Scientific roadmap for satellite remote sensing of CH_4

ESA project METHANE+ led by SRON

Task 4, WP 4000, Deliverable 9 (D9)

Lead author:
Sander Houweling (VU)

Co-authors:
Ilse Aben (SRON), Michael Buchwitz (iUP), Cyril Crevoisier (LMD), Brian Kerridge (RAL), Alba Lorente Delgado (SRON), Julia Marshall (MPI-BGC), Jacob van Peet (VU), Oliver Schneising (iUP), Richard Siddans (RAL)

Change log

Version	Date	Status	Authors	Reason for change
1	20-April-2022	Draft	See title page	New document
2	17-June-2022	Submitted version	See title page	All comments of the team account for
3	11-July-2022	Final version	See title page	Comments from ESA accounted for

Authors

Institute of Environmental Physics (IUP), University of Bremen (UB), Bremen, Germany:
- Michael Buchwitz
- Oliver Schneising

Le Laboratoire de Météorologie Dynamique (LMD), Paris, France:
- Cyril Crevoisier

Max Planck Institute for Biogeochemistry (MPI-BGC), Jena, Germany:
- Julia Marshall (currently at DLR)

Rutherford Appleton Laboratory (RAL), UK
- Brian Kerridge
- Richard Siddans

SRON Netherlands Institute for Space Research, Utrecht, The Netherlands:
- Alba Lorente Delgado
- Ilse Aben

Vrije Universiteit Amsterdam (VU), Amsterdam, The Netherlands
- Sander Houweling
- Jacob van Peet

Table of Contents

1. Executive summary

This roadmap provides an overview of the atmospheric monitoring needs for the greenhouse gas methane in support of international climate policy, the current capacity of satellite remote sensing to address those needs and opportunities and priorities for the near future. The monitoring needs concern the need for an improved understanding of the drivers of the global methane increase, including impacts of carbon-cycle climate feedbacks, as well as the need to provide independent verification of national reports of greenhouse gas emissions.

Satellite remote sensing provides useful information on scales ranging from single emitters to the entire globe, using techniques that differ in the trade-offs that are made on coverage, resolution, and measurement accuracy. To translate satellite measurements into emission estimates, (inverse) modelling techniques are developed with requirements that vary between the application areas also. The diversity of methods is critical not only to optimize the approach for each application but also to assess the robustness of emission estimates that are derived. The latter is critical because of the difficulty to reliably quantify uncertainties, notably systematic uncertainties in retrieval techniques and atmospheric inverse models. Rapid progress is made in the detection and quantification of large single emitters. To connect that information to regional emission budgets and the attribution of anthropogenic and natural emission processes remains a challenge.

Several new satellite missions are planned for launch in the coming years, providing rich datasets in terms of coverage and resolution. An important research priority is to develop the methodology needed to make efficient use of that information in a timely manner, and to combine observational constraints that address different scales and parameters. The Methane+ project takes important steps in this direction, which will need to be followed up on in future projects, such as the recently funded ESA projects MethaneCamp and Ampac-Net for improved quantification of methane emissions from Northern latitudes.

2. Context and objectives of CH_4 monitoring from space

2.1. The global growth rate of CH_4

To improve our understanding the main drivers of the observed global increase of methane requires a more accurate quantification of its global sources and sink. The most important natural and anthropogenic processes emitting methane and removing it from the atmosphere are believed to have been identified. However, to constrain the estimates for each of these processes well enough to explain the observed growth-rate variations poses a great challenge [Saunois et al, 2020]. Measurements from the NOAA-ESRL surface monitoring network indicate that the global growth of methane has varied between -5 and 16 ppb/yr (-0.3 to 0.9 %/yr) since the 1980's, with the largest increase in the year 2020. The year 2021 is on track of setting a record again of close to 17 ppb/yr.

According to the EDGARv6 emission inventory [Crippa et al, 2021], anthropogenic methane emissions have increased by about 100 Tg/yr from 1985 to 2018. Assuming a mean emission in this period of 550 Tg/yr (anthropogenic + natural) and a mean mixing ratio of 1750 ppb, this would lead to a 315 ppb increase in the global background during this period. If natural sources and sinks remained constant, this is about 50% more than observed. Important differences between inventories and atmospheric data are also seen on shorter time scales, most notably between 2000 and 2007 when the background mixing ratio remained about constant, whereas EDGARv6 reports a 30 Tg/yr increase. Numerous attempts have been made to reconcile emission and concentration increases in this period, with limited consensus so far [Saunois et al, 2020] likely explained by various influences on the growth rate acting in parallel [Lan et al, 2019; Lunt et al, 2019; Zhang et al. 2021; Scarpelli et al, 2022].

The limited understanding of the observed growth rate is problematic in the light of climate projections and the emission reductions needed to reach the goals of the Paris agreement. To resolve this issue, improved regional scale monitoring capacity will be needed world-wide, to which satellite remote sensing can make an important contribution.

2.2. Anthropogenic CH_4 and emission mitigation

For the Paris agreement and its 5 yearly global stock take to be successful in limiting climate change, it is important that national emission reports are consistent with the observed atmospheric increase of CO2 and non-CO2 greenhouse gases. The methane-emission pledge at the recent COP26 requires a 30% reduction in methane by 2030 compared with 2020, aiming to take advantage of the short-term climate benefit of reducing methane emissions (UNEP-CCAC, 2021). Atmospheric greenhouse gas monitoring can most effectively support these emission reduction efforts if it allows evaluation of the national and annual emissions of the national inventory reports that are submitted to the UNFCCC. In some countries, including UK, CH, and NZ [Henne et al, 2016; Lunt et al, 2021; https://niwa.co.nz/climate/research-projects/carbon-watch-nz], this is done already using national measurement facilities on ground. Other western European countries will follow in the coming years (e.g. Germany), supported o.a. by the ongoing measurements from the Integrated Carbon Observing System (ICOS).

In many other countries, lacking the required measurement infrastructure, this is much more difficult. Non-Annex 1 countries are not required to report their annual emissions. Nevertheless, for the Global Stock Take to provide effective guidance on the global progress towards the Paris goals, it is important that emissions from these countries are monitored also. Without the global coverage of Earth Observing satellites that will be difficult, if not impossible, to achieve within the time frame of the global methane pledge.

Emission changes of only a few % per year will be difficult to resolve, calling for multi-year time series with stringent requirements on the continuity and stability of the measurement system as well as the accuracy of inverse modelling systems that are used to translate atmospheric measurements into fluxes. Besides estimates of national scale emissions, emission mitigation efforts will benefit from the detection and quantification of the most important local sources of greenhouse gas emissions. In the case of methane, these include unknown natural gas leaks that are attractive to repair for economic and safety reasons. Here high-resolution satellite remote sensing can play an important supporting role [e.g. Sadavarte et al, 2021; Lauvaux et al, 2021; Varon et al, 2019].

2.3. Climate feedbacks on natural emissions and the role of CH_4 sinks

About 40% of global methane emissions are from natural sources, with the largest contribution from natural wetlands [Houweling et al, 2017]. These emissions arise from an intricate balance between biological production and oxidation of methane by soil microbes, which is sensitive to environmental conditions and therefore to climate change. Climate feedbacks on natural methane emissions are expected to be important in particular for high-latitude boreal and arctic peatlands, that experience rapid warming due to arctic amplification and the associated disproportional warming of the high northern latitudes. Indeed, the zone of continuous permafrost is showing significant thawing in response to climate warming, with important changes in seasonal landscape dynamics.

The transition from perennially frozen to seasonally thawed top soils that are rich in organic carbon is expected to have major consequences for methane emissions. So far, however, the evidence from atmospheric data for an increase in the pan arctic methane emission inventory is limited [Bruwhiler et al, 2021]. The observed depletion in $\delta^{13}C$ of methane in background air suggests a shift from fossil to microbial sources of methane, which could point to increasing emissions from natural wetlands in response to climate change. However, except for some regional studies confirming this hypothesis, the evidence for a large-scale increase in wetland emissions due to climate warming remains insufficient.

Besides changing natural emission, recent studies have highlighted the potential importance of temporary or longer-term changes in the hydroxyl sink [Stevenson et al, 2021; Laughner et al, 2021]. For example, the temporary pause in the methane growth rate at the beginning of this millennium and the rapid methane increase in 2020, when the COVID-19 pandemic is expected to have reduced emissions, have been attributed to variations in OH. Climate change could influence OH, although changes in the chemical composition of the troposphere, notably NO_x emissions and tropospheric O_3 formation, seem more important.

The surface monitoring network does not provide sufficient information to independently constrain emission and sink changes. Measurements of vertical methane gradients could provide the required information, but uncertainties in vertical tracer transport will complicate its use. The gradient between source and background regions (land-ocean contrast for example) could provide sufficient information, for which instruments that provide high-accuracy measurements at full global coverage are useful. For this reason, the Methane+ project explored the combined use of SWIR and TIR satellite instrumentation.

