GLOBAL MAPPING OF METHANE AND CARBON DIOXIDE: FROM SCIAMACHY TO CARBONSAT

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

Institute of Environmental Physics (iup), University of Bremen FB1,
Otto Hahn Allee 1, 28334 Bremen, Germany, E-mail: Michael.Buchwitz@iup.physik.uni-bremen.de

ABSTRACT

Carbon dioxide (CO_2) and methane (CH_4) are the two most important greenhouse gases (GHG), whose atmospheric amounts are changed by anthropogenic activity. An adequate and appropriate understanding of their natural and anthropogenic sources and sinks is a pre-requisite for reliable climate prediction. Regional surface fluxes can be inferred from inverse modeling of satellite observations of the atmospheric column-averaged dry air mole fractions of CO_2 and CH_4, i.e., XCH_4 and XCO_2. Using data from SCIAMACHY on ENVISAT, it has already been demonstrated that regional methane emissions are well constrained. Currently SCIAMACHY (2002 to 2014) and the Japanese GOSAT satellite (2009-2014) deliver GHG column-averaged mole fractions but having different spatial resolutions and sampling strategies. NASA's OCO-2 will deliver accurate XCO_2 in the time frame 2013-2015. To ensure that after the end of SCIAMACHY, GOSAT and OCO-2 missions are continued for these two important GHG and to improve the spatial resolution and sampling frequency to provide the evidence needed to test our understanding of climate change, improve its prediction and assess its management and mitigation, we proposed the satellite mission "Carbon Monitoring Satellite" (CarbonSat) in response to ESA's 8th Earth Explorer Opportunity Mission call (EE8) and its evolution to the CarbonSat Constellation. CarbonSat has a spatial resolution of 2 x 2 km^2 (nadir and sun-glint mode), good spatial coverage (500 km swath width) and high single shot precision (typically < 2 ppm for XCO_2 and < 13 ppb for XCH_4). CarbonSat will deliver about 6 million cloud free observations per day. These novel capabilities open up new and important application areas such as the monitoring of "hot spot" emission sources to meet treaty requirements, e.g., the evaluation of CO_2 emissions from coal-fired power plants or the detection and quantification of strong localized methane emitting geological and anthropogenic sources (seeps, mud volcanoes, pipelines, oil and gas fields, etc.).

1. SCIAMACHY ON ENVISAT

The measurements of SCIAMACHY [3,9] on ENVISAT (launch 2002) comprise nearly the entire solar spectral region (240–1750 nm, 1940-2040 nm, 2265-2385 nm) and the instrument observes the Earth's atmosphere using several viewing geometries (nadir, limb and solar and lunar occultation). The atmospheric concentrations (columns, profiles) of a large number of important atmospheric trace gases and parameters can be retrieved from the measured spectra [3,9].

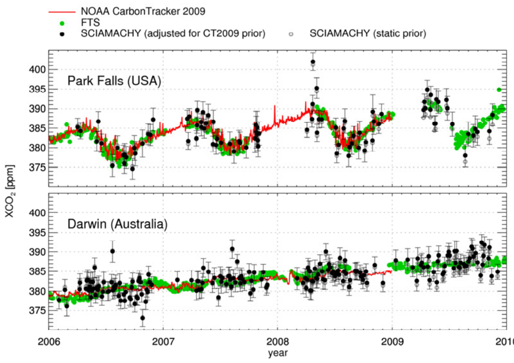

Fig.1: First results from the application of the new SCIAMACHY CO_2 retrieval algorithm BESD [22] to real SCIAMACHY data. Shown are comparisons between SCIAMACHY (black and grey), ground-based FTS retrievals (green) from the TCCON, and NOAA's CarbonTracker (red).

