Potential of improved observation missions:

Sentinel-5

H. Bovensmann

with inputs from the Sentinel-4 and -5 Mission Advisory Group

University of Bremen, Institute of Environmental Physics

3rd Post EPS User Consultation Workshop, EUMETSAT, Darmstadt, 29./30.9.2011

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Acknowledgements

- A. Richter, A. Bracher, M. Buchwitz, S. Noel, M. Weber, J.P. Burrows, IUP
- J. Landgraf, SRON
- P. Levelt, P. Veefkind, KNMI
- T. Wagner, S. Beirle, MPIC
- D. Loyola, P. Valks, DLR IMF
- A. Simmons and MACC team, ECMWF
- M. van Roozendael, N. Theys, BIRA
- R. Siddans, B. Kerridge, RAL
- T. Erbertseder, DLR DFD
- P. Ingmann, B. Veihelmann, J.L. Bezy, ESA
- R. Munro, EUMETSAT
- O3SAF (FMI, KNMI, DLR …)

Sentinel 5 - Heritage

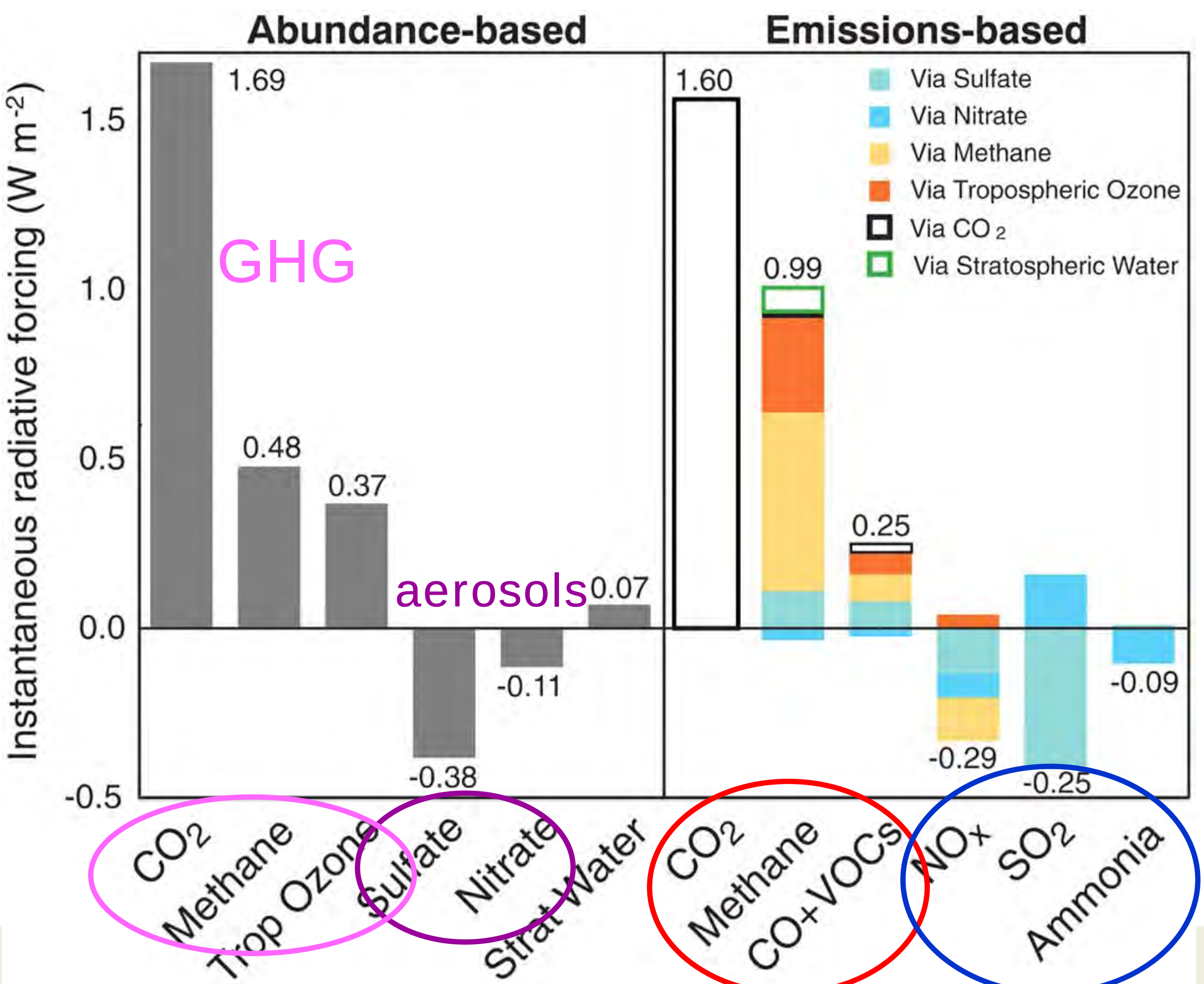
- GOME on ERS-2
  - quantitative determination of trop. column distributions of **O_3, NO_2, SO_2, BrO, HCHO, H_2O**
- SCIAMACHY on ENVISAT
  - In addition: quantitative determination of trop. column distributions of **CHOCHO, CO, CH_4 and CO_2**
  - improved spatial resolution (30 x 60 km^2)
- OMI on AURA
  - use of **2-dimensional CCDs** for trace gas applications
  - improved spatial resolution (**13 x 24 km^2**)
- GOME-2/METOP
  - **Polarisation** measurement system to characterise aerosol
  - Potential of **UV-TIR synergy** (GOME-IASI) to derive improved trop. O_3
- GeoSCIA/GeoTrope
  - Studies on requirements and instrument concepts geostationary
- MTG / Sentinel-4/-5 / Post EPS
  - Studies on requirements and instrument concepts for **operational applications**

Needs in 2020 ++

- World population further increase (strong regional variation)
- On average standard of living expected to further increase (energy consumption, increase in transport/traffic etc.)
- More people expected to live in Megacity-type agglomerations (emissions co-located with human beings -> health issues)
- Emissions into the atmosphere expected to further increase globally with strong regional variability (incl. regions of decreasing emissions) and negative impact on health and crop yield
- Ozone layer response to the combined effect of ozone-depleting substances and climate change not clear.
- Air Quality and Climate are interlinked (heat waves, droughts etc.)

Adequate data for monitoring, forecast, verfication and process understanding needed!

Impact of precursors (NO_2, SO_2, CO) and non-CO2 halocarbons on climate: **Emission based estimates needed for mitigation**



Air quality and climate are linked!

S-5 will provide unique information

D. Shindell, Science 2009, modified P.Levelt

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Monitoring atmospheric composition & climate

Atmospheric services relate to chemical and particulate concentrations

Weather agencies

GMES atmospheric environmental services

Environmental agencies

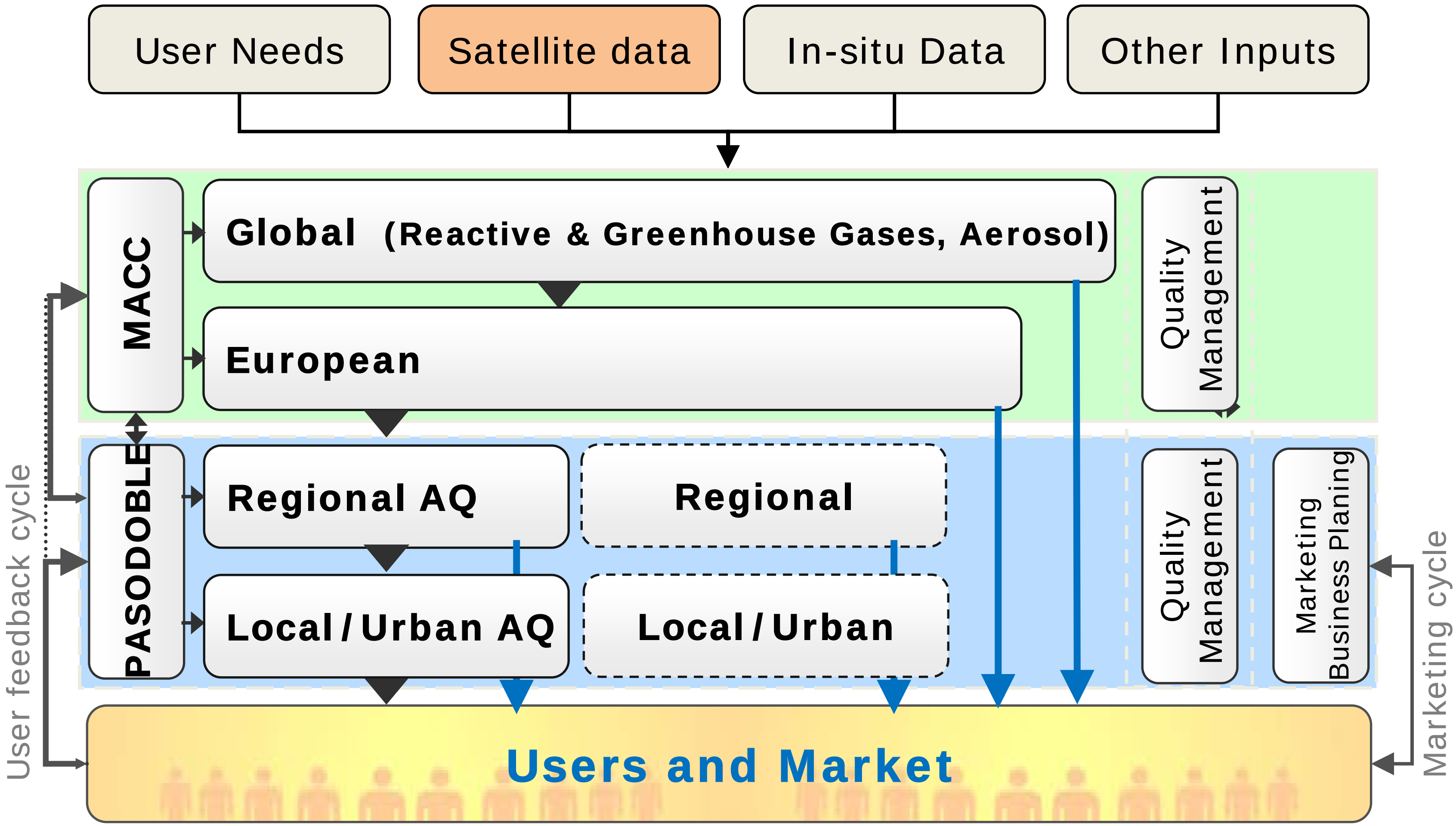
provide data & information on

- **Climate forcing by greenhouse gases and aerosols**
- **Long-range pollutant transport**
- **European air quality**
- **Dust outbreaks**
- **Solar energy**
- **UV radiation**
- **• • •**

Application Areas (S-4/S-5 MRD)

Application Area	Air Quality	Climate	O3 Layer & Surface UV
Protocol Monitoring	UN/ECE CLRTAP; EMEP / Göteborg Protocol; EC directives EAP / CAFE AQ emission verification AQ distribution and trend monitoring	UNFCCC Rio Convention; Kyoto Protocol; Climate policy EU GHG and aerosol emission verification GHG/aerosol distribution and trend monitoring	UNEP Vienna Convention; Montreal and subs. Protocols CFC emission verification Stratospheric ozone, halogen and surface UV distribution and trend monitoring
Services	Local Air Quality (BL); Health warnings (BL) Chemical Weather (BL/FT) Aviation routing (UT)	NWP assimilation and (re-analysis Climate monitoring Climate model validation	Stratospheric composition and surface UV forecast NWP assimilation and (re-) analysis
Assessement	Long-term global, regional, and local data records UNEP, EEA assessments Regional & local PBL AQ processes; Tropospheric chemistry and long-range transport AQ source attribution AQ Health and safety effects	Long-term global data records IPCC assessments Earth System, climate, rad. forcing processes; UTLS transport-chemistry processes Forcing agents source attribution Socio-economic climate effects	Long-term global data records WMO Ozone assessments Stratospheric chemistry and transport processes; UV radiative transport processes Halogen source attribution UV health & biological effects

The GMES Atmosphere Service Lines



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Adapted figure from T. Erbertseder, DLR

GMES Atmosphere Space Component

- Atmospheric composition requirements for an operational mission have been established based on in-depth analysis and studies (EUM AEGs, ESA CAPACITY, ESA CAMELOT etc.)
- Two complementary implementation components have been identified, namely
  - Sentinel-4, i.e. the **GEO related component**, will get implemented as a UVN instrument added to the MTG sounder satellites, making use of the IR sounder and MTG imager data
  - Sentinel-5, i.e. the **LEO related component**, implemented as a UVNS instrument on Post-EPS satellites, together with IASI-NG, VII and 3MI optimising on atmospheric composition products

To avoid a data gap a Sentinel-5 Precursor will get implemented on a dedicated platform making use of NPP/VIIRS

S5 (GOME-2) Products vs. Applications

Product	Application: Air Quality	Application: Climate	Application: Strat. O3 & Surface UV	Comment
O_3 total column, profile stratosphere	UV Rad	X	X	ECV
O_3 trop. Column	X	X	X	ECV, Synergy with IR
BrO, OClO total column			X	
NO_2 total & trop. Column	X	X	X	
SO2 total column	X	X	X	Also for volcanic eruptions, Synergy with infrared data from IR
HCHO, CHOCHO total column	X	X		Linked to Secondary Organic Aerosol
H_2O total column		X		ECV, Synergy with infrared data from IR
CO total column	X	X		Synergy with infrared data from IR
CH_4 total column		X		ECV, Synergy with infrared data from IR
CO_2 total column (tbd)		X		ECV, pot. observational capability, syn. IR
Aerosol extinction coeff. profile, column optical depth / type / index	X	X		ECV, also auxiliary for other S5 products Also for volcanic eruptions Synergy with VII and 3MI
Cloud optical thickness, fraction, altitude			X	ECV, auxiliary for other S5 products synergy with VII and 3MI

