InGOS
Integrated non-CO_2 Greenhouse gas Observing System

Observing Methane Concentrations over Europe with Satellites

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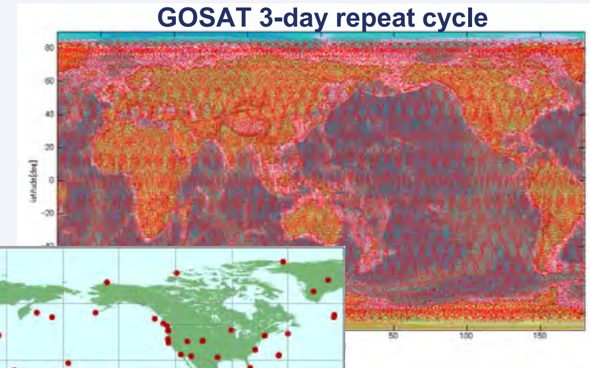
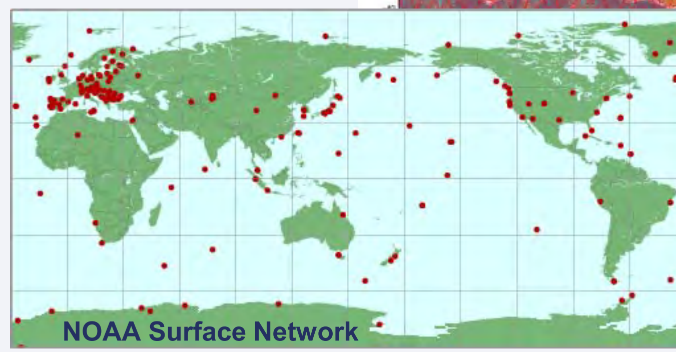
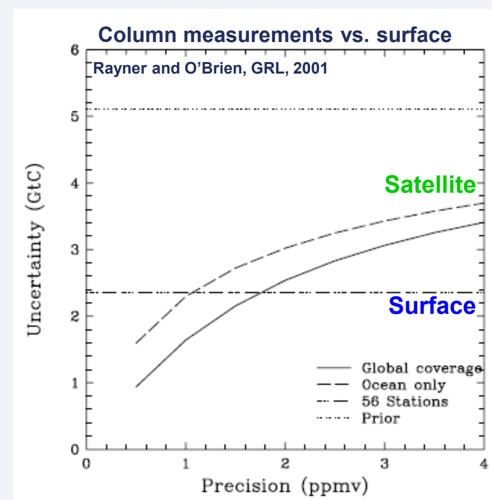
What do space based observations of GHG offer?

- **Advantages**
  - Global
  - Uniform
  - Dense
  - Frequent
  - → Source/sink estimation
  - → Quantification of underlying mechanisms
- **Challenges**
  - Column measurements
  - High precision and accuracy is needed
    - Clouds, aerosol, albedo …
  - Sensitivity to surface-near air







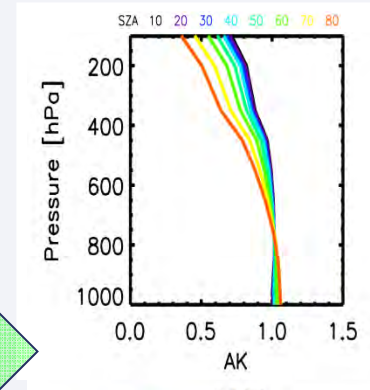
GHG Measurement from Space

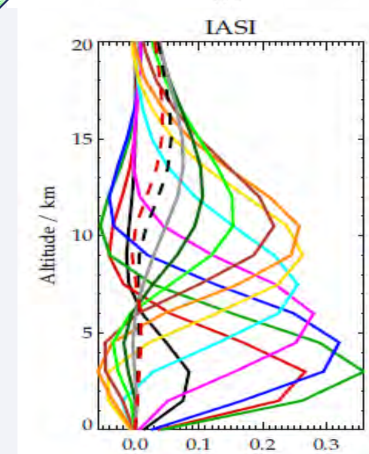
GHG	Instrument	Spectral Region
Carbon Dioxide	AIRS†	TIR
	TIROS-N/TOVS†	TIR
	TES†	TIR
	ACE†	MIR
	IASI†	TIR
	SCIAMACHY (<2012)	SWIR
	GOSAT	SWIR/TIR
Methane	ACE†	MIR
	AIRS†	TIR
	IMG†	TIR
	TES†	(S)/TIR
	MIPAS† (<2012)	TIR
	IASI†	TIR
	SCIAMACHY (<2012)	SWIR
	GOSAT	SWIR/TIR

† Limited/no sensitivity near surface

Vertical Sensitivity

Shortwave infrared
SWIR



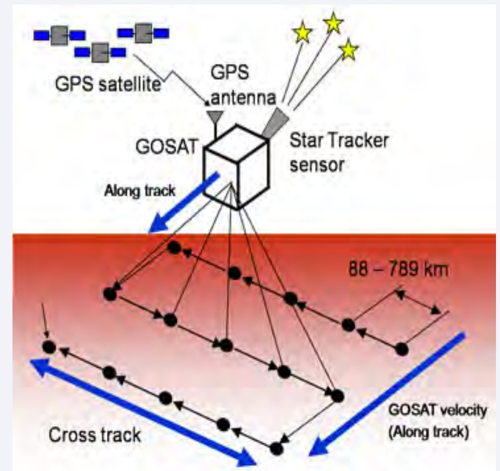


Thermal Infrared
TIR

Greenhouse gases Observing SATellite (GOSAT) launched January 23rd 2009

Mission objectives:

1) To monitor the density of greenhouse gases precisely and frequently worldwide.
2) To study the absorption and emission levels of greenhouse gases per continent or large country over a certain period of time.
3) To develop and establish advanced technologies that are essential for precise greenhouse-gas observations.



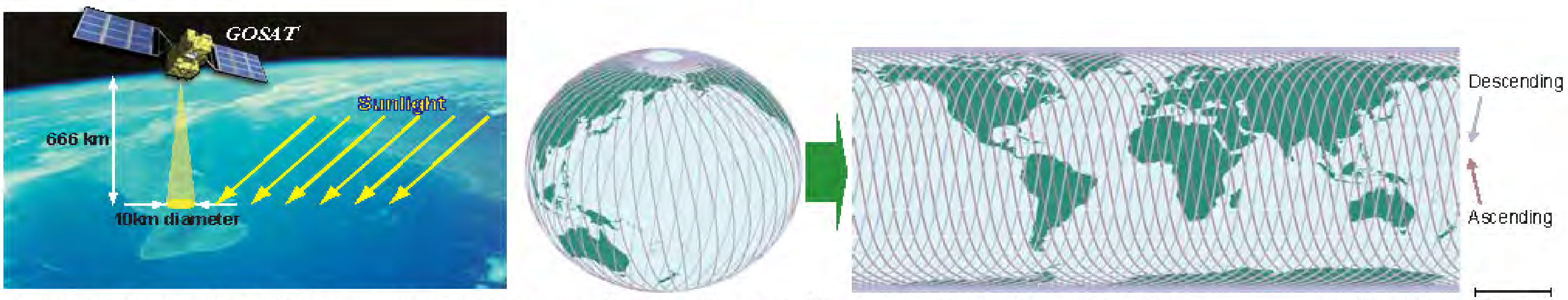


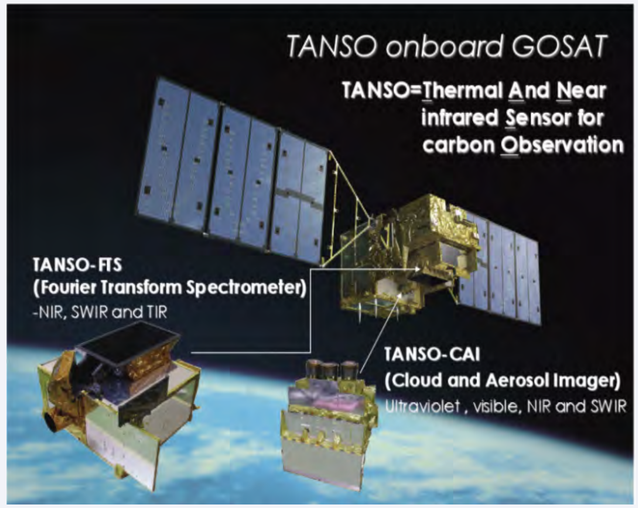
Figure 6. Conceptual diagram of GOSAT observation and the satellite orbits (three days, 44 orbits)

The GOSAT Payload

TANSO - FTS

Provides spectrally-resolved radiances for 4 shortwave-IR (polarized) and thermal-IR bands

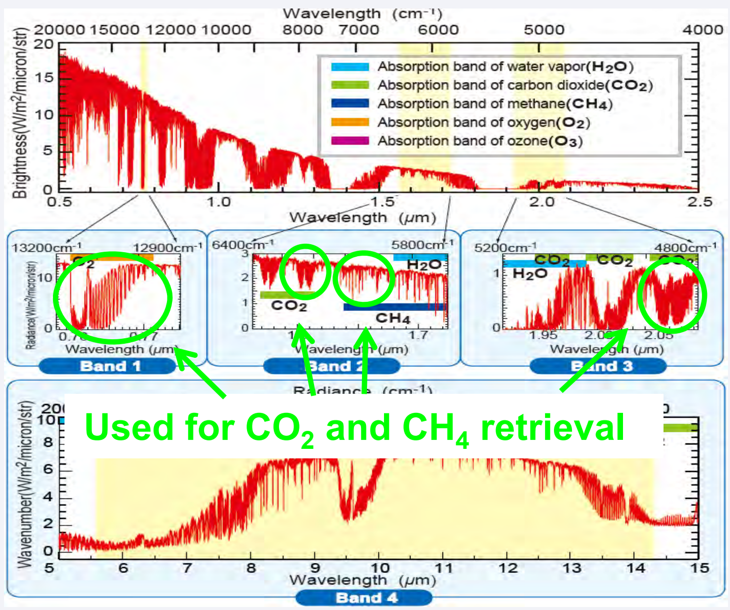
Covers several absorption bands of CO_2, CH_4, O_3 and H_2O (and others) and O_2