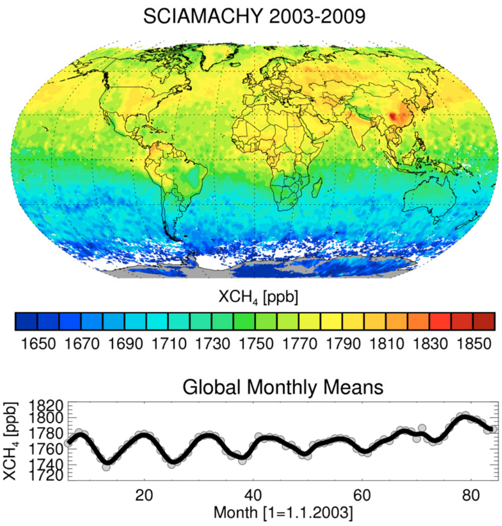

Fig. 2: The composite average dry column of methane, XCH_4, for 2003-2009, retrieved from SCIAMACHY using the WFM-DOAS retrieval algorithm [26]. Northern hemispheric concentrations are higher as most of the sources are north of the equator. The topographic modulation of the troposphere is also well observed. The large methane source regions, e.g., those in China, can be identified by regionally elevated methane column amounts and the outflows from the continents to the oceans. The time series at the bottom of the figure shows that methane increases during recent years. Note that after 2005 the retrievals are somewhat noisier due to detector degradation.

The nadir spectra yield on appropriate mathematical inversion column-averaged dry air mole fractions of the two greenhouse gases (GHG) carbon dioxide (CO_2) and methane (CH_4), i.e., XCO_2 (in ppm) and XCH_4 (in ppb). Several groups have developed algorithms to retrieve GHG information from the SCIAMACHY spectra (see, e.g., 6-8, 13, 22, 24-26, and references given therein). Recent results obtained with the BESD [22] and the WFM-DOAS algorithms [6, 24-26] are shown in Figs. 1 and 2, respectively.

XCO_2 is defined as the vertical column of CO_2 (molecules/cm^2), retrieved from the 1.58 µm spectral region, normalized with the "dry air column" obtained from O_2 vertical columns retrieved from the 0.76 µm spectral region [24]. XCH_4 is defined as the vertical column of CH_4 (molecules/cm^2), retrieved from the 1.65 µm spectral region, normalized with the "dry air column" obtained from CO_2 vertical columns retrieved from the 1.58 µm spectral region [25].

CO_2 and CH_4 are the two most important GHG, whose column amount is being modulated and changed by anthropogenic activity [16]. As CO_2 and CH_4 are long lived in the troposphere the total dry columns have small spatial modulation due to sources and sinks. Challenging measurement requirements for XCO_2 and XCH_4 in terms of (relative) accuracy have to be met in order to reliably estimate regional surface fluxes are (e.g., [1, 5, 15, 21]). For SCIAMACHY XCH_4 it has already been demonstrated that important information on regional methane emissions can be inferred from the retrieved XCH_4 [1, 2]. It has been shown that SCIAMACHY constrains strongly the regional emissions by using the SCIAMACHY XCH_4, retrievals in combination with inverse modeling of regional surface fluxes [1]. Encouraging results have been obtained for XCO_2 [24, 26]. This data product has not yet been used for inverse modeling. In general the requirements for XCO_2 retrievals are higher compared to XCH_4 and scattering related errors are potentially larger because the spectral distance between CO_2 and O_2 is larger than that between CH_4 and CO_2. Algorithm improvements to utilize all information within the spectra and thereby enhance the accuracy of the SCIAMACHY XCO_2 retrieval are therefore ongoing. One important focus is the minimization of systematic effects caused by the scattering of solar radiation within the atmosphere by aerosols and clouds at the different wavelength used in the retrieval [22].

The results show in agreement with the sparse set of ground based measurements that the dry columns of atmospheric methane have a seasonal cycle and were nearly constant in the time period 2003-2006. Surprisingly they started to increase again in recent years.

The recent methane increase is most likely due to increasing natural emission rates [12, 23]. The analysis of the SCIAMACHY methane observations is ongoing to shed more light on this highly relevant science issue. The analysis is however complicated by the degradation of the detector pixels in the spectral regions used for methane retrieval [26].

The detectors developed for SCIAMACHY in the SWIR channels are the first of their kind to fly in space. The detector pixels performance is affected by detector degradation, resulting from the impact of high energy protons during passage through the Van Allen belts, which increases the dark leakage signal of the detector. After 2005 in the spectral region used for CH_4 retrieval several detector pixels having significant information about CH_4 have increased dark leakage current [26].

