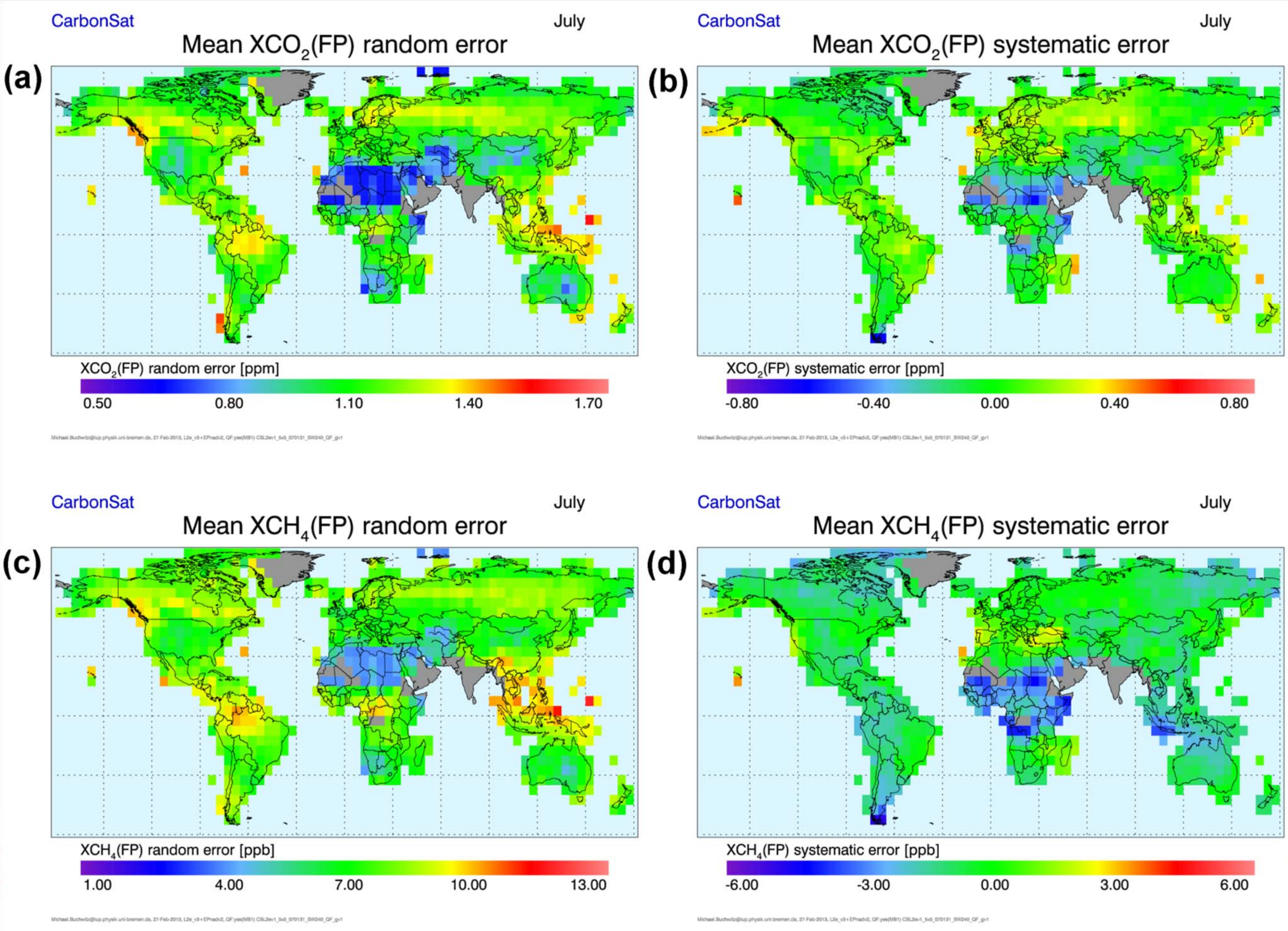
32000 per 5ºx5º per month

46 million per month (July)

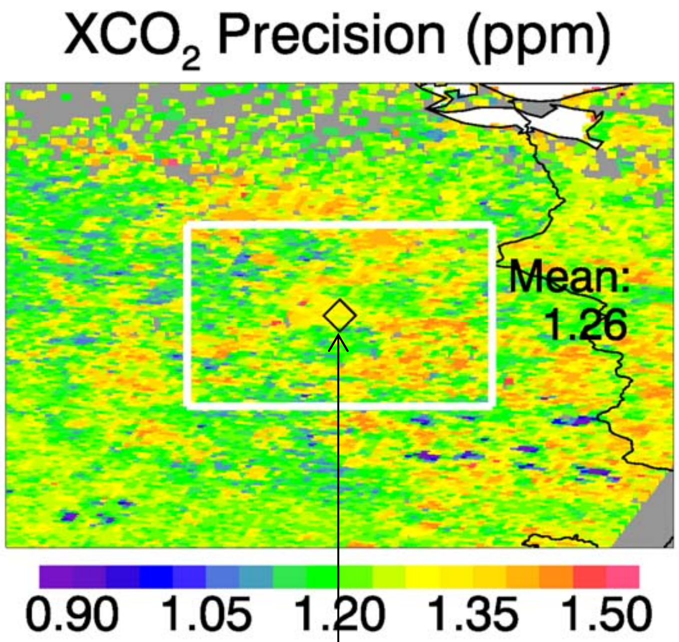
Universität Bremen

Buchwitz et al., AMT (submitted)