UV-VIS-NIR SWIR nadir observation capabilities

	Satellite	Data Availability	Orbit	Obs. Modes	Nadir Swath	Nadir Spatial Resolution
GOME	ERS-2	06/1995-6/2011 (*)	10:30	Nadir	960 km	320 x 40 km^2
SCIAMACHY	ENVISAT	8/2002 – present	10:00	Nadir, Limb, Occ.	960 km	60 x 30 km^2
GOME-2	**METOP**	**01/2007-2020**	**09:30**	**Nadir**	**1920 km**	**40 x 80 km^2**
Sentinel-5	**METOP-SG**	**2018+**	**09:30**	**Nadir**	**2700 km (tbc)**	**7 x 7 km^2**
OMI	AURA	7/2004 – present	13:42	Nadir	2600 km	13 x 24 km^2
OMPS	NPP/ JPSS	Early 2012 - 2026	13:30	Nadir (NPP Limb)	2600 km	50 x 50 km^2
Sentinel 5 Precursor	Dedicated	2015 – 2022	13:30	Nadir	2600 km	7 x 7 km^2
Sentinel 4	MTG-S	2019+	GEO	Nadir		8 km x 8 km^2

(*) GOME global coverage lost in June 2003

TOMS, SBUV omitted

Spectral Sensor Characteristics [nm]

Spectral band	Demonstrated Products	SCIAMACHY	GOME, GOME-2	S-5	S5 MRD Products
UV	O3 column, O3 profile, trop. O3 SO2, BrO, HCHO, OClO, AAI	214 – 400 0.25 nm	**240 – 400 < 0.25 nm**	**270 – 400 < 0.5 nm (< 1 nm below 300 nm)**	O3 column, O3 profile, trop. O3 SO2, BrO, HCHO, OClO, AAI
VIS	Total NO2, trop. NO2, strat. NO2 CHOCHO, IO	400 – 620 0.44 nm	**400 – 600 < 0.5 nm**	**400 – 500 < 0.5 nm**	Total NO2, trop. NO2, strat. NO2 CHOCHO, IO
NIR	H2O, Aerosol, Cloud Height, COT	620 – 1050 0.54 nm	**600 – 790 < 0.5 nm**	**685 - 710 – 775 < 0.06 (0.4) nm**	H2O, Aerosol , Cloud Height, COT
SWIR-1	XCH4 (w.r.t. CO2)	1000- 1750 1.48 nm	-	**1590-1675 < 0.25 nm**	XCH4 (w.r.t. CO2)
SWIR-2	CO2 scattering correction	1935 – 2040 0.22 nm	-	**2043-2085 < 0.125** under assessment	CO2 scattering correction
SWIR-3	CO (CH4, H2O), HDO	2260 – 2385 0.26 nm	-	**2305-2385 < 0.25 nm**	CO (CH4, H2O), HDO

Key Sensor Improvements (compared to GOME-2)

- Spatial resolution 80 x 40 km^2 -> 7 x 7 km^2
  - Higher spatial resolution will increase substantially the number of cloud free observations
  - Higher spatial resolution will allow for better quantification of Air Pollution on urban scales and of emission sources
  - Higher spatial resolution will allow for better discrimination of processes.
- Spatial coverage increased from 1920 km to 2700 km
  - Daily coverage also in the tropics
- Spectral coverage
  - optimised to assure continuity w.r.t. GOME-SCIA-GOME-2 data product time series (since 1995)
  - extended to include CO, CH_4 (CO_2 tbd)

Improvement: Number of Cloud Free Observations

Mexico City
January 20, 2005

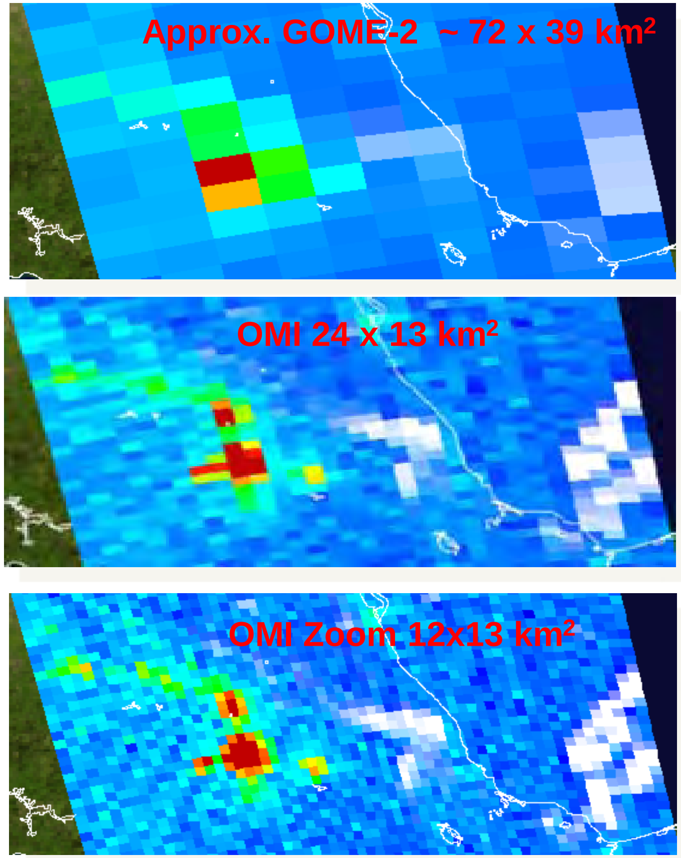


Figure: KNMI

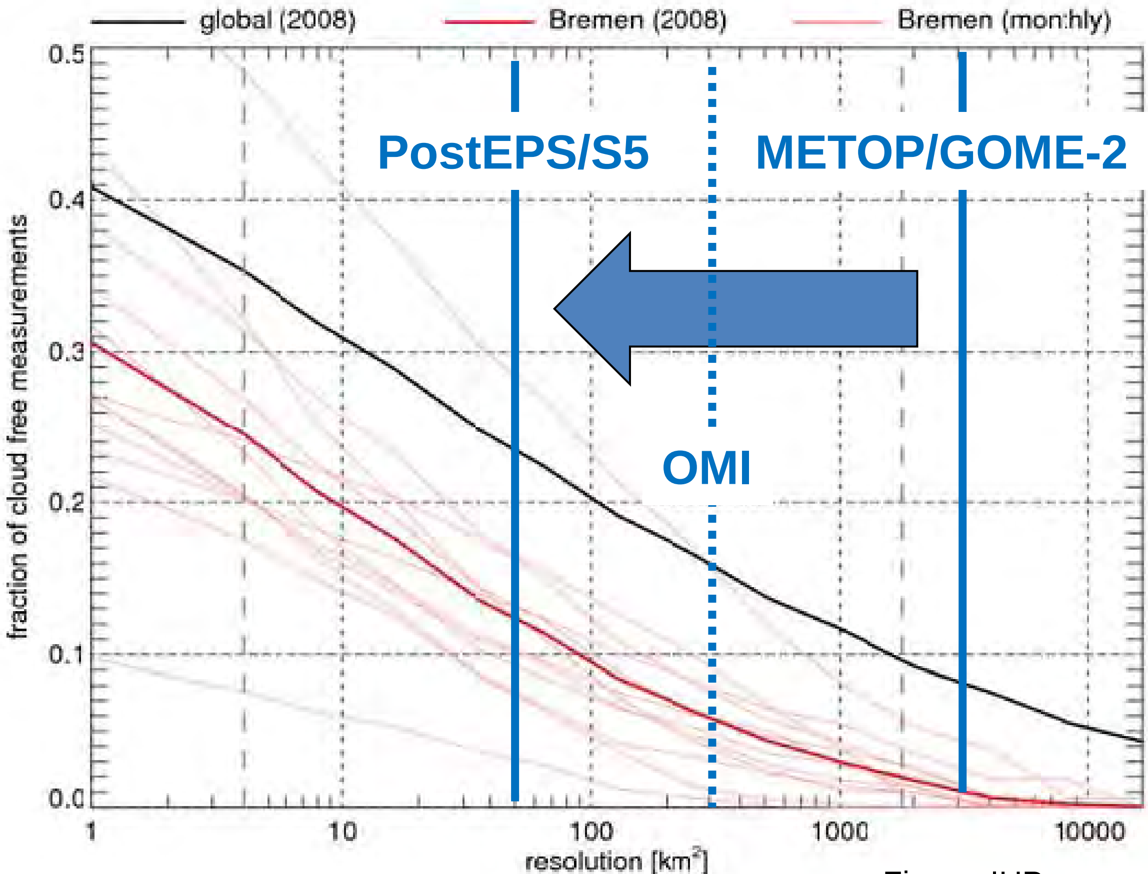
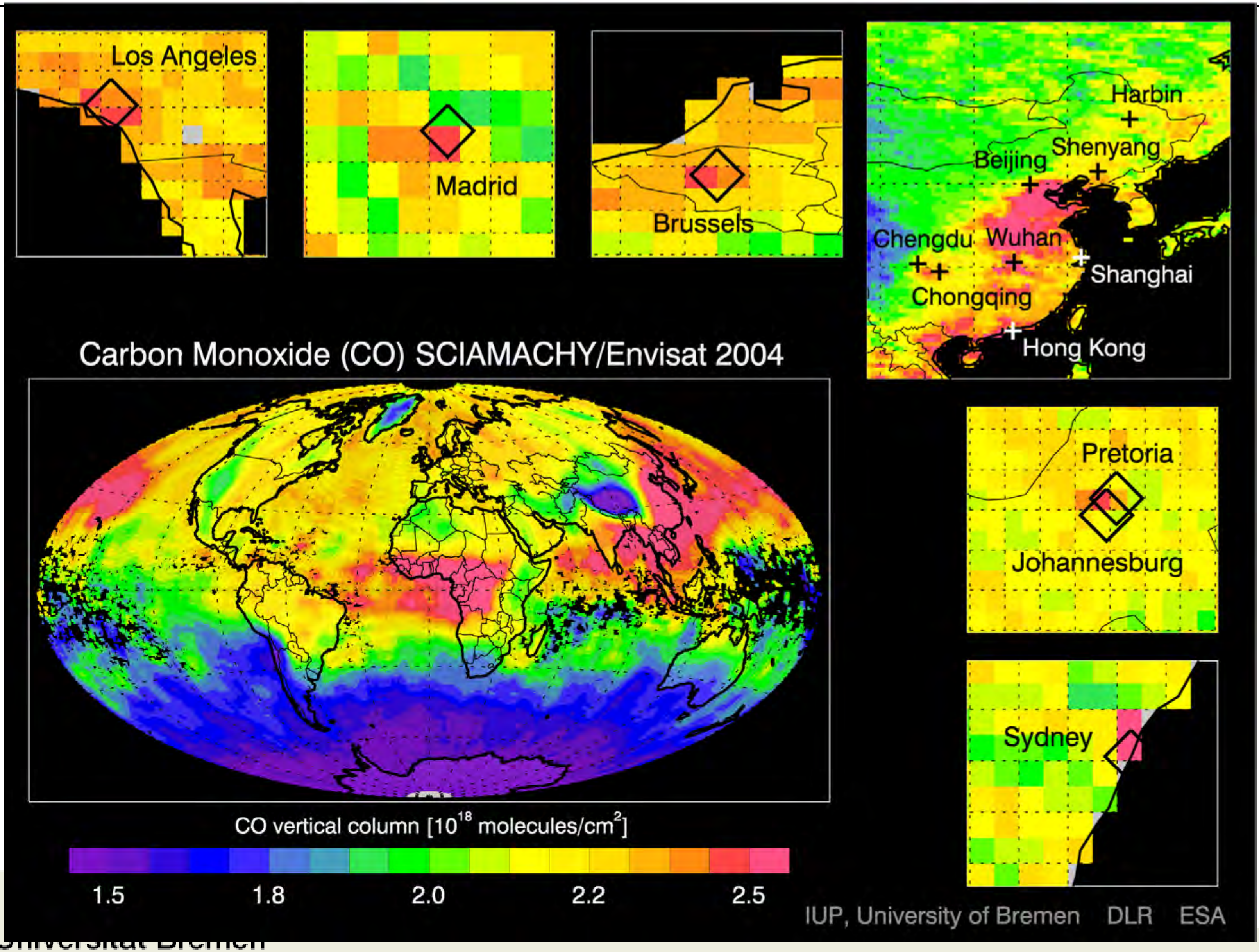