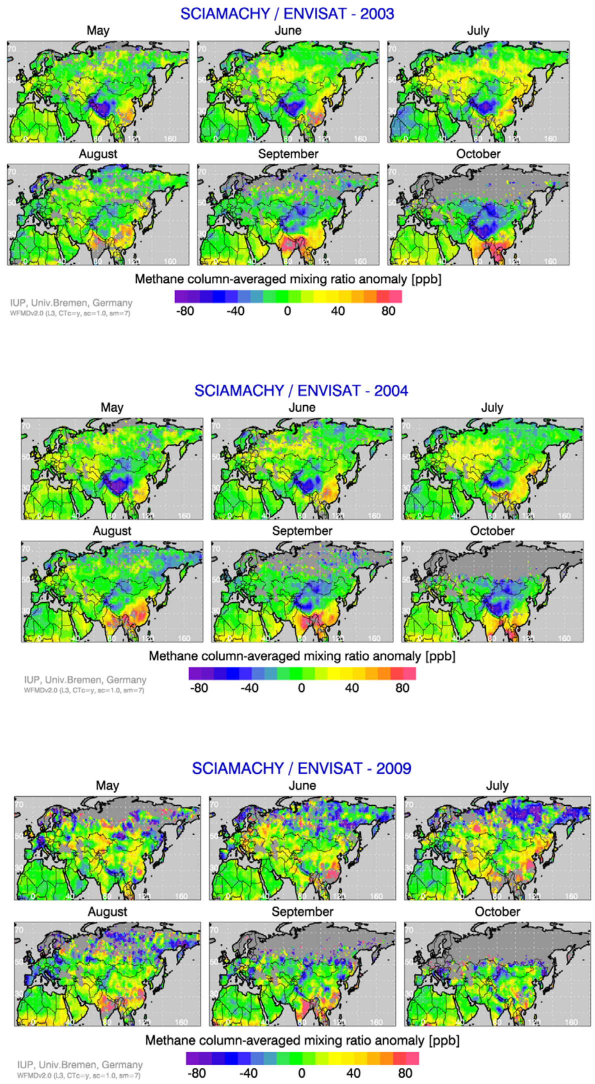

Fig. 3: Monthly composite averages of SCIAMACHY WFM-DOAS v2.0 XCH_4 [26] over Eurasia for 3 years in the time period 2003-2009. To use the same color scale and to highlight the spatial pattern the XCH_4 is shown as anomaly, i.e., the mean value has been subtracted for each map. The retrieved XCH_4 (essentially the CH_4 to CO_2 column ratio) has been CO_2 corrected using NOAA's CarbonTracker CO_2 assimilation system [19, 20]. Only data over land are shown. Regions without data result usually from the presence of cloud; such regions are flagged and not used in this analysis.

The nominal mission lifetime of SCIAMACHY/ ENVISAT was 5 years (2002-2006/7) and this lifetime has already been exceeded by several years. Fig. 3 shows monthly averages over Eurasia for several years during the time period 2003-2009. Overall SCIAMACHY's performance is still very good (apart from the degradation of the CH_4 channel) and the ENVISAT mission has been extended until 2013. No significant degradation has been detected in the spectral regions needed for XCO_2 retrieval [26] (Fig. 1).

The SCIAMACHY mission aboard ENVISAT needs to be continued for the maximum possible time. Nevertheless, the ENVISAT mission will probably come to an end somewhere in this decade. As a result new mission to measure XCH_4 and XCO_2 are needed. A brief discussion of the planned post-SCIAMACHY GHG missions with sensitivity for the lower troposphere is given in the next section.

2. EXISTING AND PLANNED OTHER GHG MISSIONS

In 2009 the Greenhouse Gases Observing Satellite (GOSAT) [17] was launched successfully. The Japanese GOSAT satellite is the world's first dedicated GHG satellite built and launched to deliver accurate CO_2 and CH_4. The main purpose of GOSAT is to produce more accurate estimates of CO_2 and CH_4 surface fluxes on a sub-continental basis (several 1000 km resolution).

