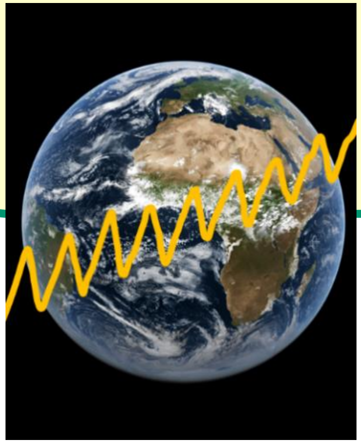
CHE & VERIFY General Assembly, ECMWF, 12-14 March 2019

Anthropogenic CO_2 emissions from existing and future satellites

Michael Buchwitz
Institute of Environmental Physics /
Remote Sensing (IUP/IFE),
University of Bremen, Germany

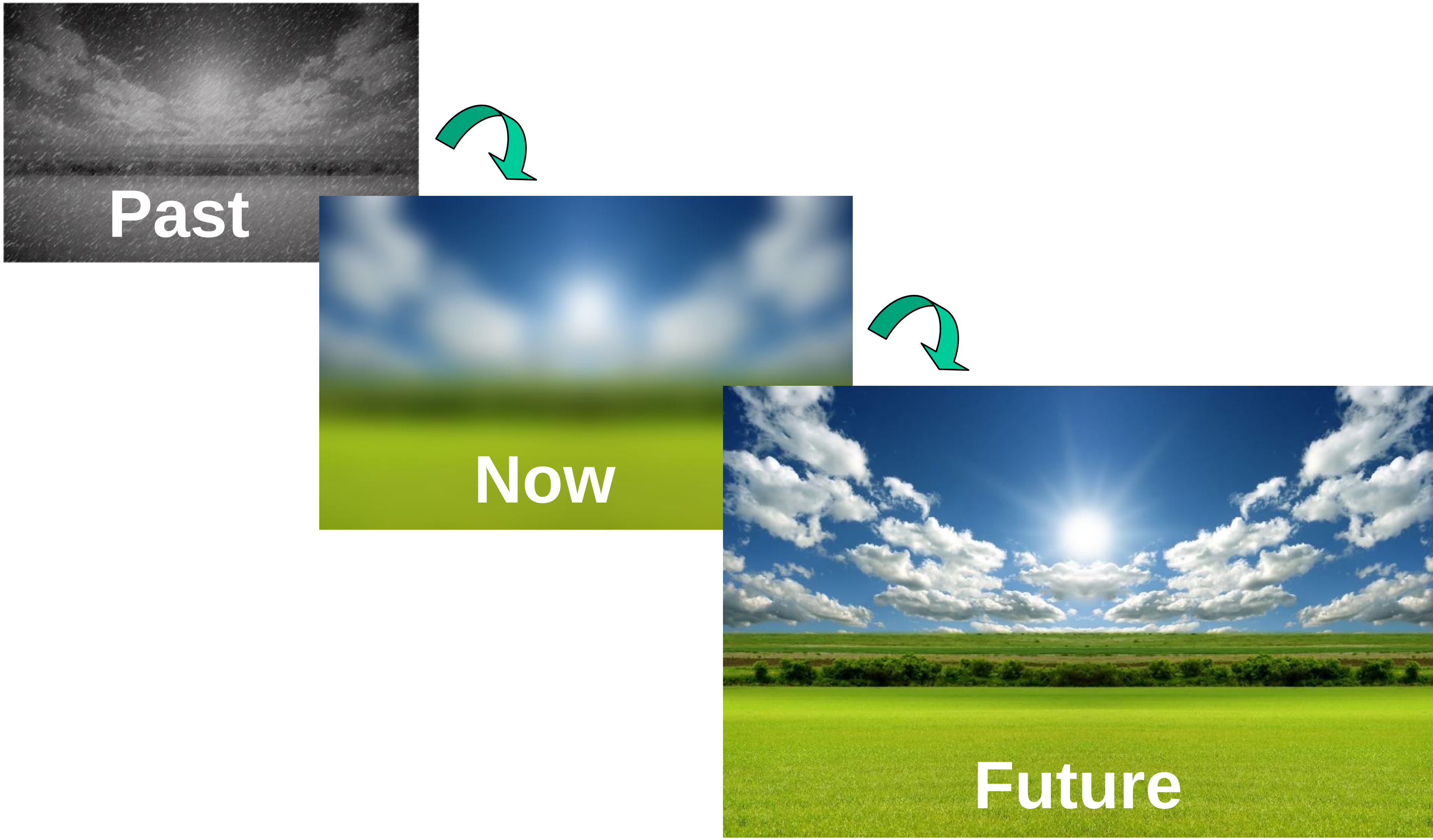


CO2 Human Emissions

VERIFY

buchwitz@uni-bremen.de

Satellite anthropogenic CO_2 monitoring: Outline



The beginning

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

Buchwitz et al., JGR, 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

A conclusion:

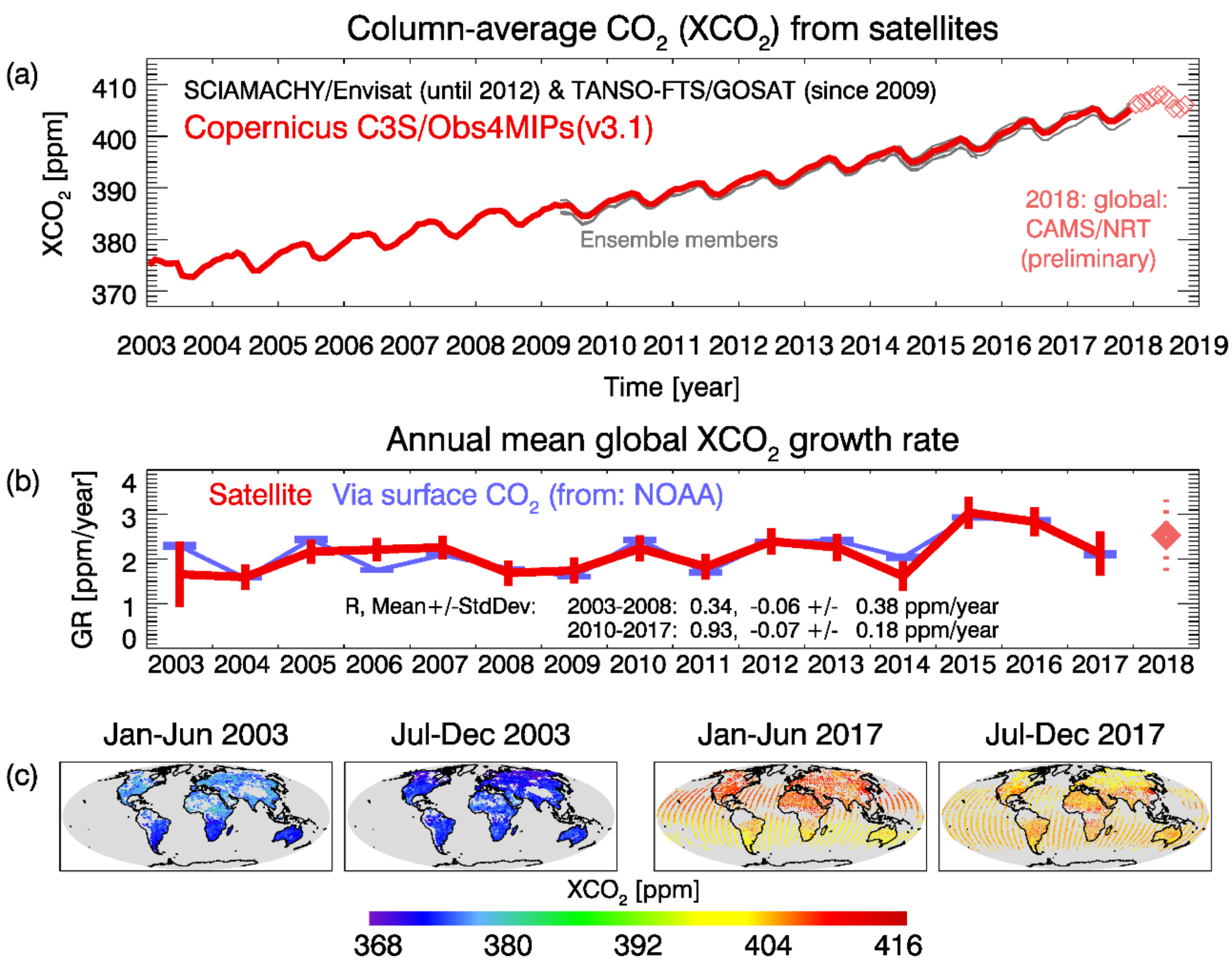
Kyoto Protocol relevant anthropogenic CO_2 emission monitoring with SCIAMACHY?:

- VERY challenging but some contribution might be possible

6. Potential Application of SCIAMACHY Measurements for the Study of Greenhouse Constituents and Their Emission Fluxes

The potential of SCIAMACHY to measure regional CO_2 and CH_4 emission fluxes has been investigated assuming simplified conditions with respect to atmospheric dynamics, scan pattern, and source variability. The estimated (best case) errors indicate that the total column measurements of SCIAMACHY in combination with 3-D source/sink transport/chemistry models of the atmosphere might contribute to the assessment of Kyoto Protocol compliance. This, however, needs further studies based on real SCIAMACHY measurements.