Figure: IUP

Estimated number of cloud free observations using MODIS

Carbon Monoxide (CO) from SCIAMACHY



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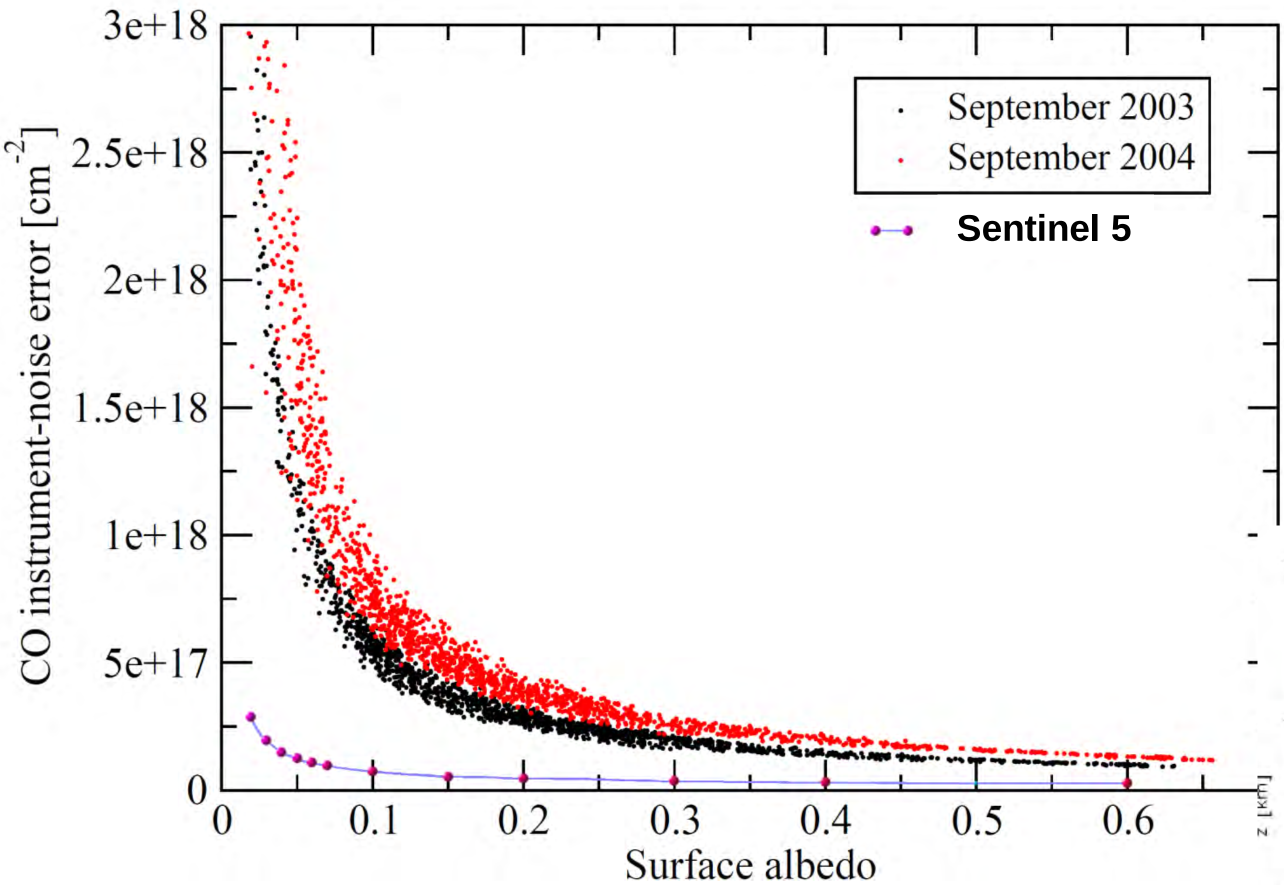
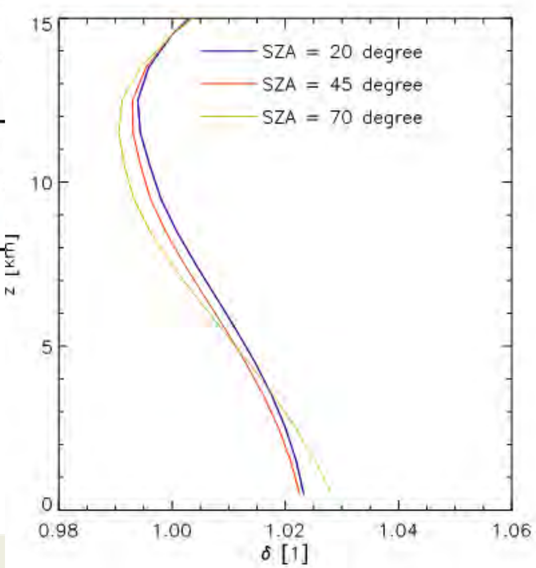
Buchwitz et al., ACP, 2007

S5 CO retrieval noise compared to SCIAMACHY



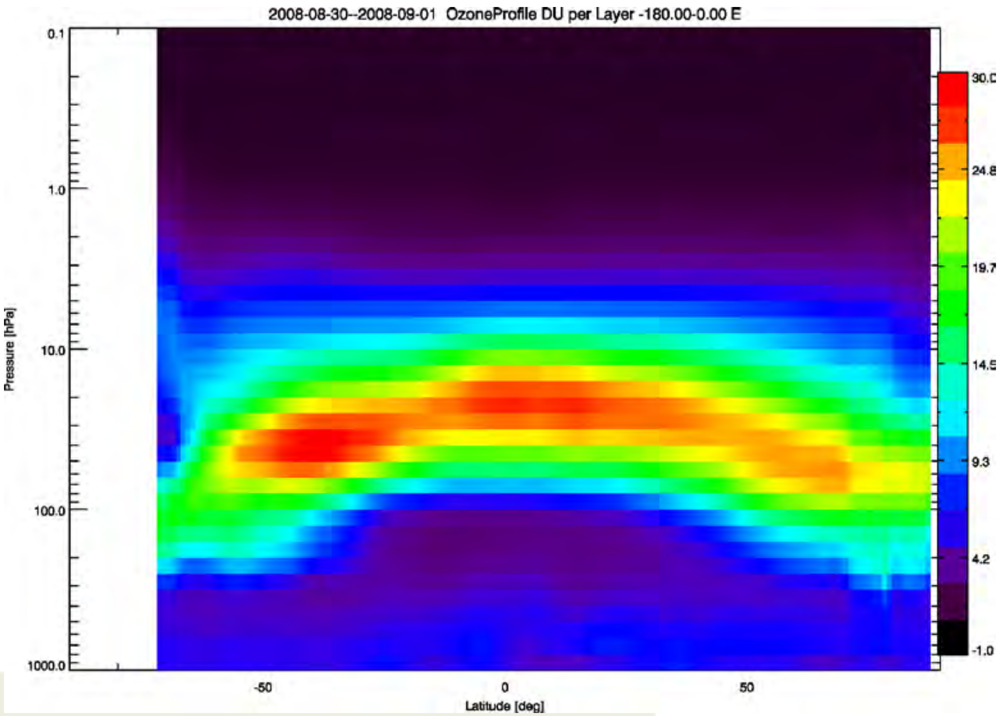
Sensitivity down to PBL/surface



S5 CO retrieval noise expected to be an order of magnitude smaller than for SCIAMACHY, with as many cloud-free data in one day as SCIA in one year

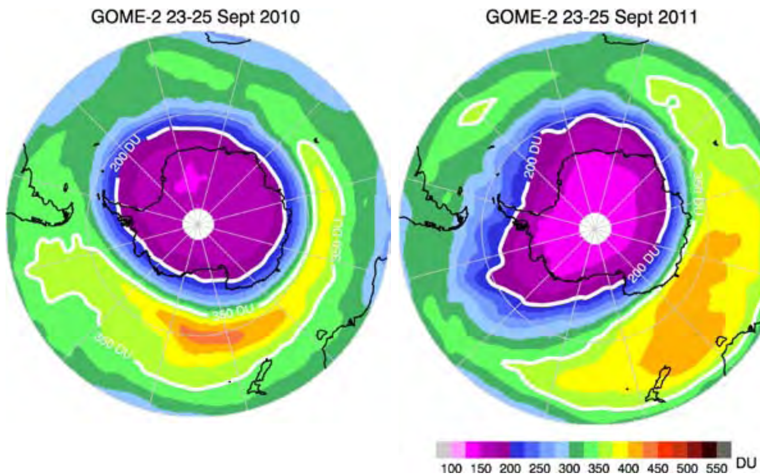
Stratosperic Ozone Layer Monitoring

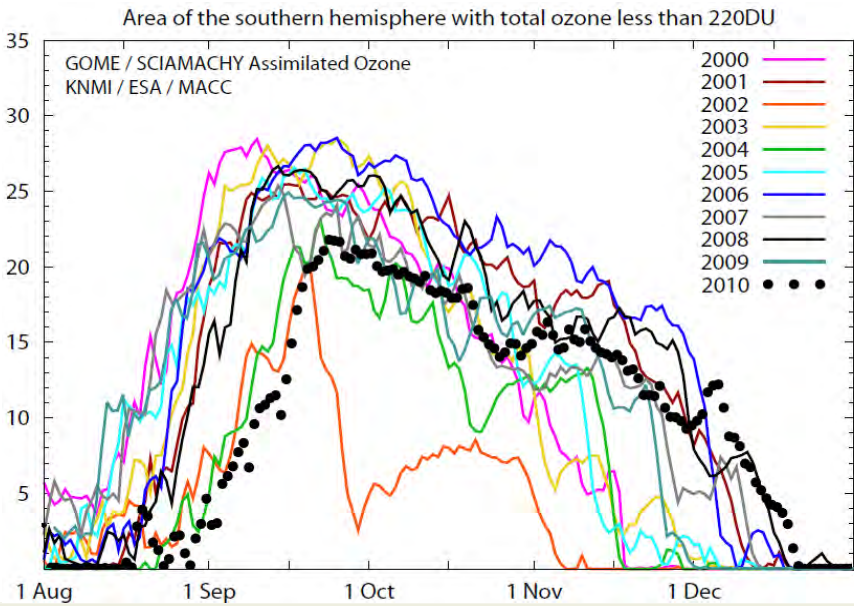
- Total Ozone time series
- Ozone profiling
- Strat. NO2
- BrO
- OClO
- Surface UV

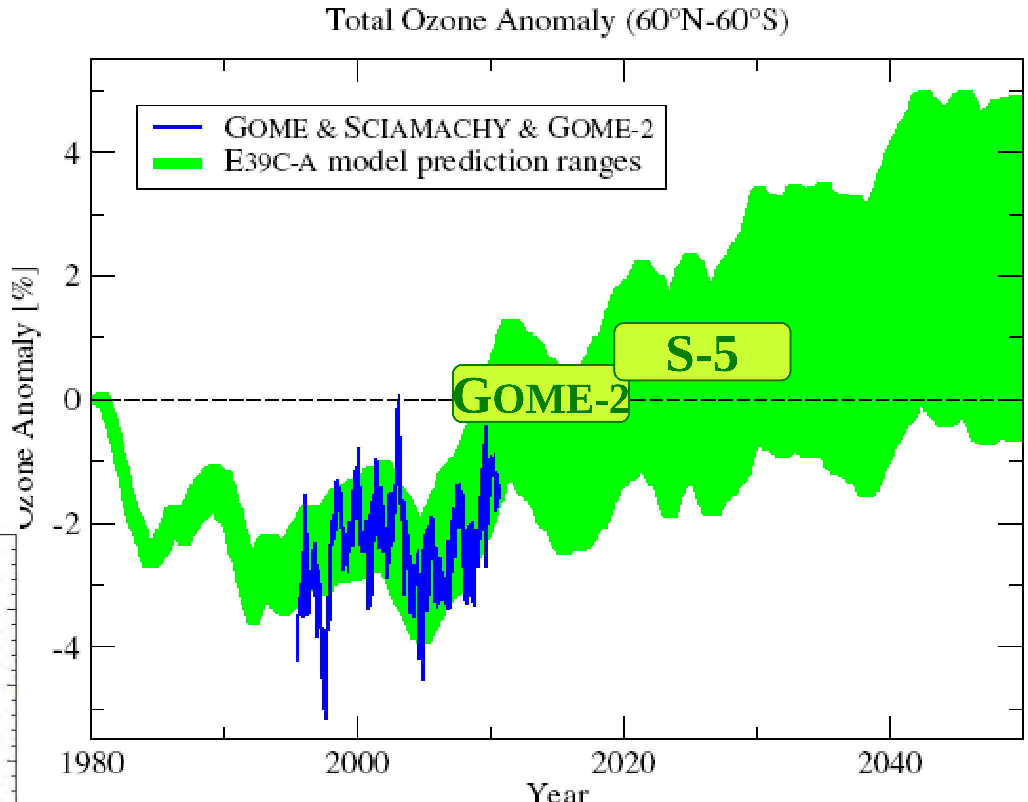


Latitudinal cross section of ozone profiles, averaged over 180W to 0.0E – 31 August 2008 (KNMI)

Continous Monitoring of the Ozone Layer since 1995







Measured and projected evolution of total ozone in response to the combined effect of ozone-depleting substances and climate change.

ESA Ozone_cci

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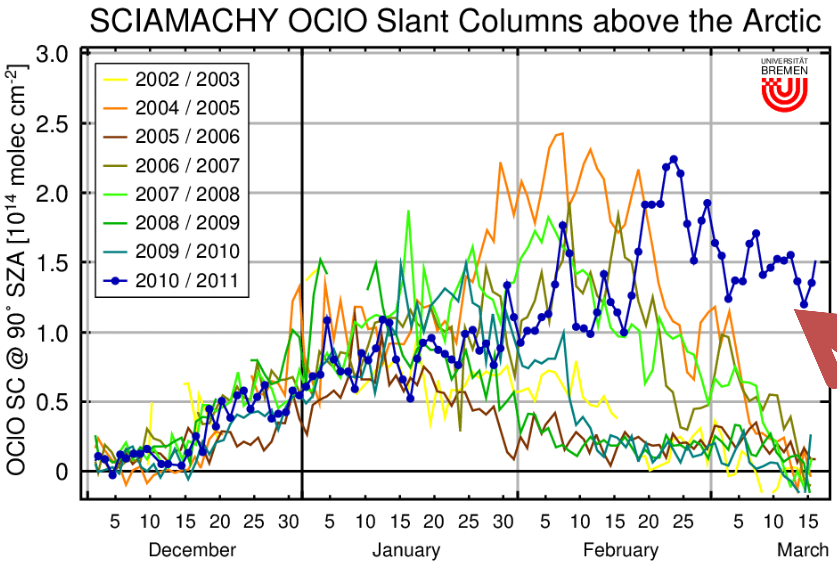
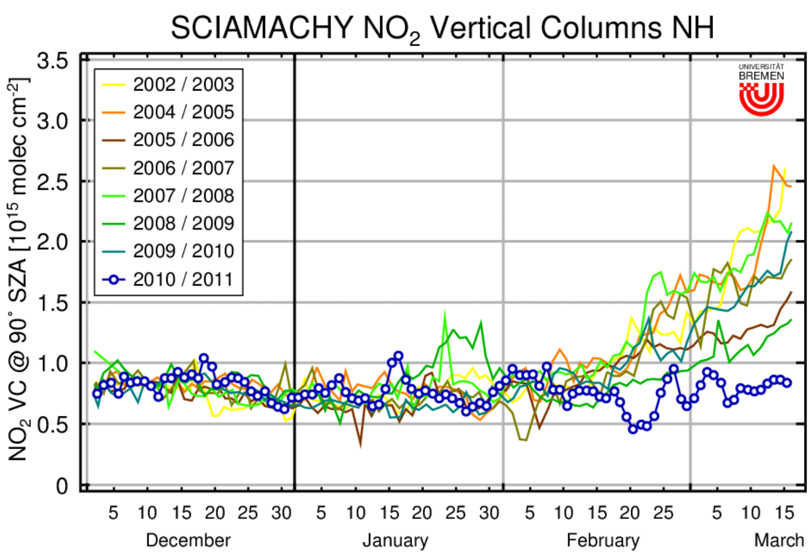
SCIAMACHY OClO and NO_2 @ 90° SZA