3. Status of available satellite datasets and their use

3.1. CH_4 emission on regional / global scale

3.1.1. L2 Datasets

Satellite measurements of atmospheric methane have been generated in past years from several satellite instruments (e.g., SCIAMACHY/ENVISAT, GOSAT/GOSAT-2, TROPOMI on Sentinel-5-Precursor (S5P), IASI on the Metop series, AIRS/Aqua, TES/Aura and CrIS/Suomi-NPP) and using several different operational and scientific retrieval algorithms. These data sets have been used to enhance our knowledge of the various methane sources and sinks as shown in, for example, the review of Jacob et al. (2016), and in several other publications as listed on the ESA GHG-CCI project website.

The key quantity retrieved from satellite sensors covering the Short-Wave-Infrared (SWIR) spectral region measuring reflected solar radiation in nadir mode is XCH_4, the total column-averaged dry-air mole fraction (or mixing ratio) of atmospheric methane, typically reported in ppb (parts per billion).

For an overview of XCH_4 products as retrieved from SCIAMACHY and GOSAT see, for example, Reuter et al. (2020), and references given therein. Latest versions of the SCIAMACHY XCH_4 data products are available via the Copernicus Climate Data Store (CDS). This is also true for latest versions of the GOSAT XCH_4 products generated using European retrieval algorithms operationally via the Copernicus Climate Change Service (C3S). The operational GOSAT XCH_4 product is available from the National Institute for Environmental Studies (NIES) in Japan. This is also true for the operational GOSAT-2 XCH_4 product. For an overview about GOSAT-2 scientific XCH_4 retrievals see Noël et al. (2022). The operational S5P XCH_4 product (Hu et al., 2016) is available via the Copernicus Open Access Hub with additional information given on relevant Copernicus websites. Scientific S5P XCH_4 products are generated by SRON (Hu et al., 2018; Lorente et al., 2021) and Univ. Bremen (Schneising et al., 2019, 2020).

Satellite sensors covering the Thermal Infrared (TIR) spectral region in nadir mode provide either mid / upper tropospheric columns (e.g., Crevoisier et al., 2013; TIR sounders AIRS) or vertical profiles with two distinct layers (eg Siddans et al., 2020; Wecht et al 2012). The "LMD/CNRS products" described in Crevoisier et al. (2013) and selected as the official IASI Level2 product are currently generated operationally in the Copernicus Climate Change Service (C3S) and are available along with detailed documentation via the Copernicus Climate Data Store (CDS) for Metop-A (2007-2021), Metop-B (2013-2021 and Metop-C (2018-2021). "RAL products" from the Version 2 scheme applied to Metop-A (2007-17) and –B (2018-21) are available via the UK Centre for Environmental Data Analysis Dataset Record: STFC RAL methane retrievals from IASI on board MetOp-A, version 2.0 (ceda.ac.uk) Dataset Record: STFC RAL methane retrievals from IASI on board MetOp-B, version 2.0 (ceda.ac.uk). The Version 2 scheme derives from that described by Siddans et al. (2017). There are also links to methane data from US TIR sounders AIRS and TES.

Atmospheric methane is an important Greenhouse Gas (GHG) and therefore also an "Essential Climate Variable" (ECV). The ECV GHG as formulated by GCOS (Global Climate Observing System; GCOS-154, GCOS-195, GCOS-200) is defined as "retrievals of greenhouse gases, such as CO_2 and CH_4, of sufficient quality to estimate regional sources and sinks". The definition contains the main application of the atmospheric methane data products, namely to use them (in combination with appropriate (inverse) modelling) to obtain (improved) information on their (primarily surface) sources and sinks. Updated requirements for this product are given in GCOS-200 (Table 3). Note however, that essentially all past, present and planned future satellite SWIR sounders dedicated to obtaining information on regional sources and sinks of CO_2 and CH_4 are optimized to deliver XCO_2 and XCH_4. However, no requirements for these quantities are given in GCOS-200. This means that the GCOS-200 requirements cannot be used directly but need "interpretation" to apply the GCOS requirements on "tropospheric CH_4 column" for XCH_4. More specific requirements for satellite-derived XCH_4 and height-resolved methane products are provided in the corresponding C3S "Target Requirements and Gap Analysis Document" available along with the corresponding data product via the CDS.

Via the C3S CDS individual sensor Level 2 (L2) methane products are available from SCIAMACHY, GOSAT and IASI but also a merged multi-sensor/multi-algorithm product generated with the Ensemble Median Algorithm (EMMA, see Reuter et al., 2020) currently covering the time period 2003 to mid of 2020.

Detailed assessments of these products are shown, for example, in the latest version of the C3S Product Quality Assessment Report (PQAR) for the satellite-derived Greenhouse Gas (GHG) data products. As shown in that document, the question "Do the products meet the user requirements for systematic errors?" cannot simply be answered with yes or no. A reason for this is that the demanding requirements especially on systematic errors are on the same order as the Total Carbon Column Observing Network (TCCON) reference data. To deal with this, probabilities that the requirements are met are reported in the PQAR document. The assessments also indicate that all products show similar performance when compared to sparse reference data such as TCCON but they often differ significantly, for example, in terms of their spatio-temporal coverage but also to some extent in terms of their XCH_4 spatial pattern. In any case, a clear "winner" has not been identified and this is to some extent also true for "strengths and weaknesses" although this is mentioned for "Proxy (PR) versus Full Physics (FP)" XCH_4 products, with PR product having much better (i.e., quality filtered) data but FP products not requiring "XCO_2 correction".

Because of this and because even small differences matter when using Level 2 data to derive source / sink information, it has been decided for C3S to make an ensemble of XCH_4 (and XCO_2) data products available for the users (e.g., the inverse modelling community). It is recommended that users take advantage of the availability of an ensemble of products in order to find out if their main findings are robust or if key results critically depend on which product has been used to derive it.

The same is recommended for products from other sensors currently not used for C3S. This includes the S5P XCH_4 products presented and analyzed in this Methane+ project (see, for example, Lorente et al., 2022). As shown in Lorente et al., 2021 and 2022, the operational S5P XCH_4 product has several issues, e.g., albedo dependent biases, whereas the scientific products generated by Univ. Bremen (Schneising et al., 2019, 2020) and SRON (Lorente et al., 2021) suffer less from biases and are therefore superior (but still not perfect) with respect to data quality. Despite suffering less from biases these two scientific products also show significant differences (see Lorente et al., 2022) and it is recommended to use the latest versions of both products for challenging applications such as those aiming at improving our knowledge of the various anthropogenic and natural methane sources and sinks.

Potential to exploit height-resolved methane information from TIR jointly with co-located XCH_4 soundings, and thereby leverage information on lower tropospheric methane in either the retrieval or data assimilation domain, depends critically on the accuracies of both and particularly on systematic biases between the two. Schneider et al. (2021) evaluated a scheme to combine MUSICA IASI and SRON S5P XCH_4 (version 14_14) soundings in the retrieval domain at locations of ground-based measurements.

In the Methane+ project, RAL IASI (Version 2) and SRON S5P XCH4 (Version v18_17) soundings have been combined in the retrieval domain and evaluated on a global basis for the period January 2018 to March 2021. To fully exploit the potential of combined wavelength approaches, further improvements will be needed to the accuracies of both TIR and SWIR schemes or more sophisticated approaches to characterize systematic biases between the two, e.g., a machine learning approach as is employed for IUP SWIR methane.

3.1.2. Data use

Satellite data have been used in several inverse modelling studies of global methane emissions starting with SCIAMACHY [Meirink et al, 2008; Bergamaschi et al, 2009]. An important interest in the use of satellite data has been the extended coverage over land compared with the surface network, particularly over Tropical continents, where the surface network is sparse. First results indicated grossly underestimated emissions from tropical rainforests, which were later corrected with improved versions of the retrieval. The improved accuracy of the GOSAT instrument allowed an important step forward, with seasonal cycles in total column methane that were consistent with TCCON and inversions using surface measurements. A difference in the north-south gradient between GOSAT retrievals and surface data optimized inverse models was identified as a bias in stratospheric tracer transport [Monteil et al, 2013], found consistently in several models [Locatelli et al, 2015]. When correcting for this bias, inverse modeling studies generally report a satisfactory agreement between results obtained using GOSAT and surface measurements.

The added value of GOSAT is mostly in the tropics and increased with the length of the observational record. An important variation of methane emissions with the ENSO cycle was found [Pandey et al, 2017], driven most likely by tropical wetlands and biomass burning. Some studies have found evidence of increasing emissions over Tropical Africa [Parker et al, 2020] and Eastern Amazonia [Wilson et al, 2021] linked, most likely, to tropical wetlands and suggesting impacts of climate change. Global studies have been complemented with regional studies for the US, Canada, and South-East Asia exploring the constraints of GOSAT satellite on regional emissions [Lu et al, 2022; Baray et al, 2021; Wang et al, 2021]. The results indicate underestimated emissions from fossil fuel production over the US and Canada, and overestimated anthropogenic emissions from China. The first was confirmed using TROPOMI data, focusing on the Permian basin in the USA, suggesting that methane emission were underestimated by a factor of 2 [Zhang et al, 2020]. Similar underestimates in methane emissions from oil and gas production were found over Mexico [Shen et al, 2021].