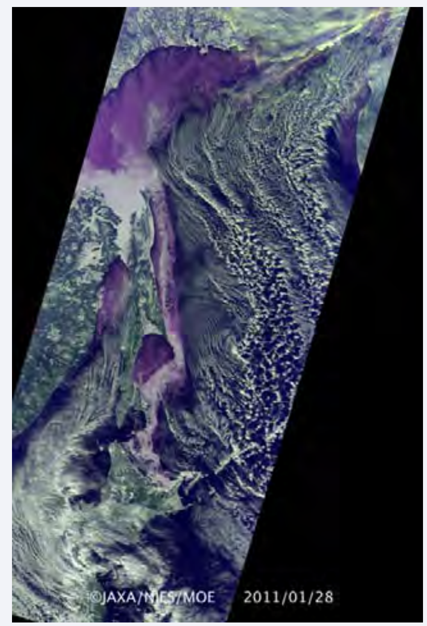


TANSO - CAI

4 broadband channels from UV to SWIR with high spatial resolution

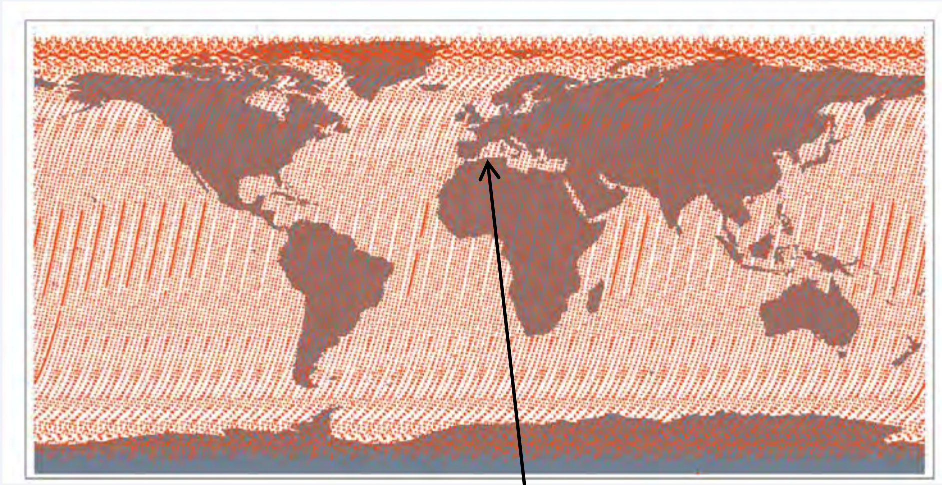
Provides aerosol and cloud information required for the greenhouse gas retrieval



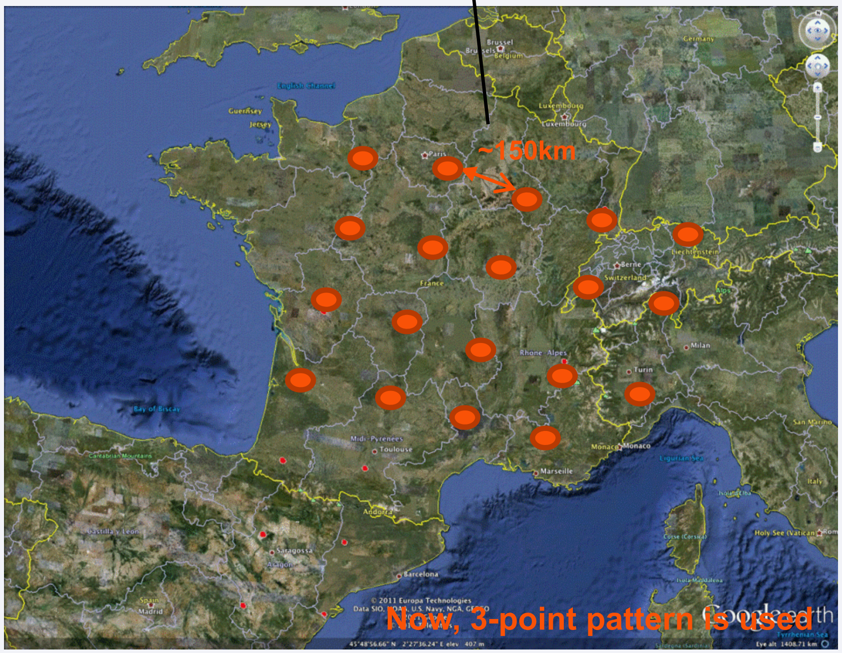


GOSAT has Global Focus

3-day repeat cycle of GOSAT



Regular sampling pattern



GOSAT XCO_2 and XCH4 Data

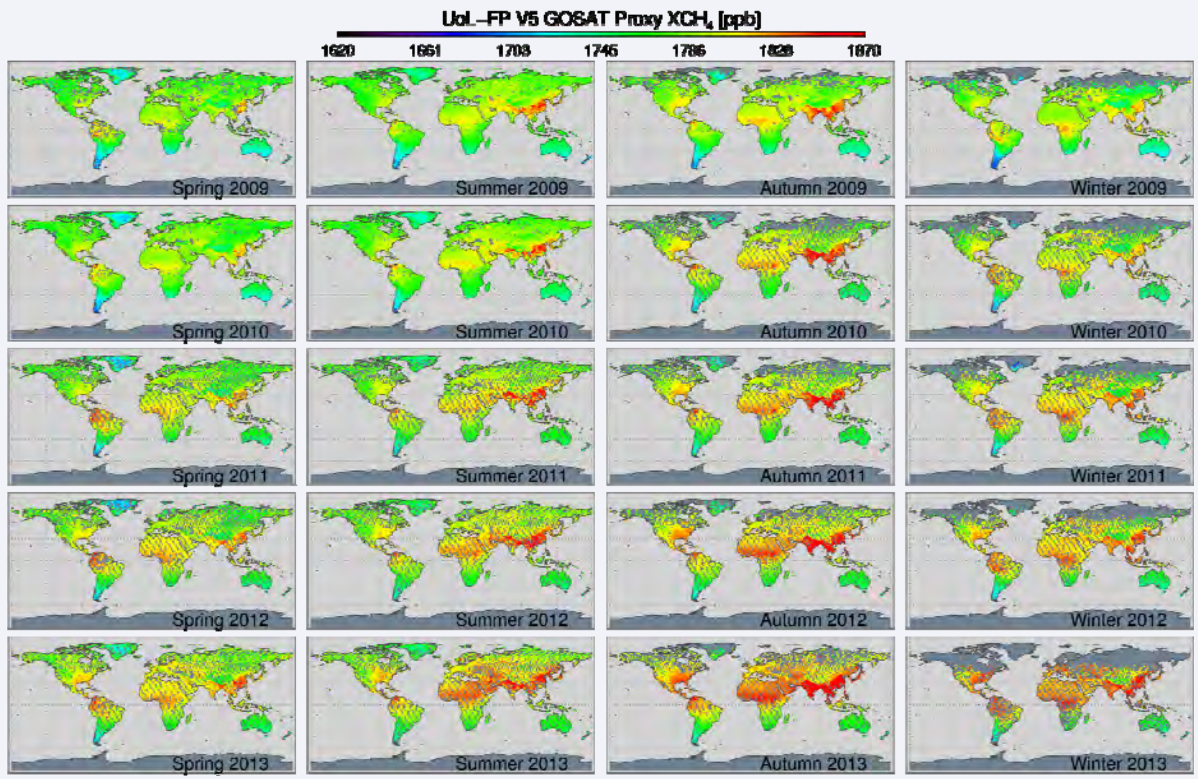
Selected Publications

Parker, R., et al. (2011), Methane observations from the Greenhouse Gases Observing SATellite: Comparison to ground-based TCCON data and model calculations, Geophys. Res. Lett., 38, L15807, doi:10.1029/2011GL047871.

Cogan, A. J., et al. (2012), Atmospheric carbon dioxide retrieved from the Greenhouse gases Observing SATellite (GOSAT): Comparison with ground-based TCCON observations and GEOS-Chem model calculations, J. Geophys. Res., 117, D21301, doi:10.1029/2012JD018087.

Buchwitz et al. (2013), The Greenhouse Gas Climate Change Initiative (GHG-CCI): comparison and quality assessment of near-surface-sensitive satellite-derived CO2 and CH4 global data sets, *Remote Sensing of Environment*, in press

Version 5: Global CO_2 and CH_4 retrievals from June 2009 to December 2013



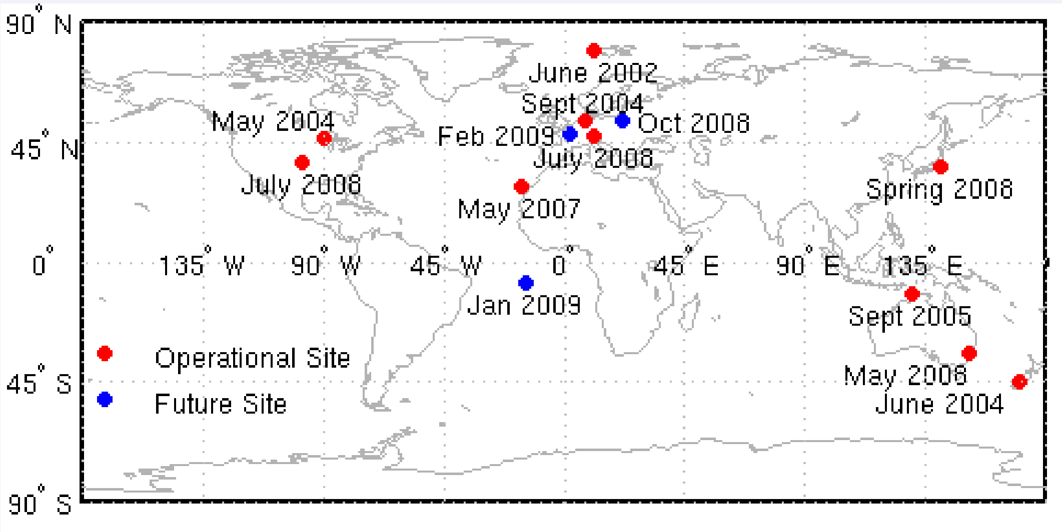
Data Access

http://www.esa-ghg-cci.org/

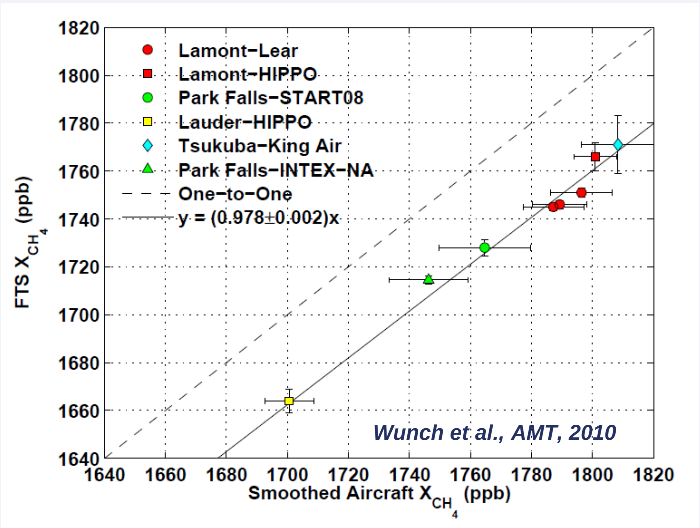
ESA
GHG-CCI

Validation against ground-based TCCON

- TCCON (Total carbon column observing network) network of ground-based Fourier Transform Spectrometers
- Provides precise, accurate total columns of CO_2, CH_4 and others gases calibrated against in-situ profiles
- But, lack of TCCON sites in Asia, S-America and Africa