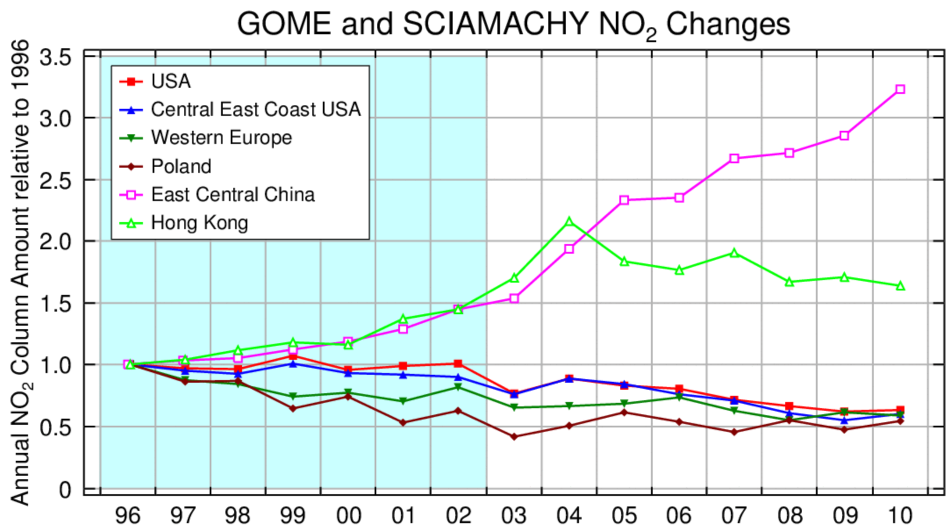
- OClO is highly variable in the Northern hemisphere, mainly following stratospheric temperatures
- Some winters have larger activation in February (2004 / 2005, 2007 / 2008
- Only in 2011, OClO was still high in March

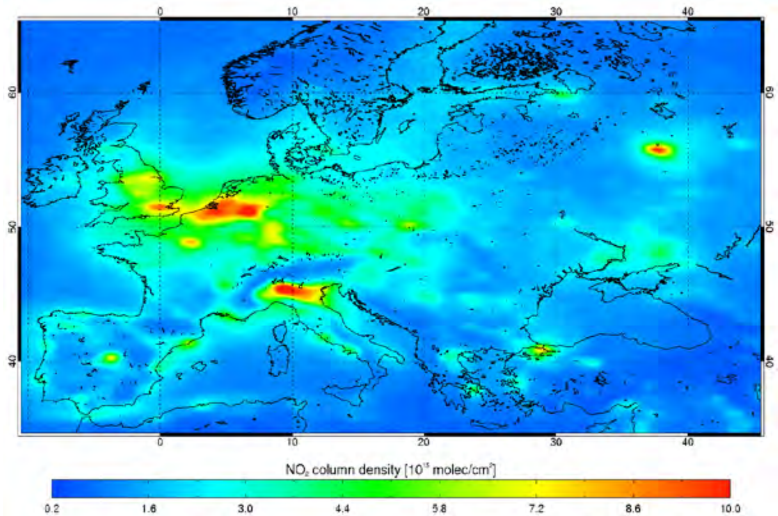


- NO_2 usually increases in late February
- Only in 2011, NO_2 remained low in March

Air Pollution & Emissions

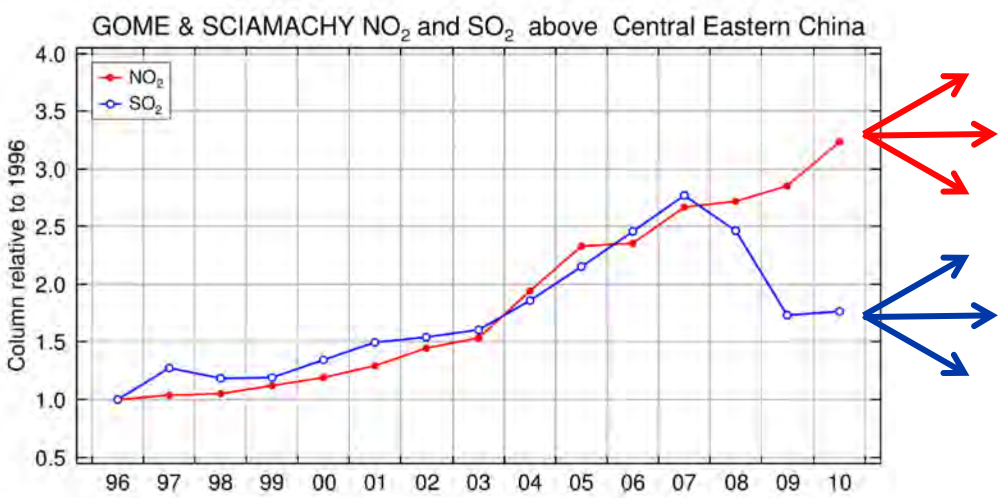
- Trop. NO2
- SO2 (volcanic, anthropogenic)
- VOC indicator (HCHO, CHOCHO)
- Carbon Monoxide
- Aerosol

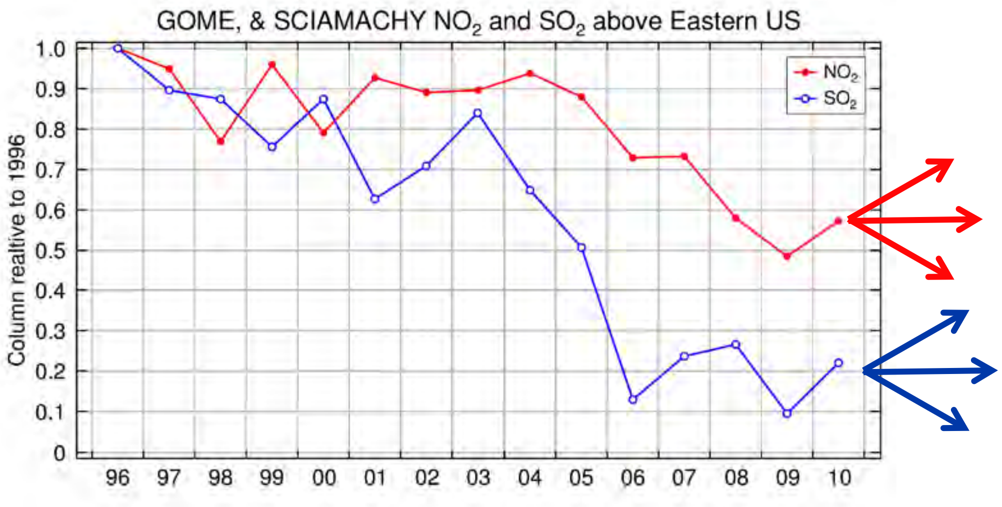




GOME-2 tropospheric NO_2 in Europe 2007-2010 (O3SAF)

NO_2/SO_2 changes GOME & SCIAMACHY



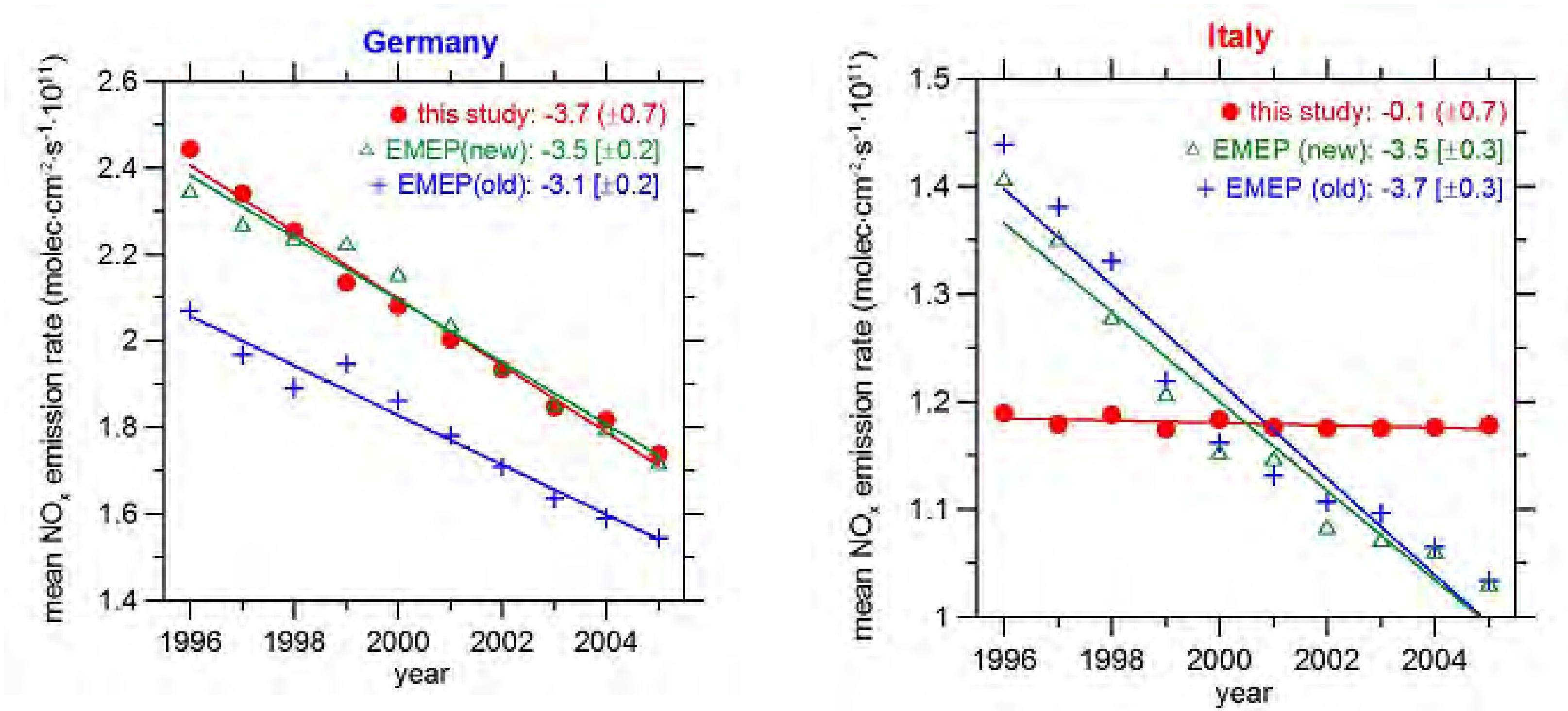


China, the increase in NO_2 and SO_2 levels was very similar until 2007 when SO_2 started to decline but NO_2 continued to increase

Eastern US, the decline in NO_2 and SO_2 started at about the same time (2005), but reductions in SO_2 were much larger than those in NO_2, probably because of other NOx sources

- **S5 will continue the time series started in 1995 until 2035 with improved spatial resolution and coverage**

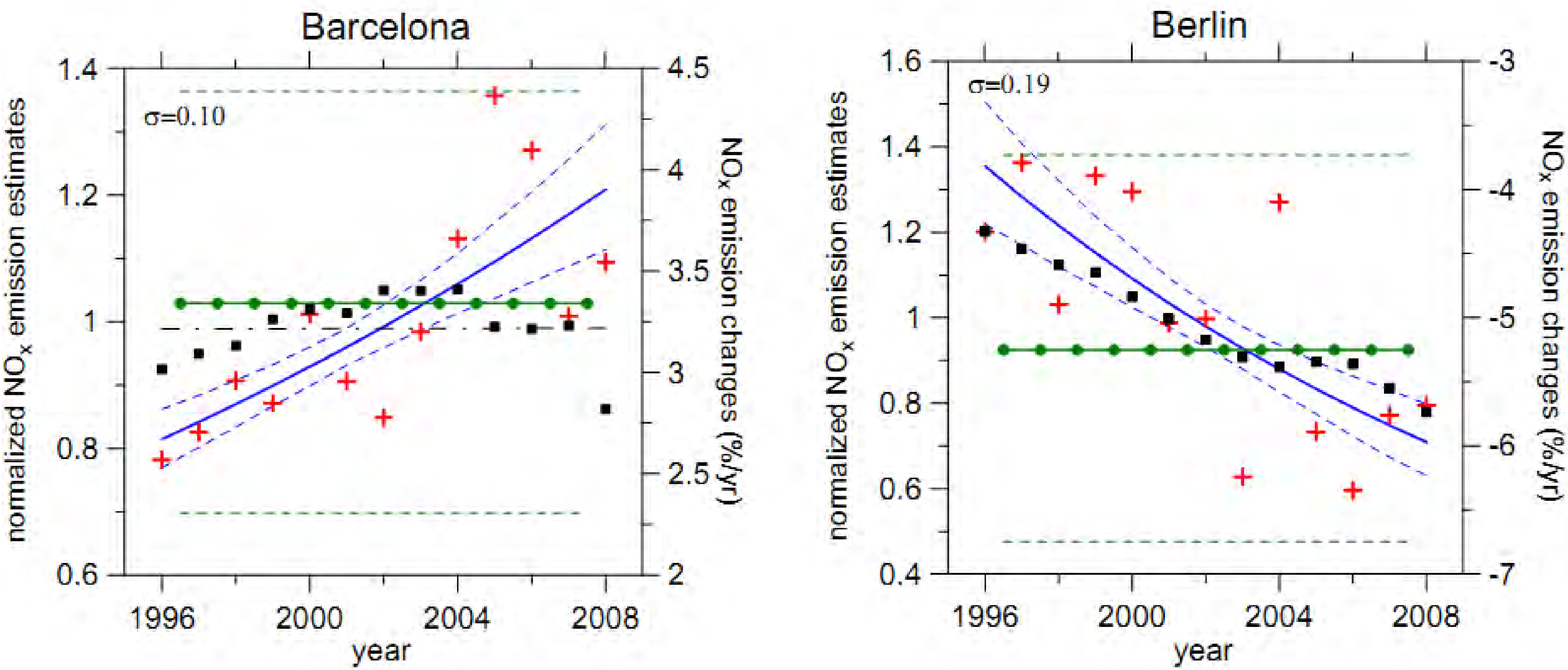
Monitoring changes in NOx emissions on country scale