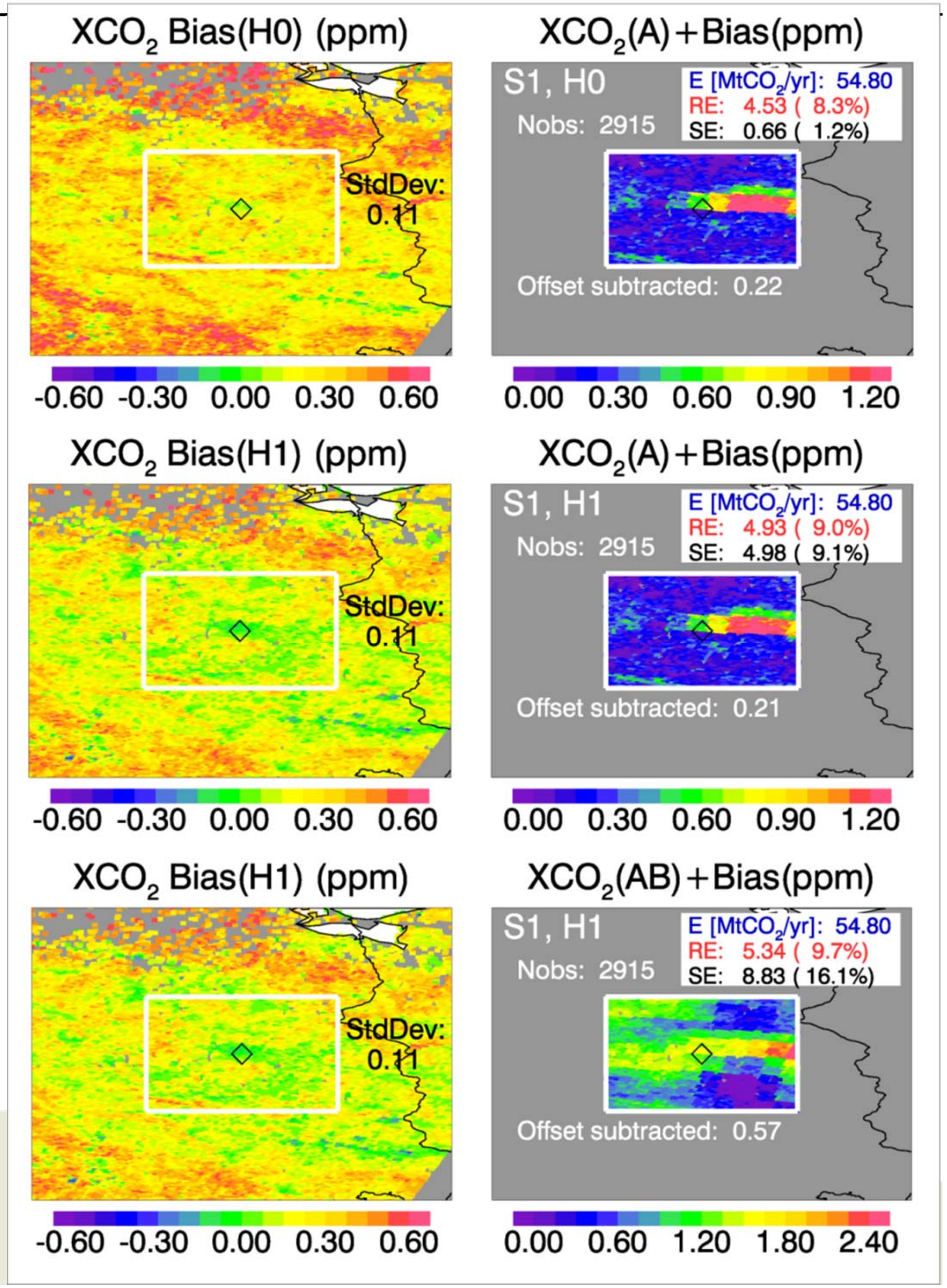
XCO2 and XCH4 errors: Monthly, 5ºx5º, 240 km



Let's zoom into city scale: Berlin

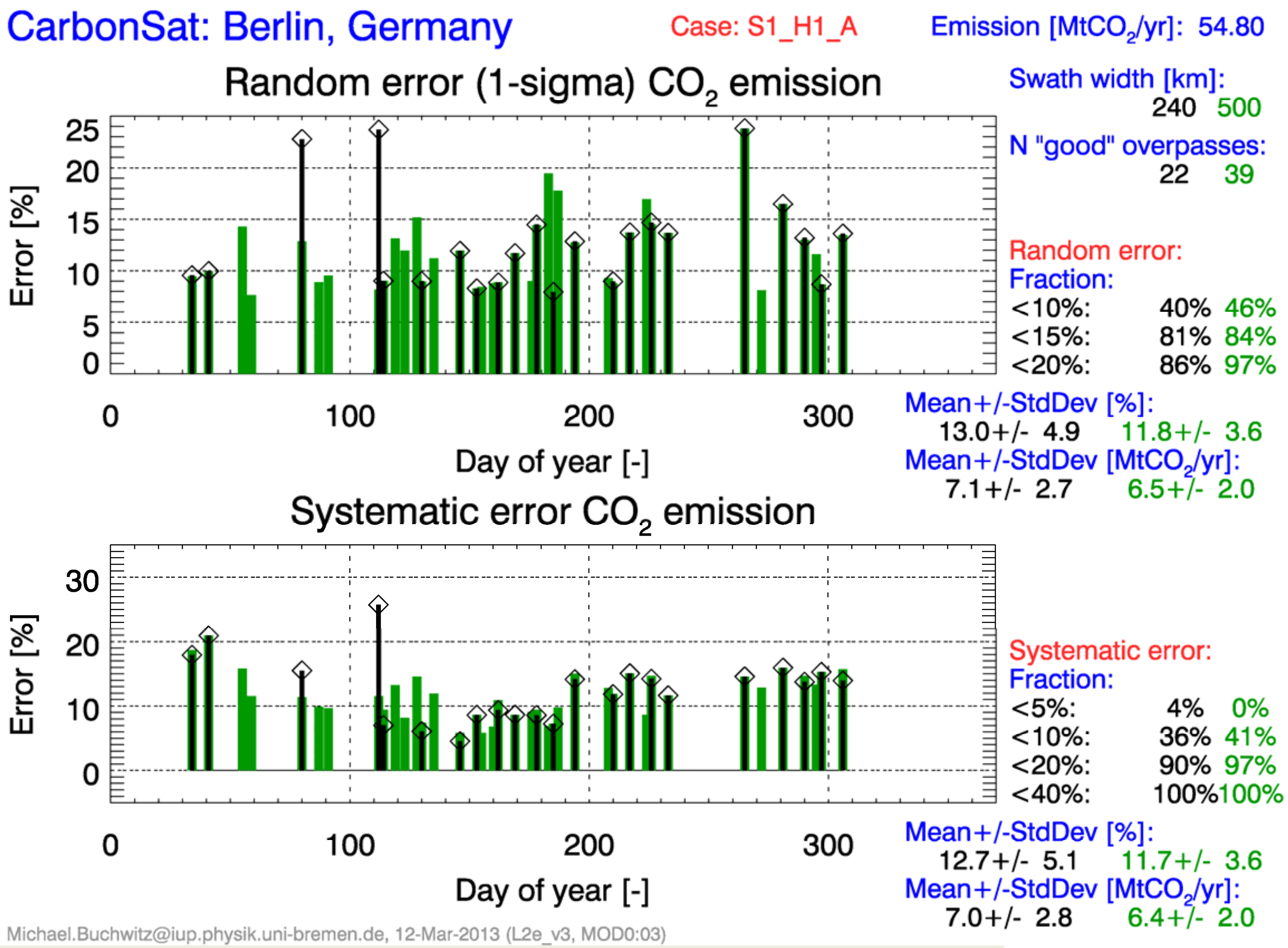


Error single overpass: 5-10 MtCO2/yr (10-20%)