The improved coverage of TROPOMI compared with GOSAT facilitates studies focusing on specific source regions. However, so far TROPOMI data has only been used in few global inverse modelling studies (Qu et al., 2021). In part because the data product is still being improved on critical issues like systematic errors related to (low) surface albedo, but also because inversion systems need to be adjusted to this new dataset with higher spatial resolution, more data, but also more varying spatial coverage when for example comparing to the proxy GOSAT product (see also suggestions in Qu et al., 2021). This is critical in particular because of the greatly

enhanced coverage of TROPOMI, increasing the constraints of the data on the fluxes but also amplifying the adverse impact of remaining systematic errors in the data.
So far, only a few inverse modelling studies made use of methane retrievals from IASI [e.g. Cressot et al, 2014], owing most likely to the reduced sensitivity of TIR sensors to the planetary boundary layer compared with SWIR instruments.

3.2. Detection and quantification of local sources

3.2.1. High resolution datasets

In 2016, GHGSat.Inc launched the first satellite instrument dedicated to measuring methane at high spatial 'facility' scale (~50 m x 50 m) resolution. GHGSat is a Canadian private company, and this first satellite was a demonstration satellite often referred to as GHGSat-D (or 'Claire'). This first satellite was a successful proof-of-concept illustrating the potential of these high spatial resolution space based measurements in detecting methane from individual coal mine shafts, as well as persistent gas vent from a pipeline near a compressor station (Varon et al., 2019; Varon et al., 2020). The instrument is a Fabry-Perot imaging spectrometer operating around 1.6 um on a small satellite (15 kg) and the detection limit of this first demonstrator was around 1000 kg CH4/hr depending on observation conditions like the surface albedo and the wind-speed. GHGSat is a targeting instrument that can observe one area of 12x12 km2 each orbit, which translates in very limited coverage so it needs to know where to look. Another important drawback is that this data is not publicly available, apart from a small fraction being made available through ESA's Third Party Mission AO.

Another important recent development in this field is the use of global Earth land mapping hyperspectral and band satellite imagers (e.g., PRISMA, Sentinel-2, LandSat, WV-3, EnMap) for the purpose of detecting methane super-emitters at very high spatial resolution (~30 m). Although these instruments were not developed for methane detection, it turns out they can detect large signals from localised methane super-emitters if they have one or two SWIR (Short Wave Infra Red) channels covering methane absorption bands. These satellites do not provide methane data products, so these are currently being developed by the atmospheric satellite remote sensing community itself using the publicly available L1B data.

There are currently two satellites in the public domain that have been shown to provide useful data for this effort, namely the hyperspectral imager PRecursore IperSpettrale della Missione Applicativa (PRISMA) [Cusworth et al., 2021b] and the band imager Sentinel-2 [Varon et al., 2021]. PRISMA is again a targeting satellite, where Sentinel-2 (A&B) has global coverage in 5 days albeit the lower spectral resolution lowers its methane detection limit compared to PRISMA. The highest spatial resolution methane detections from space have been shown for the commercial WorldView-3 (Sanchez-Garcia et al., 2022) satellite with up to 3.7 m resolution. As these land surface imagers have rather low spectral resolution, they are limited to detecting methane point sources in homogeneous surroundings, and, so far, detections have been mostly limited to e.g. desert areas.

3.2.2 Emission detection and quantification

GHGsat detections include emissions from various methane point sources ranging from Oil & Gas facilities, coal mines and landfills (Varon et al., 2019, 2020; Maasakkers et al., 2022).

Emissions detected from PRISMA and Sentinel-2 have been limited to coal mines and Oil & Gas facilities in homogeneous high surface albedo areas such as deserts.

Various techniques can be used to quantify the emissions as measured by GHGsat, PRISMA and Sentinel-2. So far mass balance methods such as Integrated Mass Balance (IME) and Cross sectional Flux methods (CSF) (Varon et al., 2018) have been used.

Although TROPOMI is capable of detecting highly emitting localised point sources of methane (e.g. Pandey et al., 2019; Maasakkers et al., 2021; Sadavarte et al., 2021; Schneising et al., 2020), with its spatial resolution of 5.5 x 7 km2 in nadir it is hard -in most cases- to identify the exact source(s) responsible for the observed localised emissions.

At the same time the high spatial resolution instruments like GHGsat, PRISMA and Sentinel-2 need prior information for their targeted observation or data analysis. By combining the daily global coverage of TROPOMI with these high spatial resolution instruments we have a very powerful tool in space to detect and identify methane super emitters from space. This Tip-and-Cue approach has been applied to detect and identify emissions from landfills from space by combining TROPOMI and GHGSat, revealing huge emissions from unlit flares in West Turkmenistan, and anomalous emissions from Oil & Gas facilities and coal mines (e.g. Maasakkers et al., 2022; Irakulis et al., 2022).

Different techniques can be used to detect localised methane hot spots in TROPOMI data. This can either be conventional analysis to find hot spots in the spatial data, or methods based on Machine learning approaches. The challenge is to do this efficiently and accurately given this huge dataset.

3.3. International organization and programs

3.3.1. Retrieval development and L2 Processing

In Europe retrieval algorithm development for the generation of improved atmospheric methane Level 2 data products has primarily been funded in previous years by ESA via ESA's Climate Change Initiative (CCI) GHG-CCI project, especially during 2010-2018 with focus on SCIAMACHY, MIPAS, GOSAT and IASI. The development of the latter has also been supported by CNES and EUMETSAT. The follow-on project GHG-CCI+ which started in March 2019, performed Research and Development (R&D) needed to generate new ECV carbon dioxide (CO_2) and methane (CH_4) satellite-derived products, which have not been generated in the GHG-CCI pre-cursor project (note that products generated in that pre-cursor project are now generated operationally via C3S). In the past ESA provided via the GHG-CCI+ project funding to further improve European GOSAT XCO2 and XCH4 retrievals. These products are now generated operationally within C3S and this R&D activity is currently not continued in CCI. In the ongoing GHG-CCI+ project focus is on R&D to improve new retrieval algorithms for new sensors such as GOSAT-2 and S5P. For IASI retrievals at high latitudes support is provided through the ESA funded project MethaneCamp.

Development of RAL's IASI scheme has been funded largely through the UK's National Centre for Earth Observation (NCEO) with some initial funding of Version 2 from Eumetsat, and from ESA Methane+ for application to Metop-B and combination with S5P.

Via C3S (reanalysis) and CAMS (NRT) satellite-derived methane data products from GOSAT, GOSAT-2 and the LMD IASI scheme are generated operationally using existing algorithms. C3S funds data processing, documentation, user support etc., but not R&D to significantly further improve the retrieval algorithms.

ESA plans to continue the GHG-CCI+ R&D activities for a period of 2 years (approx. mid 2022 to mid 2024) with some funding to further improve scientific GOSAT-2 and S5P XCH_4 retrievals plus potentially some additional activities focusing on new aspects. Additional R&D support through the Climate Space program is desirable.

As shown in scientific studies (e.g., Lorente et al., 2021; Barré et al., 2021) and by the additional analysis carried out in this project (e.g., Lorente et al., 2022) the operational S5P XCH_4 product suffers from significant biases but also the scientific products – despite being much better – also need to be further improved in order to meet the demanding requirements for the source/sink applications and for combination with TIR. These retrieval algorithm developments for S5P are also relevant for Sentinel 5 (S5) which will continue the S5P XCH_4 time series. S5P is a game changer in atmospheric methane SWIR observations but much more work is needed to fully exploit the information content which S5P (and in the future S5 and CO2M) can deliver. Likewise, further development is needed to improve the accuracy of IASI and combined IASI-S5P retrievals to leverage height-resolved information. This will benefit not only the Metop series but also Metop-SG through to 2040, which will exploit the substantially improved sensitivity to methane of IASI-NG (Crevoisier et al, 2014) alongside S5. It would benefit also co-retrieval of $\delta^{13}C$, whose potential value has yet to be assessed.

Retrieval algorithm improvements followed by re-processing and detailed data analysis needs to continue via regular (e.g., annual or bi-annual) cycles in order to iteratively achieve the best possible data quality of the satellite-derived atmospheric methane data products. Best possible data quality is mandatory in order to use the data for challenging applications related to enhancing our knowledge on the various methane sources and sinks.