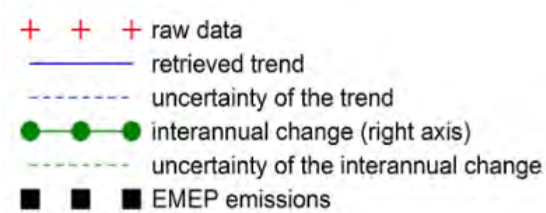


- S5 will continue (and extend to CO) the time series on **emission trends** started in 1995 until 2035 with improved spatial resolution and coverage, allowing monthly to seasonal temporal resolution

Konovalov, I., Beekmann, M., Burrows, J. P. , Richter, A., Satellite measurement based estimates of decadal changes in European nitrogen oxides emissions, Atmos. Chem. Phys., **8**, 2623-2641, 2008

Monitoring changes in NOx emissions on Megacity scale





- S5 will continue the time series on **emission trends** started in 1995 until 2035 with improved spatial resolution and coverage, allowing monthly to seasonal temporal resolution

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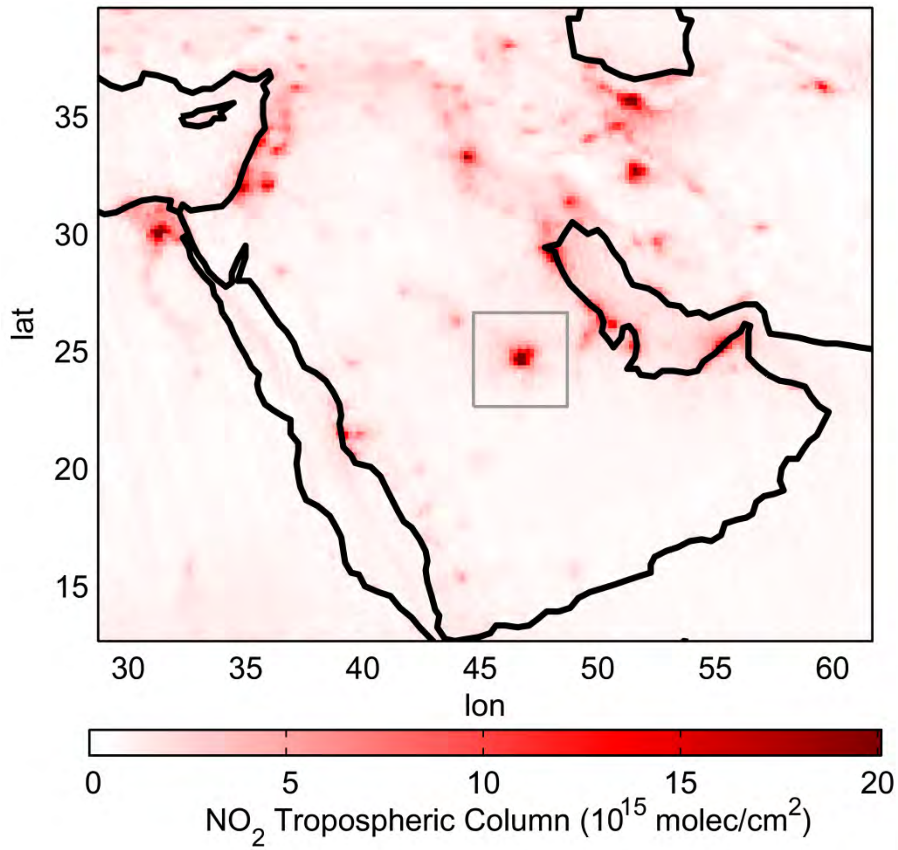
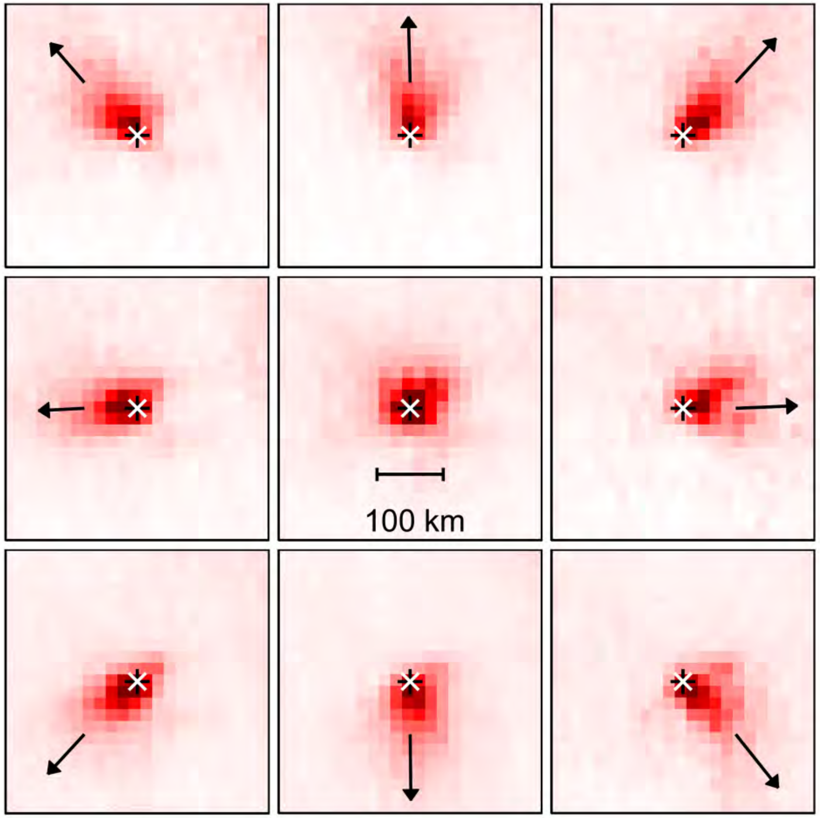
Konovalov, I. B., Beekmann, M., Richter, A., Burrows, J. P., and Hilboll, A.: Multi-annual changes of NO_x emissions in megacity regions: nonlinear trend analysis of satellite measurement based estimates, *Atmos. Chem. Phys.*, **10**, 8481-8498, doi:10.5194/acp-10-8481-2010, 2010

Independent verification of Megacity emissions





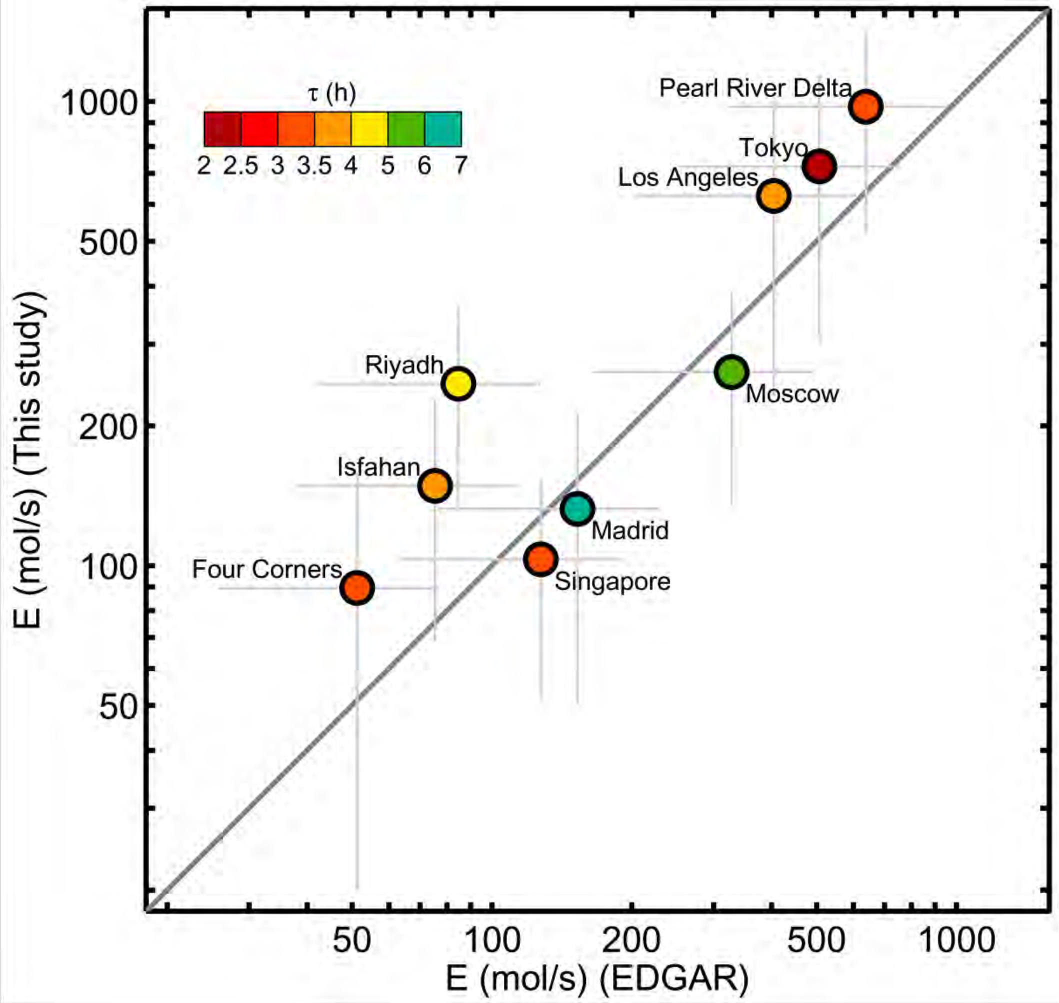
Mean NO_2 TVCD for the Middle East (OMI 2005-2009, cloud-free, calm)

TVCD around Riyadh for different wind directions (ECMWF)

Beirle et al., Science, 2011

Comparison to EDGAR v4.1, for 2005

- Approach currently limited large to well spatially isolated cities due to spatial resolution of used sensor (13 x 24 km2, OMI)
- S5 with its 7 x 7 km will allow to apply the methdod to much more cities on a yearly basis.