CarbonSat: Berlin CO_2 emissions - II

5 $MtCO_2/yr$
(10% for Berlin)



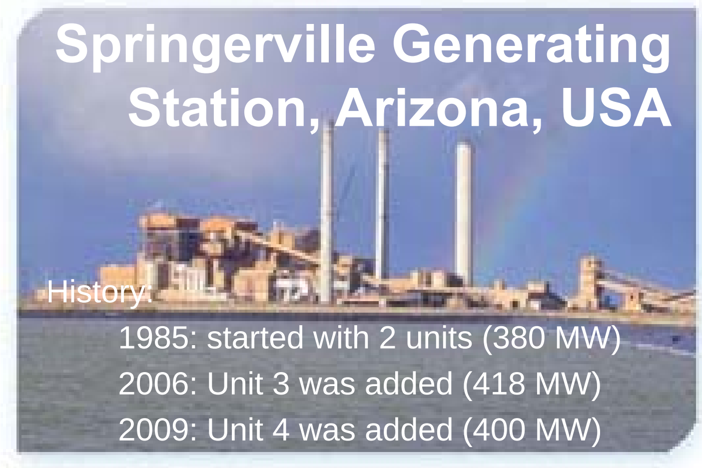
5 $MtCO_2/yr$
(10% for Berlin)

Universität Bremen

Buchwitz et al., AMT (submitted)

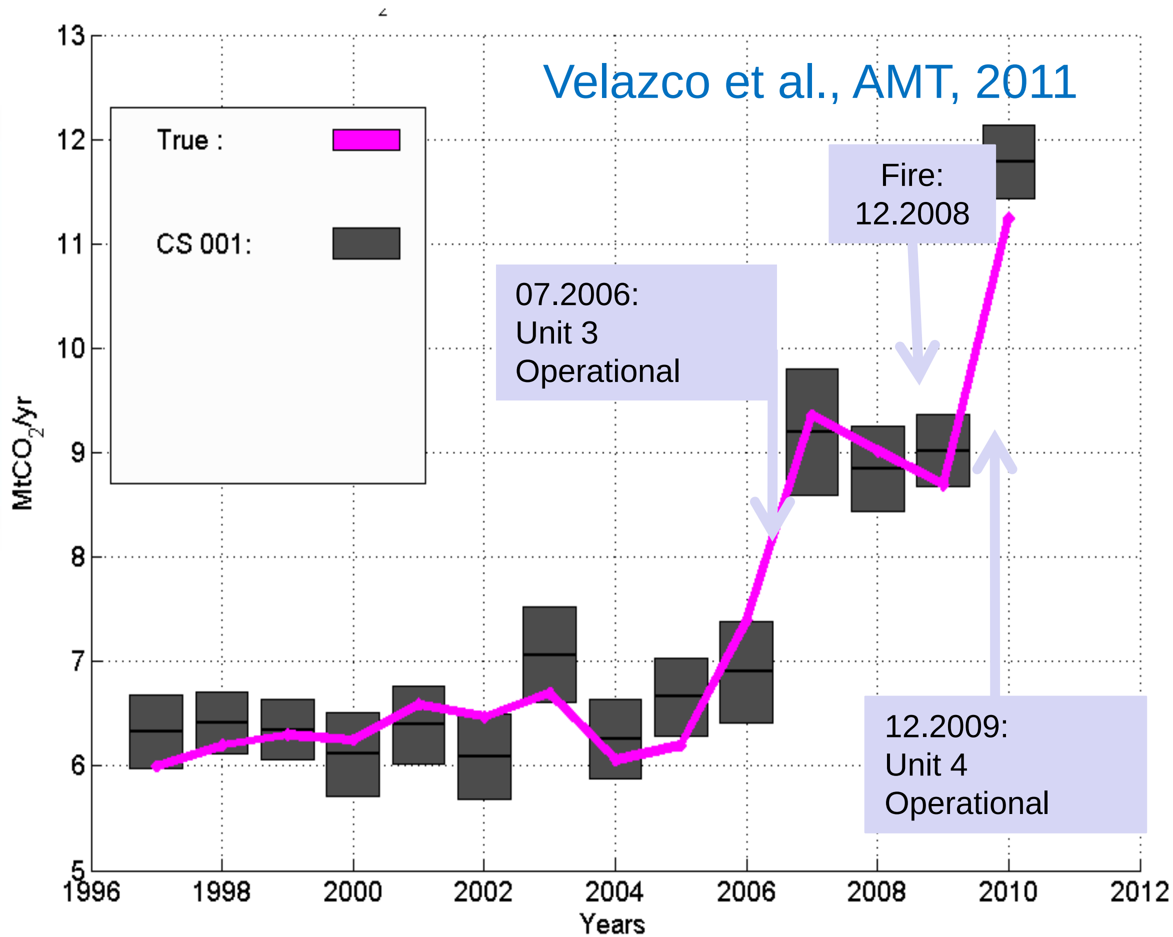
Power Plant Emissions – Facility Level Monitoring

Example: Coal fired Power Plant:



True annual emission

CarbonSat

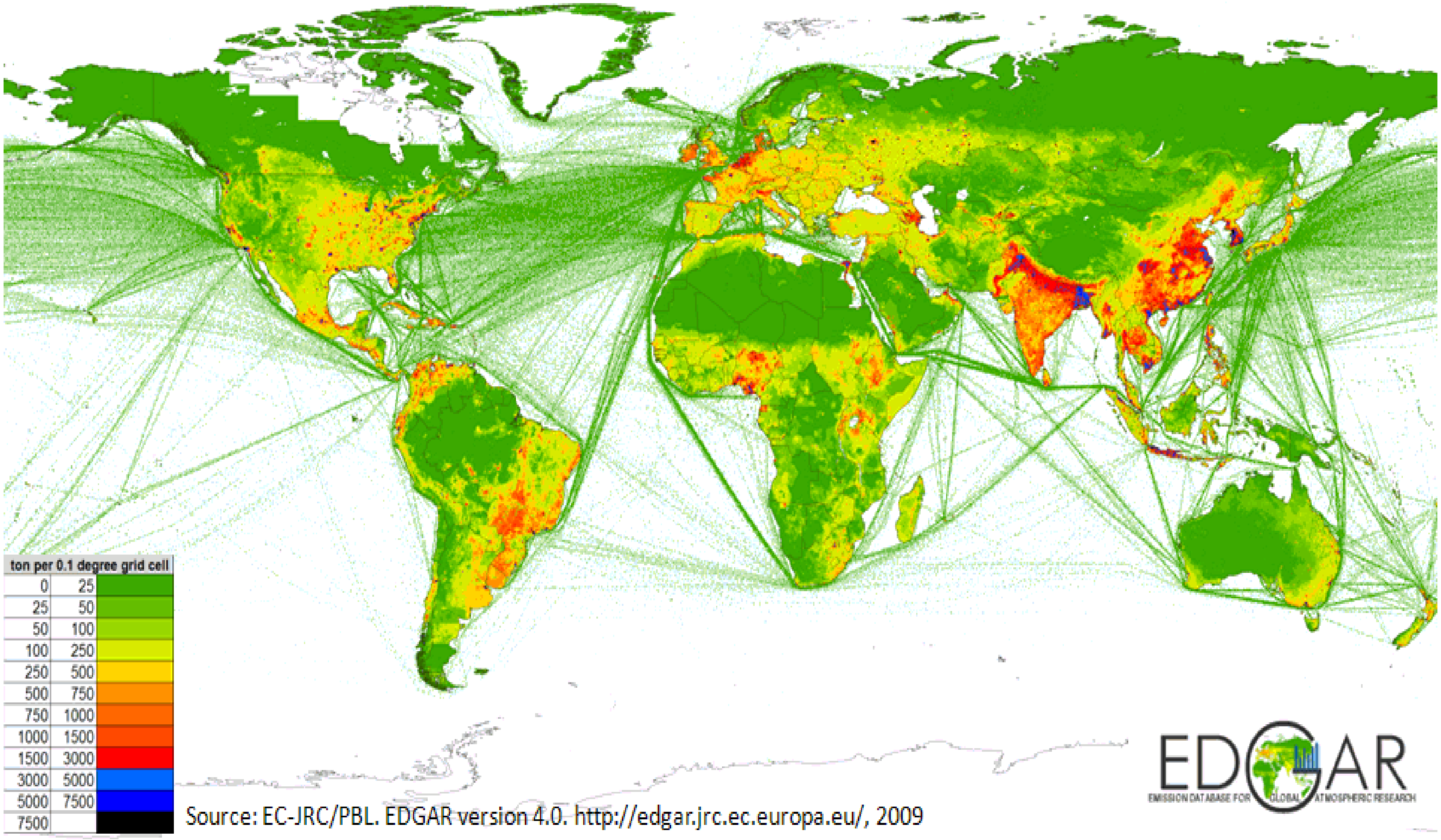


Towards space based verification of CO_2 emissions from strong localized sources: fossil fuel power plant emissions as seen by a CarbonSat constellation

V. A. Velazco[1,*], M. Buchwitz[1], H. Bovensmann[1], M. Reuter[1], O. Schneising[1], J. Heymann[1], T. Krings[1], K. Gerilowski[1], and J. P. Burrows[1]

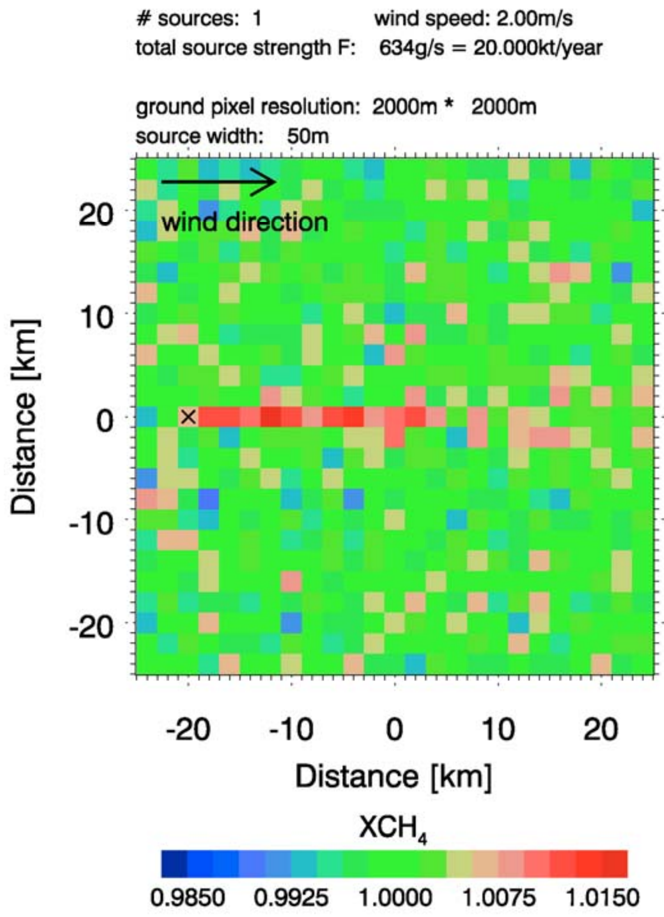
[1]Institute of Environmental Physics (IUP), University of Bremen, 28359 Bremen, Germany
[*]now at: Center for Atmospheric Chemistry, University of Wollongong, Wollongong, NSW 2500, Australia