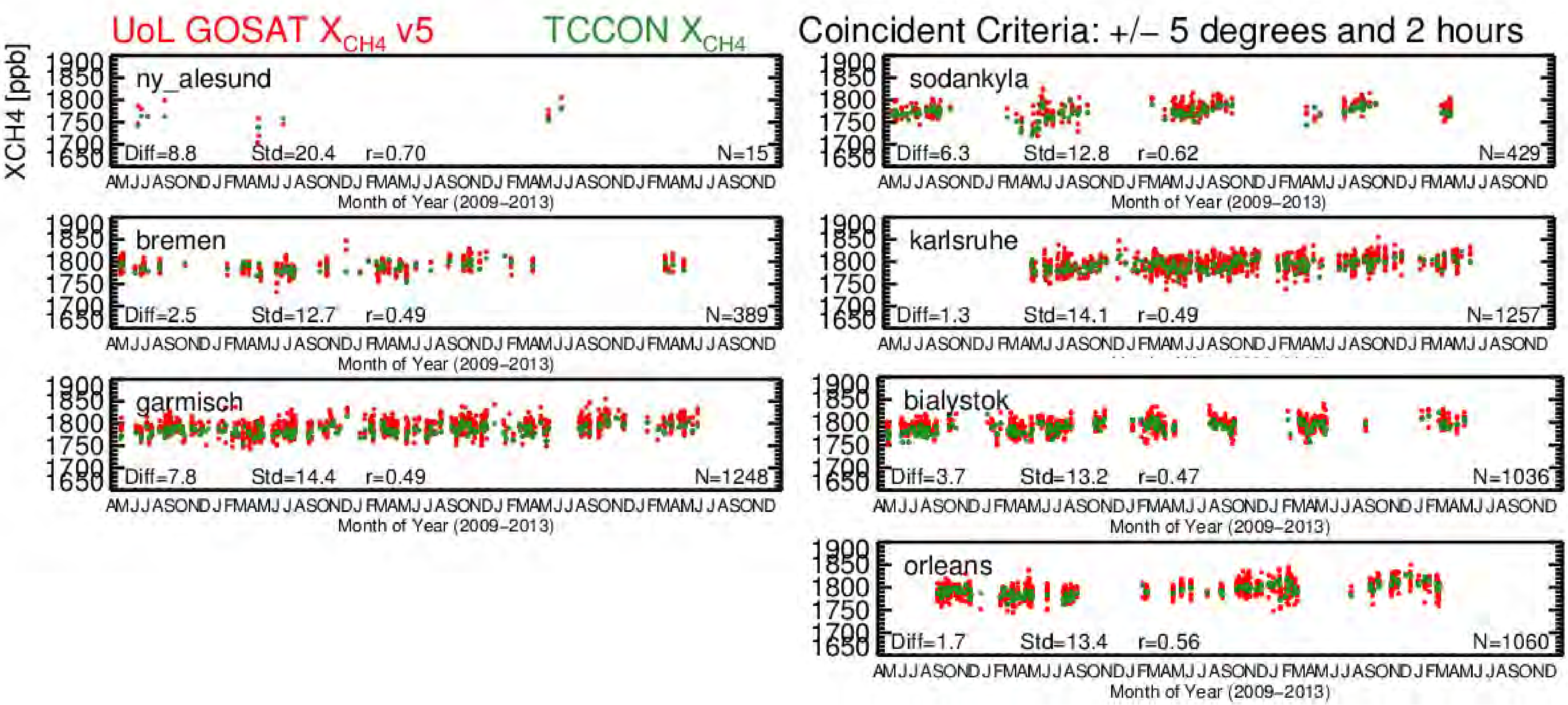


TCCON calibration against in-situ data from aircraft profiles



Validation against ground-based TCCON

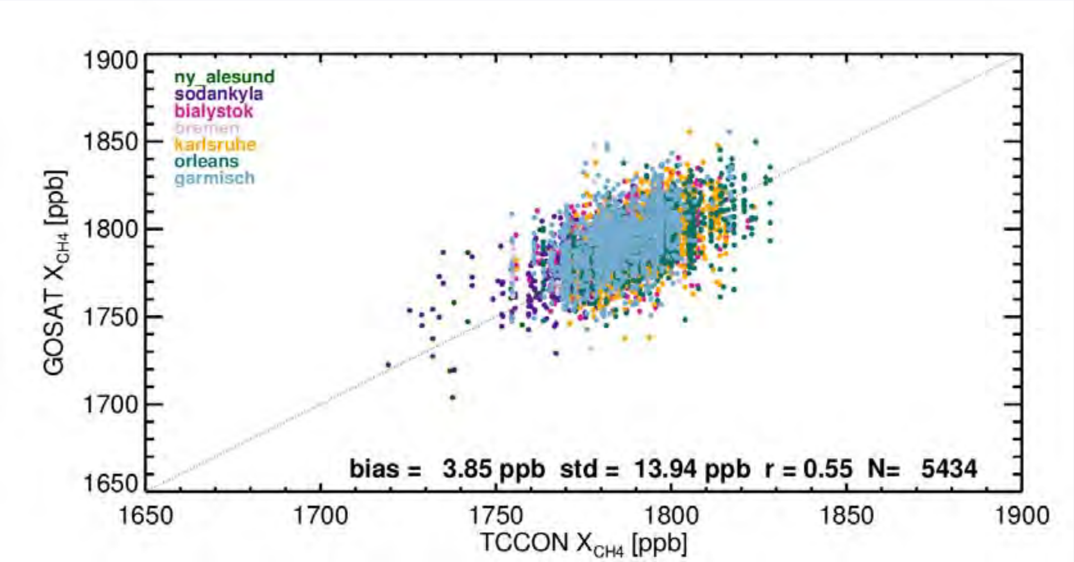
European Sites only



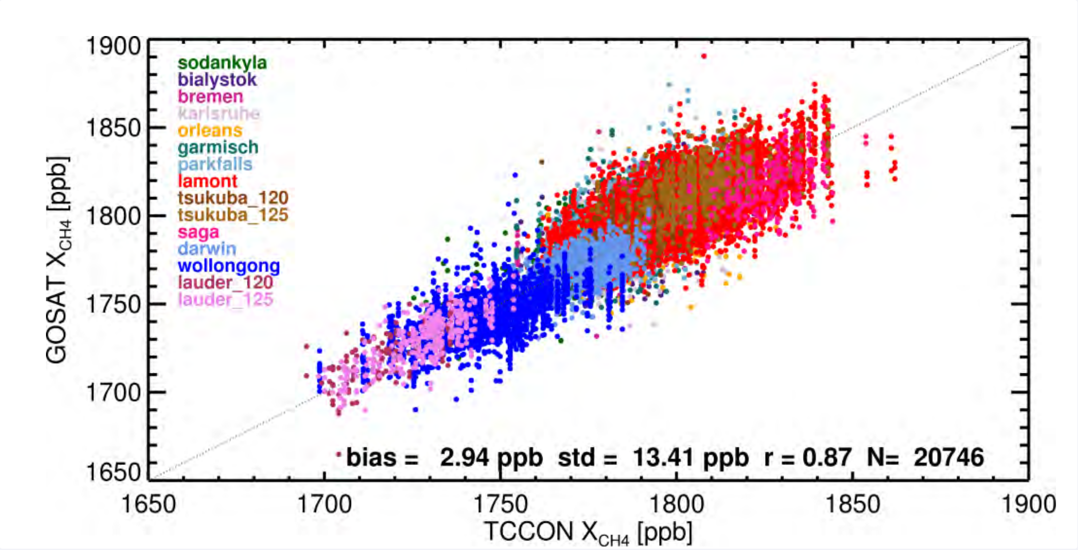
- ➢ **Very good consistency between GOSAT and TCCON**