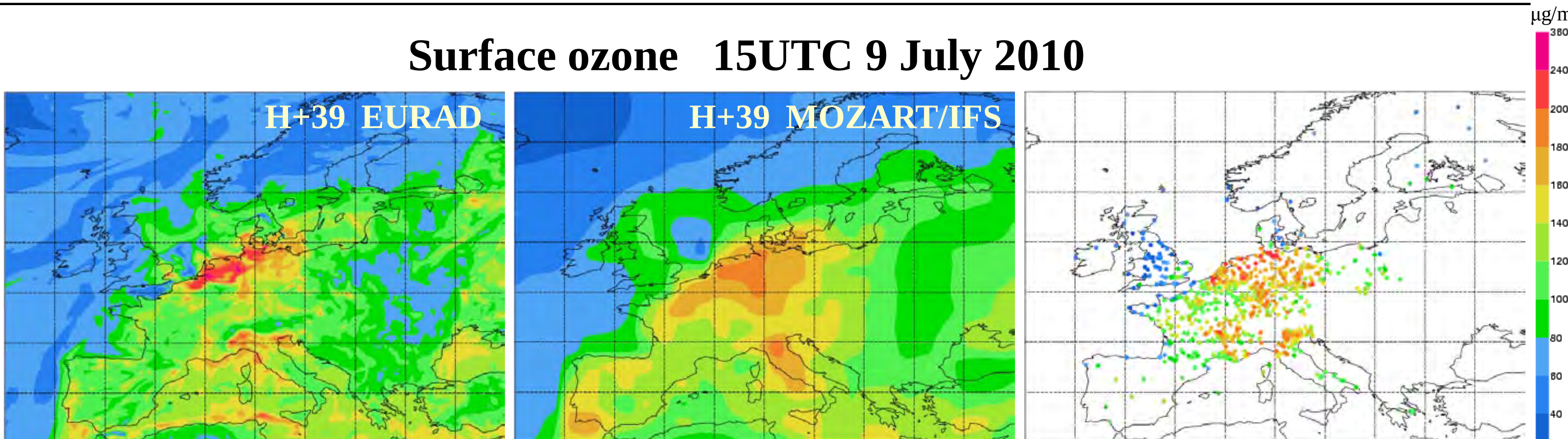


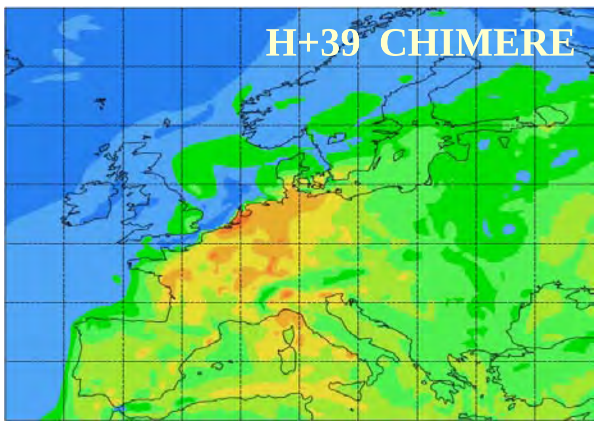
http://edgar.jrc.ec.europa.eu

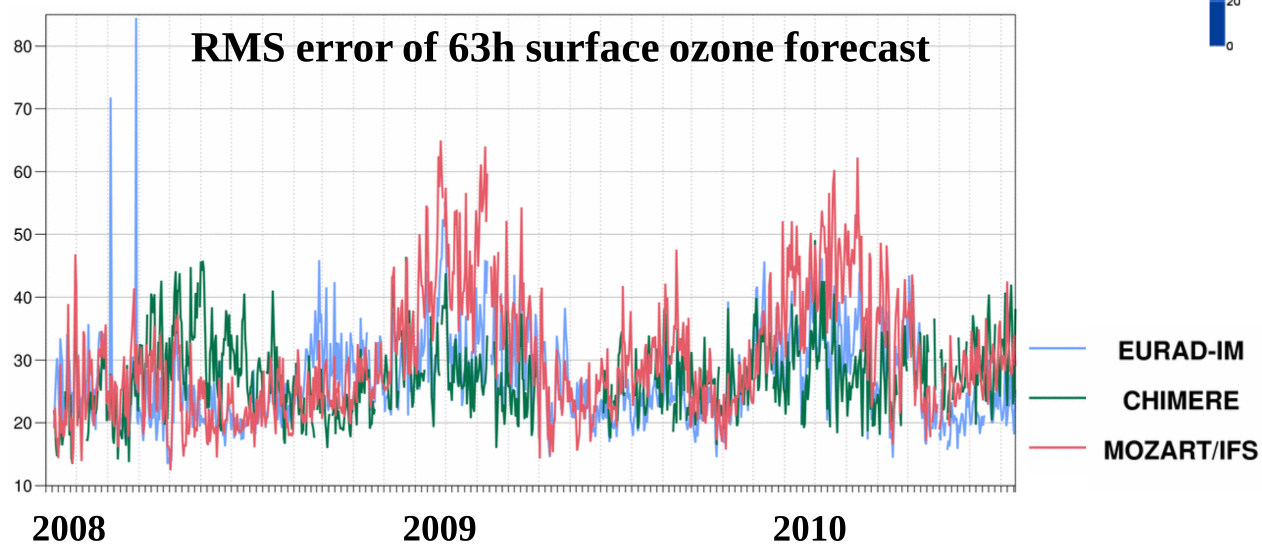
Beirle et al., Science, 2011

Improving global and regional AQ forecasts

Surface ozone 15UTC 9 July 2010







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- S5 data on O3, CO, NO2, VOC(HCHO, CHOCHO) will significantly contribute to improved AQ forecasts

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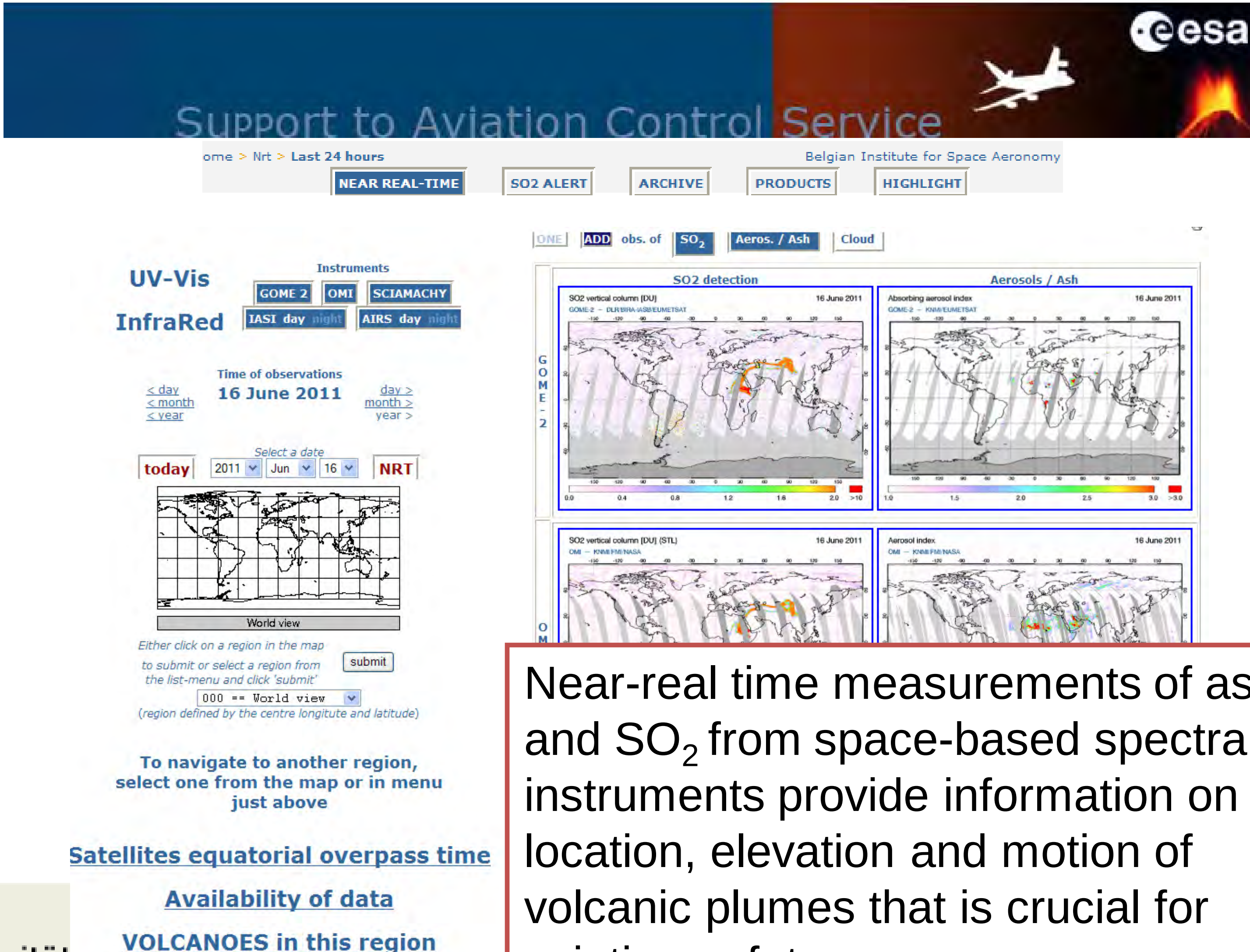
Monitoring atmospheric composition & climate

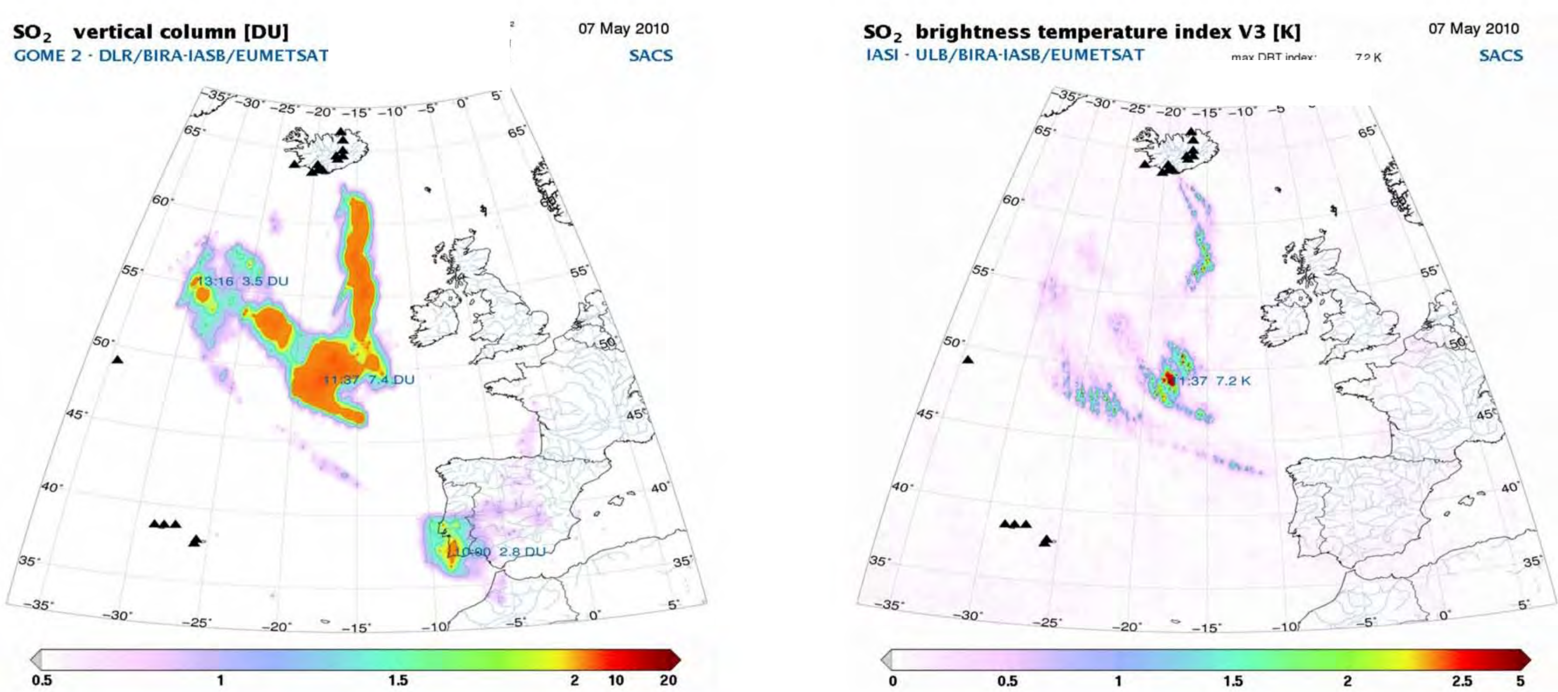
Support to Aviation Control Service

http://sacs.aeronomie.be/



Near-real time measurements of ash and SO_2 from space-based spectral instruments provide information on the location, elevation and motion of volcanic plumes that is crucial for aviation safety.

Satellite Data UV & IR



SO_2 plume, Eyjafjallajökull (May 7, 2010)

- Key measurements from space: high spatial resolution and coverage.
- UVN and IR Soundings are complementary in terms of measurement sensitivity and temporal sampling.

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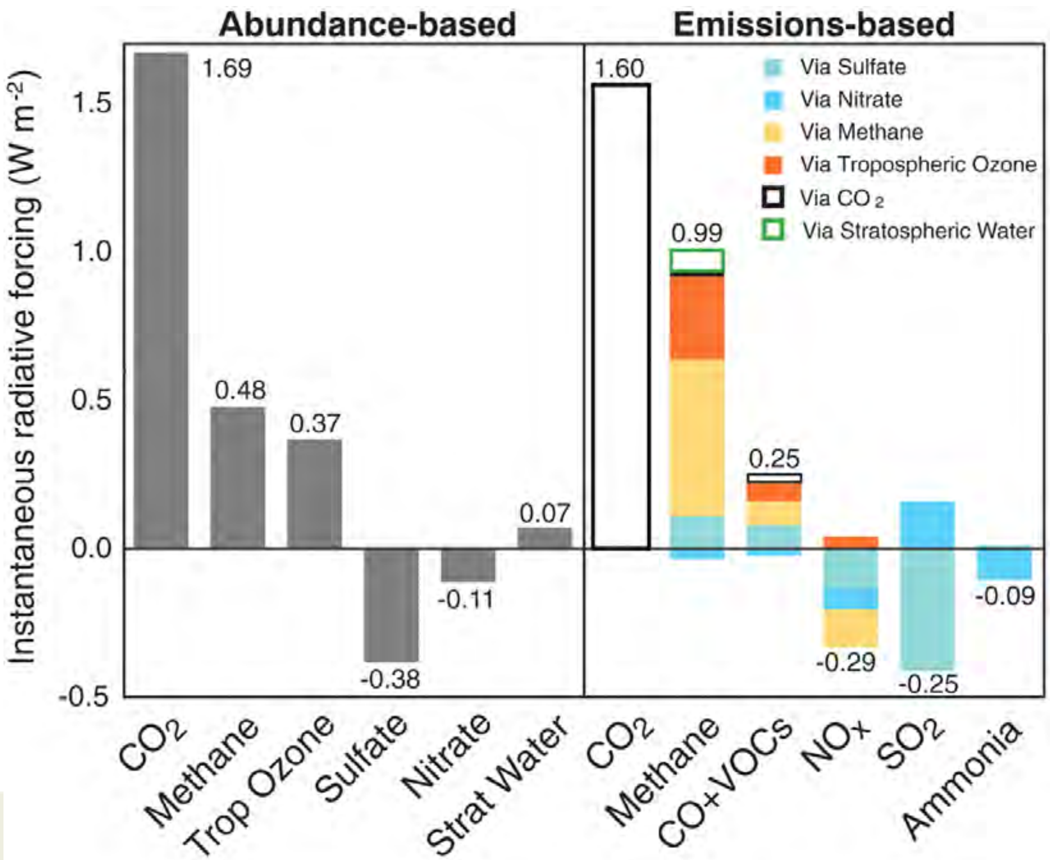
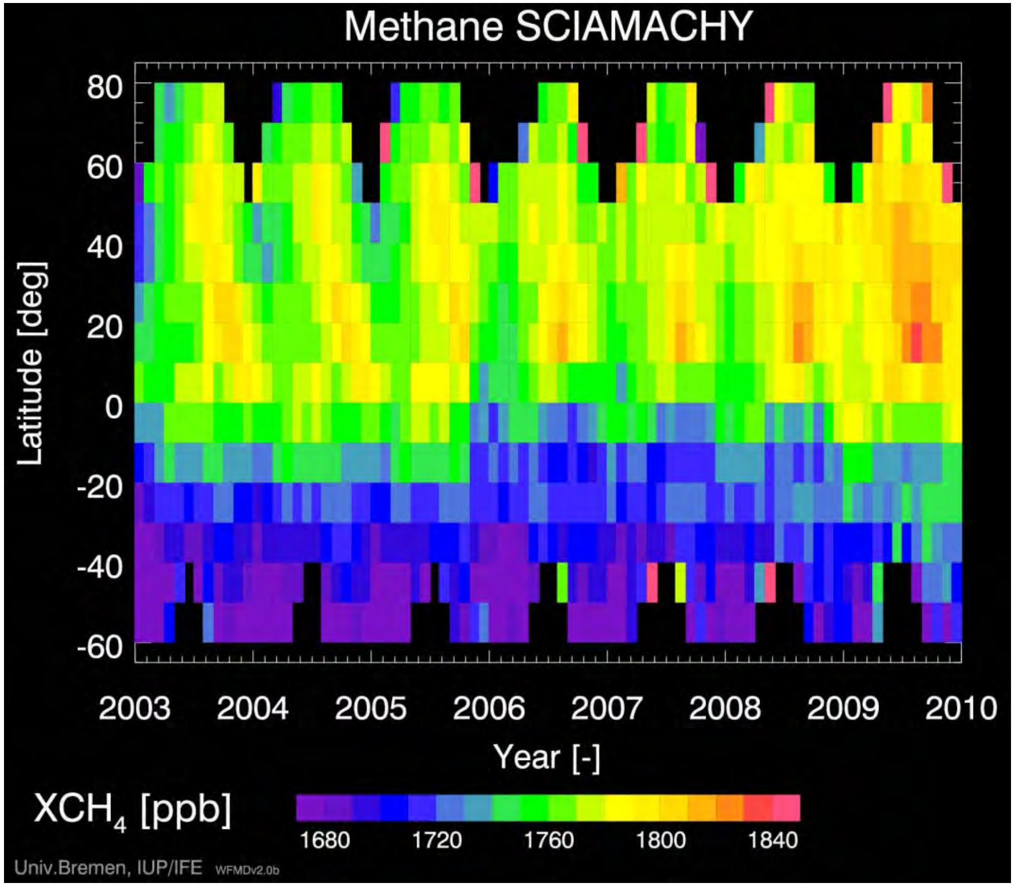
Climate Data Sets