The overlap between the SCIAMACHY and GOSAT GHG time series permits detailed comparisons between the XCO_2 and XCH_4 data products of the two sensors. Fig. 4 shows an initial comparison using recent versions of the data products of the two sensors which are continuously being improved. As can be seen, significant differences exist between the data products of the two sensors, which are under investigation and are not yet fully understood. The ultimate goal is to generate a consistent, consolidated and continuous CO_2 and CH_4 time series from both SCIAMACHY and GOSAT. GOSAT has a nominal lifetime of 5 years.

The launch of NASA's Orbiting Carbon Observatory (OCO) mission [10, 11] in 2009 failed but it is planned to launch a carbon copy, OCO-2, in early 2013. This mission, which was a pathfinder, has a planned nominal duration of 2 years.

ESA's Sentinel 5 Precursor (S-5P) mission (2014-2020/21) will enable the retrieval of total ozone and large number of trace gases relevant for tropospheric air quality (O_3, NO_2, SO_2, CO, …). In addition methane columns will be retrieved from the 2.3 µm spectral region optimized for CO column retrieval. However, S-5P will not be equipped with a dedicated 1.6 µm methane channel and XCO_2 will not be measured by S-5P.

Around 2015 it is planned to launch the first laser based GHG mission. This mission is a German/France (G/F) initiative, MERLIN, to deliver accurate XCH_4 along the satellite's track. This again is planned to have a limited lifetime.

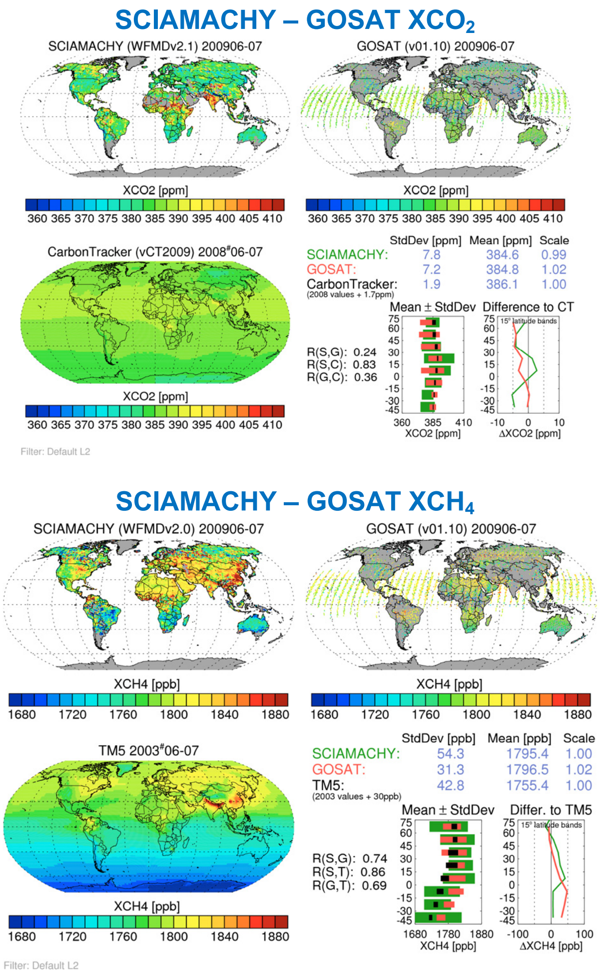

Fig. 4: Comparison of SCIAMACHY WFM-DOAS version 2.1 XCO_2 and GOSAT v01.10 XCO_2 (top) and XCH_4 (bottom) for June-July 2009. All "quality filtered" Level 2 data have been used for comparison without any additional filtering.

An overview about existing and planned GHG missions with sensitivity for the Planetary Boundary Layer (PBL) is shown in Fig. 5. As can be seen, there are no mission planned to have dedicated CO_2 measurements after the flights of SCIAMACHY/ENVISAT, GOSAT and OCO-2. Unless new missions dedicated to XCO_2 and XCH_4 are commissioned, there will be an XCO_2 data gap after OCO-2; for XCH_4 there will be a data gap between the end of MERLIN and Sentinel 5. Further none of these planned measurements or existing measurements will provide the global high spatial and temporal sampling fit for purpose.