Validation against ground-based TCCON

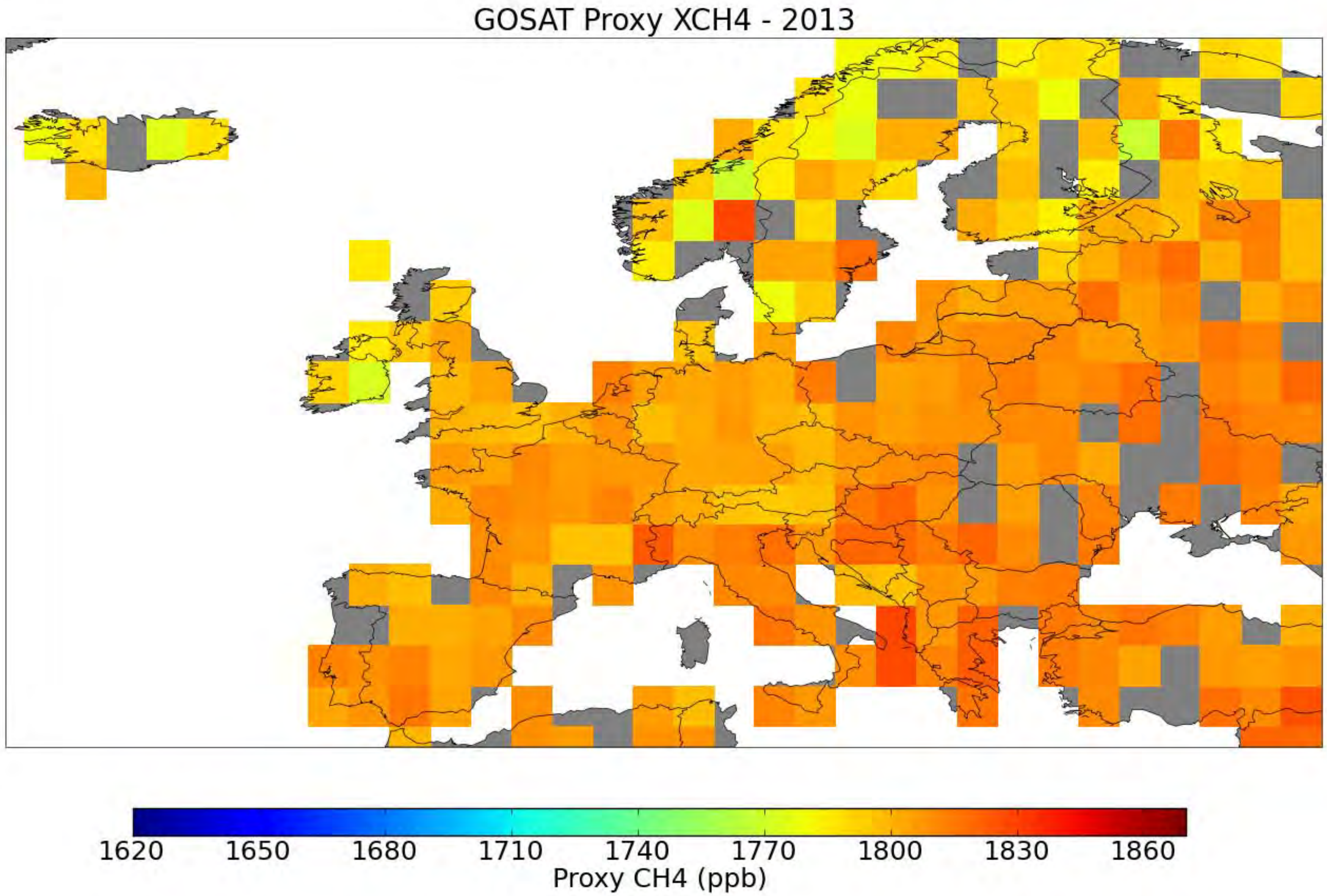
European Sites only



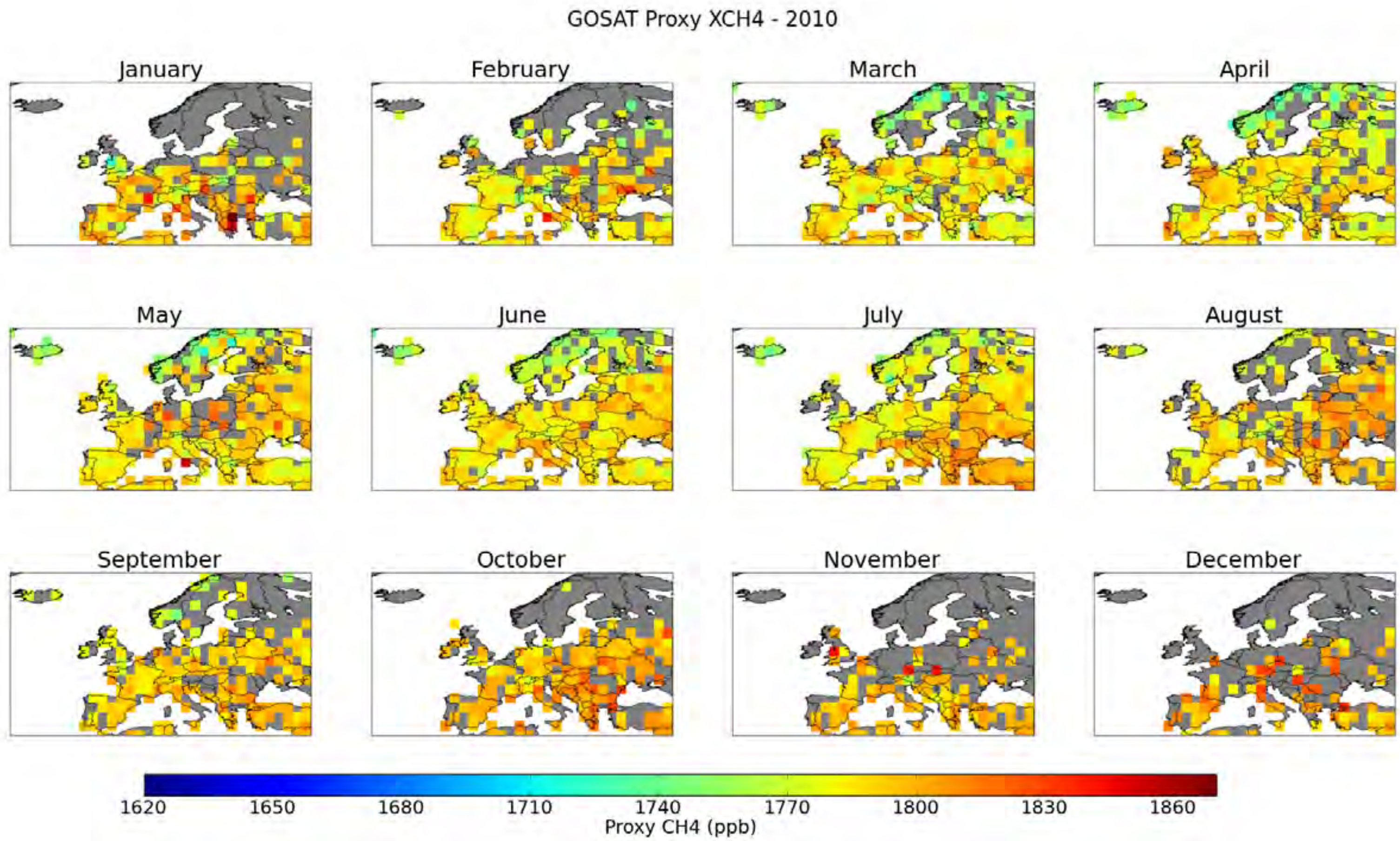
All Sites (global)



GOSAT Observations over Europe: Annual Mean



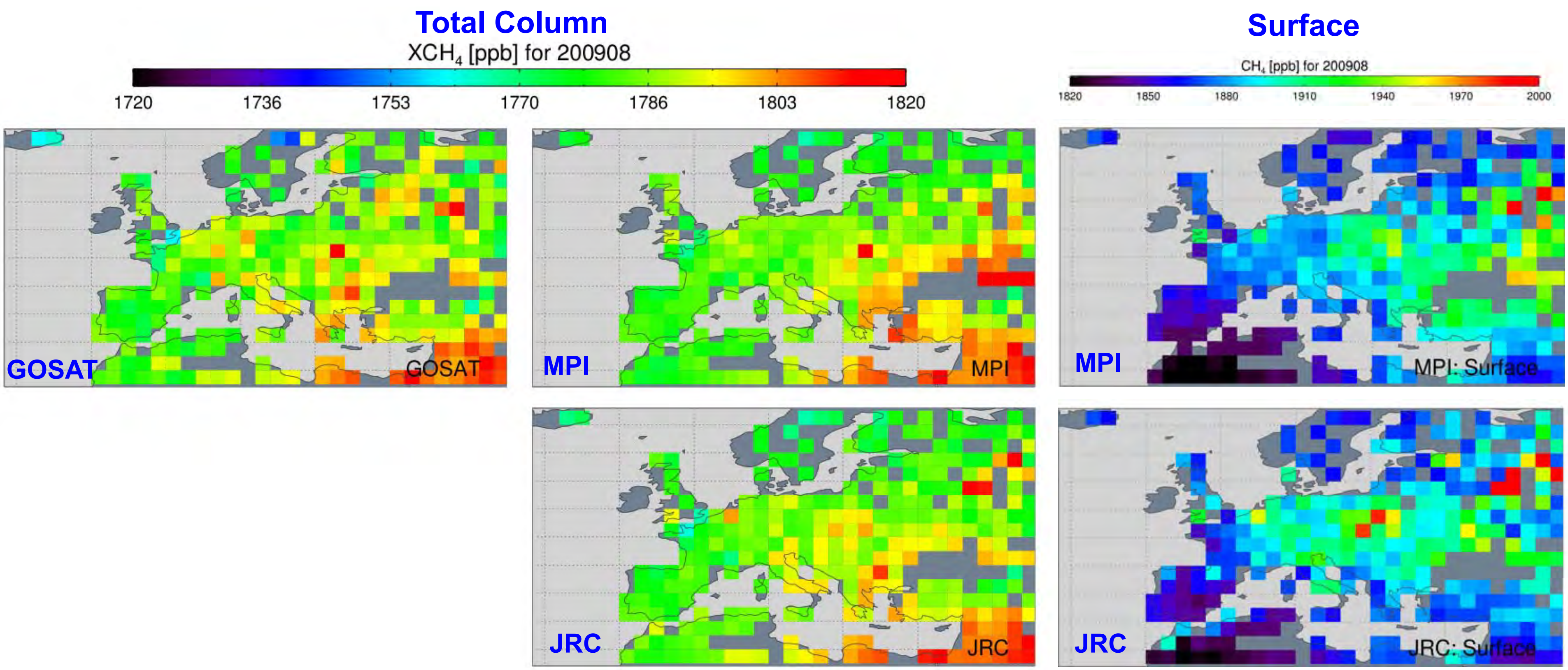
GOSAT Observations over Europe: Monthly Mean



Clouds, snow cover, low sun reduce coverage ☹

GOSAT-Model Comparison

During peak of column seasonal variations

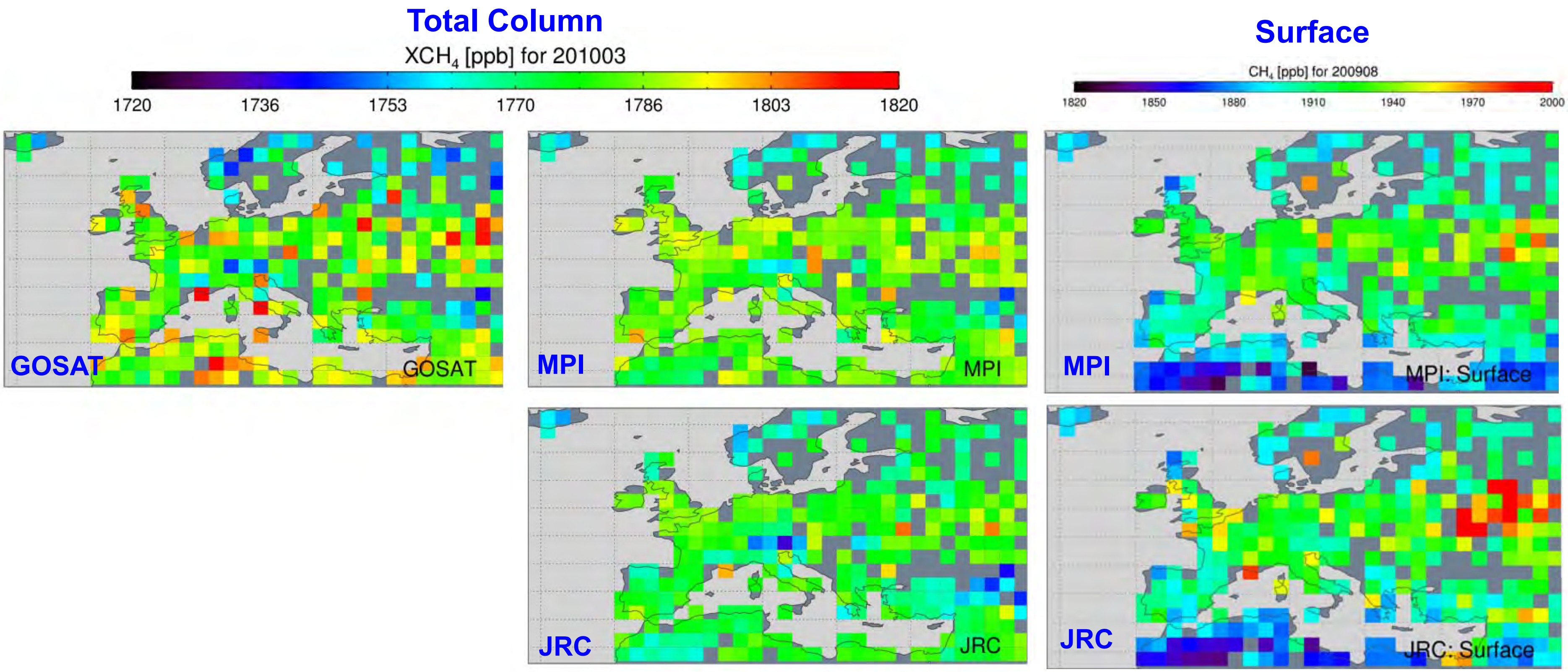


Model fields with optimized fluxes (surface in-situ station):