Methane emissions are often localised

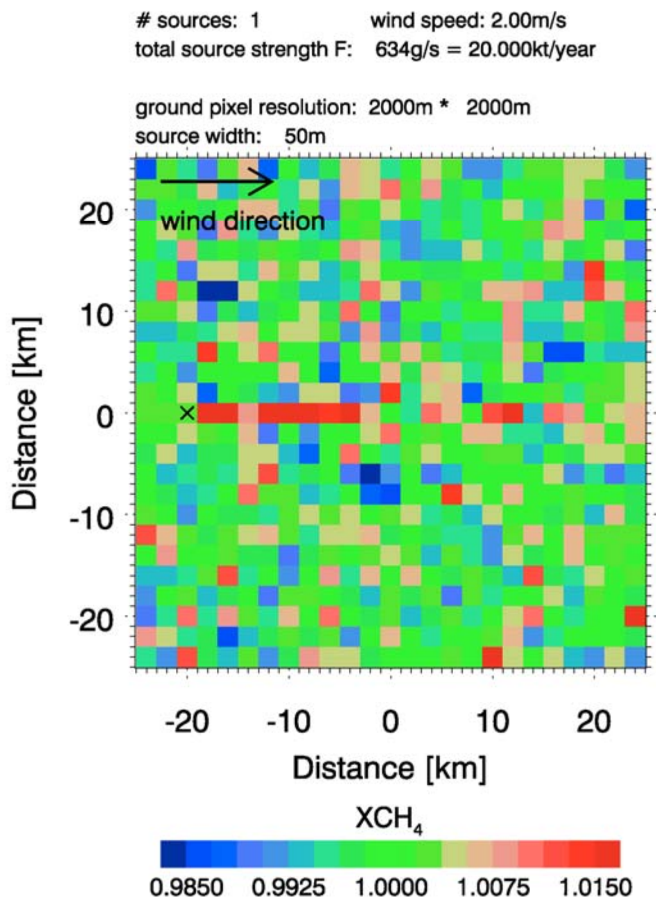


Source: EC-JRC/PBL. EDGAR version 4.0. http://edgar.jrc.ec.europa.eu/, 2009

Example: CH_4 @ 2 km

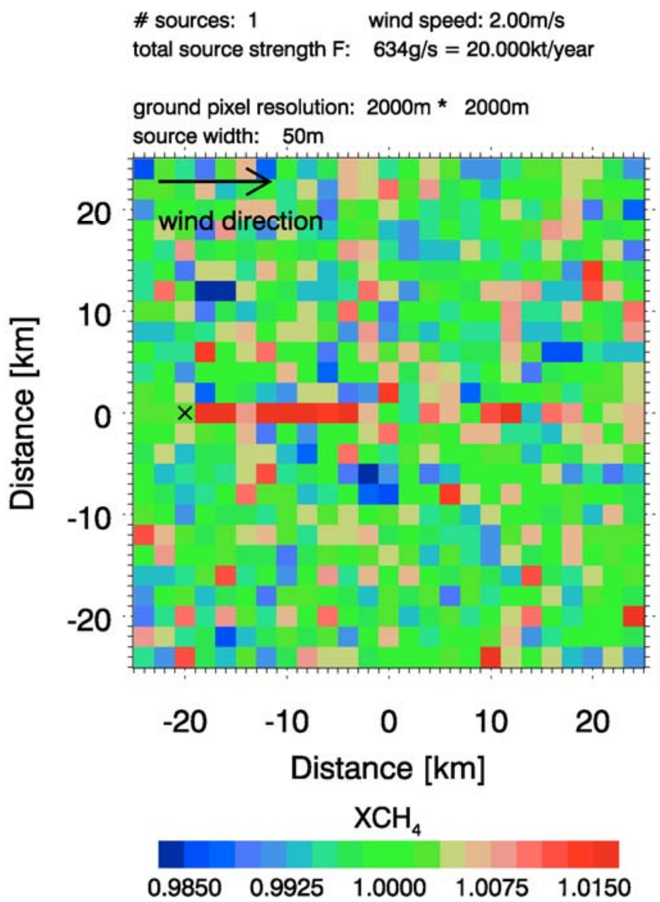


Noise : 6 ppb
Error in emission: 1.3 ktCH4/yr

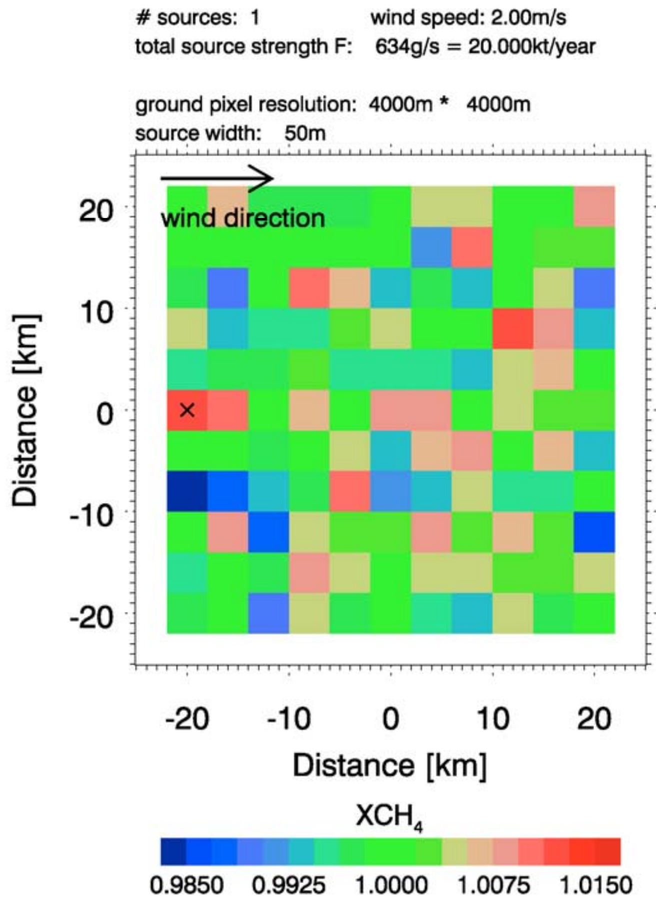


Noise : 10 ppb
Error in emission: 2.3 ktCH4/yr

Example: CH_4 2 km vs. 4 km



Noise : 10 ppb
Error in emission: 2.3 ktCH4/yr



Noise : 10 ppb