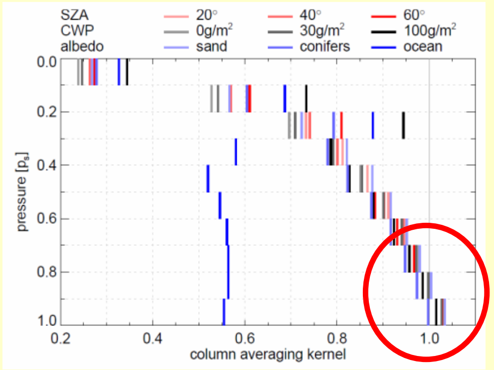
XCO_2 from satellite NIR/SWIR spectra



XCO_2: Column-averaged dry air CO_2 mole fraction

CO_2 information via (absorbed and) reflected solar radiation

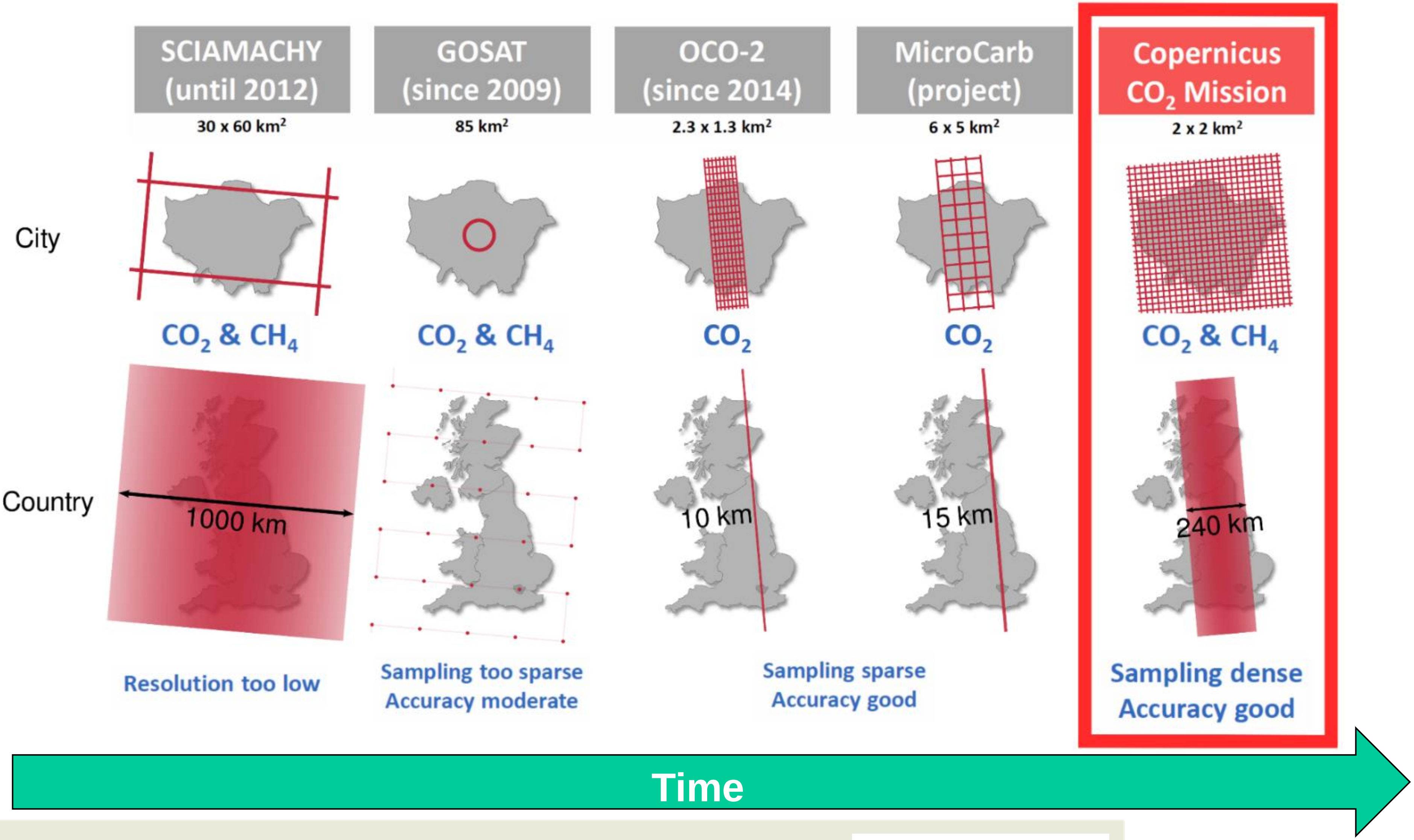
-> sensitive to near surface CO_2 concentration changes (averaging kernels approx. 1 near surface)



Reuter et al., 2010

Universität Bremen

XCO_2 satellites: From SCIAMACHY to CO2M



CO_2 emissions: SCIAMACHY XCO_2: „First detection“

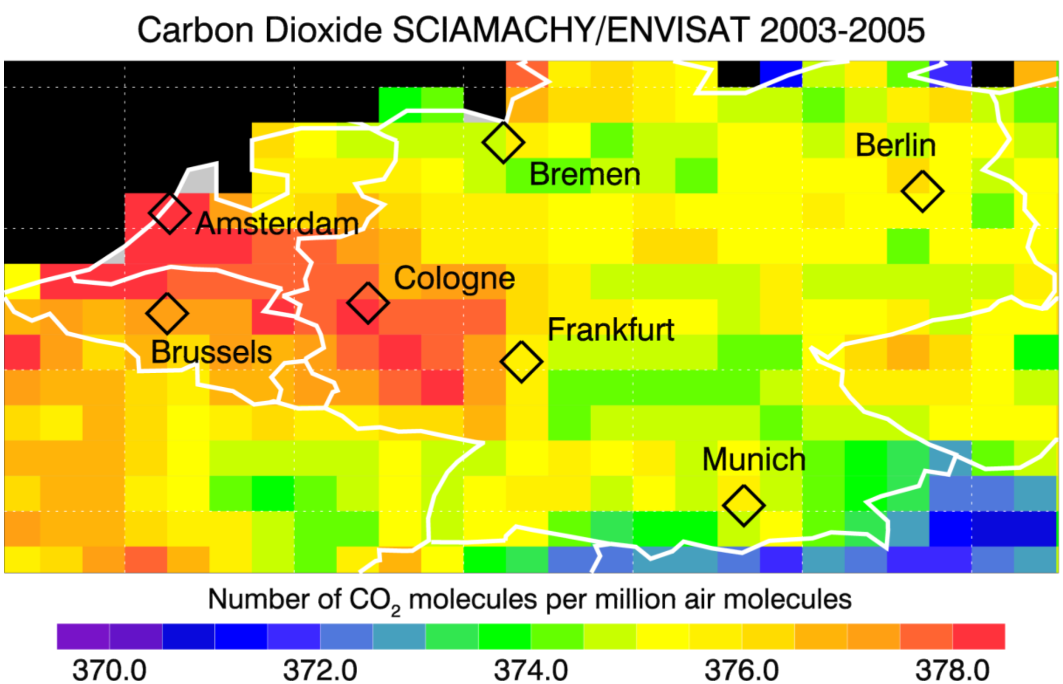
Atmos. Chem. Phys., 8, 3827–3853, 2008
www.atmos-chem-phys.net/8/3827/2008/

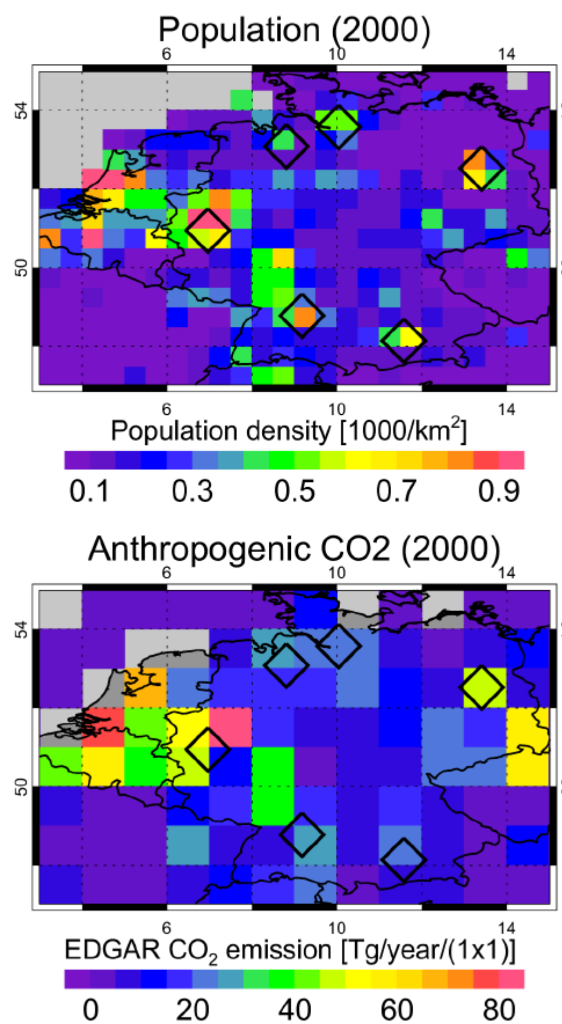
Atmospheric Chemistry and Physics

Schneising et al., ACP, 2008

Three years of greenhouse gas column-averaged dry air mole fractions retrieved from satellite – Part 1: Carbon dioxide

O. Schneising, M. Buchwitz, J. P. Burrows, H. Bovensmann, M. Reuter, J. Notholt, R. Macatangay, and T. Warneke
Institute of Environmental Physics (IUP), University of Bremen FB1, Bremen, Germany