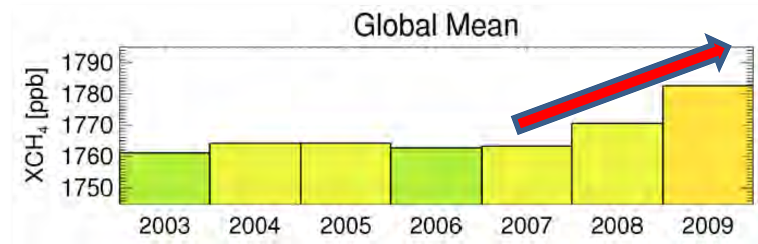
- Ozone
- CH_4
- CO_2 (ESA study)
- H2O
- Aerosol



D. Shindell, Science 2009

Methane (CH_4) from SCIAMACHY





Latitude band	Mean amplitude seasonal cycle [ppb]		Anomaly since 2007 [ppb yr^{-1}]	
	SCIA	TM5(2003)	SCIA	TM5(2003)
Global	13.4±4.0	9.8±2.9	7.4	−0.4
NH	13.7±2.6	9.3±0.3	8.2	−0.5
SH	8.5±5.3	8.5±1.7	5.4	−0.6
30° N–90° N	12.4±8.0	11.2±0.8	6.6	−0.6
30° S–30° N	7.3±3.7	5.1±0.9	8.2	−0.2
30° S–90° S	10.6±1.2	8.5±3.1	4.4	0.0
0° N–30° N	17.2±1.9	10.8±1.0	9.1	−0.4
0° S–30° S	6.1±2.7	5.2±0.3	5.8	−0.5

~8 ppb/yr > 30°S

S5 CH_4 will have as many cloud-free data in one day as SCIA in one year

Atmos. Chem. Phys., 11, 2863–2880, 2011
www.atmos-chem-phys.net/11/2863/2011/
doi:10.5194/acp-11-2863-2011

Atmospheric Chemistry and Physics

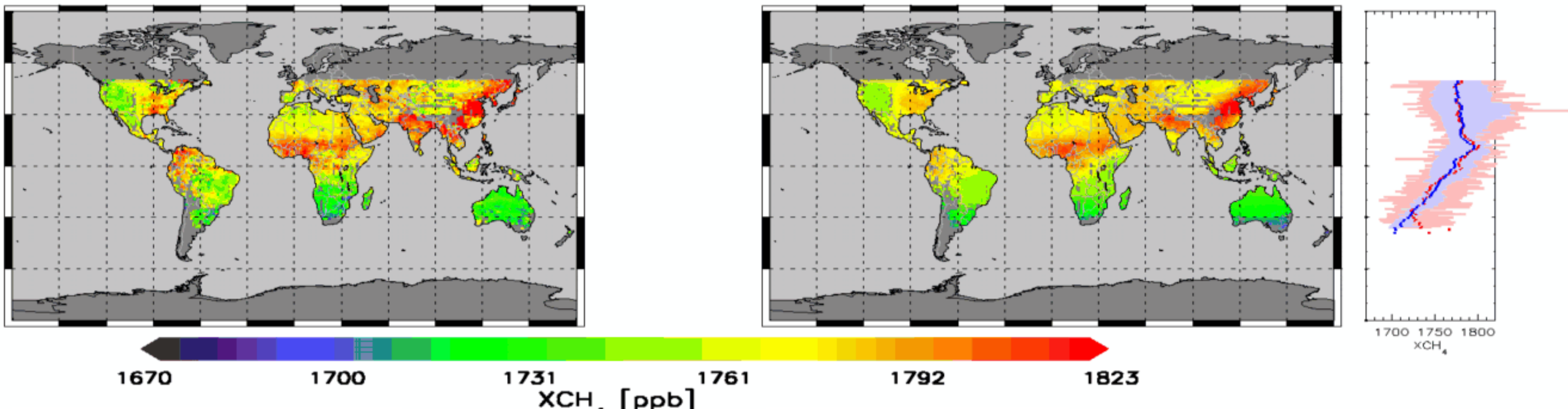
Long-term analysis of carbon dioxide and methane column-averaged mole fractions retrieved from SCIAMACHY

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

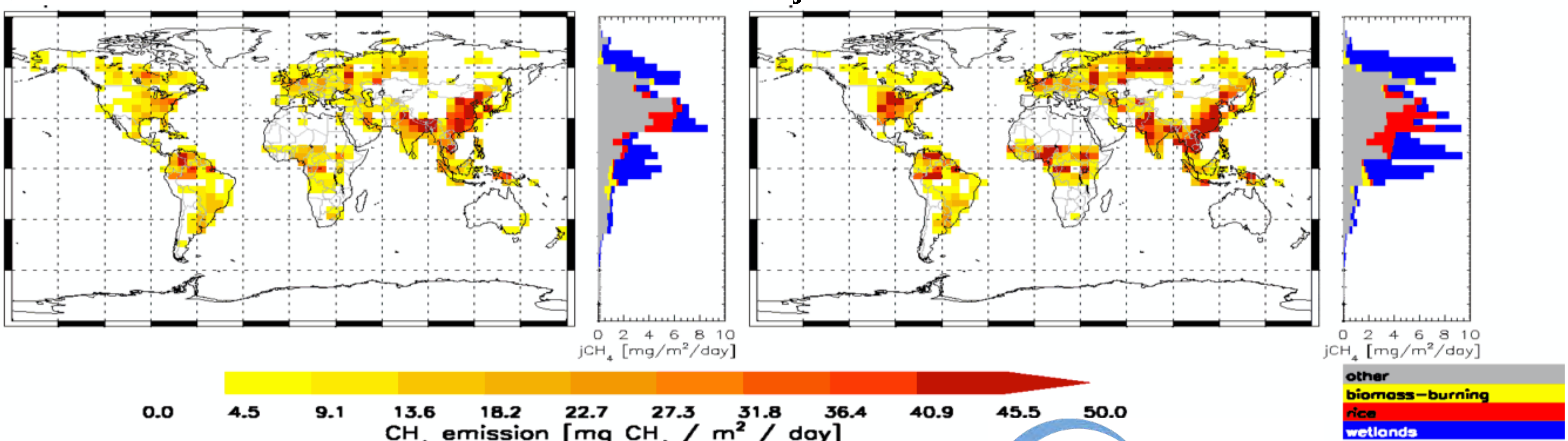
Institute of Environmental Physics (IUP), University of Bremen FB1, Bremen, Germany

First six months of routine methane flux inversion

SCIAMACHY satellite data **Assimilated data**



Prior modelled emissions **Adjusted emissions**



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Courtesy of Peter Bergamaschi, JRC

macc Monitoring atmospheric composition & climate

Synergies across Post EPS – S5 perspective

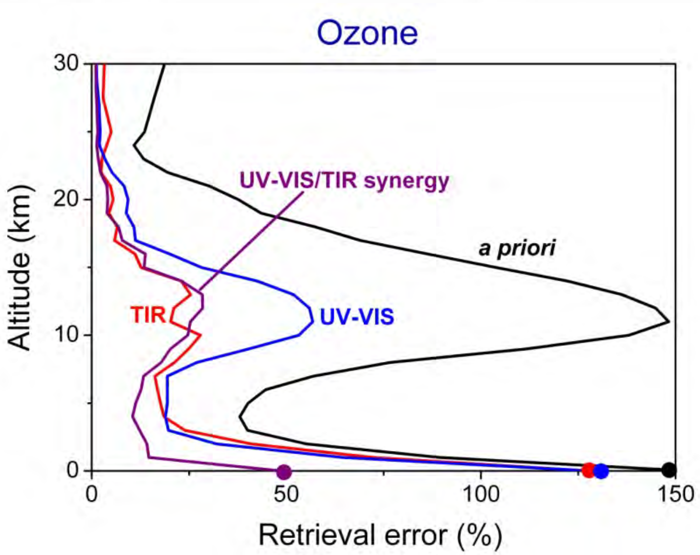
- S5-IASI-NG:
  - improved trop. O_3 (UV-IR)
  - improved trop. H_2O (VIS-IR)
  - improved CO (SWIR-IR)
  - improved CH_4 (SWIR-IR)
  - improved trop SO_2 (column, height etc.)
  - tbd: improved CO_2 (SWIR-IR)
  - Synergistic data usage Air Pollutiond & Climate

- S5-VII/3MI:
  - improved trop. trace gas products using colocated high resolution cloud and aerosol data
  - "increase" in spatial resolution of trop. trace gas products using high resolution colocated cloud coverage data
  - unique aerosol characterisation (see presentation J. Riedi/P.Stammes)

S5-IASI-NG Synergies

H. Bovensmann et al. / Advances in Space Research 34 (2004) 694–699

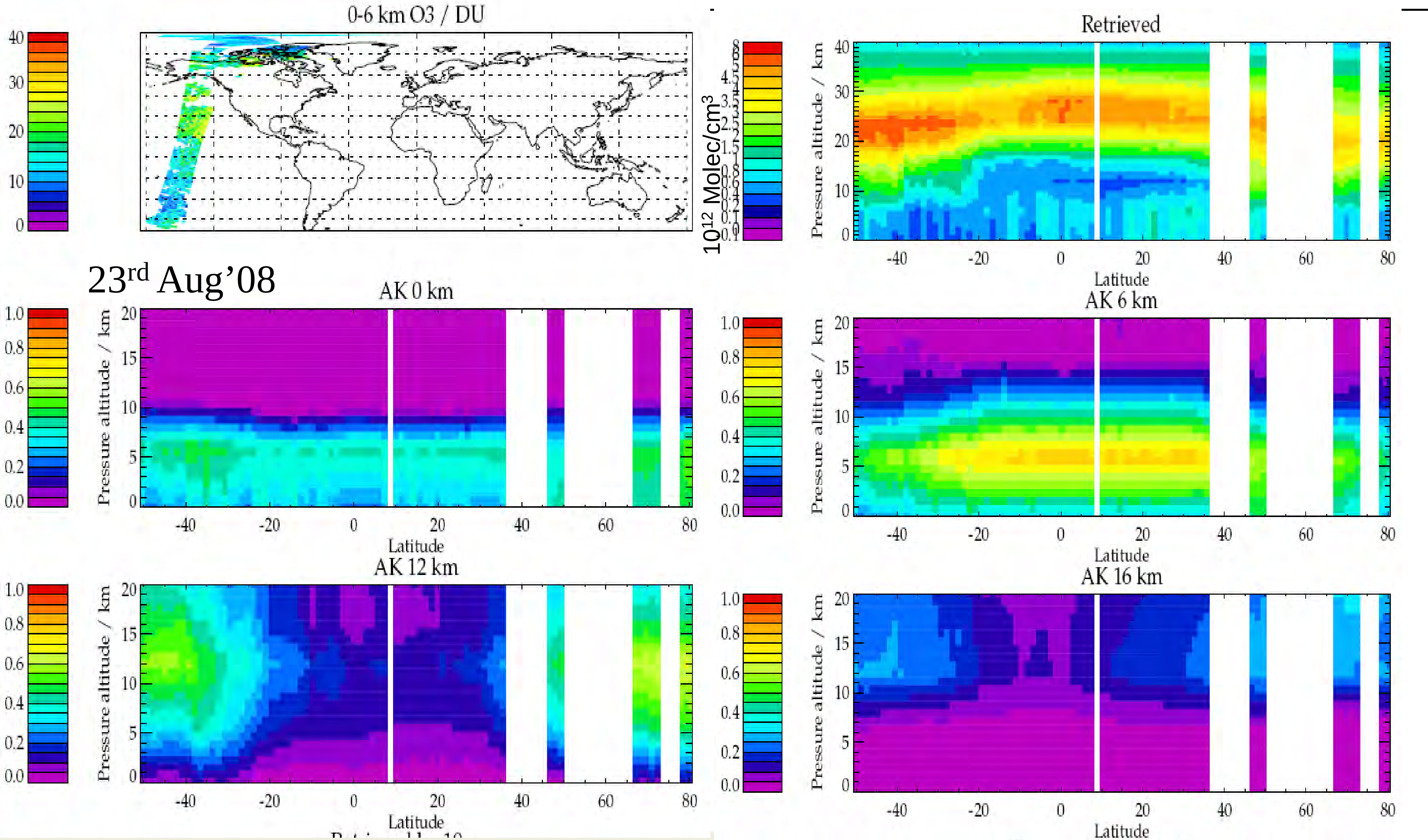
Species		Vertical layers boundaries 0–2 km		2–7 km		7–12 km	
O_3	Combined	5%		<5%		<5%	
	TIR		28%		13%		6.6%
	UV-VIS		<10%		<6%		<13%
CO	Combined	10%		<10%		<10%	
	TIR		24%		10%		10%
	SWIR			Column <10%			
CH_4	Combined	2%		1%		1%	
	TIR		7.1%		3%		2.6%
	SWIR		13%		12%		18%
H_2O	Combined	<1%		<1%		<1%	
	TIR		1.2%		1.1%		2.8%
	VIS		5%		5%		30%