- **JRC: TM5-4DVAR (Peter Bergamaschi, JRC)**
- **MPI: TM3 Inversion (Ute Karstens, MPI Jena)**

GOSAT-Model Comparison

During through of column seasonal variations



Model fields with optimized fluxes (surface in-situ station):

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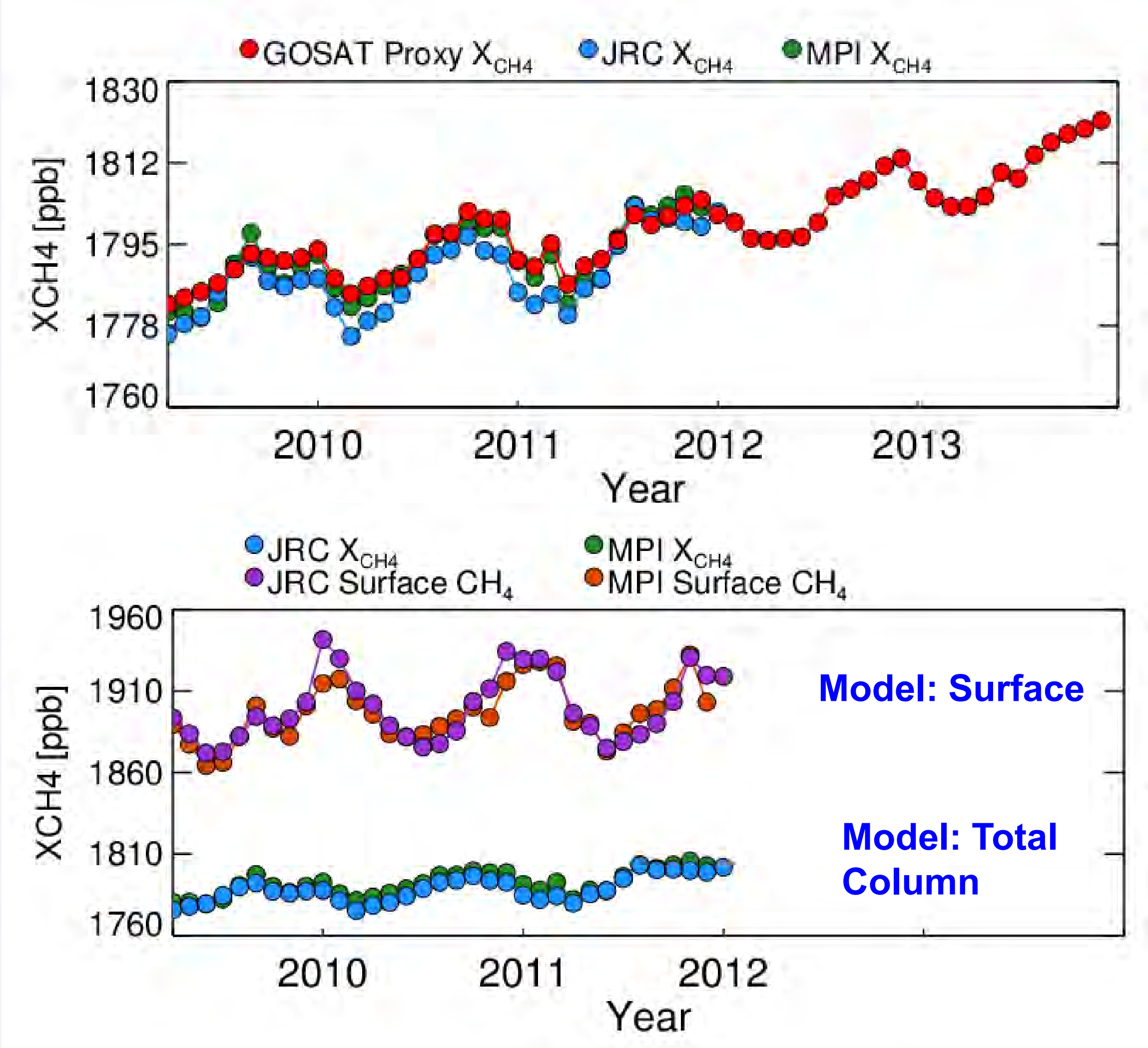
GOSAT-Model Time Series Comparison



Model fields with optimized fluxes (surface in-situ station):

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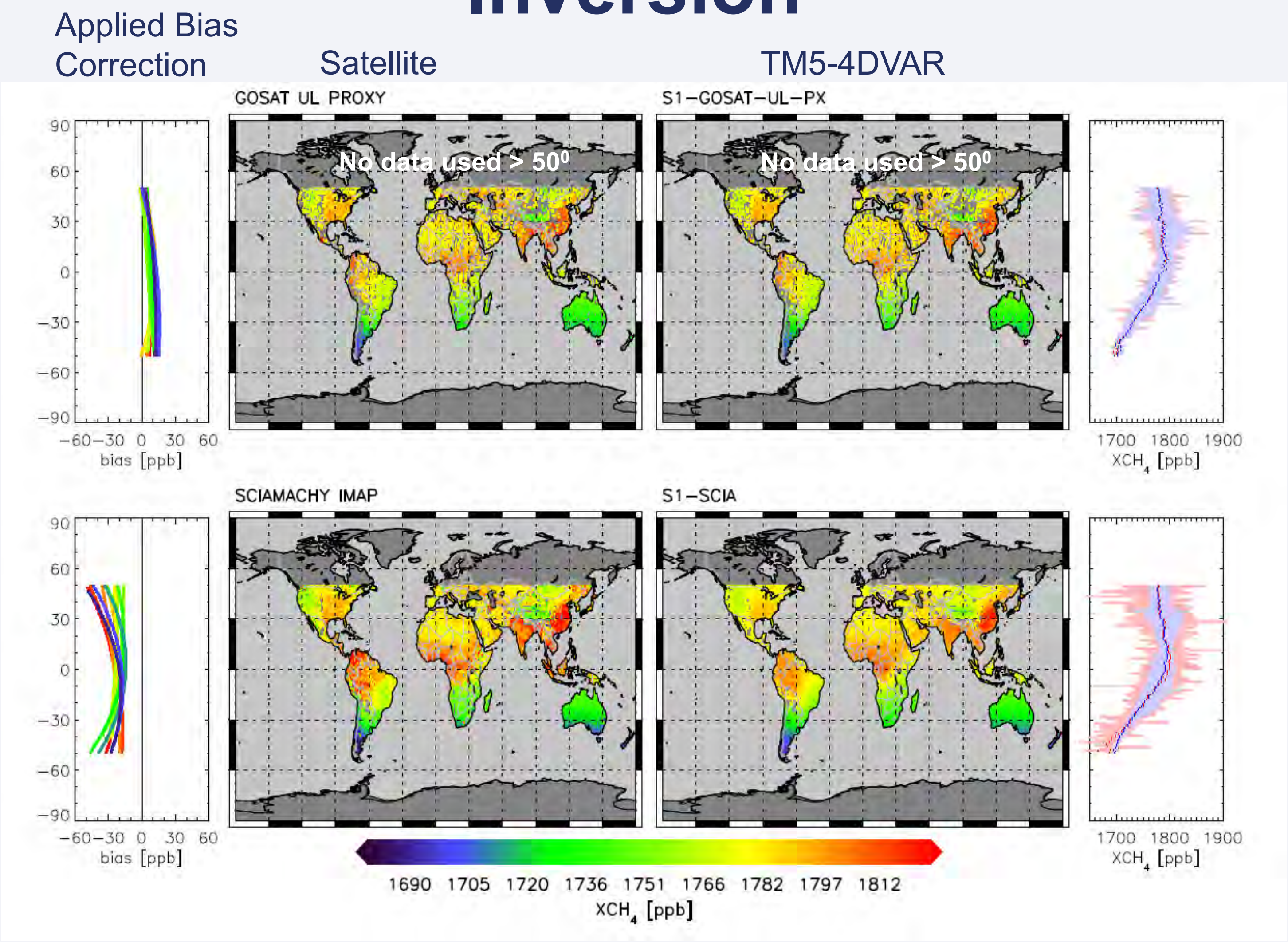
Assimilation of GOSAT CH_4 Columns for Flux Inversion