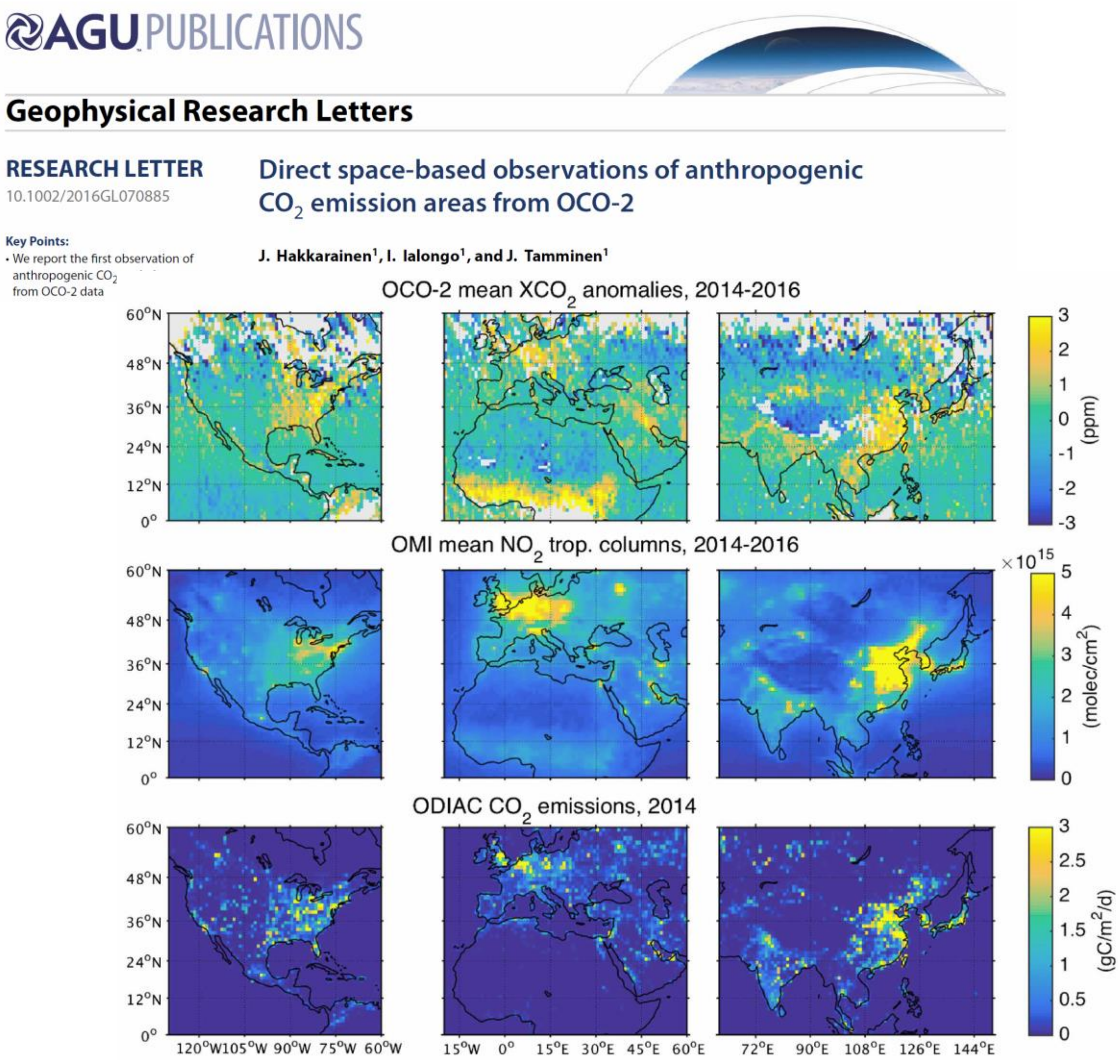
Universität Bremen

ife

CO2 Human Emissions

VERIFY

CO_2 emissions: OCO-2 XCO_2: „Improved detection“


AGU PUBLICATIONS

Geophysical Research Letters

RESEARCH LETTER

10.1002/2016GL070885

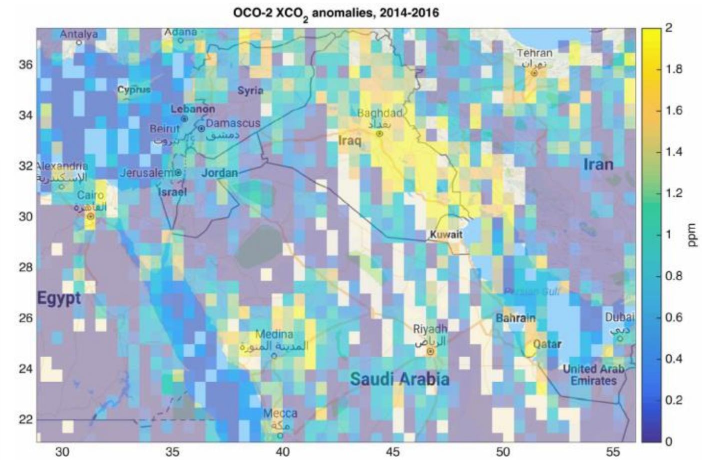
Key Points:

- We report the first observation of anthropogenic CO_2 from OCO-2 data

Direct space-based observations of anthropogenic CO_2 emission areas from OCO-2

J. Hakkarainen[1], I. Ialongo[1], and J. Tamminen[1]

Hakkarainen et al., GRL, 2016



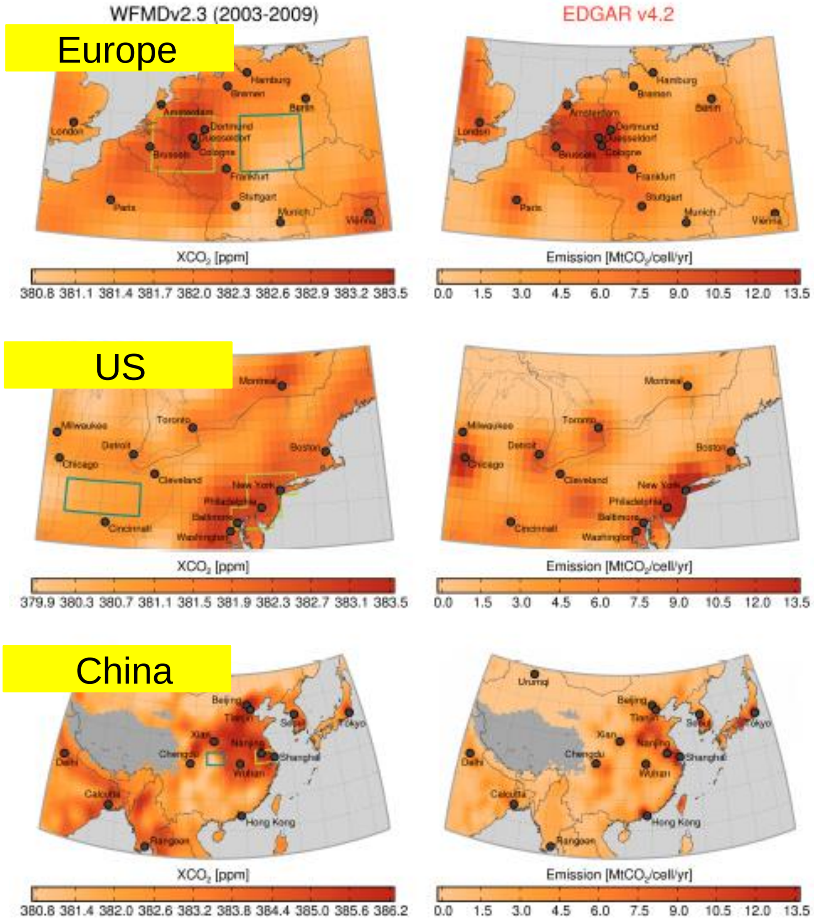
Key Points:

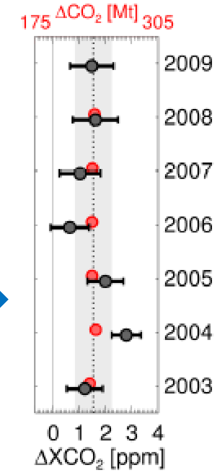
- We report the first observation of anthropogenic CO_2 emission areas from OCO-2 data
- We present a novel methodology for direct fine-scale mapping of CO_2 emission areas
- We observe positive correlation between XCO_2 anomalies and emissions inventories

CO_2 emissions: SCIAMACHY XCO_2

SCIAMACHY XCO_2

EDGAR CO_2 emissions



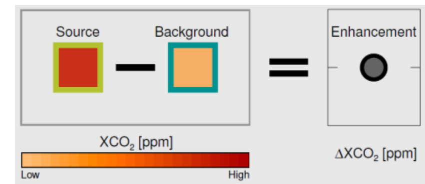


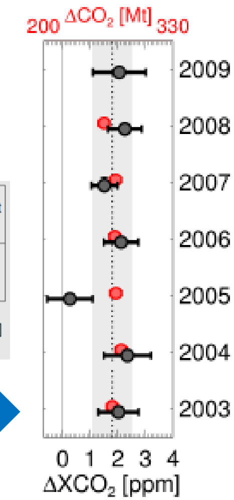
Schneising et al., ACP, 2013

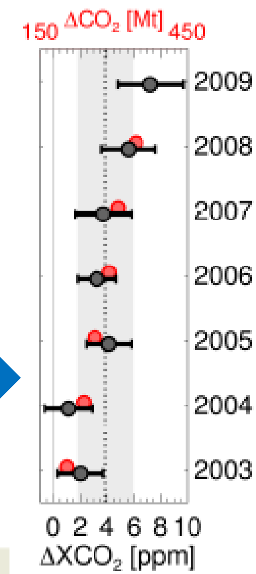
SCIAMACHY

EDGAR

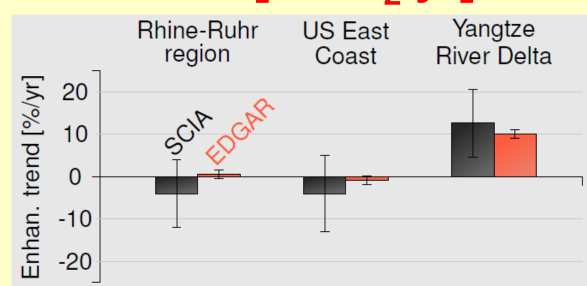
Regional enhancement =
Source - Background







Trend [%CO_2/yr]



EDGAR emissions consistent with SCIAMACHY

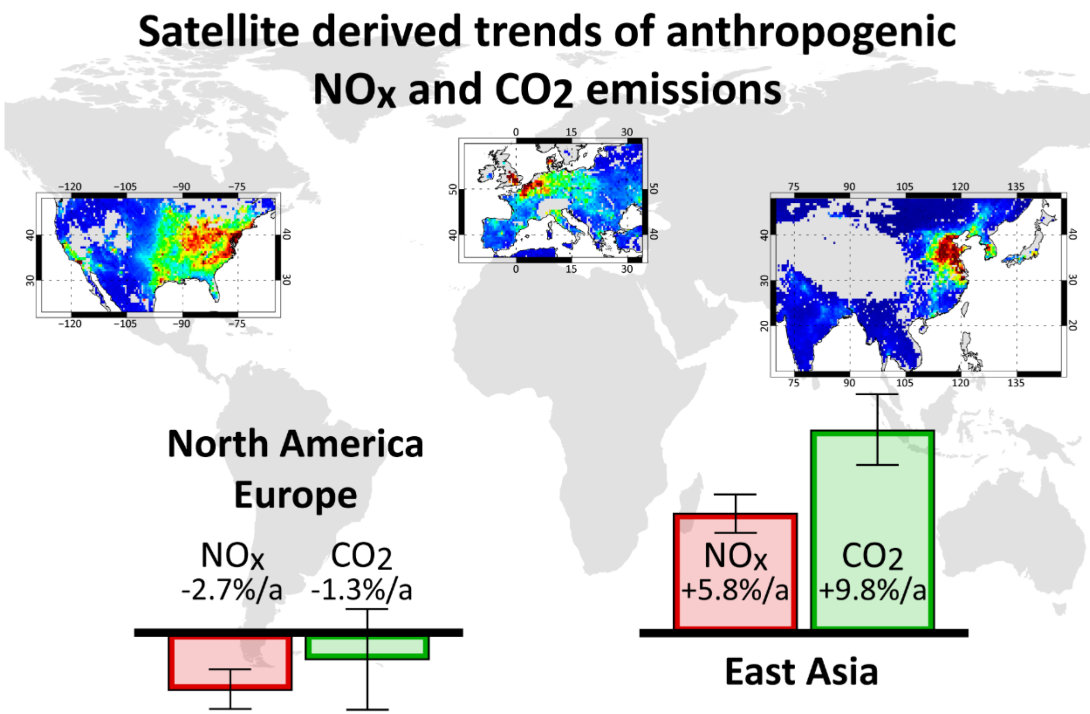
CO_2 emissions: SCIAMACHY XCO_2 & NO_2

nature geoscience LETTERS
PUBLISHED ONLINE: 28 SEPTEMBER 2014 | DOI: 10.1038/NGEO2257