Distinguishing PBL from free-tropospheric ozone and CO for determining long-range transport of pollution and emission sources

Courtesy: P.F. Coheur (ULB)

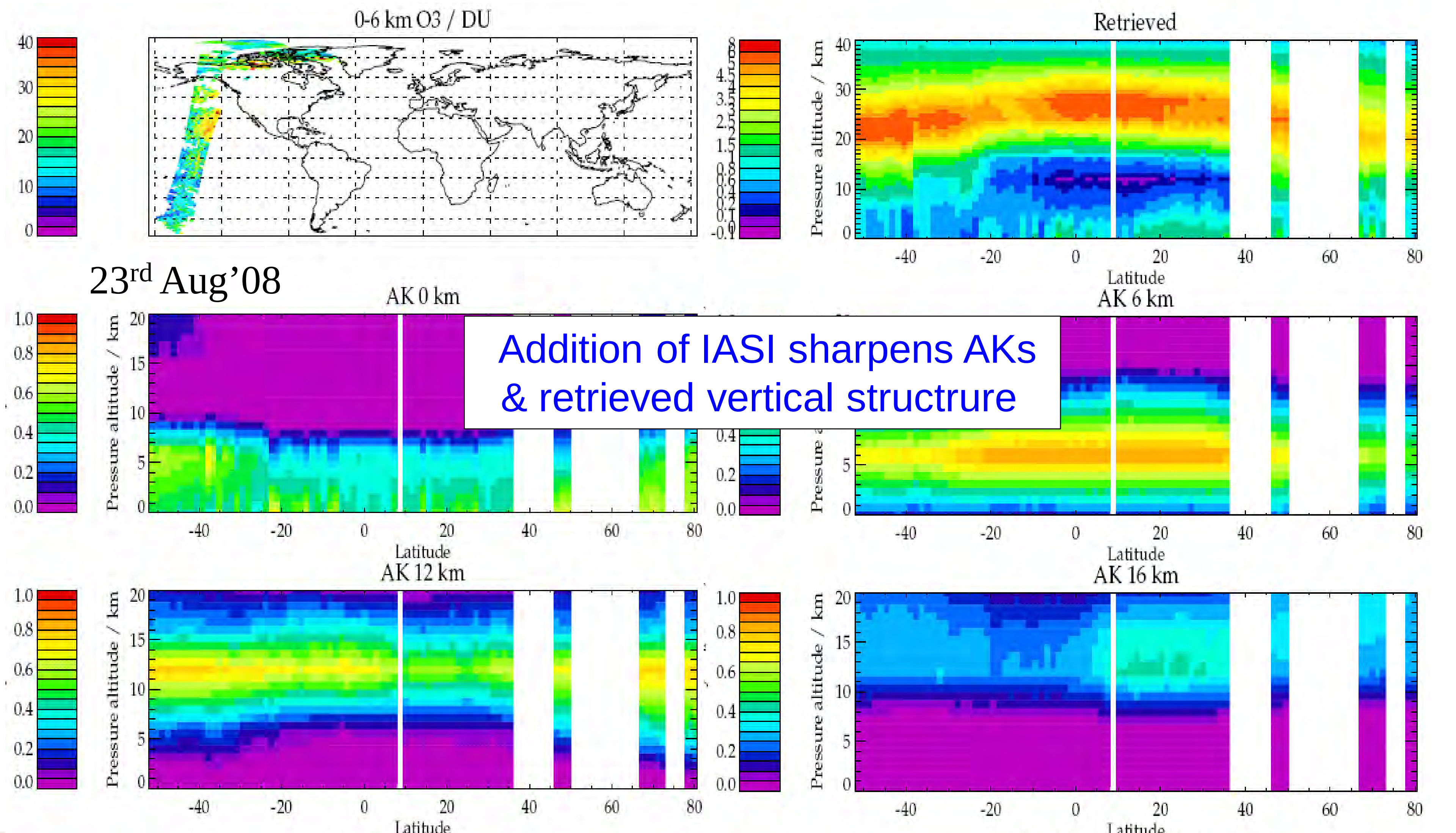
Orbit x-section: GOME-2 only Retrieval & Averaging Kernels



Universität Bremen

Science & Technology Facilities Council
Rutherford Appleton Laboratory

Orbit x-section: GOME-2 **+ IASI** Retrieval & Averaging Kernels



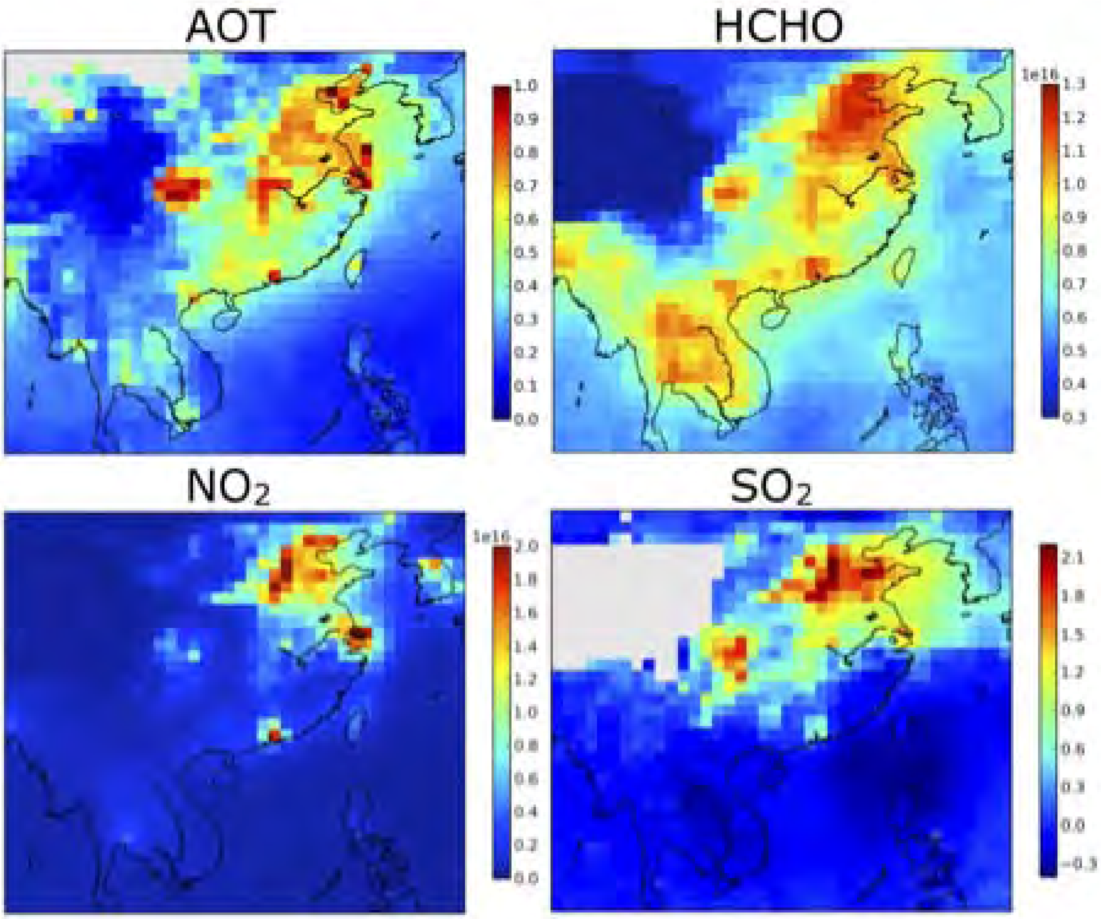
Synergies by Data Utilization (S5, VII/3MI, IASI)

Analysis based on multiple species to constrain processes
Need for consistency in retrieval methods.

Data assimilation
Sophisticated error analysis are needed.

Focus on the troposphere
Sensitivity varies with altitude, aerosols and clouds.

Operational data usage
near-real-time data



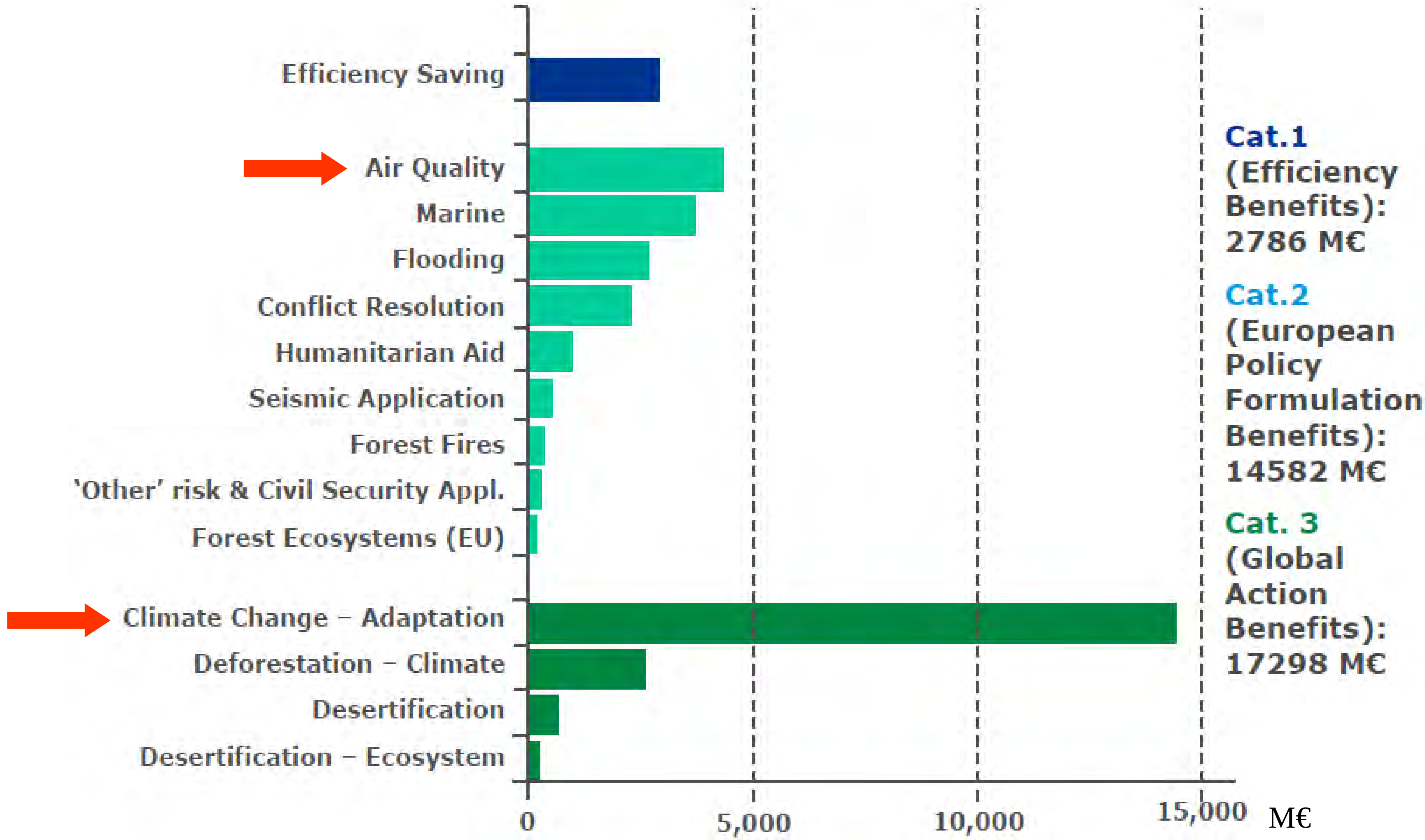
Veefkind, J. P., et. al.: Atmos. Chem. Phys. 10, 2011

+ IASI-NG: NH_3, HNO_3, Methanol, C_2H_4 …
+ S5/IASI-NG synergistics: trop. O3, trop. CH4, PBL CO …

Synergies across Sentinel – S5 perspective

- S5-S4
  - Cross-calibration
  - Improved S4 tropospheric products using stratospheric constrain from S5 (O3, NO2 etc.)
  - S4 adds the high temporal resolution needed of regional to urban AQ applications

Affordability: Socio-oeconomic benefits of GMES(up to 2030)



Adapted from EC, based on PWC Study

Summary

- Sentinel 5 will serve key PostEPS MRD and GMES Atmosphere requirements in a unique and affordable way (Air Pollution, Climate, Ozone)
- Continuation of GOME-SCIA-GOME-2 products time series (since 1995)
- Drastically increased spatial resolution in combination with improved coverage will boost tropospheric applications
- CO and CH_4 (CO_2 tbd) adds very important products
- Synergistic products require good co-location of sensor, => S5 UVNS needs to be accomodated on one platform with IASI-NG, VII & 3MI
- S5 in combination with its Post-EPS „colleagues“ IASI-NG, VII and 3MI will allow to continue established and establish new air quality, chemistry and climate services and applications.
- Pre-operational services well underway (MACC, PASODOBLE etc.)