Error in emission: 5.3 ktCH4/yr

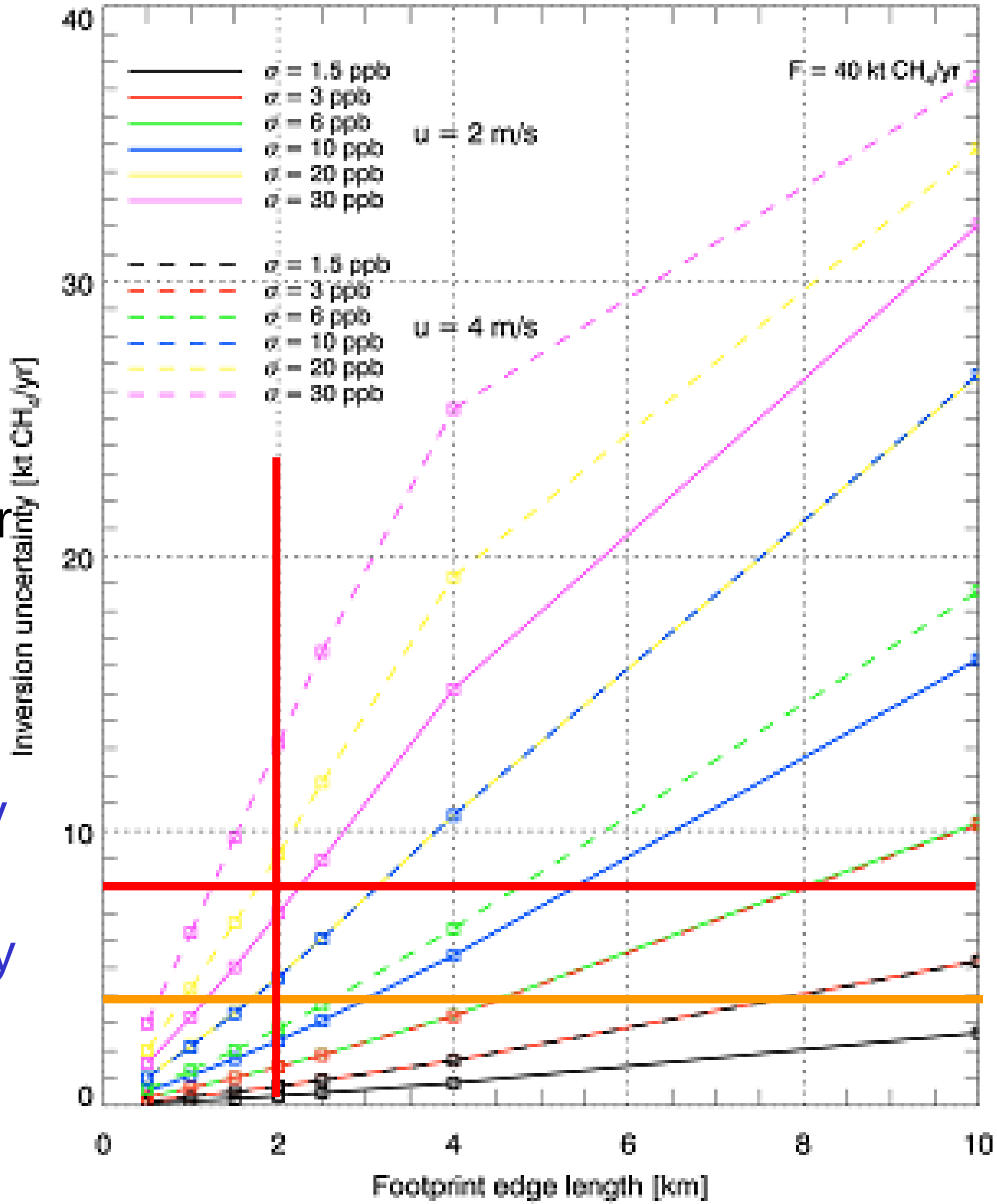
CH_4 inversion uncertainty for 40 kt CH_4 /yr

Inversion sensitivity as a function of:

- **footprint edge length l**
- **single measurement precision σ**
- **wind speed u**
- fixed emission rate 40kt CH4 /yr

For 40 kt, 4 m/s (surface)

- 2 km -> 4 km:
- T prec. 20 ppb -> ~6 ppb to maintain T emission uncertainty
- G prec. 10 ppb -> ~ 3 ppb to maintain G emission uncertainty