3.3.2. Inverse modelling development

Several groups world-wide are actively developing inverse modelling systems exploring the use of satellite retrieved methane [Bergamaschi et al, 2018]. International cooperation was greatly stimulated by the GOSAT Research Announcement (RA) projects. However, the GOSAT-RA and the OCO science team inverse model intercomparisons focused primarily on CO2. Inversion intercomparisons for methane using surface and/or satellite data were coordinated by GCP-CH4 [Saunois et al, 2020]. Regional inverse modelling studies in made use of the ICOS tall tower network in Europe [InGOS, VERIFY]. With support of IG3IS and COCO2 the VERIFY intercomparison for Europe is being extended with the use of TROPOMI data and allows any interested research group to participate. The international TRANSCOM initiative brings the global inverse modelling community together to discuss recent progress in global and regional inverse modelling, including the use of satellites. ESA's recently launched WorldEmission initiative (https://eo4society.esa.int/projects/world-emission/), the Copernicus Emission Monitoring Service, and recently funded H-Europe projects (EYE-CLIMA, PARIS, AVENGERS) are important programs supporting the development of inverse modelling systems in the coming years.
An important objective of recently launched initiatives is to operationalize the scientific tools that have become available in the past years, for near real-time monitoring and evaluation of national emission inventory reports by international organizations and countries. The development of operational systems is important but should remain in balance with the scientific development of inverse modelling methods. In many applications of inverse modelling, improvements in emission estimation accuracy are still needed to reach the level that is required for the operational applications that are being setup.

4. Gap analysis & opportunities

4.1. Application to regional / global sources and sinks

4.1.1. L2 Datasets

In recent years, significant progress has been made in the area of satellite remote sensing of atmospheric methane, at least in terms of enhanced availability of satellite sensors and their exploitation with respect to atmospheric methane and related source/sink information. Nevertheless, more work is needed to address the challenging application of enhancing our knowledge on the various anthropogenic and natural methane sources. This is particularly important because of the expected changes in the coming years. See, for example, the "Global Methane Pledge", signed by more than 100 countries, which aims to reduce methane emissions by 30% by 2030, as agreed upon during the COP26 at Glasgow in 2021.

Initially from 2002 onwards only SCIAMACHY on ENVISAT was available but in 2006 the first IASI instrument was launched on Metop-A and GOSAT in 2009. Currently there are (in addition to GOSAT/GOSAT-2 and the IASI-series) S5P/TROPOMI, AIRS, CrIS, and the GHGSat series operating at high spatial resolution (<50m). Other high-resolution satellite sensors are available (WV3, S-2, S-3, Landsat, PRISMA) that were primarily designed for land surface remote sensing but can detect local methane plumes over homogeneous terrain if leakage rates are high enough (~10 th^{-1}, Varon et al, 2021). High-resolution sensors that provide global coverage may also support the analyses of large-scale methane, although methods that can bring information together representing largely difference scales are not available yet.
More satellites will be launched in the near future, which will deliver high-quality XCH_4 e.g., MethaneSat, Sentinel 5 (S5), Merlin, and IASI-NG on Metop-SG, and the Anthropogenic CO_2 Monitoring (CO2M) mission constellation, the high spatial resolution CarbonMapper constellation, as well as lower-accuracy but high-resolution land imagers (e.g. EnMap, see Cusworth et al., 2019). Because of the extended future capabilities, it is expected that the community will be in a good position also in the future thanks to the planned satellite series and the continuation and further improvements.

The application of satellite products to estimate regional and global sources and sinks requires satellite observations with good spatio-temporal coverage such as SCIAMACHY in the past and S5P now. However, also high spatial resolution is required together with high signal-to-noise ratio to have sufficient sensitivity. In this context, S5P is a significant improvement compared to SCIAMACHY. Nevertheless, higher spatial resolution is required to further enhance sensitivity especially for more localized emission sources and for this aspect CO2M will be an improvement compared to S5P and S5, but more in terms of complementarity as the CO2M swath width will be much smaller compared to S5P and S5. Despite the work that has been done in the past and large datasets that are available, the current observational capabilities are not yet sufficient to address important "large scale aspects" such as identification of the reasons for the high methane growth rate observed since 2020 (e.g., Copernicus Press Release). This has to do, at least in part, with a non-optimal analysis of existing satellite data (starting from the quality of Level 2 products). Important improvements have been achieved in the Methane+ project to bring the S5p retrieval quality to the level needed to take advantage of the improved spatial coverage that the instrument provides compared with GOSAT.

With substantially higher spectral resolution and photometric signal to noise, IASI-NG will have better vertical resolution than IASI. In combination with precisely co-incident

S5 measurements, Metop-SG therefore provides an excellent opportunity to leverage methane information in the lower troposphere. CO2M will also include a Multi Angle Polarimeter (MAP) instrument which allows for much better aerosol scattering correction and thereby more accurate and less systematically biased CH4 (and CO2) product(s). The spaceborne Lidar Merlin has intrinsic advantages in controlling the light path that is sampled, offering so far unexplored opportunities for improving retrieval accuracy. The use of a laser also offers the opportunity to extend the coverage of SWIR retrievals to latitudes and seasons that cannot be covered by passive instrumentation for lack of solar illumination and the limited surface reflection of snow covered regions in the SWIR. All these methane observing satellite sensors have different advantages and disadvantages, as each satellite represents a different choice in terms of coverage, resolution, revisit time, precision, and accuracy. No single satellite is the optimum in terms of all these critical parameters for all relevant applications.

There is a need for very detailed methane emission information and this requires to use as many information sources as possible including also future non-European satellites such as GOSAT-2, GOSAT-3 and the planned US and Chinese satellites possibly also combined with high spatial resolution imagers (despite their typically poor spatio-temporal coverage) [Crisp et al, 2018].

This shows that potentially a lot of detailed information on the various methane sources will be available in the future. But there is a large step / gap between a potential and its realization.

In order to obtain reliable emission information by exploiting the data these satellites will deliver it is important to carefully address all three major processing steps:

1. Level 0 to 1 processing: Needed to convert the raw data to accurately calibrated geolocated radiances (= Level 1 product)
2. Level 1 to 2 processing: Interpretation of the radiances in terms of atmospheric methane information (= Level 2 product) using appropriate retrieval methods
3. Level 2 to Level 4 processing: Interpretation of the retrieved atmospheric methane products in terms of methane fluxes / emissions

The results of the “interpretation” steps 2 and 3 depend on many choices to be made when implementing a corresponding algorithm and the result, i.e., the resulting data product, depends on these choices. And because even small differences in the atmospheric concentration often results in large differences of the inferred emissions, even small differences matter. Therefore, there is not a single method that will provide reliable results for all situations and even reliable error analysis is hardly possible because of unknown systematic errors and unknown error correlations.

To address this, it is recommended to use an ensemble approach and to take the results from this ensemble analysis into account when reporting emissions.

Using an ensemble is considered mandatory - especially for politically sensitive information such as methane emission information - as it is hardly possible to simply use a single Level 2 product and a single Level 2 to Level 4 algorithm to get reliable emission information.

It is important to establish an ensemble analysis for the Level 1 to 2 processing using more than one retrieval method and to combine the resulting Level 2 products with different Level 2 to Level 4 inversion methods to obtain robust emission estimates per sensor. The final step comprises comparisons of the results from the different sensors per emission target (i.e., for each region of interest such as an oil and gas field, an industrial area, an entire country, etc.).
Currently only very first steps in this direction have been made, e.g., as part of the ensemble activities of the past GHG-CCI project (2010-2018) and via the comparisons of the operational and scientific S5P XCH_4 products in this Methane+ project (see Lorente et al., 2022).

A general need for Level1 to Level2 processing concerns the improvement of the spectroscopy of methane on which relies radiative transfer simulations and retrieval procedures. Improvement in the knowledge of spectroscopic parameters, line shapes (more advanced than the classic Voight shape) and large-scale feature (continua) requires ad-hoc spectroscopic chamber experiments, line models, enhanced spectroscopic databases (such as GEISA or HITRAN) and radiative transfer models able to use them.

It is also essential to be able to evaluate the quality of the retrievals and detect, or even correct, features stemming from methodological choices or unknown errors. Support for observation networks such as TCCON, COCOON or vertical profile observations (aircraft, AirCore) is mandatory.

Much more needs to be done in these directions in order to meet the demanding requirements related to methane emission monitoring as required by the Paris Agreement and its follow on agreements. This refers to emission information on all scales including more local sources as discussed in more detail below (see Sect. 4.2).

4.1.2. Data use

The flux inversion method and the atmospheric transport model it uses have been developed originally to exploit the information delivered by highly accurate surface measurements from sparse sampling networks. Since satellite measurements became available, the same techniques have been applied to large but less accurate datasets. This change has important implications for the design of models and optimization methods. The methods have evolved in response to this change, but important hurdles remain to be taken.

The lifetime of methane is long compared with the time scale of its transport in the atmosphere. As a consequence, the observed variability in the methane mixing ratio, which inverse models make use of to constrain surface emissions, is determined largely by the complex dynamical flow and mixing in the atmosphere acting on a large range of spatiotemporal scales. These processes disperse mixing ratio gradients arising not only from recent local emissions, but also from older emissions advected from elsewhere, all adding up to the complex varying signal that is observed.

Inversions most effectively constrain sources or sinks of methane that cause prominent and systematic features in the observed mixing ratio pattern, that are observable regardless of the actual weather conditions. For this reason, inversions using data from surface networks are effective in quantifying year-to-year changes in the source/sink balance, changes in the north to south mixing ratio gradient or the mean seasonal variation in each hemisphere. Since these observed mixing ratios variations are caused by large-scale variations in sources and sinks, the spatio-temporal resolution of flux inversions is generally low.