To close this information gap and to provide data products at a spatial resolution and sampling required to increase the sensitivity to diffuse large scale and moderate to strong small scale sources and sinks, IUP in co-operation with several partners has developed the "Carbon Monitoring Satellite" (CarbonSat) instrument concept and the idea of a CarbonSat Constellation. This meets the recommendation of the EU GMES working group 4 with respect to the space segment of measurement need for European contribution to GEOSS (The Global Earth Observing System of Systems). The proposal has been endorsed by the WMO WCRP and the GEO secretariat. It addresses the key challenges defined by the CEOS Carbon Task Force. Details on CarbonSat will be given in the following section.

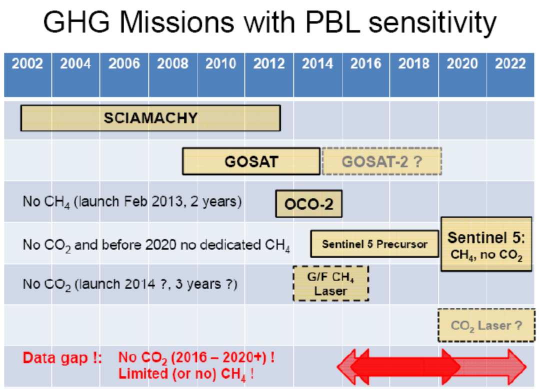

Fig. 5: Existing and planned experiments and missions to measures Greenhouse gas amounts from orbiting satellites, having sensitivity to the GHG in the planetary boundary layer (PBL) close the surface in the period 2002-2022. As can be seen, a data gap exists in the time period 2016-2020 or potentially longer. Furthermore, none of the existing and planned GHG missions has been optimized to monitor localized "hot spot" emission sources. This lack of required information and gap in the long term data record can be closed with CarbonSat.

3. CARBONSAT

The primary mission objective of CarbonSat (http://www.iup.uni-bremen.de/carbonsat) is the quantification and monitoring of natural and anthropogenic CO_2 and CH_4 sources and sinks to provide the following:

i) a better understanding of the processes that control the carbon cycle dynamics on the regional scale with global coverage, and

ii) an independent estimate of local greenhouse gas emissions (fossil fuel, geological CO_2 and CH_4, etc.) in the context of international treaties [see, e.g., 18].

This can be achieved by a unique combination of high spatial resolution (ground pixel size 2x2 km^2), sufficiently good coverage (500 km swath) (see Figs. 6 and 7) and high spectral resolution measurements covering the relevant absorption bands of CO_2, CH_4 and O_2 in the Near-Infrared/Shortwave-Infrared (NIR/SWIR) spectral region (Fig. 8). CarbonSat has been proposed to ESA in response to ESA's 8th Earth Explorer Opportunity Mission call (EE8). The CarbonSat science team is led by IUP and the industrial team is lead by the German company OHB (also) located in Bremen.

The CarbonSat payload – as currently planned - will consist of the following instruments:

- An Imaging Spectrometer (IS) for nadir observations and sun-glint tracking which is the core instrument of the CarbonSat mission.
- A Cloud and Aerosol Imager (CAI) to deliver additional information on clouds and aerosols, including sub-scene and around scene information.

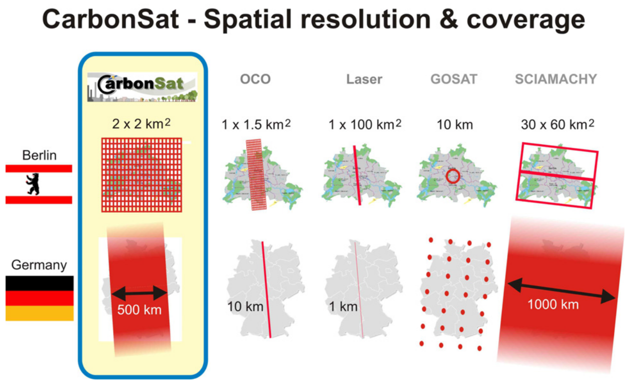

Fig. 6: A comparison of the spatial resolution (2 x 2 km^2) and coverage (500 km swath width) of CarbonSat, compared to other existing and planned satellite missions. As can be seen, only CarbonSat achieves the required spatial resolution and coverage.