Reuter et al., 2014

Decreasing emissions of NO_x relative to CO_2 in East Asia inferred from satellite observations

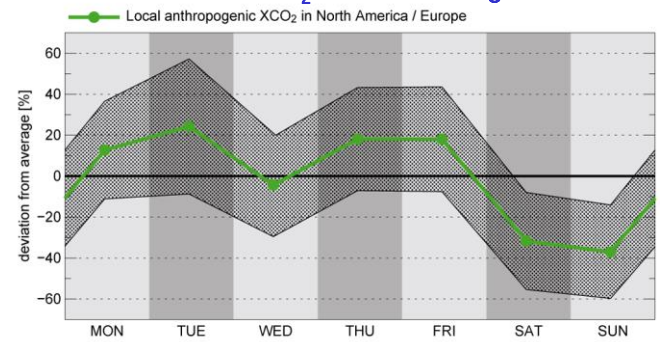
M. Reuter*, M. Buchwitz, A. Hilboll, A. Richter, O. Schneising, M. Hilker, J. Heymann, H. Bovensmann and J. P. Burrows



Reuter et al., 2014 (Nature Geoscience)

maximilian.reuter@iup.physik.uni-bremen.de

North America & Europe:
34+/-15% less CO_2 emitted during weekends



- **Anthropogenic CO_2 emission signal from localized sources isolated via simultaneous SCIAMACHY XCO_2 and NO_2 observations & new spatial filtering method**
- **North America & Europe: Decreasing emissions (but uncertain for CO_2)**
- **East Asia: Increasing emissions but less NOx per CO_2: Trend towards cleaner technology in East Asia**

CO_2 emissions: OCO-2 XCO_2

AGU PUBLICATIONS

Geophysical Research Letters

RESEARCH LETTER

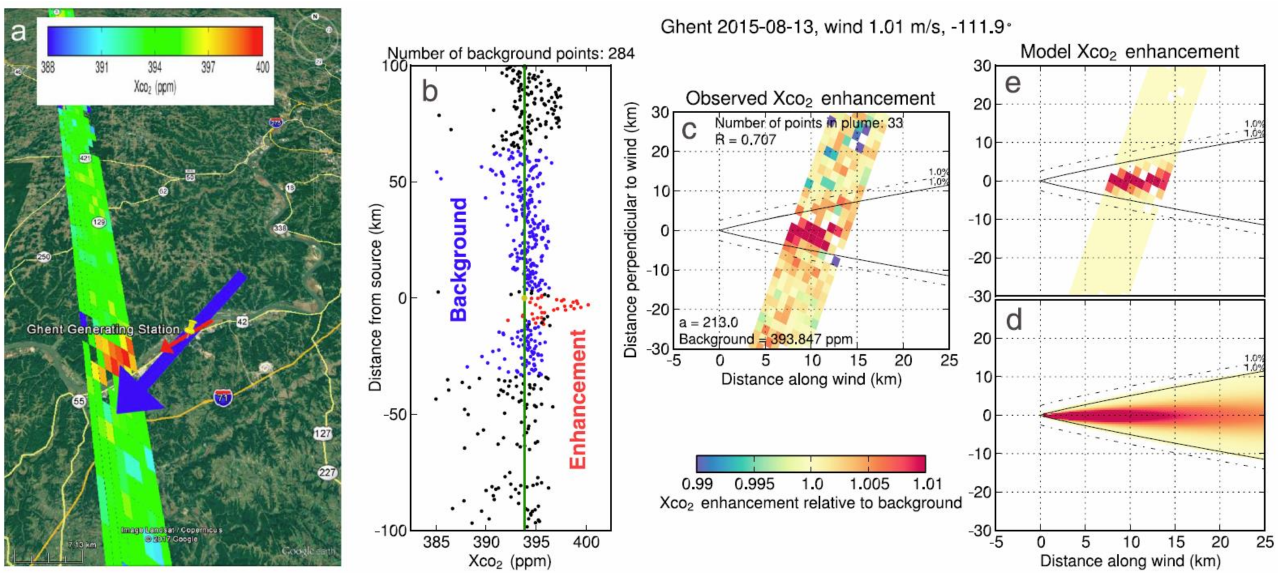
10.1002/2017GL074702

Key Points:
- The combustion of coal for electricity generation accounts for more than

Quantifying CO_2 Emissions From Individual Power Plants From Space

Ray Nassar[1], Timothy G. Hill[2], Chris A. McLinden[3], Debra Wunch[4], Dylan B. A. Jones[4], and David Crisp[5]

Nassar et al., GRL, 2017



Key Points:
- The combustion of coal for electricity generation accounts for more than 40% of global anthropogenic CO_2 emissions
- Orbiting Carbon Observatory 2 observations can be used to quantify CO_2 emissions from individual coal power plants, in selected cases
- This work suggests that a future constellation of CO_2 imaging satellites could monitor fossil fuel power plant CO_2 emissions to support climate policy

Universität Bremen

ife

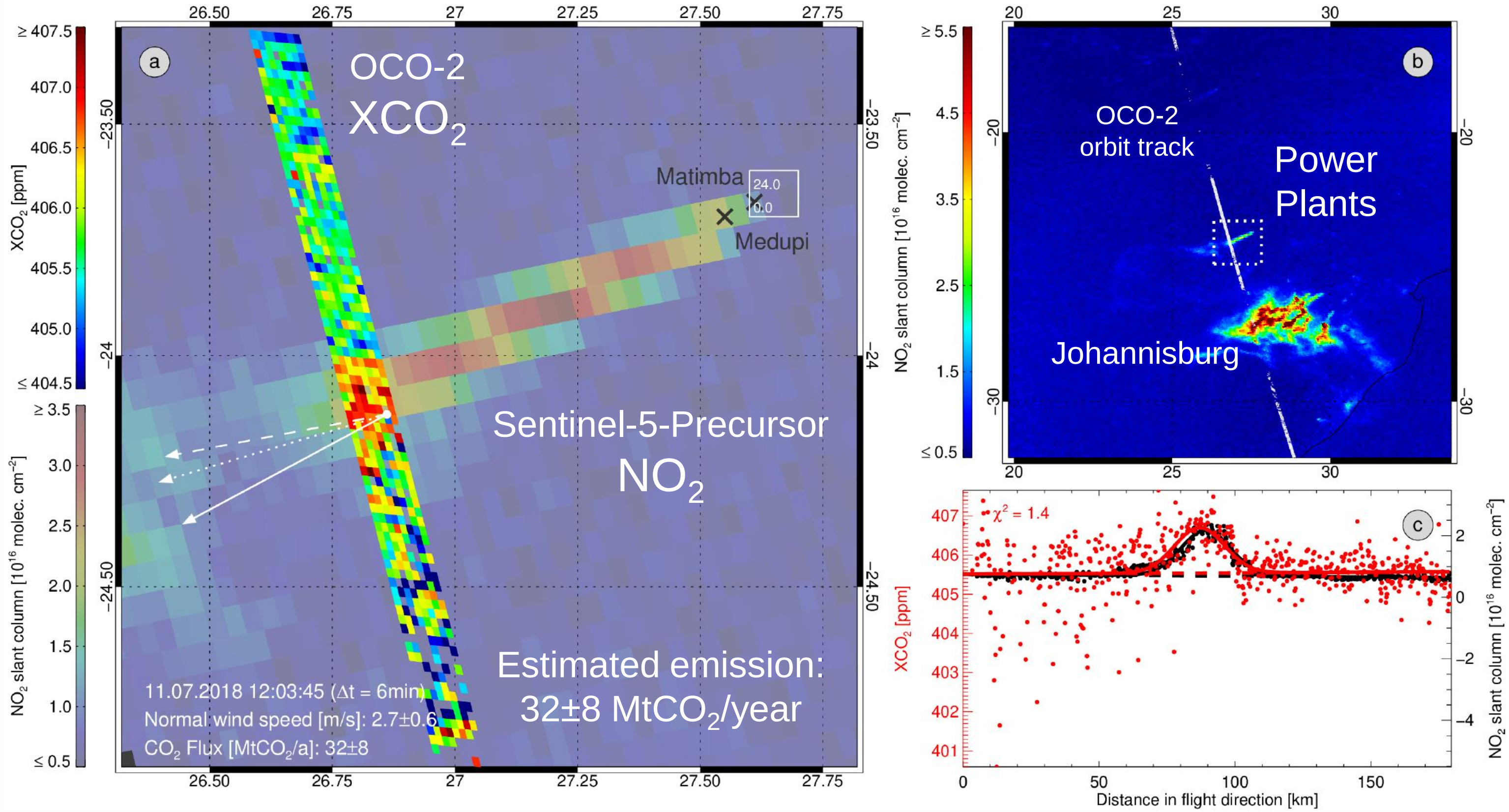
CO_2 Human Emissions

VERIFY

CO_2 emissions: OCO-2 XCO_2 & S5P NO_2

Reuter et al., ACP (submitted)

Medupi and Matimba power plants in South Africa on 11-July-2018:



See also **poster** „OCO-2 XCO_2 retrievals using the FOCAL algorithm“

Universität Bremen

iup ife

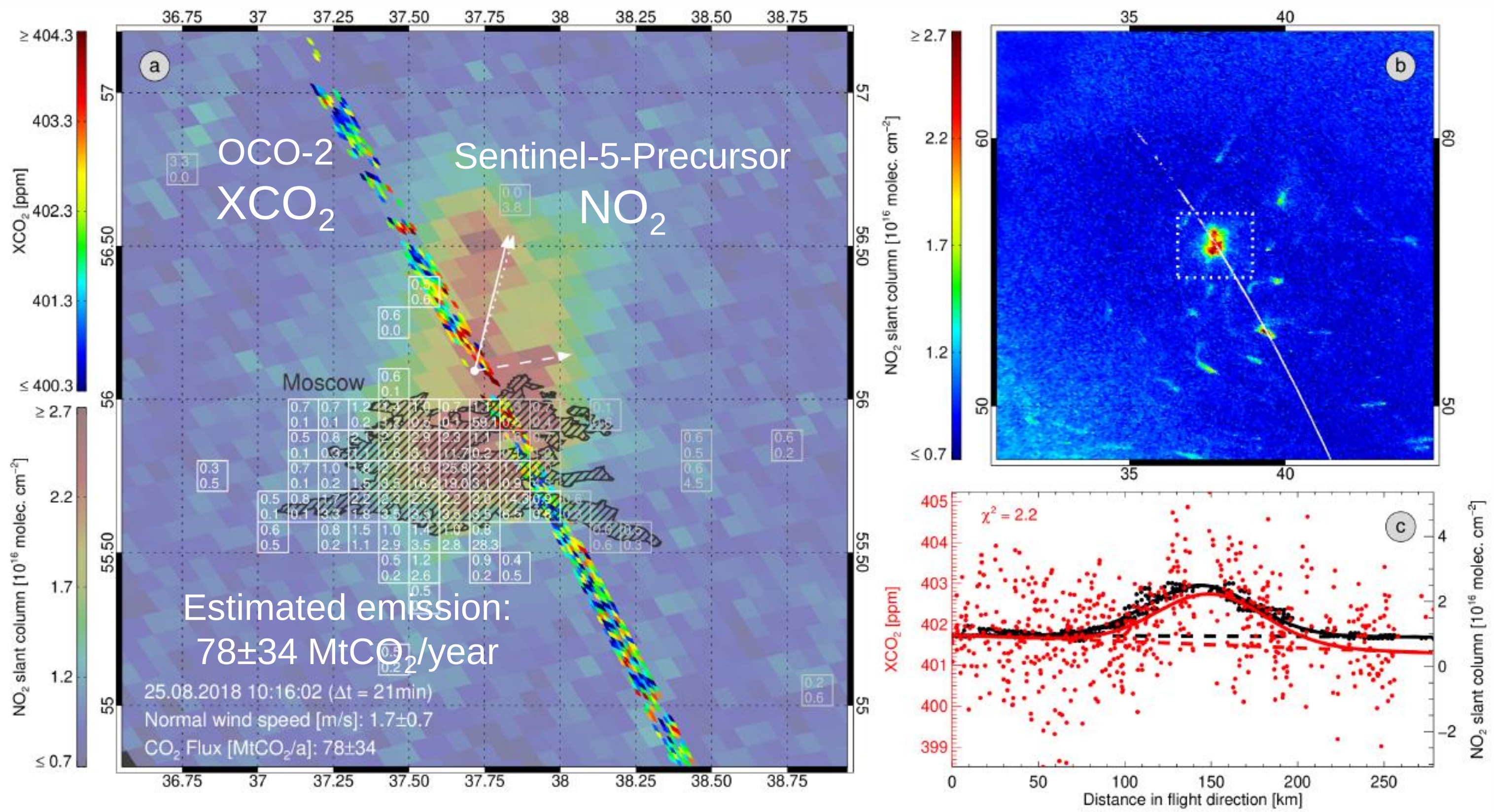
CO2 Human Emissions

VERIFY

CO_2 emissions: OCO-2 XCO_2 & S5P NO_2

Reuter et al., ACP (submitted)

Moscow on 25-Aug-2018:



See also **poster** „OCO-2 XCO_2 retrievals using the FOCAL algorithm“

Universität Bremen

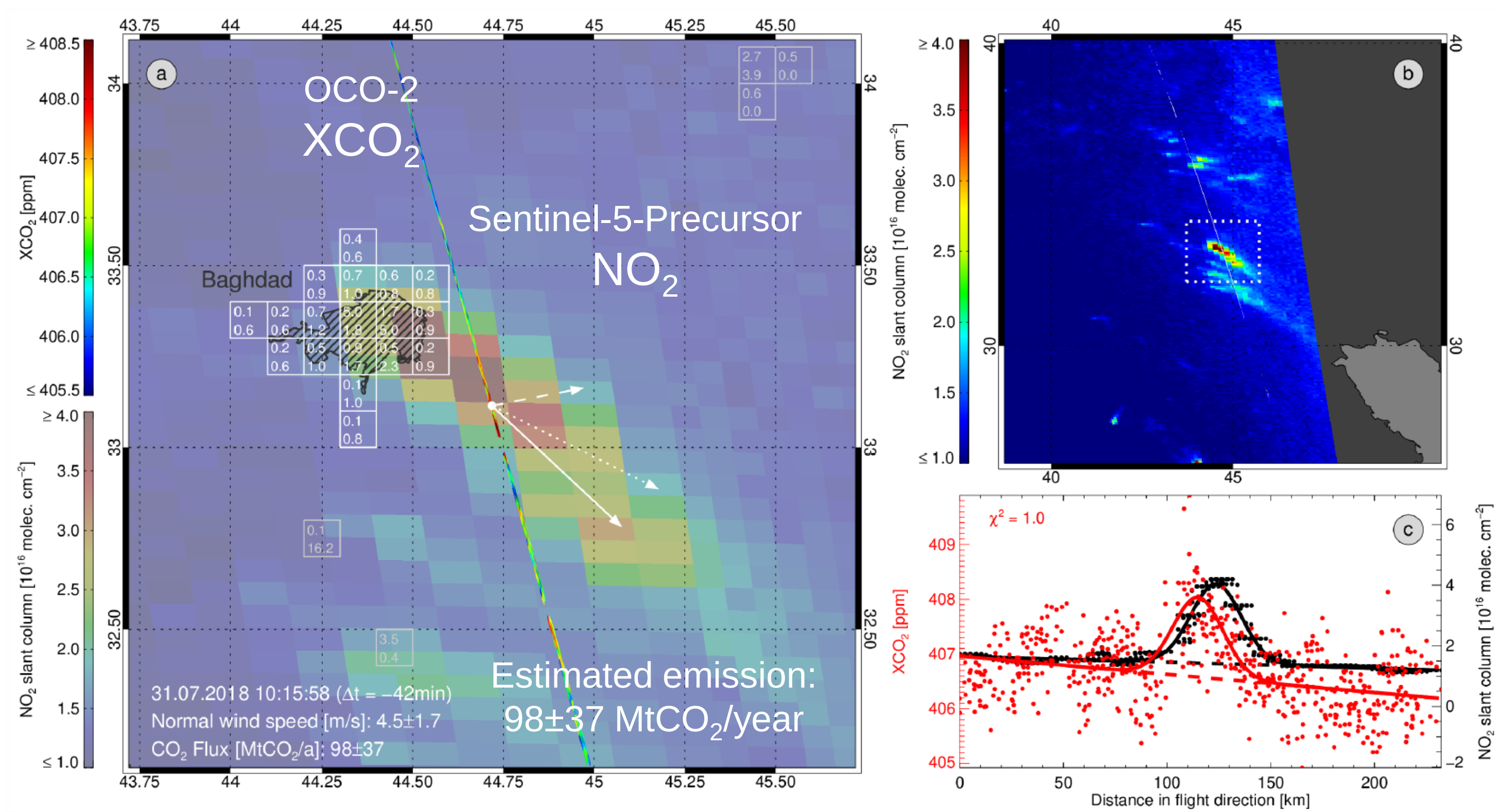
CO2 Human Emissions

VERIFY

CO_2 emissions: OCO-2 XCO_2 & S5P NO_2

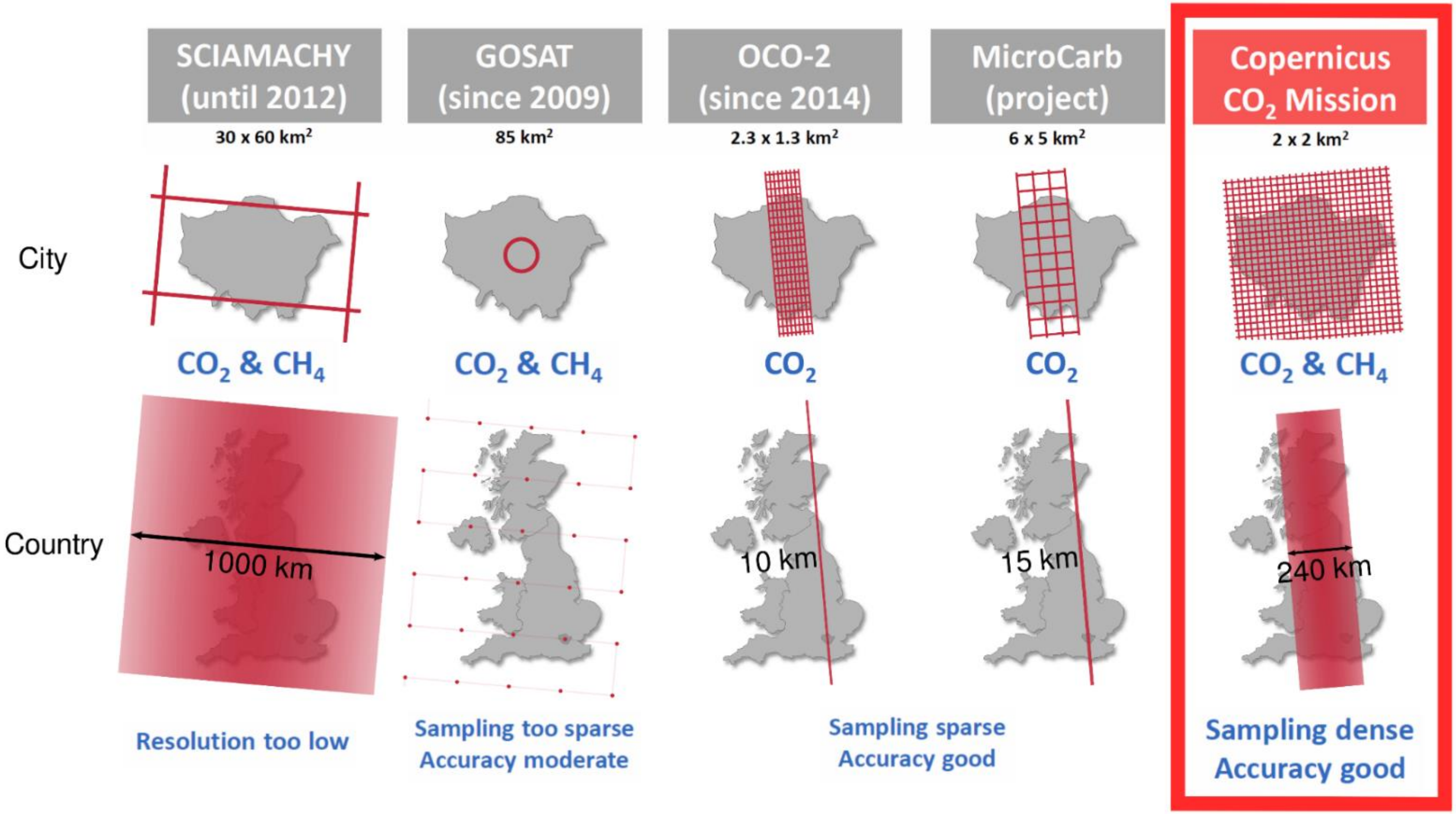
Reuter et al., ACP (submitted)

Baghdad on 31-July-2018:

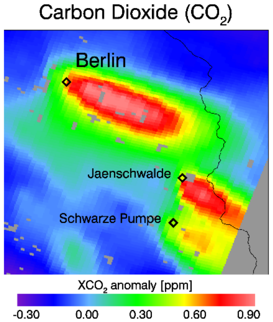


See also **poster** „OCO-2 XCO_2 retrievals using the FOCAL algorithm“

XCO_2 satellites: From SCIAMACHY to **CO2M**



CO_2 emissions via CO_2 imaging:



*Only **CO2M**: CO_2 imaging*

XCO_2 satellites: CarbonSat: XCO_2 imaging

Atmos. Meas. Tech., 3, 781–811, 2010
www.atmos-meas-tech.net/3/781/2010/
doi:10.5194/amt-3-781-2010

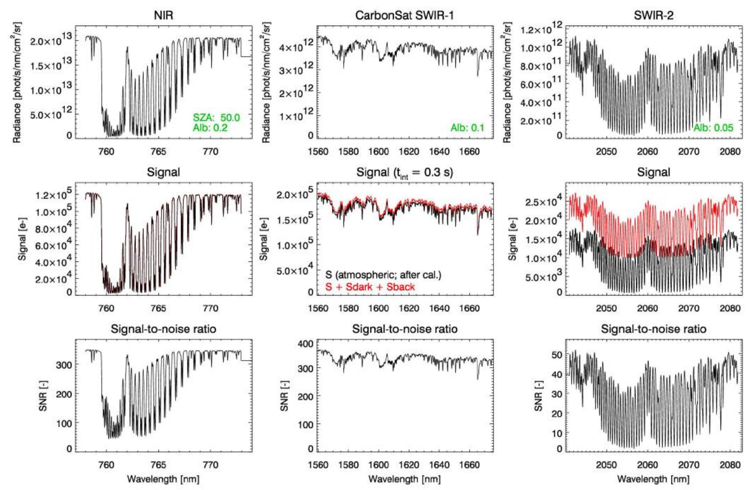
Atmospheric Measurement Techniques

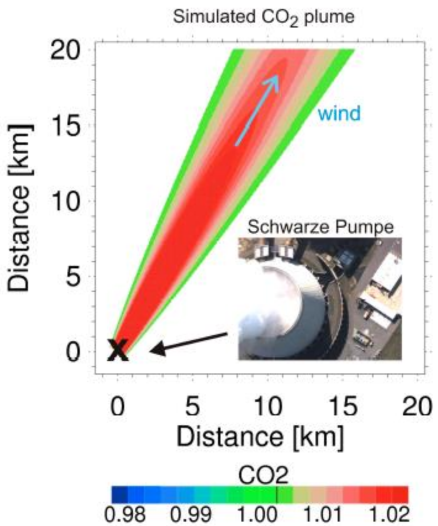
Bovensmann et al., AMT, 2010

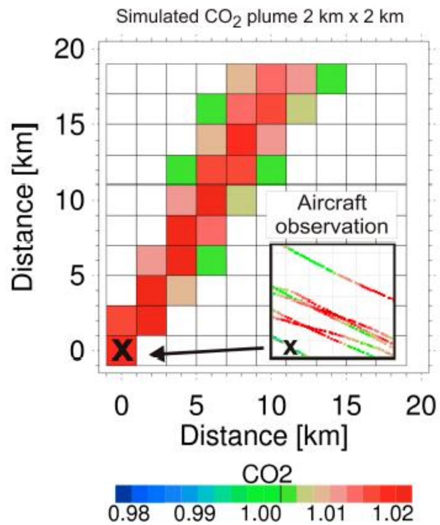
A remote sensing technique for global monitoring of power plant CO_2 emissions from space and related applications

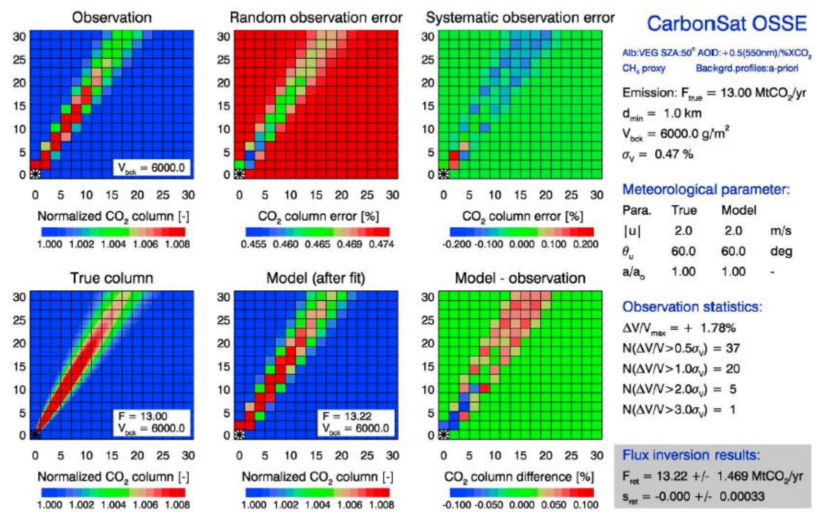
H. Bovensmann[1], M. Buchwitz[1], J. P. Burrows[1], M. Reuter[1], T. Krings[1], K. Gerilowski[1], O. Schneising[1], J. Heymann[1], A. Tretner[2], and J. Erzinger[2]

[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









Universität Bremen

CO_2 emissions: Simulations CarbonSat / CO2M

Atmos. Chem. Phys., 16, 9591–9610, 2016
www.atmos-chem-phys.net/16/9591/2016/
doi:10.5194/acp-16-9591-2016

Atmospheric Chemistry and Physics
Open Access
EGU

Pillai et al., ACP, 2016

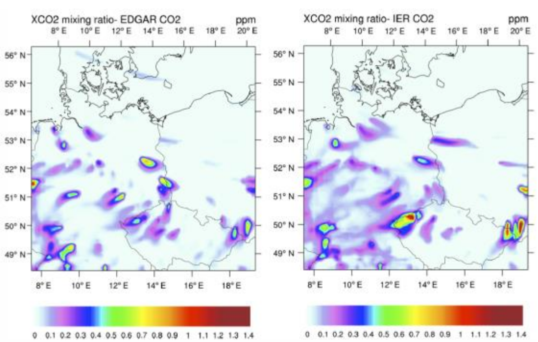
Tracking city CO_2 emissions from space using a high-resolution inverse modelling approach: a case study for Berlin, Germany

Dhanyalekshmi Pillai[1,2], Michael Buchwitz[1], Christoph Gerbig[2], Thomas Koch[2], Maximilian Reuter[1], Heinrich Bovensmann[1], Julia Marshall[2], and John P. Burrows[1]

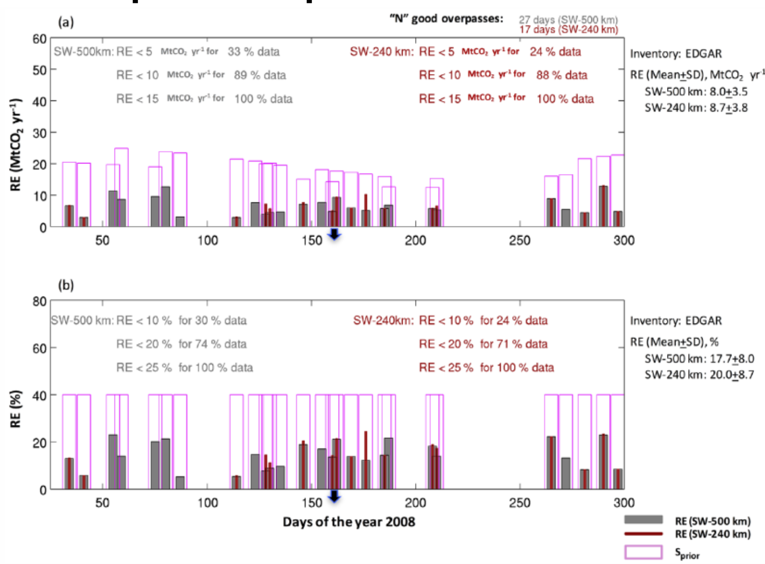
[1]Institute of Environmental Physics, University of Bremen, Bremen, Germany
[2]Max Planck Institute for Biogeochemistry, Jena, Germany

- Case study for Berlin
- Satellite data: Simulation for CarbonSat / CO2M (2x2km^2, swath width 240 km & 500 km), 1 year
- Model: WRF-GHG
- Bayesian inversion

XCO_2 simulations using EDGAR & IER



A priori & a posteriori errors



Summary:

- Number of „good“ overpasses per year: 17 (240 km) - 27 (500 km)
- Single overpass random error: Typically 9 $MtCO_2$/year
- Systematic: Typically 6-10 $MtCO_2$/year depending on assumptions

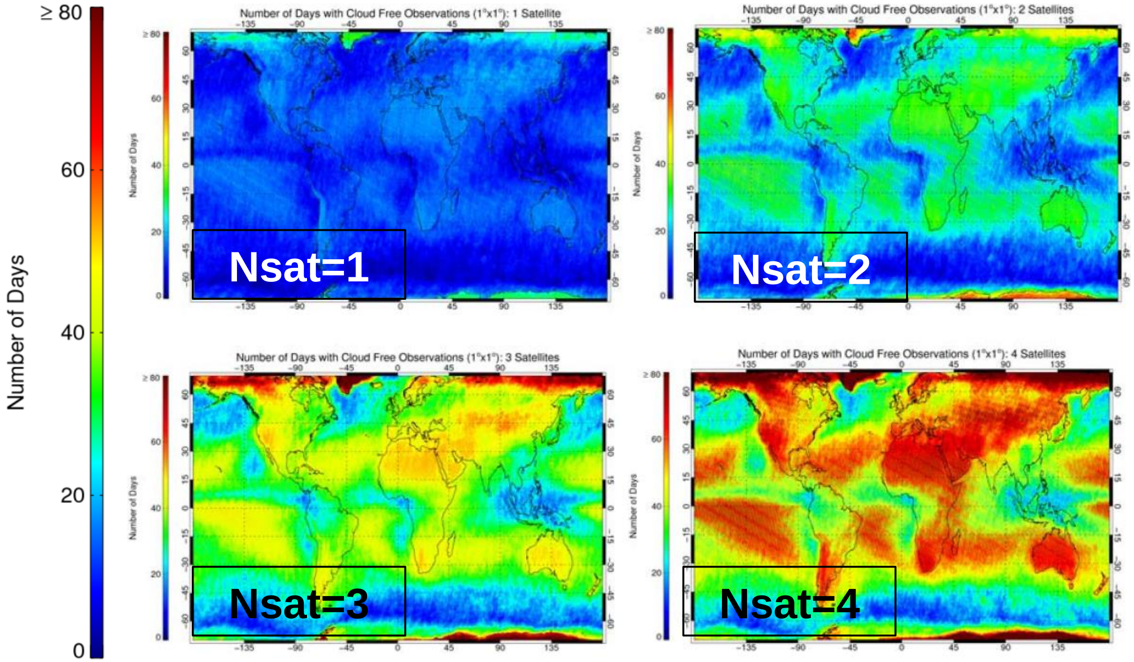
Universität Bremen

iup ife

CO_2 Human Emissions

VERIFY

CO2M: Number of cloud-free overpasses per year



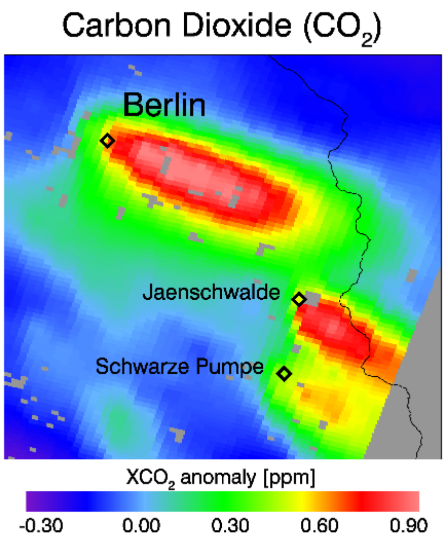
Assumed swath width:

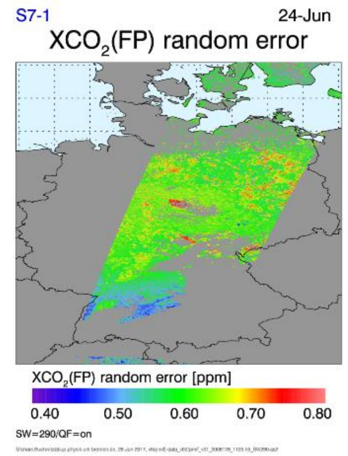
200 km
(pessimistic)

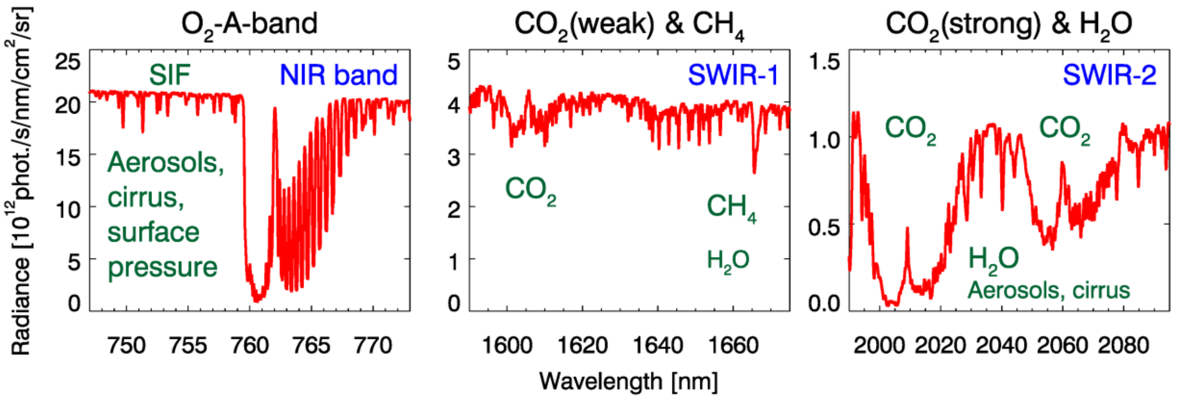
City	1 satellite	2 satellites	3 satellites	4 satellites
Berlin	14	22	38	52
Paris	15	28	34	51
New York	14	26	39	54
Moscow	12	24	36	46
Cairo	18	34	52	69
Beijing	14	27	45	56
Los Angeles	16	31	47	64

Anthropogenic CO_2 Monitoring (CO2M) mission

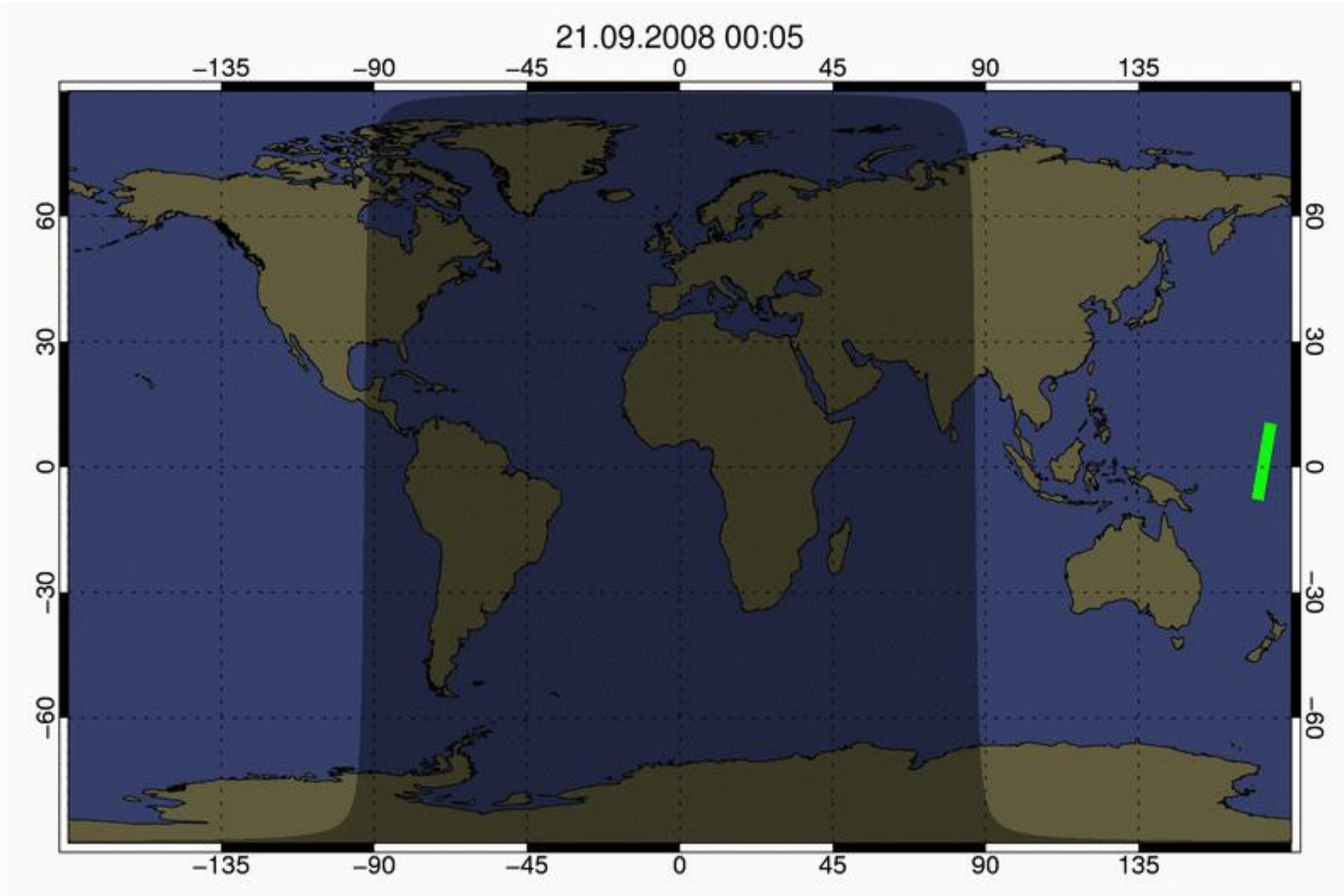
- **Spatial resolution 2 x 2 km²**
- **Wide swath (> 200 km) and gap-free across and along track sampling („CO_2 *Imaging*“)**
- **Coverage ≈ every 2-3 days (polwards of 40°)**
- **Constellation of ≈ 2-3 satellites**
- **Low random (0.5-0.7 ppm) and systematic (< 0.5 ppm) XCO_2 errors**
- **Optimal spectral coverage and resolution**
- **Information on NO_2, CH_4, H_2O, SIF, aerosols, …**