Note that large-scale mixing ratio gradients constrain the source/sink balance rather than the contributions of sources and sinks separately. Emission estimates can be obtained given an assumption on the sink. However, variations in the sink strength are very likely to be important also but difficult to constrain independently using the available data.

Satellite measurements can improve inverse modelling estimates by providing coverage in regions that are poorly observed by the surface network. For methane this has been most important over tropical land, with large and highly uncertain emissions primarily from tropical wetlands. Satellites could play a similar gap filling role at high northern latitudes, however, the quality and year-around availability of data is more difficult there.

The difficulty of estimating methane sources and sinks independently plays a role in the tropics as well as the high northern latitudes. To address this challenge, the strategy of the Methane+ project has been to collect information on the 3D structure of methane, rather than 2D total columns, by combining measurements from TIR and SWIR sensors.

At the regional scale, satellites are important for major source regions that are not well observed from the ground. Inversions using surface measurements show large emissions adjustments over China and India that become smaller using satellite data. The surface network may be too sparse for the inversion to arrive at the correct spatial allocation of emissions (possibly in combination with transport model errors). Satellites, however, show clear enhancements in total column methane over South East Asia delivering the missing spatial information.

To move beyond the main large-scale mixing ratio gradients and the most prominent signals of regional emissions is a challenge. If the goal is to support the monitoring of national greenhouse gas emissions, then models and measurements should allow a correct attribution of emission signals that are small compared with the variability due to atmospheric dynamics (‘methane weather’). The improved measurement coverage of TROPOMI is essential to make this work. However, subtle albedo dependent biases in the data may quickly dominate the emission signal that the inversion should be able to rely on to deliver useful estimates. If data accuracy and coverage do not improve in the right balance, then inversion results will deteriorate because of a strengthened constraint of wrong information on the inversion-optimized emissions. Here the need for high accuracy poses demanding requirements on the data as well as atmospheric transport models.

To make use of the regional scale variability that is resolved by high-resolution sensors the resolution of the transport model will have to increase also. Simulations would preferably be performed at resolutions that are higher than the data that are used. To ease the computational requirements, this calls for the use of limited domain meso scale models. Meanwhile, several of these systems have been developed, e.g. within the framework of the VERIFY, CHE, and COCO2 projects. However, their application to satellite data requires further investigation. The consistent treatment of lateral boundaries is known to be important in the application of limited-domain inverse models to data from regional surface networks. For satellite-observed total column data, lateral boundary conditions are expected to be even more important.

4.2. Application to local sources

4.2.1. L2 Datasets

Upcoming missions:

Based on the experience with its demonstrator satellite, GHGSat.inc improved the performance of their instrument and launched GHGSat-C1 (‘Iris’) and GHGSat-C2 (‘Hugo’) in 2020 and 2021 respectively. Meanwhile, the company launched three more satellites in 2022 (C3 - C5), followed by what should become a constellation of ten satellites in 2023. The detection limit of Iris and Hugo is ~ 100 kg CH4/hr, with a spatial resolution of 25x25 m^2. But as mentioned, GHGSat is a commercial company and the data is not publicly available.

There is an obvious need for this high spatial ‘facility’ level resolution data of methane in the public domain. As such there are two missions being prepared in the US, CarbonMapper and MethaneSat.

CarbonMapper.Inc is a US non-profit entity that will launch small satellites to measure super emitters of CH4 (and CO2) at high spatial resolution (~30 m) with a predicted 50-150 kg CH4/hr detection limit. It will mostly use targeting observation mode, but will have much larger coverage compared to GHGsat satellites. Moreover, the data will be made publicly available. The CarbonMapper-team have extensive experience detecting methane super emitters through their airborne campaigns using AVIRIS-NG (e.g. Duren et al., 2019; Cusworth et al., 2021a). First launch of satellites is planned for Q3 2023, followed by others to form a large constellation. CarbonMapper -if successful- will be a giant leap forward wrt detecting super emitters globally at ‘facility’ scale resolution.

MethaneSat is a philantropic initiave led by EDF and aims at measuring CH4 emissions at spatial resolution of ~130-400 m^2 (swath 260 km) aiming in particular at Oil&Gas fields through target observations. So not so much aiming for the localised super emitters but more at estimating emissions from entire source-fields. Data will be made publicly available, and expected launch is in 2023.

In Europe we are preparing for the CO2M mission (2025) focusing on CO_2 but also measuring methane at intermediate spatial resolution scales (2x2km^2).

Given the importance of reducing methane emissions on the short term as also expressed at COP26 through the methane pledge, more space-based high resolution ‘facility’-scale mapping capacity -e.g. through a European space program contribution- would be most useful. Further improved detection sensitivity could further push the detection towards smaller (and thus more) sources.

In addition to the methane dedicated missions mentioned above, also new hyperspectral imagers such as EnMap, CHIME, S2 NG will be launched but these should be considered a nice bonus to detect the largest super emitters over homogeneous terrain on top of the dedicated missions optimised for measuring methane.

Remaining gaps for measuring methane point sources also include methane emissions from off-shore. Because of low surface reflectivity over water CH4 can only be measured SWIR in sun glint geometry which significantly limits the opportunities. TIR observations are made over ocean but have yet to be assessed in this regard.

4.2.2. Data use

To exploit the high spatial resolution methane observations there are still quite some challenges to deal with. Automated detection methods are being developed, accurate and fast emission quantification methods are needed to adequately deal with big data streams. Machine learning is expected to significantly contribute here. Better bottom-up information on the location of large methane point sources would help to efficiently detect possible super emitters. Also, development of methane data products from the land imagers (band and hyperspectral imagers) would be useful.
At present the detection limit of high-resolution instruments is at a level where each detected leak is relevant and should urgently be fixed regardless of the accuracy at which emissions can be estimated. With improved future instrumentation, detecting many more smaller leaks, the emission quantification accuracy will become more important. Currently, we are lacking a reference dataset of accurately known and satellite detectable emissions needed to evaluate the methods that are being developed. More research is needed to investigate the potential impact of simplifying

assumptions that are being made, such as the use of a priori vertical profiles in the retrieval that represent background conditions, and the performance of high-resolution atmospheric transport models. The development of high-resolution remote sensing and the translation of satellite observed plumes into emissions would benefit from in situ measurements in emission plumes extended from the surface to the top of the planetary boundary layer.

5. Recommendations

5.1. Use of existing and upcoming missions

The main recommendations for activities on the short-term using existing data or preparing for the use of new data based on section 4 are:

- With TROPOMI an important step has been achieved in improving the SWIR XCH4 measurement coverage. To make use of this capability to extend the quantification of methane emissions an additional step in retrieval accuracy is needed. In particular, the remaining dependencies on surface albedo need to be minimized.

- More realistic retrieval uncertainties are needed. To deal with the difficulty to quantify spatiotemporal uncertainty correlations, it is strongly recommended to use ensembles of retrievals methods developed by different research teams where available.

- Accuracy of the RAL TIR scheme was improved substantially at low latitudes in the Methane+ project, however, further work is needed to reduce positive bias at high latitudes, where surface temperature low, and other anomalies.

- The TIR and joint SWIR-TIR retrieval methods need to be developed further to improve their accuracy and vertical resolution, including use of new spectroscopic data when available and evaluation with ground-based measurements of the methane vertical profile as well as column average, and in preparation for MetOp-SG S5/IASI-NG.

- The optimization of CH_4 sinks developed in Methane+ should be improved further and tested using independent data.

- More effort is needed on global (and regional) inversion modelling to take optimal advantage of the new SWIR, TIR and joint SWIR-TIR datasets that have been developed in Methane+. Global inverse modeling frameworks need to be adjusted to deal with the higher spatial resolution, larger data volumes, and different sampling characteristics of the TROPOMI XCH4 and IASI data products.

- Further research is needed to assess the benefits of using data from joint SWIR-TIR retrievals in comparison to joint use of data from the SWIR and TIR retrievals in inverse modelling.

- Further research is needed to identify the cause of the biases that are currently accounted for in an ad-hoc manner in inversions using SWIR and TIR satellite data. The evidence collected so far suggests that it is a model problem, originating in the stratosphere. A dedicated research effort is needed focused on methane in the stratosphere, in cooperation with experts in stratospheric chemistry and dynamics.

- Further explore the use of existing satellites for detecting methane emissions from single facilities.

- Develop automated methods for efficient processing of large data archives on local methane emissions.

5.2. Requirements on future missions

Priorities for the development of future missions based on section 4 are as follows:

- Improved year around measurement coverage, with sensitivity to the planetary boundary layer, is needed at high northern latitudes, to support the monitoring of methane emissions from wetlands and thawing permafrost and their response to climate warming.

- The detection limit of high-resolution methane sensors to natural gas leaks has to be improved to be able to detect not only the largest emitters, but the leaks responsible for the main fraction of global emissions from leaks in the fossil fuel mining industry (on and off-shore), as well as the main local sources in other sectors (e.g. waste management and agriculture).

- Support the ground-based validation network to help improve the accuracy of future satellite missions.