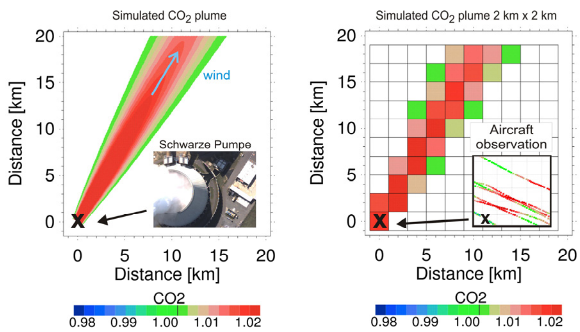

Fig. 7: Simulation of the atmospheric CO_2 column enhancement due to CO_2 emission of the power plant "Schwarze Pumpe", Germany, emitting 13 $MtCO_2$/yr. On the left the plume is shown at high spatial resolution, on the right at CarbonSat resolution of 2×2 km^2. Also shown are MAMAP aircraft XCO_2 observations [13]. Shown is XCO_2 normalized to its background value. To better visualize the extent of the CO_2 plume, values below 1.0025 are shown in white. From [4].

High spatial resolution is important in order to maximize the probability of clear-sky observations.

CarbonSat will deliver more than 6 million cloud free observations each day – much more than any of the other existing or planned dedicated GHG missions. A constellation can achieve this spatial resolution with daily global coverage. High spatial resolution is also needed to detect and quantify emissions from (strong) localized emission sources such as coal-burning power plants (Fig. 7). A summary of the characteristics of the CarbonSat mission is given in Table 1.

CarbonSat's CO_2 and CH_4 sensor is an imaging NIR/SWIR spectrometer system (SCIAMACHY, OCO, GOSAT heritage). Spectral absorptions of CO_2 (~1.6 µm and ~2 µm), O_2 (~760 nm) and CH_4 (~1.65 µm) are measured at high spectral resolution (~0.1-0.3 nm) and high signal-to-noise ratio (SNR). The spectral bands, selected for CarbonSat, are shown in Fig. 8. Additional relevant information is summarized in Tab. 2. The relative transparent band SWIR-1 delivers information on the vertical columns of CO_2 and CH_4 with high near-surface sensitivity. Bands NIR and SWIR-2 contain strong absorption bands of O_2 and CO_2, respectively, and provide additional information on aerosols and clouds. They are needed for the conversion of the vertical columns into column-averaged mixing ratios (via O_2) and to describe the scattering of electromagnetic radiation in the atmosphere, caused by aerosols and clouds with sufficient accuracy in the retrieval process, thereby minimizing any errors.

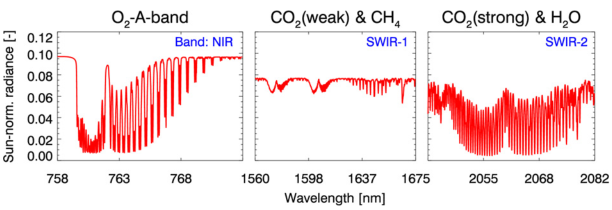

Fig. 8: Simulated CarbonSat nadir spectra of the sun-normalized radiance.

It is planned to equip CarbonSat with a Cloud and Aerosol Imager (CAI). This is a similar strategy to that of GOSAT, or the combination of SCIAMACHY and MERIS data from ENVISAT. It is used to obtain optimal knowledge about clouds and aerosols, including sub-scene and around scene information. The spatial resolution of CarbonSat/CAI is planned to be about 500 x 500 m^2. The CAI swath width is somewhat larger than the swath width of the main imaging spectrometer, which is 500 km.

A series of Observing System Simulation Experiments (OSSE) have been conducted for CarbonSat [4]. These yielded the single ground pixel retrieval precision for sufficiently cloud free measurements over land to be typically 2 ppm for XCO_2 and 8 ppb for XCH_4, i.e., approx. 0.5% for both gases. For localized sources ("hot spots") the single overpass emission uncertainty (statistical error due to instrument noise) is 0.8 $MtCO_2$/yr for a near-surface wind speed of 1 m/s (assuming sufficiently cloud free conditions) and 3.2 $MtCO_2$/yr for 4 m/s for localized CO_2 emitters such as coal-fired power plants (the dependence on wind speed is linear). For methane hot spot emission sources the emission uncertainty is 1.4 $ktCH_4$/yr for 1 m/s and 5.6 $ktCH_4$/yr for 4 m/s. This performance enables the emissions of moderate to strong localized methane sources such as landfills, coal mines, pipeline compressor stations, and various geological sources to be detected and their magnitude to be quantified[4] (Fig. 9).