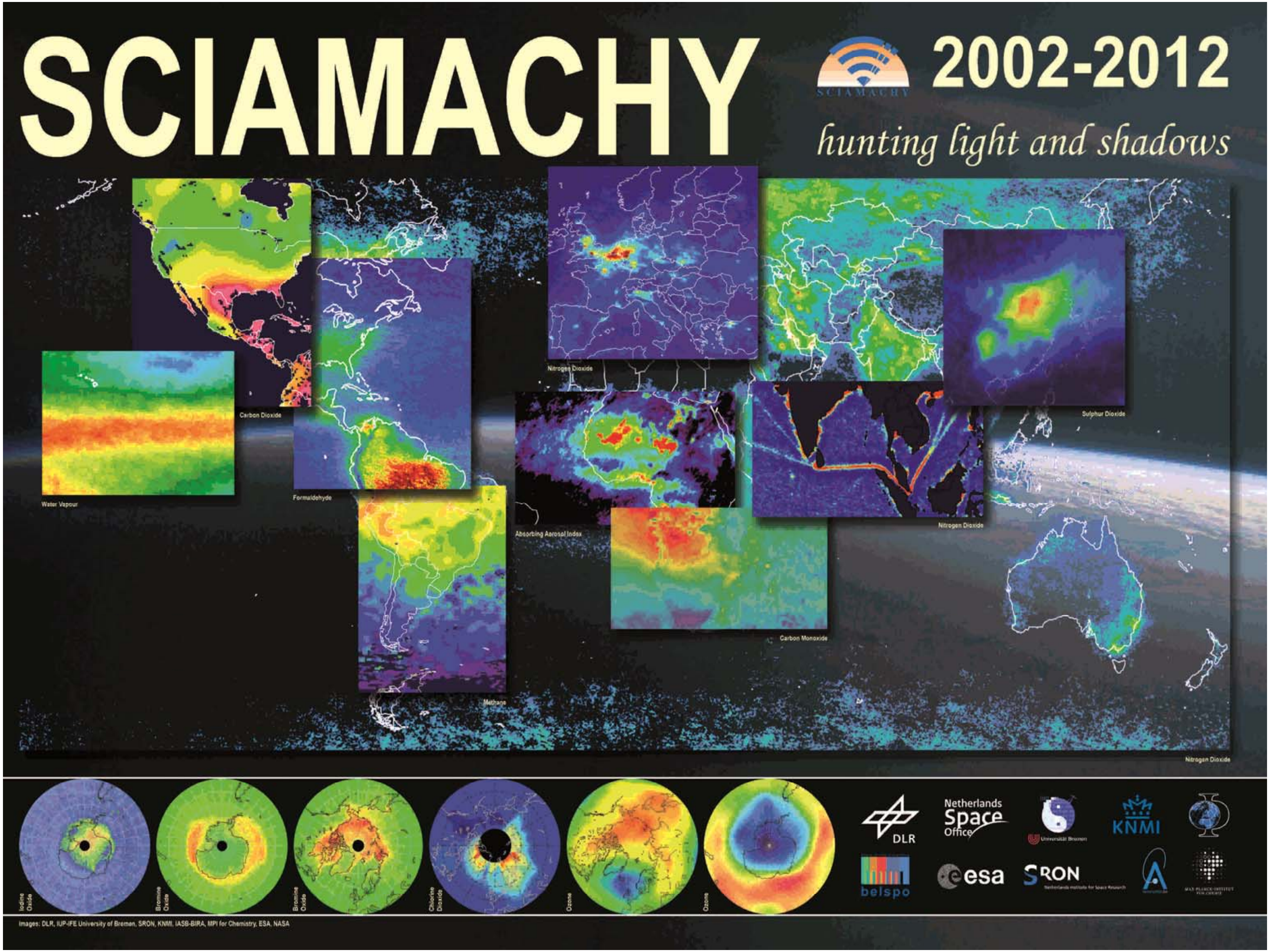


Universität Bremen

iup

Summary & conclusions

- Existing satellites have not been designed to monitor anthropogenic CO_2 or CO emissions from urban areas, especially w.r.t. high spatial resolution
- Nevertheless, first encouraging results have been obtained from SCIAMACHY/ENVISAT (e.g., Schneising et al., 2013, 2008, Tangborn et al. 2009) and TANSO/GOSAT (e.g., Keppel-Aleks et al., 2012; Kort et al., 2012)
- City scale application require (in addition to high near-surface sensitivity and high precision & accuracy) small ground pixel size AND good coverage
  - Sentinel-5 Precursor (S-5P)
    - CO columns @ 7x7 km^2, swath 2800 km, launch 2015
  - CarbonSat – Earth Explorer 8 (EE8) candidate mission
    - XCO_2 and XCH_4 @ 2 x 2 km^2, swath 240 km (goal: 500 km)
    - http://www.iup.uni-bremen.de/carbonsat/
    - EE8 launch ~2020


SCIAMACHY
2002-2012
SCIAMACHY
hunting light and shadows
Carbon Dioxide
Water Vapour
Formaldehyde
Nitrogen Dioxide
Absorbing Aerosol Index
Methane
Carbon Monoxide
Nitrogen Dioxide
Sulphur Dioxide
Nitrogen Dioxide
Iodine Oxide
Bromine Oxide
Bromine Oxide
Chlorine Dioxide
Ozone
Ozone
DLR
Netherlands Space Office
Universität Bremen
KNMI
belspo
esa
SRON
Netherlands Institute for Space Research
Images: DLR, IUP-IFE University of Bremen, SRON, KNMI, IASB-BIRA, MPI for Chemistry, ESA, NASA

Further Reading: CarbonSat

- www.iup.uni-bremen.de/carbonsat/

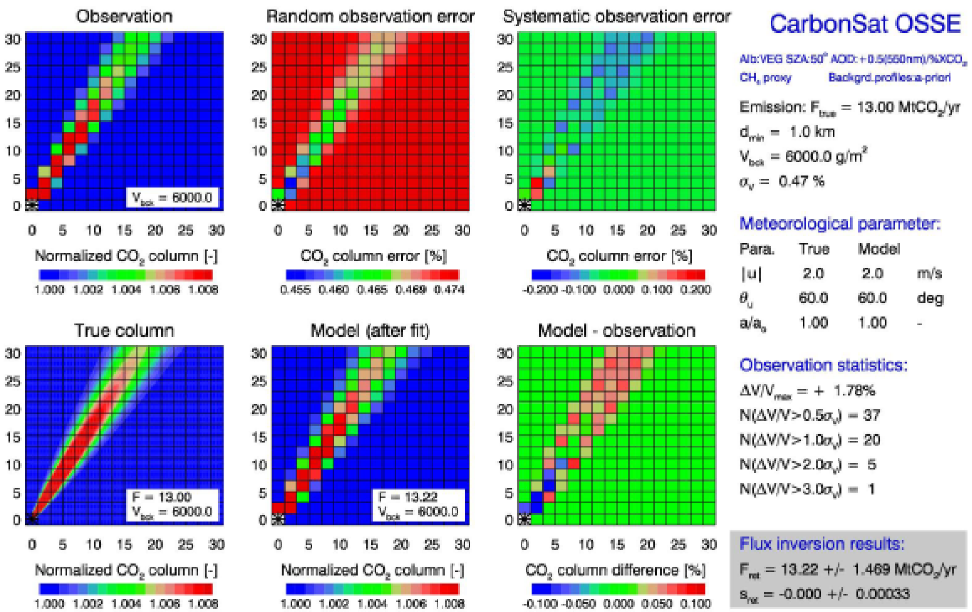
- Bovensmann, H., Buchwitz, M., Burrows, J. P., Reuter, M., Krings, T., Gerilowski, K., Schneising, O., Heymann, J., Tretner, A., and Erzinger, J.: A remote sensing technique for global monitoring of power plant CO_2 emissions from space and related applications, Atmos. Meas. Tech., 3, 781-811, 2010.

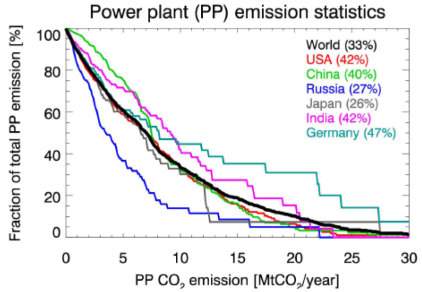
- Velazco, V. A., Buchwitz, M., Bovensmann, H., Reuter, M., Schneising, O., Heymann, J., Krings, T., Gerilowski, K., and Burrows, J. P.: Towards space based verification of CO_2 emissions from strong localized sources: fossil fuel power plant emissions as seen by a CarbonSat constellation, Atmos. Meas. Tech. Discuss., 4, 5147-5182, doi:10.5194/amtd-4-5147-2011, 2011.

Further Reading: Airborne XCO2 & XCH4

- Gerilowski, K., A. Tretner, T. Krings, M. Buchwitz, P. P. Bertagnolio, F. Belemezov, J. Erzinger, J. P. Burrows, and H. Bovensmann, MAMAP – a new spectrometer system for column-averaged methane and carbon dioxide observations from aircraft: instrument description and performance analysis, Atmos. Meas. Tech., 4, 215-243, 2011.
- Krings, T., Gerilowski, K., Buchwitz, M., Reuter, M., Tretner, A., Erzinger, J., Heinze, D., Pflüger, U., Burrows, J. P., and Bovensmann, H.: MAMAP – a new spectrometer system for column-averaged methane and carbon dioxide observations from aircraft: retrieval algorithm and first inversions for point source emission rates, Atmos. Meas. Tech., 4, 1735-1758, doi:10.5194/amt-4-1735-2011, 2011.
- T. Krings, K. Gerilowski, M. Buchwitz, J. Hartmann, T. Sachs, J. Erzinger, J. P. Burrows, H. Bovensmann, Quantification of methane emission rates from coal mine ventilation shafts using airborne remote sensing data, Atmos. Meas. Tech., 6, 151-166, 2013