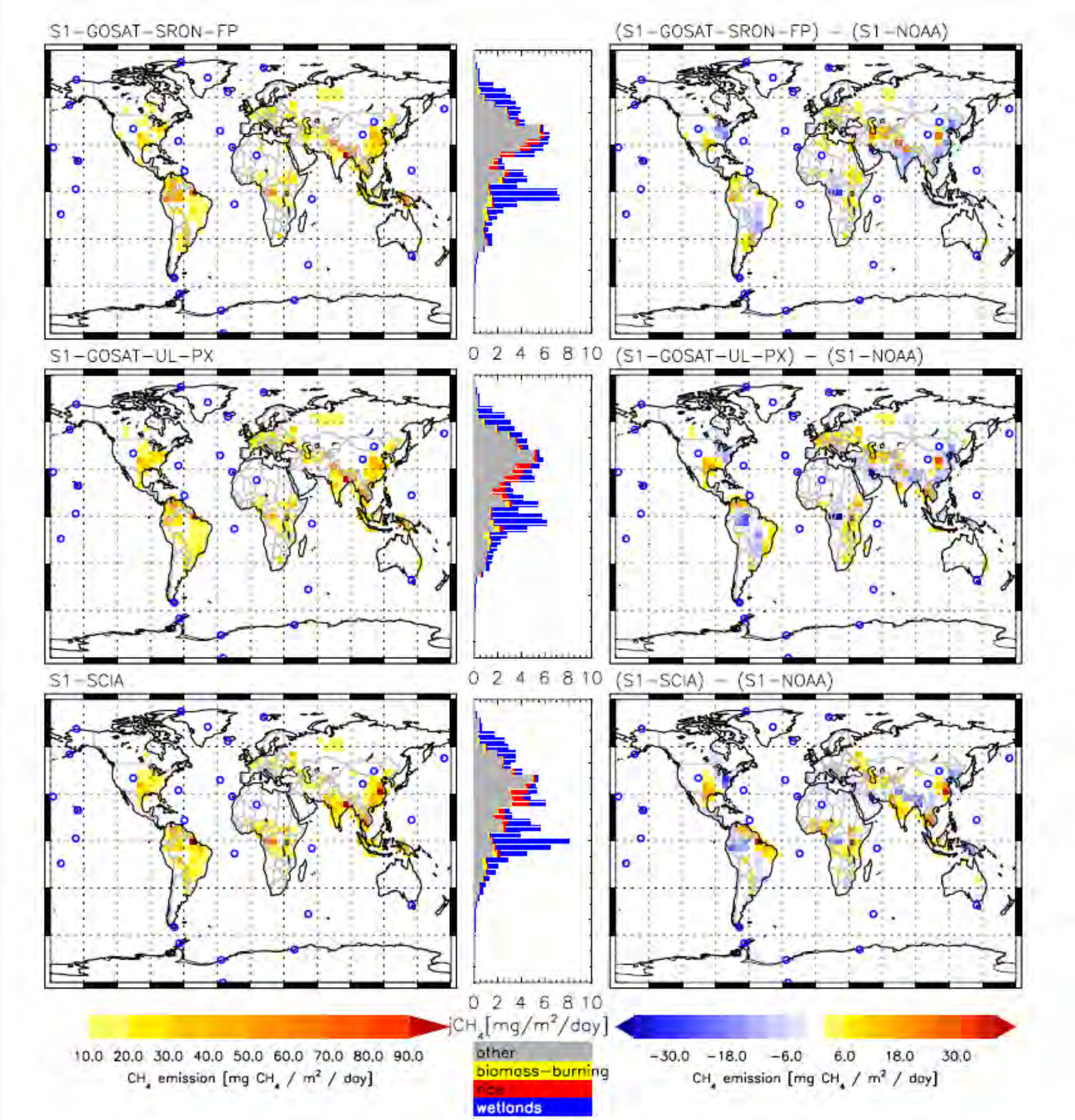
Alexe, M., Bergamaschi, P., Segers, A., Detmers, R., Butz, A., Hasekamp, O., Guerlet, S., Parker, R., Boesch, H., Frankenberg, C., Scheepmaker, R. A., Dlugokencky, E., Sweeney, C., Wofsy, S. C., and Kort, E. A.: Inverse modeling of CH_4 emissions for 2010–2011 using different satellite retrieval products from GOSAT and SCIAMACHY, Atmos. Chem. Phys. Discuss., 14, 11493-11539, 2014.

CH_4 Emissions from Satellites

- Results from different satellite products shows remarkable consistency
- Regional re-distribution of emissions
    - Eastern USA
    - Amazonas
    - Central Africa
    - European fluxes do not improve (based on ICOS comparisons) but constraints are weak

2 year average Emissions

Difference to NOAA inversion



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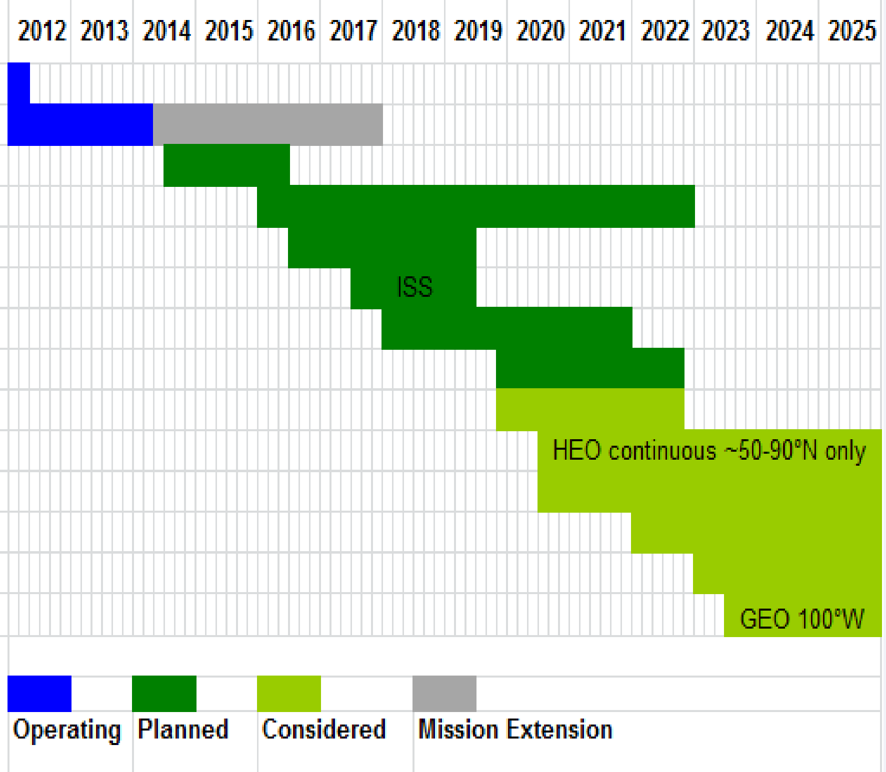
Next Steps: A Continuous Presence

Satellite, Instrument (Agencies)	CO_2	CH_4	FOV
ENVISAT SCIAMACHY (ESA)	•	•	30x60 km^2
GOSAT TANSO-FTS (JAXA-NIES-MOE)	•	•	10.5 km (d)
OCO-2 (NASA)	•		1.29x2.25 km^2
Sentinel-5P TROPOMI (ESA)		•	7x7 km^2
TanSat (CAS-MOST-CMA)	•		1x2 km^2
OCO-3 (NASA)	•		~4 km^2
GOSAT-2 TANSO-FTS (JAXA-NIES-MOE)	•	•	10.5 km (d)
MERLIN (DLR-CNES)		•	0.135 km (w)
MicroCarb (CNES)	•		25 km^2
PCW-PHEOS-FTS (CSA)	?	•	10x10 km^2
MetOpSG Sentinel-5 (ESA-EUMETSAT)		•	7x7 km^2
CarbonSat (ESA)	•	•	2x3 km^2
ASCENDS (NASA)	•		0.100 km (w)
GEO-CAPE (NASA)		•	4x4 km^2
(GEOCARB)			

Based on information from various sources

Proposed or funding not fully confirmed

d = diameter
w = width of a narrow strip along orbit track

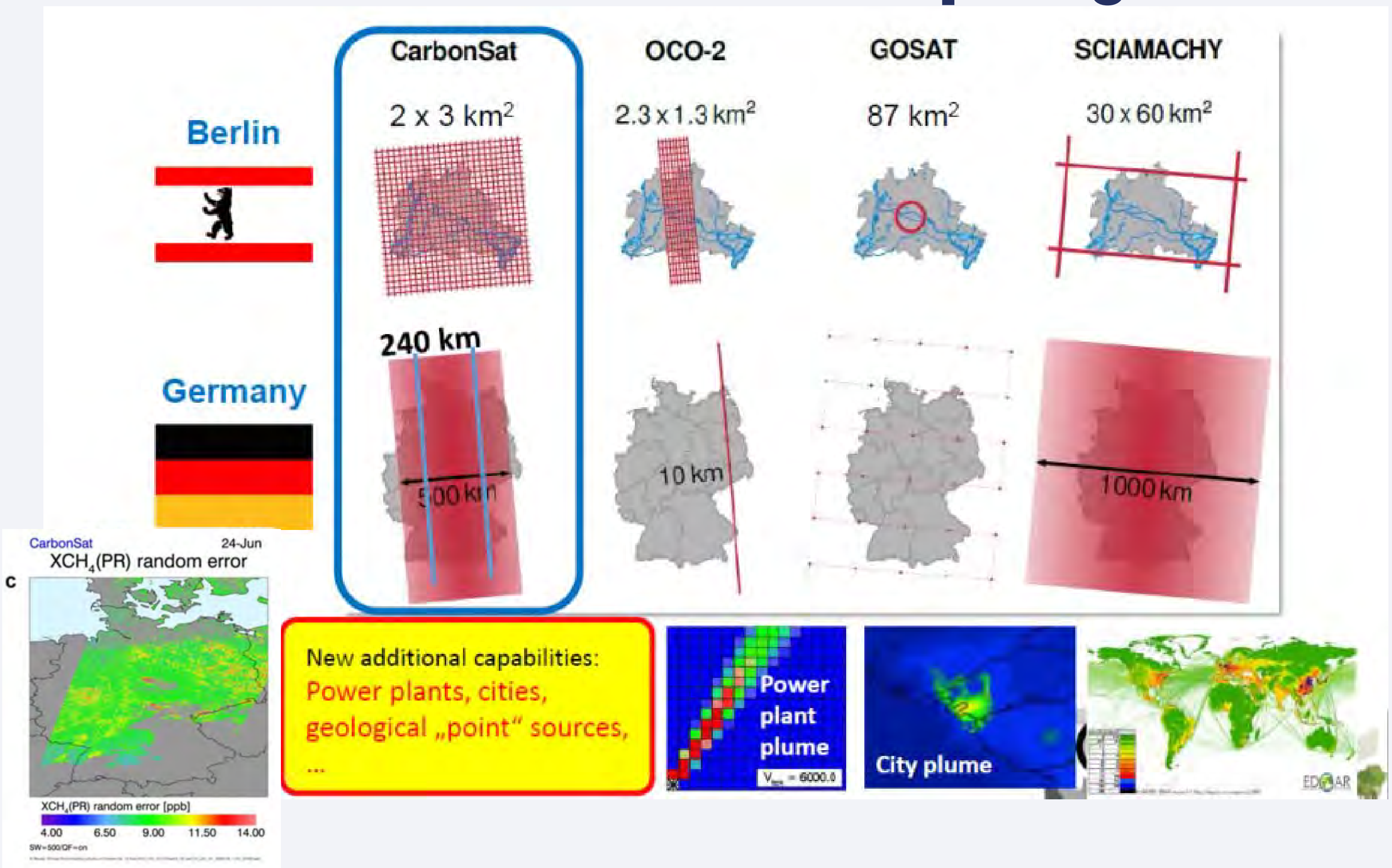


Future space-based system promise

- increased and denser coverage
- more precise and accurate datasets
- different observing systems (e.g. active sensing)

➢ Ambition: Long-term space-based monitoring system of global atmospheric CO_2 and CH_4