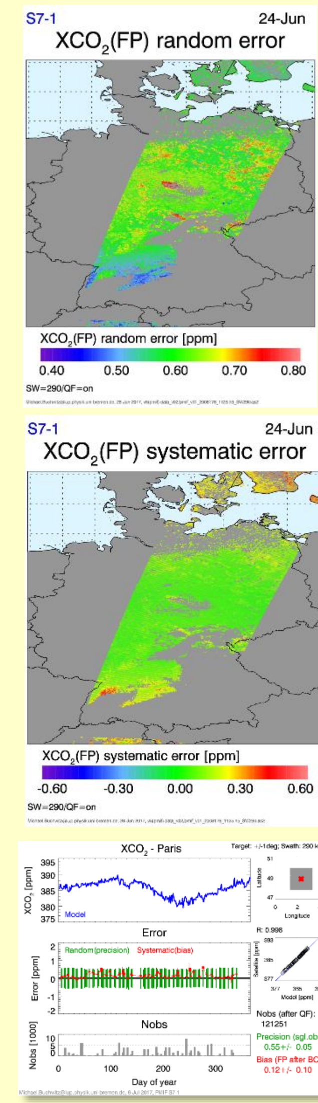


One day simulation of 3 CO2M satellites



Clouds: MODIS Terra 1 km x 1 km MOD35 L2 cloud mask

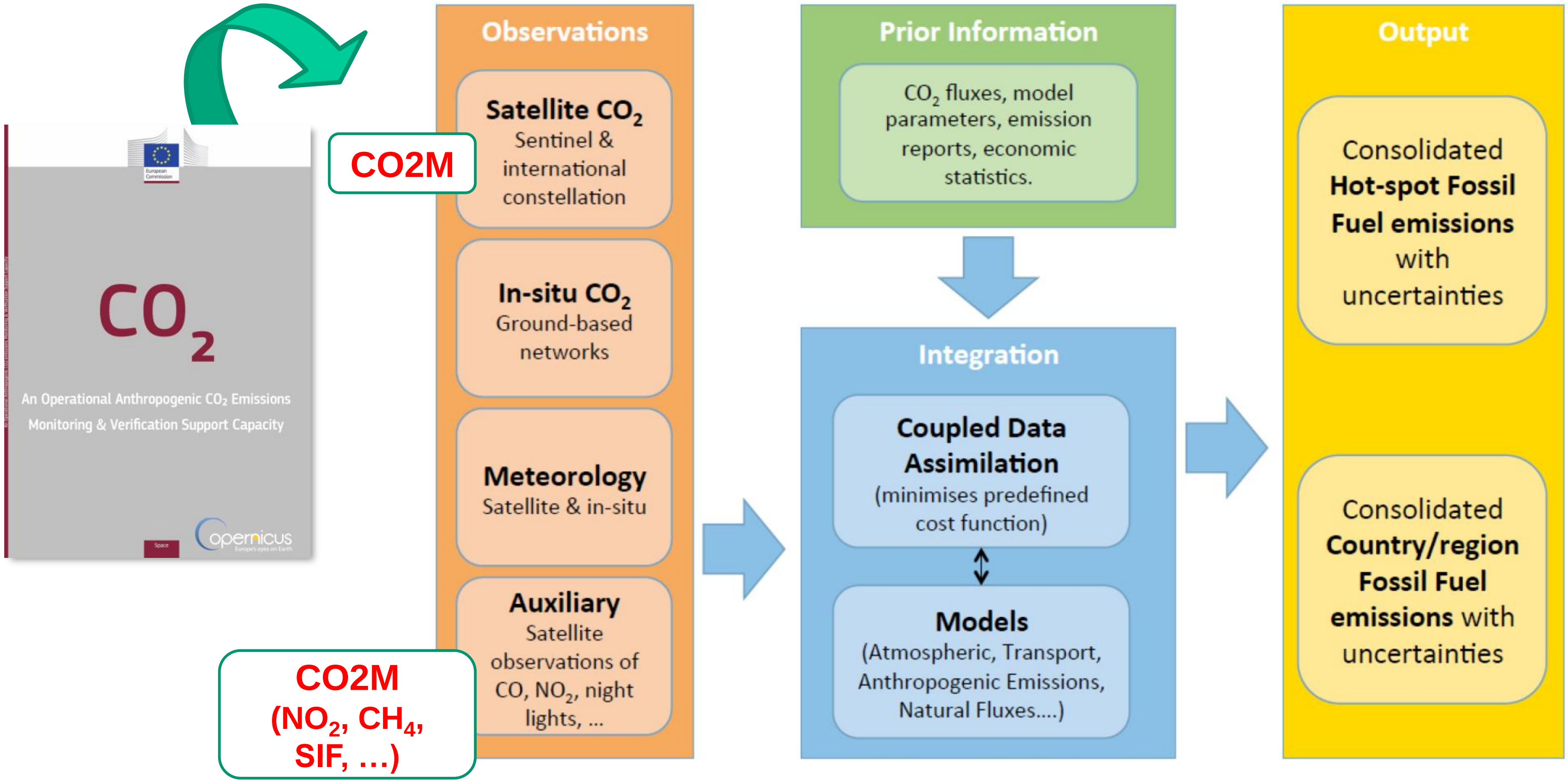
Single satellite:



Universität Bremen
ife
CO_2 Human Emissions
VERIFY

CO_2 Monitoring System

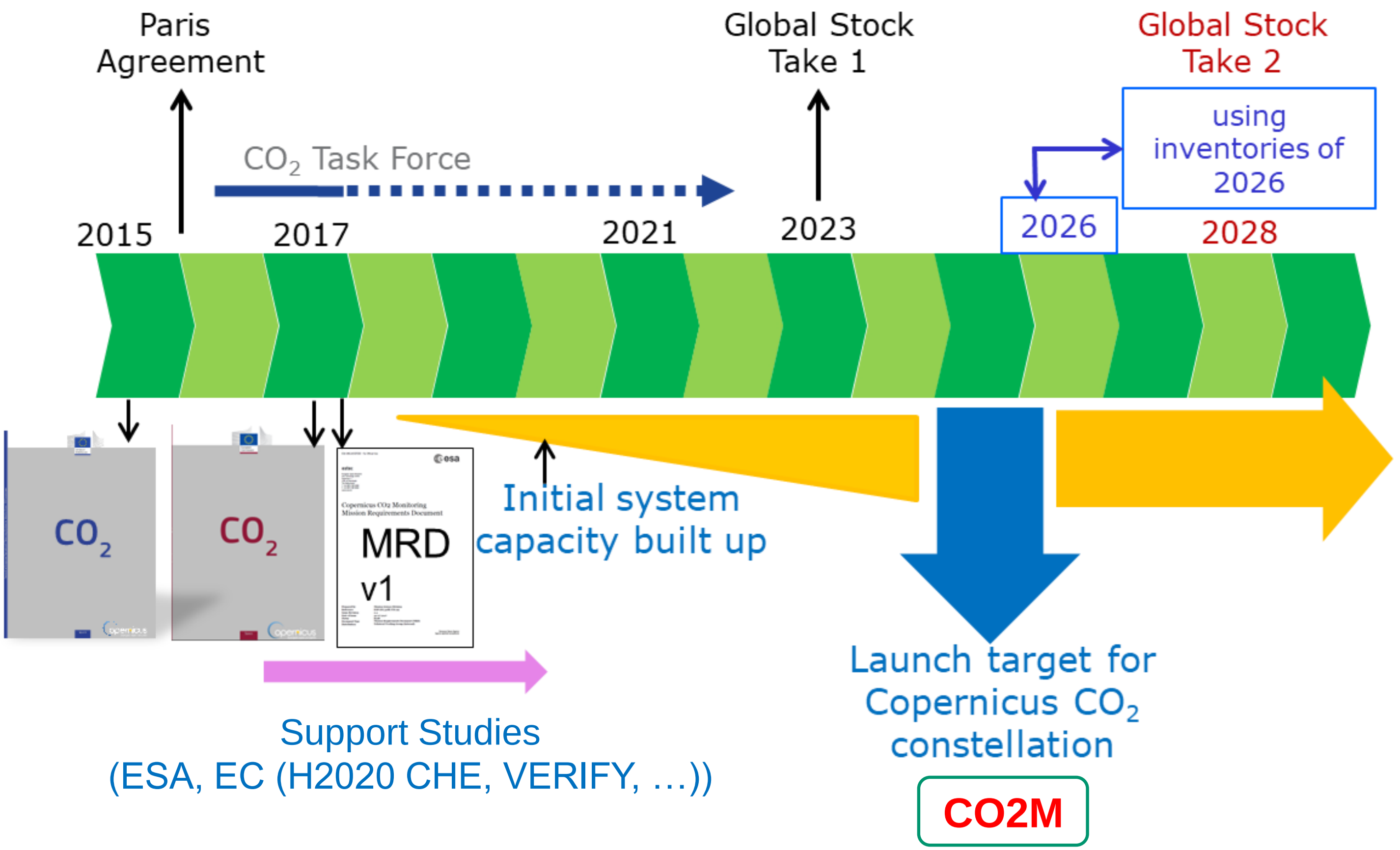
CO2M: Core component of an integrated system:



Universität Bremen

CO2M: Schedule

Towards an anthropogenic CO_2 Monitoring & Verification Support Capacity



CO2M: Further reading …

Atmos. Meas. Tech., 3, 781–811, 2010
www.atmos-meas-tech.net/3/781/2010/
doi:10.5194/amt-3-781-2010

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

Atmos. Meas. Tech., 6, 3477–3500, 2013
www.atmos-meas-tech.net/6/3477/2013/
doi:10.5194/amt-6-3477-2013

Atmospheric Measurement Techniques Open Access

Buchwitz et al., 2013

Carbon Monitoring Satellite (CarbonSat): assessment of atmospheric CO_2 and CH_4 retrieval errors by error parameterization

M. Buchwitz[1], M. Reuter[1], H. Bovensmann[1], D. Pillai[1], J. Heymann[1], O. Schneising[1], V. Rozanov[1], T. Krings[1], J. P. Burrows[1], H. Boesch[2], C. Gerbig[3], Y. Meijer[4], and A. Löscher[4]
[1]Institute of Environmental Physics (IUP), University of Bremen FB1, Otto Hahn Allee 1, 28334 Bremen, Germany
[2]Department of Physics and Astronomy, University of Leicester, Leicester, UK
[3]Max-Planck-Institute for Biogeochemistry (MPI-BGC), Jena, Germany
[4]ESA ESTEC, Noordwijk, the Netherlands

Atmos. Meas. Tech., 4, 2809–2822, 2011
www.atmos-meas-tech.net/4/2809/2011/
doi:10.5194/amt-4-2809-2011

Atmospheric Measurement Techniques

Velazco et al., 2011

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

+ several ESA study reports (LOGOFLUX, SmartCarb, AeroCarb, PMIF, CCFFDAS, …), & other documents

Atmos. Meas. Tech., 11, 681–708, 2018
https://doi.org/10.5194/amt-11-681-2018

Atmospheric Measurement Techniques Open Access EGU

Broquet et al., 2018

The potential of satellite spectro-imagery for monitoring CO_2 emissions from large cities

Grégoire Broquet[1], François-Marie Bréon[1], Emmanuel Renault[1,a], Michael Buchwitz[2], Maximilian Reuter[2], Heinrich Bovensmann[2], Frédéric Chevallier[1], Lin Wu[1], and Philippe Ciais[1]
[1]Laboratoire des Sciences du Climat et de l'Environnement, LSCE/IPSL, CEA-CNRS-UVSQ, Université Paris-Saclay, 91191 Gif-sur-Yvette, France
[2]Institute of Environmental Physics (IUP), University of Bremen FB1, Otto Hahn Allee 1, 28334 Bremen, Germany
[a]now at: Service hydrographique et océanographique de la marine, 29228 Brest, France

Atmos. Chem. Phys., 16, 9591–9610, 2016
www.atmos-chem-phys.net/16/9591/2016/
doi:10.5194/acp-16-9591-2016

Atmospheric Chemistry and Physics Open Access EGU

Pillai et al., 2016

Tracking city CO_2 emissions from space using a high-resolution inverse modelling approach: a case study for Berlin, Germany

Dhanyalekshmi Pillai[1,2], Michael Buchwitz[1], Christoph Gerbig[2], Thomas Koch[2], Maximilian Reuter[1], Heinrich Bovensmann[1], Julia Marshall[2], and John P. Burrows[1]
[1]Institute of Environmental Physics, University of Bremen, Bremen, Germany
[2]Max Planck Institute for Biogeochemistry, Jena, Germany

Summary

Anthropogenic CO_2 emissions from space:

- Retrieved quantity: Near-surface-sensitive column-averaged dry-air CO_2 mole fractions = XCO_2
- First satellite sensor SCIAMACHY/ENVISAT (launch 2002)
- Satellite XCO_2 currently generated operationally in Europe via C3S & CAMS
- None of the past & present sensors optimized for this application (currently focus is on natural fluxes); nevertheless: several relevant peer-reviewed publications using SCIAMACHY, GOSAT, OCO-2: from „detection" to more & more quantitative results (with and without NO_2) including comparisons with emission inventories
- Only the planned Copernicus anthropogenic CO_2 monitoring (CO2M) mission will be optimized for anthropogenic CO_2 emission monitoring of localized emission sources globally thanks to its „XCO_2 imaging" capability