- Support the improvement of spectroscopy of methane and related radiative transfer modeling.

- Europe does not have a high (~20-200 m) spatial resolution methane satellite planned. Currently there is only a commercial satellite-constellation (GHGSat) in space that measures methane at facility-scale resolution. CarbonMapper is a US-initiative to provide similar measurements for both CH_4 and CO_2. Europe does not have anything planned yet with similar capabilities.

- Support the development of atmospheric transport models operating at global, regional and local scales and inverse modelling methods that are used to translate satellite measurements into methane emissions and to disaggregate into different sectors.

6. References

Baray, S., Jacob, D. J., Maasakkers, J. D., Sheng, J.-X., Sulprizio, M. P., Jones, D. B. A., Bloom, A. A., and McLaren, R.: Estimating 2010–2015 anthropogenic and natural methane emissions in Canada using ECCC surface and GOSAT satellite observations, Atmos. Chem. Phys., 21, 18101–18121, https://doi.org/10.5194/acp-21-18101-2021, 2021.

Barré, J., Aben, I., Agustí-Panareda, A., Balsamo, G., Bousserez, N., Dueben, P., Engelen, R., Inness, A., Lorente, A., McNorton, J., Peuch, V.-H., Radnoti, G., and Ribas, R.: Systematic detection of local CH_4 anomalies by combining satellite measurements with high-resolution forecasts, Atmos. Chem. Phys., 21, 5117–5136, https://doi.org/10.5194/acp-21-5117-2021, 2021.

Bergamaschi, P., et al. (2009), Inverse modeling of global and regional CH4 emissions using SCIAMACHY satellite retrievals, J. Geophys. Res.,114, D22301, doi:10.1029/2009JD012287.

Bergamaschi, P., A. Danila, R. F. Weiss, P. Ciais, R. L. Thompson, D. Brunner, I. Levin, Y. Meijer, F. Chevallier, G. Janssens-Maenhout, H. Bovensmann, D. Crisp, S. Basu, E. Dlugokencky, R. Engelen, C. Gerbig, D. Günther, S. Hammer, S. Henne, S. Houweling, U. Karstens, E. Kort, M. Maione, A. J. Manning, J. Miller, S. Montzka, S. Pandey, W. Peters, P. Peylin, B. Pinty, M. Ramonet, S. Reimann, T. Röckmann, M. Schmidt, M. Strogies, J. Sussams, O. Tarasova, J. van Aardenne, A. T. Vermeulen, F. Vogel, Atmospheric monitoring and inverse modelling for verification of greenhouse gas inventories, EUR 29276 EN, Publications Office of the European Union, Luxembourg, 2018, ISBN 978-92-79-88938-7, doi:10.2760/759928, JRC111789.

Bruhwiler, L., Parmentier, FJ.W., Crill, P. *et al.* The Arctic Carbon Cycle and Its Response to Changing Climate. *Curr Clim Change Rep* **7,** 14–34 (2021). https://doi-org.vu-nl.idm.oclc.org/10.1007/s40641-020-00169-5.

Crevoisier, C., Nobileau, D., Armante, R., et al., The 2007–2011 evolution of tropical methane in the mid-troposphere as seen from space by MetOp-A/IASI, Atmos. Chem. Phys., 13, 4279-4289, 2013.

Crevoisier C., Clerbaux C., Guidard V., Phulpin T., Armante R., Barret B., Camy-Peyret C., Chaboureau J.-P., Coheur P.-F., Crépeau L., Dufour G., Labonnote L., Lavanant L., Hadji-Lazaro J., Herbin H., Jacquinet-Husson N., Payan S., Péquignot E., Pierangelo C., Sellitto P., and Stubenrauch C., Towards IASI-New Generation (IASI-NG): impact of improved spectral resolution and radiometric noise on the retrieval of thermodynamic, chemistry and climate variables, *Atmos. Meas. Tech., 7, 4367-4385*, 2014.

Cressot, C., Chevallier, F., Bousquet, P., Crevoisier, C., Dlugokencky, E. J., Fortems-Cheiney, A., Frankenberg, C., Parker, R., Pison, I., Scheepmaker, R. A., Montzka, S. A., Krummel, P. B., Steele, L. P., and Langenfelds, R. L.: On the consistency between global and regional methane emissions inferred from SCIAMACHY, TANSO-FTS, IASI and surface measurements, Atmos. Chem. Phys., 14, 577–592, https://doi.org/10.5194/acp-14-577-2014, 2014.

Crippa, M., Guizzardi, D., Schaaf, E., Solazzo, E., Muntean, M., Monforti-Ferrario, F., Olivier, J.G.J., Vignati, E.: Fossil CO2 and GHG emissions of all world countries - 2021 Report, in prep.

David Crisp, Yasjka Meijer, Rosemary Munro, Kevin Bowman, Abhishek Chatterjee, David Baker, Frederic Chevallier, Ray Nassar, Paul I. Palmer, Anna Agusti-Panareda, Jay Al-Saadi, Yotam Ariel, Sourish Basu, Peter Bergamaschi, Hartmut Boesch, Philippe Bousquet, Heinrich Bovensmann, François-Marie Bréon, Dominik Brunner, Michael Buchwitz, Francois Buisson, John P. Burrows, Andre Butz, Philippe Ciais, Cathy Clerbaux, Paul Counet, Cyril Crevoisier, Sean Crowell, Philip L. DeCola, Carol Deniel, Mark Dowell, Richard Eckman, David Edwards, Gerhard Ehret, Annmarie Eldering, Richard Engelen, Brendan Fisher, Stephane Germain, Janne Hakkarainen, Ernest Hilsenrath, Kenneth Holmlund, Sander Houweling, Haili Hu, Daniel Jacob, Greet Janssens-Maenhout, Dylan Jones, Denis Jouglet, Fumie Kataoka, Matthäus Kiel, Susan S. Kulawik, Akihiko Kuze, Richard L. Lachance, Ruediger Lang, Jochen Landgraf , Junjie Liu, Yi Liu, Shamil Maksyutov, Tsuneo Matsunaga, Jason McKeever, Berrien Moore, Masakatsu Nakajima, Vijay Natraj, Robert R. Nelson, Yosuke Niwa, Tomohiro Oda, Christopher W. O'Dell, Leslie Ott, Prabir Patra, Steven Pawson, Vivienne Payne, Bernard Pinty, Saroja M. Polavarapu, Christian Retscher, Robert Rosenberg, Andrew Schuh, Florian M. Schwandner, Kei Shiomi, Wenying Su, Johanna Tamminen, Thomas E. Taylor, Pepijn Veefkind, Ben Veihelmann, Stephen Wofsy, John Worden, Debra Wunch, Dongxu Yang, Peng Zhang, Claus Zehner. A constellation architecture for monitoring carbon dioxide and methane from space. CEOS Atmospheric Composition Virtual Constellation Greenhouse Gas Team Rep., 173 pp., 2018, http://ceos.org/document_management/Virtual_Constella tions/ ACC/Documents/CEOS_AC-VC_GHG_White_Paper_Version_1_20181009.pdf

Cusworth, D. H., Jacob, D. J., Varon, D. J., Chan Miller, C., Liu, X., Chance, K., Thorpe, A. K., Duren, R. M., Miller, C. E., Thompson, D. R., Frankenberg, C., Guanter, L., and Randles, C. A.: Potential of next-generation imaging spectrometers to detect and quantify methane point sources from space, Atmos. Meas. Tech., 12, 5655–5668, https://doi.org/10.5194/amt-12-5655-2019, 2019.

Cusworth, Daniel H., Riley M. Duren, Andrew K. Thorpe, Winston Olson-Duvall, Joseph Heckler, John W. Chapman, Michael L. Eastwood, Mark C. Helmlinger, Robert O. Green, Gregory P. Asner, Philip E. Dennison, and Charles E. Miller (2021), Intermittency of Large Methane Emitters in the Permian Basin, Environ. Sci. Technol. Lett., 8, 567−573, doi: 10.1021/acs.estlett.1c00173.

Cusworth, D. H., Duren, R. M., Thorpe, A. K., Pandey, S., Maasakkers, J. D., Aben, I., et al. (2021). Multisatellite imaging of a gas well blowout enables quantification of total methane emissions. *Geophysical Research Letters*, *48*, e2020GL090864. https://doi.org/10.1029/2020GL090864.

Duren, R.M., Thorpe, A.K., Foster, K.T. *et al.* California's methane super-emitters. *Nature,* **575,** 180–184 (2019). https://doi.org/10.1038/s41586-019-1720-3.

GCOS-154: Global Climate Observing System (GCOS), SYSTEMATIC OBSERVATION REQUIREMENTS FOR SATELLITE-BASED PRODUCTS FOR CLIMATE, Supplemental details to the satellite-based component of the "Implementation Plan for the Global Observing System for Climate in Support of the UNFCCC (2010 update)", Prepared by World Meteorological Organization (WMO), Intergovernmental Oceanographic Commission, United Nations Environment Programme (UNEP), International Council for Science, Doc.: GCOS 154, link: http://cci.esa.int/sites/default/files/gcos-154.pdf, 2011.