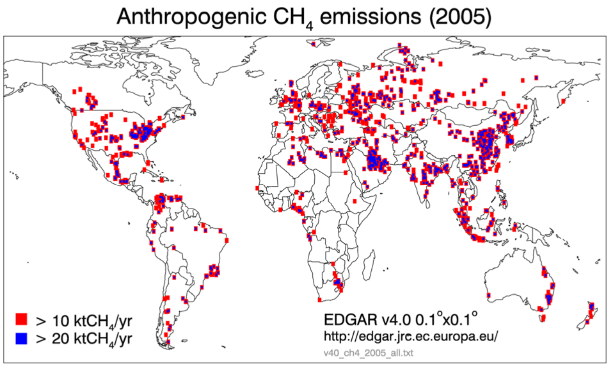

Fig. 9: Spatial distribution of strong localized anthropogenic methane sources according to the EDGAR data base (year 2005, gridded 0.1°×0.1°). The locations of methane sources, which emit more than 10 ktCH4/yr (red boxes) and more than 20 $ktCH_4$/yr (blue boxes, are shown). Emission data: EC-JRC/PBL, EDGAR version 4.0, http://edgar.jrc.ec.europa.eu, 2009. Figure from [4].

CarbonSat Mission Overview	
Parameter	**Description**

Main geophysical data products	**Level 2:**
	Column-averaged mole fractions of carbon dioxide (CO_2) and methane (CH_4) at ground-pixel resolution:
	• XCO_2:
	  ○ Unit: ppm
	  ○ Precision: < 2 ppm (threshold < 3 ppm = 0.8%)
	• XCH_4:
	  ○ Unit: ppb
	  ○ Precision: < 13 ppb (threshold < 18 ppm =1%)
	
	Level 3:
	• XCO_2 maps (e.g., monthly at 0.5^ox0.5^o)
	• XCH_4 maps (e.g., monthly at 0.5^ox0.5^o)
	Required relative accuracy for monthly averages at 1000 x 1000 km^2 resolution:
	• XCO_2: < 1 ppm (threshold < 2 ppm = 0.5%)
	• XCH_4: < 10 ppb (threshold < 18 ppb = 1%)
	
	Level 4:
	• Regional CO_2 surface fluxes (e.g., monthly at 8^ox10^o)
	• Regional CH4 surface fluxes (e.g., monthly at 8^ox10^o)
	• CO_2 hotspot emissions (e.g., power plant emissions)
	• CH_4 hotspot emissions (e.g., geological sources)

Ground pixel size	2 x 2 km^2
Main observation modes	• Nadir • Sun-glint tracking • Sun over diffuser
Payload	Imaging Spectrometer (core instrument): • Passive 3-band spectrometer system (NIR @ 760 nm, SWIR-1 @ 1600 nm and SWIR-2 @ 2050 nm) Additional instrumentation: • Cloud and Aerosol Imager (CAI): Several bands UV to SWIR
Duration	7 (5) years; Launch 2014 or later
Orbit	Baseline orbit: Sun-synchronous polar low Earth (LEO), LTAN 13:30 (flight direction south to north on day side), swath width: 500 km

Table 1: CarbonSat mission summary.

CarbonSat Imaging Spectrometer			
Band	**Spectral range [nm]**	**Resolution [nm]**	**SNR [-]** (A=0.1, SZA=50^o, t_{int}=0.3s)
NIR	757 - 775	< 0.03 (< 0.045)	> 500 (> 250)
SWIR-1	1559 - 1675	< 0.15 (<0.3)	> 600 (> 300)
SWIR-2	2043 - 2095	< 0.1 (< 0.125)	> 300 (> 120)

Table 2: Summary of the main characteristics of CarbonSat's Imaging Spectrometer. The numbers without brackets are the goal requirements, the numbers in brackets are the threshold, i.e., minimum requirements.

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