Carbonsat: Towards Increased Coverage and Denser Sampling



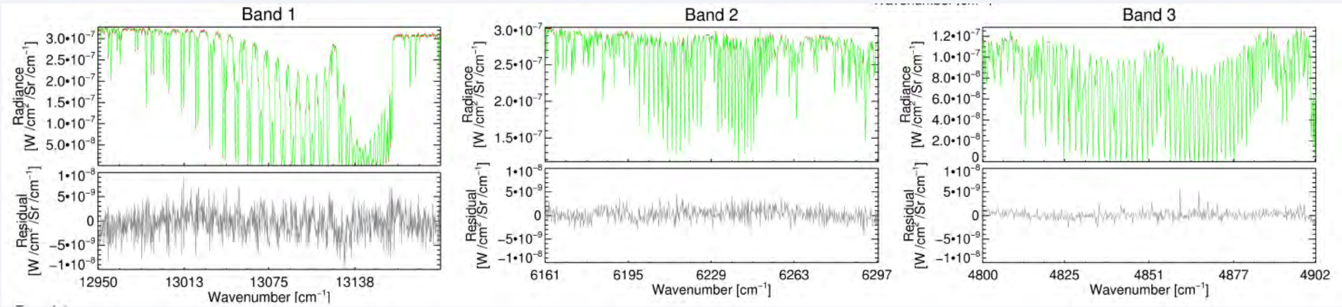
Buchwitz, M., Reuter, M., Bovensmann, H., Pillai, D., Heymann, J., Schneising, O., Rozanov, V., Krings, T., Burrows, J. P., Boesch, H., Gerbig, C., Meijer, Y., and Löscher, A.: Carbon Monitoring Satellite (CarbonSat): assessment of atmospheric CO_2 and CH_4 retrieval errors by error parameterization, Atmos. Meas. Tech., 6, 3477-3500, doi:10.5194/amt-6-3477-2013, 2013.

Summary

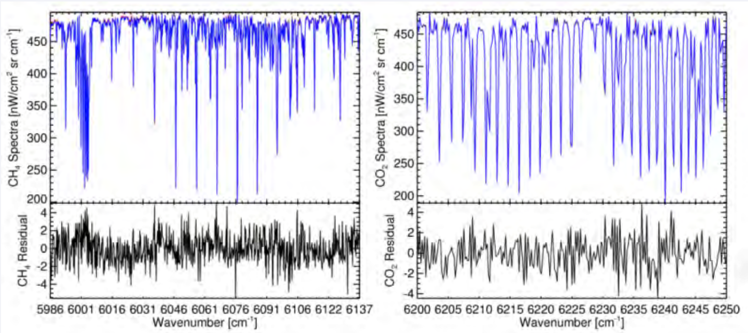
- The feasibility of greenhouse gas (CO_2 and CH_4) remote sensing from satellites with good accuracy and precision is well demonstrated and more than 10 years are now available from SCIAMACHY and GOSAT
- GOSAT observations show very good quantitative consistency with ground-based column observations from TCCON over Europe and globally
- Column observations observe integrated signals from larger regions with no sensitivity to boundary layer variations (but sensitivity to tropopause height variations) that can well complement surface networks especially for regions with poor coverage by surface networks
- Model fields over Europe (constraint with surface data) agree well with GOSAT observations but more work is needed to exploit GOSAT for emission estimates of Europe (sparse sampling, influence of stratosphere for high-lat.)
- New observations coming on-line which promise much denser sampling and better coverage
  - Surface fluxes on regional to local scales
  - New applications such as point source monitoring

The X_{CO2} and X_{CH4} Retrieval

- **Full physics CO_2 retrieval:**
  - **Simultaneous 3-band fit to retrieve CO_2 together with additional aerosol, surface and atmospheric variables**

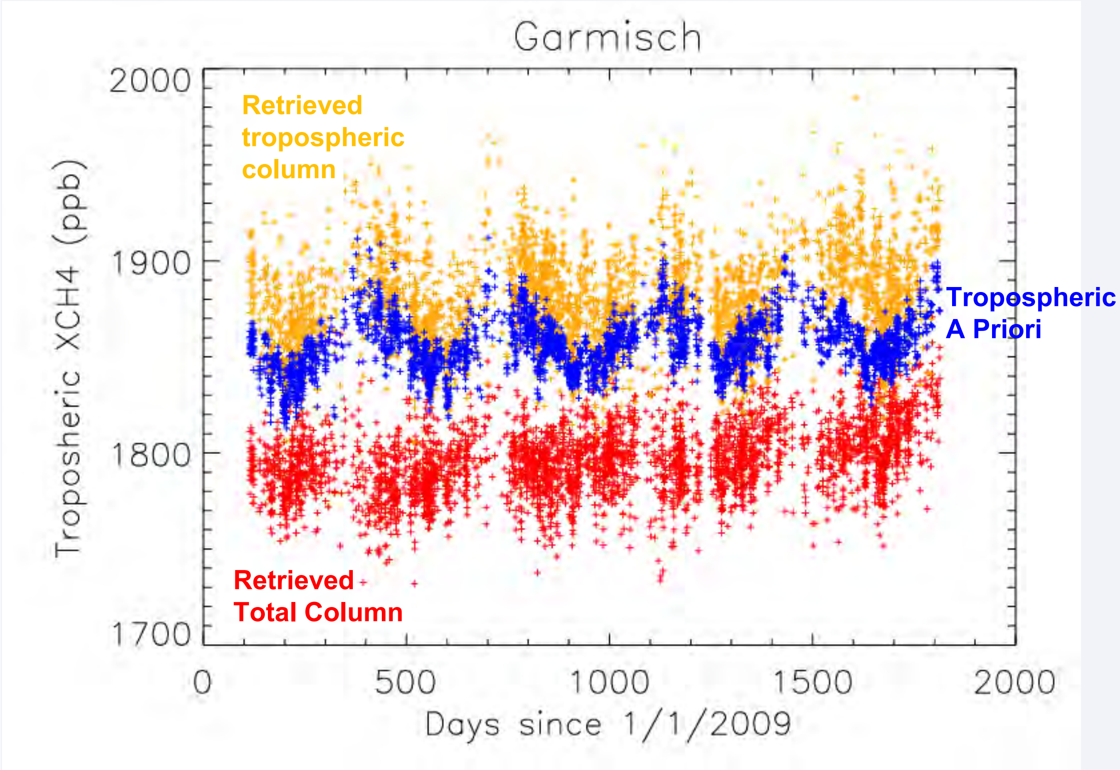


- **CH_4 proxy retrieval:**
  - **CO_2 column from spectrally-close window is used as proxy for the unknown light path for the CH_4 retrieval (Frankenberg et al., 2008)**
  - **$XCH4_{proxy} = XCH4_{retrieved}/XCO2_{retrieved} * XCO2_{model}$**



- **Very simple, fast retrieval**
- **Reduced sensitivity to aerosols/clouds and instrument calibration**
- **Requires accurate model for atmospheric CO_2 (see Schepers et al., 2012)**

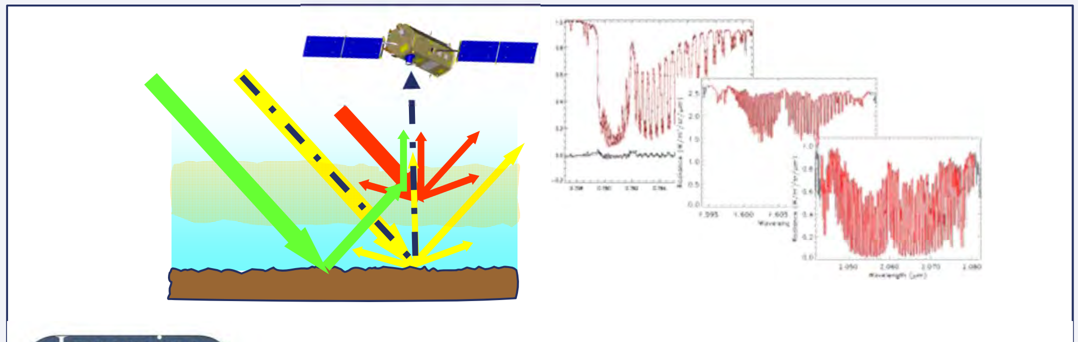
Tropospheric Column

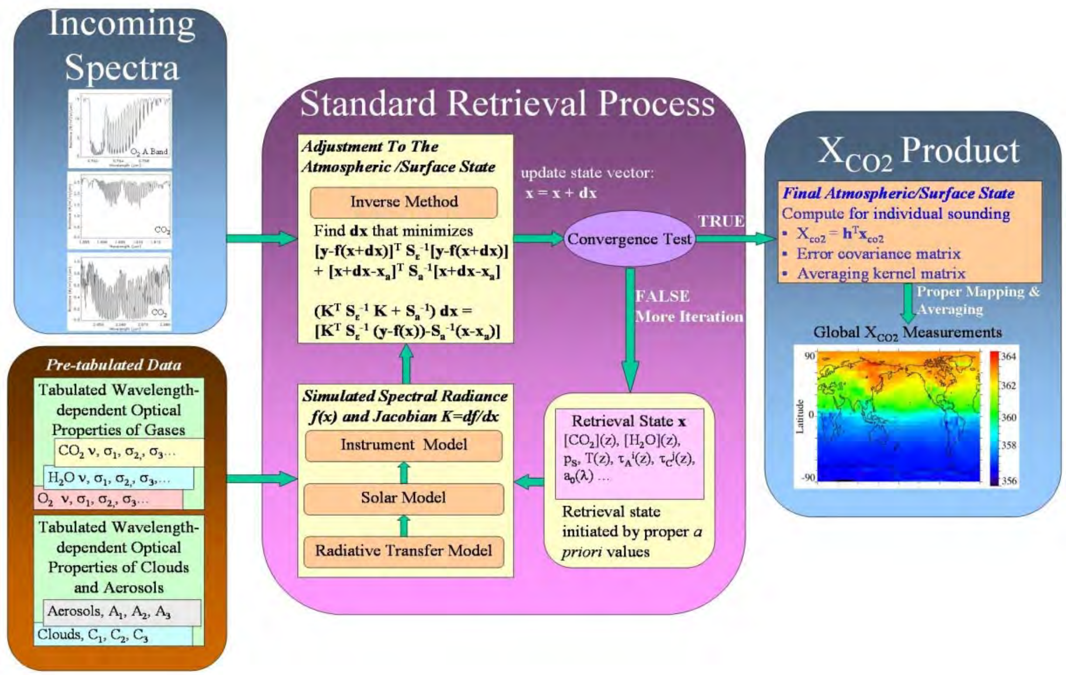


- **If a priori stratospheric column is sufficiently accurate then tropospheric column could be inferred**
- **Might be useful if atmospheric transport models have large issues with stratosphere (larger than accuracy of the subtraction of the tropospheric column)**