GCOS-195: Status of the Global Observing System for Climate. GCOS-195. Link: https://library.wmo.int/doc_num.php?explnum_id=7213, 2015.

GCOS-200: The Global Observing System for Climate: Implementation Needs, GCOS 2016 Implementation Plan, World Meteorological Organization (WMO), GCOS-200 (GOOS-214), pp. 325, link: https://library.wmo.int/opac/doc_num.php?explnum_id=3417, 2016.

Itziar Irakulis-Loitxate, Luis Guanter, Joannes D. Maasakkers, Daniel Zavala-Araiza, and Ilse Aben (2022), Satellites Detect Abatable Super-Emissions in One of the World's Largest Methane Hotspot Regions, Environ. Sci. Technol. 2022, 56, 4, 2143–2152, https://doi.org/10.1021/acs.est.1c04873.

Jervis, D., McKeever, J., Durak, B. O. A., Sloan, J. J., Gains, D., Varon, D. J., Ramier, A., Strupler, M., and Tarrant, E.: The GHGSat-D imaging spectrometer, Atmos. Meas. Tech., 14, 2127–2140, https://doi.org/10.5194/amt-14-2127-2021, 2021.

Houweling, S., Bergamaschi, P., Chevallier, F., Heimann, M., Kaminski, T., Krol, M., Michalak, A. M., and Patra, P.: Global inverse modeling of CH4 sources and sinks: an overview of methods, Atmos. Chem. Phys., 17, 235–256, doi:10.5194/acp-17- 235-2017, 2017.

Henne, S., Brunner, D., Oney, B., Leuenberger, M., Eugster, W., Bamberger, I., Meinhardt, F., Steinbacher, M., and Emmenegger, L.: Validation of the Swiss methane emission inventory by atmospheric observations and inverse modelling, Atmos. Chem. Phys., 16, 3683–3710, https://doi.org/10.5194/acp-16-3683-2016, 2016.

Hu, H., Hasekamp, O., Butz, A., Galli, A., Landgraf, J., Aan de Brugh, J., Borsdorff, T., Scheepmaker, R., and Aben, I.: The operational methane retrieval algorithm for TROPOMI, Atmos. Meas. Tech., 9, 5423–5440, https://doi.org/10.5194/amt-9-5423-2016, 2016.

Hu, H., Landgraf, J., Detmers, R., Borsdorff, T., Aan de Brugh, J., Aben, I., Butz, A., and Hasekamp, O.: Toward Global Mapping of Methane With TROPOMI: First Results and Intersatellite Comparison to GOSAT, Geophys. Res. Lett., 45, 3682–3689, https://doi.org/10.1002/2018GL077259, 2018.

Jacob, D. J., Turner, A. J., Maasakkers, J. D., Sheng, J., Sun, K., Liu, X., Chance, K., Aben, I., McKeever, J., and Frankenberg, C.: Satellite observations of atmospheric methane and their value for quantifying methane emissions, Atmos. Chem. Phys., 16, 14371–14396, https://doi.org/10.5194/acp-16-14371-2016, 2016.

Lan, X., Tans, P., Sweeney, C., Andrews, A., Dlugokencky, E., Schwietzke, S., et al. (2019). Long-term measurements show little evidence for large increases in total U.S. methane emissions over the past decade. *Geophysical Research Letters*, *46*, 4991–4999. https://doi.org/10.1029/ 2018GL081731.

Laughner, J. L., Neu, J. L., Schimel, D., Wennberg, P. O., Barsanti, K., Bowman, K. W., Chatterjee, A., Croes, B. E., Fitzmaurice, H. L., Henze, D. K., Kim, J., Kort, E. A., Liu, Z., Miyazaki, K., Turner, A. J., Anenberg, S., Avise, J., Cao, H., Crisp, D., … Zeng, Z. C. (2021). Societal shifts due to COVID-19 reveal large-scale complexities and feedbacks between atmospheric chemistry and climate change. Proceedings of the National Academy of Sciences of the United States of America, 118(46), https://doi.org/10.1073/pnas.2109481118.

Lauvaux, T., Giron, C., Mazzolini, M., D'Aspremont, A., Duren, R., Cusworth, D., Shindell, D., & Ciais, P. (2022). Global assessment of oil and gas methane ultra-emitters. *Science*, *375*(6580), 557–561. https://doi.org/10.1126/science.abj4351.

Locatelli, R., Bousquet, P., Saunois, M., Chevallier, F., and Cressot, C.: Sensitivity of the recent methane budget to LMDz sub-grid-scale physical parameterizations, Atmos. Chem. Phys., 15, 9765–9780, https://doi.org/10.5194/acp-15-9765-2015, 2015.

Lorente, A., Borsdorff, T., Butz, A., Hasekamp, O., aan de Brugh, J., Schneider, A., Wu, L., Hase, F., Kivi, R., Wunch, D., Pollard, D. F., Shiomi, K., Deutscher, N. M., Velazco, V. A., Roehl, C. M., Wennberg, P. O., Warneke, T., and Landgraf, J.: Methane retrieved from TROPOMI: improvement of the data product and validation of the first 2 years of measurements, Atmos. Meas. Tech., 14, 665–684, https://doi.org/10.5194/amt-14-665-2021, 2021.

Lorente, A., Buchwitz, M., Borsdorff, T., and Schneising, O.: Validation Report – SWIR, Technical Report ESA Methane+ project, Doc. ID: TN-D3a-CH4PLUS, Version 2.0 (in preparation), Draft 28-Feb-2022, 2022.

Lu, X., Jacob, D. J., Wang, H., Maasakkers, J. D., Zhang, Y., Scarpelli, T. R., Shen, L., Qu, Z., Sulprizio, M. P., Nesser, H., Bloom, A. A., Ma, S., Worden, J. R., Fan, S., Parker, R. J., Boesch, H., Gautam, R., Gordon, D., Moran, M. D., Reuland, F., Villasana, C. A. O., and Andrews, A.: Methane emissions in the United States, Canada, and Mexico: evaluation of national methane emission inventories and 2010–2017 sectoral trends by inverse analysis of in situ (GLOBALVIEWplus CH_4 ObsPack) and satellite (GOSAT) atmospheric observations, Atmos. Chem. Phys., 22, 395–418, https://doi.org/10.5194/acp-22-395-2022, 2022.

Lunt, M. F., Palmer, P. I., Feng, L., Taylor, C. M., Boesch, H., and Parker, R. J.: An increase in methane emissions from tropical Africa between 2010 and 2016 inferred from satellite data, Atmos. Chem. Phys., 19, 14721–14740, https://doi.org/10.5194/acp-19-14721-2019, 2019.

Lunt, M. F., Manning, A. J., Allen, G., Arnold, T., Bauguitte, S. J.-B., Boesch, H., Ganesan, A. L., Grant, A., Helfter, C., Nemitz, E., O'Doherty, S. J., Palmer, P. I., Pitt, J. R., Rennick, C., Say, D., Stanley, K. M., Stavert, A. R., Young, D., and Rigby, M.: Atmospheric observations consistent with reported decline in the UK's methane emissions (2013–2020), Atmos. Chem. Phys., 21, 16257–16276, https://doi.org/10.5194/acp-21-16257-2021, 2021.

Maasakkers, J. D., Omara, M., Gautam, R., Lorente, A., Pandey, S., Tol, P., Borsdorff, T., Houweling, S., & Aben, I. (2022). Reconstructing and quantifying methane emissions from the full duration of a 38-day natural gas well blowout using space-based observations. Remote Sensing of Environment, 270, 112755. https://doi.org/10.1016/j.rse.2021.112755.

Meirink, J. F., et al. (2008), Four-dimensional variational data assimilation for inverse modeling of atmospheric methane emissions: Analysis of SCIAMACHY observations, J. Geophys. Res.,113, D17301, doi:10.1029/2007JD009740.

Monteil, G., S. Houweling, A. Butz, S. Guerlet, D. Schepers, O. Hasekamp, C. Frankenberg, R. Scheepmaker, I. Aben, and T. Röckmann (2013), Comparison of CH4 inversions based on 15 months of GOSAT and SCIAMACHY observations, J.Geophys. Res. Atmos.,118, 11,807–11,823, doi:10.1002/2013JD019760.

Noël et al., Retrieval of greenhouse gases from GOSAT and greenhouse gases and carbon monoxide from GOSAT-2 using the FOCAL algorithm, submitted, 2022.

Parker, R. J., Webb, A., Boesch, H., Somkuti, P., Barrio Guillo, R., Di Noia, A., Kalaitzi, N., Anand, J. S., Bergamaschi, P., Chevallier, F., Palmer, P. I., Feng, L., Deutscher, N. M., Feist, D. G., Griffith, D. W. T., Hase, F., Kivi, R., Morino, I., Notholt, J., Oh, Y.-S., Ohyama, H., Petri, C., Pollard, D. F., Roehl, C., Sha, M. K., Shiomi, K., Strong, K., Sussmann, R., Té, Y., Velazco, V. A., Warneke, T., Wennberg, P. O., and Wunch, D.: A decade of GOSAT Proxy satellite CH_4 observations, Earth Syst. Sci. Data, 12, 3383–3412, https://doi.org/10.5194/essd-12-3383-2020, 2020.