CarbonSat: CO_2 emissions from power plants





Atmospheric Measurement Techniques

Bovensmann et al., 2010

A remote sensing technique for global monitoring of power plant CO_2 emissions from space and related applications

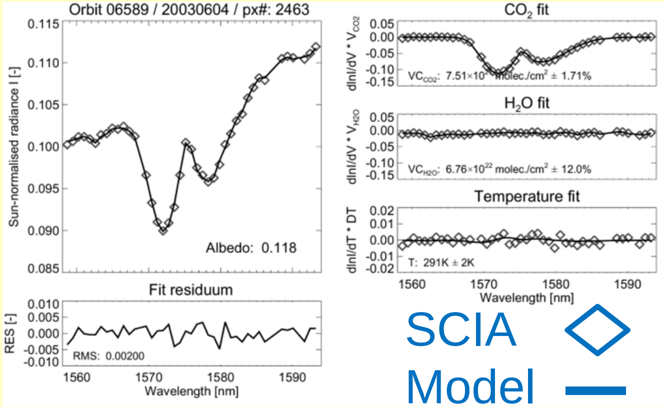
H. Bovensmann[1], M. Buchwitz[1], J. P. Burrows[1], M. Reuter[1], T. Krings[1], K. Gerilowski[1], O. Schneising[1], J. Heymann[1], A. Tretner[2], and J. Erzinger[2]

[1]Institute of Environmental Physics (IUP), University of Bremen FB1, Otto Hahn Allee 1, 28334 Bremen, Germany
[2]Helmholtz Centre Potsdam – GFZ German Research Centre for Geosciences, Telegrafenberg, 14473 Potsdam, Germany

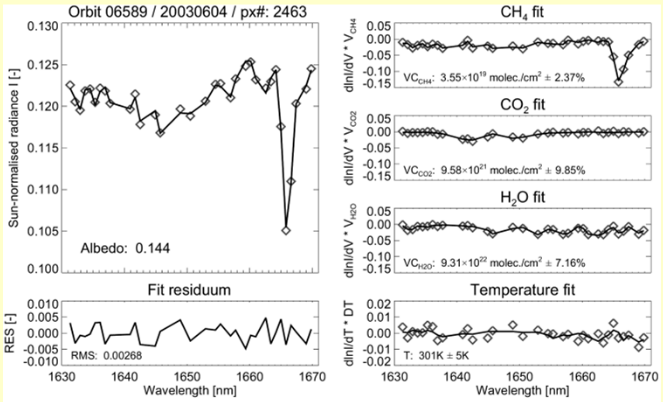
Received: 6 November 2009 – Published in Atmos. Meas. Tech. Discuss.: 7 January 2010
Revised: 14 June 2010 – Accepted: 15 June 2010 – Published: 1 July 2010

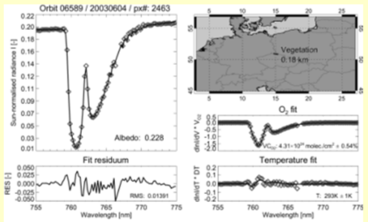
Retrieval Algorithm WFM-DOAS (WFMD)

CO_2-column fit (1.58 µm)



CH_4-column fit (1.65 µm)





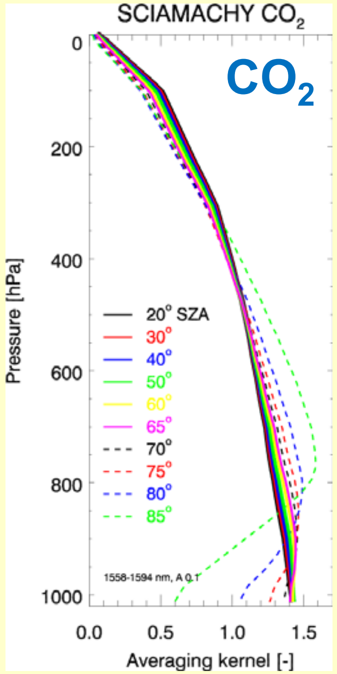
O_2 (0.76 µm)

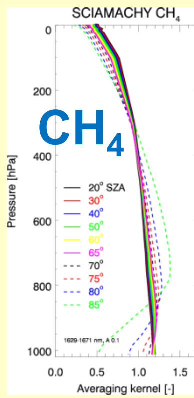
Main characteristics:

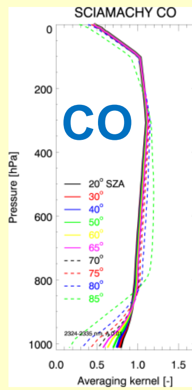
- **Least-squares** fit to retrieve CO_2, CH_4 and O_2 vertical columns independently in 3 spectral windows by scaling pre-defined vertical profiles
- Column-averaged mixing ratios **XCO_2** (~CO_2/O_2 column ratio) and **XCH_4** (~CH_4/CO_2), computed a-posteriori from retrieved columns; XCH_4 corrected for CO_2 using NOAA's CarbonTracker
- **No a-priori constraints** except profile shape. A-priori information only used as linearization point for the RT simulations; **no spatio-temporal dependencies assumed**
- Use of **fast LUT scheme** (single constant $CO_2(z)$, T(z), p(z), aerosols(z), … profiles); auxiliary algorithms for cloud detection, albedo retrieval, etc.

Altitude sensitivity

(AK(p) = $dX_{ret}/dX_{true}(p)$)







Retrieval Algorithms: WFMD & BESD

	WFMD (CO, XCO_2, XCH_4)	**BESD** (XCO_2)
Inversion Algorithm:	**Least-squares** “Proxy” (O_2 or CO_2 for light path)	**Optimal Estimation** “Full Physics”
A-priori constraints:	**No** (except profile shapes) Constant atmosphere	**Yes** Constant: CO_2, aerosol, cirrus, ... Per pixel: p, T, H_2O
Atmosphere:	**Constant** (modified US Standard Atmos.)	**ECMWF**
Aerosols:	**Constant** Filtering: AAI (CO_2 only)	**State vector** (APS) Filtering: AAI
Clouds:	**RT cloud free** Filtering: O_2 & PMD (CO_2 only)	**State vector** (CWP, CTH) Filtering: MERIS 1x1 km^2
Fit windows:	**Independent**	**Merged**
Radiative Transfer (RT):	**LUT** (SCIATRAN)	**on-line** (SCIATRAN)
Speed:	**Fast** (~few min./orbit)	**Slow** (~few min./pixel)
Optimized for:	**Compromise accuracy / speed**	**Accuracy**
References:	Buchwitz et al., 2007 Schneising et al., 2013	Reuter et al., 2010, 2011