The OCO-1 'Full-Physics' Retrieval Algorithm

- Accurately retrieving CO_2 (and CH_4) is extremely difficult and time-consuming:
  - ➔ Retrieved CH_4 and CO_2 will depend on assumptions of retrieval algorithm (retrieval biases)
- Forward Model needs to describes accurately physics of measurement:
  - Multiple-scattering RT
  - Polarization Correction
  - Spherical Geometry
  - Surface (polarized) BRDF
  - Instrument Model
  - Solar Model
- Inverse Method estimates state:
  - Rodger's optimal estimation technique

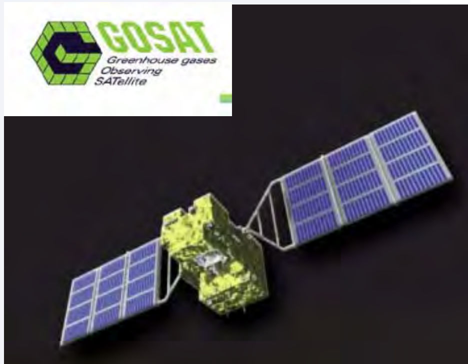




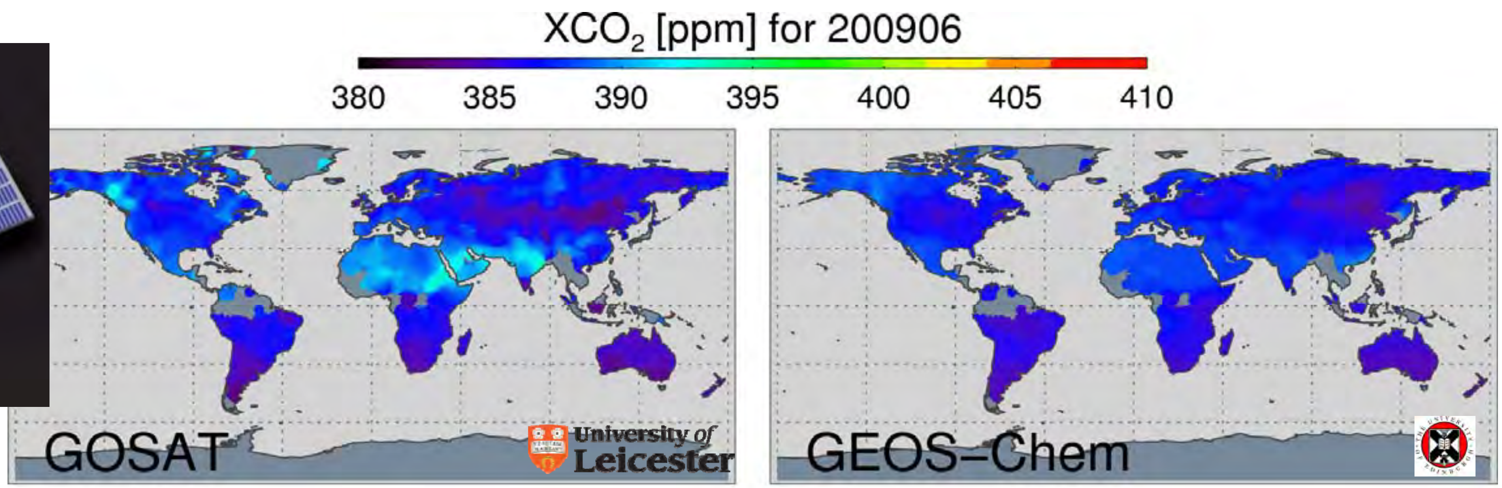
(Boesch et al., 2006, 2011, O'Dell et al., 2011)

Testing Model Calculations with GOSAT

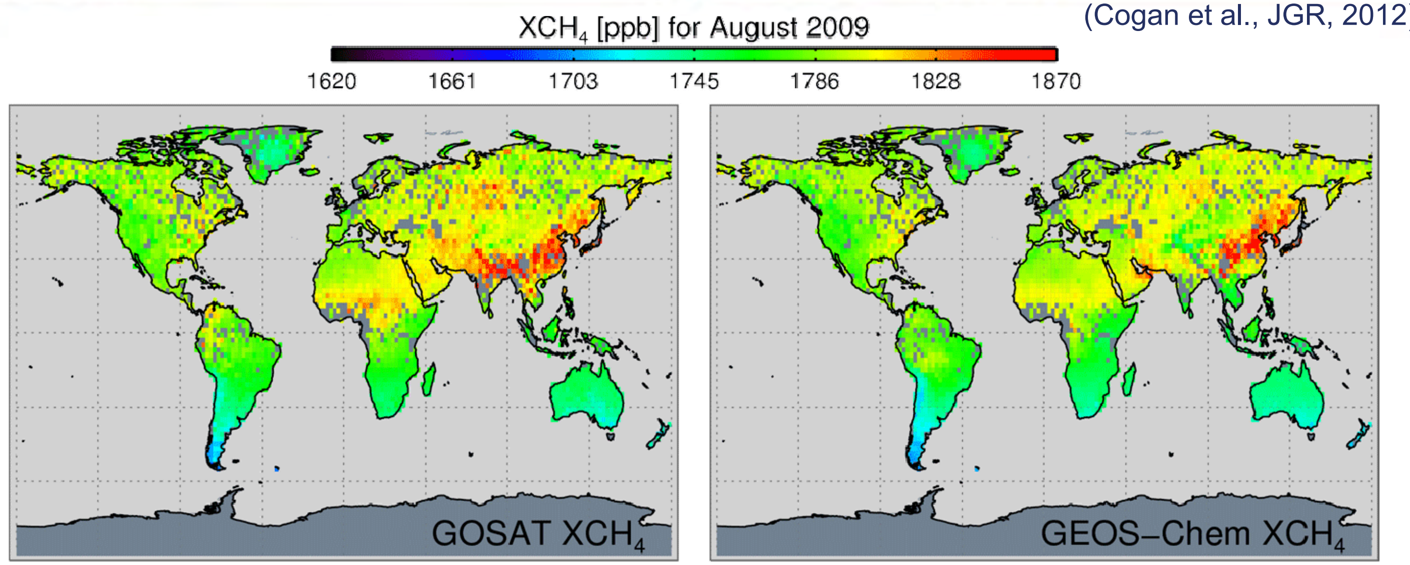
Dedicated satellite missions provide unprecedented global view of release and uptake of CO_2 and CH_4 by surface processes to critically test and improve models and to track main emission regions



GOSAT - first dedicated GHG satellite

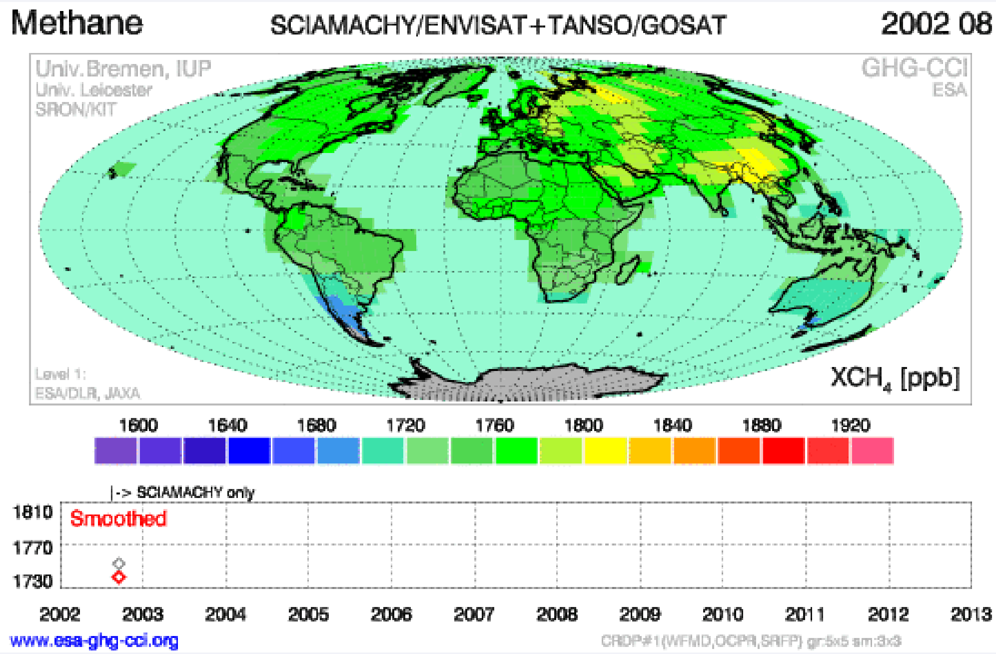


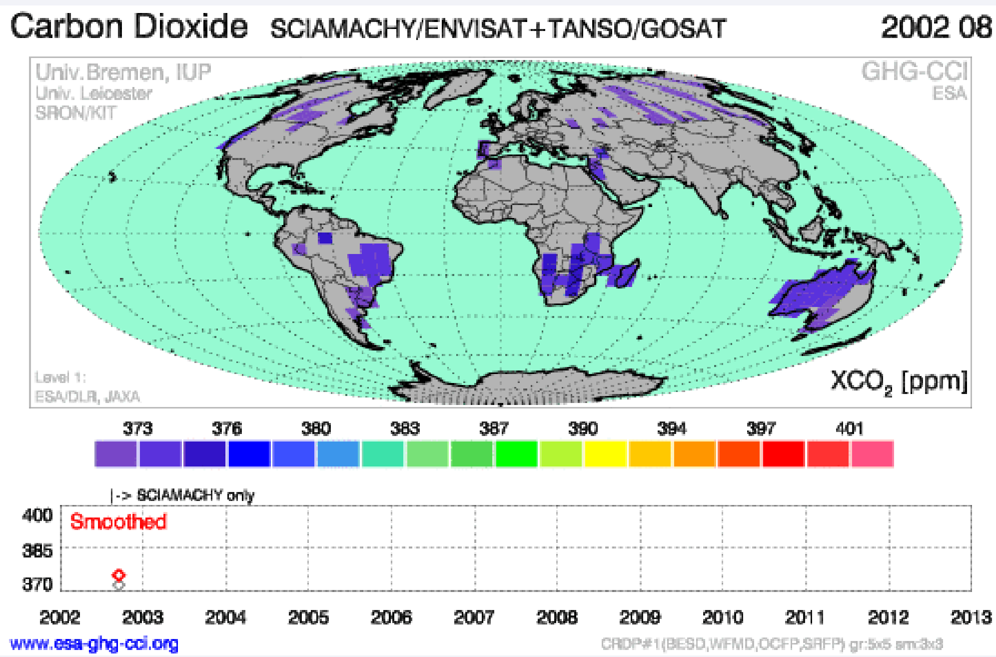
(Cogan et al., JGR, 2012)



(Parker et al., GRL, 2011)

Current Satellites Observe Large-Scale Pattern and Trends on Global Scale





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