Pandey, S., Houweling, S., Krol, M. *et al.* Enhanced methane emissions from tropical wetlands during the 2011 La Niña. *Sci Rep* **7,** 45759 (2017), https://doi.org/10.1038/srep45759.

Qu, Z., Jacob, D. J., Shen, L., Lu, X., Zhang, Y., Scarpelli, T. R., Nesser, H., Sulprizio, M. P., Maasakkers, J. D., Bloom, A. A., Worden, J. R., Parker, R. J., and Delgado, A. L.: Global distribution of methane emissions: a comparative inverse analysis of observations from the TROPOMI and GOSAT satellite instruments, Atmos. Chem. Phys., 21, 14159–14175, https://doi.org/10.5194/acp-21-14159-2021, 2021.

Reuter, M., Buchwitz, M., Schneising, O., Noel, S., Bovensmann, H., Burrows, J. P., Boesch, H., Di Noia, A., Anand, J., Parker, R. J., Somkuti, P., Wu, L., Hasekamp, O. P., Aben, I., Kuze, A., Suto, H., Shiomi, K., Yoshida, Y., Morino, I., Crisp, D., O'Dell, C. W., Notholt, J., Petri, C., Warneke, T., Velazco, V. A., Deutscher, N. M., Griffith, D. W. T., Kivi, R., Pollard, D. F., Hase, F., Sussmann, R., Te, Y. V., Strong, K., Roche, S., Sha, M. K., De Maziere, M., Feist, D. G., Iraci, L. T., Roehl, C. M., Retscher, C., and Schepers, D.: Ensemble-based satellite-derived carbon dioxide and methane column-averaged dry-air mole fraction data sets (2003-2018) for carbon and climate applications, Atmos. Meas. Tech., 13, 789-819, https://doi.org/10.5194/amt-13-789-2020, 2020.

Sadavarte, Pandey, Maasakkers, Lorente, Borsdorff, vd Gon, Houweling, Aben, (2021), Methane emissions from super-emitting coal mines in Australia quantified using TROPOMI observations, Environm. Science & Technology, https://pubs.acs.org/doi/10.1021/acs.est.1c03976.

Sánchez-García, E., Gorroño, J., Irakulis-Loitxate, I., Varon, D. J., and Guanter, L.: Mapping methane plumes at very high spatial resolution with the WorldView-3 satellite, Atmos. Meas. Tech., 15, 1657–1674, https://doi.org/10.5194/amt-15-1657-2022, 2022.

Saunois, M., R. Stavert, A., Poulter, B., Bousquet, P., G. Canadell, J., B. Jackson, R., A. Raymond, P., J. Dlugokencky, E., Houweling, S., K. Patra, P., Ciais, P., K. Arora, V., Bastviken, D., Bergamaschi, P., R. Blake, D., Brailsford, G., Bruhwiler, L., M. Carlson, K., Carrol, M., … Zhuang, Q. (2020). The global methane budget 2000-2017. Earth System Science Data, 12(3), 1561–1623. https://doi.org/10.5194/essd-12-1561-2020.

Scarpelli, T. R., Jacob, D. J., Grossman, S., Lu, X., Qu, Z., Sulprizio, M. P., Zhang, Y., Reuland, F., Gordon, D., and Worden, J. R.: Updated Global Fuel Exploitation Inventory (GFEI) for methane emissions from the oil, gas, and coal sectors: evaluation with inversions of atmospheric methane observations, Atmos. Chem. Phys., 22, 3235–3249, https://doi.org/10.5194/acp-22-3235-2022, 2022.

Shen, L., D. Zavala-Araiza, R. Gautam, M. Omara, T. Scarpelli, J. Sheng, M. P. Sulprizio, J. Zhuang, Y. Zhang, Z. Qu, X. Lu, S. P. Hamburg, and D. Jacob (2021), Unravelling a large methane emission discrepancy in Mexico using satellite observations, Remote Sensing of Environment, 260, 112461, doi:10.1016/j.rse.2021.112461.

Schneider, M., Ertl, B., Diekmann. C.J., Khosrawi, F., Röhling, A.M., Hase, F., Dubravica, D., García, O.E., Sepúlveda, E., Borsdorff, T., Landgraf, J., Lorente, A., Chen, H., Kivi, R., Laemmel, T., Ramonet, M., Crevoisier, D., Pernin, J., Steinbacher, M., Meinhardt, F., Deutscher, N.M., Griffith, D.W.T., Velazco, V.A., and Pollard, D.F: Synergetic use of IASI and TROPOMI space borne sensors for generating a tropospheric methane profile product, https://doi.org/10.5194/amt-2021-31

Schneising, O., Buchwitz, M., Reuter, M., Bovensmann, H., Burrows, J. P., Borsdorff, T., Deutscher, N. M., Feist, D. G., Griffith, D. W. T., Hase, F., Hermans, C., Iraci, L. T., Kivi, R., Landgraf, J., Morino, I., Notholt, J., Petri, C., Pollard, D. F., Roche, S., Shiomi, K., Strong, K., Sussmann, R., Velazco, V. A., Warneke, T., and Wunch, D.: A scientific algorithm to simultaneously retrieve carbon monoxide and methane from TROPOMI onboard Sentinel-5 Precursor, Atmos. Meas. Tech., 12, 6771-6802, https://doi.org/10.5194/amt-12-6771-2019, https://doi.org/10.5194/amt-12-6771-2019, 2019.

Schneising, O., Buchwitz, M., Reuter, M., Vanselow, S., Bovensmann, H., and Burrows, J. P.: Remote sensing of methane leakage from natural gas and petroleum systems revisited, Atmos. Chem. Phys., 20, 9169-9182, https://doi.org/10.5194/acp-20-9169-2020, 2020.

Siddans, R., Knappett, D., Kerridge, B., Waterfall, A., Hurley, J., Latter, B., Boesch, H., and Parker, R.: Global height-resolved methane retrievals from the Infrared Atmospheric Sounding Interferometer (IASI) on MetOp, Atmos. Meas. Tech., 10, 4135–4164, https://doi.org/10.5194/amt-10-4135-2017, 2017.

Stevenson, D., Derwent, R., Wild, O., and Collins, W.: COVID-19 lockdown NO_x emission reductions can explain most of the coincident increase in global atmospheric methane, Atmos. Chem. Phys. Discuss. [preprint], https://doi.org/10.5194/acp-2021-604, in review, 2021.

UNEP-CCAC, United Nations Environment Programme and Climate and Clean Air Coalition, Global Methane Assessment : Benefits and costs of mitigating methane emissions, Nairobi, (2021)

Varon, D. J., McKeever, J., Jervis, D.,Maasakkers, J. D., Pandey, S.,Houweling, S., et al. (2019). Satellite discovery of anomalously large methane point sources from oil/gas production, Geophysical Research Letters, 46, 13,507–13,516, https://doi.org/10.1029/2019GL083798.

Wang, F., Maksyutov, S., Janardanan, R., Tsuruta, A., Ito, A., Morino, I., Yoshida, Y., Tohjima, Y., Kaiser, J. W., Janssens-Maenhout, G., Lan, X., Mammarella, I., Lavric, J. V., & Matsunaga, T. (2021). Interannual variability on methane emissions in monsoon Asia derived from GOSAT and surface observations. *Environmental Research Letters*, *16*(2). https://doi.org/10.1088/1748-9326/abd352

Wilson, C., Chipperfield, M. P., Gloor, M., Parker, R. J., Boesch, H., McNorton, J., Gatti, L. V., Miller, J. B., Basso, L. S., and Monks, S. A.: Large and increasing methane emissions from eastern Amazonia derived from satellite data, 2010–2018, Atmos. Chem. Phys., 21, 10643–10669, https://doi.org/10.5194/acp-21-10643-2021, 2021.

Zhang, Y., Gautam, R., Pandey, S., Omara, M., Maasakkers, J. D., Sadavarte, P., Lyon, D., Nesser, H., Sulprizio, M. P., Varon, D. J., Zhang, R., Houweling, S., Zavala-Araiza, D., Alvarez, R. A., Lorente, A., Hamburg, S. P., Aben, I., & Jacob, D. J. (2020). Quantifying methane emissions from the largest oil-producing basin in the United States from space. *Science Advances*, *6*(17), 1–10. https://doi.org/10.1126/sciadv.aaz5120

Zhang, Y., Jacob, D. J., Lu, X., Maasakkers, J. D., Scarpelli, T. R., Sheng, J.-X., Shen, L., Qu, Z., Sulprizio, M. P., Chang, J., Bloom, A. A., Ma, S., Worden, J., Parker, R. J., and Boesch, H.: Attribution of the accelerating increase in atmospheric methane during 2010–2018 by inverse analysis of GOSAT observations, Atmos. Chem. Phys., 21, 3643–3666, https://doi.org/10.5194/acp-21-3643-2021, 2021.

***** End of Document *****